18/36

International Baccalaureate

Extended essay cover

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Candidate session number	0 0 0 2 5 0		
Candidate name			
School number	0 0 0 2 5 0		
School name	Saint Petersburg High School		
Examination session (May or November)	May	Year	2013

Diploma Programme subject in which this extended essay is registered: Physics

(For an extended essay in the area of languages, state the language and whether it is group 1 or group 2.)

Title of the extended essay: What is the impact, if any, of changes in surface temperature of a flat, hard surfaced object on the coefficient of friction.

Candidate's declaration

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The extended essay I am submitting is my own work (apart from guidance allowed by the International Baccalaureate).

I have acknowledged each use of the words, graphics or ideas of another person, whether written, oral or visual.

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Candidate session number	0	0	0	2	5	0			

Criteria	Examiner 1	maximum	Examiner 2	maximum	~~Examiner 3~~ Mr. Smith
A research question	1	2		2	2
B introduction	2	2		2	1
C investigation	2	4		4	3
D knowledge and understanding	2	4		4	1
E reasoned argument	2	4		4	3
F analysis and evaluation	1	4		4	3
G use of subject language	2	4		4	3
H conclusion	1	2		2	2
I formal presentation	2	4		4	2
J abstract	2	2		2	2
K holistic judgment	1	4		4	2
Total out of 36	18				24

Name of examiner 1: FERDi KAYA Examiner number: 088164
(CAPITAL letters)

Name of examiner 2: ______ Examiner number: ______
(CAPITAL letters)

Name of examiner 3: ______ Examiner number: ______
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Please comment, as appropriate, on the candidate's performance, the context in which the candidate undertook the research for the extended essay, any difficulties encountered and how these were overcome (see page 13 of the extended essay guide). The concluding interview (viva voce) may provide useful information. These comments can help the examiner award a level for criterion K (holistic judgment). Do not comment on any adverse personal circumstances that may have affected the candidate. If the amount of time spent with the candidate was zero, you must explain this, in particular how it was then possible to authenticate the essay as the candidate's own work. You may attach an additional sheet if there is insufficient space here.

In Florida, we get a lot of rain and Blake became interested in this topic because of car tires on wet pavement with different temperatures. He did all of the data collection at his home. He was able to show a good correllation between temperature and coefficient of friction.

This declaration must be signed by the supervisor; otherwise a grade may not be issued.

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To the best of my knowledge, the extended essay is the authentic work of the candidate.

I spent [6.0] hours with the candidate discussing the progress of the extended essay.

Supervisor's signature: Kyle J. Smith Date: 2/26/13

Physics Extended Essay

What is the impact, if any, of changes in surface temperature of a flat, hard surfaced object on the coefficient of friction?

Candidate #:

Word Count: 3636

Abstract

The purpose of this essay is to investigate the impact of changes in surface temperature on the coefficient of friction between a flat, hard surfaced object and a flat surface. The research is carried out through the conducting of an experiment. This is an experiment in which materials being tested, of which there are five, are fixed to a range of various surface temperatures through the use of a standard microwave and freezer. A 2.43-kilogram hanging weight is used to apply a pulling force on the objects. Once a material is set to a specific temperature, it travels a short distance due to the force applied by the hanging weight. Through the use of a motion detector and the program Logger Pro 3, the acceleration of the materials is determined for each trial.

Utilizing a combination of equations, the recorded values for acceleration can be used to calculate the coefficient of friction for each trial. These coefficient values, along with the surface temperature values, are used to create graphs representing the relationship between the two.

The investigation shows a proportional relationship between the coefficient of friction between the two objects and the surface temperature of the tested material. Furthermore, the research demonstrates that the coefficient of friction approaches a maximum value after certain temperatures have been reached.

Word Count: 217

Contents

1.0 Introduction

The aim of this essay is to determine what impact, if any, changes in the surface temperature of a flat, hard surfaced object have on the coefficient of kinetic friction.

This question was chosen out of a belief that a relationship between surface temperature and friction of a non-pliable, flat surfaced object could be found experimentally. Such a relationship, if found, could be applied to many scenarios. For example, developers and engineers are always trying to find ways of minimizing the effects of friction, in order to limit energy loss and reduce wear and tear of moving parts (Friction). A relationship such as the one being studied in this investigation could be used as another method of controlling friction.

1.1 Principles of Physics Involved:

The investigation of this topic involves knowledge of principles of physics such as Newton's Laws of Motion, the properties of kinetic friction, thermodynamics, and kinematic equations.

Newton's First and Second Laws of motion will be useful in this investigation. The First Law states that "when no forces act on a body, that body will either remain at rest or continue to move along a straight line with constant speed." (Tsokos 69) This means that in the experiment, described below, all of the motion of the tested material is caused by the measured force applied to it. The Second Law of motion provides the relationship between applied force (F), mass (m) and acceleration (a) of an object in the form of $F = ma$, which will be used in processing and analyzing the raw data. (Tsokos 77)

Friction is a force that acts in opposition to motion of one body over another. The causes of friction at the "microscopic scale are still not completely understood" (Friction) and researchers have been working hard for years to discover the precise mechanisms behind it. What is known is that the force of friction is caused by a combination of contact between rough surfaces and electrostatic attraction between molecules (Causes of Friction). Even when two surfaces in contact appear to be smooth, on the microscopic level they can be pitted and jagged, causing the molecules of the two surfaces to interact with each other, forming chemical bonds (Friction). The total force of friction opposing the motion of an object depends on two things: the force holding the objects together, or the normal force, and the nature of the two surfaces in contact. Frictional force can be shown by the equation

$$F_f = F_N \mu,$$

where μ is the coefficient of friction and F_N is the normal force (Friction). The coefficient of friction is the constant of relation between the normal force and the force of friction, and it depends on the two objects in contact (Wróbel 33). It is for this reason that this investigation aims to determine differences in the coefficient of friction, rather than the entire force of friction.

The property of thermodynamics that is most important to for this experiment is the definition of temperature. Temperature is defined as "a measure of the average kinetic energy of the molecules of a substance" (Tsokos 160). This means that at higher temperature, the molecules of an object have more motion or vibration.

Finally, this investigation requires an understanding of the kinematic equations. There are four basic equations for motion with constant acceleration; one in particular, shown below, will be useful later on in data processing. This equation, relating displacement, velocity, acceleration, and time is

$$x = x_0 + v_0 t + \frac{1}{2}at^2.$$ (Tsokos 48)

1.2 Background Research on Topic:

Background research for this investigation uncovered a few previous investigations and experiments related to this one. One such experiment investigated the "influence of temperature on friction coefficient of low density polyethylene," which is a form of plastic primarily used in plastic bags and other packaging (Wróbel 31). This experiment tested "static and dynamic friction coefficients" on low density polyethylene blocks with various meshing and surface characteristics at several temperatures. The investigation resulted in different materials used being affected in different ways by temperature depending on their "constitution and technological characteristics" (Wróbel 34). This is helpful as background research, although the objects tested by Wróbel were pliable, and therefore not the same as the hard, flat surfaced materials being focused on in this investigation.

Another experiment is described in *The Arabian Journal for Science and Engineering*. This experiment tested "the effect of heat treatment on friction and wear behavior of Al-6061 composite reinforced with 10% submicron AL_2O_3 particles," (Al-Qutub 205).which is an aluminum composite known for a high strength to weight ratio. The result of the experiment was that there was a relatively low impact on friction done by heat treatment, but where a difference did occur, the heated samples had a higher coefficient of friction (Al-Qutub 214).

1.3 Planning:

The basic plan for this investigation is to conduct an experiment to determine the acceleration the acceleration of an object when a known force is applied. Note that acceleration is being determined rather than friction in this experiment, due to the fact that friction is impossible to measure directly. The experiment will involve testing various materials for their acceleration under varying surface temperatures. The original plan for investigation was to test flat and non-pliable bricks and metals. Due to the fact that a microwave is used to heat the materials, however, no metals can be tested.

