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Simple Measurement of Conductivity of Colored Acrylic Sheets

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ABSTRACT

In many applications, colored acrylic sheets require information on thermal conductivity values. However, thermal conductivity data has not been found in the literature and research publications, especially colored acrylic sheets. The purpose of this study was to investigate the heat conductivity value of colored acrylic sheets including transparent, cloudy, white, black, green and blue colors found in the market. This research was done with the experimental method of measuring the thermal conductivity of colored acrylic in a closed room four rectangles 80 cm x 40 cm x 40cm of 9 mm plywood coated with black paper and divided into two compartments and test material 40 cm x 40 cm x 0.3cm as patisi room. The heat source used is a 75watt incandescent lamp placed on one side of the room. Acrylic thermal conductivity is calculated based on temperature data at each measurement point reaching a steady state which is obtained at the 30th minute and taking into account the convection heat and air radiation in the test chamber. The results showed that pigment additives greatly affect the thermal conductivity value of acrylic and its value is lower than the conductivity value of acrylic colorless sheet transfaran.

INTRODUCTION

Acrylic is the common name for Polymethyl Methacrylate or PMMA which is widely used as a replacement for glass, especially in areas where only a small amount of light and heat is desired to pass through. For example at the top of a carport or greenhouse where a durable material that allows light and heat transmission as well as some protection from glare and a unique visual appearance is required, colored acrylic may be the perfect solution (Hung Anh & Pásztory, 2021).Acrylic in sheet form is not only available in clear form but there are many colors that make acrylic material more popular (Murtadha, 2023). Acrylic is made artificially, it is available in a variety of colors. Some of the most popular ones include clear, opaque (cloudy), white, black, green, blue, etc (Masuda & Tsunekuni, 2022). Colored acrylic sheet is formed by mixing pure acrylic resin with pigment, which is then melted in an extruder. The ratio of pigment to resin may vary depending on the desired color intensity (Tsutsui *et al*., 2023). One factor that affects the color of acrylic sheet is its thickness. Thicker sheets may appear brighter and more saturated than thinner sheets because the color pigments are dispersed in a larger volume (Kaneko, 2022). In addition, the transparency of the acrylic sheet will also affect its color. Compared to translucent or opaque sheets, transparent acrylic sheets allow more light to pass through, resulting in different visual effects. Several recent studies have been conducted to determine the electrical conductivity of the material. However, knowledge about the heat conductivity of this material is still limited (Famengo *et al*., 2017).Thermal conductivity is defined as the quantum of heat transmitted through a unit thickness of material. Thermal conductivity can be used to assess and compare how simple materials transfer heat. Nonetheless, there is an inverse relationship between thermal conductivity and heat insulation properties. Many researchers have investigated and tested the thermal conductivity of various materials to come up with the optimum heat energy that will save the use of suitable materials to achieve their intended use (Hatzikraniotis *et al*., 2022). Measuring and understanding the thermal conductivity of various materials is very important in the field of materials science and engineering, as well as various thermal applications of various products including acrylic (Salim, 2022).The thermal conductivity of bulk polymers is usually very low which is due to the complex morphology of the polymer chains (Shi *et al*., 2019). The typical structure of a polymer, which consists of crystalline domains in which the polymer chains are periodically aligned, and amorphous domains in which the polymer chains are randomly entangled. The thermal conductivity of a polymer depends largely on its morphology. When amorphous domains are dominant, vibration modes in the polymer tend to be localized, resulting in low thermal conductivity. When the concentration of fillers is low, no network between fillers can form. The thermal conductivity is basically determined by the coupling of the filler matrix, that is, the interfacial thermal resistance, and the concentration and geometric shape of the filler. When the concentration of filler material is large enough, the filler material with high conductivity can form a thermally conductive network (Huang *et al*., 2023). Key factors affecting the thermal conductivity of polymers, such as chain structure, crystallinity, crystal form, polymer chain orientation, and ordered domain orientation in thermoplastics and thermosets have been discussed (Mathews & Hameed, 2023). The thermal conductivity of acrylic can vary

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depending on the chemical composition and structure of the material such as the addition of colourants or pigments used in the manufacture of acrylic (Hung Anh & Pásztory, 2021).At the molecular level, the addition of pigments or colours to acrylic can change the inter-molecular interactions within the material structure. This can affect acrylic's ability to conduct heat, as different molecular structures can have different levels of thermal conductivity. However, despite its importance in many applications, the effect of colour or pigment on the thermal conductivity of acrylic is not yet fully understood and documented(Barni *et al.*, 2021) .The conductivity of acrylic materials due to their conductivity properties can affect the performance and applications of products made from these materials (Selvakumar *et al.*, 2023). The conductivity of acrylic can be altered in various ways, including by chemically or physically modifying the structure of the material (Lee *et al.*, 2023). Therefore, research into the conductivity of acrylic materials has significant relevance in the development of acrylic materials technology and applications.

