Tire Materials and How They Affect Friction: From Atoms to Surface Dynamics

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DOI: 10.64823/ijter.2601007

Date of Submission: Nov 13, 2025, **Date of Acceptance (Fast Track):** Jan 06,2026, **Date of Publication:** Jan 30, 2026

Abstract: *Friction is a resistive force between two surfaces that slide against each other. This experiment investigated how different materials affect frictional behavior on an imitation road surface. Rubber, ABS plastic, aluminum, and poplar were all dry-slid using a paver stone as a ramp to imitate asphalt. Each material was placed on top of the ramp. Then, the angle was increased until the sample moved. Additionally, the angle for the object to fall at a constant velocity was found. Each material was tested five times with two recorded angles for each trial. The values were then used to calculate friction coefficients. The results showed that rubber had a static friction coefficient of $\mu = 0.91$, followed by wood at $\mu = 0.62$, then plastic with $\mu = 0.47$, and finally aluminum at $\mu = 0.30$. Rubber also had the highest kinetic friction, due to its low hardness and loose molecular structure. Alternatively, aluminum displayed the lowest friction coefficient, even though it had the highest surface energy. This demonstrates that surface bonding alone does not have a large impact on frictional behavior. These findings show the importance of variables such as material roughness, composition, weight, hardness, and intermolecular bonding in friction. Additionally, this experiment depicts possibilities for tire applications. Wood is a possible alternative due to its stability and relatively high friction. Material weight and environmental variables were all controlled to better test properties as significant variables. The demonstrated results can influence environmentally friendly tire development, balancing frictional performance with sustainability.*

Key Words: *Friction, Coefficient of Friction, Molecular Structure, Intermolecular Bonding*

INTRODUCTION

Friction is a resistive force relative to the motion of two surfaces sliding against each other. Friction is essential for many daily activities. This concept was first described by Leonardo da Vinci. Vinci recognized that friction is proportional to the normal force of an object but unrelated to the contacting surface area. Later, Guillaume Amontons created two laws that now represent friction as it is known today. The scientific observation made by Vinci and Amontons explains how objects can slow to a stop on roads today.

Together, the various sources cited in this study present a multidimensional understanding of friction. Not only at the surface level, but spanning molecular dynamics, surface chemistry, thermal behavior, material science, and sustainability. With a focus on tires and transportation, this research indicates that chemical composition, reinforcement structure, environmental exposure, and surface interaction must all be balanced to optimize safety and efficiency. As tire designs shift toward sustainable, environmentally friendly materials and innovative composites, it is important to understand every variable affecting the force of friction.

In this experiment, different materials are tested to see how they interact with an imitated road surface to better understand the effect of surface texture and material type on friction. This study wishes to magnify effects of friction at the nanoscale. The nanoscale is a small scale consisting of large molecules and the interacting particles and forces between them. Also explained is how friction can be affected by the chemical bonds found in materials. The materials used in this research include Plastic Legos, plywood, rubber bands, and aluminum foil. Those materials were placed on a pavement stone meant to mimic a real road. By gradually raising one side of the pavement stone, the angle at which the object begins to slide is measured. Then, the amount of friction each material has against the stone can be calculated. Each angle is measured using a protractor and compared as a whole. This method allows for the comparison of how each surface responds to increasing slope and identifies each material's resistance to sliding. Finally, the effect of different types of bonds that make up each material and the angle at which they slide will be described and differentiated to understand how those characteristics affect the total force of friction.

The main goal of this study is to answer the question, "How do different tire materials and their underlying properties affect friction on an imitation road surface?". By comparing their sliding angles, this study hopes to better understand which materials could be used safely and efficiently on a road surface. This study hypothesizes that the physical and chemical properties of tire materials have a significant influence on frictional behavior, with softer, more adhesive materials generating higher friction than harder materials that are smoother. The conclusions made can help drive decisions in real-world settings like tire design, road safety, and construction materials, as it strives for a more sustainable and environmentally friendly world.

I. Literature Review

1.1 Basic Friction

Gao et al. describe how friction plays a critical role in the performance of moving systems, particularly in applications such as tires, where grip, energy efficiency, and wear resistance are essential (2004). Friction is proportional to the applied load, which is the product of acceleration due to gravity and the mass of the object, and is independent of contact area and sliding speed as proposed by Amonton's Law. However, this broad view cannot portray the largely complex nature of friction, specifically at the molecular level. Alternatively, friction results from both mechanical interaction and the loss of thermodynamic energy. This energy dissipation is determined by the density of interacting atoms rather than the contact area between atoms. Furthermore, the chemical composition of materials complicates frictional behavior. At the nanoscale as described before, the chemical bonds between multiple materials influence friction changes with velocity. This concept is memory distance, as described by Tian et al. (2019). Their study describes how surface chemistry controls kinetic friction. Similarly, Chen et al. (2019) show that surface features on the atomic level and hydrogen bonding play major roles in complex views of friction. Markov (2022) experiments with both attractive and repulsive forces during surface contact, rather than solely adhesion models. With this, he portrays the large role of electron orbits and molecular bonds in shaping friction. These articles offer insights into the nanoscale differences and bonds between objects that can affect friction and advance tribology. Lastly, Devaraju (2016) provides a large-scale perspective of the variables that affect dry sliding friction, including surface roughness, temperature, load, and sliding speed. His study reinforces the idea that material properties, environmental conditions, and surface geometry all must be considered when designing or selecting tire materials.

