COMPARING ALUMINUM COMPOSITE SHEETING TO FIBRE PANEL FOR THERMAL PERFORMANCE IN RESIDENTIAL HOUSING

A Thesis

by

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ABSTRACT

In the United States, the building industry is one of the main consumers of energy and materials such as concrete and walling systems. Exterior wall systems play an important role in determining the energy consumption for heating and cooling required for a residential house. This research work investigates the development of a simple thermal test to rapidly determine the potential use of different materials on exterior walls in terms of thermal performance. Tests on cement fibre panels are compared to an aluminum composite sheeting to review the utility of the test method when compared to the standard ASTM test method for thermal performance. The aluminum composite sheeting was tested in two thicknesses, three and six millimeters. The test results showed that the proposed rapid test method has some issues in terms of interpretation of the results. The tests on the aluminum composite sheeting suggest that it does not provide an improvement compared to a standard fibre board in terms of thermal performance. Future research is suggested on the development of a simpler test with better air flow and temperature control.

DEDICATION

I would like to dedicate the completion of my thesis work to my parents. There is no doubt in my mind that I could not have finished the research work without their endless love, support and encouragement.

ACKNOWLEDGEMENTS

I would like to thank my committee co-chairs, John Nichols and Kevin Glowacki, and my committee member, Leslie Feigenbaum, for their guidance and support throughout the course of this research.

Thanks also go to my friends and colleagues and the department faculty and staff for making my time at Texas A&M University a great experience. I also want to extend my gratitude to Jim Titus at the Texas A&M Woodshop which provided the facilities and help for the study. Thanks to Piedmont Plastics for the sheeting and permission to test the materials.

Finally, thanks to my mother and father for their encouragement.

NOMENCLATURE

LCA	Life Cycle Assessment
PSG	Piedmont Sign Grade
EIFS	Exterior Insulation Finishing System
MDF	Medium-Density Fiberboard

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CHAPTER I

INTRODUCTION

Background to the Study

There is a growing concern about excess energy consumption in building construction. The concern comes from fossil-fuel use, global warming and corresponding environmental pollutants (Pérez-Lombard, Ortiz, Coronel, & Maestre, 2011). This community concern is reflected in the engineering and construction community with the development of national and international standards to measure the thermal and other performance indicators for buildings and building wall systems.

ASTM International (2011) provides guidance on one standard test to measure the thermal performance of wall systems and wall system components. ASTM International (2012) provides the overarching measure for the standard guide to the evaluation of exterior building wall systems. In developing a new wall system, the key constraint is the need to obtain the requisite approvals, such as International Code Council (2012) compliance certificates. These types of approvals are expensive and time consuming, the first question often asked is the likelihood of success in pursuing a National Approval. This research reviewed the development of a rapid thermal test to provide guidance to a manufacturer as to whether to expend the significant funds to undertake the formal and highly expensive work to obtain National Approvals.

Of course from the manufacturer's perspective, buildings are one of the main consumers of energy consumption in today's world. Both residential and commercial buildings consume about forty percent of the global energy, which has exceeded the other major sectors: industry and transportation. Yang, Yan, and Lam (2014) note that buildings contribute to over thirty percent of the CO_2 emissions. Edmonds and Smith (2011) observe that in the U.S., building users consume sixty percent of generated electricity and thirty nine percent of the country's total energy. Table 1 presents global resource consumption in building industry.

Table 1.

Global resources used in buildings construction from (Tajsic, 2014)

Resource	(%)
Energy	45-50
Water	50
Materials for buildings and infrastructure	60
Agricultural land loss to buildings	80
Timber products for construction	60 (90% of hardwoods)
Coral reef destruction	50 (indirect)
	20 (indirect)

Table 2 shows a breakdown of the influences with respect to pollutant emissions.

Table 2.

Building's side effects on global pollution from (Tajsic, 2014)

Pollution	(%)
Air quality (cities)	23
Climate change gases	50
Drinking water pollution	40
Landfill waste	50
Ozone depletion	50

Buildings consume energy in three main ways: lighting, cooling and heating. U.S. Environmental Protection Agency (1993) observe that heating and cooling systems account for forty percent of all electricity use in the U.S. Mosteiro-Romero et al. (2014) comment on the current concerns about excessive energy consumption, ask the design of buildings that can reduce energy use and comment on the need to minimize the overall environmental burdens.

U. S. Department of Energy National Energy Technology Laboratory (2009) note that a well-designed building envelope (roofs, walls, and foundations) can influence fifty-one percent of the building energy consumption.

This chapter outlines the background to the study and the basic study hypothesis and limitations. The study purpose is to consider the development of a simple thermal test procedure and then to use a comparison between aluminum composite sheeting and a cement fiber board to review and comment on the proposed procedure.

Problem Statement

Cement fibre panels are widely used in commercial and residential buildings. Aluminum composite sheeting is an alternative siding material that could be used for residential housing, but as far as is known it has not been tested for thermal performance. In this study, the fibre panel and the aluminum composite sheeting will be tested for thermal performance in new thermal test to see if a simple rapid test can be developed for thermal performance.

Research Objectives

The main objective of the research is to test and compare the thermal performance of the aluminum composite sheeting and cement fibre panel using an alternative test procedure to the ASTM International (2011) thermal test system.

Hypothesis

The hypothesis of the research is:

The aluminum composite sheeting has better thermal performance than the cement fibre panel, and its use will reduce the cost of heating and cooling systems in the interior.

Study Limitations

The study limitations of the research are:

- There are three major types of energy consumption in buildings: lighting, heating, and cooling. This study focuses only on cooling and heating energy usage affected by the thermal performance of different sheeting materials used on wall system.
- The research experiment is self-designed and performed.
- There is a measure range of the thermometer, from 0-70 ºC.

Study Assumptions

The study assumptions of the research are:

- The residential house in this research is representative around the United States.
- The instruments perform in the same state during the experiment.

Significance of the Study

The significance is to determine if a cheaper test is available for determining thermal performance.

CHAPTER II

LITERATURE REVIEW

Introduction

In the U.S., buildings account for about fifty percent of the country's energy consumption, which greatly exceeds energy usage in either the industry and transportation sectors. Figure 1 shows the U.S. energy consumption by each sector, from the recent work by Mazria and Kershner (2008).

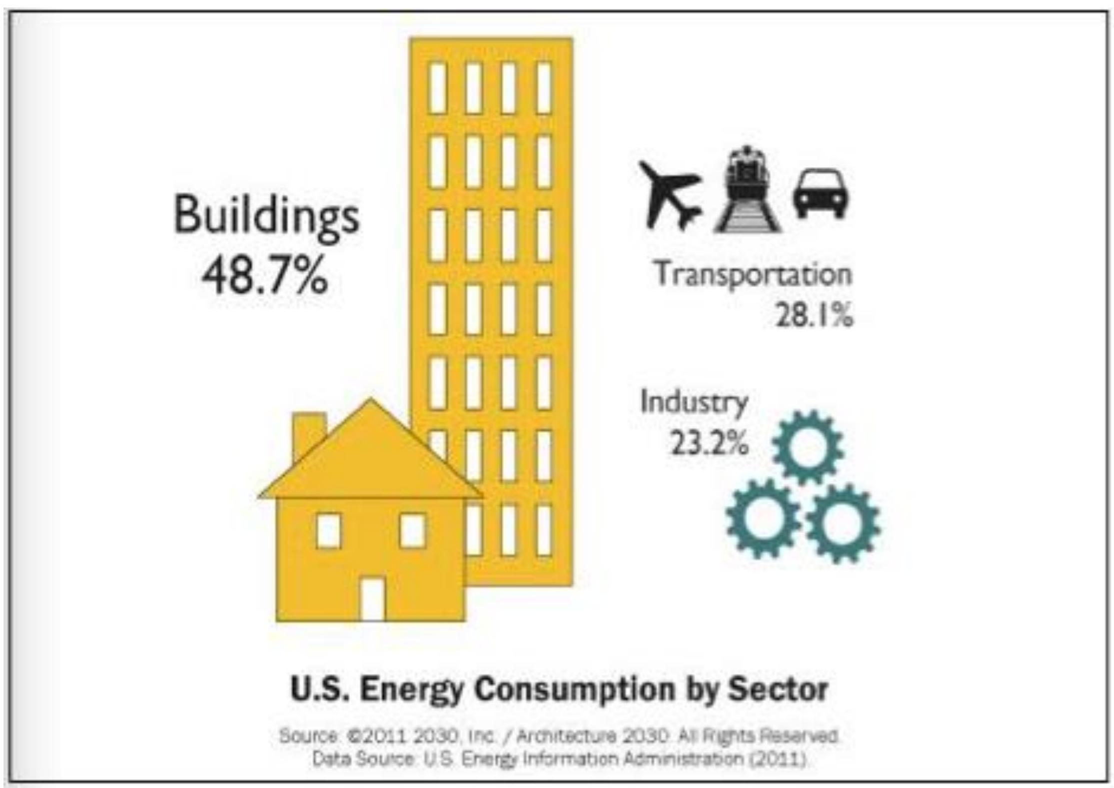

Figure 1. U.S. Energy consumption by sector from (Mazria & Kershner, 2008)

Pérez-Lombard et al. (2011) offer the opinion that the growing tendency in building energy consumption will not change in the future years because of building areas expansion and related energy needs. For most of buildings, energy efficient strategies have positive influences on reduction of energy consumption. Environmental destruction and the high cost of energy in recent years means that building energy efficiency has become a concern for building owners and governments around the world.

This chapter presents the literature review, considering the following topics:

- Life Cycle Assessments
- Building Envelopes
- Building Energy Efficiency
- Walls
- Heat Transfer Efficiency
- Cement Fibre Panels
- Piedmont Plastics (PSG) ALUPOLY
- ASTM Standards

Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) evaluates the total environmental impacts of products, processes and services by identifying and analyzing all consumed resources and released emissions (Iannone, Miranda, Riemma, & De Marco, 2016). It is known as a " Cradle to Grave" analysis that starts from the gathering of raw materials to the last phase in the life cycle of any building (e.g. demolition). The International Standard ISO

14040 defines LCA as an established way to assess the environmental aspects and potential effects related to a product. LCA is divided into 4 different phases. They are goal and scope definition, inventory analysis, impact assessment, and interpretation of results (International standard 14040, 1997).

A thermal analysis provides one of the significant inputs to a life cycle cost assessment procedure as thermal energy is an expensive component in buildings. A typical residential dwelling in Texas may have a monthly energy charge of about $120 per month in winter and $550 per month in summer. This work does not include a life cycle cost assessment.

Building Envelope

The building envelope is defined as all the building elements that separate the interior of the building from the outdoor environment. There are various factors that influence the design of the building envelope, such as function, technology, or aesthetic concerns. ASTM International (2012) provides the standard test for thermal performance of wall elements.

Figure 2 illustrates the parameters with effects on the design of the building envelope. The building envelope serves as a thermal barrier and has impact on the amount of energy expended to keep the indoor environment comfortable.

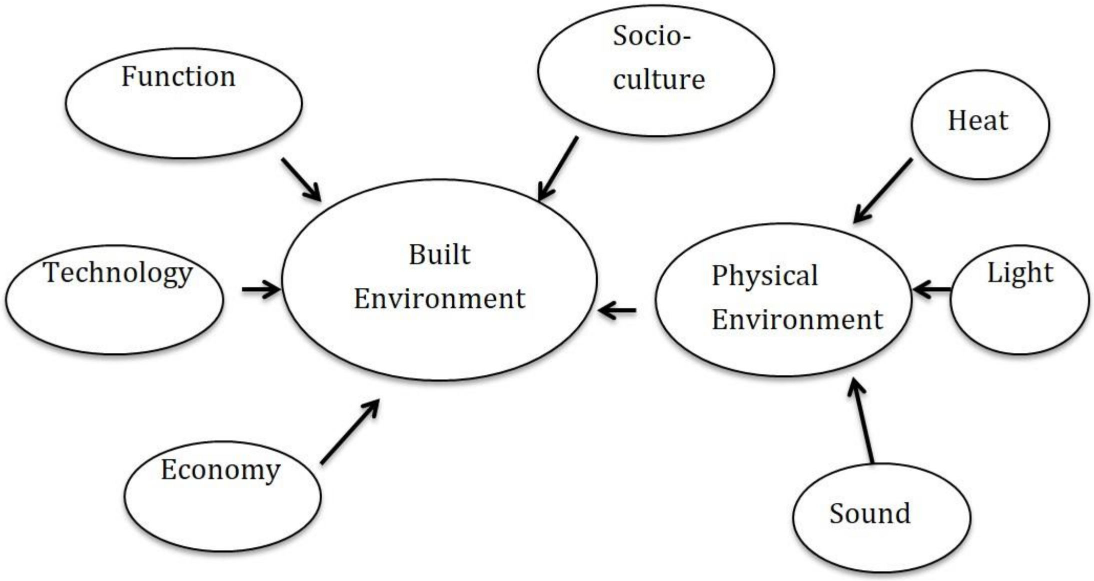

Figure 2. Parameters with effects on the design of the building envelope from Oral, Yener, and Bayazit (2004)

Building Energy Efficiency

The US Department of Energy (2002) show space heating and cooling accounts for 50-70% of the energy consumption of a typical residential building in the U.S. The percentage will increase in some extreme climate conditions or with lower energy efficiency. Either active or passive energy efficient strategies can be employed to improve the building energy efficiency. Improvements to heating, cooling and ventilation systems, electrical lighting etc. can be classified as active strategies while improvements to building envelope elements are categorized as passive strategies. The building envelope helps to minimize the heat transfer through the building which is critical for reducing the energy consumption for heating and cooling.

Tuhus-Dubrow and Krarti (2010) note that the envelope can reduce the amount of energy needed for heating in cold climates and for cooling in hot climates. There are numerous design features that can affect the energy efficiency of building envelopes, such as the building shape, foundation type, roof and wall construction, window type, insulation levels and so.

There are several studies in how to improve building envelopes and the effects on energy usage of buildings around the world. For example, Cheung, Fuller, and Luther (2005) showed in Hong Kong where the climate is sub-tropical, energy is saved about 31.4% in space cooling and 36.8% in the peak cooling load annually by improving the building envelope design. These results are realized by adding extruded polystyrene thermal insulation to walls, changing external finishes of the exterior walls according to the solar absorption, using a single layer of Evergreen™ glass with reflective coatings, increasing the glazed areas, and utilizing 1.5m fixed shading devices.

Tuhus-Dubrow and Krarti (2010) comment on a simulation-optimization tool has been created and applied for the selection of the most appropriate values of comprehensive parameters in relation to the building envelope; these help to achieve energy efficiency for residential houses. The parameters include building orientation, insulation of wall, roof and foundation, window area, air leakage level, glazing type and thermal mass. Perini, Ottelé, Fraaij, Haas, and Raiteri (2011) note that using green roofs or vertical greening plays a vital role in the thermal performance of buildings and brings about the buildings’ efficiency and environment benefits.

In this paper, thermal performance of the wall material is studied to observe whether an alternative material can reduce the energy consumption of the building and bring benefits to the environment, when compared to a commonly used product.

Walls

Walls are a primary part of the building envelope and can provide thermal comfort without sacrificing the aesthetic of the building. Exterior Insulation Finishing System (EIFS) is a cladding system of exterior building wall that provides an insulated finished surface and waterproofing to the material system while improving the efficiency of thermal insulation, resulting in saving energy (Ghosh, 2015). In addition to studies on the thermal insulation of exterior walls, there has also been a study about interior thermal insulation, which also plays an important role in building energy conservation by minimizing the heat transfers between adjacent zones at different temperatures (Cao et al., 2015).

The entire wall assembly has to be tested to determine the final thermal performance, but components can be tested individually to determine relative performance. In this research the interest is in relative not absolute performance, as the standard comparison material is used extensively in the USA and beyond.

Heat Transfer Coefficient

It is critical for energy saving to control the flow of thermal energy through the building envelope. Heat transfers from higher temperature space to lower temperature space by conduction, convection and radiation. The heat transfer coefficient is a crucial index to assess the thermal performance of the building envelope (Fang, Xue, & Li, 2011).

There are four main methods to measure the heat transfer coefficient of the building envelope. These are the hot box method, the temperature controlled tank-heat flow meter method, the heat flow meter method, and power plane heat source method (Wu, Mai, & Lu, 2011).

- Hot box method: The hot box consists of two closed rooms divided by the specimen under test or by a panel on which is installed with the specimen. The temperature of warm side and cold side is measured until temperature of the both side reaches at a steady state (Wakili & Tanner, 2003).
- Temperature controlled tank-heat flow meter method: A one-dimensional steady-state thermal environment is created by heat box. The cold side is outdoor natural environment. The temperature of the surface wall through the tank is controlled to make the temperature difference between the indoor and outdoor above a certain temperature. The heat flow will keep transferring from indoor to outdoor. When the heat of the hot box is equal to the heat transferred from indoor to outdoor, the amount of heat is measured (Fei & Kai, 2000).
- Heat flow meter method: The heat flow meter supposes the only type of heat transfer is one-dimensional conduction. It's easy to use but limited to certain ranges of the spectrum of thermal conductivity (Mahanta & Abramson, 2010).

- Transient power plane heat source method: The fundamental principle of the method is that there is a plane element used both as the heater and the temperature sensor. This method is fast and easy to operate and offers the potential to measure a variety of building materials (Solórzano et al., 2008).

Cement Fibre Panel

Cement fibre panels are typically single-faced, cellulose fiber-reinforced cement products. A normal density of the panel is about 1350 kg/m^3.

A typical panel is tested according to ASTM E84, there is a 5 or less in flame-spread index and a 50 or less in a smoke-developed index. When a typical panel is tested according to ASTM E136, the Panel is classified as noncombustible (ICC Evaluation Service, 2015). Fibre cement panel is used on exterior structural wall sheathing, cladding, soffit, structural and non-structural interior wall backer board and lining board.

This type of panel has been in common use for construction for many decades.

