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Preparation of Sustainable Thermal Insulators from Waste Materials

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Abstract. This work aims to produce an experimental and theoretical analysis of thermal insulator specifications for buildings with sustainable requirements. In the experimental work, three categories of thermal insulators were prepared from composite materials, and each category had ten models. These composites included the addition of two types of waste (sawdust and tyre waste) as fillers for two types of matrices (liquid polyurethane and polyurethane foam) to obtain composite materials for thermal insulation samples. The prepared samples were subjected to tests to show their thermal properties, such as thermal conductivity and specific heat capacity as well as undergoing a hardness test. The theoretical analysis included the discovery of empirical equations for thermal properties as functions of two variables (temperature and mass ratio) and hardness as a function of one variable (mass ratio). A genetic algorithm optimisation technique was used to find the optimum mass ratio of the composite that produced the required insulation specifications. The results showed that thermal conductivity decreased when the sawdust mass ratio and the rubber waste mass ratio increased but remained under the thermal insulation range. Furthermore, the prepared insulator samples showed an improvement in thermal storage and the hardness of tyre waste (liquid polyurethane composites) and sawdust (polyurethane foam composites). Finally, optimum results were obtained using the optimisation technique.

1. Introduction

The first definition of sustainable development was created by the World Commission on Environment and Development (WCED) in 1987: ‘Sustainable development is the development that meets the needs of the present without compromising the ability of future generations to meet their own needs’ [1]. The 2005 World Summit showed that sustainable development is based on three fundamental pillars (social, economic and environmental) [1, 2].

Recently, a new area of sustainable development, known as sustainability science, has emerged [3].

Now, sustainability is an area for solving a problem that exists and is directed towards creating an area that helps make relevant decisions in solving this problem [4].

‘The building industry is at a crossroads and the question is where do we go from here? The “green” train has left’ [5].

In recent years, many researchers have looked at solutions for social mobilisation that are closely related to technological development, using terms such as zero emissions, zero energy housing, energy efficiency, etc. [5]. The biggest energy consumers are buildings, and to reduce consumption there has been an increase in the manufacture of thermal insulators, especially in hotter and colder areas around the world. However, energy sources are constantly depleted, so waste is used as an alternative energy source for sustainable development [6]. The construction sector consumes around 40% of the world's energy and this necessitates the use of sustainable architecture standards. Proper application of building insulation is the best measure of conserving energy in buildings [7].

Thermal insulators can be defined as substances that reduce the transfer of heat between surfaces of a specific object. The thermal insulation principle is based on the replacement of a short heat flow pathway, which has low thermal resistance with long-lasting and high thermal resistance [8].

Many researchers have presented studies on the manufacture of thermal insulators using different methods. Khunthon et al. (2007) tested the manufacture of insulating sheets from waste tissue paper and corn husk and used polystyrene foam as a packaging surface to enhance performance. The study concluded that thermal conductivity was less corrected with an increased amount of corn husk in the mixture. Alternatively, the addition of waste tissue paper increased the strength of the insulating plates. The addition of polystyrene foam has greatly improved mechanical properties [9]. Panyakaew and Fotios (2008) used agricultural waste in Thailand as a thermal insulator for walls and ceilings. After adding certain materials, they chose the best insulators after testing thermal conductivity. The materials used in the test were rice straw, coconut husks, sugar cane waste, palm oil leaves, corn stalks and Durian husks. The first three waste materials recorded the highest values of thermal insulation [10]. Monika et al. (2011) discussed the effect of adding natural fibres to enhance the value of thermal conductivity, using bamboo fibres for their study. The results showed a decrease in the values of conductivity when the number of natural fibres was increased. The results were compared with the addition of synthetic fibres, which were less expensive and less harmful to the environment and improved mechanical properties [11].

Lakrafli et al. (2013) used wood and leather waste to conduct tests of their thermal properties. These waste materials were used as fillers for hollow samples or as separating material for cement slabs. The samples significantly reduced thermal conductivity when dry. As the moisture content increased, the thermal conductivity of the materials increased. Furthermore, the effects of weight, volume and humidity on thermal conductivity and the probability of conductivity increased with increasing moisture content [12].

Binici et al. (2014) used waste materials to manufacture thermal insulators for buildings. Rectangular samples were used measuring 30 * 40 * 2.5 cm. Two types of epoxy were used as the bonding material. The waste materials used were cotton and the roots and stems of sunflowers. Samples were tested for mechanical properties and thermal conductivity, and the obtained results met Turkish Standard 601 TS 805 EN. The study solved two industrial problems: first, useful building materials were produced and second, waste was disposed of in a manner that was less harmful to the environment. Results also showed that the gain in electric power was up by 8% with respect to ISO operating conditions, while thermal efficiency increased by 1.5% [13].

Binici and Kekili (2015) investigated the use of vegetable and animal fibres for manufacturing thermal insulation for buildings in Turkey to reduce energy consumption and heating costs in the winter and cooling in the summer. Several types of plant and animal fibres were used and plaster was used as a bond. The results showed that most of the thermal coefficients of the samples matched Turkish standards. Similarly, these materials could be used to produce local thermal insulation more economically and provide a solution for the disposal of agricultural waste sustainably [14].

El Wazna et al. (2018) manufactured thermal insulators with new materials that were non-woven fabric waste and conducted thermal and physical tests to determine their efficiency in terms of thermal conductivity and performance. Low values of thermal conductivity and good thermal performance demonstrated the feasibility of producing new competitive low-cost insulation materials that met sustainability criteria [15].