1.4 Hypothesis:

Changes in surface temperature will have a proportional impact on the coefficient of kinetic friction in the tested materials. This hypothesis is based on the background research above as well as the basic principles of kinetic friction and temperature. It is theorized that because at higher temperatures there is more motion in the molecules of an object and that because friction is caused, at least in part, by intermolecular attraction, then there would be more friction at higher temperatures. This is because, it is believed, more motion and vibration in the molecules would allow for more electrostatic attraction between two objects.

2.0 Experiment Description

2.1 Testing Area Set Up:

The testing area designed for the purpose of this experiment is described below and shown in Figures 1 and 2.

Figure 1 – Testing Area

Figure 2 – Testing Area

1. A smoothed sheet of hard plywood with the dimensions of 1 meter by 30 centimeters is secured to a sturdy table with a height of 0.686 meters. It is important that at least one end of the plywood overhangs past the edge of the table. This will serve the function of the testing surface for the experiment.

2. A well-oiled pulley is tightly secured on the overhanging end of the plywood sheet. This pulley is fitted with a $\frac{3}{4}$ inch metal wire.

3. The $\frac{3}{4}$ inch metal wire is fitted through the pulley. The mass of this wire is considered negligible.

4. The overhanging end of the wire was secured to a hanging weight with a total mass of 2.430 ± 0.005 kilograms

5. On the opposite end of the length of wire a small loop is tied. This loop can be connected to hooks of negligible mass that are secured into the tested materials.

6. A Vernier Motion Detector is secured at the end of the testing surface opposite of the pulley. This is connected to a Vernier LabQuest device. The motion detector is set to take 25 samples per second, which is the fastest rate available.

7. A temperature probe, accurate to $0.1\,^{\circ}$Celsius, is also attached to the Vernier LabQuest device.

2.2 Tested Materials Description:

In this investigation, five different brick materials are tested. The bricks used were chosen for their accessibility as well as for their structure. The bricks were also chosen for not being made of the same material, so as to increase the range of materials tested. For this experiment, it is necessary to use bricks that are of relatively uniform size with flat surfaces. They also need to be made up of materials that can be safely heated in a microwave, which is the reason metals could not be tested in this experiment. These materials are described below in order of smoothness and shown in their corresponding figures.

1. The first brick tested was called Tortuga. This brick is the smoothest of the materials that were tested. This brick has a mass of 2.268 ± 0.005 kilograms.

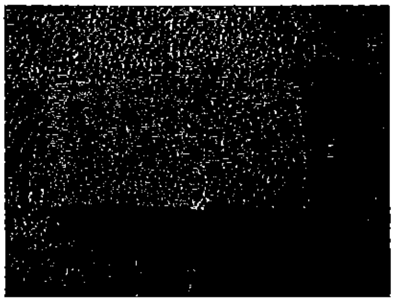


Figure 3 – Tortuga

2. The Bimini brick is less smooth but is the heaviest, with a mass of 2.948 ± 0.005 kilograms.

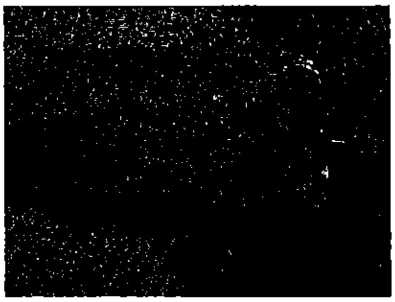


Figure 4 - Bimini

3. The Everglade brick seems to have the hardest surface and has a mass of 2.495 ± 0.005 kilograms.

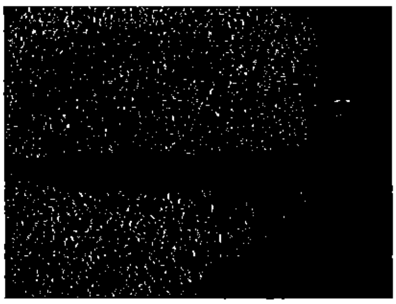


Figure 5 – Everglade

4. A standard Concrete brick has a mass of 2.041 ± 0.005 kilograms.

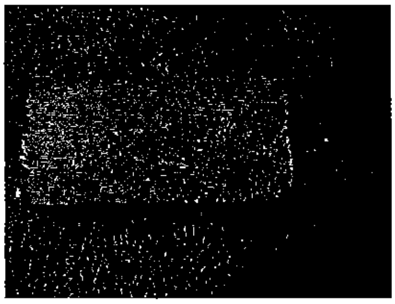


Figure 6 – Concrete

5. The final material is a brick called Sienna. This brick has the most surface roughness. This brick is also the lightest, with a mass of only 1.950 ± 0.005 kilograms.

Figure 7 - Sienna

2.3 Brick Preparation:

Before conducting the experiment, the testing area must be prepared as described in the equipment section above. Once this is completed, a hook needs to be secured to each brick in order to be able to attach it to the wire. To accomplish this, a small hole is drilled into the side of each. Complications can arise here if it proves difficult to drill into some of the harder bricks, so it is necessary to use a special drill bit. Once the holes are properly drilled, metal hooks are screwed into them. Unfortunately, the holes do not provide enough grip to hold the hooks in once a force is applied. In order to counteract this problem, it is necessary to use screw anchors, which are plastic devices that are inserted into a drilled hole. The hooks can then be screwed directly into the anchors and be much better secured.

2.4 Experimental Procedure:

The goal of this experiment is to determine the acceleration of the bricks at different temperatures. Because of this, the most efficient plan for testing is to begin with the bricks set at the coldest temperature possible for the initial test then to heat them up for each subsequent test.

For this to be most easily achieved, the five bricks are placed in a freezer and left to cool overnight. This ensures that they all reached the coldest temperature that is possible.

Once this is finished, one brick at a time is removed from the freezer to be tested. This brick must be wiped off with a cloth to ensure that all frost covering which might reduce friction is removed. Next, the temperature probe is held onto the side of the brick that would be face down until it shows the true surface temperature of the material. This takes longer than expected because although the temperature probe can provide an exact temperature reading, it is slow to adjust to different temperatures.

Immediately after the temperature is measured and recorded, the brick must be immediately attached to the pulley system and held by hand in front of the motion detector.

With the LabQuest instrument connected to a computer and the use of the Logger Pro 3 program, an experiment is created in which the motion detector measures the distance between itself and the brick every 0.04 seconds. Still holding the brick in place, data collection is started. Once measurements begin, the brick is released and the force provided by the hanging weight causes it to slide across the testing surface.

In order to be certain that temperature does not change by a significant amount, the data set provided by Logger Pro must be saved and the test immediately repeated. The test is done a total of three times for each temperature and recorded. Finally, after all three trials have been completed the temperature is measured again. If the tests are done quickly enough, the temperature should not change by a large amount. If it does, however, this change represents a possible source of error in the data.

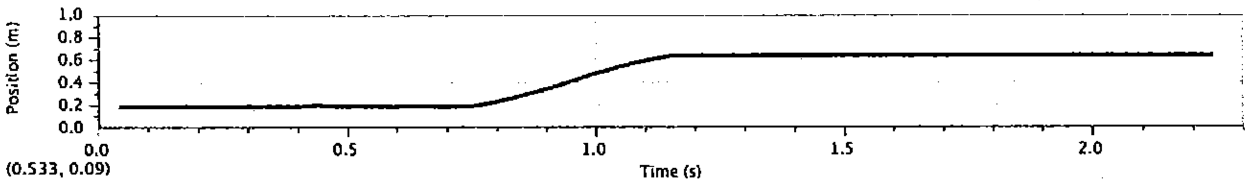
Now the brick needs to be heated to the next temperature. The fastest and most efficient way of achieving this is to place the brick in a microwave for a minute at a time until it is at least ten degrees Celsius higher than the previous temperature. Because a microwave is used, the metal hooks of course pose a problem. Fortunately, due to the anchors in the bricks, the hooks can easily be unscrewed from the brick before heating then replaced once the temperature has increased.