Empirical information on the thermal conductivity of coloured acrylics from the literature and research results on the conductivity of coloured acrylics is currently limited. Therefore, this study aims to investigate and analyse the effect of colour additives in acrylic on thermal conductivity and gain useful insights into the actual performance of coloured acrylic materials for future practical applications (Žiljak Gršić *et al.*, 2023) .

Weak Conductor (Bad) Welding Theory

Heat energy is exchanged between two systems through conduction, convection and radiation. There are several methods that can be used theoretically and experimentally to measure the thermal conductivity of a material. Conductive heat transfer, which is expressed as W/mK. For one-dimensional and steady state heat flow, the heat conduction rate is expressed by the Fourier equation (Dehghan *et al.*, 2015).

$$Q=kA\ \Delta T/L. \quad (1)$$

$$J=Q/A=k\ \Delta T/L \quad (2)$$

where Q is the heat transfer rate (W); J is the heat flux (W/m2), k is the thermal conductivity W/(m K); A is the cross-sectional transfer area (m2); ΔT is the temperature difference (°C); L is the length of the conduction path (m).

Heat energy flow (Q) in an enclosed space

The heat supplied to the room through the incandescent lamp QT is equal to the sum of the radiation output Qr and convection Qc (Atreya, 2016).

$$Qt = Qc + Qr \quad (3)$$

Radiant heat Qr is calculated using the equation (Atreya, 2016):

$$Qr = A\ \sigma\ \varepsilon\ (T^4_{\ 1}-T^4_{\ 2}). \quad (4)$$

Qr = Radiant heat, Watt
A = Heat transfer surface area, m2 .
ε = Surface emissivity
υ = Kinematic viscosity, m2 s-1
σ = Stefan Boltzmanns constant, 5.67𝑥10-8 W m-2 K-4
T_{14} = Radiation source surface temperature C or oK
T_{24} = Room temperature oC or oK

Heat of Convection is calculated using the equation (Atreya, 2016):

$$Q_C = Hc \cdot A \cdot (T_1 - T_2) \quad (5)$$

Qc = Room convection heat transfer, Watts
Hc = indoor heat transition coefficient, W m-2 K-1
A = Heat transfer surface area, m2 .
T_1 = Surface temperature oC or oK
T_2 = Room temperature oC or oK

The heat transfer coefficient in the case of natural air movement in enclosed spaces is for all wall materials encountered in practice is; hc = 8.1 W/K.m (Zemani-Kaci & Sabeur-Bendhina, 2023).

Thermal Conductivity Measurement Technique

The heat energy flow Q through a homogeneous flat wall is determined in steady state through air-wall heat transfer and heat conduction in the wall. The energy flow depends on the wall surface area A and a certain temperature difference. Illustration of heat energy flow through a wall in the case of an enclosed room with room temperatures 1 and 2 and an insulating wall: TR1, TR2, T1, T2 like Figure 1. (Ganguli *et al.*, 2013).

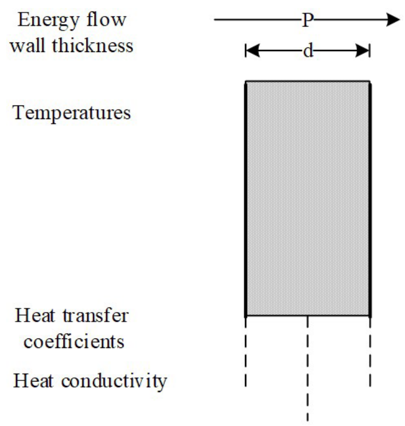

Figure 1: Heat Energy Flow in an enclosed space

MATERIALS AND METHODS

Research Equipment

- Four-square box 40x40x80 (cm) long with two compartments
- 9 mm polywood box material, laminated with 0.1 mm thick black paperboard
- The thickness of the acryli test material of each colour used is 3 mm
- Clear incandescent lamp Classictone standard 75W E27 220-240 A55 CL 1 CT/10X10F
- Digital thermometer (6 pieces)
- Timekeeper using Acer video camera