This work investigates the manufacture of thermal insulators for buildings from composite materials where waste materials (sawdust and tyre waste) will be added as a filling to matrices. They will be tested to find several properties, including thermal and mechanical properties. The optimum thermal insulator will then be extracted depending on a genetic algorithm optimisation technique that achieves sustainability requirements.

2. Materials and Method

2.1 Sawdust

Sawdust is a type of waste from wood processing (wood dust). Particles of different sizes are formed either from drilling, cutting, grinding or milling using wood grinding tools or a saw [12]. Samples were collected from a carpentry workshop in Zubayr (Basrah). They were screened to the required size of 500 µm, as shown in Figure 1.

2.2 Tyre waste

Tens of millions of tyres are abandoned in the Middle East every year. Disposal of tyre waste is a difficult task because they have a long, unbreakable life. The traditional way of managing tyre waste is to store, dump or landfill illegally, all of which are short-term solutions. The tyres provide a fertile ground for breeding mosquitoes, insects and snakes. Sudden or accidental fires in tyre dumps have also released toxic gases for months [16].

One solution to this problem is to recycle these materials. In this research, these waste products were used as raw materials in the manufacture of environmentally friendly thermal insulation. Tyres were treated in the welding workshop at the Faculty of Engineering in Basrah to obtain the tyre powder, and it was screened at 500 µm or less, as shown in Figure 2.

Figure 1 Sawdust

Figure 2 Rubber waste

2.3 Polymer (PU)

Polyurethane (PUR and PU) is a polymer composed of organic units joined by urethane links. Most polyurethanes are thermosetting polymers that do not melt when heated, but thermoplastic polyurethanes are also available [17]. Polyurethane is produced by the reaction of isocyanates containing two or more groups of isocyanates for each molecule (R- (N = C = O) n) with polyol containing the average of two or more hydroxyl groups in the molecule (R '- (OH) n) in the presence of a stimulant or tonic using ultraviolet light [18]. The polyurethane used in this work was manufactured by Henkel Polybit Industries Ltd and is a two-component solvent-free epoxy resin-based primer and sealer coat for polyurethane-based coatings and toppings [19].

3. Preparation of Composites

The samples consisted of sawdust (liquid polyurethane), tyre waste (liquid polyurethane) and sawdust (polyurethane foam). The samples were prepared in the metal laboratory in the Department of Materials Engineering, College of Engineering, University of Basra. Models were made in normal weather conditions of pressure and temperature. The composites were 35 mm in diameter and 5 mm thickness depending on subsequent tests. At first, the waste materials had different mass ratios as different percentages were added to the polymer (5, 10, 15, 20, 25, 30, 35, 40, 45 and 50%); then they were hardened. The samples were mixed until they were homogenised, and then they were poured into moulds and left to cross for 24 hours. They were extracted and placed in an oven at 80 °C for one hour to complete the crucifixion [20]. Except for the polyurethane foam (sawdust) the samples did not need a post-curing process. Figure 3 shows a sample of sawdust (liquid polyurethane).

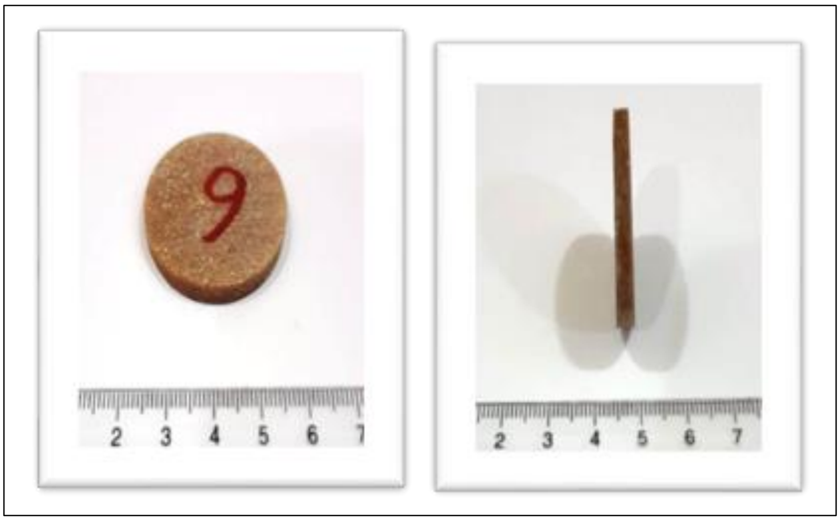

Figure 3 Sample of sawdust (liquid polyurethane) representing its diameter and thickness

4. Experiment

To evaluate insulation performance under field conditions, dimensioning the heating and cooling systems correctly is necessary, as is assessing the functionality of the design. This can be done by conducting the following tests.

4.1 Thermal conductivity measurement

In this work, a Lee's-disk method was used to evaluate the thermal conductivity of bad conductor materials. Measurement was performed at a steady state in the metal laboratory of the Engineering College Material's Department according to BS 4745.

Thermal conductivity is equal to the heat flux through the material layer's unit thickness when the temperature of the material on opposite sides of the layer differs by 1 °K [8].

Fourier's law of heat conduction is expressed as:

$$\boldsymbol{k} = \frac{\boldsymbol{Q}.\Delta \boldsymbol{x}}{\boldsymbol{A}.\Delta \boldsymbol{T}} \quad (1)$$

where $\boldsymbol{k}$ is the thermal conductivity coefficient of the material of dimensions w/m.K, Q is the heat flow at steady state, A is the cross-section area in mm^2, x is the sample thickness in mm and $\Delta\boldsymbol{T}=T_h - T_c$ is the temperature gradient at the thickness of the sample.