Piedmont Plastics - Sign Grade (PSG) AluPOLY

PSG AluPOLY, is an aluminum composite material. It can be used in various applications and markets. AluPOLY is anti-corrosive, which helps the material to be impervious to water and most chemicals. The majority types of ink and paints can be accepted for polyester painted surface so that the surface can be screen printed, digitally printed or media applied to the substrate directly. AluPOLY has excellent ultraviolet ray protection and strong weather ability, with the result that can withstand extremely harsh outdoor conditions. Piedomont Plastics (2015) note that it is easy to fabricate, cut and install by using general tools, which results in numerous benefits, such as reducing labor costs, increasing efficiency and so on.

The material appears to provide an alternative walling material for residential uses, the first question relates to thermal properties.

ASTM Standards

ASTM International (2012) provides the standard for reporting on wall performance measurements. ASTM International (2011) provides the standard for testing the thermal performance of walls and other elements. The standard provides the following comments on a test box as shown in Figure 3.

The major components of a hot box apparatus are (1) the metering chamber on one side of the specimen; (2) the climatic chamber on the other; (3) the specimen frame providing specimen support and perimeter insulation; and (4) the surrounding ambient space. These elements shall be designed as a system to provide the desired air temperature, air velocity, and radiation conditions for the test and to accurately measure the resulting net heat transfer. A diagram of the relative arrangement of those spaces is shown in Figure 3.

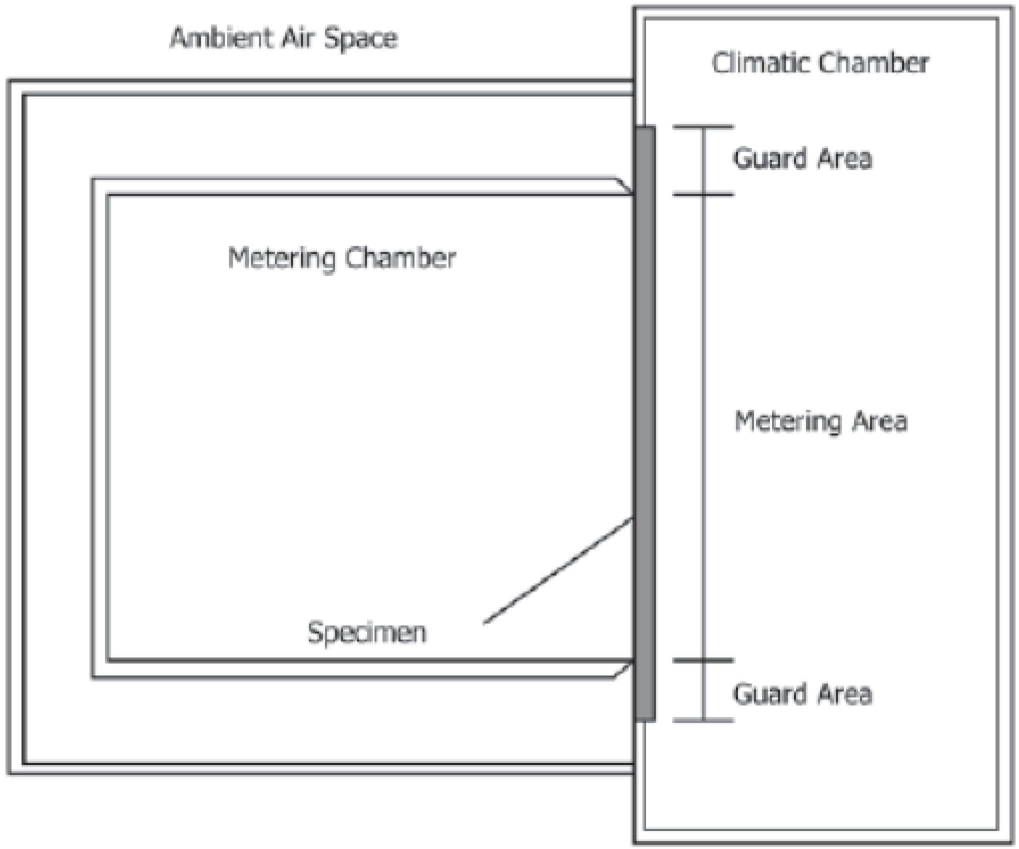

Figure 3. ASTM Standard – Hot Box Layout

The purpose of standards is to provide a method for comparing different things to a common standard. There are national and international standards. The development of a standard whether national or international does not mean that standard fully or completely addresses the issues or provide the best method available.

Three elements are required for a standard development:

1. Reasonable consensus on the need for the standard and the extent and scope of the standard
2. A standard that offers a reasonable precision level, (Johnson, 2000)

3. A standard that offers a known and low bias when compared to other similar tests, (Borowski & Borwein, 1989)

In terms of reasonable consensus, the development of standards such as ASTM International (2002) have been accepted for more than 100 years and are direct copies of the earlier standard developed by a committee from the American Society of Civil Engineers, (Baker, 1914).

Baker further reported on the development of a tensile test for mortars. As Nichols (2005) notes two types of lime were tested by Baker; these were High Calcium Lime and Magnesium Lime. The tensile strength of the Lime Mortar samples was determined using Lime Mortar briquettes. The results for the tests are presented in Table 3. The tests were completed with a 3:1 sand to lime mix.

Table 3.

Lime Mortar Briquettes – Tensile Strength

Ref No.	Age when tested	Tensile Strength (MPa)	
		High Calcium Lime	Magnesium Lime
1	Four Weeks	0.21	….
2	Eight Weeks	0.25	0.20
3	Three Months	0.27	0.25
4	Four Months	0.27	0.35
5	Six Months	0.35	0.57
6	One Year	0.31	0.64

The high calcium lime has been given the colloquial name of quick lime, it is a good solvent for many things, and the magnesium lime was slow lime as it has a slower heat evolution. The magnesium limes are also called dolomitic and have at least 10 % magnesium oxide. Limes with less than 10 % magnesium oxide are classified as high calcium limes. The mould used to form the briquettes is shown in Figure 4. This mould was developed by the American Society of Civil Engineers (American Society of Civil Engineers, 1904).

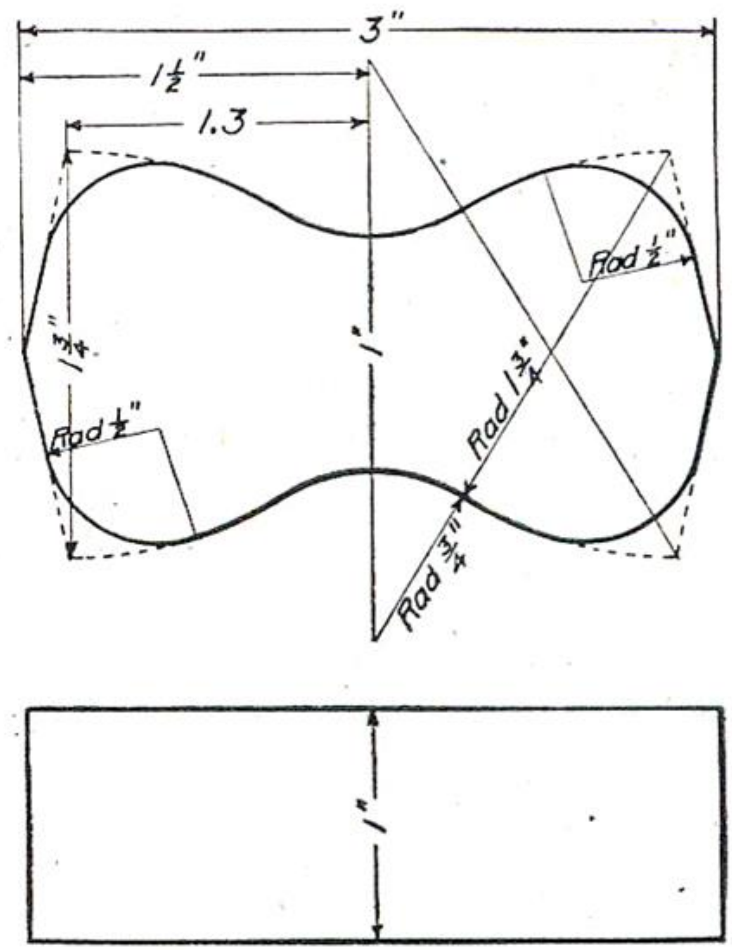

Figure 4. Briquette Mould – 1904

A similar test mould is used for modern tests of cement mortar, however the ASTM standard for the modern test has not transcribed all dimensions correctly.

Summary

Engineering standards evolve, for many reasons, such as improved knowledge, new materials or evolving community standards. One must be careful to ensure that the standard achieves the required objective with an acceptable precision and bias.

CHAPTER III

METHODOLOGY

Introduction

ASTM International (2012) provides alternative test methods for determining the thermal performance of wall elements. This chapter outlines the methodology developed for an alternative test arrangement, one that is designed to be simple and rapid. The point is not to replace the ASTM work, but to provide a manufacturer with a simple test to determine if further and significantly more expensive tests are warranted.

Basic Concept

An experiment was designed to study the overall heat transfer coefficient of three specimens that could be used as the wall system in a residential building. Fisher (1971) provides the typical standard for the design of experiments. In this case the control sample is the cement fibre board that is commonly used in building construction in the USA and the world. The experiment models a typical American residential house environment and heat transfers through the exterior walls.

The hot box method is a common method used to study the overall heat transfer coefficient U of the materials in the building envelope. The difference in this experimental arrangement is the temperature is allowed to vary and the values determined from instantaneous point measurements in place of steady state conditions.

The objective of the experiment is to determine which material performs better in thermal performance, comparing the composite sheeting to a control standard fibre cement board.

Experiment Design

The experiment requires firstly the construction of the test chamber. An insulated wooden box was constructed at the TAMU woodshop.

The specimen panel is used to divide the box into two sections. Figure 5 shows the box arrangement in conceptual form.

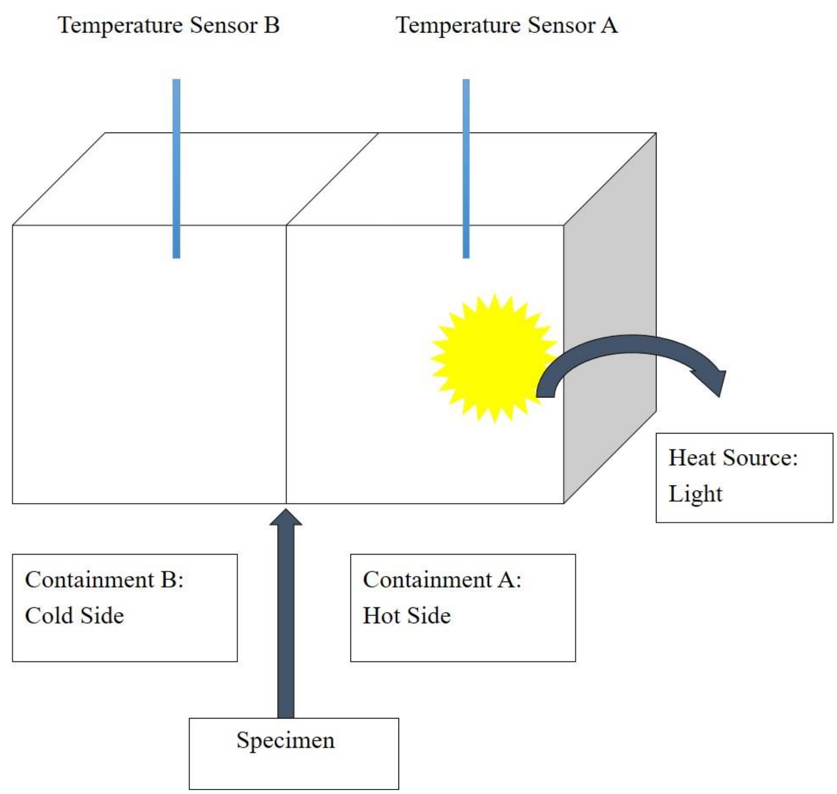

Figure 5. Wooden box arrangement

The description of the test set arrangement is:

- containment A is the hot side of the box
- containment B is the cold side of the box
- a flat specimen is inserted into the middle of the hot box, which represents the exterior wall of a residential house.
- each specimen is not fixed in the box, it is flexible and replaceable
- a light was installed in containment A as the heat source
- temperature sensors are used in each side of the box to record the temperature data

The specimens are:

A. Fibre cement panel
B. 3mm aluminum composite sheeting
C. 6 mm aluminum composite sheeting

The test procedure is:

A. For each specimen, repeat three tests to verify the results.
B. From the results,
    a. determine whether or not the thermal performance of the specimen is stable,
    b. the delay time between containment A and containment B reaching 70 °C
    c. the overall heat transfer coefficient.

Hot Box Construction

A cuboid box was constructed for this experiment. It was divided by the specimen panel into two equal containment chambers. Medium-density fiberboard (MDF) was used to build the box. The thickness of MDF is three quarters of an inch. The box was insulated with seven- eighths of an inch thermal insulation outside of each side panels. In addition, there are five enclosed sides, a ¾” width slot in the middle, and two separate open faces of both containment A and containment B.

Figure 6 shows the dimensions in inches of the main elements of the containment volume.

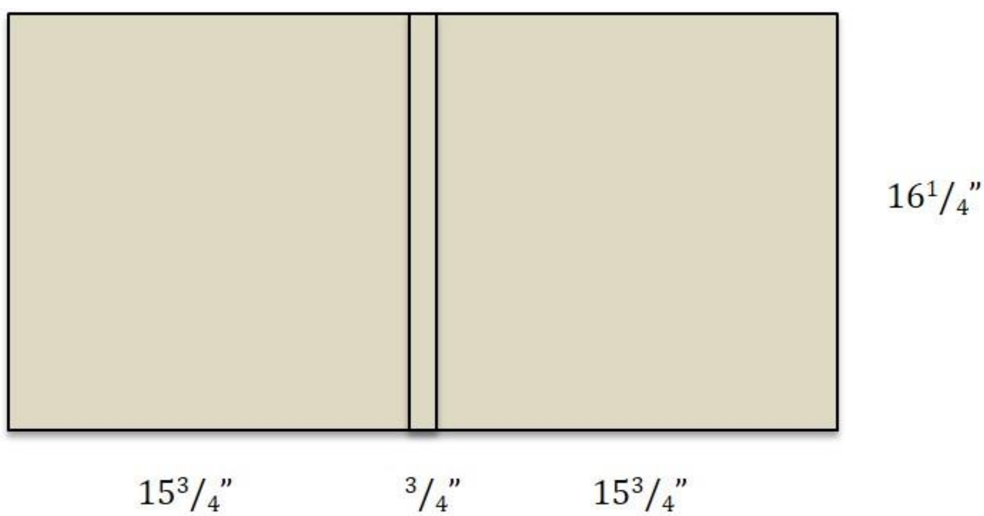

Figure 6. Dimensions of top/bottom/back pieces

Figure 7 shows the dimensions of the end pieces of the containment volume. Figure 8 shows the dimensions of the front side to each containment volume. Figure 9 shows the interior separation pane.

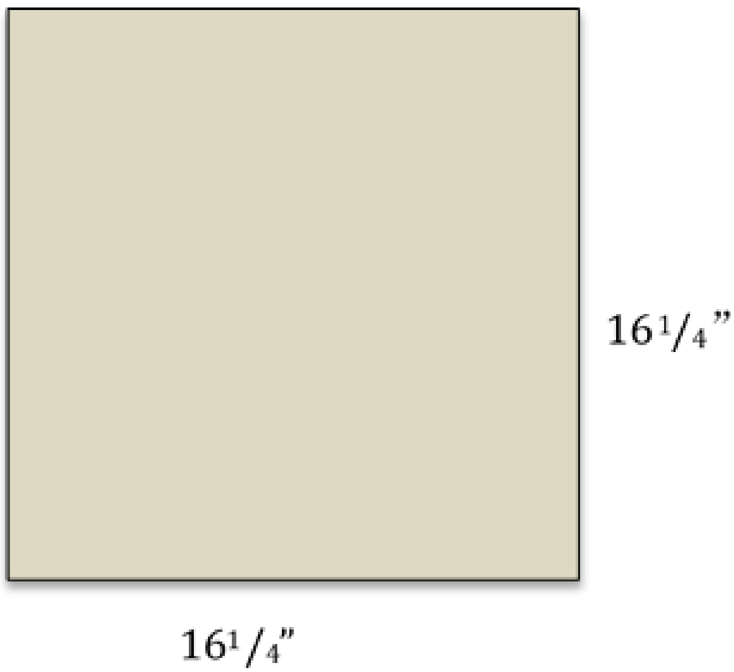

Figure 7. Dimensions of left and right pieces

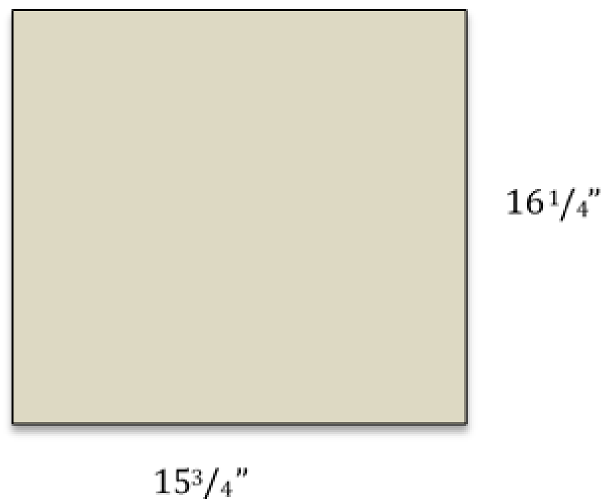

Figure 8. Dimensions of front pieces in both hot and cold sides

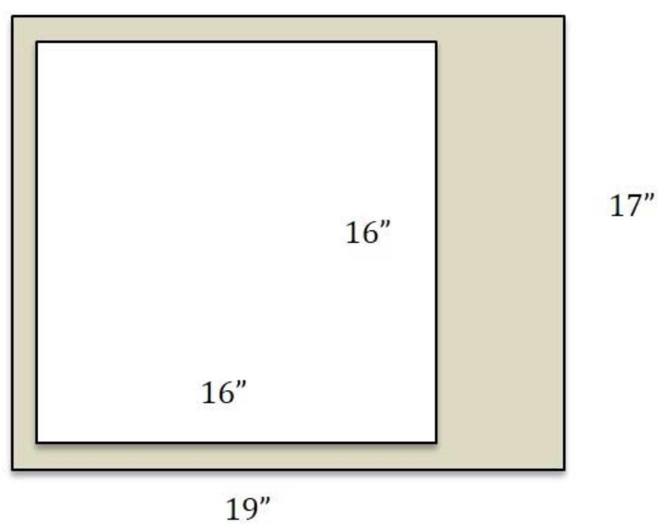

Figure 9. Dimensions of panel installed with the specimen inside

Figure 10 shows that after determining the dimensions of the box, MDF was cut by using the panel saw.

