DOI: https://doi.org/10.4038/engineer.v58i2.7689

ENGINEER - Vol. LVIII, No. 02, pp. [01-14], 2025
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Production of Coir Fibre-Reinforced Natural Rubber Composite Using Vacuum-Assisted Resin Transfer Moulding (VARTM) Process for Roofing Insulation Applications in Buildings

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Abstract: This research paper aims to produce a coir fibre-reinforced natural rubber composite using a Vacuum-Assisted Resin Transfer Moulding (VARTM) process for building roofing applications. Using coir fibre as a reinforcement in different applications is a much-researched feature because it is a readily available natural fibre. Coir fibre is a low-cost material with a high strength-to-weight ratio. The thermal properties of a composite mainly depend on volume fraction, arrangement of fibre reinforcement, and the production process. The novelty of this research lies in using the VARTM process for producing composite materials while allowing precise control over the resin infusion process, resulting in uniform distribution of natural rubber latex throughout coir fibre reinforcement. This research addresses challenges in existing manufacturing processes for coir fibre-reinforced composites, such as poor resin distribution and inadequate fibre-matrix interaction. By utilising VARTM, the primary purpose of this research is to overcome these challenges and achieve a high-quality composite with improved mechanical and thermal properties. The methodology includes a state-of-the-art review and analytical, numerical, and experimental analysis. Expected outcomes comprise an improved manufacturing process for developing natural bio-composite material. Research significance lies in the potential for creating a sustainable and eco-friendly composite. Analytical calculations and numerical simulations validated the experimental thermal conductivities. However, experimental results have deviated from the analytical and numerical results due to the limitations of theoretical equations available in the literature. Hence, the underlying reasons for this difference have been discussed in detail. According to this research, the VARTM method manufactured 4cm coir fibre length and 275g coir fibre weight sample was selected as the best sample for roofing insulation in a building. The lowest thermal conductivity of the specified sample was 0.08W/(mK), and the respective tensile stress was 0.19MPa.

Keywords: Coir Fibre, Natural Rubber, Composite, Vacuum-Assisted Resin Transfer Moulding (VARTM), Manufacturing

1. Introduction

Composite materials denote combining two or more materials with distinct properties to form a single material with enhanced characteristics. Coir fibre-reinforced composite materials have attracted researchers' attention due to their upgraded physical, mechanical, and thermal properties. The focus of recent research has moved to developing new thermal insulators due to the current importance of saving energy in high-temperature industrial applications and buildings. Most energy consumption in a building is for the Heating, Ventilation, and Air Conditioning (HVAC) process. In this process, the thermal comfort in the building is maintained in a way that is comfortable for the people inside the building. The roof of a building plays a critical role in the building's overall energy efficiency and thermal comfort [1]. Compared to walls, the roof is directly exposed to the sun, making it a major source of heat gain.

Roof thermal insulation was noted many years ago because nearly 60% of the heat energy transferring happens across the roof of the

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building [2]. Therefore, a percentage of the heat entering the building can be controlled by adding an insulation layer to the roof to reduce the energy spent on HVAC systems. According to Table 1, DIN 4108 standards say that the thermal conductivity of a thermal insulating material must be lower than 0.1W/ (m.K) [3]. According to this standard, the value of a perfect thermal insulator should be lower than 0.03W/ (m.K).

Table 1 – Classification of thermal insulating materials [3]

According to the DIN 4108, "Thermal insulation and energy economy in buildings"	
Thermal insulating materials	Lower 0.1 W/(m.K)
Very good thermal insulator	Lower 0.03 W/(m.K)
Moderate thermal insulator	0.03 W/(m.K) - 0.05 W/(m.K)
Less effective thermal insulator	Higher 0.07 W/(m.K)

Most thermal insulation materials are produced from mineral and fossil sources. For example, fibreglass, extruded polystyrene (XPS), expanded polystyrene (EPS), and polyurethane (PUR) are widely used in many building applications due to their affordability [4].

However, these traditional insulation materials are toxic to human health and the environment [5]. These insulation materials are effective in thermal performance, yet often depend on synthetic and non-renewable components that can cause significant risks.

Table 2 lists the presently used materials for roofing thermal insulations and their respective thermal conductivities.

Table 2 – Thermal conductivities of common roofing insulators

Roof thermal insulator materials	Thermal Conductivity values (W/mK)
Polyisocyanurate Board	0.018 - 0.025
Extruded Polystyrene Board	0.029 - 0.039
Expanded Polystyrene Board	0.032 - 0.044
Spray Polyurethane Foam	0.023 - 0.032
Fiberglass Batts	0.032 - 0.045
Mineral Wool Batts	0.034 - 0.048
Cellulose Insulation	0.038 - 0.045
Perlite Board	0.05 - 0.07
Concrete Roof Tile	0.81 - 1.4
Clay Roof Tile	0.69 - 1.0

Fibreglass insulation is made from glass fibres, which can annoy the skin, eyes, and breathing system when exposed to the atmosphere. Polystyrene foam is a widely used insulation material. It is derived from petroleum and can release harmful chemicals, such as styrene, during production and disposal. In addition to the health concerns, another significant issue is the environmental impact of these traditional insulation materials. The production and disposal of conventional insulation materials may have harmful environmental effects, contributing to greenhouse gas emissions, water pollution, and the depletion of natural resources.

Researchers have been searching for sustainable insulation materials to solve this issue. These materials are becoming popular because they are biodegradable, non-toxic, and have significantly low embodied energy during manufacturing. These types of sustainable insulation materials are typically produced by using lignocellulose fibre. Coir fibre is one of the lignocellulose fibres derived from coconut husk. It is a renewable, abundant, and environmentally friendly raw material for manufacturing composites. Polymeric composites reinforced with natural fibres like coir fibre have been developed recently and exhibit significant potential for various engineering applications due to their sustainability, low cost, low weight, and low thermal conductivity [6]. However, adding a binder material such as natural rubber to the coir fibre is essential to create the final material. Then, the final composite material will be fully biodegradable.