Figure 4 shows the structure of Lee's device and the temperature gradient through the sample. The heat lost from the sides of the sample was neglected and, on this assumption, thermal conductivity was calculated [21, 22].

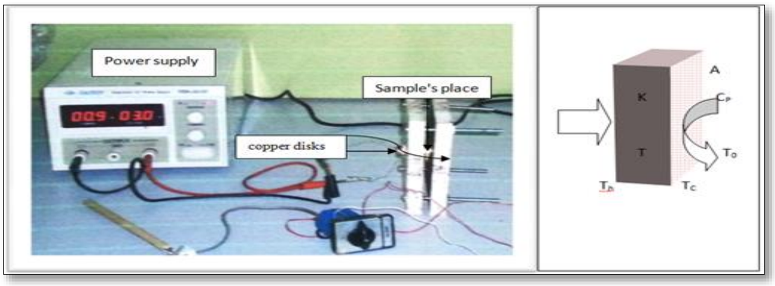

Figure 4 Lee tested with graded temperatures during the sample

A Lee's-disk device consists of two brass discs and an electric heater source to cause a heat gradient through the sample; the sample is placed between the two brass discs. The test continues until thermal equilibrium is reached, where T_c is constant for more than 10 min (the steady-state of heat transfer).
To determine the heat transfer, Q, heat entering the brass plate (2), equals the rate of heat loss due to cooling (at the equilibrium). The heat loss can be determined by measuring the cooling rate of the equilibrium temperature T_C of the brass plate (2) placed with the insulator (sample) as shown in Figure 5. If the disc cools at a rate of $\frac{dT}{dt}$, then the rate of heat loss is given by:

$$\boldsymbol{Q = mc_p \frac{dT}{dt}} \ \textbf{(2)}$$

where M is the mass of the plate and c_p is the heat capacity of brass (0.38)$\frac{kJ}{kg.K}$. The cooling curve of the brass plate determines the slope $\left[\frac{dT}{dt} = \frac{\Delta T}{\Delta t}\right]$ at temperature T_C [22, 23].

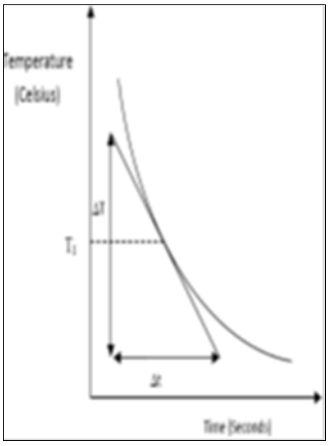

Figure 5 The temperature–time relation for the calculation of Q [23]

4.2 Specific heat capacity (C_P)

Specific heat capacity is known as the amount of heat energy emitted or soaked up under the cooling or heating of the material sample with a unit mass over a temperature change of 1 °K [24].

The specific heat capacity of inorganic building materials (concrete, break, natural stone) is varied within 0.75–0.92 kJ/ (kg °C); for wood, it is 0.7 kJ/ (kg °C).

The specific heat capacity of composite materials can vary if temperature variations are accompanied by phase changes [25]. A high-quality insulator has a higher specific heat capacity because it takes time to absorb more heat before it truly heats up (temperature rising) to transfer the heat [25].

4.2.1 Specific heat capacity measurement

This test is easy to implement as the tools used for measuring are simple and inexpensive. Its reliability for composite materials is better for samples weighing more than 5 mg to ensure the excellent mixing of samples [26]. Specific thermal capacity (expressed as $\mathbf{C_P}$; the pressure of solids is often constant unless stated) is related to the heat index, as illustrated by the following equation:

$$\mathbf{Q = m\, C_P\, \Delta T} \quad \mathbf{(3)}$$

where Q represents the amount of heat, m represents the mass of the substance and ΔT represents the difference of temperature [26]. The temperature difference will cause a continuation of heat exchange between the hot and cold body until it becomes stable, as shown by the law of conservation of energy in the following equation:

$$\mathbf{m_h\, C_{Ph}\, \Delta T_h = m_c\, C_{Pc}\, \Delta T_c} + Q' \quad (4)$$

$\mathbf{m_h}$, $\mathbf{C_{Ph}}$ and $\mathbf{\Delta T_h}$ represent the mass, specific heat capacity and temperature difference of a high-temperature object, while $\mathbf{m_c}$, $\mathbf{C_{Pc}}$ and $\mathbf{\Delta T_c}$ represent the mass, specific heat capacity and temperature difference of a low-temperature object.

Equation (4) contains an energy loss (Q′) that can be cured in two ways. The first is to use a double insulation barrel system and the second is by using a calliper made of a low thermal conductivity material so that it can be neglected. In the test, the second method was used. The equation will be:

$$\mathbf{m_h\, C_{Ph}\, \Delta T_h = m_c\, C_{Pc}\, \Delta T_c} \quad \mathbf{(5)}$$

The hot side represents water and the cold side represents the specimen [26]. Instruments used in the test consisted of simple tools that are calorific and sensors of temperature, as shown in Figure 6.