The equipment in this coloured acrylic heat conductivity testing experiment refers to the procedures and modifications of the Heat insulation / Heat conduction test equipment developed by PHYWE LEP 2003 (Dai *et al.*, 2019). Heat insulation / Heat conduction model in the form of a cube-shaped room with replaceable side walls is used to determine the heat transition coefficient (K value) of various wall materials and to determine the heat conductivity of various materials. The heat source used comes from the heat energy of incandescent lamps placed outside the Heat insulation room. Heat energy enters through the window into the room and will exit through the side walls which can be replaced with test materials. For this purpose the temperature inside and outside the wall is measured at a constant inside and outside air temperature (in a stable state). The model used in this experiment is slightly different from the Heat insulation model, which is carried out in an airtight enclosed space in the form of a rectangular building divided into two compartments. As partitions of the room compartments are used materials that can be exchanged to determine the heat conductivity of each material. As a heat source, an incandescent lamp is placed in the room on one side of the wall in a closed room. Measurements in a closed room are carried out to avoid the possibility of the influence of changes in ambient temperature. The measurement method is used in the steady state, that is, when the system has been measured. achieve stability (Chen, *et al* 2016) and take into account the convection and radiation heat of room air. The unit of the coloured arylic conductivity measurement device is shown in Figure 2.

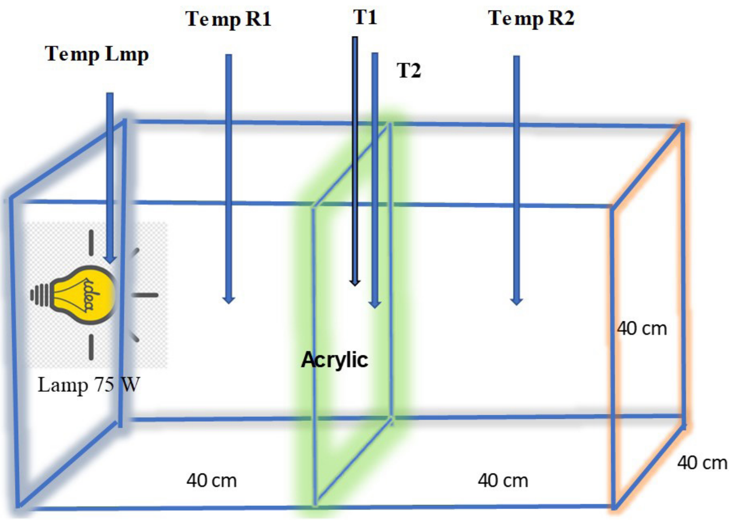

Figure 2: Coloured Acrylic Heat Conductivity Measurement Room

Experiment Procedure

Initially the installation of a 75 W incandescent lamp on one side of the first compartment wall within 40 cm of the room compartment partition in the form of a coloured acrylic test material and the installation of a thermometer on the side of the incandescent lamp, on the front and back of the test material and on the surface of the second compartment wall behind the test material which is 40 cm from the compartment partition (Test material). The thermal conductivity measurement technique is the steady state method. applied when the system has reached stability, (Chen, *et al.*, 2016). The heat from the incandescent lamp will reach the face of the test material and then conduction of the test material to the second compartment. The following procedure was used in its entirety for all six test material colours: transparent, cloudy, white, black, green and blue:

1. Determining the location of the test material from the heat source of a 75W incandescent lamp. Based on the distribution measurement results where the temperature on each surface of the xy axis partition is homogeneous (evenly distributed). Measurements were made before the main research was carried out. and obtained a minimum distance of 40 cm.
2. The first test condition is to record the initial temperature on the incandescent lamp side, the front side, the back side of the test material and the side of the wall in the second compartment.
3. Then the incandescent lamp is switched on and temperature measurements are taken at all predetermined points at every one second interval and until a constant or steady state of tempeartur of all points is achieved.
4. Data relating to the steady state region were recorded.
5. The temperature measurement data at each time and each test material is then used as input data to calculate the convection heat, radiation and heat conductivity of each test material.
6. Steps 2-4 were then repeated for the other five test materials.

