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Validation of cylindrical pavement specimen thermal conductivity protocol

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Validation of cylindrical pavement specimen thermal conductivity protocol

by

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ABSTRACT

Pavement thermal property plays a vital role in forming Urban Heat Island effect that influences the comfort level and the environment. While other pavement properties are relatively easy to acquire using field instruments, thermal conductivity needs to be obtained using laboratory measurements. A method to measure the thermal conductivity was developed by Arizona State University (ASU). In this study, this method which utilizes cylindrical specimen geometry was validated for its feasibility and accuracy. However, the effectiveness of the thermal interface filler materials used to fill the air gap between the heat source and testing pavement materials has not been thoroughly evaluated. Four different types of filler materials were selected and evaluated: high pressure lithium grease, Moly-lithium grease, petroleum jelly, and Omega paste. The test results indicate that Omega paste, a silicone-based thermal grease commonly used in electronic devices, gave the highest thermal conductivity of the asphalt and concrete samples tested. This is due to its higher thermal conductivity (2.3 W/m-K) as compared to the other three filler materials tested even though the workability of Omega paste was not as good as the other three. The Omega paste was confirmed as a suitable filler by conducting tests on a material with a known thermal conductivity. For the ASU method to be accurate, the thermal conductivity of the selected filler material needs to be higher than the top and bottom insulation of the test piece, due to the one-dimensional steady-state heat flow in the test piece.

CHAPTER I
INTRODUCTION

1.1 Problem Statement

Measuring thermal properties of paving materials have become ever-increasingly important to understand and solve some environmental problems. With the ever-increasing interest in sustainability, the pavement industries are investing in technologies that balance three principles: Social, Environmental, and Economic. To maintain the well-being of the environment while satisfies basic social and economic means, present and future, industries and regulators have reviewed a number of factors that can create profound impacts on the balance. One of them is the urban heat island effect, which directly relates to the thermal property of pavements. While it remains as one of the important factors that contribute to heat island effect, it is also regarded as one of the solutions. The definition of cool pavement brought up by U.S. Environmental Protection Agency described it as a type of pavement that could potentially make its surface cooler and release a greater amount of heat to the atmosphere in the contrast with conventional pavements (USEPA, 2008). Gui et al. have developed a thermophysical model which showed that surface properties, including solar reflectivity and emissivity the most importantly account for the maximum and minimum surface temperature in paving materials. Nonetheless, the internal thermophysical properties, which include thermal conductivity, heat capacity, and density, were also significant to the overall thermal behavior of paving materials.

Thermal conductivity is defined as the capacity of conducting heat. In other words, it is a constant of proportionality between heat flux and temperature gradient. While albedo and emissivity are relatively easy to acquire using various types of field instruments, the field measurement of pavement thermal conductivity is yet to be developed. Conventionally, the laboratory measuring procedure for paving materials is based on ASTM C-177. This widely-accepted procedure employs a one-dimensional steady-state heat flux measurement using a guarded-hot-plate apparatus. However, this method is unsuitable for measuring paving materials, as it requires a steady temperature to determine *k* and regulate the geometries of slab specimen. Furthermore, it is not recommended for inhomogeneous materials, which paving materials are, for their aggregate gradations. Another test method developed by Carlson et al. employs cylindrical specimen geometries that are commonly used for mechanistic testing. In addition, this method requires less preparation and uses a transient technique that allows the process of heating up. However, the contacting materials that fill between the heating source and measuring objective are a research gap that is yet to be studied. In order to get an accurate measurement of pavement thermal conductivities, a cylindrical specimen apparatus needs to be developed and the thermal conducting interface materials that can potentially optimize the results need to be identified.

1.2 Study Scope

This study intends to validate cylindrical pavement specimen thermal conductivity testing method developed by Carlson, Bhardwaj et al. (2010) and solve some of the issues that was not identified in the previous literature. The issues include: the method of dealing with non-perfect central hole drilled through the specimen, the filler materials to use at the interface between heat source and specimen body, determination of heat source temperature, and the time required to research steady-state temperature.

1.3 Outline of Report

This report consists of six chapters that is to discuss the process of designing, testing, data analyzing, evaluating, and validating the test methods. Chapter 2 includes a literature review on the subjects of urban heat island effect, concepts of cool pavement, lab testing methods, and thermal interface materials. Chapter 3 explains the basic concepts, definition, and theoretical analysis of the experiment and calculation. Chapter 4 describes the experimental design for the cylindrical specimen apparatus and the accessories used to assist data acquisition. In addition, this chapter also verifies the test method by measuring the materials with known thermal conductivities as well as validates the accuracy of thermocouple measurement. Chapter 5 presents the test results for paving material thermal conductivities and the evaluation of thermal interface materials used in the tests. Chapter 6 concludes the study and provides future recommendations.

CHAPTER II
LITERATURE REVIEW

2.1 Introduction

To mitigate local heat island through sustainable pavement technologies in an effective manner, it is of great significance to fully understand the concept of heat island effect and how it impacts our environment. This chapter will start with a literature review on heat island effect. Furthermore, a brief review on the current cool pavement technologies will help to understand the importance of measuring thermal properties for paving materials. Lastly, an overview on the current thermal conductivity measuring methods and thermal interface materials will lay fundamental background knowledge for the further discussion.

2.2 Urban Heat Island Effect

Associated with urbanization and industrialization that improve our material needs and comfort, Urban Heat Island (UHI) emerged as one of the major problems that hinder human health and the surrounding environment. UHI is defined as the phenomenon that urban and suburban areas experience elevated temperature compared to the outlying rural surroundings. The dense urban structures absorb and re-radiate solar radiations as well as the anthropogenic heat source generate large amounts of heat and become the main factors of UHI. The annual mean air temperature of a city with more than one million people is reported to be 1 to 3 ℃ warmer than its surrounding areas. For a clear, clam night, the temperature difference can be as much as 12 ℃ (Akbari, Pomerantz et al. 2001)

Figure 2.1 shows the typical temperature distribution and how that of city and rural areas distinguishes from each other.

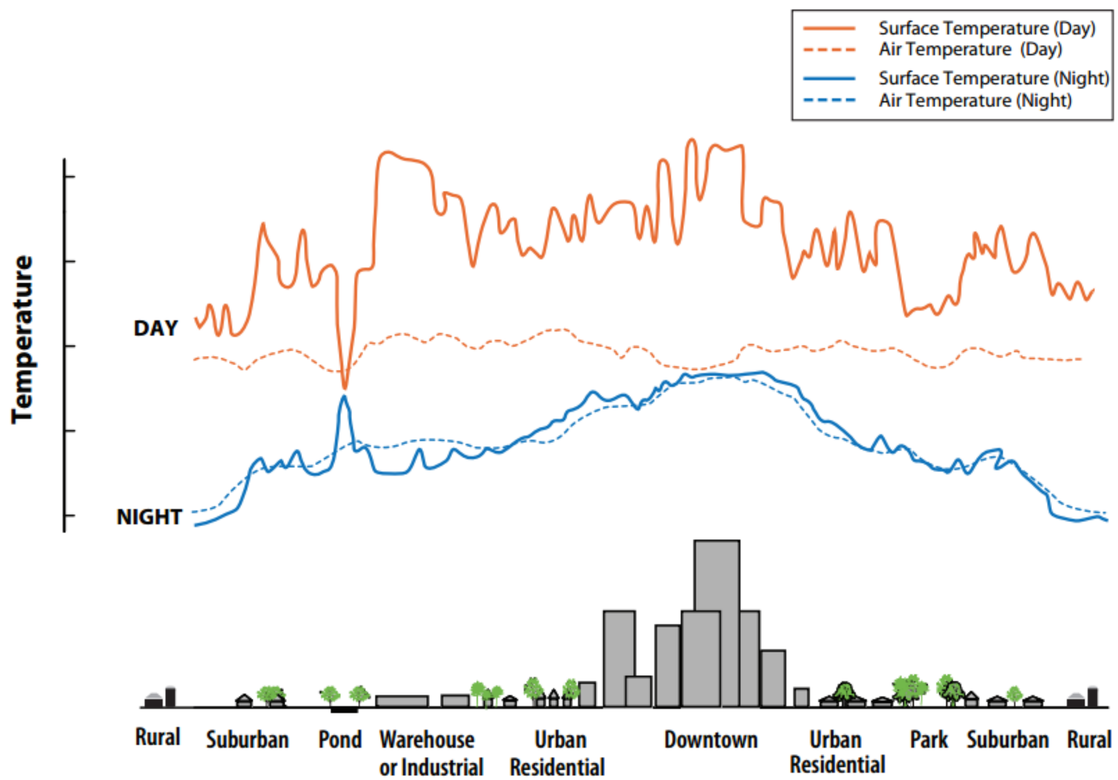

Figure 2.1 Temperature Variations for Different Locations (Akbari, Pomerantz et al. 2001).

Higher urban temperature is the result of the anthropogenic heat released from vehicles, power plants, air conditioners and other heat sources. Huge quantities of solar radiations are mainly stored and released to urban areas due to dense building materials and the sky view factor. In addition to the factors stated above, less vegetation due to massive residential and commercial land use and high roughness structure that reduces the convective heat removal also contribute to UHI (Rizwan, Dennis et al. 2008).

UHI is the result of many factors work collectively as shown in **Figure 2.2**. Those factors could be generally divided into controllable and uncontrollable variables, and then further categorized as the temporary effect variables, permanent variables, and cyclic effect variables. Temporary variables includes air speed and cloud cover, and they are positively correlated with UHI (Kim and Baik 2002). Green areas, building material, and sky view factor constitute permanent effect variables; Green areas and building materials continue to capture and store solar radiation during the daytime and then release the energy back to the environment after the sun goes down. Meanwhile, the quantity of heat released was also on the account of controllable factors such as building materials and sky view factor. The reflected energy was fairly low due to the decreased level of sky view factor and low albedo of the paving materials. Therefore, design values of albedo and sky view factor are reported to be significant in creating UHI (Giridharan, Ganesan et al. 2004). The scarcity of vegetation results in the lack of latent heat of vaporization of the cities. For instance, the city of Tokyo reported a reduction of evapotranspiration by 38% from 1972 to 1995 (Kondoh and Nishiyama 2000); Cyclic effect variables consist of solar radiations and anthropogenic heat sources. The heat source in one area comes from two sources: solar radiation and anthropogenic sources. Almost all anthropogenic sources affect the environment directly. Anthropogenic sources include things like home appliances, automobiles, power plants etc. For the solar radiation, only part of it heat up the environment directly, the rest is absorbed by the complex urban structures and contributes to UHI indirectly.

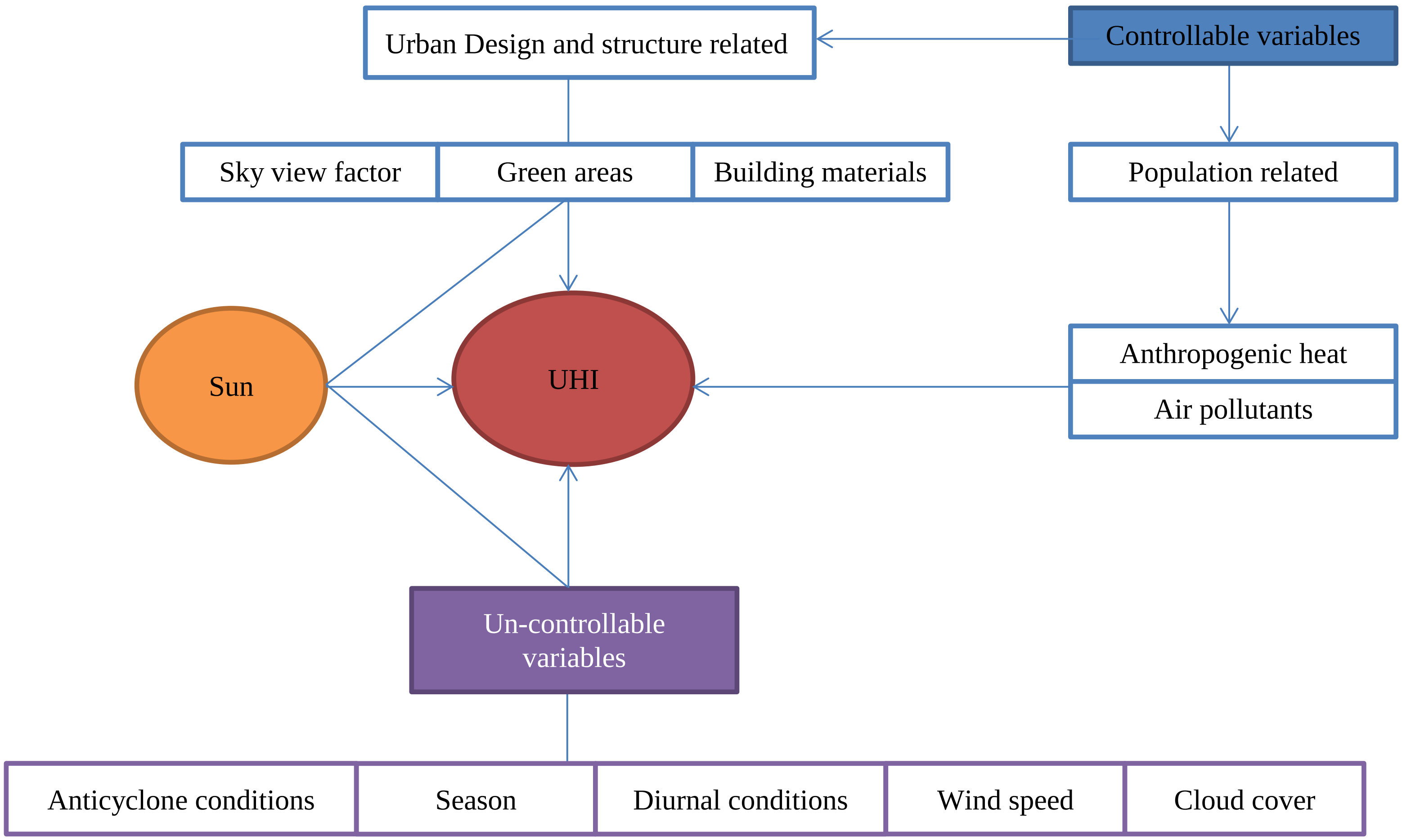

Figure 2.2 Generation of Urban Heat Island (modified from Rizwan et al., 2007).

Elevated temperature in the city areas has been seen as a problem that affects the local environment and hinders the human comfort level (Gartland 2008). Although some of the impacts are regarded as positive, for instance, the reduction in heating energy use in cold climate, most impacts are negative regarding human health and ecological circles. **Table 2.1** presents a literature summary of the negative impacts of UHI.

Table 2.1 Potential Impacts of Urban Heat Island

Type of Impact	***Source***
Impaired human health and comfort	Sheridan and Dolney, 2003
Elevated energy use	Akbari et al., 2001; Heiple and Sailor, 2008
Increased air pollution	Bloomer et al., 2009
Decreased water quality	Akbari et al., 2001
Pavement life	Pomerantz and Harvey, 1999

2.3 Pavement Heat Transfer Mechanism

The mechanism of pavement Heat Transfer shown in **Figure 2.3** describes the complex system of incoming energy in the form of solar radiation which is reflected, absorbed, stored, and re-radiated by paving materials. The general factors that influence those heat transfer activities are as follows.

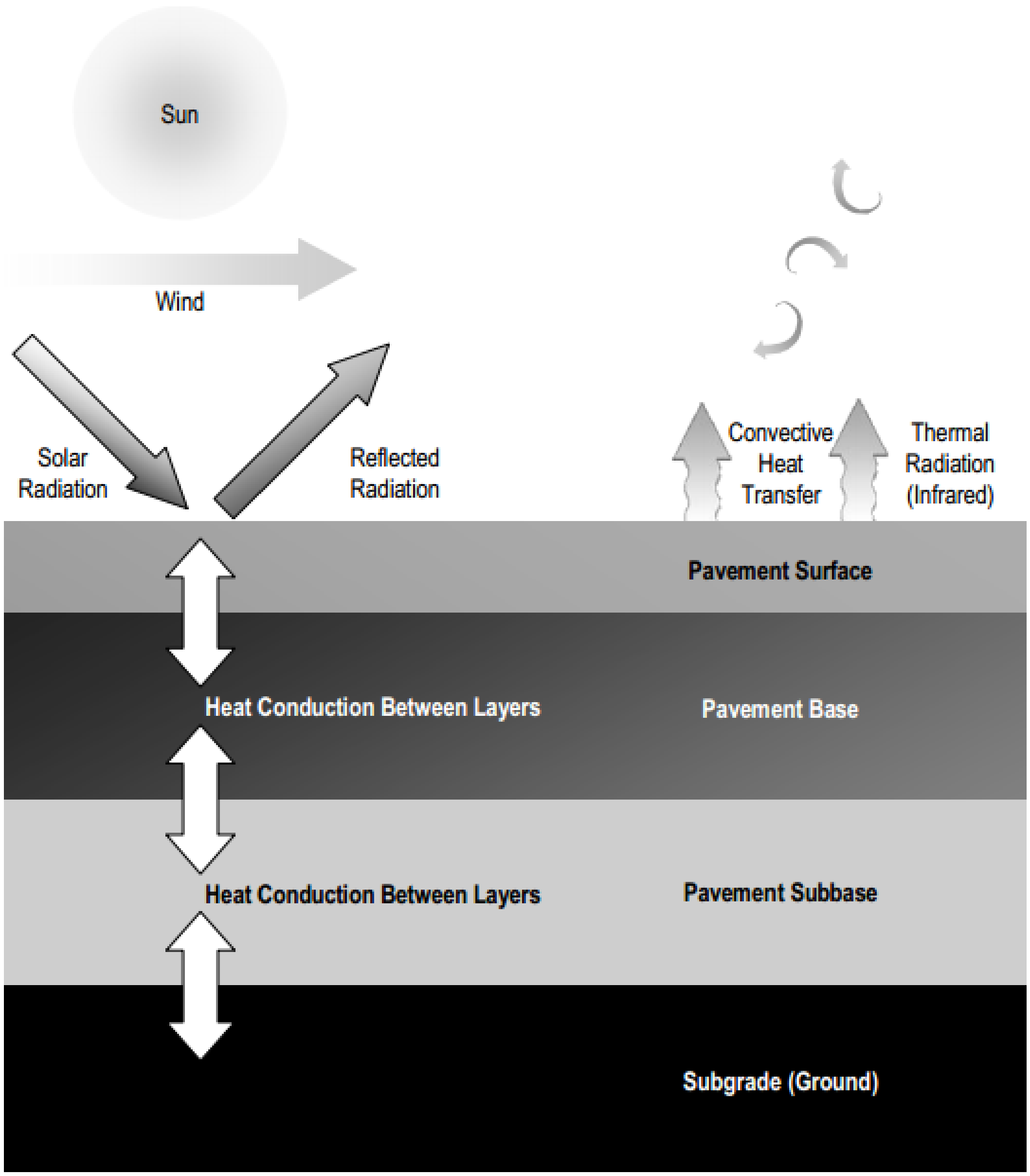

Figure 2.3 Mechanism of heat transfer in the paving materials (USEPA, 2005)

- **Albedo.** Albedo is defined as the fraction of reflectance of solar radiation from a surface in the form of short wave radiation. A higher albedo means more energy is reflected away. Therefore, paving materials with greater albedo have better cooling effects, as the energy was reflected back to the atmosphere instead of being stored in the pavement.