A composite material containing one or more bio or natural components is called a bio-composite [7]. A bio-composite can be fully degradable or partially degradable, according to the materials it contains. For example, coir fibre-reinforced natural rubber bio-composite can be named a fully degradable bio-composite because both materials are biodegradable. This is important because non-biodegradable materials such as plastic have become a disaster for the environment. These plastic materials create numerous problems, such as blocking drainages, polluting rivers and oceans, reducing the strength and quality of the soil, and triggering the greenhouse effect.

Using coir fibre as a reinforcement material improves the final material's physical, mechanical, and thermal properties [8]. Coir fibre has some unique characteristics, such as resistance to seawater, microbial attack, and high impact [9]. Coir fibre-reinforced natural rubber latex composite has good mechanical properties and comparatively low thermal conductivity values that ideally match roofing insulation requirements [10]. However, when manufacturing coir mats for roofing insulation, it is essential to modify the mat's surface to make it chemically moisture-resistant. This modification could be achieved by applying an appropriate coating or giving some treatment while enhancing the moisture resistance [11].

Researchers have identified how the composite is made up, and the fibre percentage in the composite can significantly impact the mechanical and thermal properties of the product, such as thermal conductivity, tensile strength, and flexural strength [12]. Thermal conductivity is the ability of a material to conduct heat, which is a remarkable factor when finding the heat transfer reduction efficiency of roofing insulation materials. In steady-state conditions, heat transfer through a solid material is essentially controlled by its thermal conductivity. A combination of thermal conductivity and specific heat capacity decides the heat transfer in transient situations [13]. Incorporating air voids into a material significantly decreases its effective thermal conductivity [14]. Composite material like coir fibre reinforced natural rubber latex composites consisting of some percentage of volume fractions of air voids is exposed to a thermal gradient [15]. Heat transfer happens through vibrational conduction in the solid phase, conduction by colliding gas molecules in the void phase, and radiation either through a partially transparent solid phase or across large voids [16]. For air void sizes smaller than 5 mm (about 0.2 in), convection heat transfer can be ignored for the material under consideration in this investigation [17]. Therefore, the thermal conductivity of coir fibre-reinforced natural rubber latex composites, commonly used in roofing insulation applications, can be significantly decreased by incorporating some (percentage of) air voids into the composite materials. This can be achieved by increasing the material's air void volume fraction using longer coir fibres [18]. Longer coir fibres make air-filled cavities within the material more prominent, reducing the overall thermal conductivity. The air void volume fraction of the natural rubber latex composite with coir fibre reinforcement must be selected to preserve its strength and mechanical properties while minimising thermal characteristics.

This balance can be established by experimenting and testing to measure the thermal conductivity and mechanical properties of the coir fibre-reinforced natural rubber latex composite with different fibre lengths [19].

A detailed investigation is essential to select an effective air void volume fraction of the composite to achieve the desired mechanical strength while minimising thermal conductivity. Various techniques can be implemented to select the composite material's desired air void volume fraction. These may include controlling the volume fraction of coir fibre/natural rubber and the arrangement of coir fibre reinforcement within the natural rubber matrix during the manufacturing process. Additionally, post-processing methods such as heat treatment or surface modifications could be investigated to fine-tune the air void volume fraction of the composite [20]. Selecting the desired volume fraction of air void for the coir fibre-reinforced natural rubber Latex composite ensures that the material meets the thermal insulation requirements for roofing applications while maintaining its structural integrity. By addressing the air void volume fraction, the composite can effectively achieve the desired balance between mechanical strength, thermal performance, and energy efficiency, thus enhancing its suitability for sustainable and environmentally friendly roofing insulation solutions. The research study's next phase will investigate the methodologies for selecting the desired volume fraction of air voids of the composite material and explore its impact on the overall performance of roofing applications.

Similarly, the composite's manufacturing process will be affected to ensure the coir fibre distribution and alignment along the overall structure of the composite. The focus has been on implementing Vacuum-Assisted Resin Transfer Moulding (VARTM) to enhance control over the resin infusion process and achieve a uniform distribution of natural rubber matrix within the coir fibre reinforcement. Manufacturing coir fibre-reinforced natural rubber latex composites addresses the difficulties faced in current manufacturing methods for coir fibre-reinforced materials, including insufficient resin distribution and limited fibre matrix interaction [21]. This study mainly intends to analyse the mechanical and thermal properties of the developed composite material as a roofing insulator for residential buildings. Several methods can be employed to select the desired air void volume fraction of the coir fibre-reinforced natural rubber latex composite manufactured by VARTM. These may include adjusting the vacuum level during the resin infusion process, exploring different moulding pressures, and introducing innovative surface treatments to regulate the air void volume fraction at a micro-level [22]. These methods help ensure the composite maintains its structural integrity while achieving the desired thermal insulation properties essential for roofing applications.

The next research phase will involve experimenting to validate the effectiveness of the identified methods for selecting the desired air void volume fraction. This experimental validation will provide important data on the composite's mechanical strength, thermal conductivity, and insulation performance, further contributing to developing a sustainable and energy-efficient roofing material. Implementing these methodologies for selecting the desired air void volume fractions will significantly enhance the composite's suitability for roofing insulation applications, addressing the industry's need for environmentally friendly and high-performance materials. The research aims to improve the production process of coir fibre-reinforced natural rubber latex composites using VARTM and evaluate the thermal properties of the composite for roofing insulation applications. As an initial investigation of this journey, a research study examined the influence of coir fibre length and volume fraction of coir fibre, natural rubber latex and air voids for obtaining the lowest thermal conductivity composite. Thirty-six coir fibre-reinforced natural rubber composite mats were produced using the commonly used traditional Hand Layup (HL) manufacturing process and the modern VARTM process. Experimental thermal conductivity values were measured using a hot disk analyser at the Open University Sri Lanka. Analytical equations available in the literature helped validate these experimental results. Finite Element Analysis (FEA) was conducted using ANSYS software to validate these results further.