1.2 Rubber

Fukahori et al. (2019) explains motion in which rubber slides with another surface in an irregular manner alternating with periods of no relative motion. Additionally, they explain how adhesive forces control rubber's behavior, especially in high-friction applications like tires. They present a new theory integrating adhesion, deformation, and crack formation, providing a more accurate framework for understanding rubber wear and performance under load. It was found that behaviors such as high friction coefficient and intense stick-slip motion are all caused by the sticky characteristic of the surface of cross-linked rubber. This means that the nanoscale differences between rubbers are less impactful on the larger frictional force. However, the total friction coefficient of rubber consists of an adhesion term, a deformation term, and a crack formation term, which creates a larger total force of friction. Therefore, rubber's physical properties, like low hardness, high resilience, high elasticity, and abrasion resistance, make it a strong candidate for tire materials.

1.3 Wood

Atack and Tabor (1958) studied wood friction, finding that adhesion and deformation both contribute to friction and are influenced by environmental conditions such as moisture content. Their study demonstrates how natural lumber responds to humidity and surface pairing. This allows for friction models with modern interpretations in soft, porous, or biological materials. As found in this research, the sliding friction of wood is equivalent to the sum of the tangential force deforming the wood and the tangential force required to overcome adhesion between the face of the wood and other surfaces. Due to the hydrogen bonds found in wood, friction is fairly high with a low moisture content, but decreases as moisture exceeds thirty percent. Therefore, surface structure is incredibly important for adhesion, impacting friction. Aside from the hydrogen bonds, physical properties like lower hardness in soft woods, strength and rigidity of hardwoods, and high stiffness also affect friction.

1.4 Plastic

When it comes to plastic friction, thermal properties and contact heat transfer determine the majority of the force (Endo & Marui, 2004). This study found that materials with high tensile strength perform poorly under frictional load if they cannot resist heat. Acrylonitrile butadiene styrene (ABS) plastic, as seen in LEGO bricks, does not conduct heat well, softens at temperatures above 105 degrees Celsius, and has a low contact area. Based on the findings in this study, plastics have a relatively low frictional force. This study is important for plastic components in transportation, where heat buildup can lead to wear and reduced efficiency. However, when heat is not a factor, plastic is very resistant to various chemicals, wear, and impact, which makes it viable for tire structure.

1.5 Aluminum

Another largely used material in the transportation industry is aluminum composite material. Wang and Zhang (2023) review how aluminum alloys reinforced with other particles improve wear resistance. These particle-reinforced aluminum matrix composites decrease deformation and adhesive wear. This is primarily due to its underlying properties, including high specific strength, specific stiffness, hardness, a stabilized surface roughness, a low coefficient of thermal expansion, and wear resistance. On the atomic level, aluminum's electron configuration allows for strong metallic bonds to be created, which gives it a larger coefficient of friction than other metals. Therefore, aluminum offers a lightweight alternative to primarily rubber tires.

1.6 Alternatives

There is an increased need to create alternatives to conventional tire materials as more widely used plastics are released into the atmosphere from plastic rubbers. Thomas and Patil (2023) describe how biobased, recycled, and renewable polymers are more sustainable and environmentally friendly. These materials are largely based on plant materials such as soybean oil, rice husks, and guayule dandelion, or recycled polymers from bottle waste, polystyrene, and scrap tires. These materials present significant environmental benefits, but their frictional properties have yet to be made safe. Creating a sustainable and durable material is at the heart of tire innovation.

1.7 Safe Friction

While everything generates a frictional force differently, there must be certain levels of friction on roads to create a safe environment. Wallman and Åström (2001) measure the correlation between levels of road friction and danger. They focus on the importance of friction for safety while keeping complexity in mind. It was found that a precise conclusion is extremely unlikely, but rough estimations can be made to create common levels for safe friction. Additionally, there is no standard friction measurement across other countries. As a result, international data comparisons are unreliable. The report also takes driving conditions into account. These include road appearance, vehicle feedback, and weather conditions. Research consistently shows an increase in accident risk on roads when friction levels decrease below 50 or a frictional coefficient of 0.5. Therefore, too much friction would be harmful to the environment and inefficient, while too little friction leads to drastically less road safety.

