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HEAT RESISTANT AND TENSILE PROPERTIES OF GLASS FIBER REINFORCED POLYMER COMPOSITES

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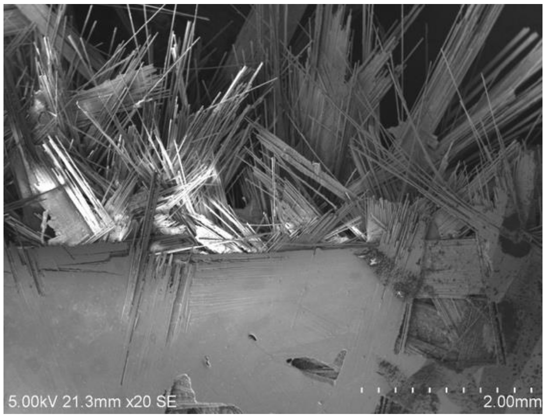
Graphical abstract



CSM fiber


WR fiber

Abstract

The study focuses on E glass fiber laminate with vinyl ester resin. Two types of fiber glass are used namely chopped strand mat (CSM) and woven roving (WR). The objective of this research is to determine the thermal conductivity, specific heat capacity and Modulus Young of glass fiber-reinforced polymer (GFRP) prepared by vacuum bagging resin infusion process. The samples of GFRP were exposed to cooking gas fire for 5 minutes and 10 minutes for fire test. The tensile test was also conducted for the three samples and the microstructure was analyzed using Scanning Electron Microscope (SEM) after tensile testing. The result discovered that WR sample was better than CSM sample because CSM sample yield an average value of 0.236 W/mK for thermal conductivity and 521.6 J/KgK for specific heat capacity while WR sample give a value of 0.205 W/mK for thermal conductivity and 589.5 J/KgK for specific heat capacity. The Modulus Young of WR sample is higher (24.2 GPa) compared with CSM sample (16.1 GPa). From SEM micrograph, the failure occurred on the samples were matrix cracking and fibers separation. From the fire and tensile test conducted, the damage occurred on the samples were quite the same with the failure of the reinforcement and matrix. The findings could be used in the building construction as engineers always looking for the best material as they may have the possibilities of fire exposure and tension load as well as this is a part of the safety requirement for buildings.

Keywords: Chopped strand mat (CSM), woven roving (WR), vinyl ester resin, tensile test, thermal conductivity

1.0 INTRODUCTION

Glass Fibre Reinforced Polymers (GFRP) has a wide applications in the construction of boats, hull decks, water pipes, buildings and others. As already knew, buildings may be exposed to fire and tension load thus it is vital to determine the resistant of GFRP under these conditions. Engineers have always show a strong interest in new building materials. Among these Glass Fibre Reinforced Polymers (GFRP), also known as advanced polymer composites, have recently attracted a lot of interest due to their high strength to weight ratio, ease of producing unique shapes, flexible aesthetics, low thermal transmissibility and low carbon footprint in a life-cycle perspective [1, 2]. Although some doubts about the durability of GFRPs are sometimes raised, these material have repeatedly proved exceptional durability and corrosion resistance compared to common building materials. Properly fabricated GFRPs do not rot like wood or rust like steel, have very good resistance to chemical corrosion and their multi-decades of use in the boat industry shows efficient in environments where other typical materials will be unsuitable. Given these substantial characteristics, GFRPs must still demonstrate good performance related to elevated temperature, especially expected "fire loads" (design fires) to contribute to a building's passive protection to ensure life safety and property protection in case of fire [3]. Moreover, the increasing awareness towards building energy saving and more in general towards sustainability issues, suggests the use of GFRPs in modern building construction.

For most materials, thermal properties are temperature and moisture dependant. Variations of thermal properties with temperature are obtained experimentally. The thermal properties that are of interest to the researcher are specific heat and thermal conductivity of which the empirical formulas have been established. A predictive model for the thermal response of composite materials, validated against standard fire-test methods will help to minimize the number of tests required to qualify a new material. Realistic thermal modelling of fire behaviour provides the designer with the capability to demonstrate innovative, new designs, to a specified fire rating, with the minimum initial recourse to expensive standard fire testing.

Arifin *et al*. [4] evaluated and compared the impact strength of chopped strand mat-woven roving-foam Klegecell reinforced epoxy/polyester composites. Laminates were molded using hand lay-up technique. Epoxy blended composites performed better than polyester laminates. Shokrieh *et al*. [5] studied the influence of multiwall carbon nanotubes on the mechanical properties of chopped strand mat reinforced polyester composites. Burn-off test was adopted to envision the dispersion state of carbon nanotubes. Addition of carbon nanotubes enhanced the strength aspects of the composites.