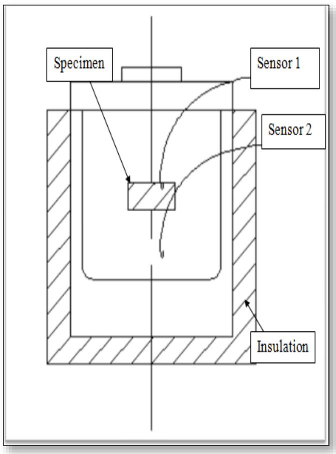

Figure 6 Diagram of heat exchange test

The procedures of the test included:

1- The water was heated to a certain temperature and quickly placed in the calliper.
2- The sample (at temperature -20 ºC) was placed in the calliper.
3- The temperature difference was recorded as required.
4- The specified heat capacity was calculated from equation (5) [26].

4.3 Hardness

The hardness test is the most widely used test for evaluating the mechanical properties of materials. The purpose of the hardness test is to determine the suitability of a material for a given application, conformance to a specification, standard, or particular treatment to which the material has been subjected (heat treatment, thermal process) [27].

The hardness of the samples (wood polymer and rubber polymer) was measured by placing a load of 60 kg on each sample to measure the resistance shown by the body. The hardness of the foam and wood samples was tested using a Shore D scale.

5. Theoretical Analysis

The theoretical work includes empirical analysis and optimisation techniques. Empirical analysis is an evidence-based approach to the study and interpretation of information. The empirical approach relies on real-world data, metrics and results rather than theories and concepts.

In addition to the analytical data of the thermal properties (thermal conductivity, specific heat capacity) and hardness test data, the equations of the composite materials were used to explain their behaviour as composite material behaves very differently from the original materials depending on the method of mixing (mass ratio, volumetric ratio).

Finally, the optimisation technique was used to find the optimum result that achieves sustainability requirements.

5.1 Empirical analysis

Depending on the experimental approach, the data on the practical side was explained. The relationship between two or more variables was found due to their importance in engineering applications. Several points were made.

5.1.1 Empirical equation for thermal conductivity k. This was based on the 10-point experimental data for each composite. The equation for each compound was discovered based on two independent variables (temperature and mass ratio).

5.1.1.1 Sawdust (liquid polyurethane) composite. With 10 experimental points and two independent variables (temperature and mass fraction), the empirical equation was found using the LAB Fit program. The empirical equation can be expressed as:

$$k = T_1/(A+(B*M^2\%)) \quad (6)$$

where k represents the thermal conductivity in W/m.˚C, T_1 represents the temperature of the hot surface in ˚C and A&B are the equation's constants. The values of the regression correlation coefficient are as follows:

- $R=0.998865$
- $R^2=0.997$

5.1.1.2 Tyre waste (liquid polyurethane) composite. LAB Fit was used to discover the empirical equation. The constant of the equation and the regression correlation coefficient is as follows:

$$k = T1/(A-(B*M^2))$$

- $R=0.999536$
- $R^2=0.999$

5.1.1.3 Sawdust (polyurethane foam) composite. The empirical equation, the constant of the equation and the regression correlation coefficient are as follows:

$$k = A*((T_1/M)^B) \quad (7)$$

- $R=0.987273$
- $R^2=0.974$

5.1.2 Empirical equation for specific heat capacity

The experimental equations for specific heat capacity were discovered by the same method. The following are the regression results for each category.

5.1.2.1 Sawdust (liquid polyurethane) composite. The model of this category is linear and depends on two variables: the temperature and mass ratio of wood waste. The equation was discovered and its parameters added to the regression correlation coefficient:

$$C_p = A*T+B*M^2 \quad (8)$$

- $R=0.994816$
- $R^2=0.989$

5.1.2.2 Tyre waste (liquid polyurethane) composite. The model of this category was smaller and its result is below:

$$\mathbf{C_p = A*M+B*T^2}$$

- R=0.981291
- R^2=0.962

5.1.2.3 Sawdust (polyurethane foam). The equation of this model was exponential and the following is the result of this category:

$$\mathbf{C_p = A*M^{(B*M)}} \quad \mathbf{(9)}$$

- R=0.997142
- R^2=0.994

5.1.3 Empirical equation for hardness

The experimental results of the hardness tests were based on one variable, mass ratio, and 10 points were tested for each category. The equations derived from the empirical test and the equation constants in addition to the convergence coefficients are as follows:

5.1.3.1 Sawdust (liquid polyurethane) composite

$$\mathbf{H = -A*M-B} \quad \mathbf{(10)}$$

- R=0.993225
- R^2=0.986

5.1.3.2 Tyre waste (liquid polyurethane) composite

$$\mathbf{H = -A*M^3+B*M^2-C*M+D} \quad \mathbf{(11)}$$

- R=0.993897
- R^2=0.987

5.1.3.3 Sawdust (polyurethane foam) composite

$$\mathbf{H = A*M^2-B*M+C} \quad \mathbf{(12)}$$

- R=0.988438
- R^2=0.97

5.2 Genetic algorithm optimisation technique

Optimisation represents the optimum result under given circumstances and enables engineers to make important decisions (technology and managerial) in the construction, maintenance and design of any engineering system. It is used to estimate the maximum or minimum value of a condition function [28]. Optimisation techniques can be divided into two categories: traditional and non-traditional. In response to solving complex optimisation problems, traditional, or modern, methods have been developed [28]. In this work, a genetic algorithm (GA) was adopted to find the optimal values of the thermal insulators manufactured using the properties of thermal conductivity and hardness. GAs are extremely suitable for solving problems as they can find the best global solution with high probability [28]. GA is a method for solving optimisation problems based on natural selection: the process that drives biological evolution [29]. It acts as a random search system for a set of extracted solutions. At each step, the GA selects individuals at random to be parents and uses them to produce children for the next generation. Step by step, the generations reach an optimal solution. A GA uses three types of operators at each step to create the next generation from the present population [30]: representation, crossover and mutation. Solving a problem and finding optimal solutions via a GA goes through five stages**:**

- **Initial population**
- **Fitness function**
- **Selection**
- **Crossover**
- **Mutation**

The initial population represents a set of individuals who are selected to solve a problem. Fitness function represents the environment that the solution lives in. The selection operator represents the best fitness function of individuals and copies them. Crossover matches individuals from the mating pool as pairs. Mutation represents a change in the gene of a single chromosome [28, 30]. Figure 7 represents a simple flowchart of the working principle of a genetic algorithm [30].

