How does the rock temperature affect the grip of climbing shoes?

Introduction.

Rock climbing is a widely practiced sport consisting in climbing sheer rock faces or walls that simulate those rock faces, especially by means of specialized equipment and techniques (1)

I have always been interested in rock climbing as a sport and in the equipment required for its practice, as one of the most important factors to succeed in rock climbing is the equipment used, both for safety and to get the necessary grip to move forward. Therefore, rock climbers all around the world use a special type of shoe specifically design for this activity.

Rock climbing shoes have a special design and use specific rubber materials to maximize the grip on the rock. First modern rock climbing shoes available in the market were developed by a Spanish based company called Boreal, the model being called Boreal Fire, in 1982, and consisted in light and durable sport shoes with a revolutionary sticky rubber sole (2). Since then, rock climbing shoes have evolved massively with new designs and new materials, with many brands promising new levels of grip and using new rubbers for different types of climbing.

(3) Rubber is a polymer which can have two solid states: glassy (like plastic bottles) and rubbery (like in tires). The glass transition temperature is the temperature for which the polymer changes from one state to the other. Also, rubber belongs to the visco-elastc materials, which means that after deformation the material reverts to its original shape after a delay (hysteresis), which is accompanied by a loss of energy. The stiffness of the rubber decreases with the temperature and the glass transition temperature and therefore the grip of the rubber depends on the composition of the polymer. In a study on tires (for which rubber compounds I found most information) it was stated that the maximum grip is achieved close to the glass transition temperature (maximum hysteresis), and this is the reason why winter tires have more grip at lower temperatures, as the chemical composition of the rubber polymer used in them has a lower glass transition temperature. In summer tires, the maximum grip is achieved at higher temperatures because the glass transition temperature is higher. The previous study provides some background on the properties of rubber, even when is a study on tire safety. We can assume that being the types of polymers used in climbing shoes similar to the rubber used in tires, the material will behave similarly in terms of static friction (grip).

In regard of these rubber compounds used for the shoes, one would expect that the materials would be designed to provide maximum grip at a certain temperature, but what would that temperature be? Sport climbing happens in a wide variety of conditions, especially regarding temperature, as there is climbing in many countries with different weather. Even in the same country, the temperature variation between summer and winter can be very noticeable. Yet, climbing shoes do not seem to advertise being tailored made for different temperature conditions, and the same brands and models are widely used across the globe in different temperatures. First thing that one could guess is that the performance of the rubbers used by the different brands would change according to the temperature of the rock.

Logically, there is not much information about the exact composition of the rubber used by the different brands to make their climbing shoes, as there is a fierce competition between them for the market.

(1)http://www.thefreedictionary.com/rock+climbing , (2) Timothy W Kid, Jennifer Hazelrigs (2009): " Rock climbing", Wilderness Education Association (U.S.),

(3) http://ec.europa.eu/transport/road_safety/pdf/tyre10062014/discussion_document.pdf

Their own rubber formulae and their research about their compounds grip is highly confidential and other than knowing the 'names' that they give to the different rubbers they formulate and use in their shoe soles, there is not much information available. There is, however, information accessible about the general types of sticky rubbers used in climbing shoes and these include (i) Vibram (ii) Stealth and (iii) Trax rubber (4). Each type of rubber developed by different brands has different compounds with different properties.

There is wide agreement in climbing that 'hand grip' is optimal when rock temperature is around 0°C or a bit less. This is because hands sweat less at such temperatures, which in turn affects the friction. At low temperatures vasoconstriction happens and the skin gets stiffer, which apparently increases friction as well. (5) Based on this knowledge, climbing shoes are supposed to be designed to perform best at such low temperatures. **Static friction** is defined as the force generated by the interlocking of the irregularities of two surfaces, and will increase to prevent any relative motion up until some limit where motion occurs. It is that threshold of motion which is characterized by the coefficient of static friction, which is typically larger than the coefficient of **kinetic friction**. (6)

In rock climbing the static friction is far more important than the **kinetic friction**, as climbers rely on the static friction between their shoe soles and the rock face. In this experiment, I am going to investigate how 'rock' temperature affects the static grip of climbing shoes, with the shoe being Boreal Bamba climbing shoe.

Research question:

How does the temperature of a granite rock (from -7°C to +18°C) affect the grip (measured as the force of static friction) of a Boreal Bamba climbing shoe using a Vernier force sensor?

