Squishy Circuits Resistivity

RESISTIVITY TESTING – INTRODUCTION

Electrical resistivity describes how much a certain material resists electrical flow. Every material has an associated resistivity, ρ, which is constant. Conductors, such as copper have a low resistivity, while insulators, such as glass, have a high resistivity. Resistivity is an important property of any electrical object because it directly relates to the resistance, which relates to Ohm's law. Ohm's law relates voltage, current and resistance, making if a powerful and unifying equation describing the behavior of all electrical circuits.

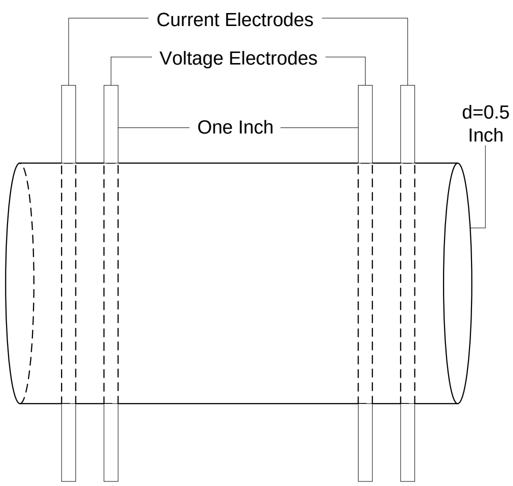
$$Resistivity(\rho) = Resistance(R)\frac{Area(A)}{Length(l)}$$

$$Ohms\ Law: \quad Resistance(R) = \frac{Voltage(V)}{Current(I)}$$

RESISTIVITY TESTING – CONDUCTIVE DOUGH

To test the resistivity of the conductive dough, a more specific recipe had to be developed to ensure a homogenous test subject. To do this, we followed the published recipe [9] with the modification of adding ¼ cup of flour, which the recipe leaves open-ended based upon the user's preferences. In this manner, four batches of conductive dough were made.

Samples of the dough were then inserted into the testing apparatus, a 0.5 inch PVC tube. Through the tube, four tin-copper wire electrodes were inserted, with the centermost electrodes placed one inch apart. A current source was attached to the outer two electrodes, while a voltmeter was attached to the centermost electrodes.



Picture of Setup / Figure of Test Apparatus

In order to measure the conductive dough's resistance, a predefined DC current was run through the dough and apparatus, and the resulting voltage was measured. The resistance of the sample was then calculated using Ohms law. Using this four-wire measurement technique, or Kelvin measurement, all resistance caused by the wires, electrodes and electrochemical reactions are negated [3], resulting in the resistance of the conductive dough sample, measured in ohms. The resistivity of the conductive dough can be found by inserting the resistance into the resistivity equation, along with the length and area.

The test was conducted using a bench power supply and bench multimeter, both of which were controlled using LabView [4] via a GPIB interface. The LabView program instructed the power supply to provide a current, starting at 1mA, hold that current for two seconds, and then increment the current by 1mA. 750ms after the power supply changed the current output, the multimeter was prompted to measure the voltage across the dough. This process looped until 50mA of current was reached. The data was logged and a linear regression line relating the voltage and current was generated, from which all samples had a strong linear correlation (r^2=99.8-100%). The data presented in this paper represents the resistivity of the dough at 50mA.

When we planned this experiment, we wanted to test the variability of resistivity in a single batch of conductive dough, and then compare the findings to other batches of conductive dough to get an idea of batch-to-batch variability in resistivity. In other words, we wanted to prove our hypothesis that each batch would have specific resistivity, but that the resistivity varied from batch-to-batch slightly.

Fifteen samples of the first batch were measured to determine stability of resistivity readings within a batch. Then 5 samples of each of the remaining batches were measured. The results of our tests on multiple samples of multiple batches are shown in the table below. The uncertainties given are ± 2 standard deviations of the mean.

Batch	Number of Trials	Resistivity Ω-inches
1	15	10.33±0.08
2	5	9.96±0.12
3	5	9.04±0.13
4	5	10.03±0.09
Average		9.8±1.1

Resistivity of Conductive Dough

Samples within a single batch vary in resistivity by less than 2%. While batch to batch variability is greater than intra-batch variability, we still find a reproducibility of approximately 11%.