Figure 10. Panel saw used to cut MDF and thermal insulation

Next, all pieces, including the top, bottom, front, back, and the panel were trimmed down accurately using a table saw, refer to Figure 11.

Figure 11. Table saw used to cut MDF, specimens and thermal insulation

The panels used to install the box are shown in Figure 12.

At first, a drill was used to bore a hole at the corner, and then a jigsaw was used to cut the inside area, as shown on Figure 13 and Figure 14. The slot on the middle of the top, back and bottom piece was cut by table saw. The specimens were installed on the panel by using a wood glue.

Figure 12. Panels of the box

Figure 13. Drill with drill bits to bore holes or drive screws

Figure 14. Jigsaw used to cut interior 16 inch square out of the panel

After all pieces were cut appropriately, the box was assembled by wood glue along joints. Finally, everything was fixed tightly with nails by using a nail gun. The back piece was connected with the bottom one at first and then the left and right side piece were connected, followed by the top piece.

The light was installed on the right side piece in the containment A. Two holes at the center of the top piece in both containment A and containment B were bored by drill to accommodate the temperature gauges.

Figure 15 shows the completed box ready for final assembly.

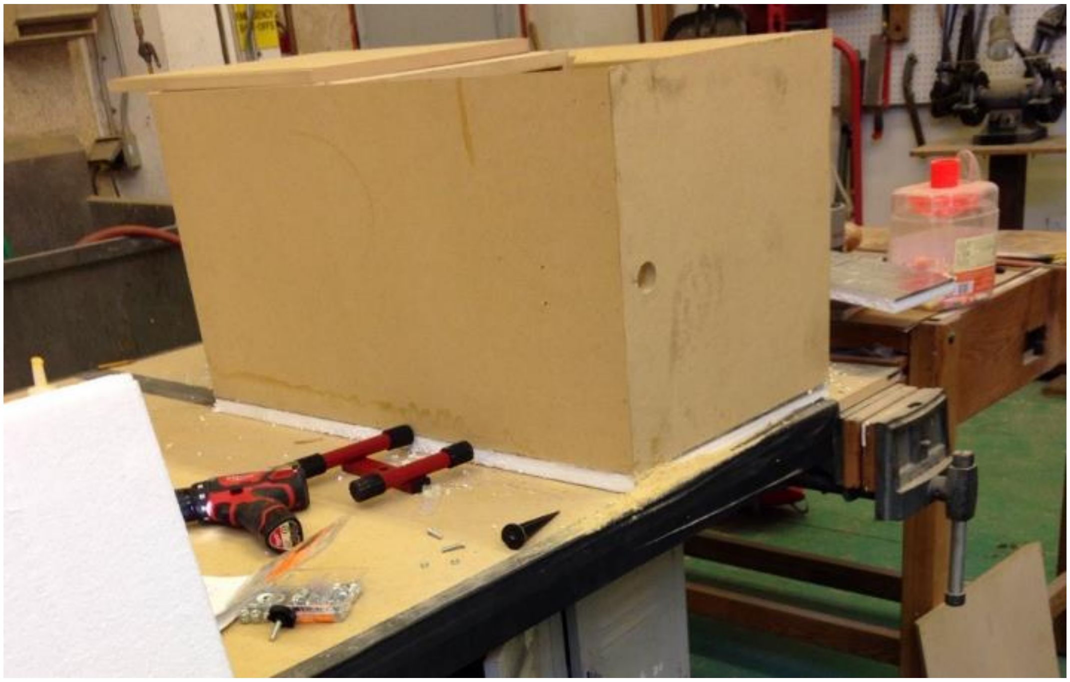

Figure 15. Completed box

Next, all pieces were insulated with thermal insulation outside the box, including the front pieces that were unconnected at that time. The final step was to join the front piece in containment A by wood glue and screws with a drill, refer to Figure 16.

Figure 16. Other tools used-wood glue, temperature sensor and nail gun

Figure 17 and Figure 18 show the separation piece with the test elements in place.

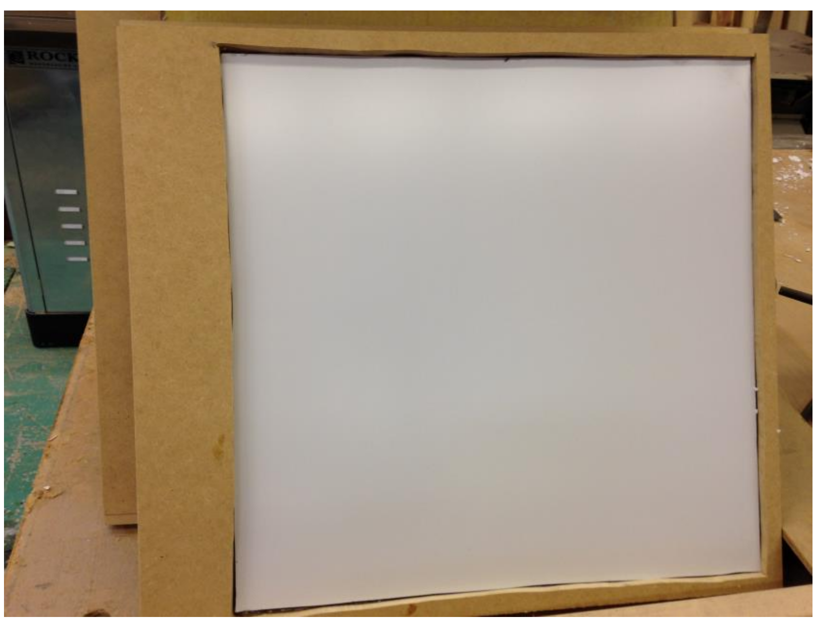

Figure 17. Panel installed with the aluminum composite sheeting

Figure 18. Panel installed with fibre cement board panel

Figure 19 shows the 250 watt light installed in the box. The light is directed away from the test wall so as to provide reasonably uniform heating in the box.

Figure 19. Installed light

Test Procedure

The test procedure for testing specimens A, B and C is:

1. The air inside the box cools down to the outside temperature

2. The box is closed
3. The specimen is inserted into the middle of the box
4. The test will begin with the light turned on and the temperature sensor recording data. The measuring range of the temperature sensor is from 0-70 °C
5. As, the indoor temperature of the residential house above 70 °C is impossible, this was the upper limit for the tests and the analysis. Therefore, when the temperature of both containment A and containment B reaches 70 °C, the test stops
6. After turning off the light and stopping the data recording by the temperature sensor, it will be necessary to uninstall one panel of containment A or B and take the specimen out so as to cool down the inside air as soon as possible

Summary

The test procedure uses a steady increase in the temperature for the measurements instead of a constant temperature.

CHAPTER IV

RESULTS AND ANALYSIS

Introduction

This chapter summarizes the test differences, provides the results for the tests and provides the numerical analysis. Three tests were completed for specimens:

A. Fibre cement panel

B. 3 mm aluminum composite sheeting

C. 6 mm aluminum composite sheeting

Test Specimen A – Test Outline

The specimen for first test was a fibre cement panel. The first test commenced on the 22 January 2016. The test protocol was:

1. The box was put on a table with wheels and then moved outside the woodshop so as to cool down the air inside the box, outside air temperature was in the range of 10-12 ºC compared to the woodshop at 20ºC
2. The interior temperature of the box was measured by temperature sensor and monitored every 10 to 20 minutes, as shown on Figure 20
3. The box was moved back inside when the temperature at a steady state
4. Set the front piece in the cold side to the box by driving screws with a drill, as shown on Figure 21

Figure 20. Box placed outside to cool off

Figure 21. Front piece in cold side installed

5. The center element holding the fibre cement panel was inserted into the box along the slot, as shown in Figure 22

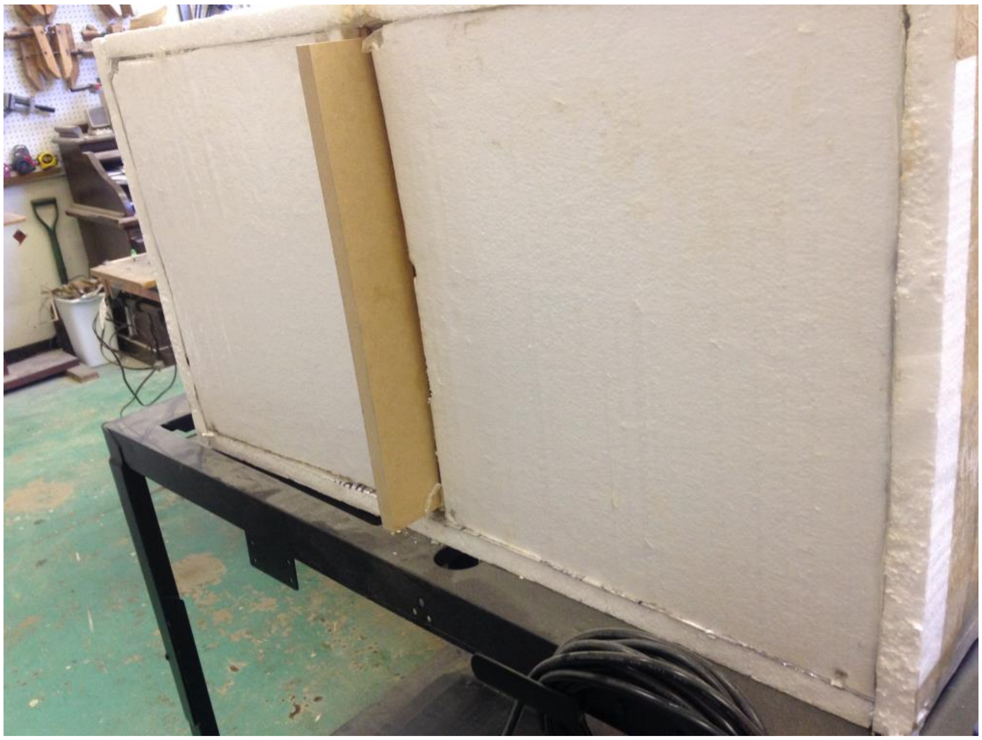

Figure 22. Specimen inserted into the box along the slot

6. Two pieces of insulation were cut to fill small gaps between the panel and the front piece, as shown in Figure 24

7. After setting the time and formatting the SD card of the temperature sensor in both hot side and cold side, the logger button on the sensor was pressed to make it record and save data in the SD card

8. At the same time, the light was turned on

Figure 23. Box in test

9. The first trial began at 10:15:26 am

10. After 24-hours, at 10:15:26 am on January 23, 2016, the experiment was stopped

11. The light was turned off and logger of the temperature sensor was stopped at the same time

12. The front piece of the cold side was extracted along with the center piece with the panel

13. The parts were allowed to cool down along with the inside air before the next trial

14. The final step was to extract the SD card, copy the test data from it to the computer and check the data, as shown in Figure 24

Figure 24. Box after the test

This test was repeated three times. The second trial began at 10:42:29 am on January 26, 2016. The third trial began at 12:29:33 pm on January 27, 2016. All three trials followed the same procedures.

There were no unexpected issues or problems with the first test.

Test Specimen B – Test Outline

The specimen for second test set was a three mm aluminum composite sheeting. The second set of tests commenced on January 28, 2016. The test protocol was identical to the first test series from Stage 1 to 8. However instead of waiting for 24 hours as for the first series, the test protocol was modified so that once both sides reached 70 C the test was terminated, as a result of the temperature limit of the thermometer. Stages 11 to 14 followed the original protocol.

The test was repeated four times. The second trial began at 8:30:35 am on February 1, 2016. The third trial started at 8:56:40 am on February 2, 2016. After three trials there were obvious differences between the results. So a fourth trial was performed at 9:53:16 am on February 10, 2016.

All of the four trials followed the same procedures.

Test Specimen C – Test Outline

The specimen for third test set was a six mm aluminum composite sheeting. The third set of tests commenced on 9:07:21 am on February 3, 2016. The test protocol was identical to the first test series from Stage 1 to 8. However instead of waiting for 24 hours as for the first series, the test protocol was modified so that once both sides reached 70 ºC the test was terminated, as a result of the temperature limit of the thermometer. Stages 11 to 14 followed the original protocol.

The test was repeated three times. The second trial began at 9:06:25 am on February 5, 2016. The third trial started at 9:40:38 am on February 8, 2016. There were no issues with the third test.

All of the three trials followed the same procedures.

Analysis

The standard equation for the measurement of heat flow through a media is presented in equation (1):

$$Q = UA(T_1 - T_2) \tag{1}$$

Where Q is the heat crossing in Watts, U is the thermal transmittance, W/m^{2}K, A is the area of the test surface in m^2, T_1 and T_2 are the hot and cold side respectively and are reported in Celsius for convenience. Squires (2001) provides the methods for the error analysis.

The sides of the test square are 16 ± 0.06 inches or 406 ± 1.5 millimetres, which provides an area of 0.164 ± 0.01 m^2. Q is 250 ± 10 Watts. Equation (1) reduces to:

$$U(T_1 - T_2) = k \tag{2}$$

k is a test constant with a value of 1510 ± 110 W/m^2.

Test Specimen A – Test Results

The thermometer recorded the temperature on each side of the box, the hot and the cold side.

Each of the data files was aligned in time and entered into a single EXCEL spreadsheet. Figure 25 shows the plot for the temperature on the hot and cold sides of the first trial in Specimen A. In the diagram, T1 is the temperature in hot side, and T2 is temperature in cold side. The results indicate that temperature in hot side increased far faster than the temperature in the cold side. The delay time of the cold side reaching 70°C was 17,106s or 4 h 45 min 6 s.

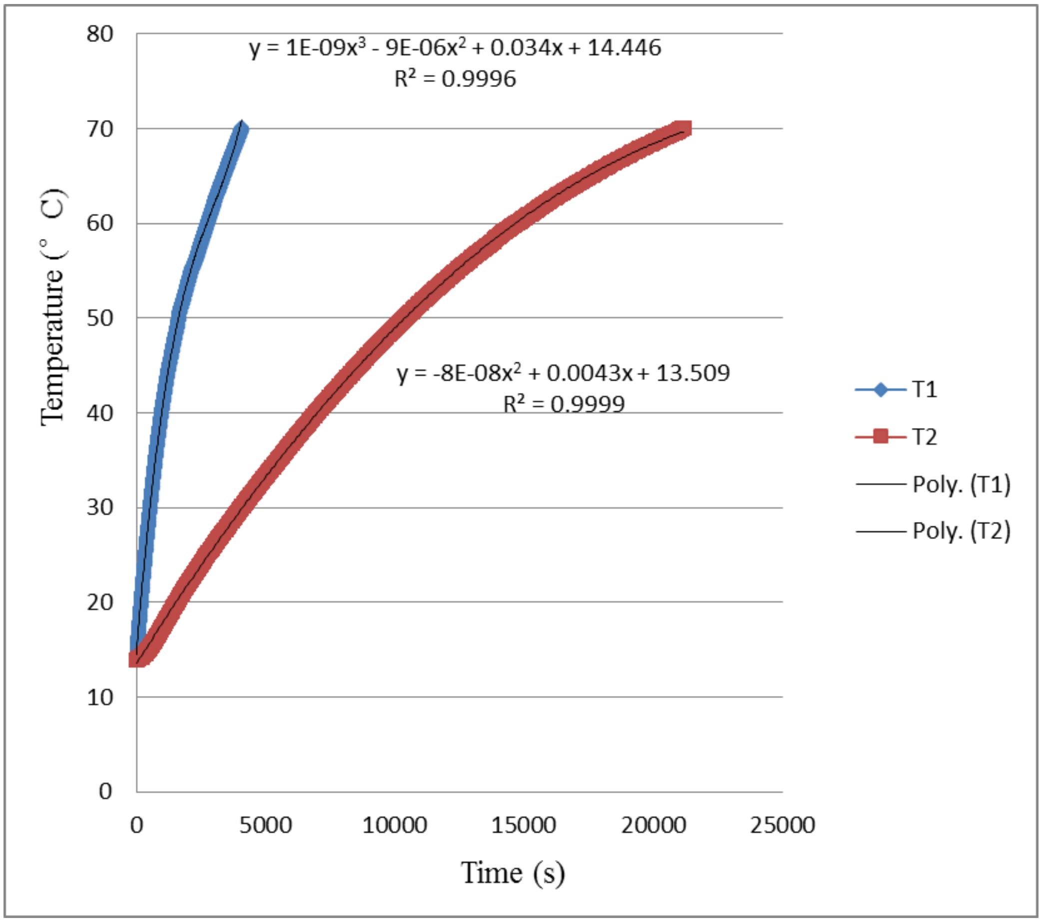

Figure 25. Temperature in both hot and cold sides of the first trial for Specimen A

The hot side had a third order polynomial temperature rise and the cold side had a parabolic temperature rise. Rate of temperature rise was 0.034 ºC/s on the warm and 0.0043 ºC/s on the cool, a ratio of eight. The fibre panel delays the temperature rise significantly. Figure 26 shows the temperature delta for the first test on Specimen A. The time to achieve a 70 ºC temperature on the hot side was 68 minutes. Figure 27 shows a logarithmic plot of the temperature against thermal transmittance