Variables

Independent variable: Change in the core temperature of the granite rock measured with a Vernier long temperature probe inserted in a hole drilled in the block, uncertainty ±0.01°C. Temperature range: -7°C to +18°C.

Dependent variable: static friction, measured with a Vernier force meter sensor as the force required for the climbing shoe to start moving at the different temperature intervals studied, uncertainty ±0.1 N.

(4)http://www.ems.com/ea-how-to-choose-climbing-shoes.html, (5) http://threerockbooks.com/index.php/friction-and-rock-climbing/ , (6)http://hyperphysics.phy-astr.gsu.edu/hbase/frict2.html

Controlled variables:

- **Granite block**: The same granite block with regard to grain size, grain shape, sorting of the grains, porosity, chemical composition and cementation of the grains will be used. This is a key factor affecting the static friction between the block and the shoe as the rougher the surfaces in contact, the more static friction.
- **Climbing Shoe**: This is probably the most important factor to maintain constant, as we need to be testing always the same type of rubber, and the same contact area, so the same 'Boreal Bamba' climbing shoe will be placed in exactly the same position on the granite block every time.

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- **Position of the shoe on top of the block:** Different areas of the rock might have different characteristics related to properties of the rock and therefore it is important to place the shoe always in the same position and touching the granite block exactly in the same area. To achieve this, using a permanent marker, the shape of the shoe in the initial position is contoured on the block surface and the shoe is always placed in the same place, ±1 mm.
- Drying process: It was observed that when the rock is cold it tends to accumulate condensation if not dried properly. This condensation would have an impact in the static friction as the water would reduce significantly the friction between rock and rubber. As a result, the rock and shoe were wiped dry with a cloth after each trial to reduce the impact of condensation on measurements.
- **Room temperature**: The experiment is conducted in a room with air conditioning, which will dry the air (to try to minimize the condensation mentioned before) and maintained at a constant temperature of 20°C (±2°C)
- **Pulling action of shoe**: It is important that when the string is pulled the procedure is followed exactly the same way, making sure that the force exerted at the beginning is small and increases constantly over the time until the shoe starts moving. If the force applied would be too big, the shoe would slide straight away and the value of the static friction would not be accurate. This is achieved by placing a pulley in a fixed position in the edge of the table and clamping the granite block to the table so it stays in the same position all the time.
- **Mass inside the climbing shoe**: For the experiment, I will use two 500 g masses, so total 1 kg. Using the same mass is important because one of the main factors affecting the static friction is the pressure exerted by the shoe. When climbing, logically, the mass will depend largely on the mass of the climber and the number of contact points between climber and rock, but for the experiment, we will limit it to 1 kg, so 9.81 N of downward force.

Confounding variables:

- **Shoe temperature:** during climbing, the temperature of the shoe will be affected by the temperature of the rock, the temperature of the air and also the climber's foot temperature will have an impact as well, even when rubber is an insulator. I assume that the area of the rubber in contact with the rock is the most important factor to determine the static friction and this will be most influenced by the rock temperature, so during the experiment the shoe will be at room temperature and the temperature of the contact rubber will probably change as the rock temperature increases, but it will not be measured.
- **Relative humidity of the air in the room:** test was made during a 2-hour period and the humidity is assumed to be constant as there is nobody but me inside the room (when we breathe we release water vapor that would affect the relative humidity of the air). As mentioned before, the air conditioning would constantly maintain the humidity low as we know that these systems dry the room air, but I will not be measuring it.

Materials used:

Fridge with freezer
One table to lean the granite rock and fix the pulley
One granite block

One Boreal Bamba climbing shoe
One drill to make a hole in the granite block
One 4mm concrete drill bit
One Vernier data logger, to measure the change in temperature and the force
One Vernier Stainless Steel Temperature Probe, range from -40 to 135°C, resolution (average for the range of temperatures we are measuring ±0.10°C). Dimensions of the stainless steel body: 10.5 mm length, 4.0 mm diameter
One Vernier Force Sensor, resolution ±10 N range 0.01 N/ ±50 N range 0.05 N
One pulley, to clamp on the edge of the table
One piece of string, to connect the force sensor to the mass inside the shoe and pull
Two masses (500 g each), to place inside the shoe
One permanent marker to contour contact area of the shoe on the granite block
Paper tissues, to dry condensation before every measurement
One clamp to maintain the granite block in the same position on the table
Insulation tape