- **Permeability.** Paving materials that have a greater permeability will have a better cooling effect, as allowing water and water vapor to pass through the voids in the permeable body that causes evaporations.
- **Conductivity.** Conductivity is the ratio of heat flux to temperature gradient. A low conductive material is preferred for cooling effect, as it will get a high temperature faster at the surface but will not store as much heat as one with higher conductivity.
- **Emissivity.** Emissivity represents the ratio that the rate at which a surface emits thermal radiation to the rate at which a black body at the same temperature. Pavements that have higher emissivity radiate heat away faster.
- **Thickness.** The thickness of a pavement determines the amount of heat it can store. The heat transfer in the pavement also depends on how well heat can be conducted between layers.
- **Convective airflow.** The surface texture and porosity affects the heat convection between the pavement and the atmosphere. Porous pavement generally transfers heat faster than conventional ones.

2.3 Thermal Property Preference for Cool Pavement Selection

Cool pavement is defined as types of materials and technologies that could potentially make pavements have lower surface temperatures and release less heat into the atmosphere (USEPA, 2005). Pavement physical properties are critically correlated with the cooling mechanism of paving materials. Strategies that can make pavements cooler include modifying thermal properties, enhancing evaporation and convection, and reducing heat energy in/on pavements. The means of modifying thermal properties for paving materials will be discussed below.

2.3.1 ***Reduce thermal conductivity***

Thermal conductivity measures the rate at which heat is transferred throughout the pavement. Pavements with low conductivity may have a higher surface temperature as a result of bad heat transferring capacity but will prevent heat transfer through layers (USEPA, 2005). Hence, decreased thermal conductivity is favorable for paving materials, as it reduces the heat transfer into pavement and make its body cooler.

2.3.2 ***Increase heat capacity***

Heat capacity measures the amount of energy needed to raise the temperature at one unit weight by one centigrade. Pavement with higher heat capacity has greater ability to maintain its temperature, as it requires more energy for it to raise the temperature. The artificial engineering materials tend to have greater heat capacities. Reportedly, city areas with dense structures made of those materials sometimes captures twice as much as their surroundings during daytime (Christen and Vogt 2004). On the flip side of this method, increasing heat capacity also increases the heat storage during the daytime, which will re-radiate the heat away when sun goes down. Therefore, this method will increase the nighttime low temperature.

2.3.3 *Increase albedo*

Albedo measures the percentage of solar reflectance to the total radiation. Most existing literature identified it as the primary determinant of maximum pavement surface temperature (USEPA, 2005). Paving materials that have higher albedo also indirectly reduce the temperature below the surface, as less heat is available at the surface for transferring into the body. Apart from the cooling aspect, improving albedo of paving materials also help to offset global warming through radiative forcing (Akbari, Pomerantz et al. 2001).

Pavement Albedo also tends to change over time due to weathering, accumulation of dirt, and surface wear. Literature found that pavement albedo also changes over time, as light-colored concrete tends to darken with age, while dark colored asphalt tends to lighten. For instance, Santero, Masanet et al. (2011) reported that newly-cured concrete pavements typically have albedo in the range of 0.35-0.40 for regular cement and aging will result in a reduction by 35 to 45%. By contrast, Asphalt tends to lighten over the time by means of oxidation and binder wear that reveals its lighter-colored aggregates. **Figure 2.4** depicts the typical color change of pavements over time

2.3.4 *Increase thermal emissivity*

Thermal emissivity measures the amount of heat that is radiated per unit area at a certain temperature. Combining with albedo, these two factors are oftentime identified as

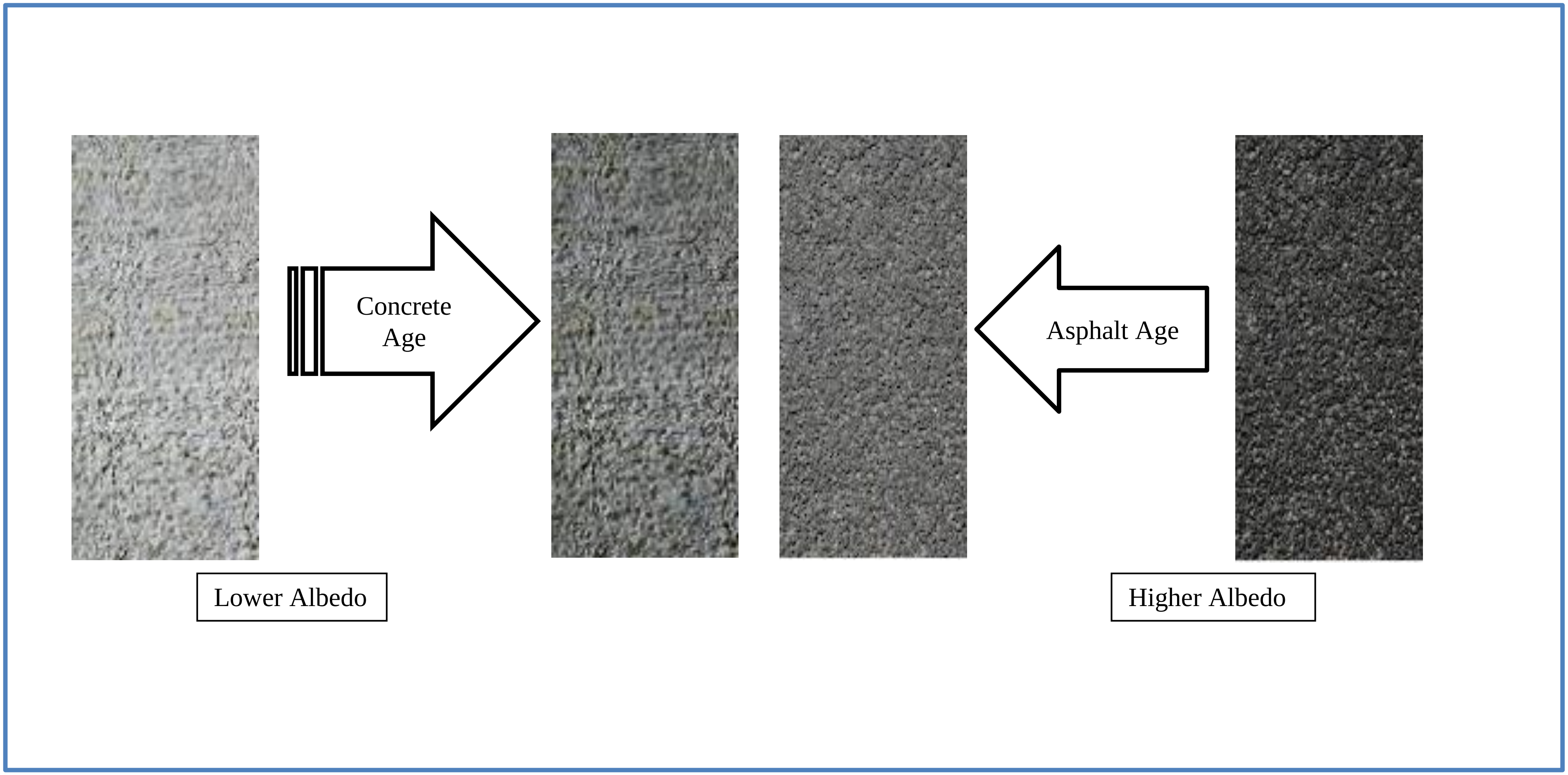

Figure 2.4 Pavement Surface Color Change through Aging.

two main factors to determine whether the material is cool pavement. While albedo affects the maximum surface temperature, emissivity affects the minimum since it measure the rate of heat going away (Gui, Phelan et al. 2007). Improving emissivity helps offset UHI, as it radiates the heat faster so the chances that the radiation gets absorbed by air become less.

2.4 Thermal Conductivity Measuring Methods for Paving Materials

Pavement thermal conductivity is critical for understanding, evaluating and modeling the thermal behavior of the materials. Due to the inhomogeneous physical property of paving materials, it is often difficult to obtain accurate values of thermal conductivities. Previous literature has identified three conditions that principally affect the thermal conductivity of paving material: water content, density, and temperature (ASTM 1978)(ASTM, 1978). In addition, the mineralogical character of the aggregates, cement/bitumen type, entrained air, water/cement ratio, and age. The following content will summarize some of the popular methods of measuring thermal conductivities for paving materials and historical thermal conductivity values measured in each methods.

2.4.1 ***ASTM Guarded-Hot-Plate Method***

ASTM C177 (Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus) has been a widely-accepted method for measuring thermal conductivity of both concrete and asphalt (Tan, Low et al. 1992). The apparatus was mainly centered with a measured area known as the guarded hot plate. Primary isothermal guards were applied on the sides of it and specimens were placed above and below this hot plate layer. On the outside, the vertical ends were made of cold surface assemblies and the horizontal ends were sealed with two isolation pieces. The whole apparatus setup was shown in **Figure 2.5**.

Regardless of its widely acceptance in the industry, this method limit the specimen size to a flat plate with thickness not exceeding one third of the maximum linear dimension due to it uses a one-dimension steady-state method. Furthermore, the temperature gradient with the test specimen is required to be small enough so that it can ensure accuracy of differential terms in Fourier equation. In addition to these requirements, this approach is not recommended for inhomogeneous specimen. In the paving materials, the aggregate gradients determine the inhomogeneous properties. Therefore, this method is not suitable for measuring pavement specimens.

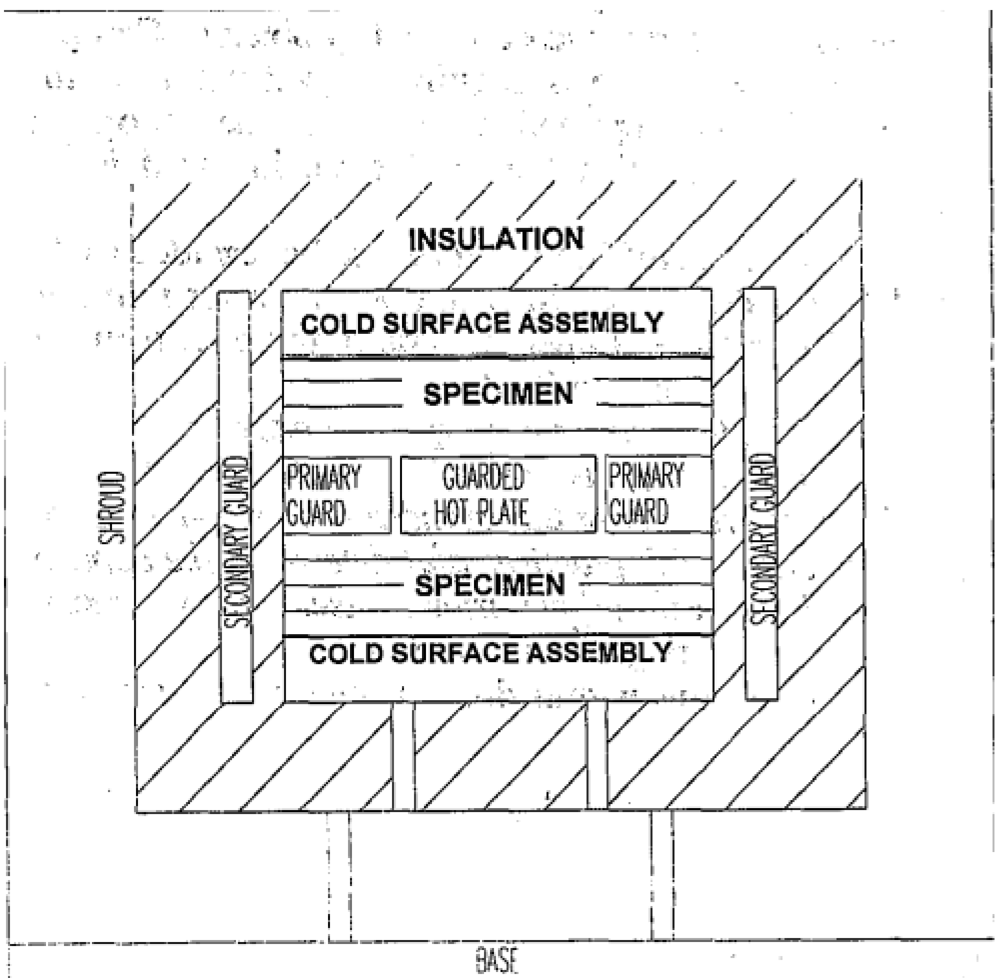

Figure 2.5 General Apparatus Setup of the Guarded-Hot-Plate Method.

2.4.2 *ASU Cylindrical Specimen Method*

Carlson et al. developed a test method that also employs one-dimension steady-state method but utilizes the geometry of a cylindrical specimen. Cylindrical geometries are commonly used in the paving material laboratory for mechanistic testing and also used for volumetric property verifications and quality control operations in the industry.

As the specimen used in this study has a cylindrical geometry, ASU method is chosen to measure the thermal conductivity and evaluate thermal interface materials. Some modification has been made to comply with our situation. For instance, in the ASU method, the final temperature of cylinder inner surface could reach as high as 130 ℃, When applies to asphalt materials, the excessive temperature could easily melt the specimen. To ensure accuracy and consistency between concrete and asphalt specimen, the input power was chosen (12.40 Volts; 0.41 Amps) to ensure the final inner surface temperature is about 45℃. The detailed methodology, experimental design, and analysis will be presented in Chapter 3.

2.4.3 ***Summary of Thermal Conductivity Measuring Methods for Paving Materials***

In addition to ASTM 177C method and ASU cylindrical specimen method, there are a few more methods developed by researchers that utilize different methodologies. One of the other common measuring approaches is using transient techniques, which employs a measurement during the process of heating up. Al-Ajlan (2006) reported that this method can produce results in a short time span that ranges from 10 seconds to 10 minutes. In general, the transient method measures thermal conductivity by sending a heat creation signal into the specimen, then measure the responses instantly. **Table 2.2** summarizes some of the previous study pertaining to measuring paving material thermal conductivities. As most of the tests were done based on one dimension steady-state heat flow method, it is of great interest for using it as future validation of this study.

Table 2.2 Summary of Literature Values for Paving Material Thermal Conductivities

Source	***Pavement Type***	***Thermal Conductivity, k (W/m-K^o)***	***Method***
Wolfe, Heath et al. (1980)	Asphalt	1.003-1.747	1-D Steady State
Highter and Wall (1984)	Asphalt	0.800-1.600	1-D Steady State/Transient
Mrawira and Luca (2002)	Asphalt	1.750	1-D Transient
Luca and Mrawira (2005)	Asphalt	1.623-2.060	1-D Transient
Nguyen, Di Benedetto et al. (2012)	Asphalt	1.35	1-D Steady State/Transient
Carlson, Bhardwaj et al. (2010)	Concrete Asphalt	1.719 0.896	1-D Steady State

2.5 Overview on Potential Filler Materials for Thermal Property Testing

In many thermal property testing procedures, various interfaces will exist between the heat source and the specimen. Frequently, these surfaces that are attached together will almost always be only a small area of actual mechanical contact between the two surfaces at the interface. In ASU methods, the diameter of the center hole that intends for heat source placement is 11mm (0.437 in.). By contrast, the heat source in the form of cartridge heat with a diameter of only 9.5 mm (0.375 in.). The dimension difference between the two will definitely result in relatively large areas of air gaps. Even for the tests uses relatively smooth materials, there will always be gaps filled with low thermal conductivity air, as it is hard to avoid micro-scale surface roughness and waviness as shown in **Figure 2.6.** In order to minimize the thermal contact resistance that caused by irregularity interface, it is necessary to find filler materials that can 1.) Maximize the contact at the interface; 2.) Has a high capacity to dissipate heat (high thermal conductivity). **Table 2.3** Summarizes the thermal conductivities selected for this study.

Table 2.3 Literature Value of Thermal Conductivities for Selected Filler Materials

Filler Material Type	***Thermal Conductivity, k***	***Source***
Lithium Grease	0.150 W/m-K	Ishchuk (2005)
Petroleum Jelly	--	--
Silicone-based Thermal Grease	3.08 ± 0.03 W/m-K	Chung (2001)

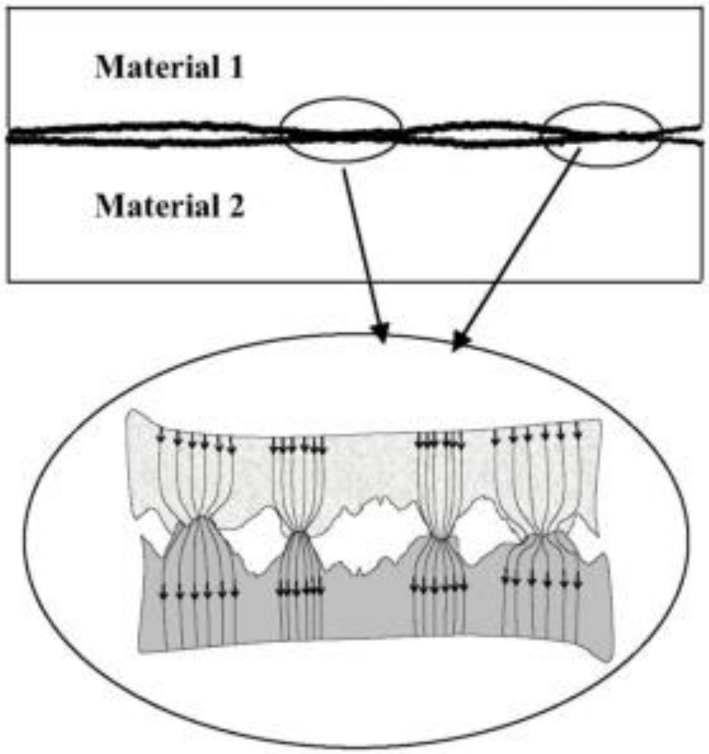

Figure 2.6 Surface Roughness and Waviness in Micro-scale that Causes Air Gap (Sarvar, Whalley et al. 2006).

2.5.1 *Lubricating Grease*

In general, Lubricating grease is one of the lubricant types for automobile operation. Together with engine oil and automatic transmission fluid, they constitute the three most important lubricants for the automotive industry. The automobile industry consumes approximately 40% of total grease consumption, as it is used in more locations in a vehicle than any other lubricant (Fuchs, 1997). Grease serves many of the same functions as liquid lubricant. **Table 2.2** Shows the general functions of each type.

Table 2.2 Functions of Liquid Lubricant and Grease (Donahue 2006).