II. METHODOLOGY

2.1 Materials and Setup

This study was conducted to investigate the frictional behavior of four common or potential tire materials—plastic (LEGO® bricks), rubber (rubber bands), aluminum (aluminum foil), and wood (plywood)—by observing the angle at which each material begins to slide on an inclined surface. To ensure fair comparison with all trials, each material was tested at a weight of 50 grams. The materials were weighed using a digital scale with ±0.1 gram precision. To get the weight of the material, the Bojangles® gift card was first placed on the scale, and the tare function was applied to zero out its mass. Then, three evenly spaced horizontal strips of 6-inch Scotch tape were taped on the bottom of the Bojangles® gift card. This layer of tape was an adhesive base for each test material. The material was added gradually and pressed firmly into a solid object until the total weight of the material reached 50.0 grams.

The testing ramp used in this experiment was a concrete paver stone because of its texture and similarity to road surfaces. One end of the paver stone was placed against a vertical wooden wall, and the other end rested on the ground. During testing, the free end of the paver was slowly lifted to increase the angle of inclination. A handheld protractor was positioned at the rear of the stone, aligned horizontally with the table surface, and used to measure the incline angle. This created a right triangle, where the paver stone was the hypotenuse, the ground was the horizontal leg, and the wooden wall was the vertical leg. As the stone was elevated, the incline angle increased until the force of gravity exceeded static friction, which caused it to slide. The experiment was conducted indoors at room temperature (~22°C) to eliminate any variables. Identical equipment and procedures were used in the experiment to ensure consistency and reliability.

2.2 LEGO® Brick Setup (Plastic Material)

To prepare the plastic sample, LEGO® bricks were placed on the digital scale until it reached 50.0 grams. The formation of the LEGO bricks was kept as uniform as possible to maintain flat contact with the ramp surface. During testing, the LEGO® sample was placed flat at the bottom of the paver ramp. The stone was gradually lifted by hand while the protractor measured the angle. The angle at which the sample began to slide was then recorded. This procedure was finally repeated five times to ensure consistent data.

2.3 Rubber Band Setup (Rubber Material)

To provide a flat base, a Bojangles® gift card was used to wrap rubber bands around to create one rubber block. Flat rubber bands were layered and pressed onto the tape until the total weight reached 50 grams. The layout also consisted of a uniform formation to keep constant flat contact with the ramp surface. The rubber sample was then placed on the ramp, and the incline was increased slowly by lifting the paver stone. The moment the rubber sample began to slide was recorded as the angle of friction. This test was performed five times to find reliable results.

2.4 Aluminum Foil Setup (Aluminum Material)

The aluminum sample trial started by first weighing out 50 grams of aluminum foil. Next, the Bojangles card was placed on the digital scale to verify a total of 50 grams. Finally, the aluminum foil was wrapped around the gift card and pressed firmly on a flat surface to create a smooth, even surface. After that, additional foil was added until the weight reached 50 grams. The foil was once again in a smooth formation to keep even contact with the ramp. During each trial, the aluminum sample was placed at the top of the ramp, and the incline angle was gradually increased. The protractor was used to obtain the angle at which the sample slid down. This was repeated five times to record accurate data.

2.5 Poplar Setup (Wood Material)

The wood sample came from a bed frame made of poplar wood. The wood was cut, and the cut edge was sanded flat to not skew any results. Then, this piece was weighed again to verify it reached a mass of 50 grams. The testing followed the same procedure. The sample was placed flat on the paver ramp and inclined gradually until the material slid down. The angle was recorded, and the process was repeated five times, ensuring that the data acquired was valid.

2.6 Testing Procedure and Data Collection

Each of the four material types was tested five times, which totals to twenty data points. In each trial, a fully assembled sample, weighing 50 grams, was placed at the top of the inclined paver stone. A handheld protractor was placed behind the ramp to measure the angle of inclination. The paver stone was then slowly raised at one end by hand. When the sample began to slide, the angle was recorded using the protractor to the nearest degree. This angle was named the angle of first movement for that trial. Then, using research from the literature review, we set the stage for the average angle shown to allow the object to move at a constant velocity. Then, the object was pushed slowly down the paver stone to observe if the velocity changes. Depending on the results, the paver stone was moved up or down to find the angle at which the object moved with a constant velocity. After each measurement, the ramp was lowered back to its original position. A 30-second pause also occurred between the trials to allow for stabilization before the next run. All trial data, which includes material type, trial number, and recorded sliding angle, was documented in a lab notebook and then entered into a digital spreadsheet. The average sliding angle was calculated for each material to find its mean frictional performance along with the standard deviation between each trial. Finally, all recorded values are converted into friction coefficients. For a kinetic friction coefficient to be safe and efficient, it should fall between the range of 0.5 to 0.8. On the other hand, static friction should be greater than 0.7. For static friction, the tangent of the angle at which the block starts moving is equivalent to the coefficient. For kinetic friction, the tangent of the angle at which the block slides at a constant velocity is equivalent to the coefficient.