RESISTIVITY TESTING – INSULATING DOUGH

Resistivity testing for the insulating dough is based upon the published recipes [9], with the variation of substituting the vegetable oil and water to the more exact amounts of 38mL of vegetable oil, 55mL of deionized water, and an additional 5 tablespoons of flour which, again, the recipe leaves to the user's preference.

A similar experimental setup was used for the insulating dough, however, a 0.225 inch PVC pipe was used in place of the 0.5 inch PVC pipe, and the voltage was measured across 0.125 inches instead of one inch as tested with the conductive dough. Furthermore, a 0-120V AC 60Hz autotransformer was used to provide power instead of a bench DC power supply. Computer controlled testing was not an option in this setup due to hardware limitations of the autotransformer, but testing was done using an ammeter to measure the current flowing from the autotransformer and a voltmeter to measure the voltage across the 0.125 inch of dough. Ten randomly selected data points, spread throughout the 120 volt range, were collected and linear regression analysis was applied to the data set. All of the produced equations also had high correlation (r^2=99.9-100%). Using the regression equations the resistivity at .5mA could be calculated via Ohms law and resistivity equations, as done with the conductive dough.

Batch	Number of Trials	Resistivity kΩ-inches
1	15	34.20±0.77
2	5	34.69±0.36
3	5	32.21±0.90
4	5	30.2±1.1
Average		32.8±4.2

Resistivity of Insulating Dough

Note that these measurements are in kΩ-inches rather than Ω-inches as above. Although variability is greater than with the conductive doughs, we still see an intra-batch variability of approximately 2% and a reproducibility of less than 13%.

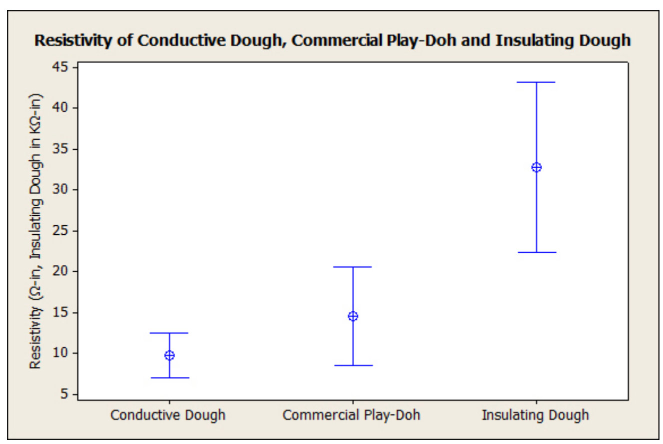
RESISTIVITY TESTING - COMMERCIAL PLAY-DOH®

While these results show that the conductive and non-conductive doughs have reproducible resistivity, it is interesting to compare their performance to proprietary Play-Doh® [7]. We found considerable variation in resistivity with color.

Color	Number of Trials	Resistivity Ω-inches
Green	3	12.412±1.644
Orange	3	16.14±3.039
Red	3	16.83±1.843
White	3	14.702±2.99
Black	3	12.756±3.673
Average		14.568±2.447

Resistivity of Play-Doh Dough

Because of the small sample size, the resistivity range shown is a 95% confidence interval based upon the t-distribution. The resistivity of the commercial dough is similar to that of the conductive homemade recipe above. Thus the commercial dough seems suitable for Squishy Circuit applications. However, the cost of buying the commercial dough is typically substantially higher than the cost of making the homemade dough. Additionally, from an education perspective, using the homemade dough means that all ingredients, and their quantity, is known, which makes discussions about the science behind the project easier to facilitate.



Comparison of Three Resistivities (Note that Insulating Dough is Measured in Kilo-Ohms)

CONCLUSION

We have presented our research indicating that the recipes for Squishy Circuits result in a product with generally consistent resistivity which can be used to construct electrical circuits and insulators. We also have compared this to commercially available dough which could be used as a conductor at this time, although is slightly less ideal and is more costly.

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