Procedure:

1- Drill a hole in the granite block. The hole is made using a 4 mm drill bit, which is the same diameter of the stainless steel probe. The length of the hole achieved with the drill is approximately 6mm deep, meaning that only this length of the probe will be inserted in the hole. The hole is drilled as close as possible to the surface of the block where the friction measurements will be taking place.
2- Place the granite block in the freezer for 24 hours. This would give time to the whole block to get to a uniform temperature to start with. In the freezer that I used the rock would have a initial temperature of around -8°C, which did increase a bit by the time I set everything up, so started the experiment at approximately -7°C.
3- Place a pulley in the edge of the table. This pulley makes it easier to pull the force sensor down all the times the same way and guarantees that the angle pulling the shoe does not change.
4- Place two 500g mass blocks inside the climbing shoe. From the one closest to the heel, attach a rope and get it through a hole in the shoe through the pulley and connect it to the Vernier force sensor.
5- Secure the granite rock on top of the table so it does not move using a clamp.
6- Insert the Vernier Stainless Steel Temperature Probe in the whole to measure the temperature in the granite rock. Previously the part of the probe that would not be able to fit in the hole has been insulated using electrical tape to minimize the impact of the air temperature in the probe.
7- Connect both the temperature probe and the force sensor to the Vernier data logger.
8- Dry the surface of the block with a clean dry tissue to minimize the impact of condensation on the rock surface.
9- Place the climbing shoe on top of the granite block on the outlined marked shoe to ensure it is in the same position every time the test is performed.
10- Start the Vernier data logger.
11- Pull gently the force sensor until the shoe moves on top of the block. The data logger will record the force applied and you will see a spike in the graph. The maximum value of the force will correspond to the force of static friction, and that is the one that will be recorded in the

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table of raw data. It is important for it to be a fair test that the force sensor is gently pulled the same way all the times.

12- Try to repeat the measurement (steps 8 to 12) at least 5 times per every temperature interval as the rock heats up. I decided to make it 2°C so I could have enough time to do all the repeats.

13- Repeat the experiment 4 more times to ensure there are 5 repeats with data averages then being processed.

Safety

The experiment did not expose me to any major risks other than dealing with a granite block that was quite heavy, but during the preparation of the block I needed to use a drill to make a hole in the block and this was the most dangerous part. In order to minimize the risks, I made sure the block was properly clamped before I started drilling it and I wore safety googles to avoid stone bits hurting my eyes and leather gloves to protect my hands. I also did the drilling supervised by an adult. Other than that the rest of the experiment was quite safe and did not require any special safety precaution.

Qualitative data

First observation that was quite evident the first time the experiment was attempted was that the granite block would accumulate condensation when cold, so a way to dry the surface for it not to affect the static friction had to be included in the method. Also, the cooling process occurred faster when the rock temperature was lower, due to the bigger difference between the rock and the air temperature in the room. Finally, for the measurement to be accurate the pulling action had to be done gently, otherwise the shoe would move straight away.

Table of raw data and static friction force values for the different block temperatures.

Temperature (°C ± .01°C)	Force (N ± 0.1 N)
-6.7	13.5
-6.8	13.9
-6.3	14.0
-5.1	15.3
-4.2	14.6
-4.1	14.0
-3.2	14.9
-3.6	13.5
-3.2	16.1
-2.9	16.3
-2.6	15.7
-2.9	16.3
-2.2	18.0
-1.7	16.9
-1.0	16.9
-0.7	16.6
-0.3	18.4
0.1	17.5
0.5	17.0
0.7	16.0
1.2	17.1
1.5	17.4
1.8	14.9
1.6	17.3
2.2	17.3
2.3	16.6
2.3	16.5
2.9	17.5
3.1	17.7
3.2	16.1
3.7	17.5
3.8	16.9
3.6	16.9
3.7	16.1
4.1	16.7
4.4	16.8
5.3	18.0
5.7	18.3
5.8	17.3
5.8	13.2
5.7	16.9
5.6	17.5
6.5	17.8
6.9	16.5
6.4	16.9
6.4	16.8
7.8	16.5
7.6	16.0