RESULTS AND DISCUSSION

From the experiment, a steady state condition was obtained at the 30th measurement, where the temperature at all points in the room and on each side of the surface of the test material showed that the average temperature did not change significantly over the measurement time. Next, calculate the value of heat supply to the experimental room by summing up the convection heat, and radiation in the experimental room, and calculating the heat conductivity coefficient of all test materials.

Analysis of thermal conductivity heat value is done on 6 different coloured test samples and obtained thermal conductivity value of the test samples with several parameters, namely:
Calculate the radiant heat value Qr/A using equation (4)
$Qrad/A = \sigma\ \varepsilon\ (T2^4 - TR2^4)$
$= 5.67x10^{-8}$ W m^{-2} K-4. 0,94 $(39.4^4 - 32{,}72^4)$
= 42,168 W/m^2
Calculating the heat of convection value Qc/Ac using equation (5)
Qc/A = hc (T2-TR2)
= 8,1 * 0,16 (39,4-32,7)
= 54,27 W/m^2
Calculate the Qt/A value using equation (3)
Qt/A = Qrad + Qc
= 96,44 W/m^2
Calculating the k value using equation (2)
Qt/A=k ((T1-T2))/L
k = Qt/A. L / (T1-T2) = 0,12 W/m °K
From the calculation of thermal conductivity values for all test materials summarised in Table 1. And for the graph can be seen in Figure 3.

Table 1: Data and calculation results of thermal conductivity values of each test material

Acrylic colour	**A**	**d**	**ε**	**TR1**	**T1**	**T2**	**TR2**	**Qc**	**QR**	**Qt**	**k**
Transfaran	0,16	0,003	0,94	45,7	41,8	39,4	32,7	54,27	42,17	96,44	0,12
Cloudy	0,16	0,003	0,95	46,3	42,1	38,8	31,6	58,32	45,42	103,74	0,09
White	0,16	0,003	0,95	47,3	42,6	36,6	31,8	38,88	29,98	68,86	0,03
Black	0,16	0,003	0,95	46,9	43,1	39,8	31,8	64,8	50,76	115,56	0,11
Green	0,16	0,003	0,95	46,3	44,8	39,6	32,6	56,7	44,55	101,25	0,06
Blue	0,16	0,003	0,95	46,4	42,1	35,9	32,6	26,73	20,62	47,35	0,02
t	measurement time (steady state), 30 minutes										
d	test material thickness, 0.003 m										
A	surface area of the test material, A = 0.16 m^2										
hc	Heat transfer coefficient in the case of displacement in a closed space, 8.1 W/m^2 °K										
ε	Emissivity of the test material										
σ	Bolzmant constant, 5.67x10-8 W m^{-2} K^{-4}										
k	Heat conductivity, W/m °K										