1.1 VARTM Process

VARTM is a composite production process that uses moulds in a closed environment (Figure 1).

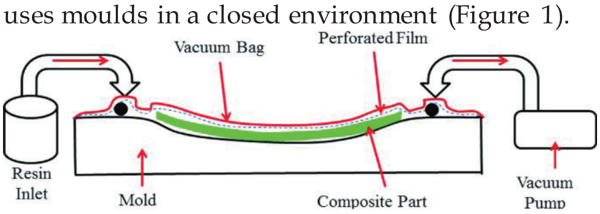


Figure 1 - Vacuum assisted resin transfer moulding (VARTM) technique

The closed vacuum space required for this process is created using a vacuum bag, which covers and seals the whole system. Then, a mould-releasing agent is applied inside the mould. Next, coir fibre is laid according to a standard unidirectional orientation. As mentioned above, the whole system is vacuumed by the vacuum bag using a vacuum pump, and the resin (natural rubber latex) is sent into the mould as required. The heater is switched on to increase the mould temperature from 90^0C to 100^0C. About one hour later, the polythene bag is removed after switching off the vacuum pump. The mould is kept upside down for another half an hour, and the heater is switched on to dry the mat. Finally, the mat is removed from the mould.

This VARTM process typically creates thermal insulation composite materials with a 60-75% fibre percentage [23]. The VARTM process can be used to manufacture boats, aircraft parts, rail cars, and furniture [24]. Deciding the physical, mechanical, and thermal properties of the manufactured thermal insulation materials depend on the weight ratio of coir fibre to natural rubber.

Increasing the amount of coir fibre improves mechanical properties [25]; however, there is a maximum limit on the amount of coir fibre that can be used, typically about 70% of the weight [26]. Factors such as corrosion resistance, resistance at high temperatures, and surface finish are decided mainly by the type of resin used [27] (e.g., natural rubber). Recent research proves that the VARTM process can help to create composite materials with numerous advantages compared to the traditional hand layup manufacturing process [28]. Comparing the VARTM process steps with the conventional hand layup process identifies several extra steps. At least one professional, well-experienced technician is required to perform this VARTM process [29].

1.2 Benefits of Using the VARTM Technique for Manufacturing Composites

The VARTM process provides many advantages over the hand layup or spray layup processes for composite manufacturers, building constructors, and end users for composite construction. Some such advantages are discussed below.

Creating a structure with more strength and good mechanical properties

The mechanical properties of the composite material structures have been developed and created using the VARTM technique; they show an increase in tensile strength. Using a large ratio between the weights of coir fibre and natural rubber helps manufacture a composite structure with fewer faults [30], and their mechanical properties are much improved. Previous research has shown that the strength of the structures manufactured using the VARTM process has increased by 26.68% compared to the traditional hand layup process [31]. The lifetime of these structures has also increased compared to the conventional methods.

Minimising the manufacturing waste

The manufacturing waste is reduced compared to the hand layup process because the natural rubber resin is used only at the final stage of the VARTM technique. The main reason is the ability to calculate the required amount of natural rubber resin earlier. Also, coir fibre and natural rubber are not collected unnecessarily. The VARTM process provides an excellent surface finish for the composites. This reduces the last steps of the finishing process and reduces material wastage.

Minimum Health Effects

The health effects have become very low and minimal because both materials used for coir fibre-reinforced natural rubber latex composites are natural and non-toxic. Manufacturing other composite materials may produce styrene, which is unhealthy for humans due to the raw materials used. Styrene is mainly used in polystyrene and resin production, and styrene vaporisation occurs during the manufacturing of many composites.

Manufacturing low-weight structures

In thermal insulators, especially roofing applications, the installation process becomes easier when the structure is low-weight. In hand layup technology, it is difficult to calculate the exact coir fibre and natural rubber ratio to get a structure with good strength. However, using the VARTM technology, the weight ratio can be arranged to obtain the maximum strength without any calculations.

Increasing the manufacturing efficiency of coir fibre-based composite materials for thermal insulations

The efficiency of the manufacturing process is significant because it directly affects the financial side of manufacturers. Therefore, manufacturers concentrate on improving efficiency by changing or developing the manufacturing process. Considering the effectiveness of thermal insulation manufacturing, coir fibre-based natural rubber thermal insulation manufacturing using the VARTM process becomes more efficient than the manufacturing processes based on fibreless clay roof tiles, concrete roof tiles, and perlite board production.

Improving the product quality

The coir/rubber mats manufactured using the VARTM technique are higher quality than those obtained from other manufacturing processes. Therefore, the defects in coir/rubber mats are considerably less than in coir/rubber mats manufactured using the HL method. Void formation, de-lamination, ply waviness, and thickness variations are the predominant defect types in composite structures. The VARTM technique provides a better product with minimum defects.

Reducing the life cycle cost (LCC)

Most composite manufacturers hesitate to use the VARTM technique despite its considerable benefits. The main reason for the manufacturers' lack of enthusiasm is the lack of awareness about the financial benefits.