Temperature (°C ± .01°C)	Force (N ± 0.1 N)
7.8	16.4
7.6	16.6
7.6	16.5
8.0	16.9
8.3	17.6
8.7	17.2
8.8	16.2
8.9	15.9
8.9	16.7
9.5	15.4
9.3	15.3
10.0	16.4
10.1	16.0
9.7	13.2
9.6	16.3
10.0	15.8
10.3	18.0
11.0	16.2
11.0	16.2
11.2	15.7
11.0	16.2
11.1	16.3
12.0	15.3
12.3	15.4
12.4	16.1
12.4	15.2
12.3	13.7
12.2	15.6
13.5	14.1
13.5	15.7
13.2	13.5
13.4	14.5
13.5	14.8
13.6	15.7
13.5	15.3
13.6	15.3
13.8	15.6
14.3	14.7
13.6	15.0
14.3	15.1
13.9	15.7
14.7	15.6
15.3	15.1
14.9	15.3
15.0	15.7
15.3	15.5
15.0	15.1
15.6	13.1

Temperature (°C ± .01°C)	Force (N ± 0.1 N)
15.7	15.3
15.7	16.2
15.4	14.9
15.8	14.4
15.8	15.4
16.1	15.4
16.2	14.9
16.5	15.4
16.4	15.3
16.8	15.3
16.3	15.4
16.6	14.7
16.6	16.7
17.3	16.3
16.9	15.7
16.9	15.7
16.8	16.2
17.0	15.4
16.8	13.7
17.0	15.8
17.2	17.6
17.6	16.0
17.2	16.0
16.9	15.3
17.4	16.1
18.2	17.2
18.3	13.7
18.1	14.9
18.5	16.1
18.3	16.2
18.1	14.6
18.8	14.7
18.6	15.3
18.8	14.8
18.8	15.7
18.9	16.3
19.0	15.4
18.9	15.3

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Processed data.

The whole data collection took place in about two hours, which was the time that it took to the granite block to reach approximately room temperature. From the start of the experiment, the procedure was repeated constantly during the range of temperatures, obtaining many values of static friction at the block temperature range (between -6.8°C to +18.9°C). The whole process was only repeated once, but in order to process the data and represent it in a graph the raw data was grouped into different temperature intervals of two degrees, starting at -7.0°C and up to +19.0°C.

Averages for these temperature intervals were calculated, coefficient of static friction for the different temperatures and standard deviations also to see the variability of the different groups of measurements for each temperature range. Below some sample calculations are shown. For the temperature range of -7.0°C to -5.0°C:

Average force= ∑values for the temperature range / number of values = (13.5+13.9+14.0+15.3)/4 = 14.17 N. As we are using one decimal place it is rounded into 14.2 N.

$$\text{Coefficient of static friction} = \frac{\text{force of static friction}}{\text{mass } \times g} = \frac{14.2}{1.25 \times 9.81} = 1.16$$

Where the total mass is the 1kg of the weights used and 0.250 kg of the climbing shoe. Note that the result is given with two decimal places because if it is rounded to one decimal place the coefficient of static friction for several temperature ranges would be exactly identical, as it is very similar. All the values are calculated exactly the same way, and therefore the coefficients of static friction are proportional to the static friction itself, which is the value used to produce the graph.

The standard deviation has been calculated using a spreadsheet using the formula: $\sqrt{\frac{\sum (x-\bar{x})^2}{(n-1)}}$

Sandard deviation=√[(13.5-14.2)^2+(13.9-14.2)^2+(14.0-14.2)^2+(15.3-14.2)^2/(4-1)] = 0.78, which is rounded to 0.8 in the table of processed data.

Table of processed data for different temperature intervals of two degrees (-7.0°C and up to +19.0°C)

Temperature (°C ± 0.5°C)	**Average Force (N ±0.1 N)**	**Coefficient of static friction**	**Standard Deviation**
-7.0°C to -5.0°C	14.2	1.16	0.8
-5.0°C to -3.0°C	14.6	1.19	1.0
-3.0°C to -1.0°C	16.7	1.36	0.8
-1.0°C to +1.0°C	16.9	1.38	1.0
+1°C to +3.0°C	16.9	1.38	0.6
+3.0°C to +5.0°C	16.8	1.37	1.6
+5.0°C to +7.0 °C	16.5	1.35	0.6
+7.0 °C to +9.0 °C	16.1	1.31	0.8
+9.0°C to +11.0°C	16.3	1.33	0.8
+110.0°C to +13.0°C	15.0	1.22	0.8
+13.0°C to +15.0°C	15.2	1.24	0.7
+15.0 °C to +17.0°C	15.6	1.27	0.8
+17.0 °C to 19.0 °C	16.0	1.31	0.9