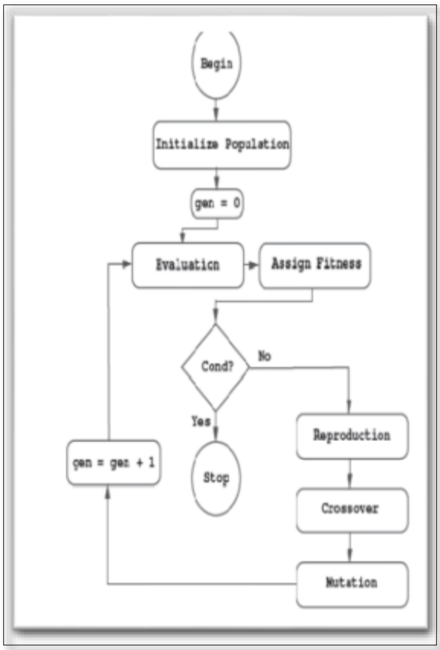

Figure 7 Simple flowchart of the working principle of a genetic algorithm [30]

The purpose of this study is to find the optimum values of two objective functions (thermal conductivity and hardness) for the thermal insulation of buildings based on design variables that include temperature and mass fraction.

We needed to improve more than one objective, so the multiple objective optimisation (MOO) method was used. Although MOO is tough, it presents realistic issues whenever the objectives are usually conflicting, which prevents the synchronic improvement of every objective [31]. The GA is considered as one of the most fashionable heuristic approaches for the resolution of multi-objective improvement issues because the multi-objective genetic algorithm (MOGA) does not need the user to prioritise, scale or weight objectives [31].

There are three steps in solving MOO problems using a GA [31–33].

1. *Fitness function assignment and selection*

In MOO, the fitness assignment is not straightforward; therefore, many approaches have been proposed to solve this issue, and Pareto-ranking is the most popular [31–33]. In this approach, the population is ranked according to a dominance rule, and then each solution is assigned a fitness value based on its rank in the population, not its actual objective function value [32]. MOO is different from single-objective optimisation (SOO); in SOO, there is just one optimum solution while in MOO, there is a set of optimal solutions called the 'Pareto optimal set' [31]. Furthermore, the set of solutions is known as non-inferior or non-dominated [34].

2. *Diversity*

Diverse solutions are intended for distribution on the border, which gives a clear idea of the decision-making about the true trade-off of the MOO problem [31].

3. *Elitism*

Elitism means always promoting the best individual to the next generation. This improves the GAs performance. There are several possible elitist solutions; therefore, two strategies have been adopted to overcome this problem: (i) maintaining elitist solutions in the population; (ii) storing elitist solutions in an external secondary list and reintroducing them to the population [32].

5.2.1 Multi-objective optimisation of this study using GA

The extraction of the optimum values of thermal insulators manufactured in this study depends on two objective functions in terms of their design variables.

One of the most important thermal properties was chosen as the first objective: thermal conductivity. The second objective is hardness, which is one of the important mechanical properties of thermal insulators.

The design variables are the temperature and mass fraction of waste material. The optimisation process was performed using MOO (gamultiobj) in MATLAB R2014, which is software that optimises the two objectives simultaneously.

The options in MOO (gamultiobj) were specified as follows:

1. Population size = 100
2. Population initial range = [25 5; 50 50]
3. Lower bound = [25; 5]; Upper bound = [600; 50], which were considered as objective constraints
4. Creation function = Feasible population
5. Selection function = Tournament; tournament size = 10
6. Crossover function = Two-point crossover; crossover fraction = 0.8
7. Mutation function = Adaptive feasible
8. Pareto fraction = 0.7
9. Plot function = Pareto front

6. Results and Discussion

6.1 Thermal conductivity

6.1.1 The effects of temperature on the thermal conductivity of the composites

The effects of temperature on thermal conductivity are shown in Figures 8, 9 and 10. For all composites, increasing the temperature causes an increase in thermal conductivity and this can be explained as follows: the connection of heat in any matter from the hot point to the cold point depends on the movement of electrons, phonons, or both. The movement of electrons and phonons is linked to kinetic energy. However, the thermal conductivity values of the three categories remain within the thermal isolation range. The highest values were recorded at 45 °C (0.035332, 0.179394, 0.049224 W/m.ºC) for each of the composites (sawdust [liquid polyurethane]; tyre waste [liquid polyurethane]; sawdust [polyurethane foam]), respectively.

6.1.2 The effects of waste addition on the thermal conductivity of the composites

The thermal conductivity of the composites was reduced after adding the sawdust; as shown in Figure 8, it reduced from 0.019629 W/m.ºC to 0.008389W/m.ºC at 25 °C. The addition of sawdust, whose thermal conductivity is less than the polymer, in addition to the formation of small air chambers, reduced the contact points in the polymer matrix, thus, dispersing the electrons, which led to reduced thermal conductivity [12, 25].