Liquid Lubricant	***Grease***
Reduce friction	Stay put—does not wash away or drip off
Wear protection	*Function poorly as a coolant*
Reduce corrosion	Prevent contaminants from entering
Reduce sludge, varnish, and deposits	Water resistance
Dissipate heat	Works well under extreme conditions
Suspend/transport particles, debris, and contaminants	Good for parts that are not easily accessible
Serve as sealants	

Lubricating grease has three main components: Base oil, grease thickener, and lubricant additives. Although base oil serves as the primary factor of lubricating, thickener determines some critical physical property of grease, hence, grease product commonly name the grease after thickeners. In general, grease thickener can be divided into soap thickener, non-soap thickener, and complex soap thickener. Soap-thickened grease is the most common in the market (Fuchs, 1997). Grease thickeners contribute to better physical properties, which includes higher dropping point (defines the point where it start to liquefy), higher shear stability, and water resistance (Donahue 2006). Most common complex lithium grease products available in the market uses 12-hydroxystearate and azelaic acid (Donahue 2006). Lubricant additives are added for antioxidizing, corrosion-protection, and physical property enhancement. There are various types of additive. One common additive worth mentioning is molybdenum disulfide. Molybdenum disulfide is a type of natural solid lubricants possessing a layered structure. The adding of it will increase the lubricating capacity of grease and reduce wear to the metal surface.

Limited literature regarding grease thermal property is available. One source reported that the thermal conductivity of complex lithium grease at 80 centigrade is 0.150 W/m-K (Ishchuk 2005).

2.5.2 ***Petroleum Jelly***

Petroleum jelly is defined as a purified and partially decolorized mixture of semi-solid hydrocarbons obtained from petroleum and high-boiling liquid hydrocarbon. Its most commonly application includes skin care, cosmetic and personal care products. In addition it has been widely used in the various industries. For instance, lubricant grease, candle wax additive, plasticine, metal coating, and leather conditioning. Price and Jarratt (2002) investigated thermal conductivity testing method for polytetrafluoroethylene (PTFE). In their experimental design, petroleum jelly was used to “facilitate good thermal contact.” Hence, it worth the attention to evaluate the effectiveness of petroleum jellies as a thermal interface material.

2.5.3 *Silicone-based Thermal Grease*

Silicone-based thermal grease is widely used in electronic devices due to its good fluidity and thermal conductivity. Polymer base and ceramic or metallic fillers are the two components of silicone-based thermal grease. Silicone is used as the base for its good thermal stability, wetting characteristics, and low modulus of elasticity (Prasher 2001). Materials that can be used for ceramic fillers include alumina, aluminium nitride, zinc oxide, silicon dioxide, and beryllium oxides. Silver and aluminium are commonly used for metallic fillers (Sarvar, Whalley et al. 2006). The high thermal conductive fillers and good fluidity make silicone-based thermal grease ideal material for filler material at the interface. However, there are several drawbacks of this grease. Firstly, excessive grease will flow out of the interface and may cause contaminations. Due to its semi-solid "sticky" property, it is also difficult to clean up the joint after testing. Another weakness of silicone-based grease is that it dries out over time, which makes it unfavorable for cyclic testing since it cannot be reuse. Silicone-based thermal grease commonly has a high thermal conductivity value, one source reported a value of 3.08 W/m-K (Chung 2001).

CHAPTER III
METHODOLOGY

This chapter introduces the theoretical analysis of cylindrical specimen thermal conductivity calculation. For the ASU cylindrical specimen test, a heat source is embedded into the center axis of the cylindrical specimen from top to bottom. Heat loss is minimized by placing two insulations at each end so that one-dimensional steady heat flow can be acquired.

Fourier's Law is a time rate equation that determines the conduction heat flux from knowledge of the temperature distribution in a medium. Based on Fourier's law, use Q/A to represent steady-state conduction heat flux ($W \cdot m^{-2}$) and dT/dx as steady-state temperature gradient (Çengel and Boles 2008), we then get:

$$\frac{Q}{A} = -k\frac{dT}{dx} \tag{1}$$

The heat transfer diagram for ASU cylindrical specimen is shown in **Figure 3.1**. Use cylinder radius *r* to replace *x*. The heat transfer of the cylinder can be expressed as, $Q_{cond,cyl}$.

$$Q_{cond,cyl} = -kA\frac{dT}{dr} \tag{2}$$

Çengel and Boles (2008) stated that the equivalent thermal resistance of the cylinder wall R_{cyl} is a function of the total length of the cylinder *L*, and the radii r_1 and r_2. Set the cross-section area of the cylinder $A = 2\pi rL$, we get:

$$R_{cyl} = \frac{\ln(r_2 / r_1)}{2\pi Lk} \tag{3}$$

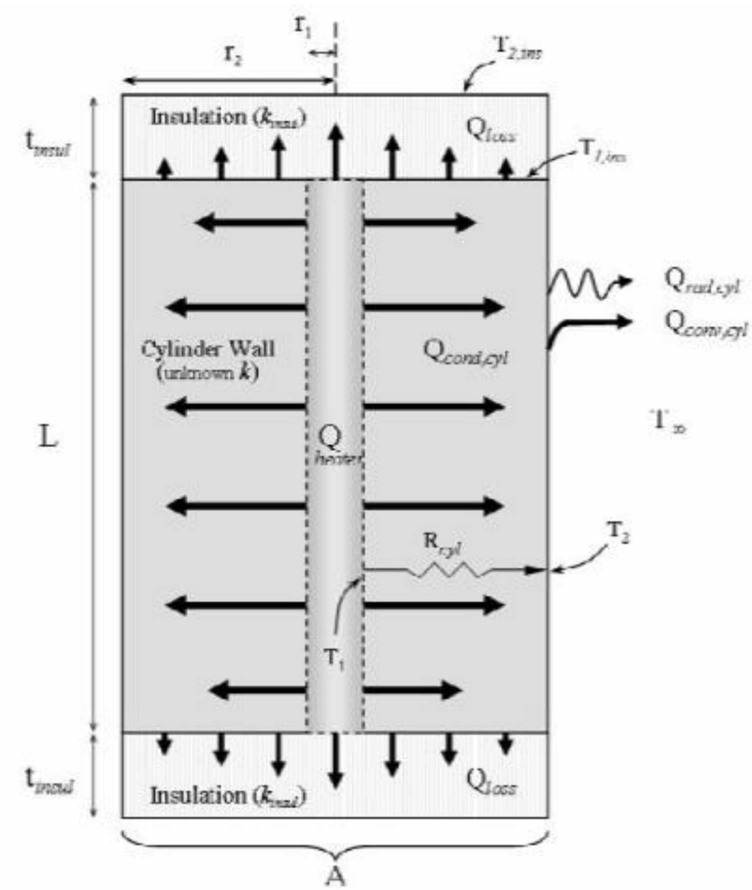

Figure 3.1 Heat Transfer Scheme for ASU Cylindrical Specimen Test Carlson, Bhardwaj et al. (2010).

As cylinder wall thermal resistance $R_{cyl} = \frac{1}{k}$ and internal and external temperature, T_1 and T_2 can be obtained, Equation 1 can be rewritten as:

$$Q_{cond,cyl} = 2\pi Lk \frac{T_1 - T_2}{\ln(r_2 / r_1)} \quad (4)$$

Practically, the heat loss will occur at the top and bottom of the cylinder, as shown in **Figure 3.1**. End energy loss is consistent as cylinder wall thermal conductivity calculation.

$$Q_{cond,cyl} = Q_{heater} - Q_{loss} \tag{5}$$

The heat loss through insulation at each end is reported to be only approximately 2% (Carlson, Bhardwaj et al. 2010). To calculate the approximate heat energy loss, Q_{loss} *the* temperature at each side, $T_{1,ins}$ and $T_{2,ins}$, contact interface, *A*, insulation thickness, t_{insul} ,and thermal conductivity through the insulation layer, k_{insul}, are needed.

$$Q_{loss} = k_{insul} A \frac{T_{1,ins} - T_{2,ins}}{t_{insul}} \tag{6}$$

Solving Equation 3 for k, we will get:

$$k = \frac{Q_{cond,cyl} \ln(r_2 / r_1)}{2\pi L (T_1 - T_2)} \tag{7}$$

As Q_{heater} = power supplied to the heat source = $V \times I$, substitute Equation 4, 5 for $Q_{cond,cyl}$.

$$k = \frac{\left[(VI) - k_{ins} \pi r_2^2 \frac{(T_{1,ins} - T_{2,ins})}{t_{ins}} \right] \ln(r_2 / r_1)}{2\pi L (T_1 - T_2)} \tag{9}$$

Equation 9 determines the final thermal conductivity for the ASU method.

CHAPTER IV
EXPERIMENTAL DESIGN

In order to evaluate how different types of thermal grease affect the result of thermal conductivity tests, ASU cylindrical specimen testing method is used for measuring thermal conductivity. This chapter includes detailed narratives pertaining the developing, modifying, assembling, and testing based on ASU method

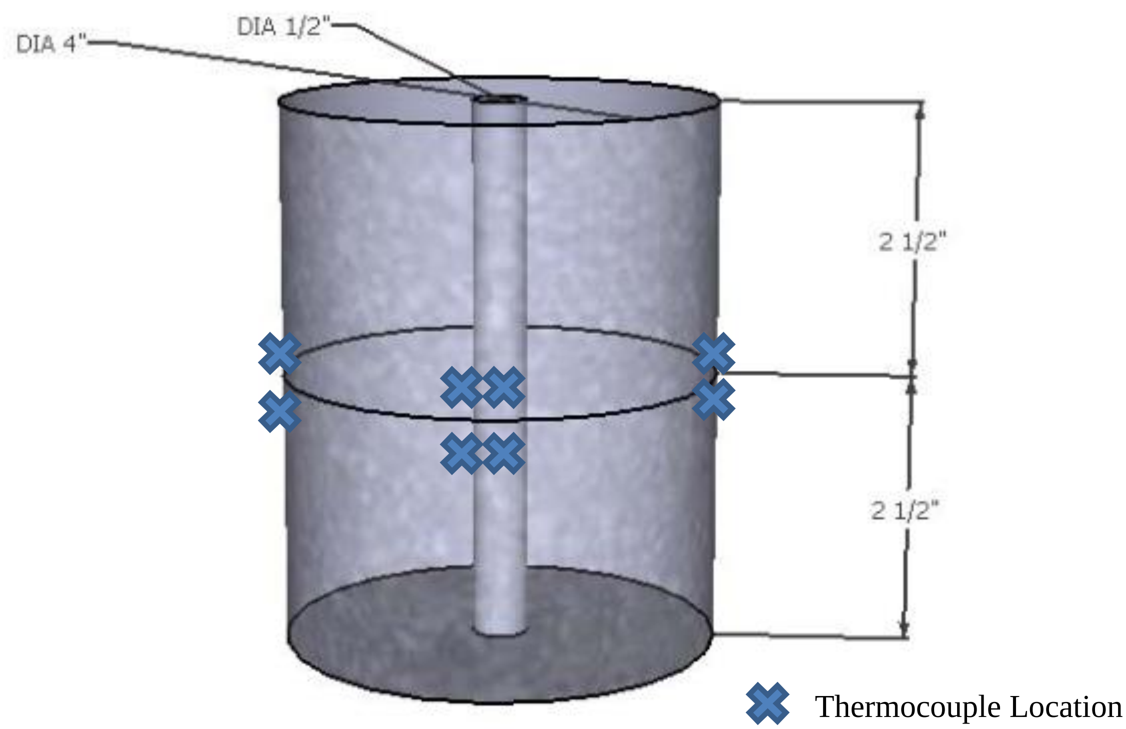

Figure 4.1 Distributions of Thermocouples and Cartridge Heater on the Cylindrical Specimen

4.1 Cylindrical Specimen Preparation

Pavement cylindrical specimens have diameters of 10.16 cm (4 in.), including concrete pavements and asphalt pavement, were extracted from Cape Girardeau, MO. using a core drill. Original Specimens were then shortened to be 12.7 cm (5 in.) tall by using a Lapro® slab saw. The center axis hole that goes from end to end is drilled using a rotary hammer drill and has a diameter of 1.27 cm (0.5 in.). Ideally, symmetrical axis hole needs to be achieved to ensure accuracy. However, it is difficult to make it perfectly symmetric in practice. The method used to adjust the offset of axis hold is to be discussed in thermocouple placement section.

4.2 Heat Source

In order to achieve good accuracy, a steady-stead heat flow requires a constant heat source. A 55 Ohm cartridge heater (FIREROD, part No. G6A83—Watlow Electric Manufacturing Company, St. Louis, MO.) with a diameter of 9.5 mm (0.375 in.) and a length of 10.16 mm (4 in.) is selected for the heat source as shown in **Figure 4.2**. The smaller diameter makes the cartridge slide into the specimen center axis hole very easily and leaves extra space for thermocouple wires. The cartridge heater is a cylindrical “rod” shape resistance heater. The electrical power transfers from

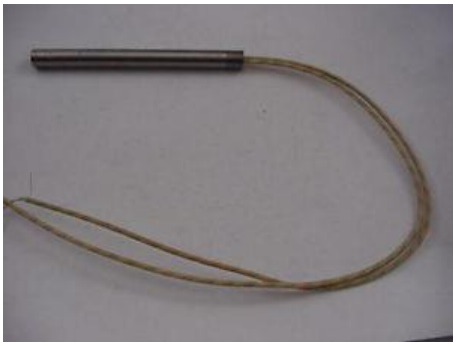

Figure 4.2 Cylindrical Cartridge Heat Source

two lead wires to the core, the heat generated there will then transfer to the surface of the heater through a stainless steel outer sheathing. A voltage regulator is used to adjust the power input that goes into the cartridge heater and a clamp meter is utilized for measuring electric current and validating voltage value. Since the asphalt was also selected as experiment objectives, temperature is strictly monitored to prevent it from melting.

4.3 Thermocouple Type and Placement

The measured section of the testing specimen utilized eight J-type thermocouples with a measuring range between 0 ℃ to 750 ℃ and limits of error of $\pm$2.2 ℃. The metered locations include internal surface and external surface. At each measuring location, a pair of thermocouple will be placed above and below the middle line (Same distance to top and bottom) of the cylindrical specimen and fixed by rubber bands as shown in **Figure 4.1.** Two thermocouples will be placed in the axis hole along with the cartridge heater. The rest of thermocouples will be used for outer surface temperature measurements. As previously discussed, due to the asymmetrical axis of the center hole, two thermocouples will be placed at where the outer surface has the shortest distance to the center axis; two will be selected to be placed at the opposite side of the diameter; the last two will be placed where the distance to center axis is the radius of the specimen. This special distribution of thermocouple amends the measuring error due to imperfect drilling, by evening out the measuring distances from the inner heat source.

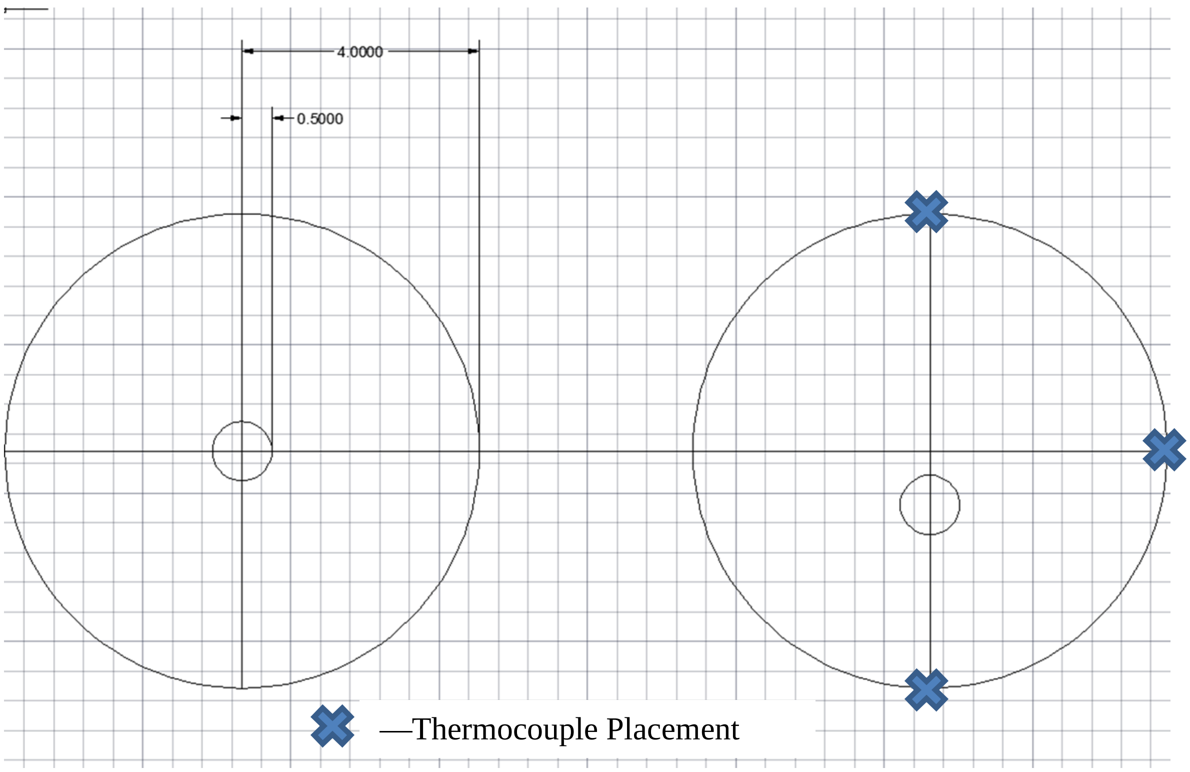

Figure 4.1 Illustration of Thermocouple Placement Selection due to Imperfect Craftsmanship

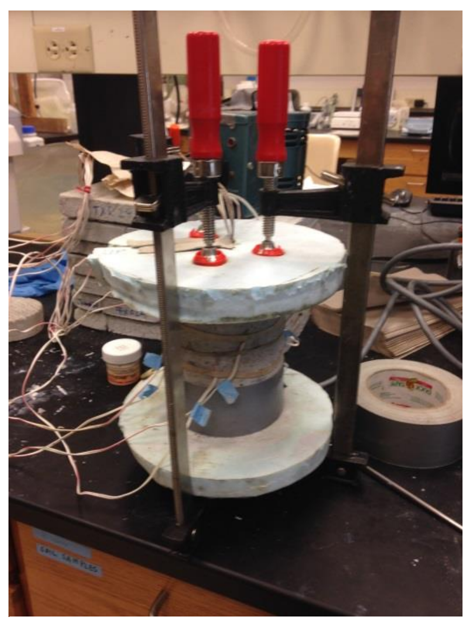

Figure 4.4 Cylindrical Specimen Support Structure

4.4 Insulation and Support Structure

To prevent excessive heat loss from each end surfaces of the cylinder, 2.54 cm (1 in.) thick sheets of insulation (THERMAX™ Wall System, STYROFOAM™ Brand Spray Polyurethane Foam (SPF) (CM Series)—The Dow Chemical Company, Midland, Michigan) was cut into 15.24

cm (6 in.) diameter plates for top and bottom insulation. The styrofoam sheet has a thermal conductivity of 0.167 W/m*K and the modified size is large enough to prevent heat loss. To make space for thermocouple wires that goes into the center axis hole, a small slice of insulation was cut off. When experiment set up was completed and ready for testing, the piece will be placed back followed by using plumber's putty as a sealant to prevent heat loss as shown in **Figure 4.4** and **Figure 4.5**.