The test is now repeated at every new temperature, until a range of temperatures has been measured. Note that once the temperature is increased safety equipment such as gloves must be used in order to be able to handle the tested materials.

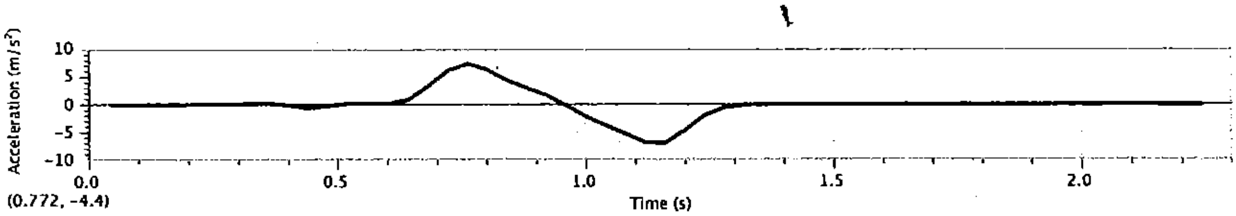
3.0 Data Collection and Processing

3.1 Raw Data:

The raw data collected with the Logger Pro program provides the position, velocity, and acceleration of a brick at 0.04-second intervals, along with graphs of each of these. Example graphs of both position and acceleration measurements of the Sienna brick are shown below in Graph 1 and Graph 2 respectively.



Graph 1 – Logger Pro: Sienna Position vs. Time



Graph 2 – Logger Pro: Sienna Acceleration vs. Time

As is clearly visible, the acceleration is not shown to be constant throughout the time range that the brick is in motion. This is because the Logger Pro program calculates the acceleration of the brick between two successive measurements rather than over the entire range of motion. For the purposes of determining the coefficient of friction, however, average acceleration is necessary. For this reason, only the position and time data points are important and necessary to record.

After all of the tests have been completed for every material, the saved Logger Pro files are reviewed and four pieces of data collected from each. This data includes the initial position of each brick before its movement begins as well as the final position after movement has stopped. The corresponding initial and final times are also recorded. As an example of raw data, the data recorded for the Bimini brick at its coldest temperature is shown below in Table 1. The collected raw data for the other tested materials can be found in Appendix 1.

Bimini Position and Time Measurements at Temperature 2.5°C to 3.7°C ± 0.1°C			
	Trial 1	Trial 2	Trial 3
Initial Position (x_0) /m	0.184 ± 0.0005	0.186 ± 0.0005	0.185 ± 0.0005
Final Position (x) /m	0.645 ± 0.0005	0.694 ± 0.0005	0.656 ± 0.0005
Initial Time (t_0) /s	0.60 ± 0.05	0.74 ± 0.05	0.68 ± 0.05
Final Time (t) /s	1.01 ± 0.05	1.20 ± 0.05	1.08 ± 0.05

Table 1 – Bimini Raw Data

3.2 Data Processing:

Data processing consists of two steps in this experiment. The first step is to determine the acceleration of the brick for each trial. The second step of data processing is to compute the coefficient of friction between the brick and the testing surface for each trial.

3.2.1 Acceleration:

In order to calculate the average acceleration of a brick for any given trial, the collected raw data must be inserted into the kinematic equation

$$x = x_0 + v_0 t + \frac{1}{2}at^2.$$ (Tsokos 48)

In this equation v_0, or initial velocity, is zero because the brick begins at rest. This allows the equation to be rewritten as

$$x = x_0 + \frac{1}{2}at^2,$$

which can be solved for a, or acceleration, to give

$$a = \frac{2(x-x_0)}{t^2}.$$

Initial and final values for time are substituted into this equation to provide the equation

$$a = \frac{2(x-x_0)}{(t-t_0)^2},$$

where x and t represent final position and time respectively and x_0 and t_0 represent initial position and time.

With this final equation for acceleration, a table of all the acceleration values for each material can be created. For example, Table 2 contains acceleration values for the Bimini brick, along with the corresponding temperatures. Appendix 2 contains the acceleration value tables for the other tested materials.

Bimini Acceleration and Temperature Values				
	Acceleration /m-s^{-2}			
Temperature /°C (±0.1°C)	Trial 1	Trial 2	Trial 3	Average
2.5 - 3.7	5.485	4.802	5.888	5.392
11.5 - 12.5	5.313	5.01	5.196	5.173
21.2 - 21.6	4.540	5.382	3.802	4.575
42.6 - 39.5	4.523	3.920	4.731	4.391
57.4 - 57.1	4.540	3.987	3.162	3.896
65.4 - 64.8	3.972	3.735	3.348	3.685
81.2 - 79.8	3.839	3.425	3.558	3.607

Table 2 – Bimini Acceleration vs. Temperature

From this processed data there is a clear trend of acceleration decreasing as temperature increases. This shows that the coefficient of friction is increasing as temperature increases. It is still necessary, however, to calculate the actual coefficient of friction in order to have graphical data.

3.2.2 Coefficient of Friction

This calculation makes use of Newton's Second Law of motion as well as the definition of friction. Newton's Second Law shows that total force acting on an object is equal to the mass of a body multiplied by the acceleration of the body, or

$$\sum F = ma. \text{ (Tsokos 77)}$$

In this equation $\sum F$ represents net force applied to an object, m represents the mass of the object, and a represents the acceleration of the object.

The definition of friction shows that the force of friction is equal to the normal force between two surfaces multiplied by the coefficient of friction, or μ (Friction). This is shown in the equation

$$F_f = F_N\mu,$$

which can be rewritten by substituting acceleration due to gravity multiplied by mass for F_N to give the equation

$$F_f = mg\mu.$$

free body diagram.

Now that these two equations are defined, an equation for including all of the forces in this experiment can be written. This is shown as

$$\sum F = ma = Mg - mg\mu,$$

where M represents the mass of the hanging weight, g represents the acceleration due to the force of gravity, or 9.81 ms^{-2}. This means that Mg represents the pulling force applied by the hanging weight and $mg\mu$ represents the resisting force of friction.

Because the value of Mg is constant throughout the experiment, the numerical value can be substituted in.

Therefore,

$$\sum F = ma = (2.430kg \pm 0.005kg)(9.81ms^{-2}) - mg\mu,$$

So

$$\sum F = ma = 23.83N - mg\mu.$$

This equation can now be rewritten and solved for the coefficient of friction.