For the R-PU thermal insulator in Figure 9, thermal conductivity increased with an increasing mass fraction of rubber particles. This is attributed to the thermal conductivity of waste rubber, which is larger than the thermal conductivity of PU. Where the waste rubber contained the compound (black carbon), the thermal conductivity of the composite increased. When the percentage of waste rubber increased, particles joined together to form filler conductive chains, which greatly contributed to the thermal conductivities of the composite, but the values of thermal conductivity remained within the range of thermal insulations [16].

The foam structure contained many small air pockets making it well insulated. The addition of sawdust led to the dispersion of the particles between the air chambers and the foam material, which led to a greater dispersion of electrons as well as reducing the vibrations, which, in turn, reduced the thermal conductivity of the compound (as shown in Figure 10) [24].

Figure 11 shows the comparison of thermal conductivity between the three compounds. Sawdust (liquid polyurethane) is the lowest and tyre waste (liquid polyurethane) is the highest.

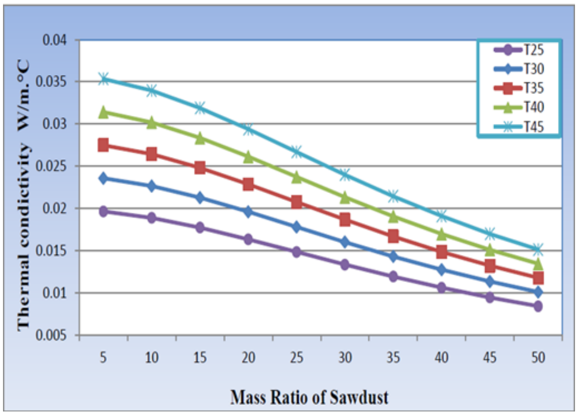

Figure 8 The effect of mass ratio and temperature on the thermal conductivity of sawdust (liquid polyurethane)

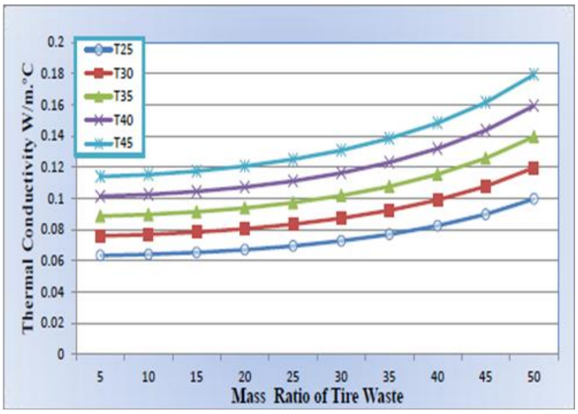

Figure 9 The effect of mass ratio and temperature on the thermal conductivity of tyre waste (liquid polyurethane)

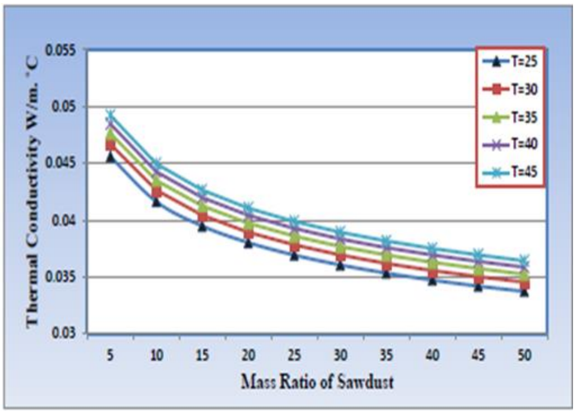

Figure 10 The effect of mass ratio and temperature on the thermal conductivity of sawdust (polyurethane foam)

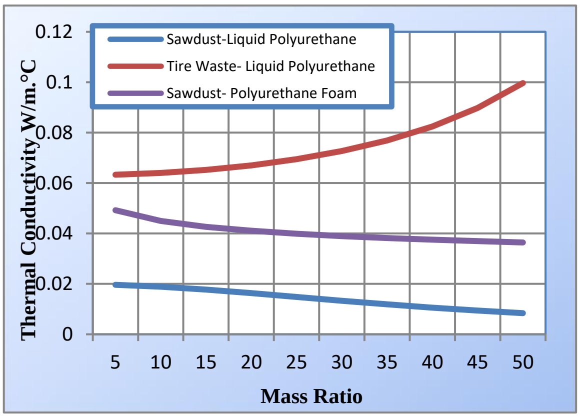

Figure 11 Comparison between thermal insulators at T=25 °C

6.2 Specific heat capacity (C_P)

6.2.1 The effects of waste addition on the specific heat capacity of the composites

Figures 12, 13 and 14 present the variations in specific heat capacity (C_P) with the loading of sawdust and tyre waste on the polymer matrix and the loading of sawdust on the foam matrix, respectively. For Figures 12 and 13, the increase in content increases specific heat capacity because the specific heat capacity of the sawdust (2.3 kJ/kg.ºC) and waste rubber (2.01 kJ/kg.ºC) is greater than the specific heat capacity of the polymer (1.800 kJ/kg.ºC); the specific heat capacity of the sawdust is less than the foam (2.32 kJ/kg.ºC). From previous measurements, the loading of sawdust and tyre waste in the polymer matrix resulted in the composites improving their specific heat capacity. Furthermore, sawdust (polyurethane foam) had the least specific heat capacity of all the composites. This approach is fully consistent with the equation below, which represents the weighted average of the specific heat capacity of the components [24].