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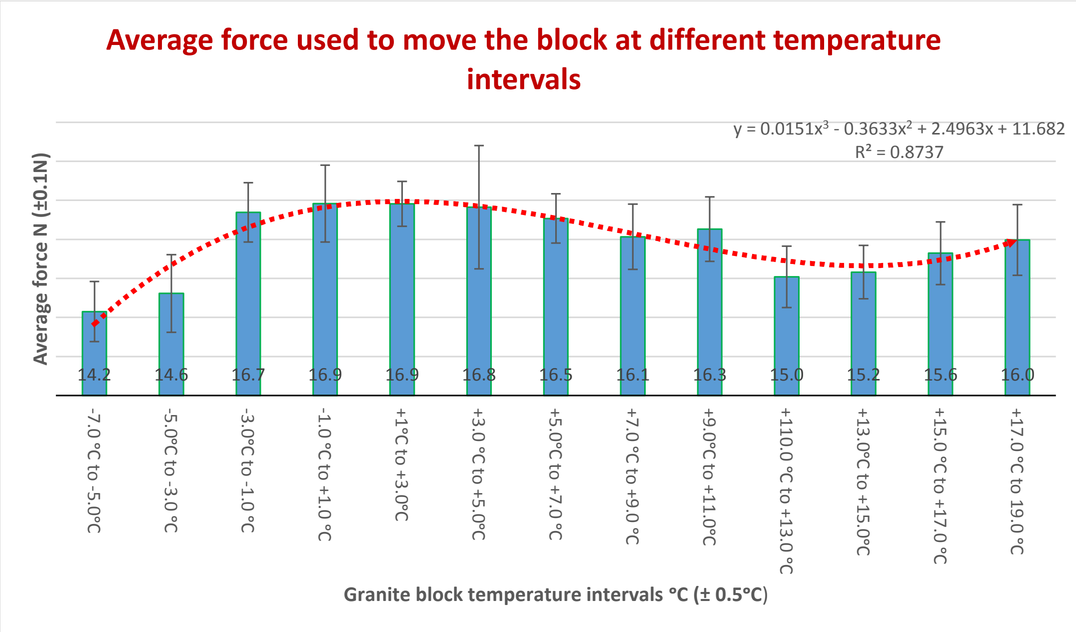
Processed data was represented in a bar chart and a polynomial line of best fit was represented using Microsoft Excel. Included in the graph are error bars representing the standard deviation for the values within each range of temperatures. Also included are the equation for the polynomial curve and the coefficient of determination, both calculated as well using Excel.



CONCLUSION, ANALYSIS AND EVALUATION

First of all, the graph presented corresponds to the average force employed for the climbing shoe to move in every temperature range, meaning the static friction. Another graph using the calculated coefficient of static friction could have been included, but the shape of the curve, coefficient of determination and curve equation would be exactly the same, as for its calculation we only had to divide all the forces by the same number, not changing the shape of the curve or the interpretation of the graph at all. The force of static friction is proportional to the coefficient of friction, and therefore to the grip of the shoe at different temperature ranges. In the graph we can observe that the minimum grip of the climbing shoes corresponded to low temperatures, and as the rock temperature increased so did the grip, going from a minimum of 14.2 N between -7.0°C to -5.0°C and reaching a maximum of 16.9 N at temperatures between -1.0°C to +1.0°C, which agrees with some of the literature available online, where it was said that the design and rubber compounds used to build climbing shoes was optimized for cold temperatures, same temperatures where the hand grip is also optimal. This is the reason why apparently elite climbers try their hardest routes when the temperatures are lower. Applying the information consulted on the "Study on safety-related aspects of tire use" mentioned

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before, and knowing from the Michelin tire grip study (see bibliography), I found that engineers (at least related to tire rubber and tire grip) can formulate different rubbers where the glassy state is close to the temperature that the rubber in the particular tire is recommended to be used for, being able to modify the glass transition temperature from -60°C to 0°C. If this is the case for tires, one could assume that the engineers in charge of formulating the rubber compounds in climbing shoes would have probably designed them to have glass transition temperatures for the temperature where hand grip is optimal, being around 0°C. We can observe in the graph as well that as temperature goes up, initially the grip decreases up to around 12°C to 14°C, which also matches the literature available, although later, at temperatures between 15°C and 19°C the grip starts increasing again, which is not the predicted behavior. It would have been interesting to see if this ascending trend would have continued for temperatures above 19°C, but unfortunately that would have required the use of an oven and the experiment would have been much more complicated to set up.