2.7 Controlled Conditions

To maintain accurate data throughout the study, all testing was conducted in an indoor environment, with the temperature maintained at approximately 22°C. The same Bojangles® gift card, digital scale, Scotch tape, paver stone, and protractor were used across all materials and trials. Each sample was also assembled using the same method, beginning with taping the card and followed by attaching material up to 50 grams. All incline angles were measured with the same protractor to maintain consistent techniques. By controlling the external factors and applying a consistent construction and testing across the experiment, it ensured that variations in sliding angle were the reason it slid, rather than inconsistencies in setup or measurement.

III. Results and Discussions

Trial	Angle of First Movement	Angle of Constant Velocity	Coefficient of Static Friction	Coefficient of Kinetic Friction
Plastic 1 -	36	31	0.45	0.38
Plastic 2 -	37	33	0.47	0.41
Plastic 3 -	44	38	0.60	0.49
Plastic 4 -	34	30	0.42	0.36
Plastic 5 -	35	30	0.44	0.36
Plastic Average -	37.2 ± 3.96	32.4 ± 3.36	0.47 ± 0.073	0.4 ± 0.054
Rubber 1 -	52	46	0.80	0.65
Rubber 2 -	54	47	0.86	0.67
Rubber 3 -	59	53	1.04	0.83
Rubber 4 -	57	50	0.96	0.74
Rubber 5 -	55	48	0.89	0.69
Rubber Average -	55.4 ± 2.70	48.8 ± 2.77	0.91 ± 0.093	0.71 ± 0.072
Aluminum 1 -	30	25	0.36	0.29
Aluminum 2 -	23	18	0.27	0.20
Aluminum 3 -	26	22	0.30	0.25
Aluminum 4 -	27	23	0.32	0.27
Aluminum 5 -	23	18	0.27	0.20
Aluminum Average -	25.8 ± 2.95	21.2 ± 3.11	0.3 ± 0.04	0.24 ± 0.039
Wood 1 -	43	34	0.58	0.42
Wood 2 -	45	36	0.62	0.45
Wood 3 -	47	38	0.67	0.49
Wood 4 -	42	33	0.56	0.41
Wood 5 -	47	38	0.67	0.49
Wood Average -	44.8 ± 2.28	35.8 ± 2.28	0.62 ± 0.049	0.45 ± 0.038

(Figure 1). Table showing data for each of the five trials for all four objects. Shows angles for both the first movement and constant velocity, along with coefficients of static and kinetic friction. Additionally, averages and standard deviations are shown for each material.

3.1 Plastic

After all trials were completed between each material, plastic showed a moderate frictional force. Across five trials, the angle at which the plastic first began to move ranged from 34 to 44 degrees from the horizontal. All together, the average angle was 37.2 degrees. The angle at which the plastic moved at a constant velocity had a range of 30 to 38 degrees and an average of 32.4 degrees. The coefficient of static friction averaged 0.47, while the coefficient of kinetic friction averaged 0.40. Therefore, plastic moderately resisted motion on the paver stone surface, with a consistent difference between static and kinetic friction. The standard deviation was ±0.073 for static friction and ±0.054 for kinetic friction. Plastic's surface energy was relatively moderate at a value of 40. Also at the nanoscale, ABS plastic contains covalent bonds, van der Waals, and dipole-dipole forces, which give it a moderately strong intermolecular structure. Lastly, ABS plastic was the second hardest material with a Rockwell R hardness of 110.

3.2 Rubber

Rubber had the highest frictional resistance out of all the tested materials in this experiment. The angle of first movement ranged from 52 to 59 degrees, with an average of 55.4 degrees. The angle at which the rubber moved with a constant velocity was 48.8 degrees. The average coefficient of static friction was 0.91 with a standard deviation of ±0.093. Kinetic friction had a coefficient of 0.71 with a standard deviation of ±0.072. Rubber had the lowest surface energy among the tested materials, with a value of 30mJ/m^2. Similarly, rubber had the lowest hardness. Rubber generally falls at a value of 25 on the Shore A durometer scale. In correlation with its hardness, rubber's molecular structure includes covalent bonds and van der Waals forces, which give it a very loose structure and low intermolecular force.

3.3 Aluminum

Aluminum showed the lowest friction values of all the materials tested in this experiment. The angle of aluminum's first movement ranged from 23 to 30 degrees and averaged 25.8 degrees. For constant velocity, the angle ranged from 18 to 25 and averaged 21.2 degrees. The coefficient of static friction averaged 0.30, and the kinetic coefficient averaged 0.24.