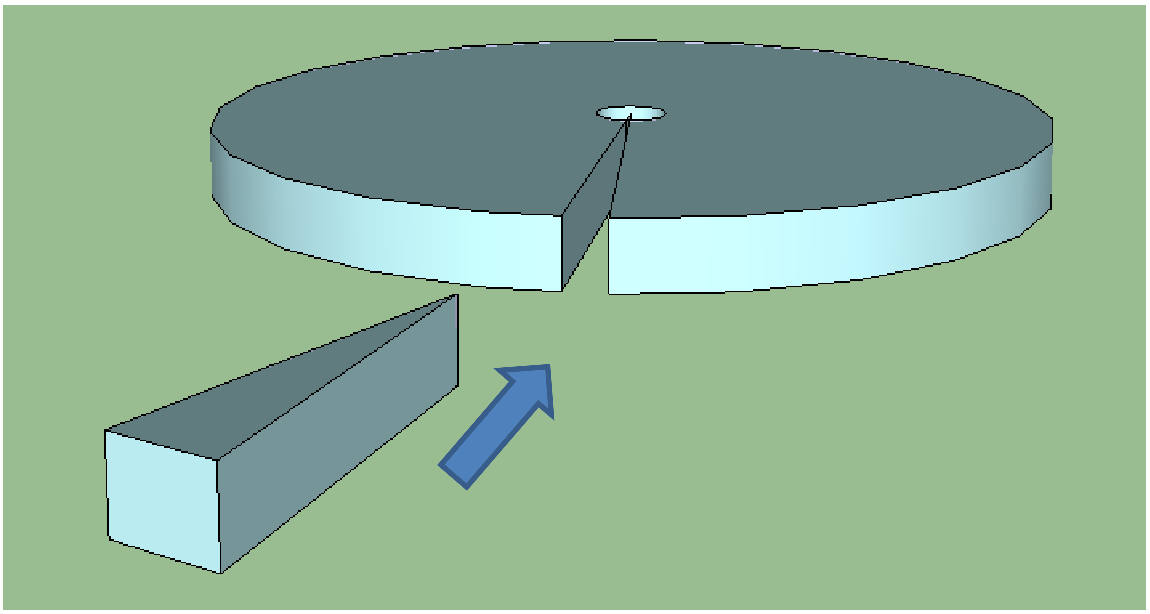

Figure 4.5 Insulation Foam with Cut-off Piece That Can Be Inserted Back.

After placement of cartridge heater, thermocouples, and insulation, three bar clamps were utilized to tighten the contact interface between cylinder and insulations. This three-clamp setup also serves as a support structure to prevent movement.

4.5 Thermal Conductive Grease

Four different kinds of grease were selected to evaluate their effectiveness in determining thermal conductivity: high pressure lithium grease, moly-lithium grease, petroleum jelly, and silicone-based thermal grease. High pressure lithium grease and moly-lithium grease are obtained from local auto part retail store. Petroleum jelly was bought from supermarket under skin care category. Silicone-based thermal grease was manufactured and distributed by Omega Engineering, Inc. While the thermal conductivities for other products were unknown, Omega paste has a thermal conductivity of 2.3 W/m*K.

These filler materials were first filled into the center axis hole before inserting cartridge heater and thermocouple wires. When operating, a thin laboratory spatula was used to compact the grease repeatedly so to eliminate air gaps. On the outer face of the cylinder, a small amount of grease is used to create a better contact between the thermocouple wire tips and the cylinder external surface.

4.6 Date Acquisition

CAMPBELL® SCIENTIFC CR1000 datalogger was selected as the data acquisition system as shown in **Figure 4.5**. The datalogger has many input/output terminals for wiring thermocouples and a 9-pin DCE port for connecting the computer with USB cable for software data logging and on-time monitoring. Each thermocouple wire and connecting terminals were numbered and tagged so to prevent confusion.

4.7 Testing procedure

The complete setup of the apparatus is shown in **Figure 4.6**. To start the test, a specimen is to be cleaned with water and then dried in the oven for 24 hours to ensure result accuracy. A natural cooling process of two-hour long will take place before any further operation. The specimen then will be equipped with thermocouple wires on the external surface fixed by three parallel rounds rubber bands. A small amount of grease will be added at the contacting spot for good thermal contact. The bottom of the

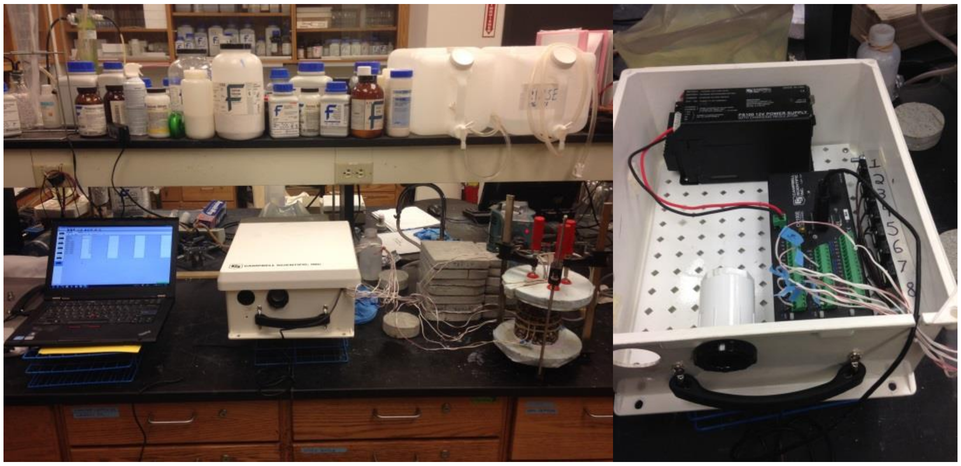

Figure 4.6 Data Acquisition System and Full Apparatus Setup for Cylindrical Specimen.

specimen will also be filmed with an even layer of grease to eliminate the air gaps when being placed on the insulation. The specimen will then be placed on the bottom part of the insulation to fill up the grease in the central hole.

The extended cartridge heater wires and two thermocouples that go into the center are to be bonded with a piece of duct tape so to ensure the position of thermocouple tips when inserting. The excessive grease comes out the hole, after inserting cartridge heater, is to be evenly applied on the top before placing the top insulation piece. When placement of top insulation is done, cutoff slice will be inserted back to the “mother” piece, and then a strip of plumber’s putty will be used to seal the gaps on the top. The whole thing will then be clamped by the three bar clamps, placed gently on the platform and ready for testing.

The voltage regulator will be plugged in and the electrical information will be verified by means of using the clamp meter. The computer program will be connected with Campbell datalogger, and then the cartridge heater will be plugged in. The test starts at this point.

4.8 Validation of Cylindrical Specimen Thermal Conductivity Measuring Method

In order to validate the test results, Hardibacker® Backerboad is selected as a material with given thermal conductivity for control test. Hardibacker® Ceramic Tile Backerboard is a cellulose fiber-reinforced cement building board commonly used for interior walls and floors. The ES Legacy Report, NER 405, provided its thermal conductivity of 0.33 W/m*K.

Figure 4.7 Hardibacker Cylinder

The backerboad has a thickness of 1.27 cm (0.5 in.) and was cut into 10.16 cm (4 in.) diameter round plate. The plates were then glued together using silicone chalk to form a cylindrical specimen that is suited for the test method as shown in **Figure 4.7**. The specimen will then be tested following the standard test procedure of cylindrical specimen thermal conductivity measuring method using all four types of filler materials.

The result of thermal conductivities of Hardiboard is shown in **Table 4.1**. The filler material used for this result is Omega paste. The results that used other filler materials will be presented and discussed in the next chapter. The mean value of control test is 0.3425 W/m-K, which is only 3.8% different than the value reported by the manufacturer. This test succefully validates the accuracy of the ASU cylindrical specimen thermal conductivity measuring method, as the result is only 3.79% different than literature value.

Table 4.1 Results of Validation Tests using Backerboards

	Thermal Conductivity, k(W/m-K)
Test #1	0.336
Test #2	0.348
Test #3	0.347
Test #4	0.339
Mean	0.3425
Standard Deviation	0.00592
Literature Value	0.33

4.9 Validation of Temperature Measurement using J-type Thermocouple Wire

The accuracy of temperature measurement is critical for thermal conductivity measuring. To verify the accuracy of thermocouple wires, ice water mixture and boiling water are used for data validation.

Thermocouple temperature measuring accuracy is an important factor that affects the thermal conductivity measurement, as the internal and external temperatures of the cylinder directly affect the final result. In order to verify the accuracy of the thermocouple measuring capacity, ice water mixture (0 ℃) and boiling water (100 ℃)are used as measuring objectives. The result of validation is shown in **Table 4.2**. As the error is within the reasonable range (±2 ℃), the type J thermocouples used in measuring thermal conductivity are validated to be fair.

Table 4.2 Results of Thermocouple Validation Tests

	Mean (℃)	*Standard Deviation*
Ice Water Mixture	1.711	0.169
Boiling Water	99.05	0.119

CHAPTER V
RESULTS AND DISCUSSIONS

5.1 Calculations

ASU cylindrical specimen thermal conductivity measuring methods utilizes two pieces of insulation at top and bottom of the specimen to reduce the excessive heat loss. The primary measurement focuses on the horizontally one-dimensional steady-state heat transfer. As the literature reported a merely 2% of the total heat energy loss at the top and bottom insulation pieces (Carlson, Bhardwaj et al. 2010), it is reasonable to neglect the heat loss for the practical calculation. The final thermal conductivity will then be calculated using equation (7).

$$k = \frac{Q_{cond,cyl} \ln(r_2 / r_1)}{2\pi L(T_1 - T_2)} \quad (7)$$

Upon the completion of the data collection performed by Campbell® Datalogger, the temperature data of each thermocouple is then to be transmitted through a USB cable into the software program designed to monitor and collect data for the data acquisition system. The data collection process usually takes four hours to complete and the final data file will be plotted and analyzed using Microsoft® Excel program. **Figure 5.1** shows the typical thermocouple temperature profile of the whole testing process. To verify if the final temperature data has reached stability, another plot was plotted to indicate the differential temperature of the whole process, as shown in **Figure 5.2**.

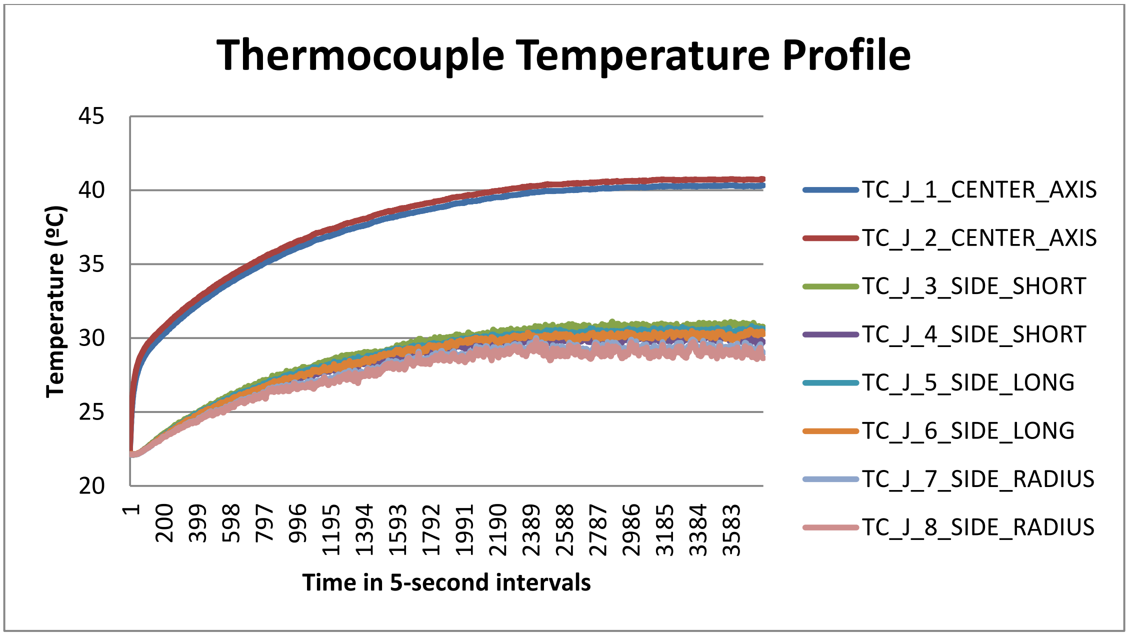

Figure 5.1 Typical Thermocouple Temperature Profile through the data collection process.

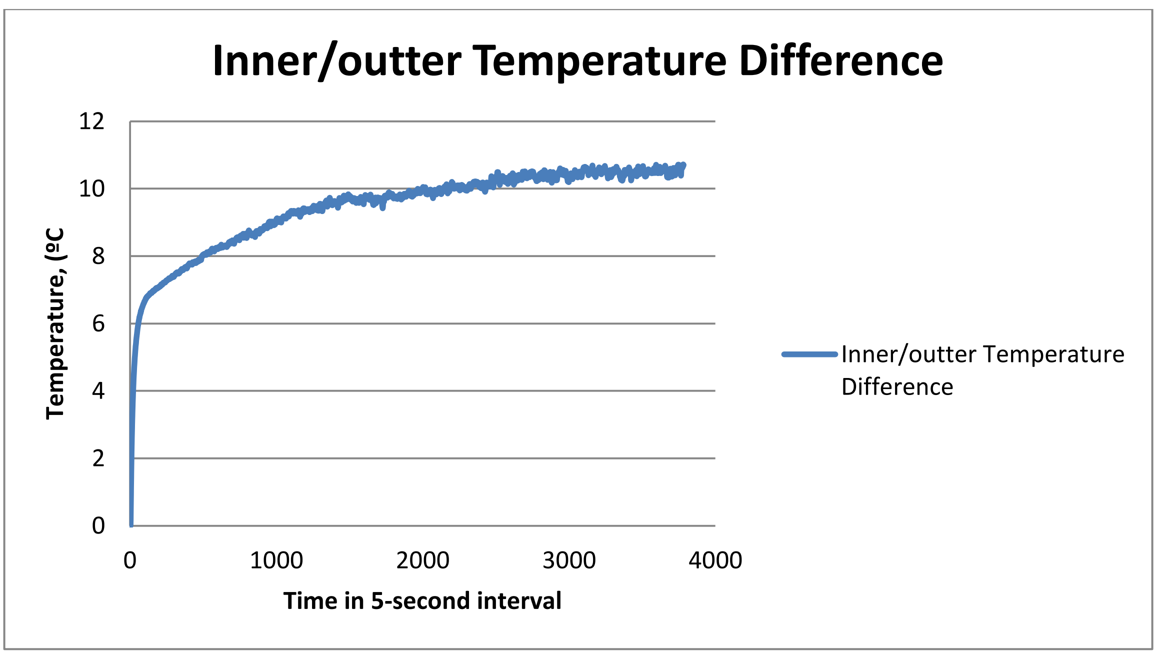

Figure 5.2 Typical Temperature Difference Shown in the Temperature Profile for the Entire Test Run.

5.2 Thermal Conductivity Testing Results for Paving Materials and the Effectiveness of Filler Materials for ASU Cylindrical Specimen Thermal Conductivity Measuring Method

In order to evaluate the effectiveness of the filler materials for the ASU cylindrical specimen thermal conductivity measuring method, one concrete and one asphalt specimen were selected to conduct the tests. Four different types of filler materials were chosen for the evaluation. They are high pressure lithium grease, moly lithium grease, petroleum jelly and omega paste (silicone-based thermal grease). For each type of filler material, two tests on each kind of cylindrical paving specimen were conducted.

The entire test results and data collection can be found in the Appendix. The final temperature of each thermocouple was determined by using the average value of the last 20 readings of the data collection. The thermal conductivity for each tests are shown in **Table 5.1**, **Table 5.2**, **Figure 5.3**, **Figure 5.4** and **Figure 5.5**

Table 5.1 Test Results of Thermal Conductivities for Concrete and Asphalt Cylindrical Specimen.

	Omega Paste		***Petroleum Jelly***		***High Pressure Lithium***		***Moly-Lithium***	
	1	2	1	2	1	2	1	2
Concrete	1.345	1.296	0.855	0.858	0.938	0.938	0.9	0.869
Asphalt	1.109	1.11	0.655	0.659	0.716	0.728	0.743	0.73

Table 5.2 Test Results for Backerboard Using Different Types of Filler Materials.

Filler Type	***Lithuium***	***Moly-Lithium***	***Omega Paste***	***Petroleum Jelly***
Thermal Conductivity, *k*	0.241	0.239	0.343	0.207