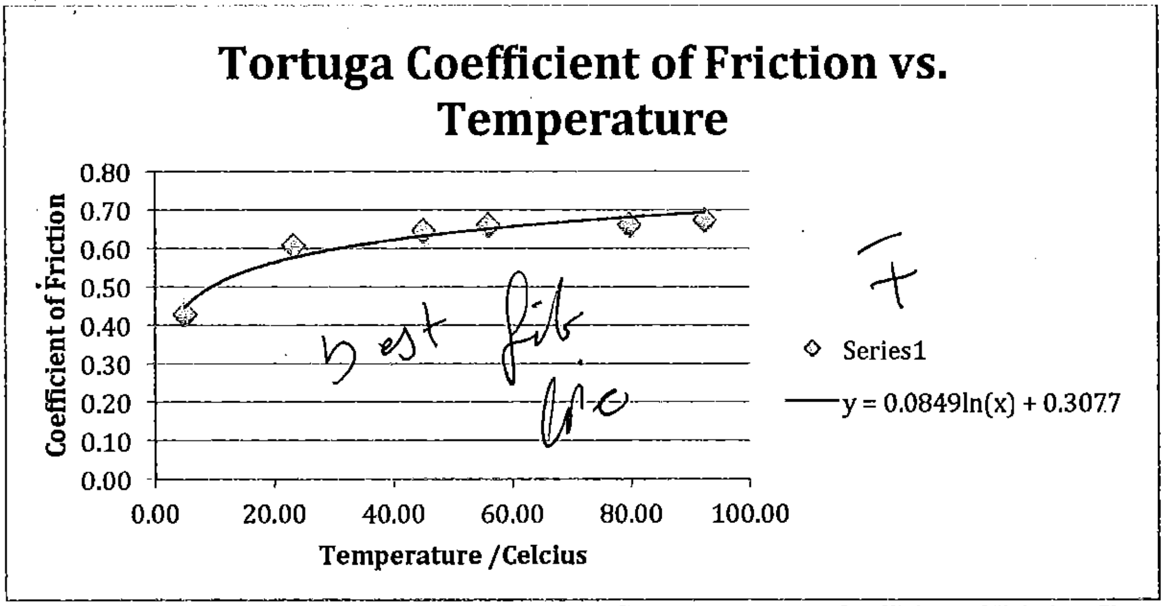
$$\mu = \frac{23.83N - ma}{mg}.$$

By inserting the values for the mass and acceleration, this equation provides the coefficient of friction.

Tortuga Coefficient of Friction and Temperature Values				
	Coefficient of Friction			
Temperature /C (±0.1C)	Trial 1	Trial 2	Trial 3	Average
3.8 – 6.4	0.42	0.37	0.48	0.43
24.6 – 21.9	0.65	0.62	0.55	0.61
45.1 – 45.0	0.65	0.65	0.64	0.65
59.0 – 53.0	0.65	0.65	0.69	0.66
84.5 – 75.0	0.66	0.67	0.65	0.66
95.0 – 90.0	0.66	0.68	0.68	0.67

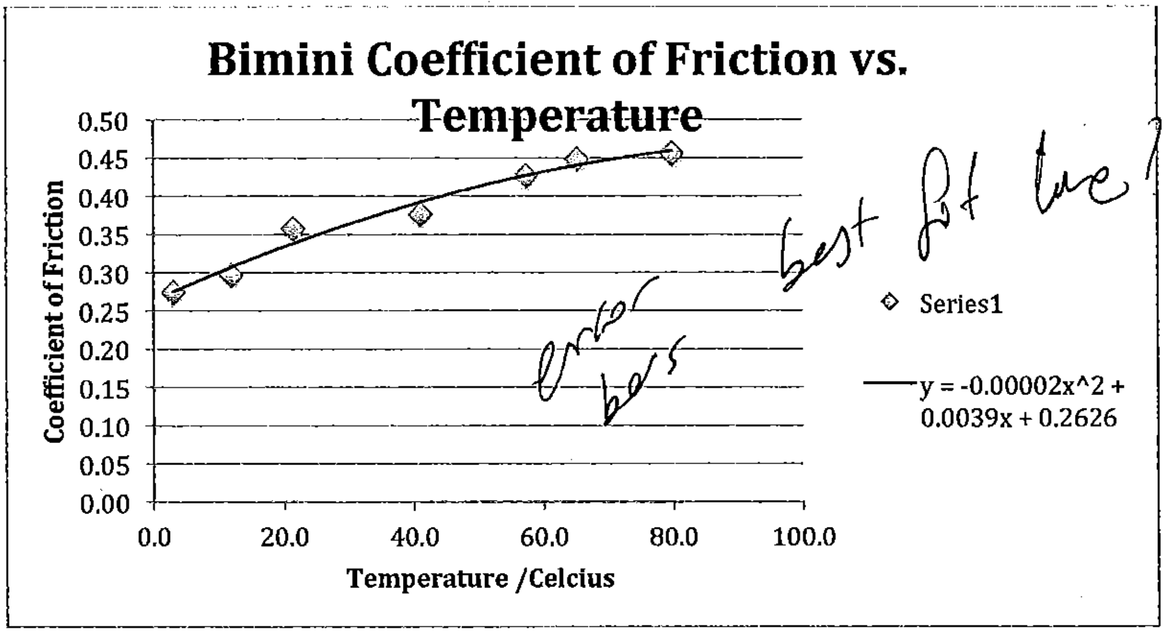
Table 3 - Tortuga Coefficient of Friction vs. Temperature

Shown above is the processed data table containing the coefficients of friction and the respective temperatures for the Tortuga brick. The other processed data tables for the coefficient of friction can be seen in Appendix 3. Using the average values in these tables, graphs can now be created to represent the relationship between surface temperature and the coefficient of friction, each of which are presented below.



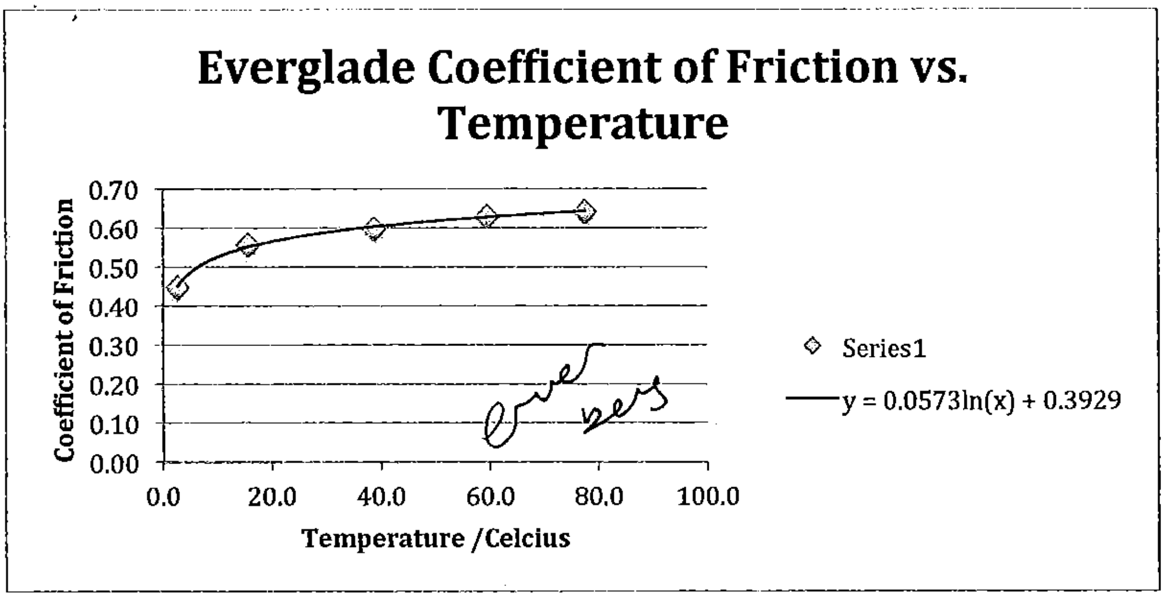
Graph 3 – Tortuga Coefficient of Friction Chart

This graph shows an increase in the coefficient of friction as temperature is increased. The value of the coefficient appears to stop increasing around 0.70.