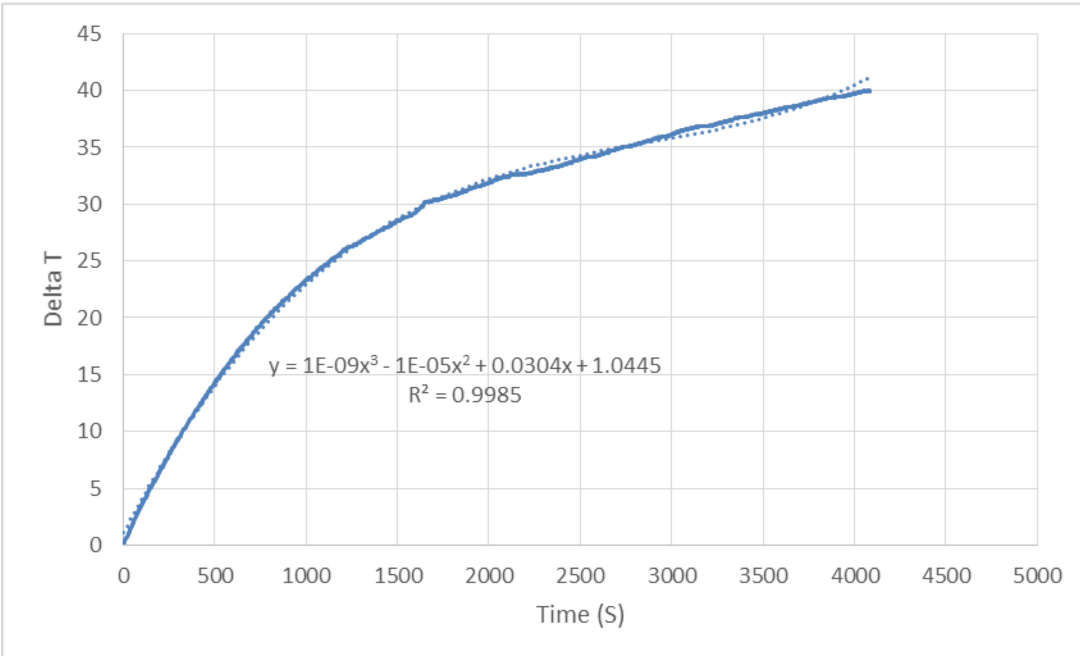

Figure 26. Temperature delta graph for the first trial for Specimen A

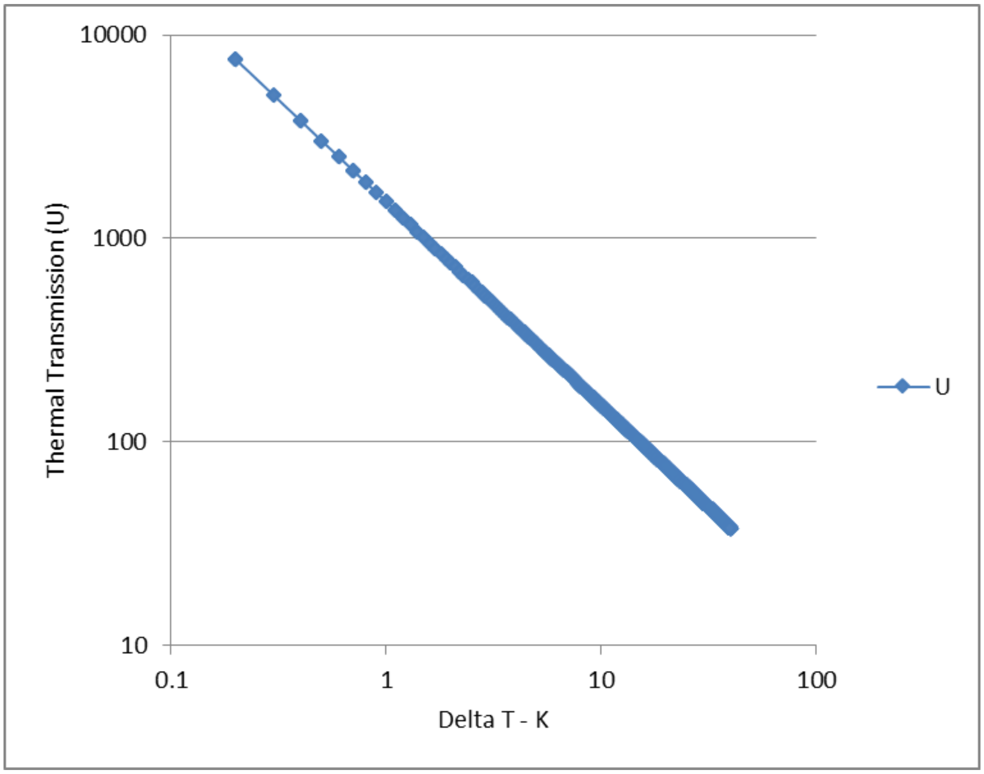

Figure 27. Thermal resistance against Delta T for first trial for Specimen A

The inverse of U is the thermal resistance R. The thermal resistance is clearly a linear equation in temperature and the normal probability plot for the plot of the thermal resistance R against delta T is shown in Figure 28, where the bilinear nature of the system is shown.

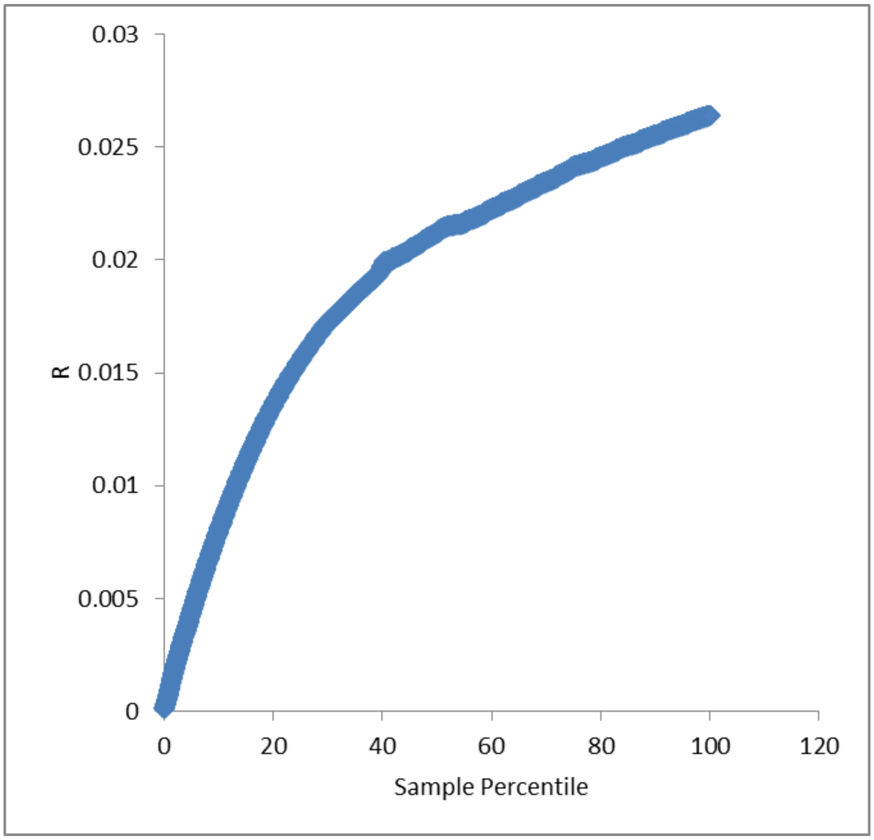

Figure 28. Normal Probability Plot for the Resistance against Delta T for the first trial for Specimen A

Figure 29 shows the temperature rise against time for the hot and cold side for the second trial for Specimen A. Rate of temperature rise was 0.0342 ºC/s on the warm and 0.0042 ºC/s on the cool, a ratio of 8.1.The delay time of cold side reaching 70°C was 16,046 s or 4 h 27 min 26 s.

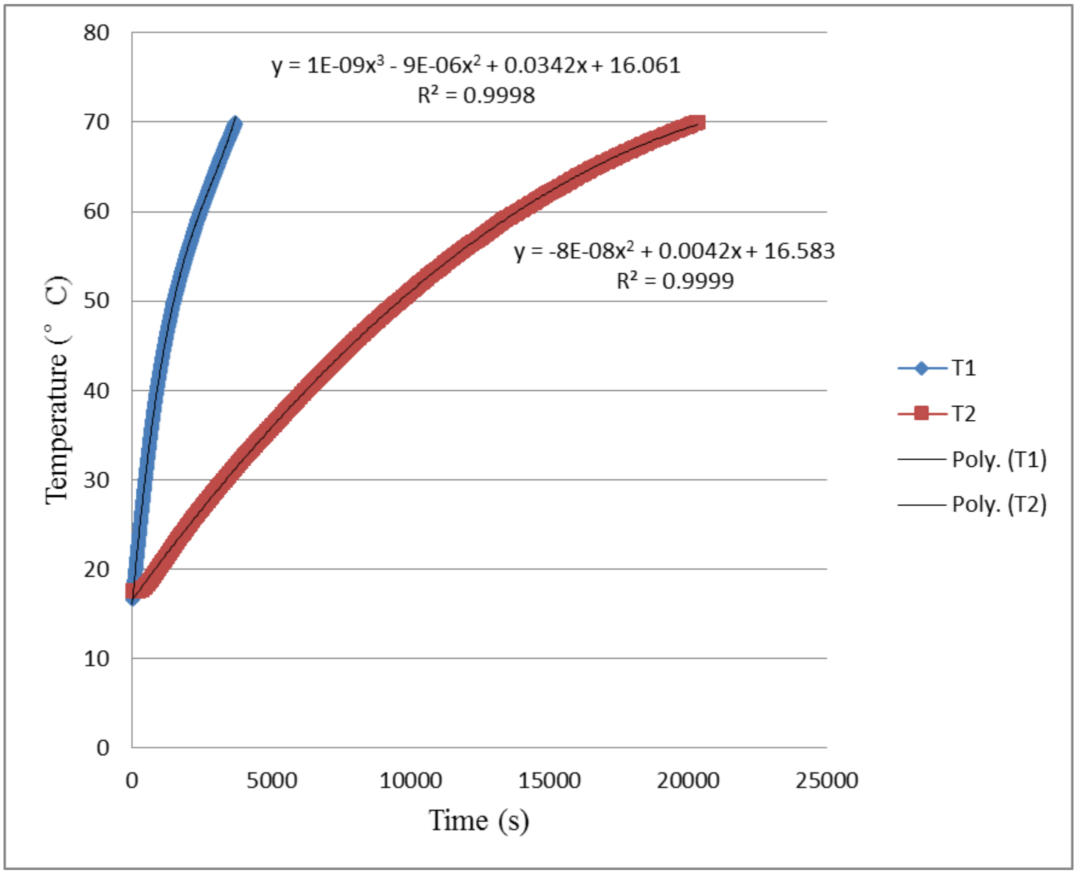

Figure 29. Temperature in both hot and cold sides of the second trial for Specimen A

Figure 30 shows the temperature delta graph for the second trial on Specimen A.

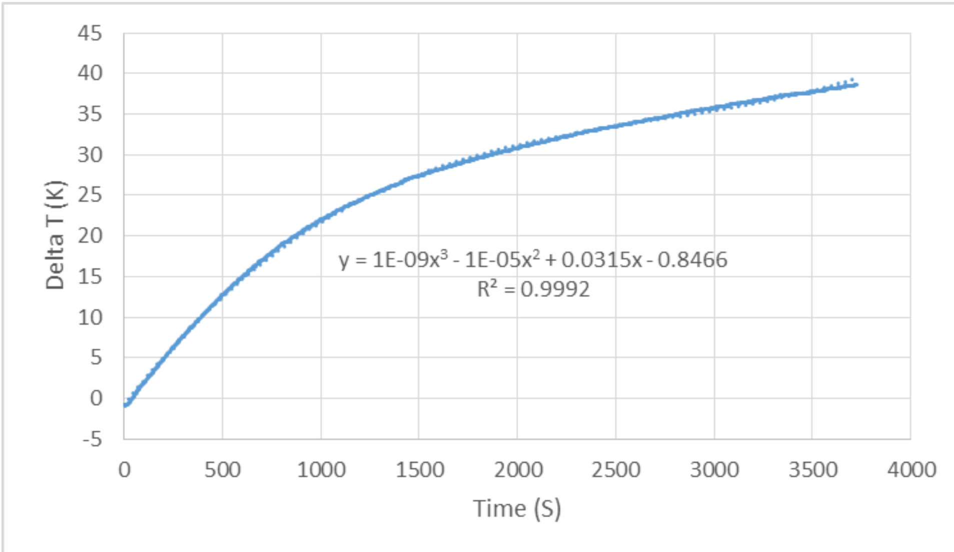

Figure 30. Temperature delta graph for the second trial for Specimen A

Figure 31 shows the temperature rise on the cold and the hot side for the third trail for specimen A. The delay time of cold side reaching 70°C was 14,273s or 3h 57min 53s.

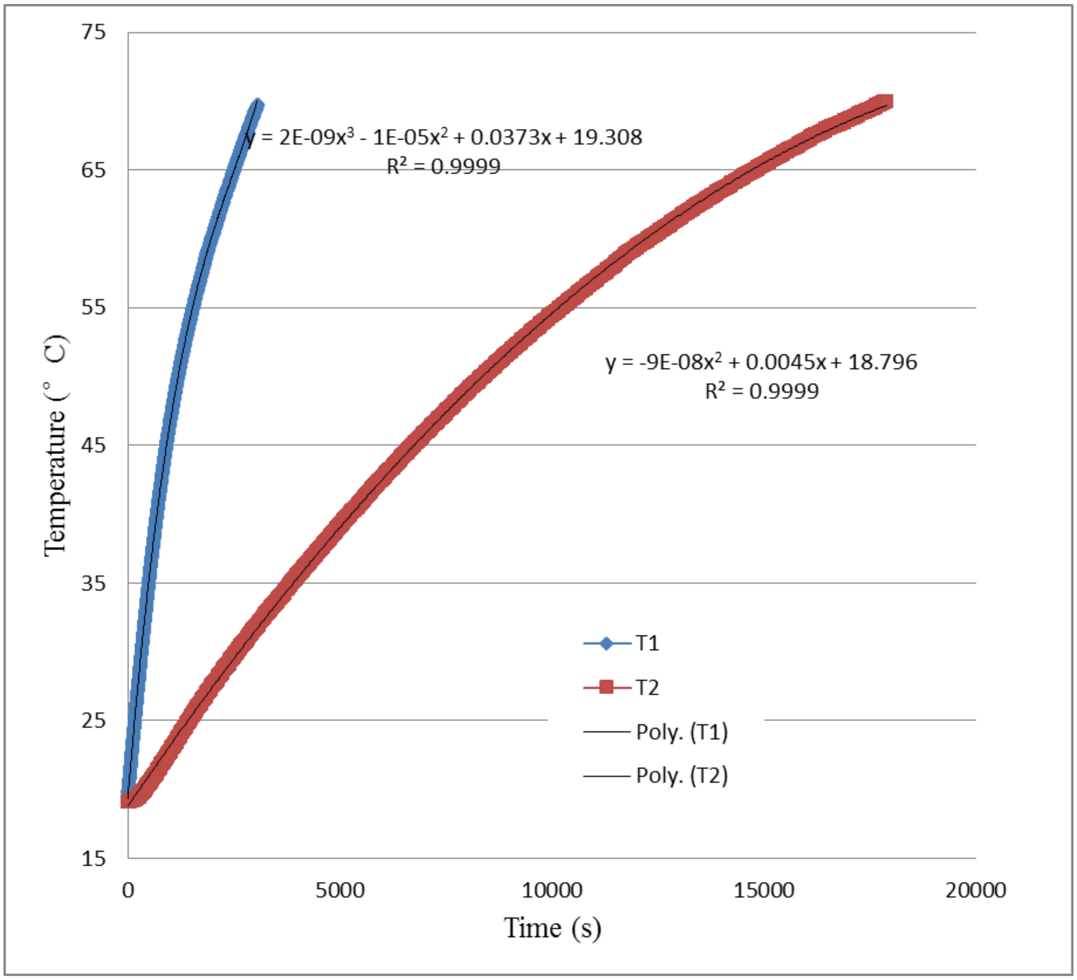

Figure 31. Temperature in both hot and cold sides of the third trial for Specimen A

Figure 32 shows the temperature delta graph for the third trial on Specimen A.

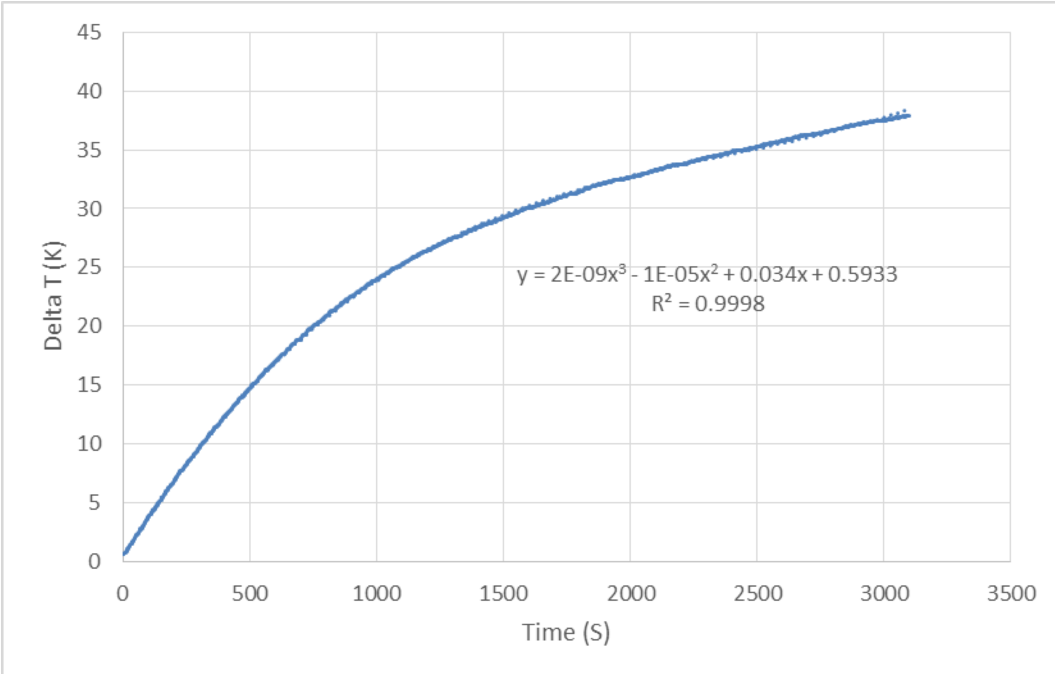

Figure 32. Temperature delta graph for the third trial for Specimen A

The rise to time for the temperature to reach 70 ºC on the cold side is shown in Table 4.