2. Materials and Methods

Thirty-six coir fibre-reinforced natural rubber latex samples were manufactured using the traditional hand layup (HL) method and the Vacuum Assisted Resin Transfer Molding (VARTM) method. Untreated brown coir fibres were collected from a site in the Wennappuwa area in Sri Lanka. Chamath et al. [32] have selected the optimum alkaline concentration as a 4% NaOH solution. Hence, the collected coir fibres were treated using a 4% NaOH solution for better surface roughness, chemical composition, and thermal stability. Ammonia-treated centrifuge natural rubber latex was collected from S & C Pvt (Ltd), Horana, Sri Lanka. Pre-vulcanized natural rubber latex was manufactured with the assistance of the Rubber Research Institute (RRI), Ratmalana, Sri Lanka. Eighteen VARTM coir/rubber mats were manufactured using the vacuum pump apparatus in the composite laboratory, Department of Mechanical and Manufacturing Engineering, University of Ruhuna. Other coir rubber mats were produced using the hand layup (HL) method. Thermal conductivities of all coir/rubber mats were measured using a hot disk thermal analyser at the Open University of Sri Lanka. The tensile test was performed using the tensile test machine in the Division of Chemical and Polymer Engineering Technology, Institute of Technology, University of Moratuwa.

3. Analytical Calculations

The literature introduces several analytical models to calculate the effective thermal conductivity of composite materials theoretically. In these models, the effective thermal conductivity is calculated utilising the thermal conductivity of each material and respective volume fraction of the individual materials, in this research, thermal conductivity of coir fibre – 0.05W/mK [33] and thermal conductivity of natural rubber – 0.12W/mK [34]. Some analytical models commonly used for predicting the thermal conductivity of the composites are mentioned below [35]. Table 3 summarises analytical equations for respective analytical models and the symbols used are given below:

- K_c is the effective thermal conductivity of the composite
- V_f is the volume fraction of the fibre (for this case, in coir fibre)
- K_f is the thermal conductivity of the fibre
- V_m is the volume fraction of the matrix (for this case, in natural rubber latex)
- K_m is the thermal conductivity of the matrix

3.1 Rule of Mixtures Model (Eq.1)

This is a simple model, which assumes that the effective thermal conductivity of the composite becomes the weighted average of individual components. Table 3 presents the rules of mixtures equation for the effective thermal conductivity.

Limitations:

Simplicity is the most crucial factor of this model. It ignores the following factors:

- Fibre orientation
- Thermal resistance between fibre and the matrix (Interface resistance)
- Air void volume fraction

Table 3 – Analytical equations

Analytical Equations		
Eq.No.	Analytical Model	Equation
Eq.1	Rule of Mixtures Model	$K_c = V_f K_f + V_m K_m$
Eq.2	Parallel Model	$K_c = V_f K_f + V_m K_m$
Eq.3	Series Model	$\frac{1}{K_c} = \frac{V_f}{K_f} + \frac{V_m}{K_m}$
Eq.4	Maxwell-Eucken Model	$K_c = K_m * \left[\frac{(K_f+2K_m)+V_f(K_f-K_m)}{((K_f+2K_m)-V_f(K_f-K_m))}\right]$
Eq.5	Hashin-Shtrikman Bounds Lower bound	$K_{c-} = K_f + \frac{V_m}{\left[\frac{1}{(K_m-K_f)}+\frac{V_f}{3K_f}\right]}$
Eq.6	Hashin-Shtrikman Bounds Upper bound	$K_{c+} = K_m + \frac{V_f}{\left[\frac{1}{(K_f-K_m)}+\frac{V_m}{3K_m}\right]}$

3.2 Parallel Model (Eq.2)

The parallel model assumes that the heat flow is parallel to the fibre orientation. It gives an upper bound for the effective thermal conductivity. The formula for the parallel model is straightforward. The parallel model equation seems equal to the rule of mixtures equation, but the interpretation and application are different.

- Upper Bound: The parallel model gives an upper bound of the effective thermal conductivity. The heat does not flow parallel to fibre orientation in the real world. Therefore, the value from the parallel model is higher than the practical value of the effective thermal conductivity.
- Fibre Alignment: This model applies only to well-aligned fibres, and the heat flow aligns in the same direction.
- Not always realistic: When the composite's fibre orientation is

- random, it is impossible to get realistic thermal behaviour from this model.
- Therefore, an overestimation is possible in a parallel model.

This model provides an idea about the maximum thermal conductivity of the composite.

3.3 Series Model (Eq.3)

This model assumes the composite's heat transfer is perpendicular to the fibre orientation. Therefore, the Series Model gives a lower bound value of the effective thermal conductivity.

- Assumptions of the Series Model: Heat flow is perpendicular to the fibre orientation.

The equation of the Series Model is different from all previously mentioned models.
The reciprocal of the effective thermal conductivity (1/K) is considered here.

- Lower Bound: The series model gives a lower bound of the effective thermal conductivity. The heat flow of a composite very rarely becomes perpendicular to the fibre orientation. Therefore, the actual thermal conductivity value must be higher than the value given by this model.
- Limiting factor: The lowest thermal conductivity value of the composite is a limitation.
- Less Common: Common usage of the Series Model is rare compared to the Parallel or the Rule of Mixtures models because the heat flow becoming perpendicular to the fibre orientation is rare.

3.4 Maxwell-Eucken Model (Eq.4)

This model considers the geometry and the distribution of the fibre material (coir fibre) in the matrix (Natural rubber latex), and is more suitable for low-volume fractions of fibre materials. Two equations are related to this model, but the one used for low fibre volume fraction composite is the most important.
Key points:

- Geometry matters: The fibre particle shape is considered in this model (assumed as spherical), unlike in other models.
- Low to moderate fibre content: This equation produces the most accurate results when the fibre volume fraction is low to moderate.
- More realistic: The results obtained using the Maxwell-Eucken model are more accurate than those obtained using the above-mentioned simple models.
- Shape Assumptions: This model assumes that coir fibres are spherical. However, coir fibres are cylindrical in actual situations. Therefore, this assumption is not 100% accurate.

Fibre interactions: Fibre interactions such as fibre alignments and contact resistance, which should be considered for higher fibre loadings, are not considered here.

