Thermal evaluation of Vacuum Insulation Panels with recycled cellulose based core material

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Abstract
Vacuum Insulation Panels (VIPs) have emerged as an advance thermal insulation material for enhancing thermal insulation for various applications. The conventional core material used in VIPs, such as fumed silica, offers excellent insulation properties but has some limitations in terms of cost and environmental impact. This research investigates the thermal properties of recycled cellulose insulation material for use in the core of Vacuum Insulation Panels as an alternative material. This cellulose based material offers a potentially environment friendly alternative core material by partially replacing fumed silica which requires high energy consumption during its manufacturing and considered as the main factor for VIP environmental impact. Average thermal conductivity of recycled cellulose insulation material at atmospheric pressure was measured to be 0.039 W/mK. VIP prototype made with the sample containing 45% cellulose, 45% fumed silica and 10% SiC opacifier at 5 mbar pressure resulted in thermal conductivity of 0.0154 W/mK which is 40% lower than that of 100% cellulose sample measured at 5 mbar. It is expected that further reducing the pressure to 0.5 mbar for VIP prototype manufacturing can potentially reduce the thermal conductivity of VIP prototype samples made with recycled cellulose-fumed silica composite core.

Keywords: Core material; Cellulose; Vacuum insulation panel; thermal conductivity

1. Introduction

Vacuum Insulation Panel (VIP), an advance thermal insulation material with its low thermal conductivity (0.004 - 0.008 W/mK) offers five to eight times superior thermal insulation performance whilst requiring up to 10 times thinner sections compared to conventional polyurethane, polystyrene foams, and mineral fibre. VIP offers a thin thermal insulation solution for buildings where deploying conventional thick foam insulation is difficult e.g.internal wall insulation and walls with narrow cavities [1]. Despite their superior thermal insulation performance, only 10% of total VIPs being produced are used in the building industry worldwide [2]. Higher material cost and durability are the main issues for large scale acceptance of VIPs in building applications. Expensive fumed silica material currently used in VIP core contribute to its higher cost and have higher associated environmental impact. Replacing fumed silica fully or partially with low-cost environmentally friendly material presents the potential of reducing VIP cost and environmental impact. Fumed silica is a common core material used in the manufacturing of VIPs owing to its optimal thermo-physical properties required for low thermal conductivity of VIPs. However, fumed silica has two main disadvantages for VIP applications: i) high cost [3] and ii) high environmental impact [4]. Fumed silica is mainly responsible for at least 90% of the environment impact among all core materials used in VIPs [5] Global Warming Potential (GWP) of 25 mm VIP with weight of 4.5 kg/m^2 is declared as 42.40 kgCO2eq at manufacturing stage of which 95-99% is arising from the VIP core [5]. Cost and environmental impact of fumed silica-based VIPs needs to be reduced for their wider application in different sectors. One way of achieving this is by fully or partially replacing fumed silica in VIP core with low-cost and low environmental impact alternative materials. In this research, cellulose bases recycled insulation material has been examined as potential alternative core material which can be used in VIP core as a partial replacement of fumed silica for manufacturing low cost-low environmental impact VIPs. This paper presents the development and testing of composites of recycled cellulose and fumed silica for use in VIP core. The main aim of this work is to optimise thermal and physical properties of recycled cellulose-fumed silica composite as low environmental impact VIP core material.