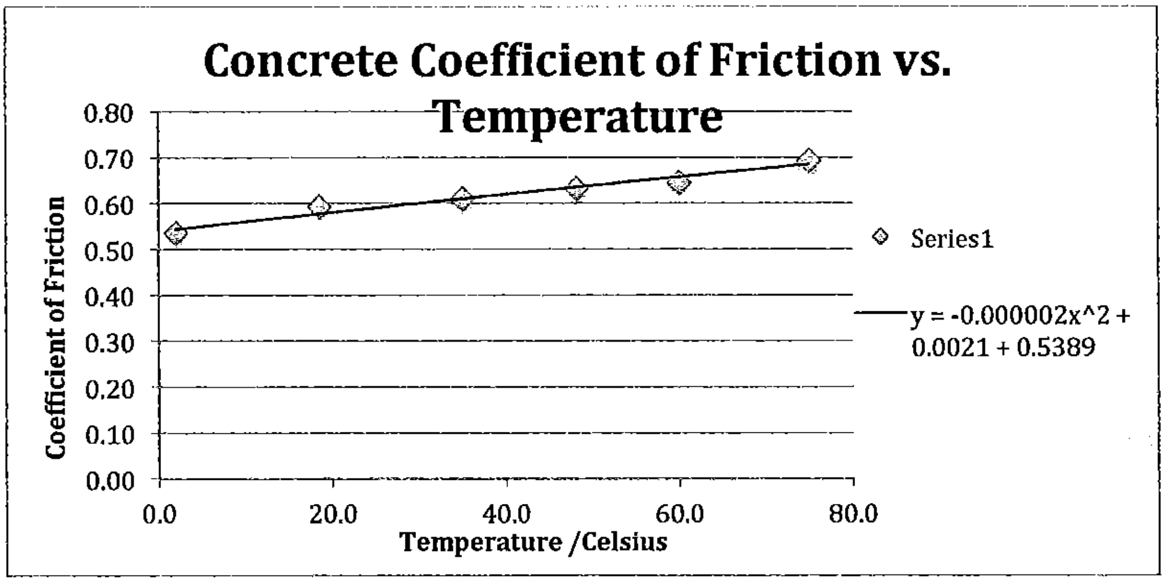
Graph 4 – Bimini Coefficient of Friction Chart

This graph shows a steady increase in the coefficient of friction as temperature is increased. The results suggest that the coefficient will eventually stop increasing, most likely in between 0.45 and 0.50.



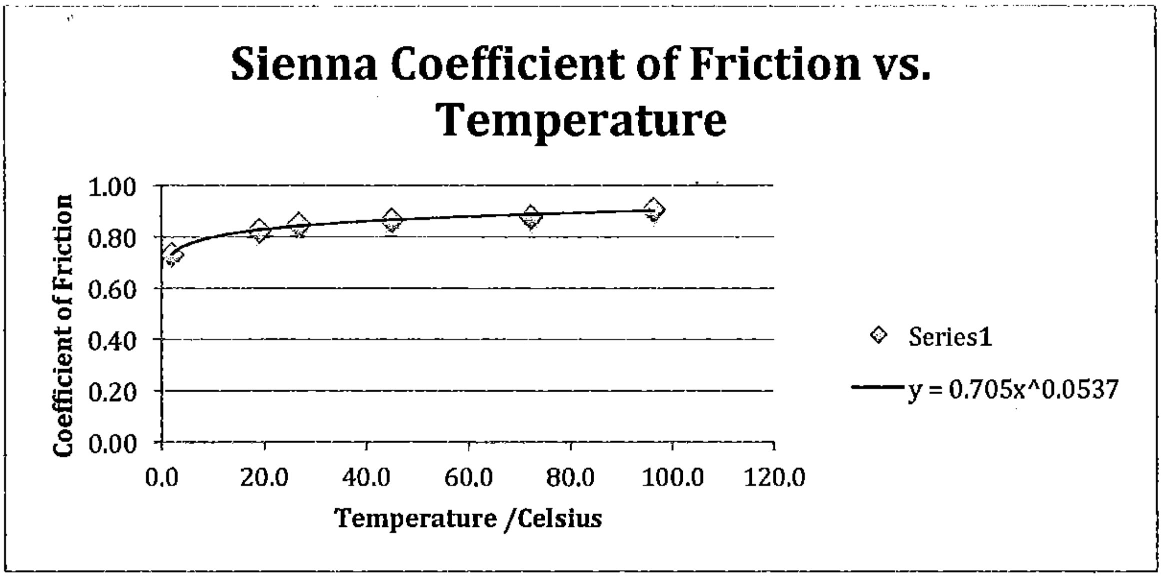
Graph 5 - Everglade Coefficient of Friction Chart

This graph also portrays that the coefficient of friction increases with temperature, leveling off at about 0.65.



Graph 6 - Concrete Coefficient of Friction Chart

The trend in this graph shows a somewhat more linear relationship between the coefficient of friction and temperature. This may be caused by the grainy surface of the concrete. It seems as if the value will cease increasing at close to 0.80.



Graph 7 - Sienna Coefficient of Friction Chart

The results of this graph show that the coefficient of friction was highest in this brick, most likely due to the surface roughness. The data appears to follow the trend, however, of leveling off after a certain coefficient has been reached. For the Sienna brick this appears to be 0.90.

4.0 Conclusion and Evaluation

4.1 Research Question Conclusion:

What is the impact, if any, of changes in the surface temperature of a hard surfaced object on the coefficient of kinetic friction of the object?

Through this investigation it has been found that heightened values of surface temperature in hard surfaced objects increase the value of the coefficient of friction until it reaches a maximum value.

4.2 Justification for Conclusion:

The graphs above all show a trend of the coefficient of friction increasing as temperature is increased. This confirms the hypothesis that there is a proportional relationship between surface temperature and the coefficient of friction in flat, non-pliable objects. The graphs do not, however, portray a linear relationship. Instead they show a relationship in which the coefficient of kinetic friction appears to level off as it approaches a maximum value at high temperature. For example, in Graph 4 above the maximum value for the coefficient of friction appears to be roughly 0.68, which is 0.20 higher than the value at the coldest temperature.

Of course, when considering a maximum value for the coefficient of friction, one must keep in mind that once a solid reaches the melting temperature the coefficient friction will inevitably change.

4.3 Evaluation of Experiment

This experiment was a valid method of determining the acceleration of the tested materials at various temperatures, and through acceleration, the coefficient of friction. There were, however, some limitations that may have caused changes in the outcome.

Firstly, only five materials were tested. Although they all provided very similar data, five samples are not enough to make a claim about all hard surfaced materials. Also, because of the use of a microwave, no metals were able to be tested. Had this been possible, the results would have represented a much wider range of materials. This is because metals have a much different composition than non-metals do, and so could have reacted differently to heightened temperature.

Another limitation of the experiment was that the temperature range only extended from 2° Celsius to 96.4° Celsius at the most. Unfortunately, this was the maximum range possible with the heating and cooling methods that were available. If the maximum temperature tested was, for example, 500° Celsius or even 1000° Celsius then there may have been changes in the trend at higher temperatures that, as the test was conducted, were missed. A higher temperature would also have provided more data points, which would make any trends more accurate representations of the relationship between temperature and the coefficient of friction.

4.4 Further Investigation:

Due in part to some of the limitations of this experiment as well as its specific nature, this topic could be subject to further investigation. Further investigation could help to support the conclusion found in this experiment or it could supplement the experiment with new ideas.

For example, this experiment does not test for the cause of the relationship between surface temperature and the coefficient of friction. It is possible that through further investigation a cause might be determined. To do this, an experiment may be set up to measure specific aspects of changes in temperature, such as increasing the contact of molecules between two objects without actually changing the temperature.

Further investigation could also be used to minimize some of the limitations of this experiment. For example, as said above, the test could be conducted at a much larger range of temperatures. The experiment could also be done with more materials being tested. If the new heating method is one in which heating metals is safe and possible, these materials could be tested as well as many others.

4.5 Applications

There are many possible applications to which the findings of this investigation could be useful. These applications include, for example, the development of driving safety techniques. Because it has been determined that the coefficient of friction increases as temperature increases, developers of driving techniques and vehicle safety laws could now consider that would have a tendency to skid further distances at lower temperatures. This is of course assuming that there is no ice or water involved. Many corporations could also use the findings of this experiment when designing products or for applications in research where friction must be controlled. The results could also be applied to machinery and engineering.

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APPENDIX 1 – Raw Data

This appendix contains the Raw Data for the tested materials.