3.5 Hashin-Shtrikman Bounds (Eq.5 & Eq.6)

This model calculates the composite's upper and lower bounds of effective thermal conductivity by considering the geometry and other properties of the individual materials. Researchers have predicted effective thermal conductivity using one or more models. It is difficult to decide which model to use precisely for any application, as it needs additional details. These bounds are based on the variational principle.

- Statistical isotropy: This composite material is assumed to be statistically isotropic. That means the properties of the composite material are equal for every direction at the macroscopic level.
- Two-phase material: This model assumes two distinct phases (in this example, coir fibre and natural rubber latex).

Key points:

- Tightest bounds: The Hashin-Shtrikman bounds provide the narrowest possible range of the thermal conductivity values for a two-phase composite.
- Microstructure independent: One advantage of this model is that these bounds are independent of the microstructure. They depend only on volume fraction and individual properties.
- Theoretical limits: A critical factor is that these are only theoretical limits. The actual thermal conductivity value must be in between these two bounds. Their thermal conductivity depends on

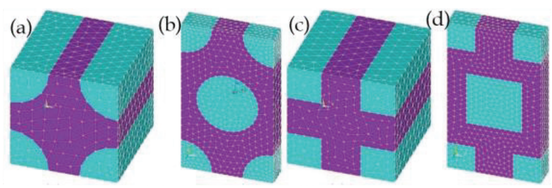
the microstructure of the composite material.

4. Numerical Simulation

In numerical simulation, Finite Element Analysis (FEA) evaluated the thermal conductivity of the coir fibre-reinforced natural rubber composite. Manufacturers can accurately forecast the filling time and flow front pattern of the natural fibre latex resin all around the mould by simulating the VARTM process with ANSYS software [36]. This simulation allows for better control and optimisation of the manufacturing process for coir mats, ensuring uniform quality and geometrical accuracy. ANSYS software provides a diversified platform to simulate the VARTM process, allowing manufacturers to analyse various parameters such as resin flow and pressure distribution inside the mould. Operators can learn about process optimisation, material use efficiency, and potential areas for operation improvement by introducing ANSYS simulation into the manufacturing workflow.

The Finite Element Model (FEM) based on a 3D-dimensional micro-mechanical Representative Volume Element (RVE) with a square and hexagonal geometry was implemented while using ANSYS software [37], [38]. A circular cross-section of fibre and a square cross-section of fibre were considered in developing RVE. The steady-state heat transfer simulations were performed in thermal analysis to calculate the thermal conductivity of the composite.

Thermal conductivity results obtained using FEA were compared with different analytical methods, and good agreement was achieved. Finally, those results were compared with the experimental thermal conductivity values in the discussion section. Many parameters influenced the results: the volume fraction of fibres, the geometry of fibre, and RVE. Figure 2 displays the meshed models used in the numerical simulation for different RVEs.



Meshed model of (a) square RVE with circular fiber, (b) hexagonal RVE with circular fiber, (c) square RVE with square fiber, and (d) hexagonal RVE with square fiber

Figure 2 – Meshed models of different RVEs [39]

Numerical simulation was conducted using the ANSYS workbench software. A material designer toolbox was selected in the ANSYS workbench to start the project. Coir fibre and natural rubber materials were defined as new materials in engineering data. Material designer space claim window was opened to define the unidirectional RVE model as hexagonal RVE with circular fibre. Natural rubber was selected as the matrix material, and coir fibre as the fibre material. Figure 3 illustrates the numerical analysis process in the ANSYS workbench software.

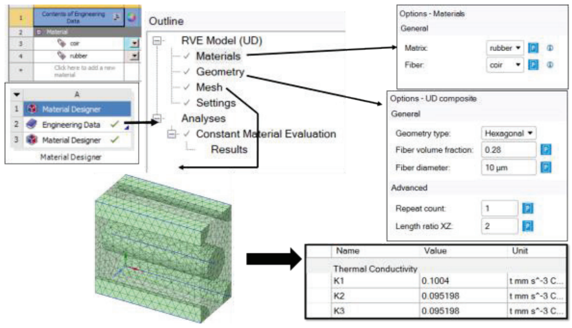


Figure 3 – Numerical analysis Process in the ANSYS workbench

5. Results

The hot wire disk apparatus at the Open University of Sri Lanka was used to measure thermal conductivity data. Figure 4 demonstrates how the hot wire disk analyser measured thermal conductivity. Table 4 provides the experimentally measured thermal conductivity data for 36 coir fibre-reinforced natural rubber latex composite mats. These mats were produced using 2cm, 4cm, and 6cm long coir fibres. The traditional hand layup and the modern VARTM methods were the production processes. Table 5 presents the analytical results obtained for their respective theoretical equations in Table 3. Table 6 gives the data from numerical analysis obtained by finite element simulation using ANSYS software, as explained in Section 4. Tables 5 and 6 reveal that analytical and corresponding numerical results are approximately equal. However, these values deviated from the experimental results. The causal factors for this difference were identified and discussed in the Discussion section (Section 6) of this research paper.

Figures 5, 6, and 7 show the multiple bar charts that plotted analytical, numerical, and experimental thermal conductivity data against the coir fibre weight.