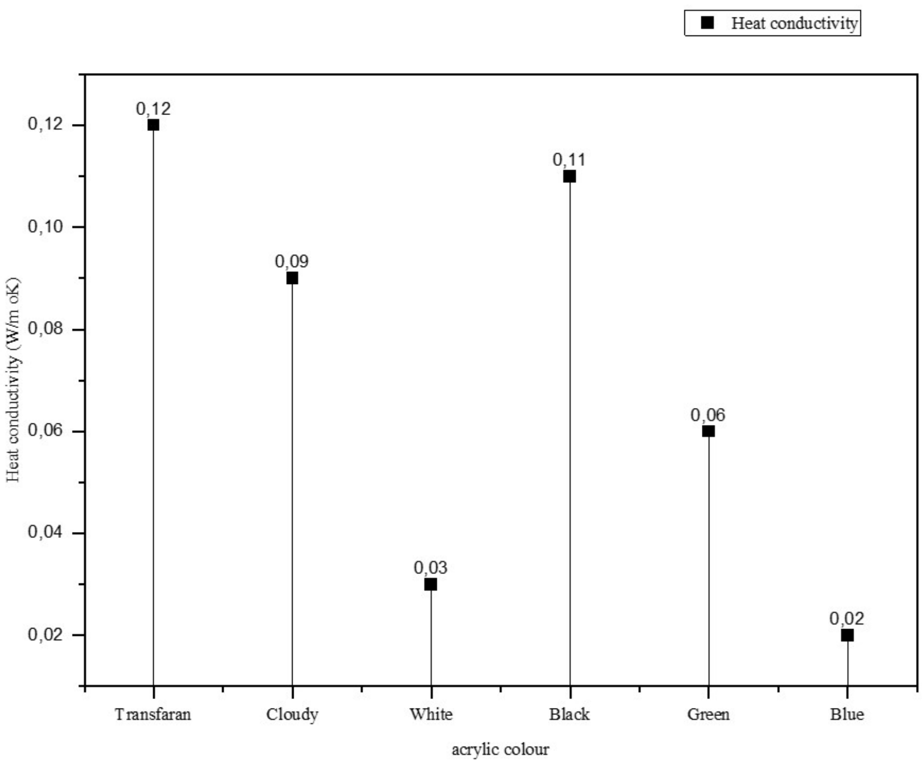

Figure 3: Conductivity Value of Arylic Coloured Sheet, W/m °K

DISCUSSION

From the measurement results Figure 1 shows the thermal conductivity value of the measurement results on each test material acrylic coloured from the same heat source in a closed space there are differences. The conductivity value of the six test materials shows the transfaran colour has the highest conductivity value, and the next colour black, cloudy, green, white and the lowest is blue. The difference in conductivity values indicates the influence of pigment materials added to acrylic resin during the extrusion process, namely the formation of coloured acrylic leaflets and the ratio of pigment and acrylic resin and the type of colour pigment added (Erofeev *et al*., 2023). The effects of pigment additives and the concentration added on the formation of coloured sheet acrylic resin. Colouring agents as additives can increase specific gravity, density and porosity (Dehghan *et al*., 2015).chemical composition and structure of monolayer-forming materials when adsorbed and chemical bonding occurs and affect the morphology of complex polymer chains. At the molecular level, the addition of pigments or colours to acrylic can alter the inter-molecular interactions within the material structure. When amorphous domains are dominant, vibration modes in the polymer tend to be localised, resulting in low thermal conductivity. When the concentration of filler material is low, no network between filler materials can form. The thermal conductivity is basically determined by the coupling of the filler matrix, that is, the interfacial thermal resistance, and the concentration and geometric shape of the filler. When the concentration of filler material is large enough, the filler material with high conductivity can form a thermally conductive network. The conductivity of acrylic can be altered in various ways, including by chemically or physically modifying the structure of the material. Therefore, research into the conductivity of acrylic materials has significant relevance in the development of acrylic materials technology and applications. These results differ from the thermal conductivity data published in the literature for acrylic which ranges from 0.167-2.5 W/m/K. From the literature data provides results from different material thicknesses, namely with a thickness of 1.48-3.0 mm, and some do not include the thickness, temperature, colour and components of acrylic materials used in thermal conductivity testing.For bulk polymers, the thermal conductivity is usually around 0.1-0.5W-m-1K-1. Based on the data obtained, when compared to the literature data, it can be seen that this result is lower, indicating the presence of colour material components contained in the acrylic used. This confirms that conductivity can be influenced by several factors, namely, components of constituent materials such as pigment additives, thickness, porosity of materials and temperature.

CONCLUSIONS

Simple experimental equipment was built in the form of a closed room 180 cmx 40 cm x 40 cm of 9 mm polywood coated with black paper which is divided into two compartments with a barrier of 40cm x 40 cm test material and 3 mm thick and installed a 75W transfaran incandescent lamp on one side of one of the compartments to measure the effect of coloured acrylic sheets on the thermal conductivity value of coloured acrylic.

Based on the experimental results obtained steady state conditions achieved in temperature measurements at each measurement point is at the 30th minute, and the heat conductivity value of each coloured acrylic test material is calculated by considering convection and radiation heat in a closed space and the resulting conductivity value of each coloured arylic with a thickness of 3 mm ie: Transparent colour: 0.121 W/m °K, Black colour: 0.105 W/m °K, Turbid colour: 0.094 W/m °K, Green Colour: 0.058 W/m °K, White Colour: 0.034 W/m °K, Blue Colour: 0.023 W/m °K.

Thermal Conductivity of transfaran acrylic is slightly smaller than the value of thermal conductivity from published research results (without mentioning the thickness and colour of acrylic) which is 0.15-0.25 W/moK,

Based on the findings of this study, it is necessary to continue investigating the effect of material type and dye composition on conductivity, especially dyes for acrylic materials.

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