Table 4.

Temperature Rise Time Specimen A

Test	Time to Seventy Degrees – Cold Side
1	17,106
2	16,046
3	14,273

It would appear evident from Table 4 that the material is degrading as the temperature is cycled through the tests. The temperature on the hot side will be significantly above 70 ºC at the end of the test.

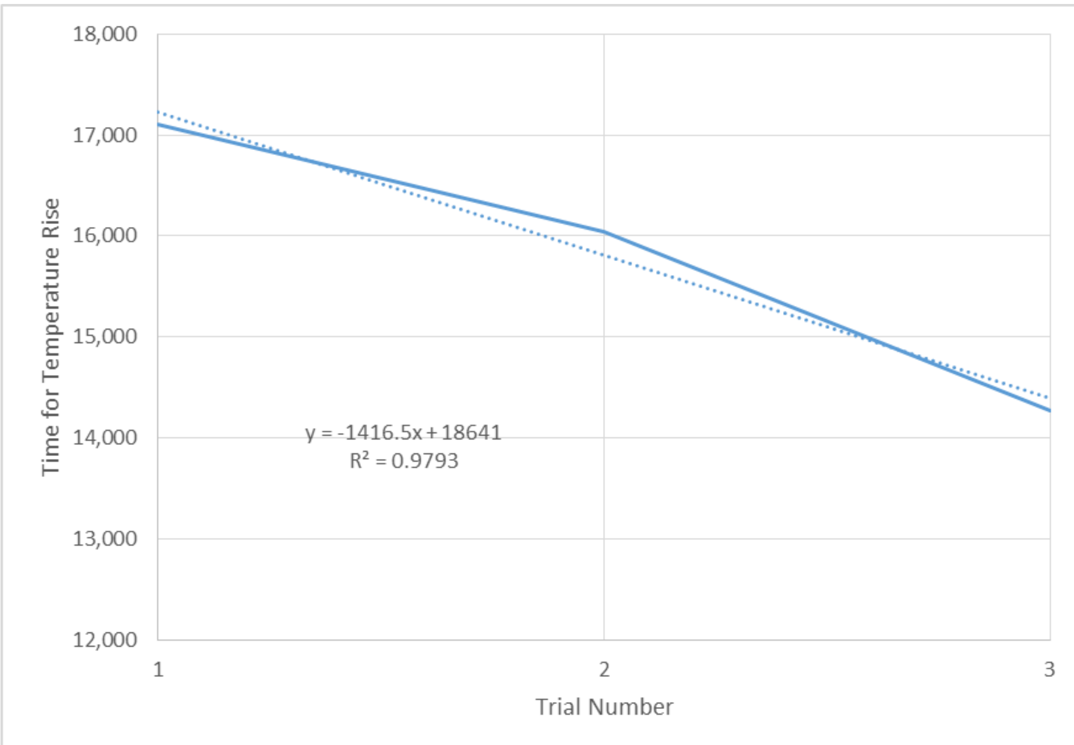

Figure 33. Time to 70 ºC for three trials for Specimen A

A linear regression analysis shows that the results are significant at the 10% level and the material appears to be degrading as the temperature cycles.

Figure 34 indicates temperature in both hot and cold side of three trials for Specimen A as well as their average temperature in both sides. In the diagram, Tha is the average temperature of three trials of the hot side and Tca is the average temperature of three trials of the cold side.

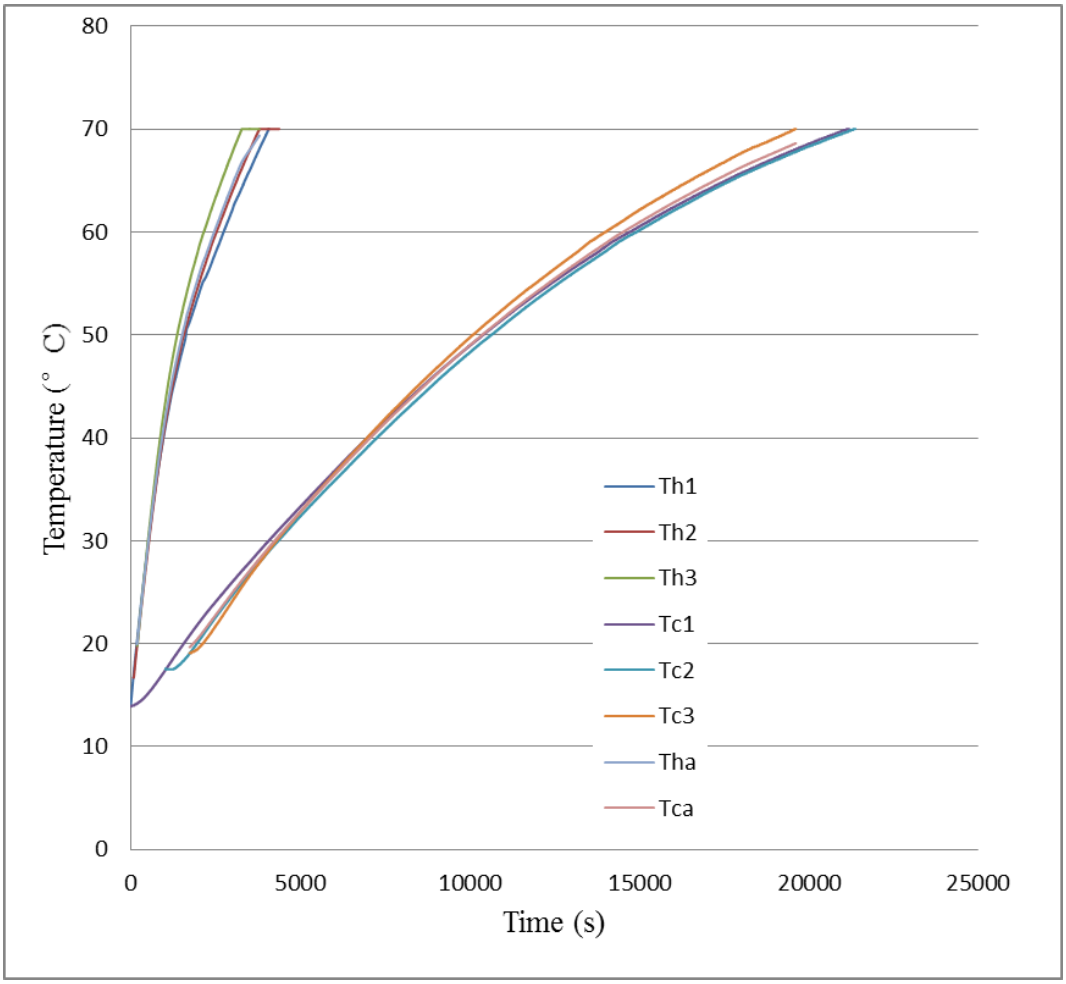

Figure 34. Temperature in both hot and cold sides for all tests for Specimen A

Test Specimen B – Test Results

Specimen B was 3mm aluminum composite sheeting. Figure 35 shows the temperature in both hot and cold sides of the first trial for Specimen B. In the diagram, T1 is temperature in the hot side and T2 is temperature in the cold side. The delay time of the cold side reaching 70°C was 14,253 s or 3 h 57 min 33 s.

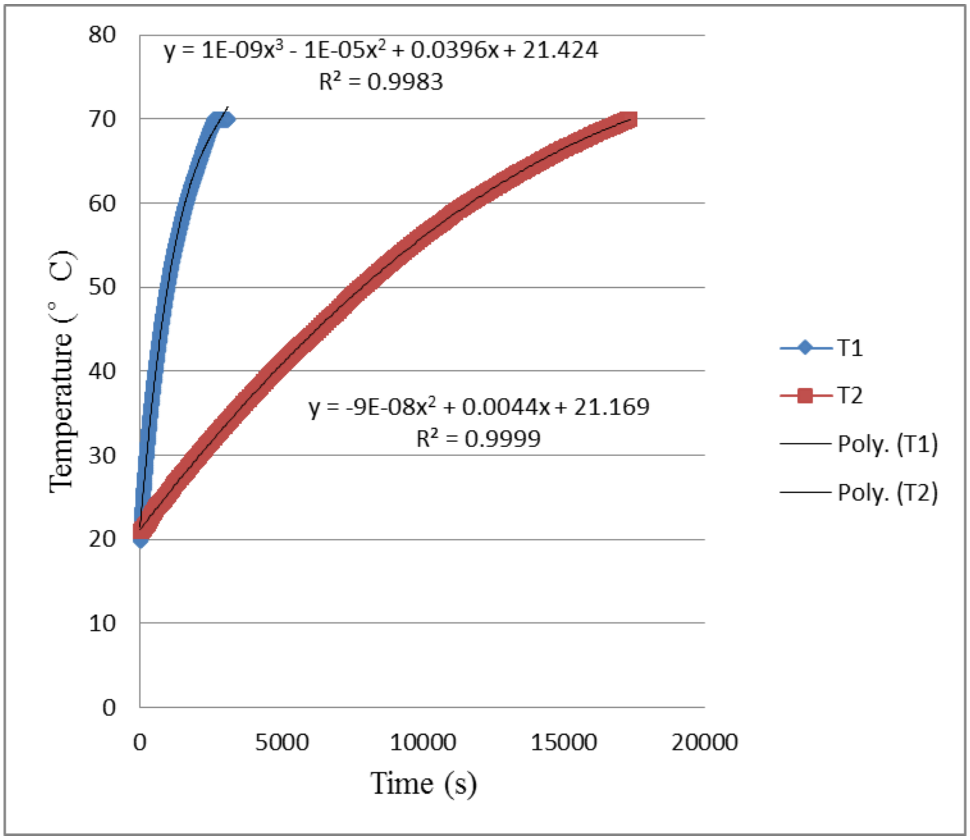

Figure 35. Temperature in both hot and cold sides of the first trial for Specimen B

Figure 36 shows the temperature delta graph for the first trial for Specimen B.

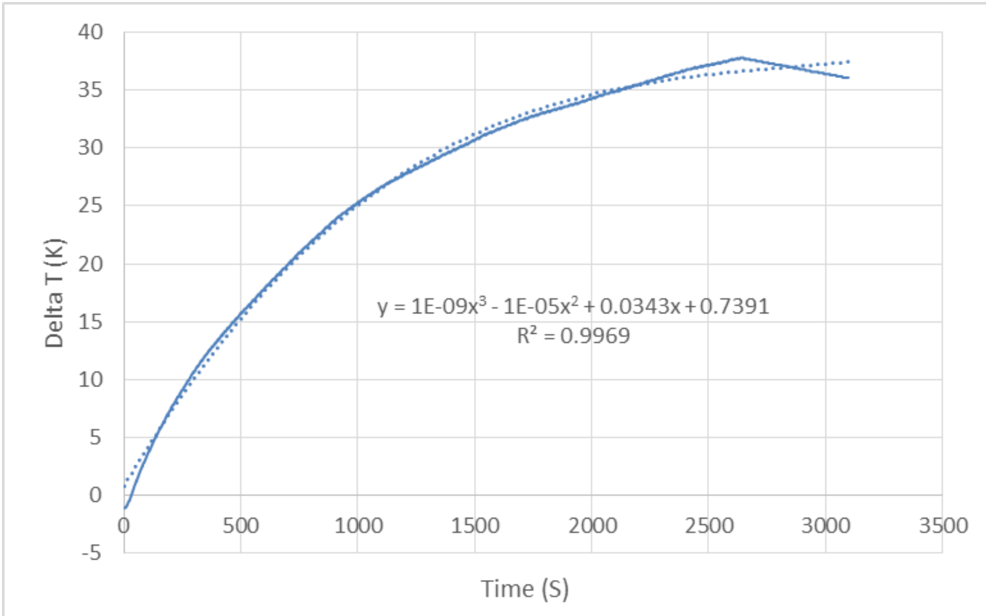

Figure 36. Temperature delta graph for the first trial for Specimen B

Figure 37 shows the temperature in both the hot and cold side of the second trial in Specimen B. Similarly, T1 is the temperature in the hot side and T2 is the temperature in the cold side. The delay time of the cold side reaching 70°C was 20,999 s or 5h 49 min 59 s.

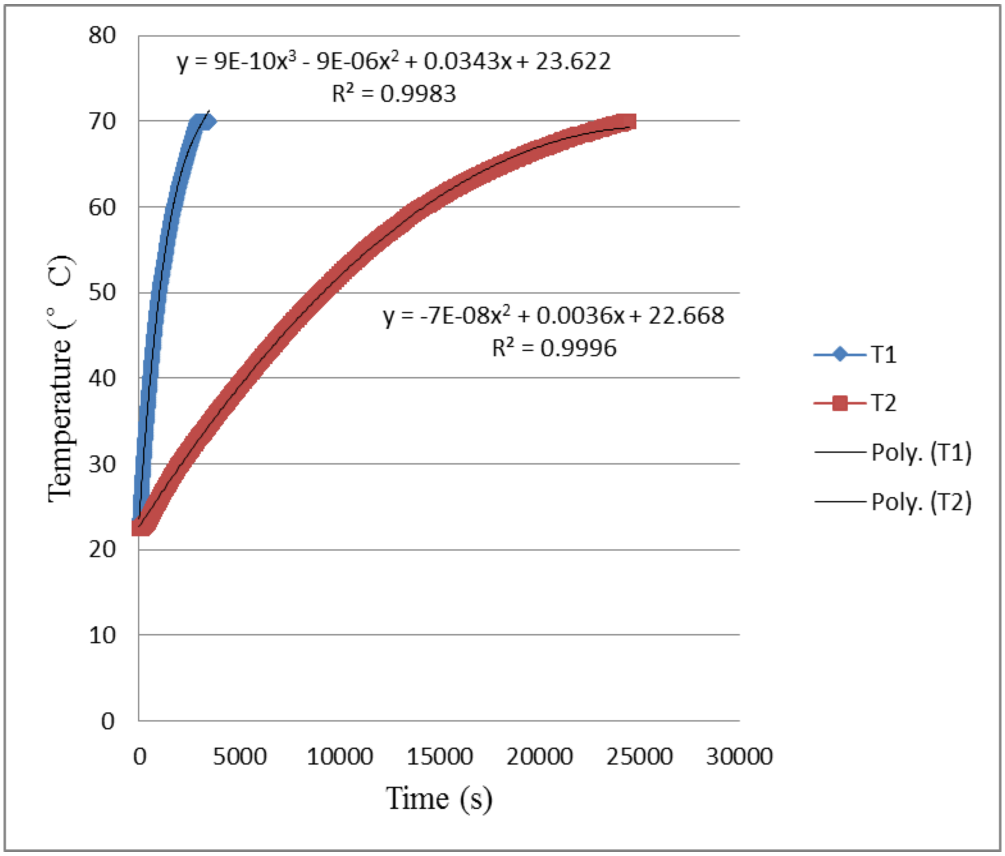

Figure 37. Temperature in both hot and cold sides of the second trial for Specimen B

Figure 38 shows the temperature delta graph for the second trial for Specimen B.

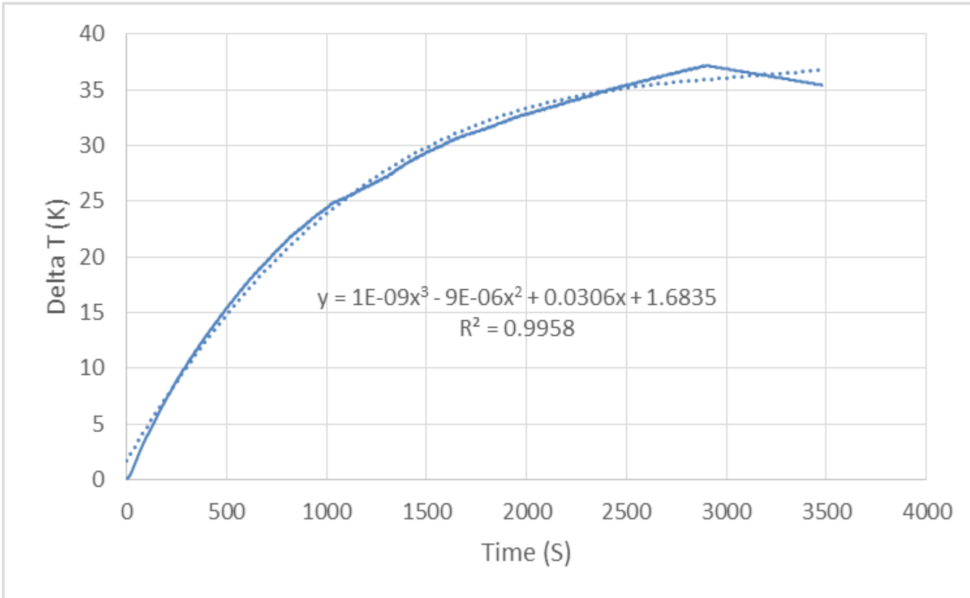

Figure 38. Temperature delta graph for the second trial for Specimen B

Figure 39 presents the temperature in both the hot and cold sides of the third trial for Specimen B. The delay time of the cold side reaching 70°C was 8,330 s or 2 h 18 min50 s.