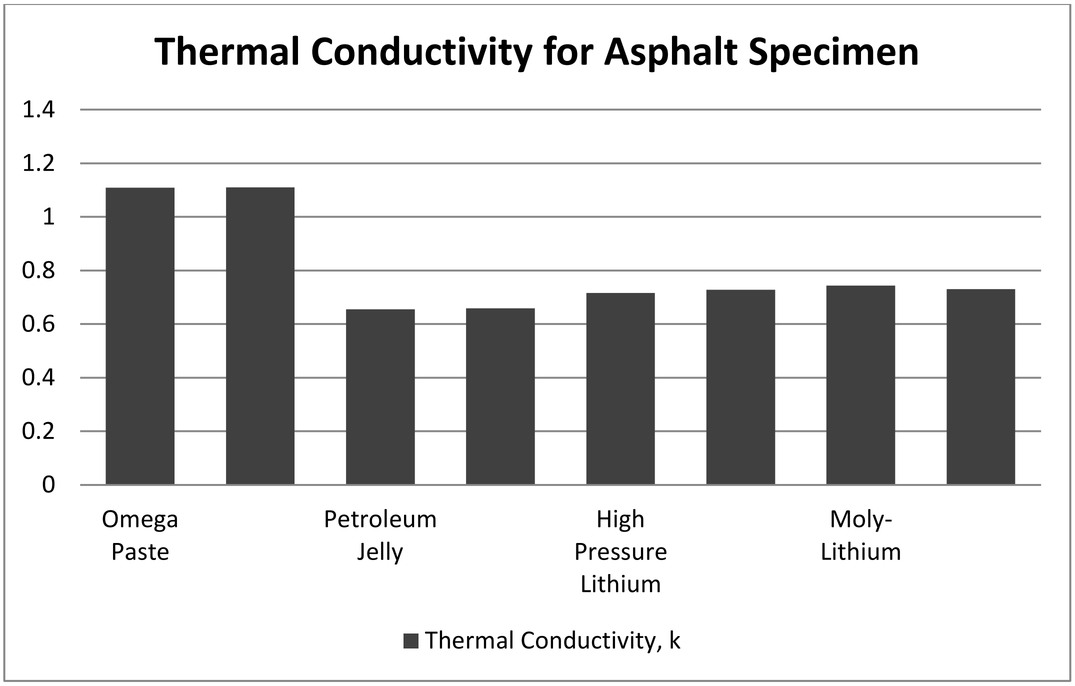

Figure 5.3 Thermal Conductivities for Asphalt Specimen

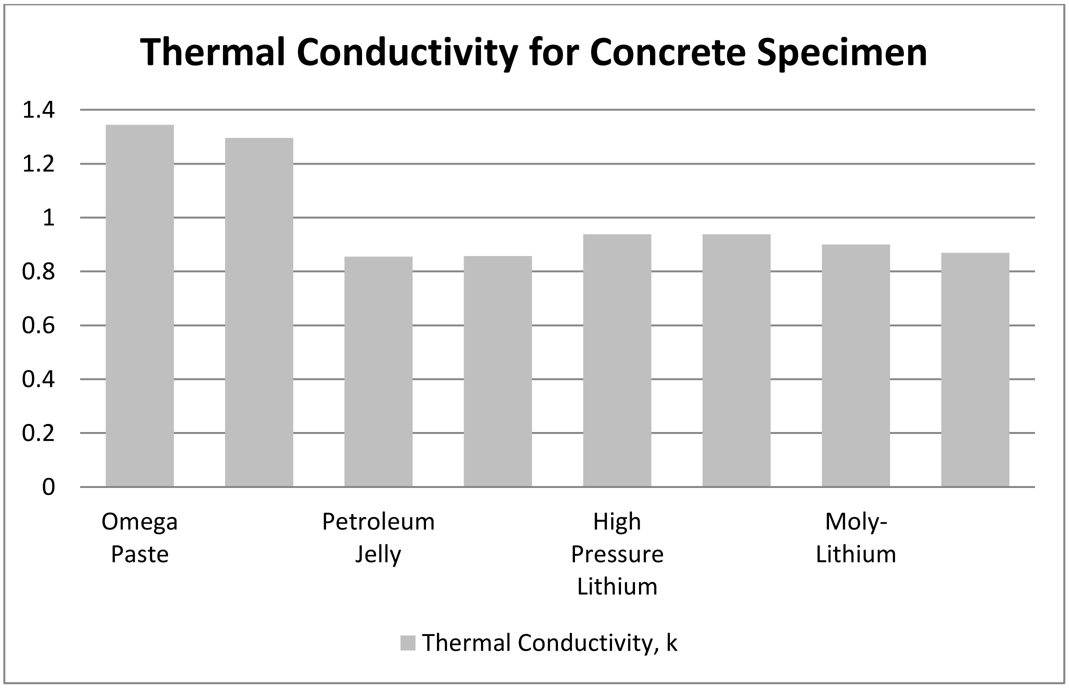

Figure 5.4 Thermal Conductivities for Concrete Specimen

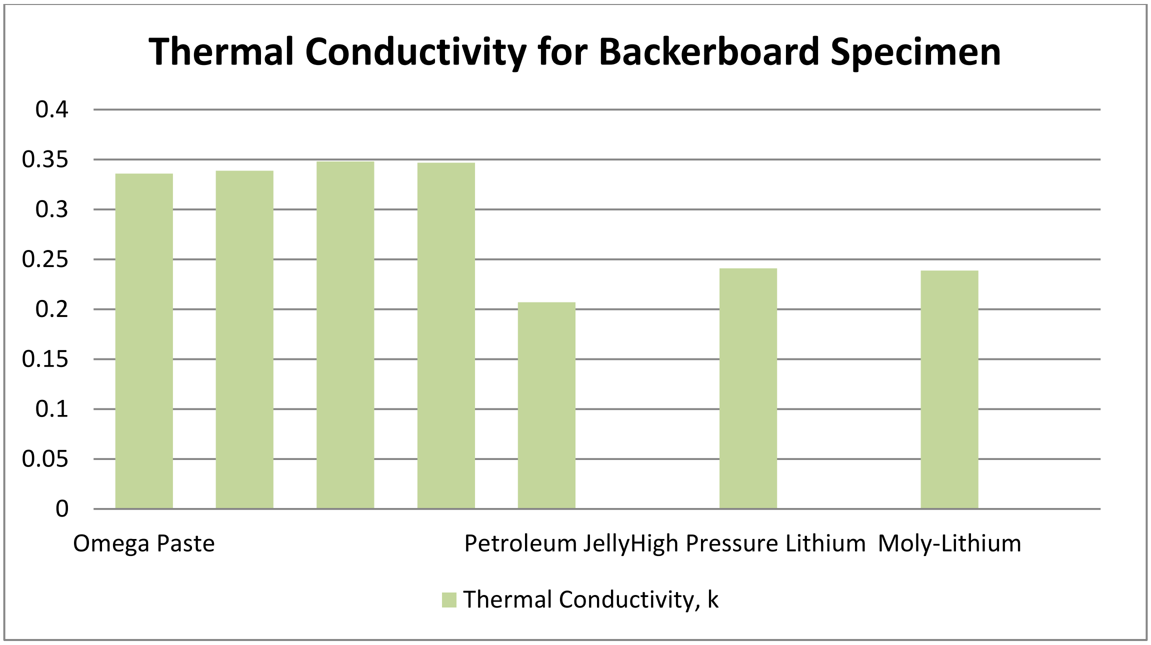

Figure 5.5 Thermal Conductivities for Backerboard Specimen

The test results conclude that the Omega paste has the best effectiveness in the experiment of ASU cylindrical specimen thermal conductivity measuring method, due to its effectiveness in obtaining decent results that close to literature value of Backerboad thermal conductivity (3.79% difference). Among other filler materials, high pressure lithium grease and moly-lithium grease have similar performance, as both of the greases have the same level of thermal conductivity as well as similar compositions, except moly lithium grease have molybdenum disulfide as a solid lubricant additive, as reviewed in **Chapter II**. Petroleum jelly has the worst performance among the filler materials, due to possible low thermal conductivity.

In theory, the heat loss of insulation pieces located at the top and bottom of the cylindrical specimen is neglected only when the filler materials at the interface between specimen inner surface and heat source have a much higher thermal conductivity. As literature reported that lithium grease has a low thermal conductivity (0.150 W/m-K)

(Ishchuk 2005), comparing to that of insulation (0.167 W/m-K). The heat energy transfer will then be similar for vertical and horizontal direction, as the low thermal conductivity of the grease limits the energy going horizontally, even though paving materials have much higher thermal conductivity. Therefore, lubricating grease and petroleum jelly are not suitable as the filler materials for thermal property tests.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

ASU thermal conductivity measuring method for cylindrical specimen was proved to be effective, efficient, and of decent accuracy. The modified method developed by Iowa State University addressed issues with imperfect center hole drilling by distributing thermocouples in a certain way to reduce the inaccuracy. Furthermore, in order to prevent asphalt specimen from melting, ISU method used a decreased power input to reduce the final inner temperature. As a result, the duration of the test increased from 1.5 hours (ASU) to 4 hours. Lastly, comparing to the literature values (1.719 for PCC and 0.800-2.060 for ACC), the results for paving materials thermal conductivities obtained by ISU method were proved to be reasonable.

Based on the test results obtained, the filler materials for thermal property testing are proved to be of great importance to the accuracy of the final result. Firstly, silicone-based thermal grease, which is widely used in the electronic devices, works well in conducting thermal conductivity measuring, for its high value of thermal conductivity. Furthermore, the filler materials chosen needs to have a much higher thermal conductivity than the insulations used at the top and the bottom. Based on the theoretical analysis, the total input energy stays constant, as shown in **Equation (5)**. Decreased energy transfer result in a higher energy lost through the insulation.

6.2 Recommendations

Although several duplications of tests have been done, more runs of test will further validate the accuracy of ASU cylindrical specimen method. Meanwhile, the power input was maintained during the whole study period. Tests running with different power input might have different results. Additionally, it is also beneficial to test different sizes of samples with various diameters and length to further validate the suitability of the method.

More types of filler materials can also be evaluated. In addition to silicon-based grease, several other high thermal conductive grease products are available in the market. For instance, sodium silicate-based thermal grease is reported to have a better thermal conductivity and higher fluidity (Chung 2001). However, those greases are expensive and have a low workability. It's mostly used in the electronic device industry and only a small amount is needed for regular use. For example, silicone-based grease usually applies between the electronic part that needs to dissipate heat and heat sink, so the amount of grease needed is very little and it does not expect to be removed and reused for future events.

For thermal property testing, filler materials are expected to be used in relatively larger amount. The physical property of thermal grease also makes it hard to be removed and reused. By contrast, although lubricating grease is not suited for the tests due to its low thermal conductivity, its workability stands better, as it has a better fluidity and easy to be removed and cleaned. Therefore, a new type of grease with both high thermal conductivity and workability are in demand for the thermal property testing.

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APPENDIX:

DATA COLLECTION AND TEST RESULTS

Sample Name: LaSale_C_Omega_1	
Sample material:	Concrete
Grease Type	Omega
Inner Radius, r1 (m)	0.00635
Outer Radius, r2 (m)	0.058
Cylinder Height, L (m)	0.127
Voltage, U (V)	12.1
Current, I (A)	0.41
Inner Temperature, T1 (ºC)	40.693
Outer Temperature, T2 (ºC)	30.466
Thermal Conductivity, k (W/m-K) (1)	1.345

Last 20 Data Points Collected from Campbell Datalogger CR1000								
	TC_1	TC_2	TC_3	TC_4	TC_5	TC_6	TC_7	TC_8
1	40.43	40.9	31.03	30.4	30.74	30.56	30.23	30.01
2	40.45	40.9	31.01	30.4	30.72	30.58	30.25	30.01
3	40.45	40.9	30.99	30.33	30.75	30.6	30.21	29.99
4	40.45	40.9	30.99	30.25	30.81	30.62	30.09	29.88
5	40.45	40.91	31.03	30.29	30.85	30.64	30.03	29.84
6	40.45	40.91	31.01	30.33	30.85	30.7	30.05	29.82
7	40.45	40.91	31.05	30.31	30.79	30.74	29.99	29.74
8	40.45	40.91	31.11	30.35	30.75	30.72	29.97	29.7
9	40.47	40.91	31.11	30.35	30.75	30.72	30.01	29.7
10	40.47	40.91	31.15	30.36	30.79	30.66	30.09	29.78
11	40.45	40.91	31.09	30.35	30.81	30.68	30.11	29.84
12	40.47	40.92	31.03	30.38	30.87	30.66	30.15	29.9
13	40.47	40.92	31.09	30.46	30.95	30.64	30.09	29.9
14	40.45	40.92	31.03	30.4	30.93	30.66	30.05	29.86
15	40.47	40.92	30.99	30.31	30.91	30.68	29.99	29.76
16	40.47	40.92	30.99	30.29	30.87	30.7	29.97	29.76
17	40.5	40.96	31.05	30.37	30.86	30.72	30.08	29.84
18	40.5	40.96	31.02	30.35	30.86	30.7	30.08	29.84
19	40.5	40.96	31	30.39	30.88	30.68	30.08	29.88
20	40.5	40.96	30.94	30.27	30.84	30.57	30.02	29.84
Average	40.465	40.9205	31.0355	30.347	30.829	30.6615	30.077	29.8445

Sample Name: LaSale_C_Omega_2	
Sample material:	Concrete
Grease Type	Omega
Inner Radius, r1 (m)	0.00635
Outer Radius, r2 (m)	0.058
Cylinder Height, L (m)	0.127
Voltage, U (V)	12.1
Current, I (A)	0.41
Inner Temperature, T1 (ºC)	40.521
Outer Temperature, T2 (ºC)	29.905
Thermal Conductivity, k (W/m-K) (1)	1.296

Last 20 Data Points Collected from Campbell Datalogger CR1000								
	TC_1	TC_2	TC_3	TC_4	TC_5	TC_6	TC_7	TC_8
1	40.29	40.72	30.71	29.87	30.6	30.38	29.58	29.29
2	40.27	40.72	30.73	29.89	30.65	30.44	29.6	29.35
3	40.29	40.72	30.75	29.89	30.64	30.36	29.56	29.29
4	40.29	40.72	30.73	29.83	30.6	30.34	29.41	29.11
5	40.32	40.75	30.68	29.76	30.64	30.37	29.3	28.98
6	40.32	40.75	30.64	29.71	30.66	30.35	29.18	28.87
7	40.29	40.72	30.6	29.66	30.64	30.32	29.15	28.84
8	40.29	40.72	30.6	29.64	30.62	30.3	29.13	28.8
9	40.32	40.75	30.6	29.65	30.66	30.33	29.12	28.79
10	40.29	40.72	30.58	29.62	30.6	30.3	29.03	28.72
11	40.29	40.72	30.65	29.7	30.58	30.28	29.11	28.82
12	40.29	40.72	30.69	29.78	30.56	30.36	29.13	28.8
13	40.32	40.75	30.7	29.76	30.6	30.43	29.14	28.79
14	40.32	40.75	30.76	29.76	30.6	30.45	29.1	28.71
15	40.32	40.75	30.78	29.8	30.51	30.39	29.1	28.71
16	40.32	40.75	30.78	29.78	30.55	30.31	29.06	28.65
17	40.32	40.75	30.7	29.69	30.56	30.31	29	28.63
18	40.32	40.75	30.72	29.73	30.58	30.29	29	28.63
19	40.32	40.75	30.76	29.73	30.6	30.27	29.04	28.67
20	40.32	40.75	30.74	29.74	30.62	30.27	29	28.65
Average	40.3055	40.7365	30.695	29.7495	30.6035	30.3425	29.187	28.855

Sample Name: LaSale_C_Moly_1	
Sample material:	Concrete
Grease Type	Moly-Lithium
Inner Radius, r1 (m)	0.00635
Outer Radius, r2 (m)	0.058
Cylinder Height, L (m)	0.127
Voltage, U (V)	12.1
Current, I (A)	0.41
Inner Temperature, T1 (ºC)	46.841
Outer Temperature, T2 (ºC)	31.555
Thermal Conductivity, k (W/m-K) (1)	0.900

Last 20 Data Points Collected from Campbell Datalogger CR1000								
	TC_1	TC_2	TC_3	TC_4	TC_5	TC_6	TC_7	TC_8
1	45.46	48.2	32.02	31.39	31.63	31.04	32.31	31.27
2	45.46	48.2	32.11	31.43	31.53	31	32.29	31.27
3	45.46	48.2	32.11	31.39	31.51	30.94	32.17	31.2
4	45.46	48.2	32.03	31.35	31.51	30.94	32.21	31.2
5	45.46	48.2	32.02	31.31	31.45	30.94	32.23	31.22
6	45.46	48.2	31.94	31.27	31.49	30.98	32.29	31.27
7	45.48	48.2	31.94	31.24	31.49	31	32.29	31.27
8	45.48	48.2	31.92	31.24	31.53	31	32.37	31.29
9	45.48	48.2	31.94	31.18	31.59	31.06	32.4	31.33
10	45.48	48.2	31.88	31.16	31.59	31.08	32.44	31.35
11	45.48	48.2	31.88	31.14	31.57	31.08	32.44	31.39
12	45.48	48.2	31.94	31.14	31.59	31.08	32.37	31.35
13	45.48	48.22	31.88	31.12	31.55	31.06	32.4	31.37
14	45.48	48.22	31.84	31.12	31.49	31.02	32.42	31.37
15	45.48	48.22	31.84	31.1	31.49	31	32.42	31.33
16	45.48	48.22	31.84	31.1	31.45	30.94	32.46	31.33
17	45.48	48.2	31.82	31.06	31.49	30.98	32.48	31.37
18	45.48	48.22	31.84	31.06	31.49	30.98	32.48	31.37
19	45.48	48.22	31.8	31.04	31.49	30.98	32.48	31.37
20	45.5	48.22	31.84	31.08	31.53	31	32.48	31.33
Average	45.475	48.207	31.9215	31.196	31.523	31.005	32.3715	31.3125

Sample Name: LaSale_C_Moly_2	
Sample material:	Concrete
Grease Type	Moly-Lithium
Inner Radius, r1 (m)	0.00635
Outer Radius, r2 (m)	0.058
Cylinder Height, L (m)	0.127
Voltage, U (V)	12.1
Current, I (A)	0.41
Inner Temperature, T1 (ºC)	47.263
Outer Temperature, T2 (ºC)	31.424
Thermal Conductivity, k (W/m-K) (1)	0.869

Last 20 Data Points Collected from Campbell Datalogger CR1000								
	TC_1	TC_2	TC_3	TC_4	TC_5	TC_6	TC_7	TC_8
1	45.95	48.53	32.06	31.34	31.36	30.77	32.16	31.03
2	45.95	48.53	32.08	31.34	31.46	30.83	32.2	31.05
3	45.95	48.55	32.04	31.34	31.52	30.91	32.12	31.03
4	45.95	48.55	31.98	31.34	31.54	30.95	32.16	31.03
5	45.95	48.53	31.93	31.3	31.54	30.99	32.18	31.07
6	45.95	48.55	31.93	31.28	31.38	30.91	32.16	31.01
7	45.95	48.55	31.93	31.24	31.32	30.85	32.14	31.01
8	45.95	48.55	32	31.26	31.34	30.83	32.04	30.97
9	45.97	48.55	31.96	31.26	31.42	30.87	32.08	30.95
10	45.95	48.57	31.93	31.28	31.42	30.91	32.12	30.99
11	45.97	48.57	32.04	31.38	31.42	30.87	32.16	31.01
12	45.95	48.57	32.08	31.4	31.3	30.79	32.12	31.03
13	45.97	48.57	32.02	31.4	31.28	30.75	32.12	31.05
14	45.99	48.57	31.94	31.32	31.18	30.72	32.14	31.03
15	45.99	48.57	31.89	31.26	31.26	30.75	32.2	31.07
16	45.99	48.57	31.89	31.22	31.38	30.79	32.2	31.03
17	45.99	48.57	31.87	31.15	31.38	30.81	32.16	30.99
18	45.99	48.57	31.85	31.09	31.2	30.7	32.12	30.87
19	45.99	48.57	31.81	31.11	31.18	30.68	32.16	30.83
20	45.99	48.59	31.81	31.11	31.3	30.72	32.2	30.87
Average	45.967	48.559	31.952	31.271	31.359	30.82	32.147	30.996

Sample Name: LaSale_C_Lithium_1	
Sample material:	Concrete
Grease Type	High Pressure Lithium
Inner Radius, r1 (m)	0.00635
Outer Radius, r2 (m)	0.058
Cylinder Height, L (m)	0.127
Voltage, U (V)	12.1
Current, I (A)	0.41
Inner Temperature, T1 (ºC)	45.070
Outer Temperature, T2 (ºC)	30.394
Thermal Conductivity, k (W/m-K) (1)	0.938

Last 20 Data Points Collected from Campbell Datalogger CR1000								
	TC_1	TC_2	TC_3	TC_4	TC_5	TC_6	TC_7	TC_8
1	44.59	45.55	30.95	30.78	30.45	30.14	30	29.96
2	44.59	45.55	31.03	30.84	30.39	30.15	30	30
3	44.59	45.55	31.07	30.86	30.41	30.17	29.96	29.98
4	44.59	45.55	31.07	30.86	30.39	30.14	29.98	29.96
5	44.59	45.55	31.07	30.86	30.45	30.15	30.02	29.92
6	44.59	45.55	31.11	30.88	30.47	30.19	29.96	29.94
7	44.59	45.55	31.13	30.9	30.37	30.12	29.94	30.02
8	44.59	45.55	31.09	30.88	30.37	30.1	29.94	29.98
9	44.59	45.55	31.13	30.9	30.41	30.1	29.94	29.96
10	44.59	45.55	31.13	30.92	30.39	30.06	29.88	29.94
11	44.59	45.55	31.17	30.95	30.27	30.04	29.84	29.98
12	44.59	45.55	31.15	30.95	30.29	30.06	29.86	29.94
13	44.59	45.55	31.15	30.94	30.35	30.08	29.84	29.9
14	44.59	45.55	31.19	30.97	30.33	30.04	29.9	29.96
15	44.59	45.55	31.23	31.01	30.33	29.98	29.82	30
16	44.59	45.55	31.21	31.01	30.37	30.04	29.82	29.92
17	44.59	45.55	31.15	30.97	30.39	30.04	29.82	29.92
18	44.59	45.55	31.13	30.94	30.43	30.1	29.82	29.88
19	44.59	45.55	31.11	30.92	30.45	30.12	29.78	29.88
20	44.59	45.55	31.17	30.97	30.41	30.12	29.82	29.94
Average	44.59	45.55	31.122	30.9155	30.386	30.097	29.897	29.949