The research community has acknowledge the need for analysis of the reduction in strength with time of the composite material, under various heating and loading conditions since the structural response of the composite materials in fire is now a safety concern. Extensive analysis of different thermal, chemical, physical, softening and failure processes are required to analyse the reduction in strength during fire exposure [6].

Thermal conductivity is the ability of a material to conduct heat. It is based on the Fourier's Law of heat conduction. The value of thermal conductivity obtained in this project is based on Equation 2 [7].

To calculate the thermal conductivity of laminates, the rule-of-mixture model have been proposed. This model involve in the thermal properties of the fibres, resin and the fibre volume content [8]. The assumption made is all the fibres in the laminate are straight, aligned and evenly distributed through the material. Besides, perfect bonding exists between fibres and resin and the material is free of defects such as voids and porosity [9]. Thermal conductivity of the composite in the fibre direction can be calculated using:

$$k = k_f V_f + V_m\left(1 - V_f\right) \quad (1)$$

While thermal conductivity of the composite in the through-thickness direction can be calculated using:

$$k_T = k_{m,T}\frac{k_{f,T}\left(1+V_f\right)+k_{m,T}\left(1-V_f\right)}{k_{f,T}\left(1-V_f\right)+k_{m,T}\left(1+V_f\right)} \quad (2)$$

Where *kf* is fibre thermal conductivity, *km* is matrix or resin thermal conductivity, *Vf* is volume fraction of fibre, *km,T* is resin thermal conductivity through thickness and *kf,T* is fibre thermal conductivity through thickness. In this project, only the thermal conductivity of the composite in the through-thickness direction is considered.

Specific heat of the laminate is another thermal property that influences the fire response of composite materials. It is the amount of energy needed to change the temperature of 1 kg of the substance by 1°C. The specific heat capacity is a thermal index, expressed by c, as seen in Equation 3,

$$Q = cm\Delta T \quad (3)$$

Where Q is the quantity of heat, *m* is the material mass and ΔT represents the temperature difference. For isothermal condition, the specific heat capacity can be calculated using Equation 4,

$$C_p = \frac{1}{\rho_c}\left[C_{pf}.\rho_f.V_f + C_{pm}.\rho_m\left(1 - V_f\right)\right] \quad (4)$$

Where *ρc* is the density of composite, *ρm* is the density of resin, *Vf* is the volume fraction of fibre, *Cpf* is the specific heat capacity of the fibre and *Cpm* is the specific heat capacity of resin. This value is the same for both in-plane and through thickness.

Fire damages suffered by FRP structures are softening, degradation of the matrix, char formation, delamination, and matrix cracking [10]. Softening and degradation of the matrix takes place around the glass transition temperature; Char formation is due to the thermal decomposition of the matrix; Delamination and cracking are due to misalignment deformation of plies or local kinking. The char formation of FRP structures plays an important role in the thermal and mechanical response of FRP composites in fire. The char of FRP composites affects the thermal and mechanical responses in several ways. First, the char is a porous carbonaceous material with poor thermal conductivity and thus behaves as a thermal insulation layer to the remaining virgin material. Secondly, as the char layer becomes thicker, it limits the access of oxygen from ambience to the decomposition zone and consequently reduces the decomposition rate. Finally, the char can help keep the structural integrity of FRP structures in fire by holding fibers in place after the matrix has been degraded. The delamination and cracking reduces the resistance ability of a FRP structure to mechanical loading and eventually may lead to the collapse of the structure.

In the present study, vinyl ester resin reinforced with chopped strand mat (CSM) and woven roving (WR) are fabricated using vacuum bagging resin infusion process. Tensile testing and thermal conductivity test are studied and analysed. This work was carried to explore the potential of using CSM/WR reinforced vinyl ester composites as an alternative material for building structure.

2.0 METHODOLOGY

2.1 Sample Preparation

The composite fabricated consists of vinyl ester resin as the matrix. The reinforcement materials involved in this project are chopped strand mat (CSM) glass fiber and woven roving (WR) glass fiber. The samples were manufactured using vacuum bagging resin infusion process inside Brazen Composite's production line. The materials were cut into the desired dimensions and three layers of each material were placed on a flat glass mold. Before that, the mold was cleaned using mold release wax for the purpose of easy removal of the samples from the mold at the end of the process. The vacuum bagging process was conducted where the samples were bagged and checked for any potential leakage. For the vacuum side, the vacuum's pressure was set to 0.003 MPa. 3 kg of vinyl-ester resin added with 1.5% of methyl ethyl ketone peroxide (MEKP) was injected into the bag and left to be cured for 24 hours. Figure 1 shows the process involved for the fabrication of the samples.