Tortuga:

Tortuga Position and Time Measurements at Temperature 3.8°C to 6.4°C ± 0.1°C			
	Trial 1	Trial 2	Trial 3
Initial Position (x_0) /m	0.196 ± 0.0005	0.189 ± 0.0005	0.187 ± 0.0005
Final Position (x) /m	0.607 ± 0.0005	0.632 ± 0.0005	0.650 ± 0.0005
Initial Time (t_0) /s	0.680 ± 0.05	0.720 ± 0.05	0.560 ± 0.05
Final Time (t) /s	1.040 ± 0.05	1.080 ± 0.05	0.960 ± 0.05

Tortuga Position and Time Measurements at Temperature 24.6°C to 21.9°C ± 0.1°C			
	Trial 1	Trial 2	Trial 3
Initial Position (x_0) /m	0.187 ± 0.0005	0.187 ± 0.0005	0.187 ± 0.0005
Final Position (x) /m	0.623 ± 0.0005	0.617 ± 0.0005	0.683 ± 0.0005
Initial Time (t_0) /s	0.620 ± 0.05	0.680 ± 0.05	0.600 ± 0.05
Final Time (t) /s	1.080 ± 0.05	1.120 ± 0.05	1.040 ± 0.05

Tortuga Position and Time Measurements at Temperature 45.1°C to 45.0°C ± 0.1°C			
	Trial 1	Trial 2	Trial 3
Initial Position (x_0) /m	0.186 ± 0.0005	0.187 ± 0.0005	0.186 ± 0.0005
Final Position (x) /m	0.666 ± 0.0005	0.659 ± 0.0005	0.676 ± 0.0005
Initial Time (t_0) /s	0.440 ± 0.05	0.480 ± 0.05	0.480 ± 0.05
Final Time (t) /s	0.920 ± 0.05	0.960 ± 0.05	0.960 ± 0.05

Tortuga Position and Time Measurements at Temperature 59.0°C to 53.0°C ± 0.1°C			
	Trial 1	Trial 2	Trial 3
Initial Position (x_0) /m	0.186 ± 0.0005	0.186 ± 0.0005	0.186 ± 0.0005
Final Position (x) /m	0.666 ± 0.0005	0.662 ± 0.0005	0.695 ± 0.0005
Initial Time (t_0) /s	0.540 ± 0.05	0.700 ± 0.05	0.720 ± 0.05
Final Time (t) /s	1.020 ± 0.05	1.180 ± 0.05	1.240 ± 0.05

Tortuga Position and Time Measurements at Temperature 84.5°C to 75.0°C ± 0.1°C			
	Trial 1	Trial 2	Trial 3
Initial Position (x_0) /m	0.186 ± 0.0005	0.186 ± 0.0005	0.188 ± 0.0005
Final Position (x) /m	0.650 ± 0.0005	0.660 ± 0.0005	0.659 ± 0.0005
Initial Time (t_0) /s	0.600 ± 0.05	0.570 ± 0.05	0.560 ± 0.05
Final Time (t) /s	1.080 ± 0.05	1.060 ± 0.05	1.040 ± 0.05

Tortuga Position and Time Measurements at Temperature 95.0°C to 90.0°C ± 0.1°C			
	Trial 1	Trial 2	Trial 3
Initial Position (x_0) /m	0.184 ± 0.0005	0.186 ± 0.0005	0.186 ± 0.0005
Final Position (x) /m	0.647 ± 0.0005	0.651 ± 0.0005	0.645 ± 0.0005
Initial Time (t_0) /s	0.480 ± 0.05	0.480 ± 0.05	0.360 ± 0.05
Final Time (t) /s	0.960 ± 0.05	0.970 ± 0.05	0.850 ± 0.05

Bimini:

Bimini Position and Time Measurements at Temperature 2.5°C to 3.7°C ± 0.1°C			
	Trial 1	Trial 2	Trial 3
Initial Position (x_0) /m	0.184 ± 0.0005	0.186 ± 0.0005	0.185 ± 0.0005
Final Position (x) /m	0.645 ± 0.0005	0.694 ± 0.0005	0.656 ± 0.0005
Initial Time (t_0) /s	0.600 ± 0.05	0.740 ± 0.05	0.680 ± 0.05
Final Time (t) /s	1.010 ± 0.05	1.200 ± 0.05	1.080 ± 0.05

Bimini Position and Time Measurements at Temperature 11.1°C to 12.5°C ± 0.1°C			
	Trial 1	Trial 2	Trial 3
Initial Position (x_0) /m	0.185 ± 0.0005	0.185 ± 0.0005	0.185 ± 0.0005
Final Position (x) /m	0.610 ± 0.0005	0.670 ± 0.0005	0.688 ± 0.0005
Initial Time (t_0) /s	0.640 ± 0.05	0.520 ± 0.05	0.680 ± 0.05
Final Time (t) /s	1.040 ± 0.05	0.960 ± 0.05	1.120 ± 0.05

Bimini Position and Time Measurements at Temperature 21.2°C to 21.6°C ± 0.1°C			
	Trial 1	Trial 2	Trial 3
Initial Position (x_0) /m	0.185 ± 0.0005	0.187 ± 0.0005	0.185 ± 0.0005
Final Position (x) /m	0.708 ± 0.0005	0.708 ± 0.0005	0.699 ± 0.0005
Initial Time (t_0) /s	0.480 ± 0.05	0.680 ± 0.05	0.560 ± 0.05
Final Time (t) /s	0.960 ± 0.05	1.120 ± 0.05	1.080 ± 0.05

Bimini Position and Time Measurements at Temperature 42.6°C to 39.5°C ± 0.1°C			
	Trial 1	Trial 2	Trial 3
Initial Position (x_0) /m	0.188 ± 0.0005	0.184 ± 0.0005	0.186 ± 0.0005
Final Position (x) /m	0.709 ± 0.0005	0.714 ± 0.0005	0.731 ± 0.0005
Initial Time (t_0) /s	0.480 ± 0.05	0.520 ± 0.05	0.520 ± 0.05
Final Time (t) /s	0.960 ± 0.05	1.040 ± 0.05	1.000 ± 0.05

Bimini Position and Time Measurements at Temperature 57.4°C to 57.1°C ± 0.1°C			
	Trial 1	Trial 2	Trial 3
Initial Position (x_0) /m	0.188 ± 0.0005	0.185 ± 0.0005	0.185 ± 0.0005
Final Position (x) /m	0.711 ± 0.0005	0.724 ± 0.0005	0.717 ± 0.0005
Initial Time (t_0) /s	0.600 ± 0.05	0.760 ± 0.05	0.580 ± 0.05
Final Time (t) /s	1.080 ± 0.05	1.280 ± 0.05	1.160 ± 0.05

Bimini Position and Time Measurements at Temperature 65.4°C to 64.8°C ± 0.1°C			
	Trial 1	Trial 2	Trial 3
Initial Position (x_0) /m	0.184 ± 0.0005	0.185 ± 0.0005	0.186 ± 0.0005
Final Position (x) /m	0.721 ± 0.0005	0.690 ± 0.0005	0.711 ± 0.0005
Initial Time (t_0) /s	0.640 ± 0.05	0.560 ± 0.05	0.480 ± 0.05
Final Time (t) /s	1.160 ± 0.05	1.080 ± 0.05	1.040 ± 0.05

Bimini Position and Time Measurements at Temperature 81.2°C to 79.8°C ± 0.1°C			
	Trial 1	Trial 2	Trial 3
Initial Position (x_0) /m	0.186 ± 0.0005	0.185 ± 0.0005	0.185 ± 0.0005
Final Position (x) /m	0.705 ± 0.0005	0.648 ± 0.0005	0.666 ± 0.0005
Initial Time (t_0) /s	0.640 ± 0.05	0.440 ± 0.05	0.760 ± 0.05
Final Time (t) /s	1.160 ± 0.05	0.960 ± 0.05	1.280 ± 0.05