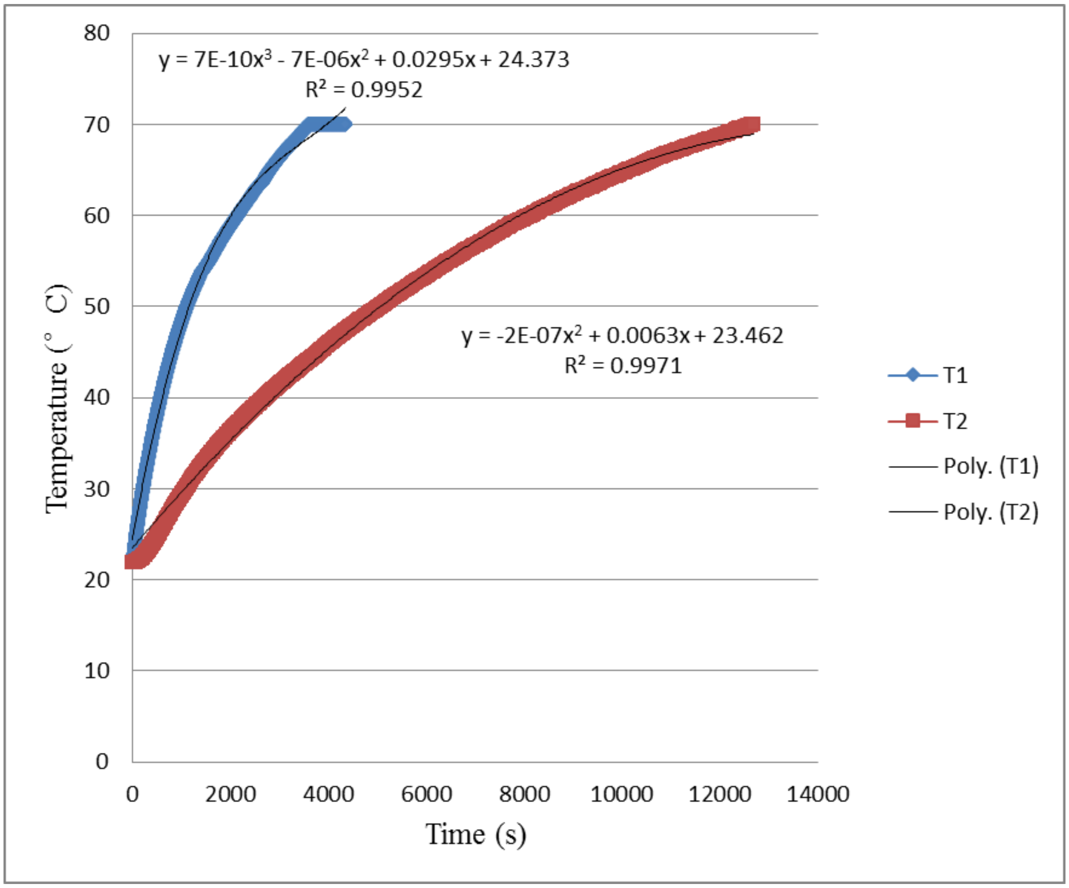

Figure 39. Temperature in both hot and cold sides of the third trial in test #2

Figure 40 shows the temperature delta graph for the third trial for Specimen B.

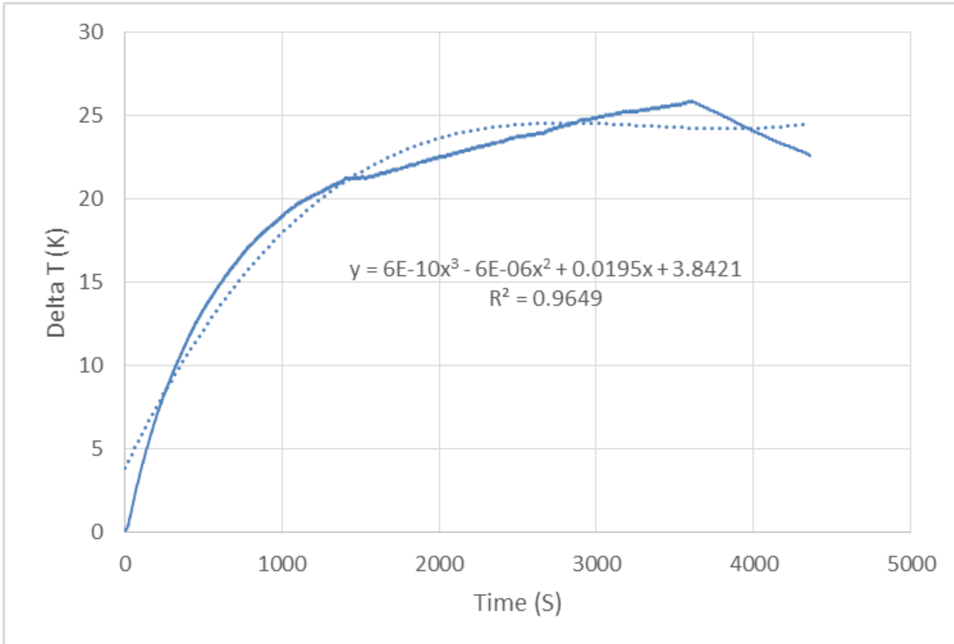

Figure 40. Temperature delta graph for the third trial for Specimen B

Figure 41 presents the temperature in both the hot and cold sides of the fourth trial for Specimen B. The delay time of the cold side reaching 70°C was 6859s or 1h 54 min 19s.

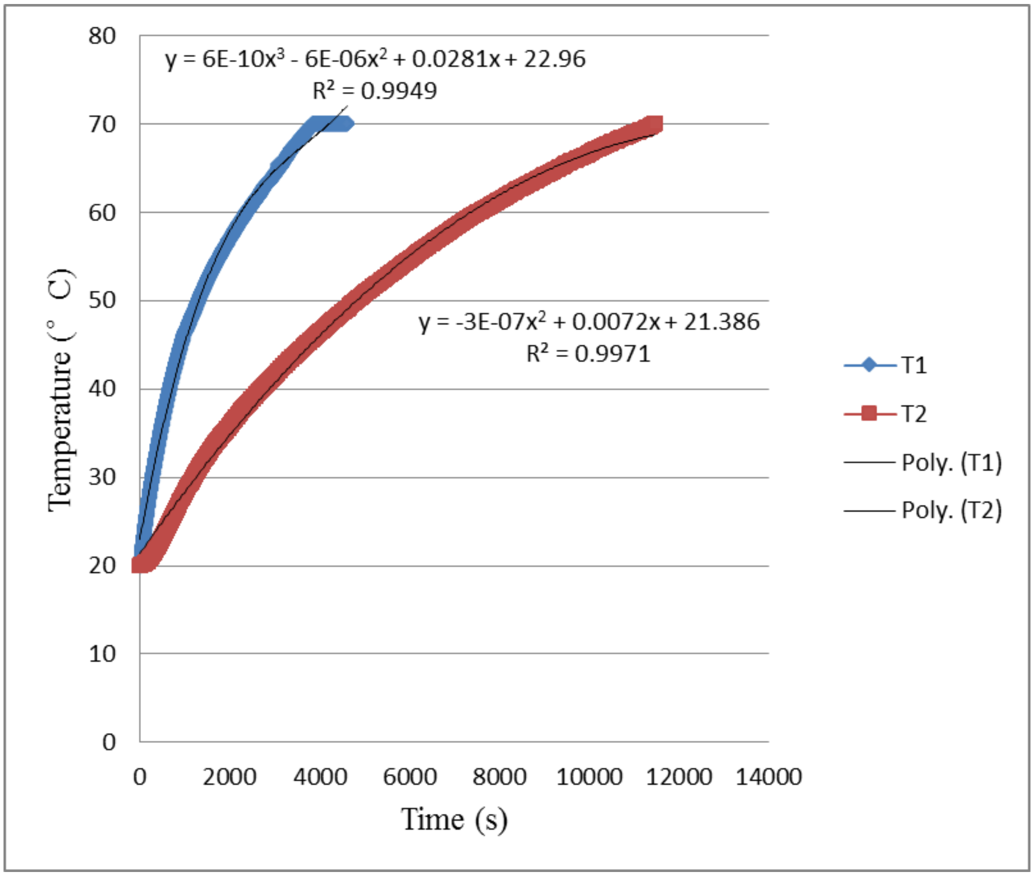

Figure 41. Temperature in both hot and cold sides of the fourth trial in Specimen B

Figure 42 shows the temperature delta graph for the fourth trial for Specimen B.

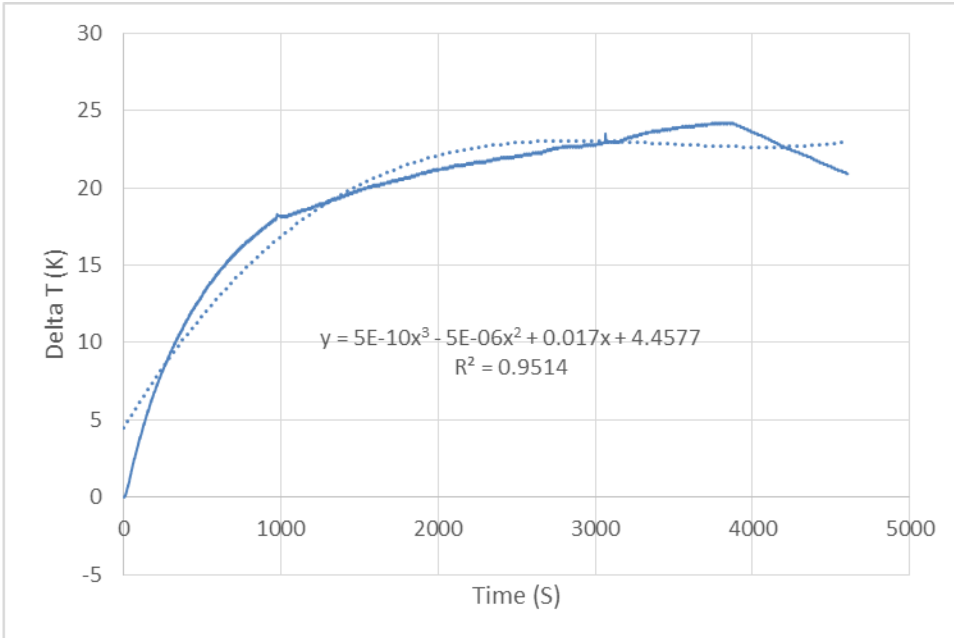

Figure 42. Temperature delta graph for the fourth trial for Specimen B

Table 5 shows the time to achieve 70ºC temperature on cold side for the four trials.

Table 5.

Temperature Rise Time Specimen B

Test	Time to Seventy Degrees – Cold Side
1	14,253
2	20,999
3	8,330
4	6859

It would appear somewhat evident from Table 5 that the material is degrading as the temperature is cycled through the tests. The temperature on the hot side will be significantly above 70 ºC at the end of the test.

Figure 43 shows the plot of the times for the four trials for Specimen B for the cold side to reach 70ºC.

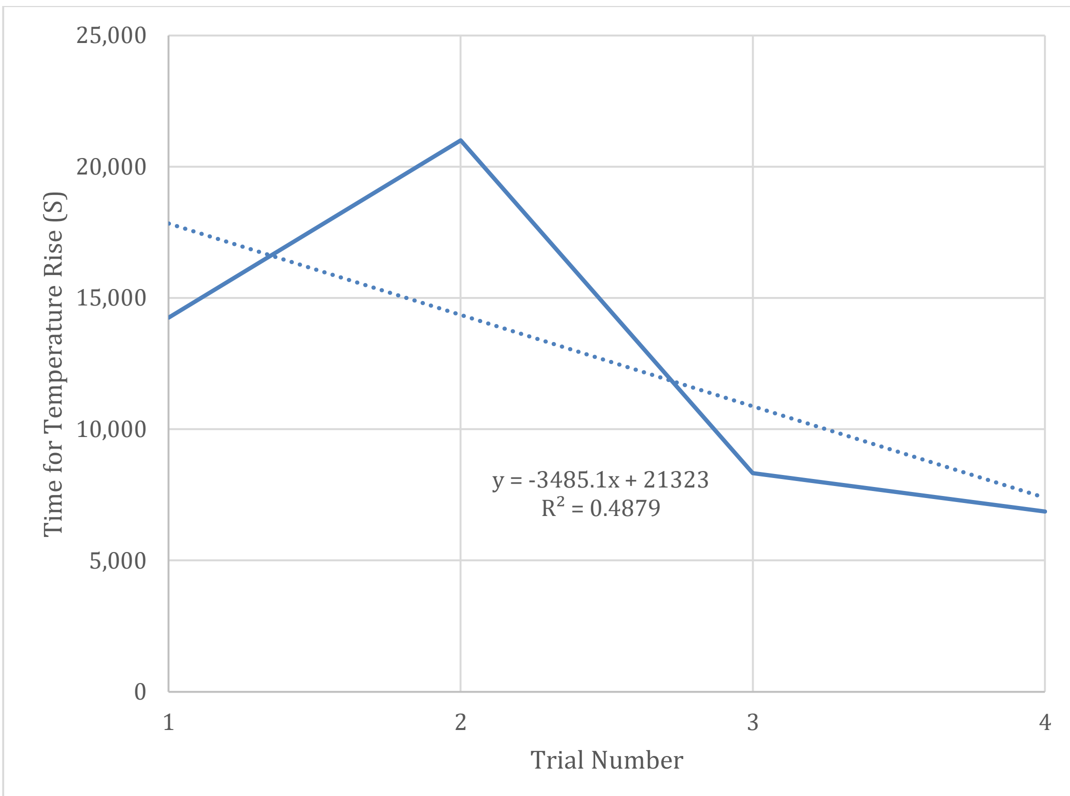

Figure 43. Time to 70 ºC for four trials for Specimen B

Figure 44 shows the results for Specimen A and B to reach 70 ºC in the cold side for the total of 7 trials. The second trial on Specimen B is unusual, which is the reason for the fourth trial. Aside from this trial the materials appear to degrade with temperature cycles in terms of their thermal resistance.

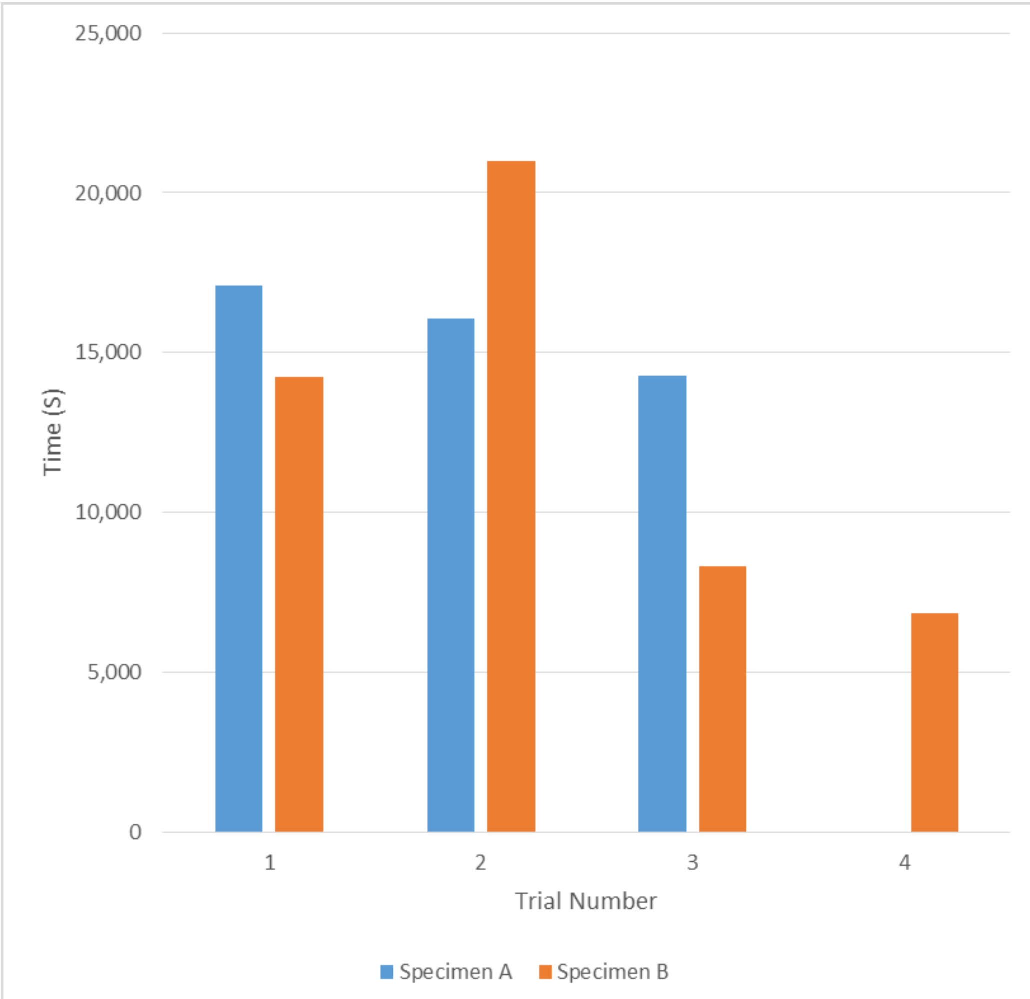

Figure 44. Histogram of the time to 70 ºC for trials for Specimen A and Specimen B

Figure 45 indicates the temperature in both the hot and cold sides of four trials in test #2, as well as the average temperature in both sides. In the diagram, Tha is the average temperature of four trials in the hot side and Tca is the average temperature of four trials in the cold side.