$C_P = C_{P1}M_1 + C_{P2}M_2$

6.2.2 The effects of temperature on the specific heat capacity of the composites

Figures 12 and 13 display the effects of temperature on the specific heat capacity of the composites. When the temperature increases, the specific heat capacity of the composites also increases. This approach demonstrates that kinetic energy is kept within the material through the vibrations of the lattice, the rotations of molecules and the molecules themselves. Every movement or rotation is alleged to be a degree of freedom. Heat is required to extend the temperature of a material as a result of the K.E. per degree of freedom; this must increase because the temperature will increase. The more degrees of freedom, the greater the specific heat capacity [24].

Figure 14 shows the effect of temperature on the specific heat capacity of the compound made of foam and wood. The figure shows that an increase in temperature leads to a decrease in specific heat capacity because the foam contains air pockets. This reduces the holes in the foam and, thus, leads to the formation of more compact material. As a result, this reduces the degree of freedom, leading to a decrease in the capacity of specific heat [34].

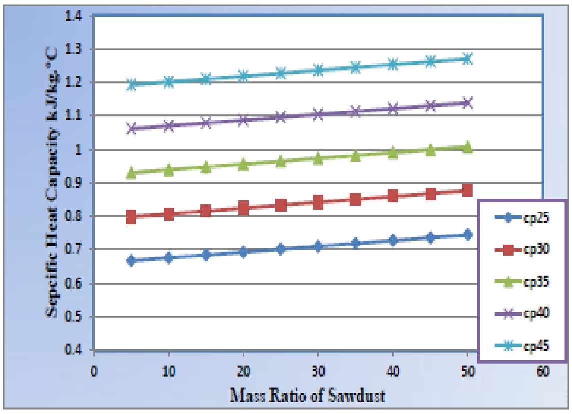

Figure 12 The effect of mass ratio and temperature on the specific heat capacity of sawdust (liquid polyurethane)

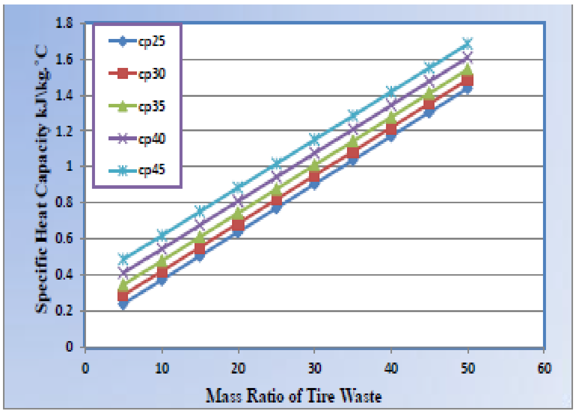

Figure 13 The effect of mass ratio and temperature on the specific heat capacity of tyre waste (liquid polyurethane)

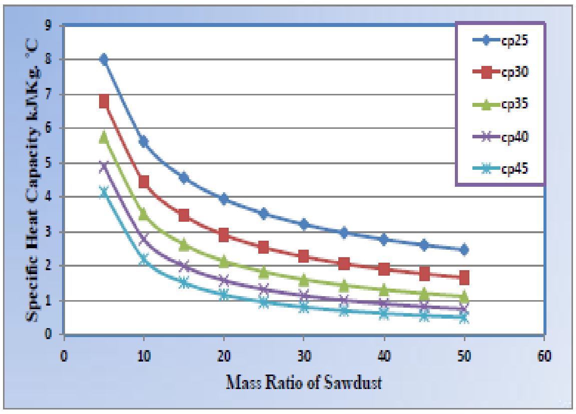

Figure 14 The effect of mass ratio and temperature on the specific heat capacity of sawdust (polyurethane foam)

6.3 Hardness

Figure 15 explains the variation of the hardness of the sawdust (liquid polyurethane) composite with a mass fraction of sawdust. The figure reveals a drop in hardness from 96.45 at 5% to 18.75 at 50%.

This behaviour is because the particles of sawdust may cause porosity, which weakens the composite [24].

Figure 16 shows the variation of hardness in the tyre waste (liquid polyurethane) composite with a mass fraction of rubber waste. First, notice a decrease in hardness until the rubber ratio reaches 20%, and then the hardness of the composite increases with the increasing ratio of waste rubber. The reason for this drop is initially due to the combination of particles in the waste rubber. Additionally, flipping the material into the air leads to the introduction of air and the formation of voids, which reduces thermal insulation hardness. The increase in the percentage of waste rubber, characterised by its dominance, leads to a more uniform distribution and collection of rubber particles, which leads to an increase in hardness; a 20% addition of tyre waste resulted in 63.78, whereas a 50% addition results in the insulator hardening to 122.52 [36].

Figure 17 shows how the sawdust load was affected by the hardness of the polyurethane foam. The increase in the composite hardness can be attributed to the structure of the foam matrix, which is generally softer because it contains bubbles or interstitial spaces. As content increases, regular dispersion begins with the penetration of fine particles from the sawdust between the polymer matrix molecules, reducing interstitial distances and increasing bond strength, thus, increasing the hardness of the composite [35].