Everglade:

Everglade Position and Time Measurements at Temperature 2.7°C to 3.2°C ± 0.1°C			
	Trial 1	Trial 2	Trial 3
Initial Position (x_0) /m	0.185 ± 0.0005	0.184 ± 0.0005	0.184 ± 0.0005
Final Position (x) /m	0.656 ± 0.0005	0.677 ± 0.0005	0.669 ± 0.0005
Initial Time (t_0) /s	0.920 ± 0.05	0.640 ± 0.05	0.560 ± 0.05
Final Time (t) /s	1.360 ± 0.05	1.060 ± 0.05	1.000 ± 0.05

Everglade Position and Time Measurements at Temperature 15.7°C to 16.3°C ± 0.1°C			
	Trial 1	Trial 2	Trial 3
Initial Position (x_0) /m	0.184 ± 0.0005	0.184 ± 0.0005	0.185 ± 0.0005
Final Position (x) /m	0.646 ± 0.0005	0.649 ± 0.0005	0.633 ± 0.0005
Initial Time (t_0) /s	0.640 ± 0.05	0.720 ± 0.05	0.680 ± 0.05
Final Time (t) /s	1.120 ± 0.05	1.200 ± 0.05	1.140 ± 0.05

Everglade Position and Time Measurements at Temperature 38.7°C to 37.9°C ± 0.1°C			
	Trial 1	Trial 2	Trial 3
Initial Position (x_0) /m	0.184 ± 0.0005	0.184 ± 0.0005	0.183 ± 0.0005
Final Position (x) /m	0.632 ± 0.0005	0.670 ± 0.0005	0.671 ± 0.0005
Initial Time (t_0) /s	0.640 ± 0.05	0.600 ± 0.05	0.720 ± 0.05
Final Time (t) /s	1.120 ± 0.05	1.120 ± 0.05	1.240 ± 0.05

Everglade Position and Time Measurements at Temperature 59.5°C to 58.7°C ± 0.1°C			
	Trial 1	Trial 2	Trial 3
Initial Position (x_0) /m	0.185 ± 0.0005	0.185 ± 0.0005	0.185 ± 0.0005
Final Position (x) /m	0.632 ± 0.0005	0.632 ± 0.0005	0.626 ± 0.0005
Initial Time (t_0) /s	0.640 ± 0.05	0.640 ± 0.05	0.680 ± 0.05
Final Time (t) /s	1.160 ± 0.05	1.140 ± 0.05	1.200 ± 0.05

Everglade Position and Time Measurements at Temperature 77.5°C to 77.0°C ± 0.1°C			
	Trial 1	Trial 2	Trial 3
Initial Position (x_0) /m	0.185 ± 0.0005	0.185 ± 0.0005	0.185 ± 0.0005
Final Position (x) /m	0.631 ± 0.0005	0.627 ± 0.0005	0.618 ± 0.0005
Initial Time (t_0) /s	0.560 ± 0.05	0.520 ± 0.05	0.760 ± 0.05
Final Time (t) /s	1.080 ± 0.05	1.040 ± 0.05	1.280 ± 0.05

Concrete:

Concrete Position and Time Measurements at Temperature 17.8°C to 18.9°C ± 0.1°C			
	Trial 1	Trial 2	Trial 3
Initial Position (x_0) /m	0.185 ± 0.0005	0.186 ± 0.0005	0.184 ± 0.0005
Final Position (x) /m	0.657 ± 0.0005	0.653 ± 0.0005	0.654 ± 0.0005
Initial Time (t_0) /s	0.600 ± 0.05	0.560 ± 0.05	0.920 ± 0.05
Final Time (t) /s	1.000 ± 0.05	0.960 ± 0.05	1.320 ± 0.05

Concrete Position and Time Measurements at Temperature 35.0°C to 34.6°C ± 0.1°C			
	Trial 1	Trial 2	Trial 3
Initial Position (x_0) /m	0.185 ± 0.0005	0.185 ± 0.0005	0.185 ± 0.0005
Final Position (x) /m	0.645 ± 0.0005	0.647 ± 0.0005	0.629 ± 0.0005
Initial Time (t_0) /s	0.600 ± 0.05	0.480 ± 0.05	0.640 ± 0.05
Final Time (t) /s	1.000 ± 0.05	0.880 ± 0.05	1.040 ± 0.05

Concrete Position and Time Measurements at Temperature 48.2°C to 47.7°C ± 0.1°C			
	Trial 1	Trial 2	Trial 3
Initial Position (x_0) /m	0.185 ± 0.0005	0.184 ± 0.0005	0.184 ± 0.0005
Final Position (x) /m	0.626 ± 0.0005	0.623 ± 0.0005	0.617 ± 0.0005
Initial Time (t_0) /s	0.440 ± 0.05	0.560 ± 0.05	0.720 ± 0.05
Final Time (t) /s	0.840 ± 0.05	0.960 ± 0.05	1.120 ± 0.05

Concrete Position and Time Measurements at Temperature 60.0°C to 59.4°C ± 0.1°C			
	Trial 1	Trial 2	Trial 3
Initial Position (x_0) /m	0.185 ± 0.0005	0.185 ± 0.0005	0.184 ± 0.0005
Final Position (x) /m	0.612 ± 0.0005	0.613 ± 0.0005	0.614 ± 0.0005
Initial Time (t_0) /s	0.520 ± 0.05	0.480 ± 0.05	0.560 ± 0.05
Final Time (t) /s	0.920 ± 0.05	0.880 ± 0.05	0.960 ± 0.05

Concrete Position and Time Measurements at Temperature 75.0°C to 74.3°C ± 0.1°C			
	Trial 1	Trial 2	Trial 3
Initial Position (x_0) /m	0.185 ± 0.0005	0.185 ± 0.0005	0.185 ± 0.0005
Final Position (x) /m	0.643 ± 0.0005	0.598 ± 0.0005	0.644 ± 0.0005
Initial Time (t_0) /s	0.400 ± 0.05	0.480 ± 0.05	0.480 ± 0.05
Final Time (t) /s	0.840 ± 0.05	0.880 ± 0.05	0.920 ± 0.05

Sienna:

Sienna Position and Time Measurements at Temperature 2.0°C to 3.1°C ± 0.1°C			
	Trial 1	Trial 2	Trial 3
Initial Position (x_0) /m	0.185 ± 0.0005	0.185 ± 0.0005	0.187 ± 0.0005
Final Position (x) /m	0.658 ± 0.0005	0.658 ± 0.0005	0.650 ± 0.0005
Initial Time (t_0) /s	0.640 ± 0.05	0.680 ± 0.05	0.560 ± 0.05
Final Time (t) /s	1.060 ± 0.05	1.120 ± 0.05	0.960 ± 0.05

Sienna Position and Time Measurements at Temperature 19.1°C to 22.1°C ± 0.1°C			
	Trial 1	Trial 2	Trial 3
Initial Position (x_0) /m	0.185 ± 0.0005	0.185 ± 0.0005	0.186 ± 0.0005
Final Position (x) /m	0.642 ± 0.0005	0.641 ± 0.0005	0.643 ± 0.0005
Initial Time (t_0) /s	0.640 ± 0.05	0.720 ± 0.05	0.740 ± 0.05
Final Time (t) /s	1.160 ± 0.05	1.160 ± 0.05	1.200 ± 0.05

Sienna Position and Time Measurements at Temperature 26.8°C to 25.7°C ± 0.1°C			
	Trial 1	Trial 2	Trial 3
Initial Position (x_0) /m	0.185 ± 0.0005	0.185 ± 0.0005	0.184 ± 0.0005
Final Position (x) /m	0.626 ± 0.0005	0.640 ± 0.0005	0.614 ± 0.0005
Initial Time (t_0) /s	0.520 ± 0.05	0.800 ± 0.05	0.680 ± 0.05
Final Time (t) /s	1.040 ± 0.05	1.240 ± 0.05	1.160 ± 0.05