Figure 4 – Thermal conductivity measurement obtained by hot wire analyser in the Open University, Sri Lanka

Table 4 – Thermal conductivity data for coir/rubber composite mats (Experimental)

CF weight (g)	200	225	250	275	300	325
2cm Coir Fibre Length-VARTM Produced Coir Mats						
NR weight (g)	240	435	385	360	485	430
CF/NR ratio	83%	52%	65%	76%	62%	76%
TC(W/mK)	0.11	0.12	0.13	0.13	0.12	0.11
2cm Coir Fibre Length-HL Produced Coir Mats						
TC(W/mK)	0.08	0.09	0.10	0.10	0.09	0.09
4cm Coir Fibre Length-VARTM Produced Coir Mats						
NR weight (g)	245	355	375	300	360	425
CF/NR ratio	82%	63%	67%	92%	83%	77%
TC(W/mK)	0.11	0.12	0.12	0.08	0.10	0.10
4cm Coir Fibre Length-HL Produced Coir Mats						
TC(W/mK)	0.08	0.09	0.09	0.08	0.08	0.08
6cm Coir Fibre Length-VARTM Produced Coir Mats						
NR weight (g)	290	305	355	340	355	345
CF/NR ratio	69%	63%	70%	81%	85%	94%
TC(W/mK)	0.12	0.12	0.13	0.13	0.12	0.11
6cm Coir Fibre Length-HL Produced Coir Mats						
TC(W/mK)	0.09	0.09	0.09	0.09	0.08	0.08

Table 5 – Analytical results obtained by respective equations in Table 3

CF weight (g)	200	225	250	275	300	325
2cm Coir Fibre Length Coir Mats						
Eq.1	0.09	0.10	0.10	0.09	0.10	0.09
Eq.2	0.09	0.10	0.10	0.09	0.10	0.09
Eq.3	0.08	0.09	0.08	0.08	0.08	0.08
Eq.4	0.10	0.10	0.10	0.10	0.10	0.10
Eq.5	0.09	0.09	0.09	0.09	0.09	0.09
Eq.6	0.09	0.10	0.09	0.09	0.09	0.09
4cm Coir Fibre Length Coir Mats						
Eq.1	0.09	0.10	0.10	0.09	0.09	0.09
Eq.2	0.09	0.10	0.10	0.09	0.09	0.09
Eq.3	0.08	0.08	0.08	0.08	0.08	0.08
Eq.4	0.10	0.10	0.10	0.10	0.10	0.10
Eq.5	0.09	0.09	0.09	0.09	0.09	0.09
Eq.6	0.09	0.09	0.09	0.09	0.09	0.09
6cm Coir Fibre Length Coir Mats						
Eq.1	0.10	0.09	0.10	0.09	0.09	0.09
Eq.2	0.10	0.09	0.10	0.09	0.09	0.09
Eq.3	0.08	0.08	0.08	0.08	0.08	0.08
Eq.4	0.10	0.10	0.10	0.10	0.10	0.10
Eq.5	0.09	0.09	0.09	0.09	0.09	0.08
Eq.6	0.09	0.09	0.09	0.09	0.09	0.09

Table 6 – Thermal conductivity values obtained numerical analysis using ANSYS software

CF weight (g)	200	225	250	275	300	325
2cm Coir Fibre Length Coir Mats						
NR weight (g)	240	435	385	360	485	430
CF/NR ratio	83%	52%	65%	76%	62%	76%
TC(W/mK)	0.09	0.10	0.10	0.09	0.10	0.09
4cm Coir Fibre Length Coir Mats						
NR weight (g)	245	355	375	300	360	425
CF/NR ratio	82%	63%	67%	92%	83%	77%
TC(W/mK)	0.09	0.10	0.10	0.09	0.09	0.09
6cm Coir Fibre Length Coir Mats						
NR weight (g)	290	305	355	340	355	345
CF/NR ratio	69%	63%	70%	81%	85%	94%
TC(W/mK)	0.10	0.10	0.10	0.09	0.09	0.09

ASTM 3039 standard test methodology for tensile properties of polymer matrix composite materials was used to measure the mechanical properties of coir/rubber mats. These measurements were obtained by the tensile testing machine available in the Division of Chemical and Polymer Engineering Technology, Institute of Technology, University of Moratuwa. Figure 8 shows how the experiments were conducted using the tensile testing machine.

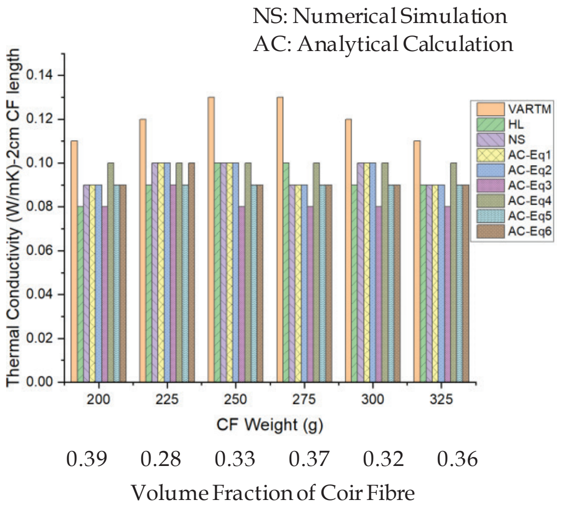


Figure 5 – Experimental, numerical, and analytical thermal conductivity comparison of 2 cm coir fibre length composites

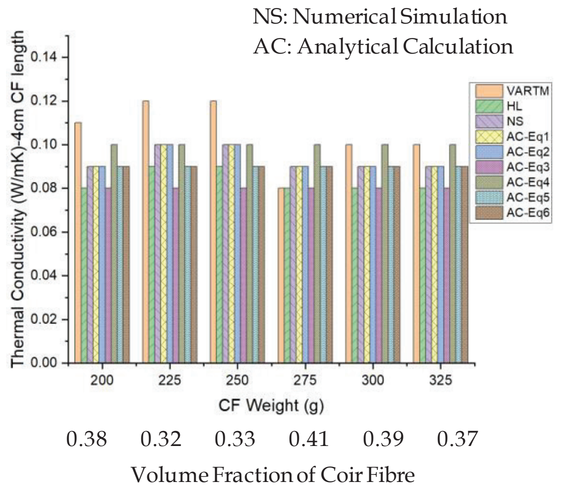


Figure 6 – Experimental, numerical, and analytical thermal conductivity comparison of 4 cm coir fibre length composites

