Thermal Conductivity of Concrete

Zachary G. Shermer ’18 and Hugh O. Thurman III

Department of Physics and Astronomy, Hampden-Sydney College, Hampden-Sydney, VA 23943

ABSTRACT

Thermal properties of building materials are crucial to understanding how a specific material will respond to the environmental conditions in which it is utilized. Concrete, which is widely used both commercially and residentially, has some unique aspects that can only be understood by studying a few key components –the thermal conductivity, thermal diffusivity, and specific heat. These key features can all be studied in the lab with relative ease and little expense. However, increased accuracy comes at a much greater expense. In my experiment, I used a cross between the Absolute and Comparative Techniques to calculate the thermal conductivity of concrete, which resulted in a value of .67 J/mK, which provides a 4.2% error when compared to the theoretical value of .7 J/mK .

THEORY

To measure the thermal properties of concrete, a reliable, real-time way to measure the temperature of the sample must be utilized. A thermistor is a resistor whose resistance varies based on temperature. There are two different types of thermistors –Positive Temperature Coefficient (PTC) and Negative Coefficient (NTC). In a PTC thermistor, resistance goes up with temperature, and in an NTC thermistor, resistance goes down as temperature goes up. NTC thermistors are the more common type and are the type of thermistor utilized in this setup.

Once a method of measuring the temperature of the sample is decided, a data-collection method is needed. An Arduino is an open source, highly modifiable circuit board that is meant to be programmed for a myriad of experimental uses. For my experiment, it is used to record the data from the thermistors, convert it to temperature (in Celsius), and then export that data to a .txt file for further analysis. However, the Arduino’s internal clock is not very accurate –it is known to lose a few seconds each day, meaning it is not very accurate over long periods of time. To fix this, a third-party application called Realtime I2C can be used to record the data from the Arduino, timestamp it using the computer’s clock, and then save it to a .txt file. From there, the data can be imported to almost any program, in this case Microsoft Excel.

The final piece of equipment that is required is a heat source. Something as simple as a hot plate or burner can be used, but the power input (in Wattage) must be known. If it is not, it is impossible to solve for the thermal conductivity directly through experimentation.

Two common methods for calculating the thermal conductivity of a material directly through experimentation are the Absolute and Comparative Methods. Both are steady-state techniques, which means that both methods require the sample to reach a steady temperature based on the amount of heat being transferred into the material. In the Absolute Method, the sample is sandwiched in between a heat source and a heat sink with two temperature sensors evenly spaced in the sample. Figure 1 depicts the setup:

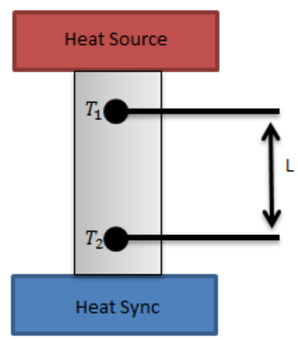


Figure 1 Absolute Method

The following equation can then be used to solve for the thermal conductivity (*k*):

Eq. 1: $k = \frac{QL}{A\Delta T}$; Where Q is the amount of heat, L is the distance, and T is the temperature

The comparative method is a similar to the absolute method, but it uses a standard, or known, material of which to compare the sample to in order to determine the thermal conductivity of the unknown sample. The setup is pictured in Figure 2:

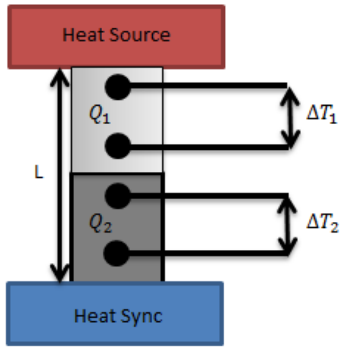


Figure 2 Comparative Method

The following equation can then be used to solve for the thermal conductivity (*k*):

Eq. 2: $\frac{\Delta T * A}{Q} = \frac{\Delta x}{k} + 2 * R_T;$

Where ΔT is temperature difference, A is the cross-sectional area, Q is heat flow rate, R is the specific interfacial thermal resistance, and Δx is the length over which temperature difference is measured

For my purposes, I will take elements from both methods to create a more cost-efficient system. Since I also lack an accurate way to measure the heat being put into the system, both methods are needed to determine the thermal conductivity of the concrete sample. The basic setup is pictured in Figure 3.