Sienna Position and Time Measurements at Temperature 45.0°C to 44.2°C ± 0.1°C			
	Trial 1	Trial 2	Trial 3
Initial Position (x_0) /m	0.189 ± 0.0005	0.185 ± 0.0005	0.185 ± 0.0005
Final Position (x) /m	0.665 ± 0.0005	0.665 ± 0.0005	0.664 ± 0.0005
Initial Time (t_0) /s	0.760 ± 0.05	0.600 ± 0.05	0.520 ± 0.05
Final Time (t) /s	1.240 ± 0.05	1.120 ± 0.05	1.040 ± 0.05

Sienna Position and Time Measurements at Temperature 72.3°C to 71.2°C ± 0.1°C			
	Trial 1	Trial 2	Trial 3
Initial Position (x_0) /m	0.184 ± 0.0005	0.185 ± 0.0005	0.187 ± 0.0005
Final Position (x) /m	0.640 ± 0.0005	0.663 ± 0.0005	0.638 ± 0.0005
Initial Time (t_0) /s	0.680 ± 0.05	0.600 ± 0.05	0.680 ± 0.05
Final Time (t) /s	1.160 ± 0.05	1.120 ± 0.05	1.200 ± 0.05

Sienna Position and Time Measurements at Temperature 96.4°C to 94.5°C ± 0.1°C			
	Trial 1	Trial 2	Trial 3
Initial Position (x_0) /m	0.186 ± 0.0005	0.186 ± 0.0005	0.184 ± 0.0005
Final Position (x) /m	0.655 ± 0.0005	0.666 ± 0.0005	0.651 ± 0.0005
Initial Time (t_0) /s	0.560 ± 0.05	0.640 ± 0.05	0.600 ± 0.05
Final Time (t) /s	1.080 ± 0.05	1.200 ± 0.05	1.120 ± 0.05

APPENDIX 2 – Acceleration Tables

This appendix contains acceleration tables from the experiment.

Tortuga Acceleration and Temperature Values				
	Acceleration /m-s^{-2}			
Temperature /°C (±0.1°C)	Trial 1	Trial 2	Trial 3	Average
3.8 - 6.4	6.343	6.836	5.788	6.322
24.6 - 21.9	4.121	4.442	5.124	4.562
45.1 - 45.0	4.167	4.097	4.253	4.172
59.0 - 53.0	4.167	4.132	3.765	4.021
84.5 - 75.0	4.028	3.948	4.089	4.022
95.0 - 90.0	4.019	3.873	3.823	3.905

Bimini Acceleration and Temperature Values				
	Acceleration /m-s^{-2}			
Temperature /°C (±0.1°C)	Trial 1	Trial 2	Trial 3	Average
2.5 - 3.7	5.485	4.802	5.888	5.392
11.5 - 12.5	5.313	5.01	5.196	5.173
21.2 - 21.6	4.540	5.382	3.802	4.575
42.6 - 39.5	4.523	3.920	4.731	4.391
57.4 - 57.1	4.540	3.987	3.162	3.896
65.4 - 64.8	3.972	3.735	3.348	3.685
81.2 - 79.8	3.839	3.425	3.558	3.607

Everglade Acceleration and Temperature Values				
	Acceleration /m-s^{-2}			
Temperature /°C (±0.1°C)	Trial 1	Trial 2	Trial 3	Average
2.7 - 3.2	4.866	5.590	5.010	5.155
15.7 - 16.3	4.010	4.036	4.234	4.093
38.7 - 37.9	3.889	3.595	3.609	3.698
59.5 - 58.7	3.306	3.576	3.262	3.381
77.5 - 77.0	3.298	3.269	3.203	3.257

Concrete Acceleration and Temperature Values				
	Acceleration /m-s^{-2}			
Temperature /°C (±0.1°C)	Trial 1	Trial 2	Trial 3	Average
1.0 - 2.5	7.145	6.100	6.038	6.428
17.8 - 18.9	5.900	5.838	5.875	5.871
35.0 - 34.6	5.750	5.775	5.550	5.692
48.2 - 47.7	5.513	5.488	5.413	5.471
60.0 - 59.4	5.338	5.350	5.375	5.354
75.0 - 74.3	4.731	5.163	4.742	4.879

Sienna Acceleration and Temperature Values				
	Acceleration /m-s^{-2}			
Temperature /°C (±0.1°C)	Trial 1	Trial 2	Trial 3	Average
2.0 - 3.1	5.363	4.886	4.897	5.049
19.1 - 22.1	3.380	4.711	4.319	4.137
26.8 - 25.7	3.262	4.700	3.733	3.898
45.0 - 44.2	4.132	3.550	3.543	3.742
72.3 - 71.2	3.958	3.536	3.336	3.610
96.4 - 94.5	3.469	3.061	3.454	3.328

APPENDIX 3 – Coefficient of Friction vs. Temperature Tables

Appendix 3 contains the processed data tables of the coefficient of friction and temperature values from the experiment.

Tortuga Coefficient of Friction and Temperature Values				
	Coefficient of Friction			
Temperature /C (±0.1C)	Trial 1	Trial 2	Trial 3	Average
3.8 - 6.4	0.42	0.37	0.48	0.43
24.6 - 21.9	0.65	0.62	0.55	0.61
45.1 - 45.0	0.65	0.65	0.64	0.65
59.0 - 53.0	0.65	0.65	0.69	0.66
84.5 - 75.0	0.66	0.67	0.65	0.66
95.0 - 90.0	0.66	0.68	0.68	0.67

Bimini Coefficient of Friction and Temperature Values				
	Coefficient of Friction			
Temperature /C (±0.1C)	Trial 1	Trial 2	Trial 3	Average
2.5 - 3.7	0.26	0.33	0.22	0.27
11.5 - 12.5	0.28	0.31	0.29	0.30
21.2 - 21.6	0.36	0.28	0.44	0.36
42.6 - 39.5	0.36	0.42	0.34	0.38
57.4 - 57.1	0.36	0.42	0.50	0.43
65.4 - 64.8	0.42	0.44	0.48	0.45
81.2 - 79.8	0.43	0.47	0.46	0.46

Everglade Coefficient of Friction and Temperature Values				
	Coefficient of Friction			
Temperature /C (±0.1C)	Trial 1	Trial 2	Trial 3	Average
2.7 - 3.2	0.48	0.40	0.46	0.45
15.7 - 16.3	0.56	0.56	0.54	0.56
38.7 - 37.9	0.58	0.61	0.61	0.60
59.5 - 58.7	0.64	0.61	0.64	0.63
77.5 - 77.0	0.64	0.64	0.65	0.64

Concrete Coefficient of Friction and Temperature Values				
	Coefficient of Friction			
Temperature /C (±0.1C)	Trial 1	Trial 2	Trial 3	Average
1.0 - 2.5	0.46	0.57	0.57	0.53
17.8 -18.9	0.59	0.60	0.59	0.59
35.0 - 34.6	0.60	0.60	0.62	0.61
48.2 - 47.7	0.63	0.63	0.64	0.63
60 - 59.4	0.65	0.64	0.64	0.64
75 - 74.3	0.71	0.66	0.71	0.69

Sienna Coefficient of Friction and Temperature Values				
	Coefficient of Friction			
Temperature /C (±0.1C)	Trial 1	Trial 2	Trial 3	Average
2.0 - 3.1	0.70	0.75	0.75	0.73
19.1 - 22.1	0.90	0.77	0.81	0.82
26.8 - 25.7	0.91	0.77	0.87	0.85
45.0 - 44.2	0.82	0.88	0.88	0.86
72.3 - 71.2	0.84	0.89	0.91	0.88
96.4 - 94.5	0.89	0.93	0.89	0.91