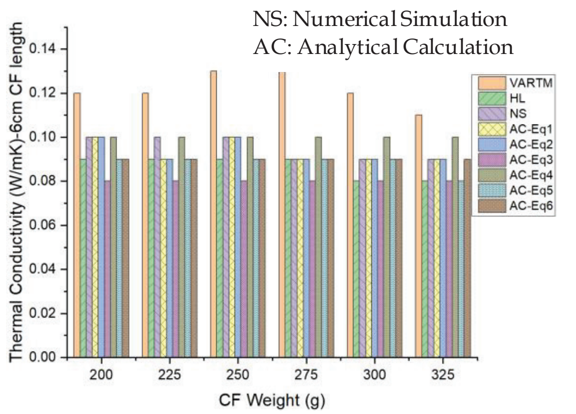


Figure 7 – Experimental, numerical, and analytical thermal conductivity comparison of 6 cm coir fibre length composites

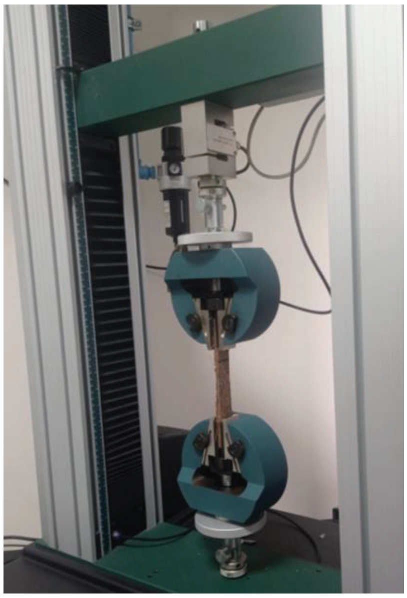


Figure 8 – Tensile testing in Institute of Technology, University of Moratuwa

Table 7 presents the experimentally measured Tensile Stress (TS) values for VARTM-produced and HL-produced coir/rubber mats.

Table 7 – Tensile stress results for coir/rubber composite mats

CF weight (g)	200	225	250	275	300	325
2cm Coir Fibre Length-VARTM Produced Coir Mats						
NR weight (g)	240	435	385	360	485	430
CF/NR ratio	83%	52%	65%	76%	62%	76%
TS(MPa)	1.20	0.73	0.40	0.57	0.28	1.2
2 cm Coir Fibre Length-HL Produced Coir Mats						
TS(MPa)	0.92	0.46	0.19	0.25	0.10	0.93
4 cm Coir Fibre Length-VARTM Produced Coir Mats						
NR weight (g)	245	355	375	300	360	425
CF/NR ratio	82%	63%	67%	92%	83%	77%
TS(MPa)	0.74	0.49	0.39	0.19	0.34	0.31
4 cm Coir Fibre Length-HL Produced Coir Mats						
TS(MPa)	0.47	0.13	0.15	0.10	0.13	0.12
6 cm Coir Fibre Length-VARTM Produced Coir Mats						
NR weight (g)	290	305	355	340	355	345
CF/NR ratio	69%	63%	70%	81%	85%	94%
TS(MPa)	1.29	0.62	0.44	0.47	0.41	0.65
6 cm Coir Fibre Length-HL Produced Coir Mats						
TS(MPa)	0.98	0.35	0.26	0.26	0.22	0.39

Figures 9, 10, and 11 illustrate the multiple graphs of experimental tensile stress data plotted against coir fibre weight.

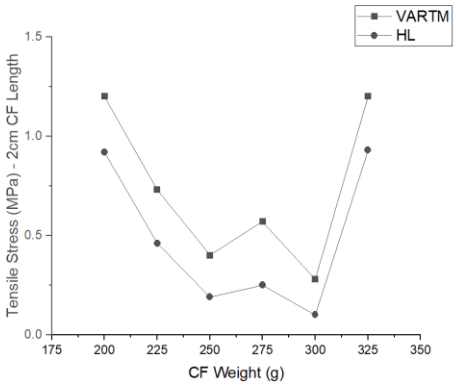


Figure 9 – Tensile stress results comparison for 2cm coir fibre lengths composites

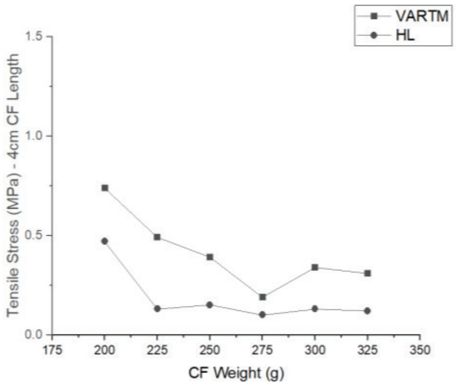


Figure 10 – Tensile stress results comparison for 4cm coir fibre lengths composites

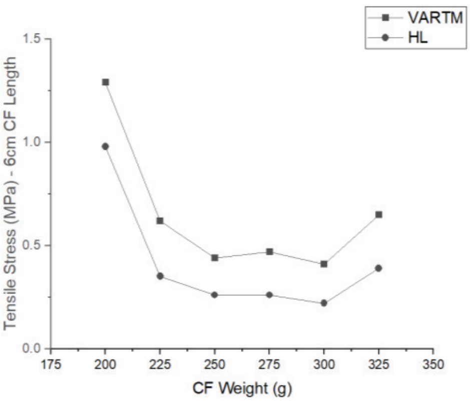


Figure 11 – Tensile stress results comparison for 6cm coir fibre lengths composites