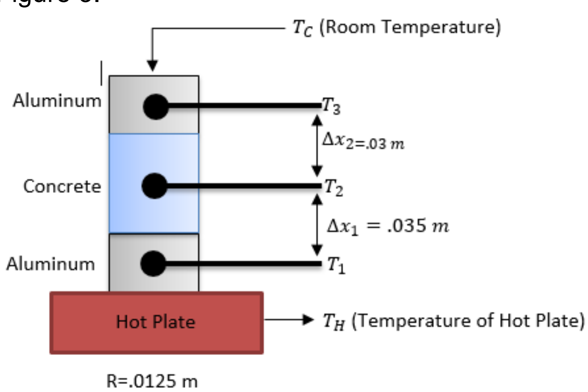


Figure 3 Absolute and Comparative Method

Equation 1, which is the absolute method, will be used to calculate the Q going into the system based off the known thermal conductivity of aluminum (205$\frac{?}{??}$). After this is done, the comparative method, or Equation 2, can be manipulated for this setup to become:

Eq. 3: $k_c = \frac{(\Delta x_1 - \Delta x_2)Q}{A(\Delta T_1 - \Delta T_2)}$

The cooling temperature of concrete will also be monitored as a function of time. This serves as both a test of the system and will show how important it is to give concrete time to set –concrete is not in a stable state for some time. The setup is pictured below:

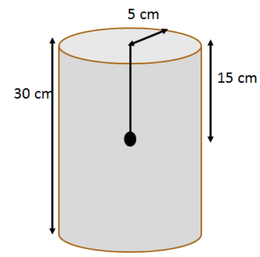
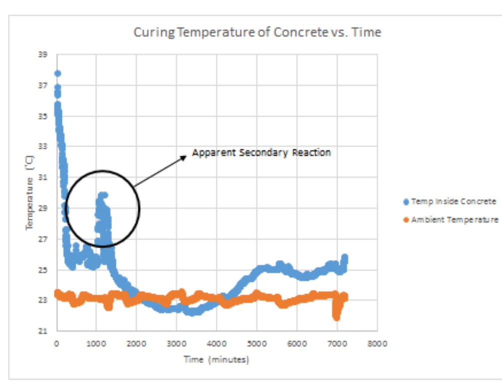


Figure 3 Sample to Monitor Cooling Temperature

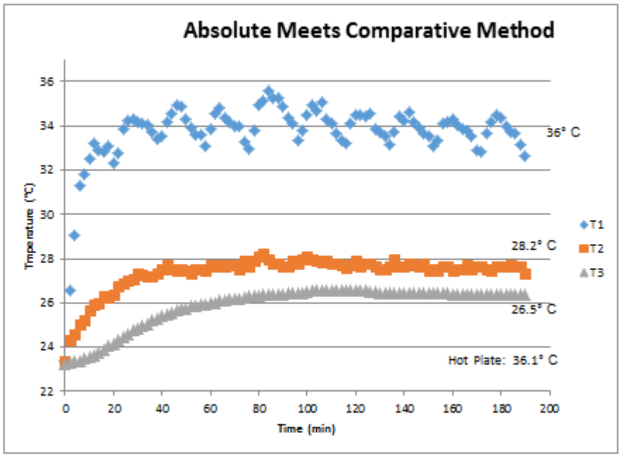
MATERIALS AND METHODS

The first step in this experiment is to program the Arduino to both record the resistance from the thermistor and convert that value into temperature. Thankfully the creators of the Arduino, AdaFruit, have a simple tutorial online for how to program the Arduino to record the data for one thermistor. However, the code must be adapted for multiple thermistors, so some basic programming knowledge is needed. Realtime I2C is an open source program that can monitor and record data streamed from an Arduino. Since Arduinos do not a have a reliable onboard clock, the program also provides a feature to timestamp it using the computer's clock. The thermistors must also be embedded within the sample while it is setting as this is the easiest time to do so. The two samples from Figures 2 and 3 must also be created as shown and given the recommended time to set (five days). The second sample can be monitored over that period to record the cooling temperature of concrete over time.

DATA



Graph 1 Curing Temperature of Concrete vs. Time



Graph 2 Absolute Meets Comparative Method

$$T_1 = 309.13K$$
$$T_2 = 301.35K$$
$$T_3 = 299.65K$$
$$T_H = 309.25K$$
$$\Delta x_1 = .035m$$
$$\Delta x_2 = .03m$$
$$\Delta T_1 = 7.5K$$
$$\Delta T_2 = 1.7K$$

$$k_{aluminum} = \frac{Qc}{A\Delta T}$$
$$205 = \frac{Q(.03)}{\pi(.0125)^2(6.1)} = .402 = \text{Q}$$
$$k_c = \frac{(\Delta x_1 - \Delta x_2)Q}{A(\Delta T_1 - \Delta T_2)}$$
$$k_c = \frac{(5 * 10^{-3}).402}{\pi(.0125)^2(6.1)} = .67\,\frac{W}{mK}$$

Figure 4 Calculations

ANALYSIS

Monitoring the curing temperature of concrete confirmed several known expectations. Concrete setting is an exothermic reaction, meaning that once water is added the sample heats up. This is clearly seen in the graph. However, around 1000 minutes in, or 16.5 hours, there is a secondary spike. This is most likely due to water being trapped somewhere in the sample and reacting again with the concrete to produce heat over half a day after the initial reaction. If this is true, it is a neat phenomenon to have captured. This also shows how important it is to let concrete set before performing tests on it.