Error bars in the graph represent the standard deviation for the different groups of data, and we can see that the values clearly overlap (standard deviation shows the variation within a group of values), which indicates that, although a difference has been observed in the mean values of the data points and a trend has been identified, the differences between those average values is not likely to be significant after all. There are other sources of error like uncertainties related to the precision of the apparatus, in this case from the measurement of the temperature and the force (uncertainties are present in the tables). Other random errors coming from changes in the experimental conditions during the experiment (room temperature, area of the rock used, temperature of the shoe, relative humidity of the air, etc.) would logically have an impact in the investigation. To minimize it the data was statistically processed and standard deviation was calculated and represented.

There are two particular points in the graph that worth extra attention, for temperatures between 3°C and 5°C, where the value of the standard deviation is high compared to the rest of the data, and for temperatures between 9°C and 11°C, which does not fit with the general pattern of the data as the grip increases opposite to the decreasing trend observed in the adjacent data. The high value of standard deviation might have been related to the use of all the values of the temperature interval, as there is clearly one of them that does not match the pattern (all the values are generally between 16 N and 18 N, except for the value of 5.8°C where it suddenly drops to 13.2 N, which seems to be too low. If this value would have been considered an odd result and would not have been used for the mean, the value of standard deviation would have been much lower and similar to the rest. The oscillation observed at the 9°C to 11°C temperature could be something normal, as even when oscillations occur the general pattern seems to be decreasing.

The coefficient of determination for the polynomial curve selected is quite high, which implies that the regression line approximates quite well to the average data points. The shape of the graph does not allow for the calculation of a coefficient of correlation, as in this case the whole data does not show a particular linear correlation, but more like an optimal temperature for the rubber of the climbing shoe to have maximum grip, which seems to be between -1 °C and +1 °C,

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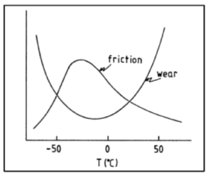
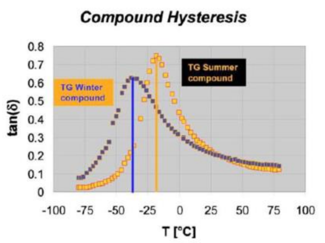
and a trend for the grip to increase up to this temperature and then to decrease up to the temperature of 11°C to 13°C.

As I mentioned before I did not find much reliable research for the specific topic of climbing shoes, but I did find a fair amount of published and reliable information regarding rubber and temperature for tires. If we compare our results with some of the results cited in the bibliography, we can observe certain similarities between them. Below, a graph representing friction and wear for tires at different temperatures from the European Union road safety discussion document, where we see how friction changes with the different temperatures in rubber. We can see in this graph that the friction increases with the temperature up to a certain point where the friction is maximum and then starts to decrease. The point of maximum friction in the graph is around -25°C. Logically being this test probably for rubber compounds used in winter tires it makes sense that the glass transition temperature will be rather low, therefore the maximum grip occurring at a low temperature. With other rubber compounds the shape of the curve remains a similar shape, although it occurs at a different temperature closer to 0°C. The other graph below compares the hysteresis (see definition and explanation in the introduction), and hence, maximum grip, for two different types of rubber compounds: winter and summer. We can observe that the shape of the graph does not change much, but the maximum friction and the temperature at which this friction is achieved does (higher for summer tires).

Relation of friction and wear versus temperature of a rubber compound





Evaluation

Regarding the experimental procedure, I found many difficulties for recording and processing the data, as in order to figure out the static friction I had to set up the data logger to take one measurement every half a second, then look at the graph produced and at the table of data and select individually all the peak force results that would correspond to the static friction. Then, reorganize this data in the table of raw data and then group it and do the calculations for the table of processed data, which took me a long time.

The apparatus used to measure the force and the temperature were very precise, as they were digital probes connected to a Vernier data logger. The main error source in this particular investigation was not coming from the precision of these apparatus, but from the type of probes available and the way to record the temperature in particular.