6. Discussion

According to these bar charts (Figures 5, 6 and 7), FEA-derived thermal conductivity results were compared with different analytical methods, which produced a good agreement. Analytical and numerical simulation results of thermal conductivities are little bit lower than the experimental values obtained for VARTM produced coir/rubber mats but they have good agreement with the HL produced coir/rubber mats. The following reasons were identified as the main factors for this difference:

- **Rule of Mixtures Model: (Eq.1)**
  This highly simplified model ignores main factors such as fibre orientation, the thermal resistance between fibre and the matrix (Interface resistance), air void volume fraction, and the manufacturing process. Hence, some difference was noted between the practical and theoretical values.
- **Parallel Model: (Eq.2)**
  The parallel model gives an upper bound of the effective thermal conductivity. This model applies only to well-aligned fibres, and the heat flow aligns in the same direction. It is impossible to get realistic thermal behaviour from this model when the composite's fibre orientation is random. Therefore, an overestimation is possible in a parallel model.
- **Series Model: (Eq.3)**
  The bar charts (Figures 5, 6 and 7) clearly show that the Series Model gives a lower bound value of the analytical thermal conductivity.
- **Maxwell-Eucken Model: (Eq.4)**
  This model considers the geometry and the distribution of the fibre material (coir fibre) in the matrix (Natural rubber latex); hence, it is more suitable for low-volume fractions of fibre materials. In this experiment, however, the fibre volume fraction is high. This model has not given a reasonable result for thermal conductivities of VARTM produced coir/rubber mats. It assumes that coir fibres are spherical. However, in actual situations, coir fibres are cylindrical. Therefore, this assumption is not 100% accurate. Fibre interactions such as fibre alignments and contact resistance, which should be considered for higher fibre loadings, are not considered in this model.
- **Hashin-Shtrikman Bounds: (Eq.5 & Eq.6)**
  This model calculates the composite's upper and lower bounds of effective thermal conductivity by considering the geometry and other properties of the individual materials. This composite material assumes that the composite material properties are equal for every direction at the macroscopic level— in nature, this is unrealistic. This model assumes two distinct phases (in this example, coir fibre and natural rubber latex). However,

coir/rubber composite consists of more than two phases in the actual situation. The result of this research emphasises that the theoretical values deviate from the practical values due to the assumptions made when deriving these equations.
The thermal conductivities of the coir/rubber composite depend on the composite material's microstructure. Still, no equation considered the effect of their microstructure.

- **Numerical simulation:**
Coir fibre and natural rubber materials are assumed to be isotropic materials while defining new materials in the simulation. The thermal conductivity of a single coir fibre and a natural rubber latex was used as the only parameter when defining the materials. The composite was considered a two-phase material. Therefore, the air void volume fraction was not considered during numerical analysis. Also, coir fibre was considered a unidirectional and a cylindrical fibre, though the real situation differs from those assumptions. As shown in the graphs, these assumptions have caused the numerical results to deviate from the experimental results.
- Material density: If the density of a material is high, the thermal conductivity is most probably high.
- Manufacturing process: Any minute change in the manufacturing process can make a significant difference in the thermal properties of the composite.
- Temperature: Thermal conductivity depends on the temperature.
- Moisture content: Moisture trapped inside the composite material can cause a drastic increase in thermal conductivity.
- Air void volume fraction: HL-produced coir/rubber mats have a higher air void volume fraction than the VARTM-produced. However, the mechanical strength of HL-produced coir/rubber mats is low.

Thermal performance and mechanical performance of coconut fibre-reinforced natural rubber latex composite could be enhanced by pretreating the surfaces of coir fibre. However, when producing coir/rubber mats for roofing insulation, it is essential to modify the mat's surface to make it moisture-resistant. This modification could be achieved by applying an appropriate coating or some treatments while enhancing the moisture resistance.

A VARTM-produced 4cm coir fibre length with a coir weight of 275g coir/rubber mat sample had the lowest thermal conductivity value. This value is 0.08W/(mK). The corresponding coir fibre weight to natural rubber weight ratio is 92%. This is a high value compared to other ratios. This indicates that, compared with coir fibre weight, the natural rubber weight is a low amount for this sample. Then, the respective air void volume fraction becomes higher than other VARTM samples, causing a lower thermal conductivity value.

The fibre length is an average value. However, the HL-produced coir/rubber mat sample with a 4cm coir fibre length and a coir weight of 275g gave the lowest thermal conductivity of 0.08W/mK. Compared to these two samples, the tensile strength is low in the HL-produced sample. Therefore, the best sample was selected as the VARTM-produced coir/rubber mat with 4cm coir fibre length and 275g coir weight.

This information proves that the coir fibre-reinforced natural rubber latex composites (coir/rubber mats) produced by the VARTM technique could solve issues with roofing thermal insulation in buildings.

7. Conclusions

This research paper expects to determine the possibility of producing coir fibre-reinforced natural rubber latex composites (coir/rubber mats) using the Vacuum Assisted Resin Transfer Moulding (VARTM) technique for roofing thermal insulation in building applications. It can be confirmed that manufacturers can produce coir/rubber mats with low thermal conductivity using the VARTM technique.
One future research area is testing for various fire-retardant chemicals suitable for medium-density coir/rubber mats, the mechanism of fire inhibition, and various methods adopted for chemical treatment. The different classes of fire retardant chemicals primarily suitable for treating coir fibre-reinforced polymer materials are identified, e.g., phosphorus-based fire retardants, nitrogen-based fire retardants, halogen-based fire retardants, and inorganic-based fire retardants. The applicability of these chemicals to coir/rubber mats, chemical treatments, and fire performance of these mats need to be further investigated.

Acknowledgement

The authors wish to acknowledge the Department of Physics, The Open University Sri Lanka, and the Division of the Chemical and Polymer Engineering Technology, Institute of Technology University of Moratuwa, Sri Lanka, for providing valuable support in resource arrangements of this study.

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