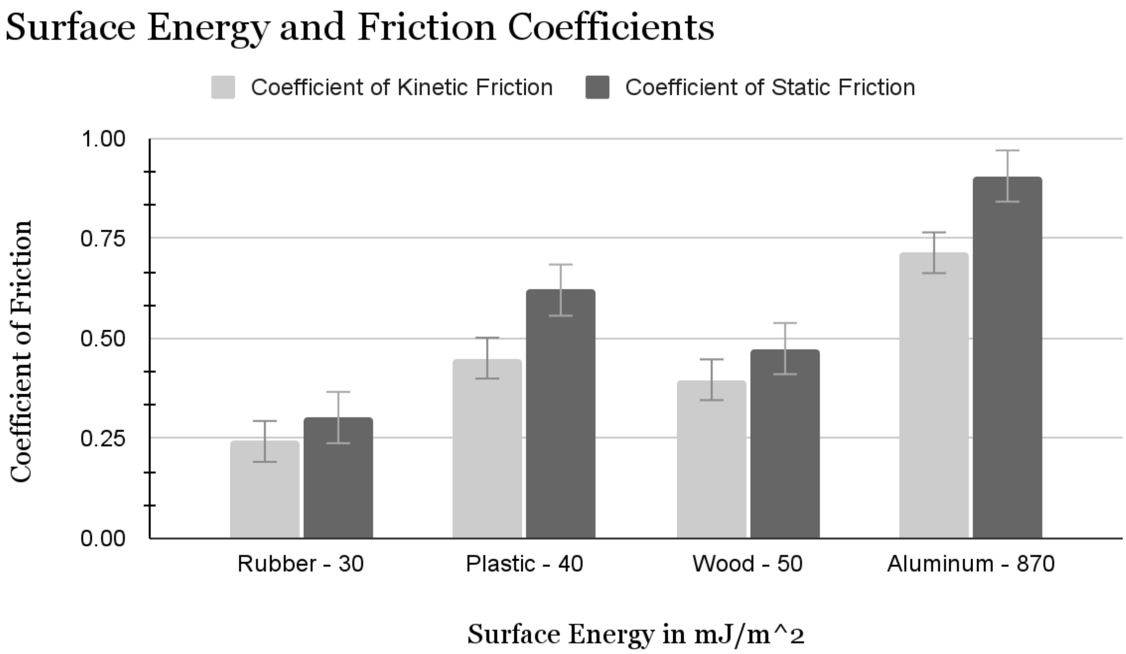
Standard deviations were ±0.040 for static friction and ±0.039 for kinetic friction, which portrays a moderate to low frictional force. However, aluminum has the highest surface energy of the attested materials, with a value of 870 mJ/m^2. In parallel, aluminum has strong metallic bonds, creating a metallic lattice and leaving electrons delocalized. This is also partly the reason for aluminum's hardness. On the Rockwell B scale, aluminum has a hardness of 60 HRB.

3.4 Wood

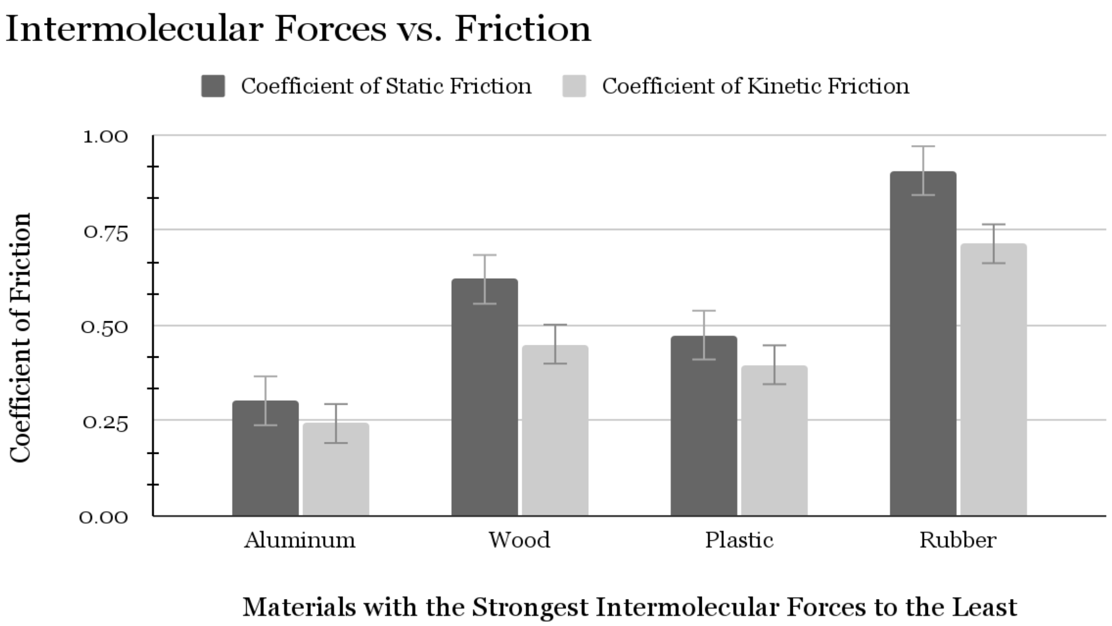
Poplar wood demonstrated a stronger frictional force in comparison to aluminum and plastic. The angle of first motion ranged from 42 to 47 degrees with an average value of 44.8 degrees. Additionally, the angle at which wood moved down the slope at a constant speed ranged from 33 to 38 degrees, with an average value of 35.8 degrees. The coefficient of static friction averaged 0.62 with a standard deviation of ±0.049. Alternatively, kinetic friction had a coefficient of 0.45 with a standard deviation of ±0.038. Poplar wood is measured on the Janka scale for hardness. This material ranked third with a hardness of 540 lbf. Similar to rubber, poplar wood has covalent bonds and van der Waals forces to hold its molecules together. However, wood has additional hydrogen bonds, which give it a stronger intermolecular structure. On the other hand, wood had a surface energy of 50 mJ/m^2.