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It was difficult as well to place the shoe always in the exact same position on top of the block, even when the contour was marked to facilitate the process. Maybe using a different material like glass, which is smoother and uniform and at the same time transparent, I could have estimated the contact area between the shoe and the glass and the position of the shoe would have not had so much impact, as all the surface of the glass is equally smooth., minimizing the impact of the characteristics of the rock surface used in each repeat. Even being the same rock it is evident that the surface could have different characteristics in different areas. In this particular experiment and considering that I was trying to investigate the grip of shoes designed for climbing rock, using rock seemed to be a more accurate representation of the real life.

When the temperature was low, due to the higher gradient of temperatures between the block and the environment, the rock temperature would increase at a faster rate, leaving me less time to take the necessary measurements, meanwhile at higher temperatures the warming process would be less noticeable and take more time, having plenty of time to make the repeats.

The room humidity and the condensation produced on the rock was also a problem, as this affects the grip. To minimize it I cleaned the rock and shoe surface with a napkin before every measurement, which was a tedious process difficult to perform when the time did not allow for many measurements within the temperatures chosen.

The temperature of the shoe is another variable that could have been considered more carefully, as it logically impacts the grip. If we consider the factors affecting the temperature of the rubber in the shoe, I think that the most important would be, though, the temperature of the rock in contact with the shoe, but also the heat produced by the friction of the shoe in the rock should be considered, as well as the air temperature and the heat produced by the foot of the climber inside it. In this experiment the shoe was originally room temperature and nobody was wearing it. The impact of the heat generated from friction would be small as the mass inside the shoe was small (1kg). In real life, climbing shoes stand much larger pressure and therefore more friction as well.

Regarding the pulling method, I think that a rubber band could have been used when holding the force sensor so the pulling action would be more uniform and gentle. I tried to be careful during all the experiment, but considering that I was performing it for a long time and the movements were very repetitive, sometimes I would not control the force applied well and had to repeat the measurement.

In the future, I think it would be interesting to repeat the experiment for a wider range of temperatures, may be using a freezer that can get down to temperatures below -15°C and in a room up to 25°C or 30°C. That way I would have been able to observe if there were more fluctuations in the grip and if the grip would really decrease sharply at much lower temperatures, as the graph seems to indicate.

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Also I could have investigated different brands of climbing shoes, as they use their own different rubber compounds and it would have given me a better idea if all the brands were using the same strategy to design rubber with maximum grip for the temperature where the hand grip is supposed to be maximum.

Ideally, as well, I could try to perform the experiment in a place where the air relative humidity could be controlled to avoid the condensation in the cold block to affect the grip. Using a Vernier relative humidity probe I could have been able to spot any changes in humidity during the experiment.

Regarding the method to measure the rock temperature, I would also use a Vernier surface temperature probe to measure the surface temperature of the block rather than in the core, as it would be more accurate since it is expected that the surface of the rock will achieve room temperature sooner than its core. Several considerations were taken to minimize the impact of the error generated by measuring the temperature inside instead of the surface one. First, the hole was drilled as deep as possible so most of the probe would fit inside. Second, the bid used was the same diameter of the probe, so most of the probe inside and the rock were in direct contact. Third, the part of the probe left outside was covered with insulation tape and this was used as well to firmly attach the probe to the rock, so it would not move during the experiment. Finally, the hole was drilled as close as possible to the rock surface that was used for the experiment, so it would reflect more accurately the change in temperature in this surface. The systematic error related before was taken into consideration and the uncertainty for the temperature readings was estimated and increased to ± 0.5°C, when the original precision of the apparatus was ± 0.01°C.

Also, using a bigger block to be able to place the shoe on top more easily and so the change in temperature would happen more slowly, giving me more time to make the measurements (a block with more volume would have a smaller surface area to volume ratio and lose heat more slowly). May be using a different type of rock, with a different specific heat capacity would have changed the time taken for the rock to heat up and would have given me more time to take the friction measurements for the different temperatures.

Regarding the experimental procedure, it might be a good idea to calculate the grip by varying the angle of the rock and figuring out what angle makes the shoe lose grip at different temperatures instead of having to physically pull the rope horizontally every time I had to make a measurement. Although this approach could be more fair since I would not have to be applying a force myself to calculate the static friction, it would be more difficult to manipulate the rock at low temperatures and I would probably not have time to make all the measurements required for the completion of the experiment.

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