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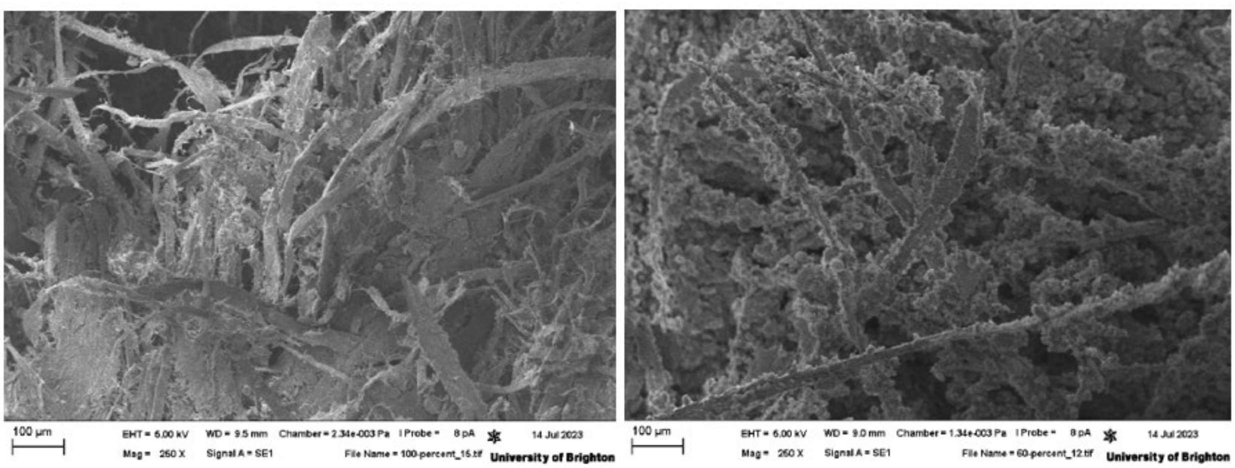
2. Materials and Methods

For this study composites with variable mass ratios of recycled cellulose insulation, fumed silica and SiC (opacifier) materials were developed by dry mixing. Details of material constituent of different samples are shown in table 1. Cellulose based insulation material used in the study was sourced from a commercial supplier which was produced from recycled newspapers mixed with mineral fire retardant.

Table1. Composition of different investigated core samples

Sample	Composition (mass %)		
	Fumed Silica	Cellulose	Silicon Carbide (SiC)
1	0	100	0
2	15	75	10
3	30	60	10
4	45	45	10

Recycled cellulose material has the following properties: thermal conductivity 0.039 W/mK and loose filled density 35-40 kg/m^3. Scanning Electron Microscopy was used to observe the morphology of cellulose and fumed silica composite material. It is evident from the micrographs (A) in figure 1 that cellulose material is continuous length fibers. Micrograph (B) show the composite of fumed silica with cellulose material where particles of fumed silica are attached to the cellulose fibers.



(A) (B)

Figure 1. SEM images of recycled cellulose material (A) and fumed silica- cellulose composite (B)

VIP core samples of size 150 × 150 mm were manufactured with new alternative core materials and thermal conductivity was measured at atmospheric and vacuum pressures. Sample thickness used was 10 mm. Centre of panel thermal conductivity of developed core and VIP samples was measured using Heat Flow Meter (HFM 446 Lambda Series- based on ASTM C518). Thermal conductivity values were measured at mean temperature of 20°C. VIP samples were manufacture by vacuum sealing the envelope at 5mbar pressure.

3. Thermal conductivity results and discussion

Three core prototypes of each sample were prepared for thermal conductivity measurement at atmospheric pressure. Results of each sample for core thermal conductivity at atmospheric pressure are shown in figure 2. The line in figure 2 represents the average values of three thermal conductivity tests. Measured values and standard deviation error bars have also been shown in figure 2. The average value for sample 1 (100% cellulose material) is 0.039 W/mK which is equal to the thermal conductivity value given by the manufacturer of cellulose material. In sample 2 to 4 fumed silica (in certain mass ratios) and SiC opacifers (10%) were added to replace the cellulose in the mixture. For samples 2 and 3 the average thermal conductivity values were found to be 0.038 W/mK and 0.037 W/mK respectively. Average thermal conductivity for sample 4 (Fumed silica 45%, Cellulose 45% and SiC 10%) was measured to be 0.027 W/mK which shows the addition of fumed silica has reduced the thermal conductivity value by about 29%.