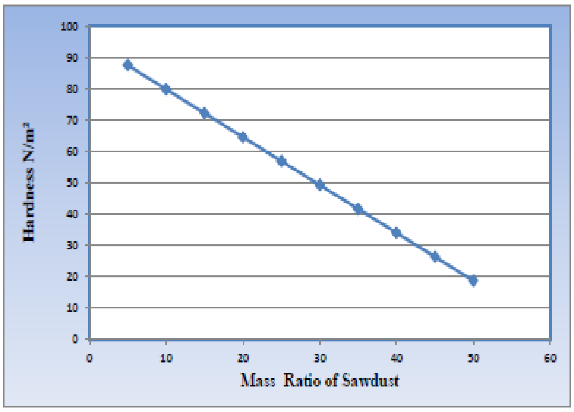

Figure 15 The effect of mass fraction of sawdust (liquid polyurethane) on hardness

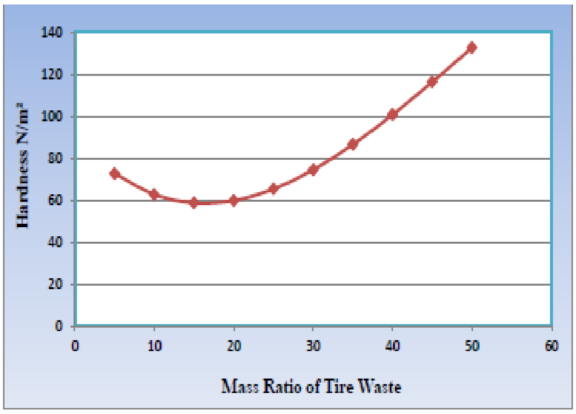

Figure 16 The effect of mass fraction of waste tyre (liquid polyurethane) on hardness

Figure 17 The effect of mass fraction of sawdust (polyurethane foam) on hardness

6.4 The result of optimisation

Figures 18, 19 and 20 show the results of the optimisation technique (Pareto optimal set) on thermal insulation composites. Table 1 below contains the optimum values of thermal conductivity, hardness and their variables.

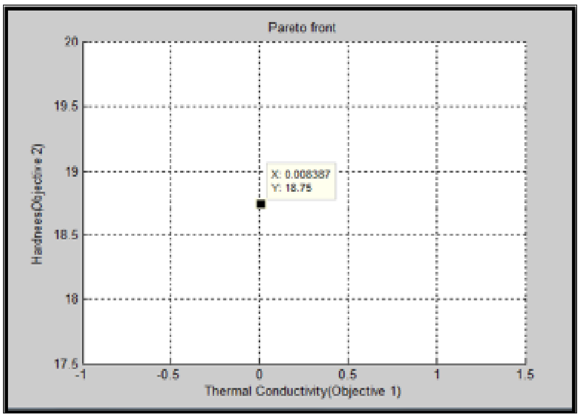

Figure 18 Pareto front set (Sawdust: liquid polyurethane)

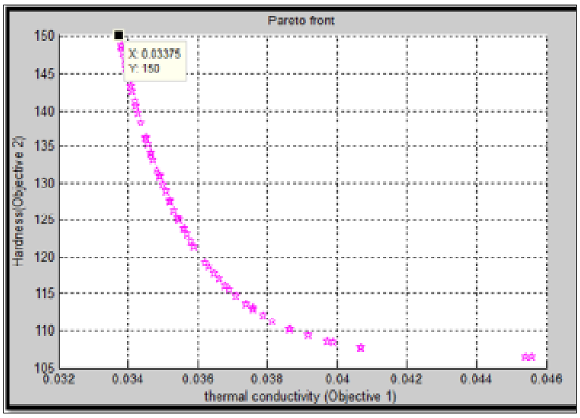

Figure 19 Pareto front set (Sawdust: polyurethane foam)

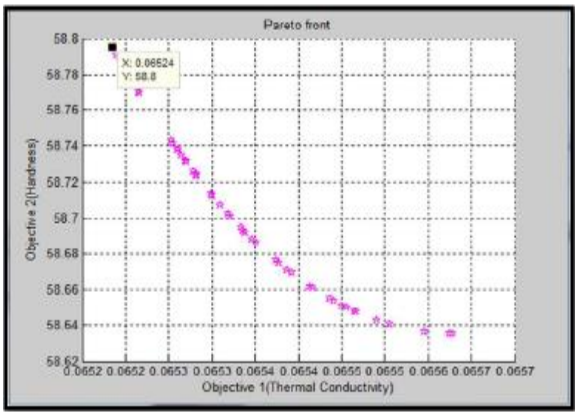

Figure 20 Pareto front set (Tyre waste: liquid polyurethane)

Table1: Optimum values of thermal conductivity, hardness, and their variables

Composites	k W/m^2.ºC	H	T ºC	Mass Fr of additives %
Sawdust: liquid polyurethane	0.008387	18.75	25.	50
Sawdust: polyurethane foam	0.033745	149.9965	25	49.99815
Tyre waste: liquid polyurethane	0.063313	72.645	25	5

7. Conclusion

Filler-loading sawdust decreased the thermal conductivity of thermal insulator composites. Filler-loading tyre waste increased the thermal conductivity of thermal insulator composites, but it remained within the range of thermal insulation. Thermal conductivity for all composites increased when the temperature increased. Specific heat capacity increased for the sawdust (liquid polyurethane) and tyre waste (liquid polyurethane) composites as the temperature increased. The mechanical properties of tyre waste (liquid polyurethane) and sawdust (polyurethane foam) improved with an increase in filler loading. The use of wood and tyre waste achieves the standard of sustainability in the thermal insulator industry because it reduces the cost of manufacturing thermal insulators. However, the use of these thermal insulators leads to a reduction in the energy consumption of the building, as well as ridding the environment of proper waste. Using the optimisation method to extract optimal values contributes to reducing the cost of thermal insulation manufacturing, which contributes to standards of sustainability.

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