Sample Name: LaSale_C_Lithium_2	
Sample material:	Concrete
Grease Type	High Pressure Lithium
Inner Radius, r1 (m)	0.00635
Outer Radius, r2 (m)	0.058
Cylinder Height, L (m)	0.127
Voltage, U (V)	12.1
Current, I (A)	0.41
Inner Temperature, T1 (ºC)	45.070
Outer Temperature, T2 (ºC)	30.394
Thermal Conductivity, k (W/m-K) (1)	0.938

Last 20 Data Points Collected from Campbell Datalogger CR1000								
	TC_1	TC_2	TC_3	TC_4	TC_5	TC_6	TC_7	TC_8
1	44.86	45.92	31.28	31.01	30.23	30.03	30.31	30.35
2	44.86	45.93	31.3	31.03	30.25	29.97	30.23	30.33
3	44.86	45.92	31.3	31.03	30.29	29.97	30.17	30.25
4	44.84	45.92	31.34	31.07	30.19	29.95	30.13	30.27
5	44.84	45.92	31.38	31.13	30.17	29.94	30.17	30.31
6	44.86	45.93	31.4	31.16	30.15	29.9	30.19	30.33
7	44.86	45.92	31.42	31.16	30.27	29.95	30.19	30.31
8	44.86	45.92	31.44	31.16	30.31	30.01	30.15	30.29
9	44.86	45.92	31.44	31.18	30.36	30.07	30.11	30.31
10	44.86	45.92	31.36	31.13	30.33	30.11	30.11	30.27
11	44.84	45.92	31.34	31.11	30.36	30.09	30.19	30.27
12	44.86	45.93	31.26	31.01	30.25	30.05	30.31	30.27
13	44.84	45.92	31.22	30.93	30.31	30.09	30.33	30.33
14	44.86	45.92	31.22	30.91	30.35	30.11	30.36	30.35
15	44.86	45.92	31.15	30.85	30.38	30.17	30.25	30.25
16	44.86	45.92	31.07	30.76	30.38	30.19	30.27	30.25
17	44.86	45.93	31.11	30.79	30.4	30.21	30.13	30.27
18	44.86	45.93	31.13	30.79	30.4	30.15	30.09	30.17
19	44.86	45.93	31.09	30.76	30.44	30.19	30.07	30.09
20	44.86	45.93	31.11	30.77	30.44	30.17	30.03	30.05
Average	44.856	45.9235	31.268	30.987	30.313	30.066	30.1895	30.266

Sample Name: LaSale_C_Petroleum_Jelly_1	
Sample material:	Concrete
Grease Type	Petroleum Jelly
Inner Radius, r1 (m)	0.00635
Outer Radius, r2 (m)	0.058
Cylinder Height, L (m)	0.127
Voltage, U (V)	12.1
Current, I (A)	0.41
Inner Temperature, T1 (ºC)	47.085
Outer Temperature, T2 (ºC)	31.002
Thermal Conductivity, k (W/m-K) (1)	0.855

Last 20 Data Points Collected from Campbell Datalogger CR1000								
	TC_1	TC_2	TC_3	TC_4	TC_5	TC_6	TC_7	TC_8
1	47.07	45.35	31.28	29.84	31.22	30.89	31.96	31.1
2	47.07	45.37	31.24	29.8	31.16	30.89	32	31.09
3	47.07	45.37	31.26	29.8	31.1	30.89	32	31.09
4	47.07	45.37	31.26	29.8	31.09	30.83	31.92	31.09
5	47.09	45.35	31.28	29.8	31.16	30.89	31.87	31.05
6	47.07	45.37	31.28	29.84	31.14	30.91	31.9	31.05
7	47.09	45.37	31.28	29.82	31.1	30.87	31.85	31.01
8	47.09	45.37	31.22	29.8	31.12	30.89	31.83	30.99
9	47.09	45.37	31.16	29.76	31.12	30.89	31.88	30.99
10	47.09	45.37	31.14	29.7	31.1	30.87	31.92	31.01
11	47.09	45.37	31.14	29.74	31.16	30.89	31.94	30.99
12	47.09	45.37	31.12	29.72	31.22	30.93	32.02	31.01
13	47.09	45.37	31.14	29.72	31.22	30.97	32.04	31.07
14	47.09	45.37	31.16	29.72	31.16	30.91	31.98	31.03
15	47.09	45.39	31.12	29.72	31.2	30.93	32	31.01
16	47.09	45.39	31.09	29.68	31.16	30.91	31.98	31.07
17	47.09	45.39	31.12	29.66	31.2	30.91	32.04	31.1
18	47.09	45.39	31.09	29.62	31.22	30.93	32.06	31.12
19	47.09	45.39	31.07	29.6	31.24	30.97	32.06	31.16
20	47.09	45.39	31.03	29.56	31.28	30.99	32.06	31.18
Average	47.085	45.374	31.174	29.735	31.1685	30.908	31.9655	31.0605

Sample Name: LaSale_C_Petroleum_Jelly_2	
Sample material:	Concrete
Grease Type	Petroleum Jelly
Inner Radius, r1 (m)	0.00635
Outer Radius, r2 (m)	0.058
Cylinder Height, L (m)	0.127
Voltage, U (V)	12.1
Current, I (A)	0.41
Inner Temperature, T1 (ºC)	47.029
Outer Temperature, T2 (ºC)	30.997
Thermal Conductivity, k (W/m-K) (1)	0.858

Last 20 Data Points Collected from Campbell Datalogger CR1000								
	TC_1	TC_2	TC_3	TC_4	TC_5	TC_6	TC_7	TC_8
1	47.03	44.95	31.42	30.19	30.93	30.64	31.67	31.22
2	47.03	44.93	31.47	30.21	30.79	30.58	31.57	31.14
3	47.01	44.93	31.51	30.24	30.79	30.52	31.47	31.06
4	47.01	44.93	31.53	30.24	30.81	30.52	31.47	31.06
5	47.03	44.93	31.53	30.23	30.87	30.52	31.47	31.06
6	47.01	44.93	31.45	30.19	30.91	30.58	31.55	31.06
7	47.01	44.93	31.47	30.21	30.87	30.56	31.57	31.06
8	47.03	44.93	31.47	30.19	30.85	30.56	31.55	31.06
9	47.01	44.93	31.45	30.19	30.91	30.62	31.57	31.1
10	47.01	44.93	31.43	30.21	30.97	30.67	31.59	31.1
11	47.04	44.96	31.36	30.14	30.99	30.72	31.66	31.17
12	47.04	44.96	31.38	30.14	30.99	30.76	31.72	31.19
13	47.04	44.96	31.42	30.14	30.94	30.7	31.73	31.21
14	47.04	44.96	31.52	30.21	30.94	30.72	31.75	31.19
15	47.04	44.96	31.5	30.19	30.95	30.7	31.75	31.19
16	47.04	44.96	31.56	30.25	30.92	30.64	31.73	31.19
17	47.04	44.96	31.54	30.25	30.86	30.6	31.73	31.21
18	47.04	44.96	31.46	30.27	30.88	30.58	31.7	31.19
19	47.04	44.96	31.5	30.29	30.9	30.62	31.73	31.19
20	47.04	44.96	31.54	30.29	30.9	30.62	31.66	31.15
Average	47.029	44.946	31.4755	30.2135	30.8985	30.6215	31.632	31.14

Sample Name:Lexington_A_Lithium_1	
Sample material:	Asphalt
Grease Type	High Pressure Lithium
Inner Radius, r1 (m)	0.00635
Outer Radius, r2 (m)	0.058
Cylinder Height, L (m)	0.127
Voltage, U (V)	12.1
Current, I (A)	0.41
Inner Temperature, T1 (ºC)	50.178
Outer Temperature, T2 (ºC)	30.954
Thermal Conductivity, k (W/m-K) (1)	0.716

Last 20 Data Points Collected from Campbell Datalogger CR1000								
	TC_1	TC_2	TC_3	TC_4	TC_5	TC_6	TC_7	TC_8
1	50.17	47.85	31	30.72	30.9	30.74	31.33	30.72
2	50.17	47.85	31.02	30.76	30.88	30.74	31.35	30.7
3	50.19	47.85	31.04	30.74	30.88	30.74	31.35	30.7
4	50.19	47.85	31	30.7	30.88	30.74	31.35	30.65
5	50.19	47.85	31.02	30.76	30.88	30.76	31.31	30.61
6	50.19	47.85	31.02	30.78	30.92	30.78	31.37	30.68
7	50.19	47.85	31.04	30.8	30.96	30.8	31.39	30.72
8	50.19	47.85	30.96	30.72	31	30.8	31.43	30.74
9	50.17	47.85	31	30.76	30.96	30.8	31.44	30.76
10	50.17	47.85	31	30.68	30.92	30.76	31.44	30.74
11	50.17	47.83	31.02	30.72	30.92	30.78	31.5	30.8
12	50.17	47.85	31.02	30.72	30.96	30.8	31.5	30.84
13	50.17	47.83	30.98	30.68	30.98	30.82	31.48	30.88
14	50.17	47.85	31	30.68	30.96	30.8	31.46	30.9
15	50.17	47.83	30.92	30.68	30.98	30.84	31.52	30.98
16	50.17	47.85	30.94	30.68	31	30.84	31.54	30.98
17	50.17	47.85	31	30.74	31	30.86	31.54	31
18	50.19	47.85	31.04	30.78	30.96	30.86	31.54	31.02
19	50.17	47.85	31	30.72	30.94	30.86	31.46	31
20	50.19	47.85	30.96	30.74	31.02	30.88	31.41	30.92
Average	50.178	47.847	30.999	30.728	30.945	30.8	31.4355	30.817

Sample Name:Lexington_A_Lithium_2	
Sample material:	Asphalt
Grease Type	High Pressure Lithium
Inner Radius, r1 (m)	0.00635
Outer Radius, r2 (m)	0.058
Cylinder Height, L (m)	0.127
Voltage, U (V)	12.1
Current, I (A)	0.41
Inner Temperature, T1 (ºC)	50.776
Outer Temperature, T2 (ºC)	31.867
Thermal Conductivity, k (W/m-K) (1)	0.728

Last 20 Data Points Collected from Campbell Datalogger CR1000								
	TC_1	TC_2	TC_3	TC_4	TC_5	TC_6	TC_7	TC_8
1	50.78	48.84	31.52	31.32	32.16	31.83	32.34	31.44
2	50.76	48.82	31.3	31.16	32.08	31.76	32.23	31.33
3	50.78	48.82	31.42	31.21	32.1	31.75	32.34	31.4
4	50.76	48.8	31.53	31.24	32.15	31.76	32.31	31.35
5	50.76	48.8	31.61	31.28	32.1	31.76	32.39	31.39
6	50.76	48.8	31.76	31.37	32.04	31.76	32.43	31.45
7	50.78	48.82	31.89	31.48	32.02	31.79	32.47	31.44
8	50.78	48.82	31.99	31.56	32.04	31.81	32.45	31.44
9	50.78	48.82	32.06	31.62	32.06	31.83	32.51	31.5
10	50.78	48.82	32.12	31.65	32.02	31.83	32.53	31.5
11	50.78	48.82	32.16	31.69	32.04	31.83	32.55	31.52
12	50.78	48.82	32.16	31.71	31.99	31.79	32.51	31.54
13	50.78	48.82	32.12	31.71	31.97	31.79	32.49	31.52
14	50.78	48.82	32.14	31.71	31.99	31.79	32.45	31.5
15	50.78	48.82	32.18	31.73	31.97	31.79	32.51	31.5
16	50.78	48.82	32.16	31.73	31.97	31.79	32.53	31.52
17	50.78	48.82	32.12	31.73	31.91	31.77	32.53	31.48
18	50.78	48.82	32.16	31.71	31.79	31.63	32.57	31.52
19	50.78	48.82	32.2	31.75	31.87	31.65	32.53	31.5
20	50.78	48.82	32.22	31.75	31.93	31.69	32.49	31.48
Average	50.776	48.818	31.941	31.5555	32.01	31.77	32.458	31.466

Sample Name:Lexington_A_Moly_1	
Sample material:	Asphalt
Grease Type	Moly-Lithium
Inner Radius, r1 (m)	0.00635
Outer Radius, r2 (m)	0.058
Cylinder Height, L (m)	0.127
Voltage, U (V)	12.1
Current, I (A)	0.41
Inner Temperature, T1 (ºC)	50.698
Outer Temperature, T2 (ºC)	32.169
Thermal Conductivity, k (W/m-K) (1)	0.743

Last 20 Data Points Collected from Campbell Datalogger CR1000								
	TC_1	TC_2	TC_3	TC_4	TC_5	TC_6	TC_7	TC_8
1	50.68	44.61	32.01	31.99	31.53	31.56	33.43	32.58
2	50.68	44.63	32.11	32.05	31.49	31.53	33.43	32.62
3	50.68	44.61	32.11	32.03	31.6	31.56	33.4	32.58
4	50.7	44.61	31.99	31.95	31.62	31.58	33.34	32.56
5	50.68	44.61	31.92	31.84	31.6	31.58	33.3	32.52
6	50.7	44.63	31.92	31.82	31.6	31.6	33.24	32.5
7	50.67	44.61	31.97	31.85	31.6	31.62	33.25	32.47
8	50.68	44.63	31.99	31.94	31.56	31.6	33.36	32.54
9	50.7	44.63	32.09	32.03	31.55	31.62	33.36	32.54
10	50.7	44.63	32.03	32.03	31.45	31.56	33.4	32.6
11	50.7	44.63	32.03	31.99	31.53	31.62	33.36	32.58
12	50.71	44.63	32.07	32.03	31.49	31.6	33.43	32.62
13	50.71	44.63	32.07	32.03	31.41	31.56	33.47	32.66
14	50.71	44.63	32.11	32.07	31.37	31.49	33.51	32.73
15	50.71	44.63	32.01	31.99	31.31	31.49	33.55	32.81
16	50.71	44.63	31.99	31.95	31.33	31.47	33.55	32.81
17	50.71	44.63	31.95	31.95	31.27	31.39	33.57	32.81
18	50.71	44.63	31.92	31.88	31.29	31.37	33.57	32.81
19	50.71	44.63	31.94	31.92	31.37	31.41	33.43	32.66
20	50.71	44.63	31.72	31.84	31.49	31.49	33.36	32.62
Average	50.698	44.625	31.9975	31.959	31.473	31.535	33.4155	32.631

Sample Name:Lexington_A_Moly_2	
Sample material:	Asphalt
Grease Type	Moly-Lithium
Inner Radius, r1 (m)	0.00635
Outer Radius, r2 (m)	0.058
Cylinder Height, L (m)	0.127
Voltage, U (V)	12.1
Current, I (A)	0.41
Inner Temperature, T1 (ºC)	51.101
Outer Temperature, T2 (ºC)	32.260
Thermal Conductivity, k (W/m-K) (1)	0.730

Last 20 Data Points Collected from Campbell Datalogger CR1000								
	TC_1	TC_2	TC_3	TC_4	TC_5	TC_6	TC_7	TC_8
1	51.11	47.77	32.28	32.19	31.41	31.35	33.67	32.81
2	51.11	47.77	32.34	32.23	31.41	31.35	33.55	32.71
3	51.09	47.77	32.28	32.25	31.41	31.35	33.55	32.69
4	51.11	47.77	32.23	32.23	31.37	31.31	33.63	32.75
5	51.09	47.77	32.13	32.23	31.39	31.33	33.67	32.79
6	51.09	47.77	32.15	32.25	31.37	31.33	33.69	32.81
7	51.09	47.77	32.27	32.34	31.35	31.33	33.69	32.85
8	51.09	47.77	32.36	32.36	31.31	31.27	33.65	32.83
9	51.09	47.77	32.4	32.36	31.37	31.29	33.57	32.73
10	51.09	47.77	32.4	32.36	31.35	31.31	33.65	32.81
11	51.09	47.77	32.25	32.3	31.41	31.37	33.55	32.75
12	51.11	47.77	32.23	32.25	31.5	31.41	33.43	32.62
13	51.11	47.77	32.23	32.25	31.52	31.41	33.41	32.56
14	51.11	47.77	32.15	32.15	31.5	31.41	33.39	32.52
15	51.11	47.77	32.21	32.17	31.43	31.39	33.45	32.58
16	51.11	47.77	32.32	32.28	31.41	31.39	33.53	32.64
17	51.11	47.77	32.27	32.21	31.43	31.37	33.57	32.64
18	51.11	47.77	32.28	32.21	31.37	31.35	33.63	32.71
19	51.11	47.77	32.19	32.21	31.43	31.39	33.61	32.73
20	51.09	47.79	32.19	32.23	31.41	31.37	33.59	32.75
Average	51.101	47.771	32.258	32.253	31.4075	31.354	33.574	32.714

Sample Name:Lexington_A_Omega_1	
Sample material:	Asphalt
Grease Type	Omega
Inner Radius, r1 (m)	0.00635
Outer Radius, r2 (m)	0.058
Cylinder Height, L (m)	0.127
Voltage, U (V)	11.4
Current, I (A)	0.37
Inner Temperature, T1 (ºC)	42.444
Outer Temperature, T2 (ºC)	31.984
Thermal Conductivity, k (W/m-K) (1)	1.109

Last 20 Data Points Collected from Campbell Datalogger CR1000								
	TC_1	TC_2	TC_3	TC_4	TC_5	TC_6	TC_7	TC_8
1	42.44	42.05	32.07	31.68	32.35	32.27	32.39	31.61
2	42.44	42.05	32.07	31.65	32.39	32.27	32.42	31.65
3	42.44	42.05	32.07	31.65	32.35	32.27	32.39	31.57
4	42.44	42.05	32.07	31.65	32.39	32.27	32.39	31.57
5	42.44	42.05	32.03	31.65	32.39	32.29	32.42	31.65
6	42.46	42.08	32.06	31.63	32.41	32.33	32.41	31.71
7	42.44	42.05	32.03	31.59	32.39	32.31	32.41	31.61
8	42.44	42.05	32.07	31.61	32.35	32.31	32.39	31.61
9	42.44	42.05	32.11	31.65	32.35	32.27	32.23	31.41
10	42.44	42.05	32.07	31.68	32.35	32.27	32.07	31.18
11	42.46	42.08	32.14	31.71	32.33	32.26	32.1	31.09
12	42.44	42.05	32.15	31.72	32.31	32.23	32.11	31.18
13	42.46	42.08	32.14	31.69	32.33	32.18	31.98	30.81
14	42.44	42.05	32.15	31.72	32.19	32.07	31.9	30.75
15	42.44	42.05	32.15	31.72	32.19	32.07	32	30.98
16	42.44	42.05	32.11	31.72	32.27	32.11	32.03	31.1
17	42.44	42.05	32.07	31.68	32.27	32.13	32.17	31.33
18	42.44	42.07	32.07	31.65	32.31	32.15	32.27	31.45
19	42.46	42.09	32.1	31.67	32.33	32.22	32.35	31.52
20	42.44	42.05	32.11	31.68	32.31	32.19	32.27	31.37
Average	42.444	42.0575	32.092	31.67	32.328	32.2235	32.235	31.3575