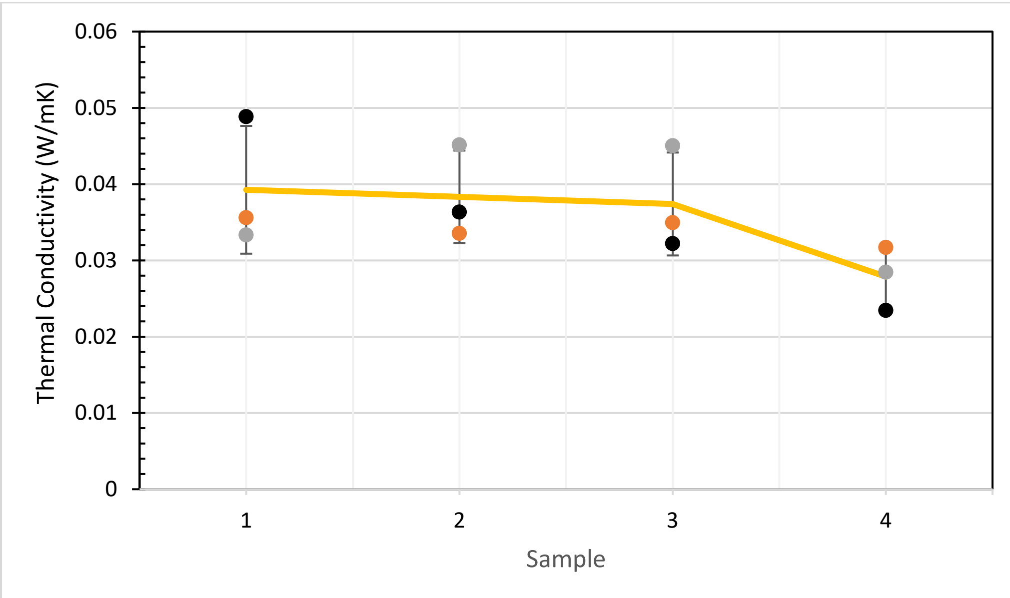


Figure 2. Thermal conductivity of core samples at atmospheric pressure

Thermal conductivity of VIP samples was measured using the heat flow meter. Thermal conductivity results of VIP prototypes sealed at 5 mbar pressure for all four core samples are shown in table 2. VIP prototype 1 made with 100% cellulose was measured to have the thermal conductivity of 0.0257 W/mK which gradually reduced to 0.0231 W/mK and 0.0196 W/mK for prototype 2 and 3 respectively. For sample 4 (45% cellulose, 45% fumed silica and 10% Sic) was measured to have the thermal conductivity of 0.0154 W/mK.

Table 2. Thermal conductivity of VIP prototype types at 5mbar pressure

VIP prototype	Composition (mass %)			VIP Thermal Conductivity at 20℃ (W/mK)
	Fumed Silica	Cellulose	Silicon Carbide (SiC)	
1	0	100	0	0.0257
2	15	75	10	0.0231
3	30	60	10	0.0196
4	45	45	10	0.0154

This thermal conductivity value is still considerably higher than thermal conductivity of 0.005-0.007 W/mK for commercially available VIPs made with fumed silica core. However, trend of decreasing thermal conductivity value has been measured for cellulose based VIP prototypes and further reducing cellulose content and adding fumed silica along with reducing the pressure to 0.5 mbar for VIP prototype manufacturing can potentially reduce the thermal conductivity of these VIP prototype samples closer to the range expected of the commercially available fumed silica core VIPs. These results indicate that cellulose based core material can be developed for VIPs which will help in partially replacing the high environmental impact and costly fumes silica in VIP core and further work will continue to optimise the cellulose mass ratio and vacuum pressure in prototypes to yield the optimised VIP with thermal conductivity results closer to commercially available fumed silica VIPs.

Conclusion

This study evaluates the use of recycled cellulose-fumed silica composite material as an alternative low environmental impact core material for VIPs. Thermal conductivity results show that adding fumed silica in the recycled cellulose in the composite led to reduction in the thermal conductivity both at atmospheric and vacuum pressures. At atmospheric pressure average thermal conductivity of sample 4 containing fumed silica 45%, Cellulose 45% and SiC 10% was measured to have the lowest value of 0.027 W/mK which shows that addition of fumed silica has reduced the thermal conductivity value by 29% compared to sample (100% cellulose). VIP prototype made with the sample 4 at 5 mbar pressure resulted in thermal conductivity of 0.0154 W/mK which is 40% lower than the sample 1 (100% cellulose). However, this thermal conductivity of 0.0154 W/mK is still considerably higher compared to that of commercially available fumed silica VIPs. Nevertheless, further reduction in thermal conductivity can be expected by adding more fumed silica and reducing the pressure to lower values such as 0.5 mbar. This will need to be further investigated to comprehensively ascertain the thermal performance of cellulose-fumed silica composite core material for use in VIPs. Future research and development efforts will continue to focus on optimising recycled cellulose-fumed silica composite as an alternative core material to realize their full potential and achieve the thermal conductivity values closer to the commercially available fumed silica VIPs.

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