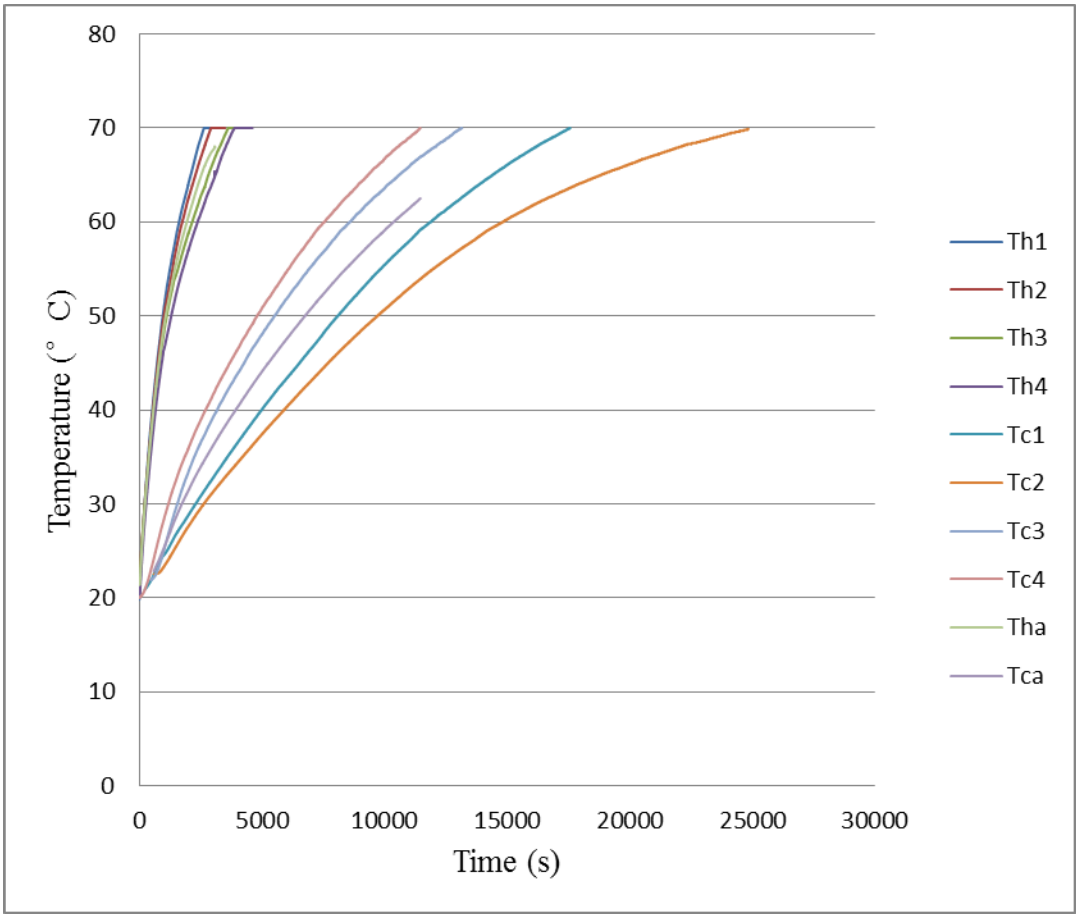

Figure 45. Temperature in both hot and cold sides for Specimen B

Test Specimen C – Test Results

Specimen C was 6mm aluminum composite sheeting. Figure 46 shows temperature in both the hot and cold sides of the first trial for Specimen C. In the diagram, T1 is temperature in the hot side and T2 is temperature in the cold side. The delay time of the cold side reaching 70°C was 14405 s or 4 h 5 s.

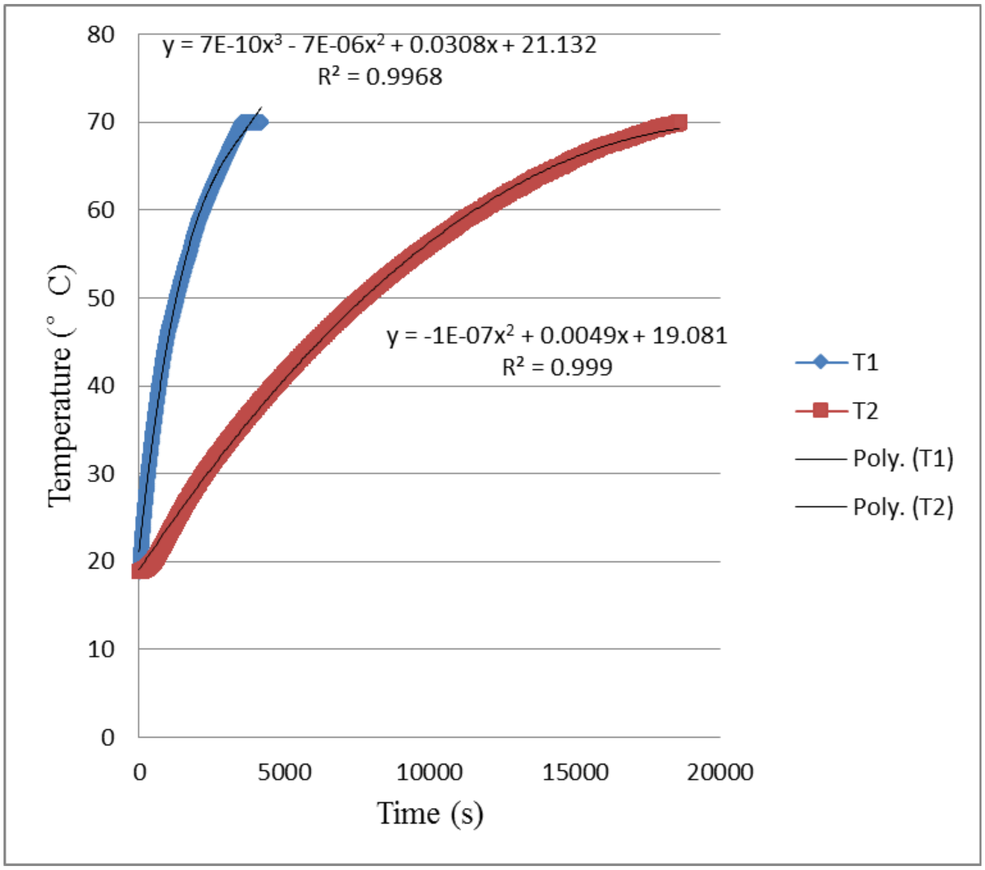

Figure 46. Temperature in both hot and cold sides of the first trial for Specimen C

Figure 47 shows the temperature delta graph for the fourth trial for Specimen C.

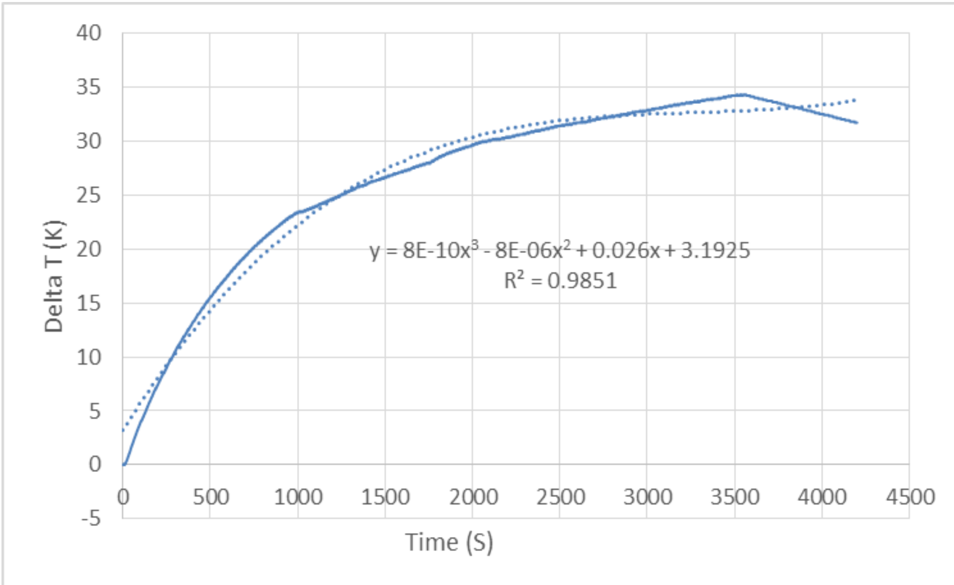

Figure 47. Temperature delta graph for the first trial for Specimen C

Figure 48 shows the temperature in both the hot and cold sides of the second trial in test #3. T1 is the temperature in the hot side and T2 is the temperature in the cold side. The delay time of cold side reaching 70°C was 21655 s or 6 h 55 s.

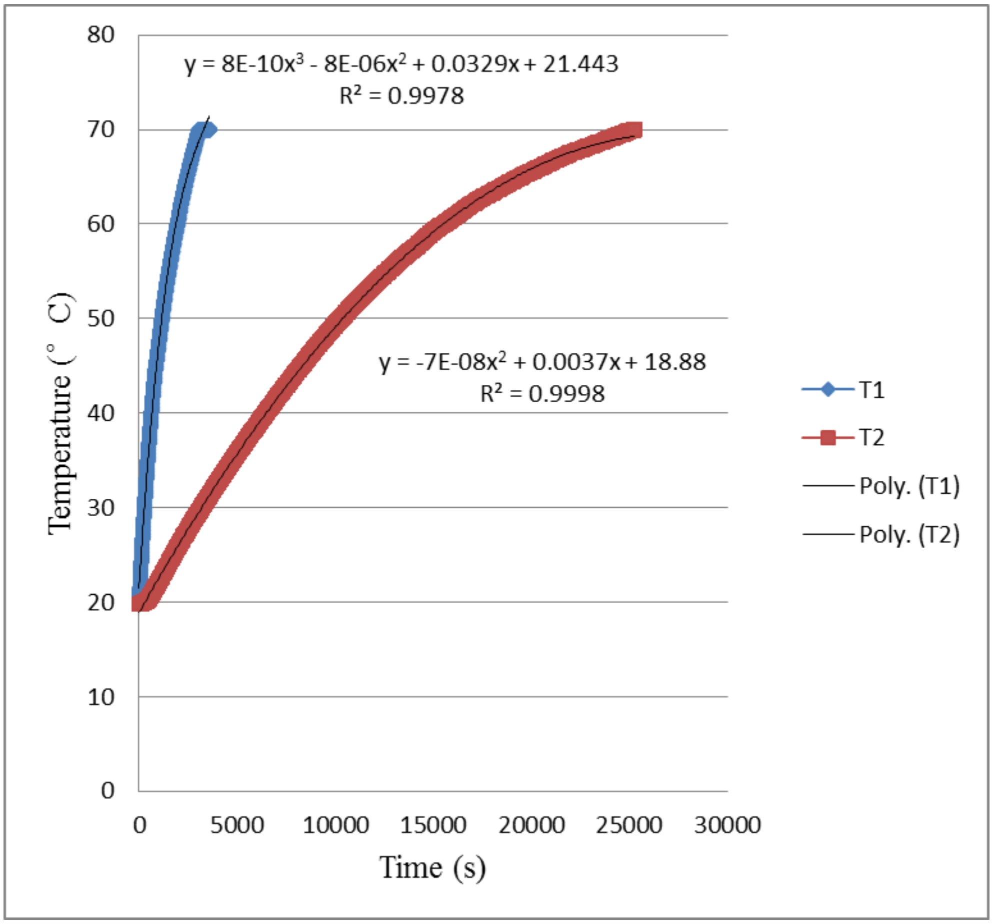

Figure 48. Temperature in both hot and cold sides of the second trial Specimen C

Figure 49 shows the temperature delta graph for the second trial for Specimen C.

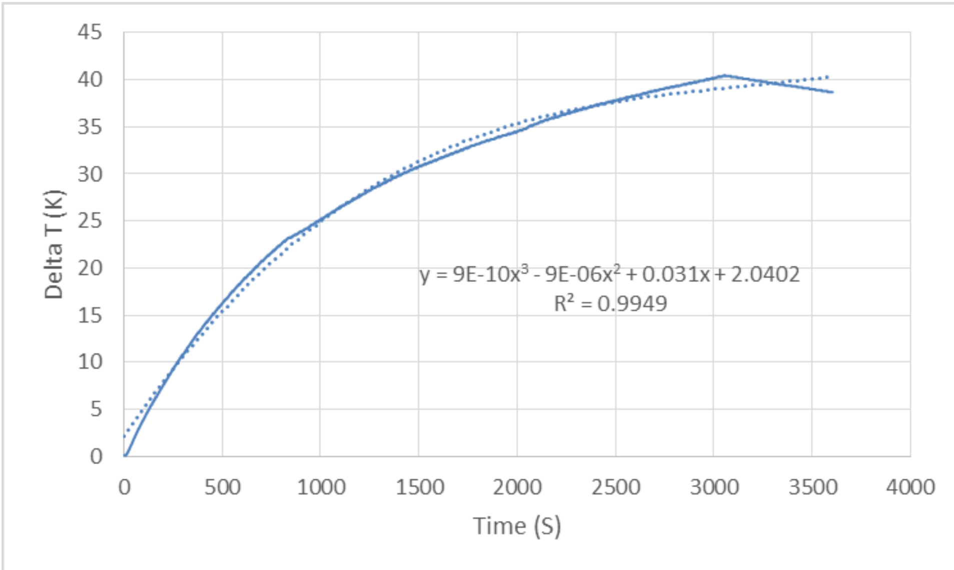

Figure 49. Temperature delta graph for the second trial for Specimen C

Figure 50 presents temperature in both the hot and cold sides of the third trial for Specimen C. T1 is the temperature in the hot side and T2 is the temperature in the cold side. The delay time of the cold side reaching 70°C was 23 888 s or 6 h 38 min 8 s.

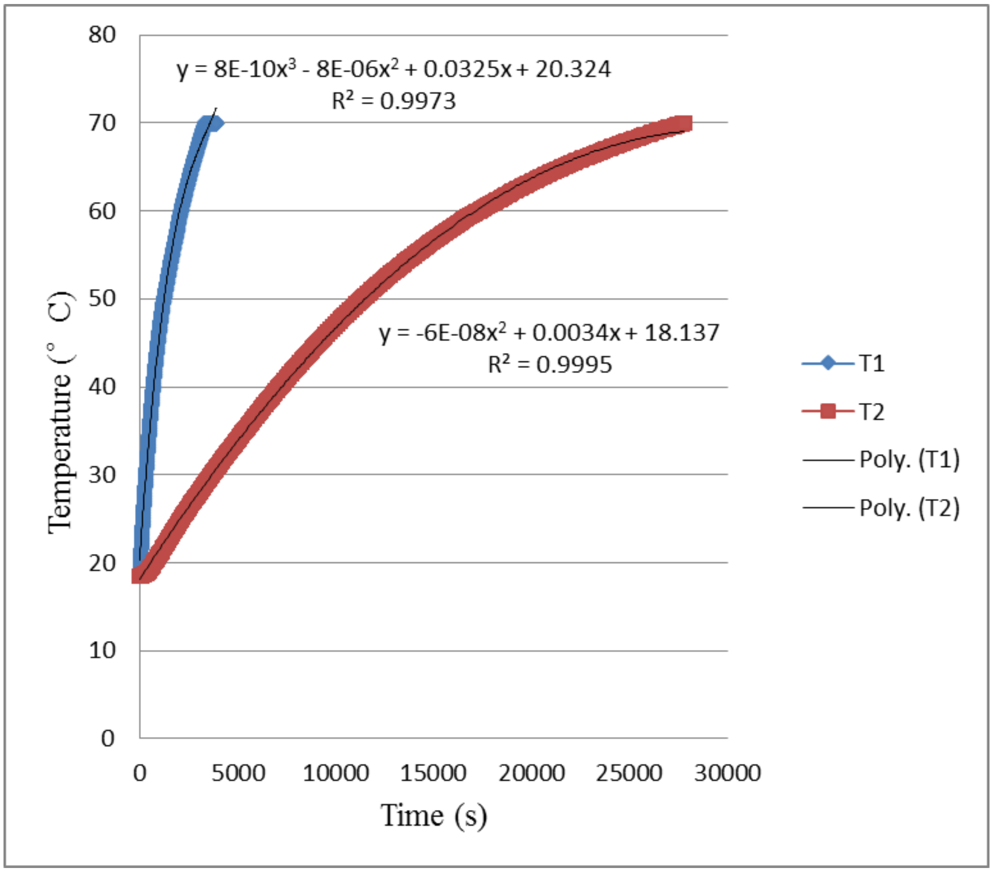

Figure 50. Temperature in both hot and cold sides of the third trial for Specimen C

Figure 51 shows the temperature delta graph for the fourth trial for Specimen B.

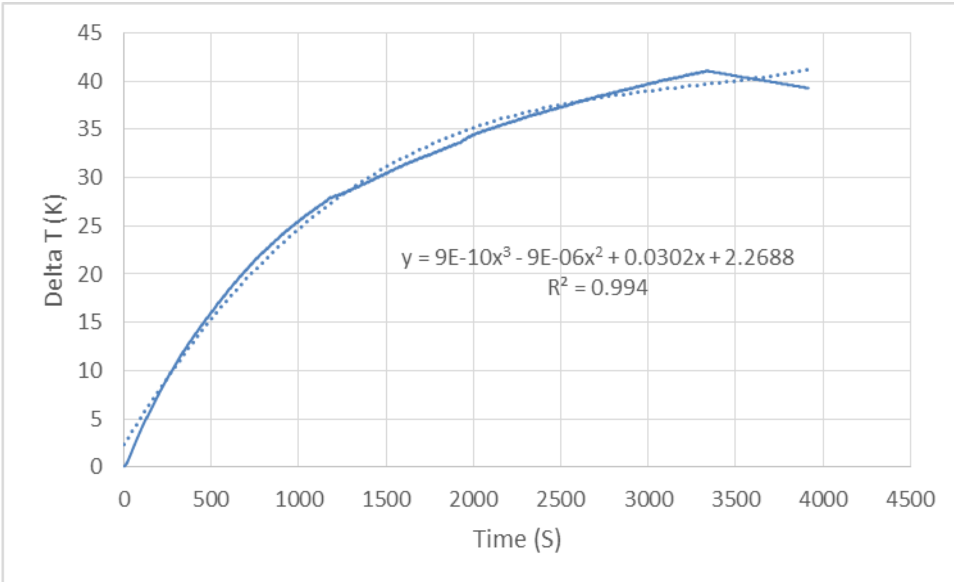

Figure 51. Temperature delta graph for the third trial for Specimen C

Table 5 shows the time to achieve 70 ºC temperature on cold side for the three trials in Specimen C.

Table 6.

Temperature Rise Time Specimen C

Test	Time to Seventy Degrees – Cold Side
1	14405
2	21655
3	23888

It would appear evident from Table 6that the material is not thermally degrading as the temperature is cycled through the tests. The temperature on the hot side will be significantly above 70 ºC at the end of the test. *Figure 52* shows the plot of the time for the three tests to reach 70 ºC on the cold side.