Sample Name:Lexington_A_Omega_2	
Sample material:	Asphalt
Grease Type	Omega
Inner Radius, r1 (m)	0.00635
Outer Radius, r2 (m)	0.058
Cylinder Height, L (m)	0.127
Voltage, U (V)	11.4
Current, I (A)	0.37
Inner Temperature, T1 (ºC)	42.450
Outer Temperature, T2 (ºC)	32.008
Thermal Conductivity, k (W/m-K) (1)	1.110

Last 20 Data Points Collected from Campbell Datalogger CR1000								
	TC_1	TC_2	TC_3	TC_4	TC_5	TC_6	TC_7	TC_8
1	42.45	42.03	32.05	31.57	32.39	32.29	32.33	31.51
2	42.45	42.03	32.02	31.55	32.39	32.25	32.37	31.63
3	42.45	42.05	32.02	31.55	32.37	32.29	32.4	31.64
4	42.45	42.05	32.03	31.59	32.29	32.23	32.4	31.63
5	42.45	42.03	32.05	31.59	32.29	32.25	32.42	31.66
6	42.45	42.03	32.05	31.59	32.33	32.25	32.42	31.63
7	42.45	42.03	32.07	31.59	32.37	32.27	32.33	31.53
8	42.45	42.03	32.09	31.59	32.37	32.29	32.21	31.41
9	42.45	42.05	32.09	31.59	32.39	32.29	32.21	31.35
10	42.45	42.05	32.05	31.59	32.39	32.29	32.25	31.39
11	42.45	42.05	32.03	31.57	32.39	32.33	32.31	31.51
12	42.45	42.05	32.05	31.55	32.4	32.35	32.4	31.59
13	42.45	42.07	32.05	31.55	32.37	32.33	32.39	31.63
14	42.45	42.07	32.07	31.55	32.31	32.27	32.35	31.49
15	42.45	42.07	32.09	31.57	32.27	32.21	32.37	31.35
16	42.45	42.07	32.09	31.57	32.31	32.19	32.25	31.22
17	42.45	42.07	32.11	31.61	32.29	32.21	32.17	31.22
18	42.45	42.07	32.13	31.63	32.29	32.21	32.19	31.29
19	42.45	42.07	32.09	31.61	32.33	32.19	32.25	31.41
20	42.45	42.07	32.09	31.59	32.35	32.21	32.31	31.51
Average	42.45	42.052	32.066	31.58	32.3445	32.26	32.3165	31.48

Sample Name:Lexington_A_Petroleum_Jelly_1	
Sample material:	Asphalt
Grease Type	Petroleum Jelly
Inner Radius, r1 (m)	0.00635
Outer Radius, r2 (m)	0.058
Cylinder Height, L (m)	0.127
Voltage, U (V)	12.1
Current, I (A)	0.41
Inner Temperature, T1 (ºC)	52.594
Outer Temperature, T2 (ºC)	31.588
Thermal Conductivity, k (W/m-K) (1)	0.655

Last 20 Data Points Collected from Campbell Datalogger CR1000								
	TC_1	TC_2	TC_3	TC_4	TC_5	TC_6	TC_7	TC_8
1	52.61	50.29	31.66	31.18	31.92	31.97	32.36	30.79
2	52.58	50.26	31.65	31.2	31.91	31.95	32.26	30.62
3	52.58	50.26	31.65	31.2	31.93	31.95	32.2	30.48
4	52.58	50.26	31.61	31.17	31.95	31.95	32.32	30.54
5	52.58	50.26	31.61	31.13	31.95	31.97	32.3	30.56
6	52.61	50.29	31.7	31.23	31.9	31.96	32.25	30.49
7	52.61	50.31	31.62	31.25	31.9	31.94	32.07	30.3
8	52.58	50.26	31.58	31.28	31.87	31.95	31.93	30.15
9	52.58	50.26	31.56	31.3	31.83	31.91	32.02	30.21
10	52.61	50.31	31.59	31.29	31.9	31.97	32.09	30.32
11	52.58	50.26	31.59	31.24	31.89	31.87	32.18	30.39
12	52.58	50.26	31.56	31.19	31.93	31.93	32.28	30.5
13	52.61	50.31	31.55	31.25	31.94	31.97	32.21	30.51
14	52.58	50.28	31.54	31.2	31.91	31.95	32.28	30.58
15	52.58	50.28	31.59	31.2	31.97	32	32.28	30.54
16	52.61	50.31	31.66	31.23	32.01	32.05	32.38	30.69
17	52.61	50.31	31.62	31.16	32.05	32.13	32.4	30.73
18	52.61	50.31	31.55	31.1	32.05	32.17	32.44	30.77
19	52.61	50.31	31.6	31.12	32.01	32.17	32.46	30.79
20	52.58	50.28	31.65	31.13	31.97	32.06	32.39	30.7
Average	52.5935	50.2835	31.607	31.2025	31.9395	31.991	32.255	30.533

Sample Name: Lexington_A_Petroleum_Jelly_2	
Sample material:	Asphalt
Grease Type	Petroleum Jelly
Inner Radius, r1 (m)	0.00635
Outer Radius, r2 (m)	0.058
Cylinder Height, L (m)	0.127
Voltage, U (V)	12.1
Current, I (A)	0.41
Inner Temperature, T1 (ºC)	52.568
Outer Temperature, T2 (ºC)	31.710
Thermal Conductivity, k (W/m-K) (1)	0.660

Last 20 Data Points Collected from Campbell Datalogger CR1000								
	TC_1	TC_2	TC_3	TC_4	TC_5	TC_6	TC_7	TC_8
1	52.57	50.25	31.8	31.27	31.97	32.11	32.4	30.86
2	52.57	50.25	31.8	31.31	31.96	32.07	32.38	30.84
3	52.57	50.25	31.8	31.29	31.97	32.11	32.42	30.86
4	52.57	50.25	31.84	31.33	31.97	32.09	32.48	30.94
5	52.57	50.25	31.84	31.35	31.99	32.05	32.38	30.88
6	52.57	50.25	31.84	31.33	31.96	32.05	32.4	30.88
7	52.57	50.25	31.82	31.33	31.96	32.07	32.34	30.79
8	52.57	50.25	31.82	31.27	31.99	32.09	32.42	30.79
9	52.57	50.27	31.76	31.27	31.99	32.11	32.42	30.8
10	52.57	50.25	31.76	31.23	31.94	32.03	32.44	30.8
11	52.57	50.27	31.8	31.23	31.92	32.03	32.52	30.9
12	52.54	50.24	31.77	31.17	31.93	32.04	32.47	30.87
13	52.57	50.27	31.78	31.18	31.94	32.07	32.4	30.75
14	52.57	50.27	31.76	31.18	31.92	31.99	32.38	30.71
15	52.57	50.27	31.8	31.21	31.88	31.96	32.46	30.8
16	52.54	50.24	31.81	31.19	31.81	31.91	32.49	30.85
17	52.57	50.27	31.86	31.25	31.82	31.92	32.54	30.94
18	52.57	50.27	31.86	31.23	31.84	31.92	32.44	30.9
19	52.59	50.27	31.84	31.27	31.84	31.96	32.21	30.77
20	52.56	50.24	31.81	31.26	31.83	31.95	32.26	30.76
Average	52.5675	50.2565	31.8085	31.2575	31.9215	32.0265	32.4125	30.8345

Sample Name: Rust_Asphalt	
Sample material:	Asphalt
Grease Type	Omega
Inner Radius, r1 (m)	0.00635
Outer Radius, r2 (m)	0.058
Cylinder Height, L (m)	0.127
Voltage, U (V)	12.1
Current, I (A)	0.41
Inner Temperature, T1 (ºC)	41.335
Outer Temperature, T2 (ºC)	32.095
Thermal Conductivity, k (W/m-K) (1)	1.489

Last 20 Data Points Collected from Campbell Datalogger CR1000								
	TC_1	TC_2	TC_3	TC_4	TC_5	TC_6	TC_7	TC_8
1	41.32	40.58	33.17	31.88	32.15	31.61	32.23	31.72
2	41.33	40.58	33.13	31.84	32.19	31.65	32.15	31.65
3	41.33	40.58	33.11	31.8	32.25	31.69	32.11	31.53
4	41.32	40.58	33.15	31.82	32.23	31.69	32.15	31.61
5	41.33	40.58	33.15	31.82	32.23	31.65	32.25	31.65
6	41.33	40.58	33.17	31.86	32.19	31.61	32.15	31.65
7	41.33	40.58	33.17	31.88	32.19	31.65	32.15	31.63
8	41.33	40.58	33.15	31.84	32.27	31.69	32.17	31.57
9	41.33	40.58	33.13	31.82	32.31	31.72	32.1	31.53
10	41.33	40.58	33.15	31.8	32.31	31.71	32.11	31.53
11	41.33	40.58	33.15	31.8	32.23	31.69	32.13	31.55
12	41.33	40.58	33.17	31.8	32.23	31.69	32.08	31.61
13	41.33	40.58	33.17	31.82	32.23	31.71	32.08	31.57
14	41.35	40.58	33.17	31.8	32.27	31.72	32.04	31.49
15	41.33	40.58	33.13	31.76	32.31	31.76	32.08	31.49
16	41.35	40.58	33.15	31.76	32.11	31.69	32.19	31.57
17	41.35	40.58	33.15	31.76	32.1	31.61	32.29	31.65
18	41.35	40.58	33.09	31.72	32.15	31.59	32.23	31.63
19	41.35	40.58	33.09	31.74	32.21	31.61	32.11	31.61
20	41.35	40.58	33.11	31.72	32.27	31.65	32.08	31.53
Average	41.335	40.58	33.143	31.802	32.2215	31.6695	32.144	31.5885

Sample Name: Lexington_Asphalt	
Sample material:	Asphalt
Grease Type	Omega
Inner Radius, r1 (m)	0.00635
Outer Radius, r2 (m)	0.058
Cylinder Height, L (m)	0.127
Voltage, U (V)	12.1
Current, I (A)	0.41
Inner Temperature, T1 (ºC)	42.927
Outer Temperature, T2 (ºC)	31.398
Thermal Conductivity, k (W/m-K) (1)	1.193

Last 20 Data Points Collected from Campbell Datalogger CR1000								
	TC_1	TC_2	TC_3	TC_4	TC_5	TC_6	TC_7	TC_8
1	42.92	42.25	31.79	31.96	31.38	31.57	30.87	30.91
2	42.92	42.25	31.77	32	31.38	31.61	30.91	30.91
3	42.92	42.25	31.77	32	31.42	31.65	30.91	30.83
4	42.92	42.25	31.77	32.04	31.38	31.61	30.91	30.83
5	42.94	42.25	31.77	32.04	31.34	31.61	30.89	30.77
6	42.94	42.25	31.77	32.04	31.38	31.65	30.87	30.79
7	42.94	42.25	31.73	32	31.38	31.65	30.91	30.83
8	42.92	42.22	31.68	31.94	31.35	31.59	30.96	30.88
9	42.92	42.22	31.66	31.9	31.31	31.51	31.08	30.96
10	42.94	42.25	31.65	31.89	31.34	31.53	31.11	30.99
11	42.94	42.25	31.61	31.81	31.38	31.53	31.14	31.07
12	42.94	42.25	31.61	31.81	31.38	31.53	31.14	31.03
13	42.92	42.22	31.59	31.78	31.31	31.51	31.16	31.04
14	42.94	42.25	31.61	31.81	31.34	31.52	31.18	31.07
15	42.92	42.22	31.59	31.78	31.23	31.43	31.08	30.96
16	42.92	42.24	31.59	31.78	31.23	31.43	31.08	30.96
17	42.92	42.24	31.62	31.82	31.27	31.51	31.08	30.94
18	42.92	42.24	31.62	31.82	31.27	31.51	31.04	30.92
19	42.92	42.24	31.62	31.82	31.27	31.51	31.04	30.92
20	42.92	42.24	31.62	31.82	31.27	31.51	31.04	30.92
Average	42.927	42.2415	31.672	31.893	31.3305	31.5485	31.02	30.9265

Sample Name: Water_Asphalt	
Sample material:	Asphalt
Grease Type	Omega
Inner Radius, r1 (m)	0.00635
Outer Radius, r2 (m)	0.058
Cylinder Height, L (m)	0.127
Voltage, U (V)	12.1
Current, I (A)	0.41
Inner Temperature, T1 (ºC)	43.066
Outer Temperature, T2 (ºC)	30.541
Thermal Conductivity, k (W/m-K) (1)	1.099

Last 20 Data Points Collected from Campbell Datalogger CR1000								
	TC_1	TC_2	TC_3	TC_4	TC_5	TC_6	TC_7	TC_8
1	43.06	43.52	29.19	30.13	31.38	30.91	31.3	30.29
2	43.06	43.54	29.19	30.17	31.38	30.91	31.3	30.32
3	43.06	43.54	29.39	30.4	31.3	30.91	31.34	30.44
4	43.06	43.54	29.39	30.48	31.3	30.87	31.38	30.56
5	43.06	43.54	29.35	30.36	31.38	30.95	31.38	30.48
6	43.08	43.54	29.39	30.32	31.34	30.95	31.32	30.4
7	43.08	43.56	29.35	30.21	31.38	30.91	31.3	30.29
8	43.06	43.54	29.35	30.21	31.38	30.87	31.26	30.29
9	43.06	43.54	29.27	30.29	31.36	30.83	31.3	30.33
10	43.06	43.54	29.27	30.17	31.26	30.75	31.3	30.33
11	43.06	43.54	29.23	30.17	31.26	30.75	31.3	30.27
12	43.03	43.52	29.2	30.1	31.35	30.84	31.27	30.26
13	43.08	43.54	29.15	30.13	31.28	30.83	31.34	30.33
14	43.08	43.54	29.13	30.09	31.28	30.87	31.34	30.33
15	43.08	43.54	29.11	30.07	31.3	30.83	31.26	30.21
16	43.05	43.52	29.13	29.99	31.27	30.83	31.23	30.18
17	43.08	43.54	29.04	30.03	31.38	30.91	31.26	30.25
18	43.05	43.53	29.05	30.06	31.43	30.96	31.23	30.18
19	43.08	43.54	29.15	30.13	31.5	31.03	31.22	30.21
20	43.08	43.54	29.23	30.13	31.52	30.99	31.22	30.17
Average	43.0655	43.5375	29.228	30.182	31.3515	30.885	31.2925	30.306

Sample Name: Cobblestone_Concrete	
Sample material:	Concrete
Grease Type	Omega
Inner Radius, r1 (m)	0.00635
Outer Radius, r2 (m)	0.058
Cylinder Height, L (m)	0.127
Voltage, U (V)	12.1
Current, I (A)	0.41
Inner Temperature, T1 (ºC)	42.607
Outer Temperature, T2 (ºC)	31.473
Thermal Conductivity, k (W/m-K) (1)	1.236

Last 20 Data Points Collected from Campbell Datalogger CR1000								
	TC_1	TC_2	TC_3	TC_4	TC_5	TC_6	TC_7	TC_8
1	42.61	43.54	30.69	31.2	31.24	32.13	31.78	31.45
2	42.59	43.54	30.65	31.16	31.28	32.25	31.78	31.47
3	42.59	43.54	30.61	31.16	31.32	32.29	31.82	31.49
4	42.59	43.54	30.59	31.16	31.35	32.33	31.8	31.51
5	42.61	43.54	30.57	31.16	31.43	32.37	31.86	31.55
6	42.61	43.54	30.57	31.16	31.49	32.37	31.9	31.63
7	42.61	43.54	30.63	31.24	31.51	32.37	31.94	31.63
8	42.61	43.54	30.77	31.39	31.43	32.35	31.67	31.43
9	42.61	43.54	30.81	31.45	31.43	32.25	31.55	31.33
10	42.61	43.54	30.69	31.28	31.47	32.29	31.63	31.35
11	42.61	43.54	30.69	31.24	31.47	32.35	31.71	31.39
12	42.61	43.54	30.65	31.2	31.43	32.33	31.78	31.47
13	42.61	43.54	30.69	31.32	31.37	32.25	31.88	31.47
14	42.61	43.54	30.69	31.35	31.32	32.21	31.88	31.47
15	42.61	43.54	30.77	31.39	31.28	32.25	31.63	31.28
16	42.61	43.54	30.77	31.43	31.28	32.25	31.67	31.32
17	42.61	43.54	30.81	31.43	31.28	32.29	31.74	31.35
18	42.61	43.54	30.77	31.39	31.28	32.29	31.74	31.35
19	42.61	43.54	30.81	31.47	31.32	32.19	31.74	31.32
20	42.61	43.54	30.79	31.51	31.35	32.23	31.67	31.24
Average	42.607	43.54	30.701	31.3045	31.3665	32.282	31.7585	31.425

Sample Name: LaSalle_Concrete	
Sample material:	Concrete
Grease Type	Omega
Inner Radius, r1 (m)	0.00635
Outer Radius, r2 (m)	0.058
Cylinder Height, L (m)	0.127
Voltage, U (V)	12.1
Current, I (A)	0.41
Inner Temperature, T1 (ºC)	41.337
Outer Temperature, T2 (ºC)	31.516
Thermal Conductivity, k (W/m-K) (1)	1.401

Last 20 Data Points Collected from Campbell Datalogger CR1000								
	TC_1	TC_2	TC_3	TC_4	TC_5	TC_6	TC_7	TC_8
1	41.34	41.38	30.44	30.62	32.49	32.65	31.83	31.52
2	41.34	41.38	30.42	30.58	32.53	32.67	31.87	31.55
3	41.34	41.38	30.38	30.46	32.49	32.68	31.81	31.55
4	41.34	41.38	30.27	30.38	32.53	32.65	31.87	31.63
5	41.31	41.35	30.12	30.2	32.46	32.62	31.84	31.6
6	41.34	41.38	30.13	30.23	32.53	32.67	31.91	31.71
7	41.34	41.38	30.15	30.34	32.45	32.63	31.83	31.63
8	41.34	41.38	30.11	30.27	32.45	32.65	31.91	31.67
9	41.34	41.38	30.23	30.38	32.45	32.65	31.71	31.59
10	41.34	41.38	30.34	30.5	32.45	32.61	31.53	31.48
11	41.31	41.35	30.51	30.59	32.5	32.58	31.25	31.25
12	41.34	41.38	30.54	30.58	32.53	32.53	31.44	31.24
13	41.34	41.38	30.5	30.54	32.53	32.53	31.48	31.32
14	41.34	41.38	30.54	30.58	32.41	32.45	31.48	31.28
15	41.34	41.38	30.5	30.62	32.45	32.49	31.52	31.32
16	41.34	41.38	30.5	30.64	32.45	32.53	31.63	31.4
17	41.34	41.38	30.5	30.58	32.49	32.57	31.67	31.44
18	41.34	41.38	30.42	30.5	32.45	32.61	31.75	31.52
19	41.34	41.38	30.34	30.42	32.45	32.65	31.75	31.52
20	41.34	41.38	30.34	30.38	32.37	32.61	31.83	31.61
Average	41.337	41.377	30.364	30.4695	32.473	32.6015	31.6955	31.4915