3.5 Calculations and Coefficients

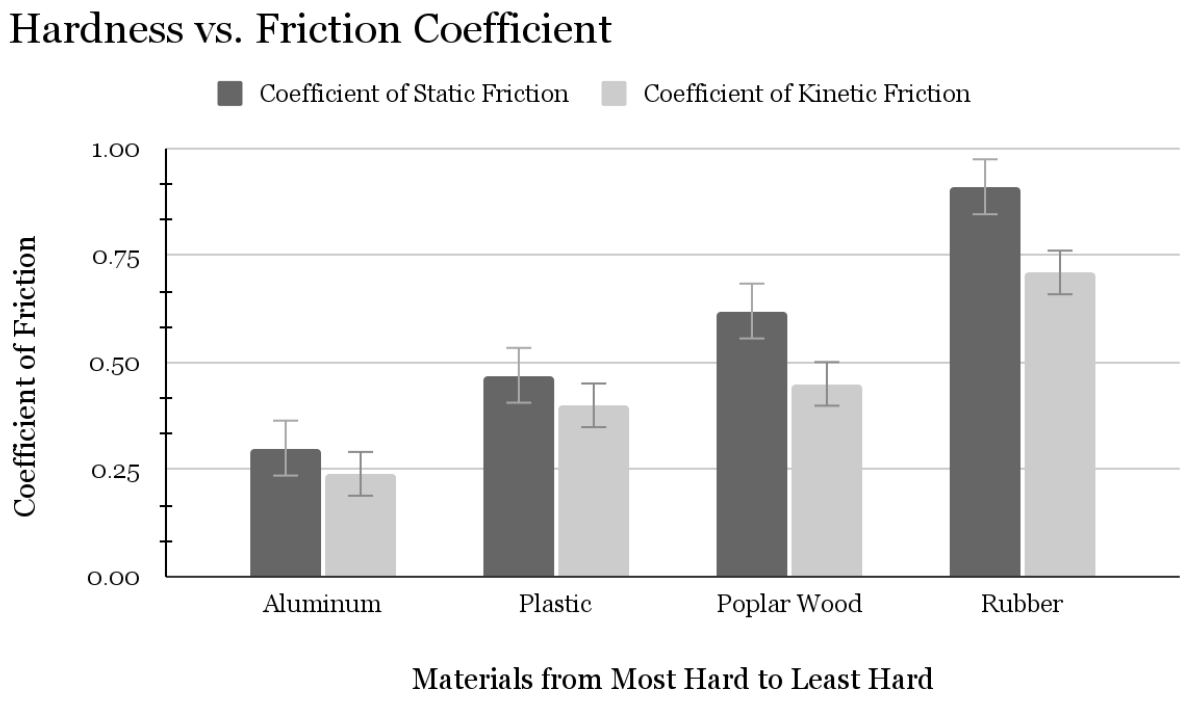
All materials tested were 50±0.1 grams. The coefficients of friction were calculated using the equation: μ = tangent (θ). Where μ is the coefficient of friction and θ is the angle at which the material began moving when testing static friction or moved at constant speed when testing kinetic friction. The values from each test, average coefficients, and their standard deviations for each material are summarized in Figure 1. Rubber has greater friction than the other materials in the experiment, both in kinetic and static conditions. On the other hand, aluminum demonstrated the lowest in most of the experiments. In total, the standard deviation was relatively low for all categories.



(Figure 2). Shows the surface energy in each material in correlation with the coefficient of friction. Standard deviation is also shown for each material and coefficient of static and kinetic friction.



(Figure 3). Bar chart depicting the correlation between friction and intermolecular forces. Intermolecular forces include bonds, attractive, and repulsive forces between molecules in a sample.



(Figure 4). Bar chart portraying the hardness of each material compared to the frictional coefficients. Hardness is calculated via the Rockwell B, Rockwell R, Shore A, and Janka scales.