The Absolute Meets Comparative Method worked very effectively. It is easy to setup –and costs a lot less than other methods that have similar accuracy (such as the Laser Flash Method). The thermal conductivity was calculated to be .67 $\frac{W}{mK}$ using this method, which has a 4.2% error when compared to the accepted value of .7 $\frac{W}{mK}$.

CONCLUSION

Over the course of the summer I tried a lot of methods to determine the thermal conductivity of concrete. With the help of my advisor, Trey, I was able to create a hybrid method to determine the thermal conductivity fairly accurately with common materials. I hope to continue this project over the following semesters and test the radial conductivity of concrete now that I have created an accurate way to do so.

REFERENCES

Akram, M. N., Nirmani, H. R., & Jayasundere, N. D. (n.d.). A Study of the Thermal and Electric Characteristics of Thermoelectric Cooler TEC1-127 Series. Retrieved from http://uksim.info/isms2016/CD/data/0665a430.pdf

Cartridge Heaters: How they are made & Why they fail! (n.d.). Retrieved June 20, 2017, from http://www.hotwatt.com/landing%20cartridge.htm#Cartridge Heaters How they are made & Why they fail!

Debois, S. (2013). Design, Construction and Validation of a Guarded Hot Plate Apparatus for Thermal Conductivity Measurement of High Thickness Crop-Based Specimens. University of Liege, Belgium. Retrieved June 2, 2017, from https://orbi.ulg.ac.be/bitstream/2268/157284/3/GHP_complete.pdf.

Ensor, C. R. (1931). The determination of thermal conductivity and its temperature-variation for medium conductors. Proceedings of the Physical Society, 43(5), 581-591. doi:10.1088/0959-5309/43/5/314

Gandage, A. S., Ram, V. V., Yaswanth, A. B., Thota, P. K., & Gupta, S. (2015). Thermal Conductivity Studies for Self-Consolidating Concrete with Sand and Fly Ash Variation. ACI Materials Journal, 112(6), 709-722. doi:10.14359/51687976

H-S Breaks Ground on Unique Energy Research Lab. (n.d.). Retrieved March 4, 2017, from http://www.hsc.edu/News/News-Archive/2014/Energy.html

INA118 Precision, Low Power Instrumentation Amplifier. (n.d.). Retrieved June 1, 2017, from http://www.ti.com/lit/ds/symlink/ina118.pdf

Sukhatme, S. P., & Kandlikar, S. G. (n.d.). Guarded Hot Plate Method for Determination of Thermal Conductivity of Thermal Insulation Materials. Retrieved from http://www.rit.edu/~w-taleme/Papers/Journal%20Papers/J003.pdf

Loflin, L. (n.d.). Build a Thermocouple Amplifier. Retrieved June 01, 2017, from http://www.bristolwatch.com/ele/thermalcouple_amplifier.htm

Najafi, Z., & Ahangari, K. (2013). Https://www.hindawi.com/journals/je/2013/946829/. Journal of Engineering, 2013. Retrieved June 2, 2017, from https://www.hindawi.com/journals/je/2013/946829/.

NTC Thermistor - Steinhart and Hart Equation. (n.d.). Retrieved June 01, 2017, from https://www.ametherm.com/thermistor/ntc-thermistors-steinhart-and-hart-equation?gclid=Cj0KEQjw9r7JBRCj37PlltTskaMBEiQAKTzTfGs0CRsp5MMV9Kqpwx60bOSqj6UrPlm1ls_2VnbjPSkaAmrB8P8HAQ One4u. (n.d.). Topic: HOW TO CAPTURE SERIAL MONITOR AS TEXT FILE AND LINK TO EXCEL WITH AUTO REFRESH. Retrieved June 01, 2017, from https://forum.arduino.cc/index.php?topic=401919.0

Shermer, Z. G. (2017, May 17). Multiple Thermistors on one Arduino . Retrieved June 01, 2017, from https://forums.adafruit.com/viewtopic.php?f=25&t=117924

Slifka, A. J., Filla, B. J., & Phelps, J. M. (1998). Thermal Conductivity of Magnesium Oxide From Absolute, Steady-State Measurements. Journal of Research of the National Institute of Standards and Technology, 103(4), 357–363. http://doi.org/10.6028/jres.103.021

Thermistor. (n.d.). Retrieved June 01, 2017, from https://learn.adafruit.com/thermistor/using-a-thermistor

Zhao, D., Qian, X., Gu, X., Jajja, S. A., & Yang, R. (2016, August 27). Measurement Techniques for Thermal Conductivity and Interfacial Thermal Conductance of Bulk and Thin Film Materials. Retrieved June 07, 2017, from https://arxiv.org/abs/1605.08469