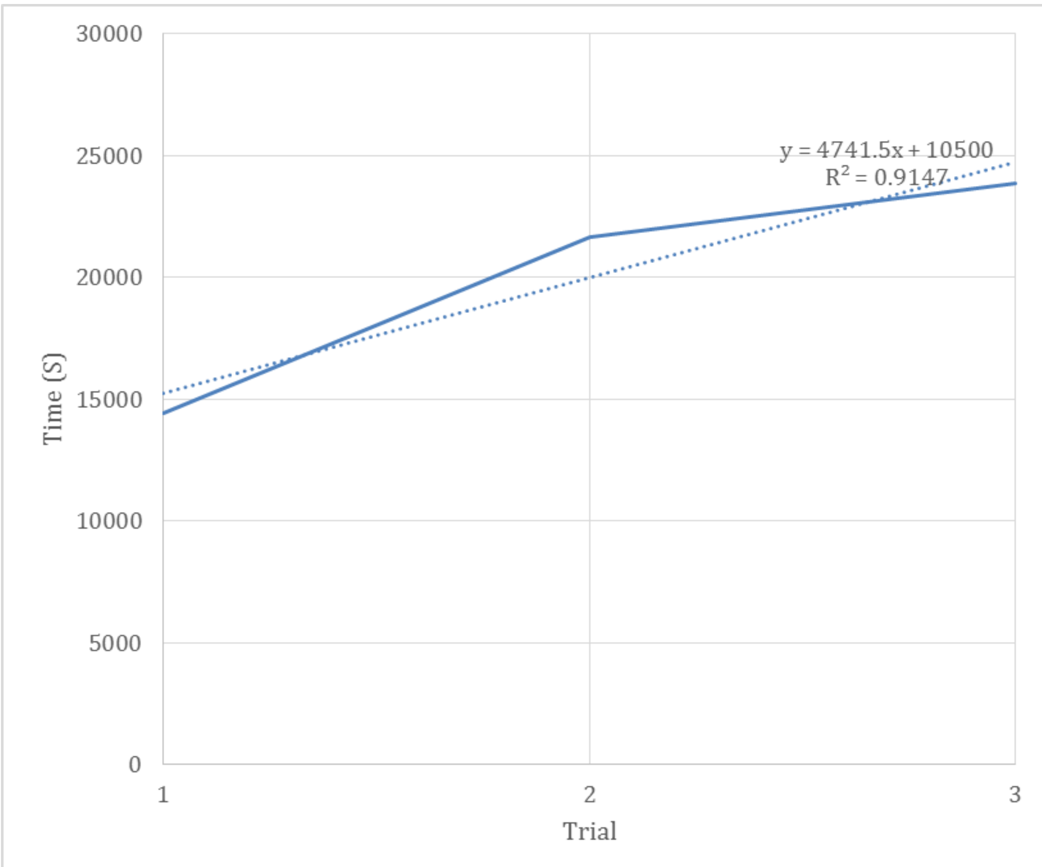

Figure 52. Time for the cold side to reach 70 ºC for Specimen C

Figure 53 indicates the temperature in both the hot and cold sides of three trials for Specimen C as well as the average temperature in both sides. In the diagram, Tha is the average temperature of three trials in hot side and Tca is the average temperature of three trials in cold side. The delay time of the cold side reaching 70°C in the second trial is close to the delay time in the third trial. However, the delay time in the first trial is notably shorter than the delay time in the second and third trial. In addition, in the following diagram, we can see that Tc1 diverges from Tc2 and Tc3. Tc2 and Tc3 are almost in the same line. Generally, 6mm aluminum composite sheeting seems to have a stable thermal property.

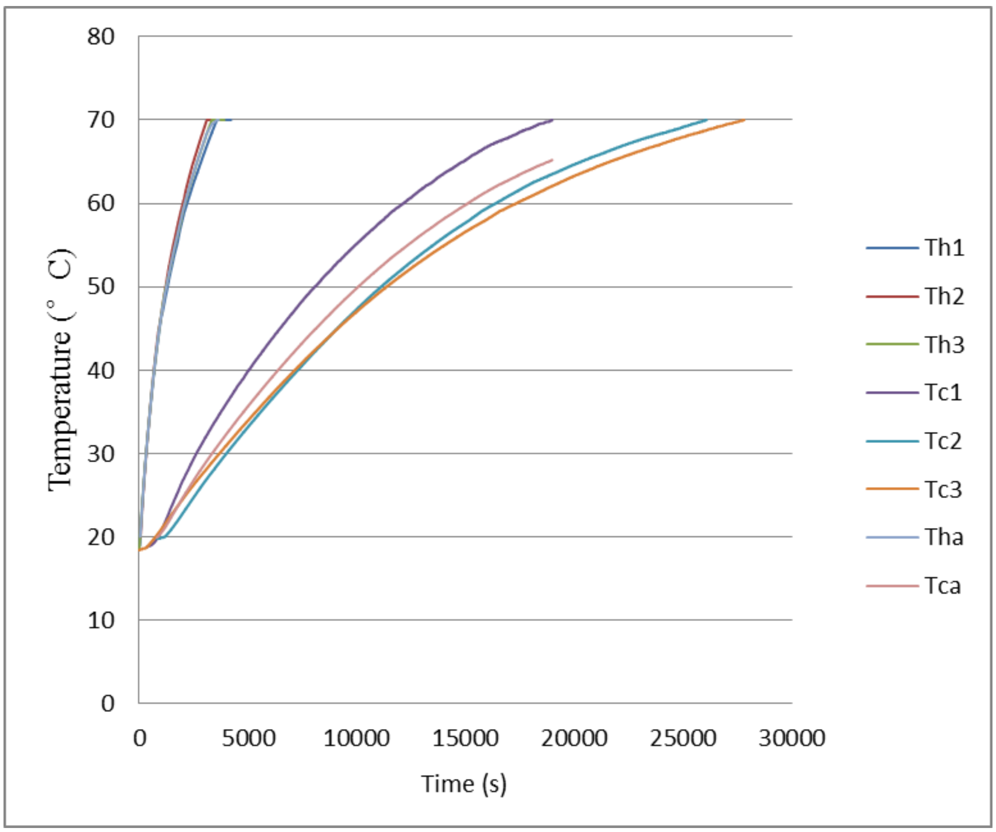

Figure 53. Temperature in both hot and cold sides for Specimen C

Figure 54 shows the times for the three panels for all tests to reach 70ºC on the cold side.

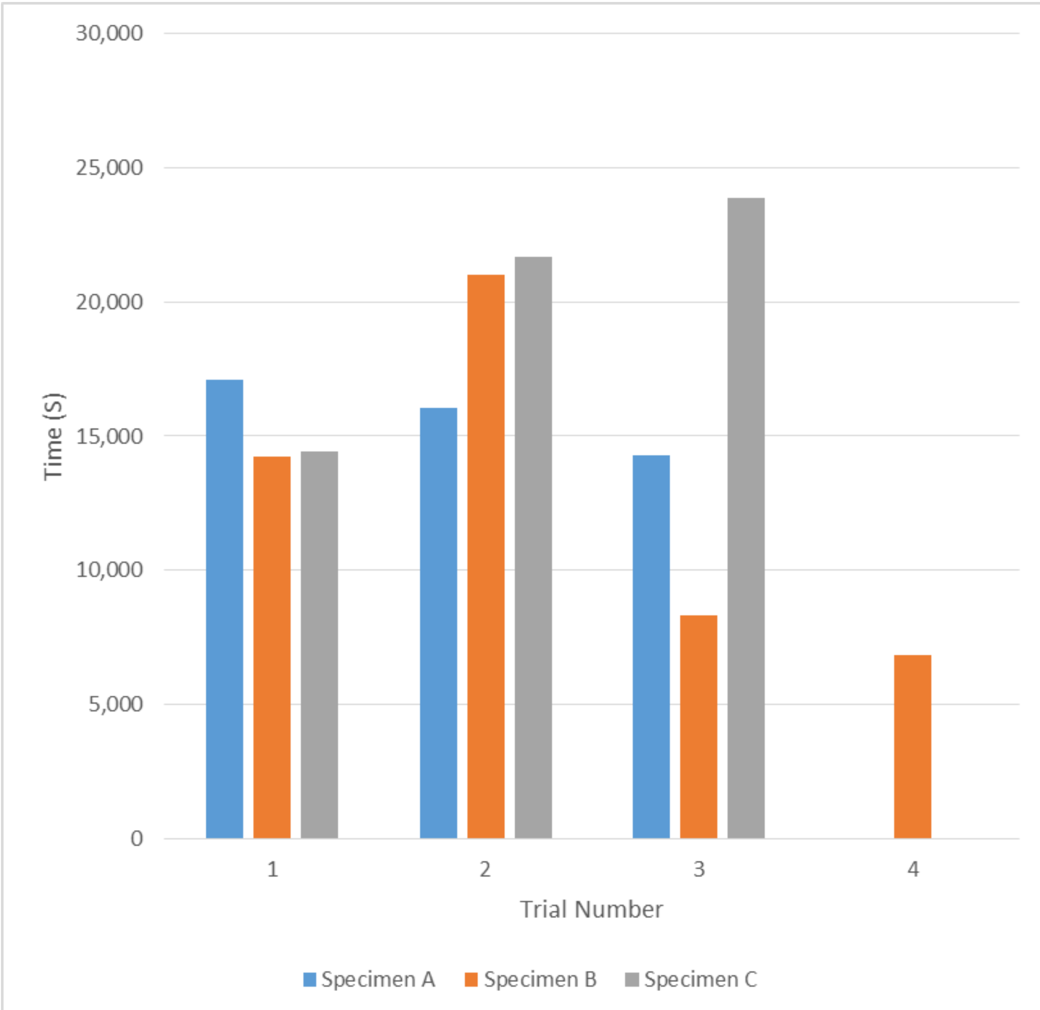

Figure 54. Time for tests to reach 70 ºC on the cold side

Overall Heat Transfer Coefficient, U

THE overall heat transfer coefficient comes from Equation (1) and reduces to:

$$U(T_1 - T_2) = k \tag{3}$$

k is a test constant with a value of 1510 ± 110 W/m^2.

Bales (1988) completed a report on the round robin review of hot boxes in the use in the USA at that time. ASTM International (2011) provides 34 references on research on this type of test method, with the latest from 2002.

The traditional reporting technique is to report the R value which is the inverse of the U value. Bales reports the results at 24 ºC. This is as logical a selection as any.

Table 7 shows the reported U values for these tests that are for the time at which the cold side reaches 24 degrees C.

Table 7.

Reported U values at 24 ºC

Specimen	Trial				
	1	2	3	4	Average
A	44.8	51.3	56.6	-	50.9 ± 6
B	83.6	89.0	128.3	107.4	102.1±26
C	62.3	63.1	45.9	-	57.1±11

The theoretical error analysis for the average values is about four, the estimated standard deviation from the results is shown in the Table 7.

CHAPTER V

CONCLUSIONS

Summary

The determination of the response of a building to an applied thermal load is an interesting and complex calculation. Piedmont Plastics supplied a new material that had no reported thermal properties. This material was tested against a standard fibre cement panel to compare the thermal properties.

The ASTM standard hot box for testing thermal properties evolved from the early 1980's to about 2000, when it became reasonably standardized for use. This research work investigated an alternative design and conceptual test method for the hot box test. Instead of stabilizing the temperature of both sides of the hot box, the temperature was allowed to rise continuously on both sides with the application of a 250 Watt heat source in the warm side of the box. Temperatures were measured on both compartments of the box from cold to 70 ºC. The critical items reported in this work is the U values and the time for the cold side to reach 70 ºC for each test.

A laboratory box was designed and constructed in general accordance with the ASTM methods. The test results show that the fibre cement panel and the three millimeter aluminum composite sheeting appear to degrade with a cyclic thermal loading, although one must consider that the temperatures used in the tests were high for normal building temperatures. The six millimeter sheeting did not show a degradation for the three applied thermal cycles. The U values reported are in line with standard measures for these types of product and show that all products are useful for building sheeting in thermal terms, although six millimeter aluminum composite sheeting probably performed slightly better than the other materials, although given the rawness of the test method the results are not considered commercially useful at this time.

It cannot be concluded from this test that the hypothesis is true or false, rather one could use the Scottish verdict of not proven. As can be observed in the ASTM literature, this type of test can take 20 years to stabilize and resolve the issues in use. This is a first use of a simple test, further work is recommended and clearly there are significant improvements that can be made in the test.

Suggestions for Future Research

More tests can be performed on 6mm aluminum composite sheeting to verify the stability in thermal property as there was a set of data that diverged from other two sets of data in the experiment. Energy simulation tools are suggested to calculate energy can be saved based on different materials.

REFERENCES

American Society of Civil Engineers. (1904). *Report of Committee of the American Society of Civil Engineers, on Uniform Tests of Cement*.

ASTM International. (2002). *C 778-02 Standard Specification for Standard Sand* (Vol. 04.01). W. Conshohocken, PA.: ASTM.

ASTM International. (2011). Standard Test Method for Thermal Performance of Building Materials and Envelope Assemblies by Means of a Hot Box Apparatus (C1363-11). Conshohocken PA.

ASTM International. (2012). Standard Guide for Evaluation of Exterior Building Wall Materials, Products, and Systems. Conshohocken PA: ASTM: .

Baker, I. O. (1914). *Treatise on Masonry Construction* (Baker 1914 Ed. Baker 1914 ed.). New York: Wiley.

Bales, E. (1988). *ORNL/Sub/84- ASTM/DOE Hot Box Round Robin, 97333/2*. Retrieved from Oak Ridge National Laboratory:

Borowski, E. J., & Borwein, J. M. (1989). *Dictionary of Mathematics* (Second ed.). Glasgow: Collins.

Cao, X., Liu, J., Cao, X., Li, Q., Hu, E., & Fan, F. (2015). Study of the thermal insulation properties of the glass fiber board used for interior building envelope. *Energy and Buildings, 107*, 49-58.

Cheung, C., Fuller, R., & Luther, M. (2005). Energy-efficient envelope design for high-rise apartments. *Energy and Buildings, 37*(1), 37-48.

Edmonds, I., & Smith, G. (2011). Surface reflectance and conversion efficiency dependence of technologies for mitigating global warming. *Renewable Energy, 36*(5), 1343-1351.

Fang, W., Xue, S., & Li, T. (2011). The analysis of existing methods of field testing the heat transfer coefficient of building wall. *Refrigeration and Air Conditioning, 25(5)*, 164-167.

Fei, H., & Kai, D. (2000). The field test method of building energy saving and its affecting factors. *Construction Technology, 29(7)*, 31-33.

Fisher, R. A. (1971). *The Design of Experiments*. London: Macmillan.

Ghosh, B. (2015). *A Parametric Study on Exterior Insulation Systems and Heat Reflective Paints for Energy Efficiency in Buildings.* Paper presented at the Key Engineering Materials.

Iannone, R., Miranda, S., Riemma, S., & De Marco, I. (2016). Improving environmental performances in wine production by a life cycle assessment analysis. *Journal of Cleaner Production, 111*, 172-180.

ICC Evaluation Service. (2015). *ICC-ES Evaluation Report* (ESR-1844). Retrieved from California: https://www.jameshardie.com/JamesHardieMainSite/media/Site-Documents/TechnicalDocuments/Reports/ESR-1844-2015.pdf

International Code Council. (2012). International Residential Code for One- and Two-Family Dwellings. Falls Church, VA: ICC.

International standard 14040. (1997). Environmental management- life cycle assessment -principles and framework. Geneva, Switzerland: International Organization for Standardization (ISO).

Johnson, R. A. (2000). *Miller and Freund's Probability and Statistics for Engineers*. Upper Saddle River: Prentice Hall.

Mahanta, N. K., & Abramson, A. R. (2010). The dual-mode heat flow meter technique: A versatile method for characterizing thermal conductivity. *International Journal of Heat and Mass Transfer, 53*(23), 5581-5586.

Mazria, E., & Kershner, K. (2008). The 2030 Blueprint: Solving Climate Change Saves Billions. *Case Study, 2030, Inc./Architecture, 2030*.

Mosteiro-Romero, M., Krogmann, U., Wallbaum, H., Ostermeyer, Y., Senick, J. S., & Andrews, C. J. (2014). Relative importance of electricity sources and construction practices in residential buildings: A Swiss-US comparison of energy related life-cycle impacts. *Energy and Buildings, 68*, 620-631.

Nichols, J. M. (2005). *"A Treatise on Masonry Construction" Application to the Modern Practices for Historic Building Restoration.* . Paper presented at the 10th Canadian Masonry Symposium, Banff, Alberta.

Oral, G. K., Yener, A. K., & Bayazit, N. T. (2004). Building envelope design with the objective to ensure thermal, visual and acoustic comfort conditions. *Building and Environment, 39*(3), 281-287.

Pérez-Lombard, L., Ortiz, J., Coronel, J. F., & Maestre, I. R. (2011). A review of HVAC systems requirements in building energy regulations. *Energy and Buildings, 43*(2), 255-268.

Perini, K., Ottelé, M., Fraaij, A., Haas, E., & Raiteri, R. (2011). Vertical greening systems and the effect on air flow and temperature on the building envelope. *Building and Environment, 46*(11), 2287-2294.

Piedomont Plastics. (2015). Piedmont Plastics Alupoly® Sign Product is now UL Certified. Retrieved from http://www.piedmontplastics.com/alupoly-sign-product-ul-certified/

Solórzano, E., Reglero, J., Rodríguez-Pérez, M., Lehmhus, D., Wichmann, M., & De Saja, J. (2008). An experimental study on the thermal conductivity of aluminium foams by using the transient plane source method. *International Journal of Heat and Mass Transfer, 51*(25), 6259-6267.

Squires, G. L. (2001). *Practical Physics* (Squires 2001 ed.). Cambridge ; New York: Cambridge University Press.

Tajsic, M. (2014). Building Envelope for Energy-Efficient Residential Homes, A Case Study for the US Department of Energy Challenge Home Student Design Competition.

The US Department of Energy. (2002). *Insulation fact sheet with addendum on moisture control*. (DOE/CE-0180). USA.

Tuhus-Dubrow, D., & Krarti, M. (2010). Genetic-algorithm based approach to optimize building envelope design for residential buildings. *Building and Environment, 45*(7), 1574-1581.

U. S. Department of Energy National Energy Technology Laboratory. (2009). *Recovery Act: Advanced Energy Efficient Building Technologies, Financial Assistance Funding Opportunity Announcement, 9*.

U.S. Environmental Protection Agency. (1993). *Introducing the Green Lights Program*. Washington, DC: EPA Office of Air and Radiation.

Wakili, K. G., & Tanner, C. (2003). U-value of a dried wall made of perforated porous clay bricks: Hot box measurement versus numerical analysis. *Energy and Buildings, 35*(7), 675-680.

Wu, P., Mai, Y., & Lu, J. (2011). The improvement and application of field test method of building envelop heat transfer coefficient. *New Building Materials, (4)*, 79-83.

Yang, L., Yan, H., & Lam, J. C. (2014). Thermal comfort and building energy consumption implications–a review. *Applied Energy, 115*, 164-173.