3.6 Overview

In this study on friction, various materials, including wood, plastic, aluminum, and rubber, were placed onto an imitation concrete surface, which was gradually increased on one side to create an angle. The angle at which each material slid was observed, recorded, and analyzed to compare the amounts of friction that each material has on a surface that imitates a concrete road. The results of the study provided important information about the differences in friction that various materials have, which also explained why each may provide different benefits or drawbacks for a tire. The results of the trial revealed that rubber had the greatest amount of friction on an imitation road surface, followed by wood, plastic, and finally aluminum. The results showed why rubber is used most commonly as the material in tires. Rubber was able to stay in place, without sliding, at an angle as high as 50 degrees. The results also showed that other materials, such as wood, plastic, and aluminum, were not as resistant to gravity, because they slid at angles of 45, 37, and 26 degrees, respectively. The high angle that rubber was able to endure represents the sharp turns and steep hills that a car typically drives through.

The experiment's findings can be explained by various properties that each material possesses. Rubber was the least hard material, which is part of the reason why it could endure a much higher angle. A common trend revealed by the research in the experiment is that hardness allows an object to slide more easily and has less friction. The research also revealed that the strength of the intermolecular forces can significantly impact the amount of friction that each material has. The trend revealed in the data is that the material with the weakest intermolecular forces, rubber, also had the highest coefficient of friction. Surface energy was also one of the forces that the study revealed affected friction. Surface energy is the level of excess energy at an object's surface, quantified by the disruption of intermolecular bonds that occur when a surface is created. Rubber has the weakest surface energy, which contradicts the hypothesis made in this study. Surface energy is an attractive force, meaning the more energy present on a surface there is, the more adhesion will be between the molecules of two surfaces. Therefore, surface energy must play a very minimal role in the true force of friction on a road surface. In conclusion, various factors such as roughness, composition, weight, intermolecular forces, and hardness all contribute to how friction changes between materials on an imitation road surface.

The hypothesis proposed that the physical and chemical properties of tire materials have a significant influence on frictional behavior, with softer, more adhesive materials generating higher friction than harder materials that are smoother. The study concluded that rubber is the most suitable material to use for tires because it creates significant amounts of friction needed for safety while still being efficient on a surface that imitates a road. Also found was that chemical and physical properties played a large role in how friction differs between materials. Therefore, sufficient evidence is provided that physical and chemical properties have a significant effect on frictional behavior, and softer, more adhesive materials, like rubber, generate higher frictional forces.

3.7 Safe Frictional Values

Safe frictional values typically can be described as the minimum amount of friction that is required between a surface and a material to prevent sliding or slipping under typical driving conditions. Safe frictional values are extremely important in the everyday lives of most people whenever they drive a car, ride a bike, or pull a wagon. Safe frictional values are the reason why a person's car does not simply hydroplane when it is wet or get stuck when driving up a hill. Throughout the experiment, various materials were tested to see how much friction they have on an imitation road surface and how they reflect the safe frictional values that are required to be used for transportation. The angle that each material slides at can be converted to a friction coefficient using mathematics, which can help show whether or not each material would be safe to use on a road.

The results from the experiment show which materials have safe friction values and which ones do not. This helps engineers and researchers narrow down which materials would be the best for making tires that do not slide on roads. From the research that was conducted, rubber slid at the highest angle, 50 degrees, which equates to a coefficient of friction greater than 0.5, which means that it exceeds the minimum frictional values that are required for typical road conditions, meaning that the rubber is ideal for safe transportation. Although rubber was found to have safe frictional values, other materials such as aluminum, plastic, and wood did not. Aluminum, plastic, and wood had coefficients of kinetic friction below the minimum 0.5 requirement, which shows why they do not have safe frictional values and should not be used as standalone tire materials. Aluminum, plastic, and wood would all pose extreme danger concerns if they were used as a material for tires, and would most likely lose grip, slide, and hydroplane. The typical safety standard for vehicle safety on roads is that the friction coefficient must be greater than 0.5 for dry roads. The friction coefficient of rubber was 0.71 on average, which is in the qualifying range. If the friction coefficient is not high enough, cars can slide, lose control, lose the ability to stop quickly, and even wear out the tires significantly faster. In general, the material that is being used for things like tires should be thoroughly tested for its friction coefficient, and only if this friction coefficient is within the safe frictional values allowed for transportation on roads should the material be approved and used.

3.8 Limitations and Future Research

Although this experiment showed significant insight into various materials and the amounts of friction that each has on an imitation road surface, there are still certain shortcomings in this experiment that can potentially be expanded upon through future research. The easiest and simplest way to expand this experiment in future research is to add more materials to the experiment. This experiment tested the friction of rubber, wood, plastic, and aluminum by measuring the angle at which each material slid on concrete. The experiment could be expanded through future research by adding other materials that were not tested, such as silicone or other materials similar to plastic. Testing more materials would provide more insight into friction and possibly help find materials that are even better than rubber that can be used for tires to prevent skidding and hydroplaning.