Sample Name: Backerboard_1	
Sample material:	Ceramic Tile Board
Grease Type	Omega
Inner Radius, r1 (m)	0.00635
Outer Radius, r2 (m)	0.058
Cylinder Height, L (m)	0.1524
Voltage, U (V)	12.1
Current, I (A)	0.41
Inner Temperature, T1 (ºC)	64.422
Outer Temperature, T2 (ºC)	31.409
Thermal Conductivity, k (W/m-K) (1)	0.347

Last 20 Data Points Collected from Campbell Datalogger CR1000								
	TC_1	TC_2	TC_3	TC_4	TC_5	TC_6	TC_7	TC_8
1	64.4	59.22	31.06	31.41	32.47	31.79	30.83	30.99
2	64.4	59.22	31.06	31.45	32.49	31.82	30.87	31.02
3	64.4	59.22	31.1	31.41	32.49	31.82	30.83	30.99
4	64.4	59.23	31.1	31.41	32.51	31.82	30.73	30.93
5	64.4	59.22	31.02	31.36	32.55	31.8	30.75	30.95
6	64.4	59.22	31.06	31.41	32.55	31.8	30.73	30.91
7	64.42	59.23	31.08	31.45	32.53	31.82	30.79	30.99
8	64.42	59.25	31.04	31.38	32.55	31.82	30.79	31.02
9	64.44	59.25	30.97	31.34	32.58	31.84	30.79	31.02
10	64.44	59.25	30.95	31.32	32.6	31.84	30.83	31.02
11	64.44	59.25	30.99	31.41	32.56	31.84	30.75	30.95
12	64.44	59.25	31.06	31.45	32.51	31.77	30.65	30.87
13	64.43	59.25	31.08	31.45	32.47	31.77	30.69	30.83
14	64.43	59.25	31.1	31.49	32.47	31.79	30.63	30.79
15	64.43	59.25	31.1	31.49	32.43	31.79	30.6	30.75
16	64.43	59.25	31.12	31.49	32.43	31.77	30.65	30.79
17	64.43	59.25	31.1	31.47	32.47	31.8	30.67	30.83
18	64.43	59.25	31.06	31.4	32.51	31.8	30.71	30.91
19	64.43	59.25	31.08	31.4	32.53	31.84	30.71	30.91
20	64.43	59.25	31.08	31.38	32.56	31.84	30.71	30.93
Average	64.422	59.2405	31.0605	31.4185	32.513	31.809	30.7355	30.92

Sample Name: Backerboard_2	
Sample material:	Ceramic Tile Board
Grease Type	Omega
Inner Radius, r1 (m)	0.00635
Outer Radius, r2 (m)	0.058
Cylinder Height, L (m)	0.1524
Voltage, U (V)	12.1
Current, I (A)	0.41
Inner Temperature, T1 (ºC)	64.947
Outer Temperature, T2 (ºC)	31.125
Thermal Conductivity, k (W/m-K) (1)	0.339

Last 20 Data Points Collected from Campbell Datalogger CR1000								
	TC_1	TC_2	TC_3	TC_4	TC_5	TC_6	TC_7	TC_8
1	64.96	59.62	31.07	31.4	32.26	31.53	30.42	30.54
2	64.96	59.62	31.01	31.32	32.26	31.55	30.5	30.62
3	64.96	59.62	30.93	31.24	32.26	31.55	30.54	30.66
4	64.96	59.62	30.89	31.2	32.28	31.55	30.58	30.7
5	64.96	59.62	30.81	31.16	32.3	31.53	30.62	30.7
6	64.96	59.62	30.7	31.16	32.26	31.52	30.7	30.77
7	64.96	59.62	30.74	31.22	32.18	31.48	30.58	30.7
8	64.93	59.57	30.82	31.23	32.07	31.45	30.43	30.57
9	64.96	59.62	30.93	31.32	32.08	31.44	30.5	30.58
10	64.96	59.62	30.95	31.32	32.02	31.4	30.46	30.54
11	64.96	59.62	30.89	31.34	32.06	31.4	30.38	30.48
12	64.93	59.59	30.82	31.25	32.03	31.39	30.39	30.51
13	64.93	59.59	30.86	31.29	32.07	31.41	30.35	30.51
14	64.93	59.59	30.84	31.29	32.15	31.45	30.32	30.51
15	64.95	59.62	30.89	31.28	32.22	31.52	30.31	30.5
16	64.93	59.59	30.82	31.17	32.19	31.49	30.24	30.47
17	64.93	59.59	30.78	31.14	32.19	31.49	30.28	30.51
18	64.95	59.62	30.77	31.13	32.22	31.48	30.31	30.54
19	64.93	59.59	30.78	31.14	32.21	31.45	30.34	30.55
20	64.93	59.59	30.74	31.14	32.23	31.47	30.32	30.55
Average	64.947	59.607	30.852	31.237	32.177	31.4775	30.4285	30.5755

Sample Name: Backerboard_3	
Sample material:	Ceramic Tile Board
Grease Type	Omega
Inner Radius, r1 (m)	0.00635
Outer Radius, r2 (m)	0.058
Cylinder Height, L (m)	0.1524
Voltage, U (V)	12.1
Current, I (A)	0.41
Inner Temperature, T1 (ºC)	64.782
Outer Temperature, T2 (ºC)	30.694
Thermal Conductivity, k (W/m-K) (1)	0.336

Last 20 Data Points Collected from Campbell Datalogger CR1000								
	TC_1	TC_2	TC_3	TC_4	TC_5	TC_6	TC_7	TC_8
1	64.77	59.41	31.11	31.3	31.38	30.87	29.51	29.66
2	64.78	59.41	31.15	31.34	31.34	30.91	29.58	29.74
3	64.78	59.41	31.11	31.38	31.38	30.91	29.47	29.68
4	64.77	59.41	31.11	31.34	31.42	30.95	29.35	29.58
5	64.78	59.41	31.15	31.34	31.38	30.95	29.39	29.62
6	64.78	59.41	31.11	31.26	31.34	30.91	29.47	29.7
7	64.78	59.41	31.09	31.22	31.42	30.95	29.39	29.66
8	64.78	59.41	31.03	31.16	31.4	30.95	29.27	29.51
9	64.78	59.41	30.99	31.18	31.44	30.99	29.27	29.51
10	64.78	59.41	30.99	31.22	31.4	30.95	29.43	29.6
11	64.78	59.41	31.05	31.26	31.46	31.03	29.56	29.74
12	64.78	59.41	30.99	31.22	31.54	31.09	29.7	29.86
13	64.78	59.41	30.97	31.22	31.61	31.11	29.78	29.97
14	64.78	59.41	30.95	31.18	31.61	31.07	29.82	30.03
15	64.78	59.43	30.95	31.22	31.61	31.07	29.86	30.09
16	64.79	59.43	30.91	31.18	31.65	31.11	29.94	30.17
17	64.79	59.43	30.79	31.15	31.59	31.11	30.01	30.25
18	64.79	59.41	30.77	31.15	31.5	31.07	29.97	30.21
19	64.79	59.43	30.76	31.15	31.4	31.03	29.99	30.21
20	64.79	59.43	30.64	31.01	31.46	31.07	30.01	30.23
Average	64.7815	59.415	30.981	31.224	31.4665	31.005	29.6385	29.851

Sample Name: Backerboard_4	
Sample material:	Ceramic Tile Board
Grease Type	Omega
Inner Radius, r1 (m)	0.00635
Outer Radius, r2 (m)	0.058
Cylinder Height, L (m)	0.1524
Voltage, U (V)	12.1
Current, I (A)	0.41
Inner Temperature, T1 (ºC)	64.106
Outer Temperature, T2 (ºC)	31.170
Thermal Conductivity, k (W/m-K) (1)	0.348

Last 20 Data Points Collected from Campbell Datalogger CR1000								
	TC_1	TC_2	TC_3	TC_4	TC_5	TC_6	TC_7	TC_8
1	64.11	58.82	30.73	31.05	32.16	31.36	30.77	31.01
2	64.09	58.84	30.7	31.05	32.18	31.4	30.77	31.01
3	64.11	58.84	30.73	31.05	32.2	31.4	30.79	31.01
4	64.09	58.84	30.7	31.03	32.22	31.4	30.85	31.05
5	64.11	58.84	30.68	31.01	32.18	31.4	30.85	31.05
6	64.11	58.84	30.68	31.01	32.22	31.4	30.89	31.05
7	64.09	58.85	30.73	31.05	32.26	31.44	30.93	31.09
8	64.09	58.84	30.73	31.05	32.26	31.42	30.89	31.09
9	64.11	58.85	30.73	31.01	32.22	31.4	30.85	31.05
10	64.11	58.85	30.73	30.97	32.18	31.36	30.85	31.07
11	64.11	58.84	30.62	30.89	32.22	31.36	30.93	31.14
12	64.11	58.84	30.62	30.93	32.18	31.32	30.89	31.12
13	64.11	58.85	30.62	30.93	31.98	31.24	30.93	31.12
14	64.11	58.85	30.62	30.93	31.96	31.2	30.85	31.09
15	64.11	58.85	30.73	31.01	31.98	31.24	30.77	31.05
16	64.11	58.85	30.73	31.01	31.94	31.28	30.81	31.01
17	64.11	58.85	30.7	30.97	31.98	31.28	30.85	31.05
18	64.11	58.85	30.68	30.97	31.98	31.24	30.77	31.03
19	64.11	58.85	30.66	30.97	32.02	31.24	30.79	31.01
20	64.11	58.85	30.58	30.89	32.02	31.24	30.77	31.01
Average	64.106	58.8445	30.685	30.989	32.117	31.331	30.84	31.0555

Sample Name: Calibration_Petroleum_Jelly	
Sample material:	Ceramic Tile Board
Grease Type	Petroleum Jelly
Inner Radius, r1 (m)	0.00635
Outer Radius, r2 (m)	0.058
Cylinder Height, L (m)	0.127
Voltage, U (V)	12.1
Current, I (A)	0.41
Inner Temperature, T1 (ºC)	98.200
Outer Temperature, T2 (ºC)	31.710
Thermal Conductivity, k (W/m-K) (1)	0.207

Last 20 Data Points Collected from Campbell Datalogger CR1000								
	TC_1	TC_2	TC_3	TC_4	TC_5	TC_6	TC_7	TC_8
1	98.15	98.15	31.8	31.27	31.97	32.11	32.4	30.86
2	98.25	98.15	31.8	31.31	31.96	32.07	32.38	30.84
3	98.11	98.15	31.8	31.29	31.97	32.11	32.42	30.86
4	98.19	98.15	31.84	31.33	31.97	32.09	32.48	30.94
5	98.21	98.15	31.84	31.35	31.99	32.05	32.38	30.88
6	98.23	98.15	31.84	31.33	31.96	32.05	32.4	30.88
7	98.21	98.15	31.82	31.33	31.96	32.07	32.34	30.79
8	98.21	98.15	31.82	31.27	31.99	32.09	32.42	30.79
9	98.21	98.15	31.76	31.27	31.99	32.11	32.42	30.8
10	98.21	98.15	31.76	31.23	31.94	32.03	32.44	30.8
11	98.21	98.15	31.8	31.23	31.92	32.03	32.52	30.9
12	98.21	98.15	31.77	31.17	31.93	32.04	32.47	30.87
13	98.21	98.15	31.78	31.18	31.94	32.07	32.4	30.75
14	98.21	98.15	31.76	31.18	31.92	31.99	32.38	30.71
15	98.21	98.15	31.8	31.21	31.88	31.96	32.46	30.8
16	98.21	98.15	31.81	31.19	31.81	31.91	32.49	30.85
17	98.21	98.15	31.86	31.25	31.82	31.92	32.54	30.94
18	98.21	98.15	31.86	31.23	31.84	31.92	32.44	30.9
19	98.21	98.15	31.84	31.27	31.84	31.96	32.21	30.77
20	98.21	98.15	31.81	31.26	31.83	31.95	32.26	30.76
Average	98.204	98.15	31.8085	31.2575	31.9215	32.0265	32.4125	30.8345

Sample Name: Calibration_Lithium	
Sample material:	Ceramic Tile Board
Grease Type	Lithium
Inner Radius, r1 (m)	0.00635
Outer Radius, r2 (m)	0.058
Cylinder Height, L (m)	0.127
Voltage, U (V)	12.1
Current, I (A)	0.41
Inner Temperature, T1 (ºC)	88.236
Outer Temperature, T2 (ºC)	31.170
Thermal Conductivity, k (W/m-K) (1)	0.241

Last 20 Data Points Collected from Campbell Datalogger CR1000								
	TC_1	TC_2	TC_3	TC_4	TC_5	TC_6	TC_7	TC_8
1	88.23	85.36	30.73	31.05	32.16	31.36	30.77	31.01
2	88.23	85.36	30.7	31.05	32.18	31.4	30.77	31.01
3	88.23	85.36	30.73	31.05	32.2	31.4	30.79	31.01
4	88.23	85.36	30.7	31.03	32.22	31.4	30.85	31.05
5	88.23	85.36	30.68	31.01	32.18	31.4	30.85	31.05
6	88.23	85.36	30.68	31.01	32.22	31.4	30.89	31.05
7	88.23	85.36	30.73	31.05	32.26	31.44	30.93	31.09
8	88.23	85.36	30.73	31.05	32.26	31.42	30.89	31.09
9	88.23	85.36	30.73	31.01	32.22	31.4	30.85	31.05
10	88.24	85.36	30.73	30.97	32.18	31.36	30.85	31.07
11	88.23	85.36	30.62	30.89	32.22	31.36	30.93	31.14
12	88.23	85.36	30.62	30.93	32.18	31.32	30.89	31.12
13	88.23	85.36	30.62	30.93	31.98	31.24	30.93	31.12
14	88.23	85.36	30.62	30.93	31.96	31.2	30.85	31.09
15	88.23	85.36	30.73	31.01	31.98	31.24	30.77	31.05
16	88.23	85.36	30.73	31.01	31.94	31.28	30.81	31.01
17	88.23	85.36	30.7	30.97	31.98	31.28	30.85	31.05
18	88.23	85.36	30.68	30.97	31.98	31.24	30.77	31.03
19	88.23	85.36	30.66	30.97	32.02	31.24	30.79	31.01
20	88.23	85.36	30.58	30.89	32.02	31.24	30.77	31.01
Average	88.2305	85.36	30.685	30.989	32.117	31.331	30.84	31.0555

Sample Name: Calibration_Moly_Lithium	
Sample material:	Ceramic Tile Board
Grease Type	Moly-Lithium
Inner Radius, r1 (m)	0.00635
Outer Radius, r2 (m)	0.058
Cylinder Height, L (m)	0.127
Voltage, U (V)	12.1
Current, I (A)	0.41
Inner Temperature, T1 (ºC)	88.712
Outer Temperature, T2 (ºC)	31.125
Thermal Conductivity, k (W/m-K) (1)	0.239

Last 20 Data Points Collected from Campbell Datalogger CR1000								
	TC_1	TC_2	TC_3	TC_4	TC_5	TC_6	TC_7	TC_8
1	88.72	84.62	31.07	31.4	32.26	31.53	30.42	30.54
2	88.72	84.62	31.01	31.32	32.26	31.55	30.5	30.62
3	88.72	84.62	30.93	31.24	32.26	31.55	30.54	30.66
4	88.72	84.62	30.89	31.2	32.28	31.55	30.58	30.7
5	88.72	84.62	30.81	31.16	32.3	31.53	30.62	30.7
6	88.72	84.62	30.7	31.16	32.26	31.52	30.7	30.77
7	88.72	84.62	30.74	31.22	32.18	31.48	30.58	30.7
8	88.72	84.62	30.82	31.23	32.07	31.45	30.43	30.57
9	88.72	84.62	30.93	31.32	32.08	31.44	30.5	30.58
10	88.72	84.62	30.95	31.32	32.02	31.4	30.46	30.54
11	88.72	84.62	30.89	31.34	32.06	31.4	30.38	30.48
12	88.72	84.62	30.82	31.25	32.03	31.39	30.39	30.51
13	88.72	84.62	30.86	31.29	32.07	31.41	30.35	30.51
14	88.72	84.62	30.84	31.29	32.15	31.45	30.32	30.51
15	88.72	84.62	30.89	31.28	32.22	31.52	30.31	30.5
16	88.72	84.62	30.82	31.17	32.19	31.49	30.24	30.47
17	88.72	84.62	30.78	31.14	32.19	31.49	30.28	30.51
18	88.73	84.62	30.77	31.13	32.22	31.48	30.31	30.54
19	88.72	84.62	30.78	31.14	32.21	31.45	30.34	30.55
20	88.72	84.62	30.74	31.14	32.23	31.47	30.32	30.55
Average	88.7205	84.62	30.852	31.237	32.177	31.4775	30.4285	30.5755

Ice Water Mixture

Last 10 Data Points Collected from Campbell Datalogger CR1000								
	TC_1	TC_2	TC_3	TC_4	TC_5	TC_6	TC_7	TC_8
1	1.608	1.628	1.89	1.427	1.709	1.628	1.588	1.85
2	1.628	1.628	1.91	1.427	1.709	1.628	1.608	1.87
3	1.628	1.648	1.91	1.427	1.729	1.628	1.628	1.89
4	1.628	1.669	1.93	1.427	1.749	1.628	1.628	1.91
5	1.628	1.709	1.95	1.427	1.749	1.648	1.628	1.93
6	1.628	1.749	1.95	1.427	1.769	1.669	1.628	1.95
7	1.628	1.749	1.95	1.427	1.789	1.669	1.628	1.97
8	1.628	1.769	1.97	1.427	1.789	1.669	1.648	1.99
9	1.628	1.789	1.97	1.427	1.809	1.669	1.669	1.99
10	1.628	1.789	1.99	1.447	1.829	1.709	1.669	2.03
Average	1.626	1.712	1.942	1.429	1.763	1.654	1.632	1.93

Boiling Water

Last 10 Data Points Collected from Campbell Datalogger CR1000								
	TC_1	TC_2	TC_3	TC_4	TC_5	TC_6	TC_7	TC_8
1	99.1	99.1	99.3	98.8	99.3	98.8	98.8	99.4
2	98.8	98.8	99.2	98.6	98.9	98.5	98.5	99.1
3	99.3	98.9	99.2	99.1	99.1	99	99.3	99.2
4	98.9	98.8	99	99.1	98.9	98.8	98.9	98.9
5	99	98.8	99	99.3	98.9	99.1	99.2	98.9
6	99.4	99.2	99.4	99.2	99.4	99.1	99.3	99.2
7	99.2	99	99.4	99.1	99.3	99.1	99.2	99.4
8	99.1	98.9	99.2	99	99	98.9	99	99.3
9	99.1	98.9	99.4	98.9	99.1	98.9	98.9	99.3
10	99	98.8	99.2	99.1	99	98.7	98.8	99.1
Average	99.09	98.92	99.23	99.02	99.09	98.89	98.99	99.18