For further understanding of friction as a whole, materials such as glass, steel, or other plant-based or sustainable rubbers could also be tested and researched. Another way to continue testing the effects of friction that various objects have would be to substitute the imitation road surface for other surfaces to see how it affects the friction that each material has. The concrete that was used in the experiment may have been extremely similar to an asphalt road, but the experiment could be improved by using a real road surface to slide the materials on. The experiment could also be tested further by making the road surface wet, rough, or smooth to represent the various types of roads that the tires might drive on. The experiment was performed in a controlled setting, with controlled variables, rather than on a real road on which the tires would drive. The experiment could be performed once more, but instead of being done in a controlled environment, it could include things like rain, wind, temperature changes, or dirt, which can all affect real friction values. The study could be improved by using digital angle finders instead of traditional protractors to be more precise. This would make the measures much closer to their true values and help to find more information about friction. Things like weight and size could also have slight impacts on the amount of friction that could be changed in future experiments to have much more similar masses and results. The experiment could be replicated many more times to see how weathering over time can affect friction, which would help to see how each material would perform as a real tire. Additionally, the behavior that each material exhibits while sliding can be measured to see how they would behave as a real tire. In the future, scientists could improve the experiment in various ways to help gain a better understanding of friction and tire materials. Lastly, the rubber found in today's tires contains large amounts of plastic, which leach out into the atmosphere. This effect can be very harmful to the environment. Therefore, in future research, the knowledge learned about friction in this study can be used to develop a sustainable alternative to a polymer-based rubber.

IV. ACKNOWLEDGMENTS

We would like to express our gratitude towards the Greensboro College for housing our research group for a month and our Natural Science teachers, Ley King-Bennett and Michelle Allison, for their help and assistance in conducting our research experiment by providing our materials and revising our paper. Furthermore, we would like to thank the Governor School program for allowing us the opportunity, resources, and academic environment to carry out this experiment and share our findings. Lastly, we would like to thank Mrs. Wendy Thorp and the rest of the cafeteria staff for providing meals to our research group throughout our month at Governor's School West.

V. BIBLIOGRAPHY

[1] J. Gao, W. D. Luedtke, D. Gourdon, M. Ruths, J. N. Israelachvili, and U. Landman, "Frictional forces and Amontons' law: From the molecular to the macroscopic scale," *J. Phys. Chem. B*, vol. 108, no. 11, pp. 3410–3425, Feb. 2004, doi: 10.1021/jp036362l. (ACS Publications)

[2] K. Tian, Z. Li, N. N. Gosvami, D. L. Goldsby, I. Szlufarska, and R. W. Carpick, "Memory distance for interfacial chemical bond-induced friction at the nanoscale," *ACS Nano*, vol. 13, no. 7, pp. 7425–7434, Jul. 2019, doi: 10.1021/acsnano.8b09714. (PubMed)

[3] Z. Chen, A. Khajeh, A. Martini, and S. H. Kim, "Chemical and physical origins of friction on surfaces with atomic steps," *Sci. Adv.*, vol. 5, no. 8, Art. no. eaaw0513, Aug. 2019, doi: 10.1126/sciadv.aaw0513. (PMC)

[4] Y. Fukahori, P. Gabriel, H. Liang, and J. J. C. Busfield, "A new generalized philosophy and theory for rubber friction and wear," *Wear*, vols. 446–447, Art. no. 203166, Apr. 2020, doi: 10.1016/j.wear.2019.203166. (ScienceDirect)

[5] D. Atack and D. Tabor, "The friction of wood," *Proc. R. Soc. Lond. A*, vol. 246, no. 1247, pp. 539–555, Aug. 1958, doi: 10.1098/rspa.1958.0163. (Royal Society Publishing)

[6] H. Endo and E. Marui, "Fundamental studies on friction and wear of engineering plastics," *Ind. Lubr. Tribol.*, vol. 56, no. 5, pp. 283–287, Oct. 2004, doi: 10.1108/00368790410550697. (ResearchGate)

[7] J. Thomas and R. Patil, "The road to sustainable tire materials: Current state-of-the-art and future prospectives," *Environ. Sci. Technol.*, vol. 57, no. 6, pp. 2209–2216, Feb. 2023, doi: 10.1021/acs.est.2c07642. (PubMed)

[8] Y. Wang and J. Zhang, "A review of the friction and wear behavior of particle-reinforced aluminum matrix composites," *Lubricants*, vol. 11, no. 8, Art. no. 317, Jul. 2023, doi: 10.3390/lubricants11080317. (MDPI)

[9] D. P. Markov, "Adhesion at friction and wear," *Friction*, vol. 10, no. 11, pp. 1859–1878, 2022, doi: 10.1007/s40544-021-0564-7. (Springer Link)

[10] A. Devaraju, "A review on important factors affecting dry sliding friction," *J. Surf. Sci. Technol.*, vol. 32, nos. 3–4, pp. 73–78, Apr. 2017, doi: 10.18311/jsst/2016/7751. (informaticsjournals.co.in)

[11] C.-G. Wallman and H. Åström, *Friction Measurement Methods and the Correlation Between Road Friction and Traffic Safety: A Literature Review*, VTI Meddelande 911A, Swedish National Road and Transport Research Institute (VTI), Linköping, Sweden, 2001. (diva-portal.org)