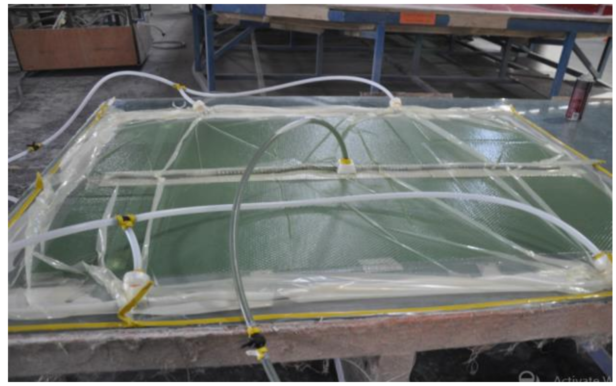


Figure 1 Vacuum bagging infusion process

2.2 Fire Test

There are two parts in the experimental fire test. The first part is to obtain the thermal properties of the samples under elevated temperature. The second part will be the verification of the failure mode occurs after burnt based on past research. The dimension of the samples for this test was 300 mm × 500 mm and the test follows Annex 1 of Part 3 of IMO Fire Test Procedures Code (ISO 5658-2) standard. The first CSM sample was placed on a stove that was already turned on. Two thermocouples were used, one was attached at the centre of the sample (channel 1) and another was attached at a quarter of the sample (channel 2). The thermocouple at channel 1 functions to determine the temperature of the samples that were exposed to direct fire below them while at channel 2, it functions as to determine the temperature at the side of the samples as the heat propagates to the side of them. The first CSM sample was burned for 5 minutes and the data was collected every minute. The first WR sample was placed on the stove after the first CSM sample was tested. The same procedure applied to the first WR sample as discussed previously. For the second CSM sample, it was burned for 10 minutes and the data was collected every 2 minutes. After the second CSM sample was tested, the second WR sample was placed on the stove and tested the same way as the second CSM sample. The schematic diagram for fire test are shown in Figure 2.

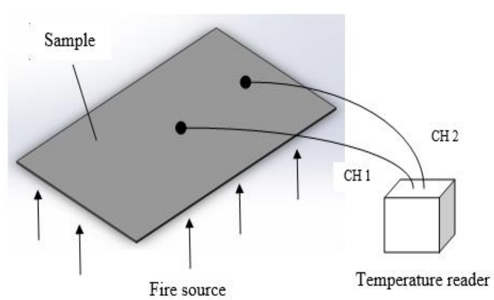


Figure 2 Schematic diagram for test sample

2.3 Tensile Test

Tensile testing is used to measure the force required to break a polymer composite sample and the extent to which the specimen stretches or elongates to that breaking point. Tensile tests produce a stress-strain diagram, which is used to determine Modulus Young. The dimension of the samples was 25 mm × 200 mm and the test follows ASTM D3039 standards [11]. The test was conducted using Universal Test Machine (INSTRON, 50 kN) machine at a speed of 2 mm/min. An extensometer or strain gauge is used to determine elongation and tensile modulus.

2.4 Microstructure Analysis

For microstructure analysis, the equipment used was scanning electron microscope (SEM, Hitachi S3400N). After the tensile test was conducted, the fracture samples of chopped strand mat (CSM) glass fibre and woven roving (WR) glass fibre were analysed to observe the mechanical failure of the samples after tensile test. Before the samples were analysed, they were coated with pure gold using the SEM coating machine to reduce the charging effect of the samples. Magnification of 20 times and 50 times were used as well as a voltage of 5 kV.

3.0 RESULTS AND DISCUSSION

3.1 Thermal properties

For the 5 minutes fire test on CSM sample, the temperature at channel 1 and 2 increase steadily at the first 3 minutes. When reaching to the 3rd minute, the temperature at both channels increase significantly until the end of the experiment as shown in Figure 3. This is due to the sample burns completely from the 3rd minute to the 5th minute during the experiment. As the fire reached to the other side of the sample which is at channel 1 and 2, the heat increases significantly. When compared to channel 1, the temperature at channel 2 slightly lower because the temperature or heat transfers from the middle of the sample is directly proportional to heat source and spread to the side of the plate [12]. The experiment was repeated but the sample was changed to WR sample. When compared to CSM sample, WR sample indicates a different kind of temperature pattern as shown in Figure 3 (a).

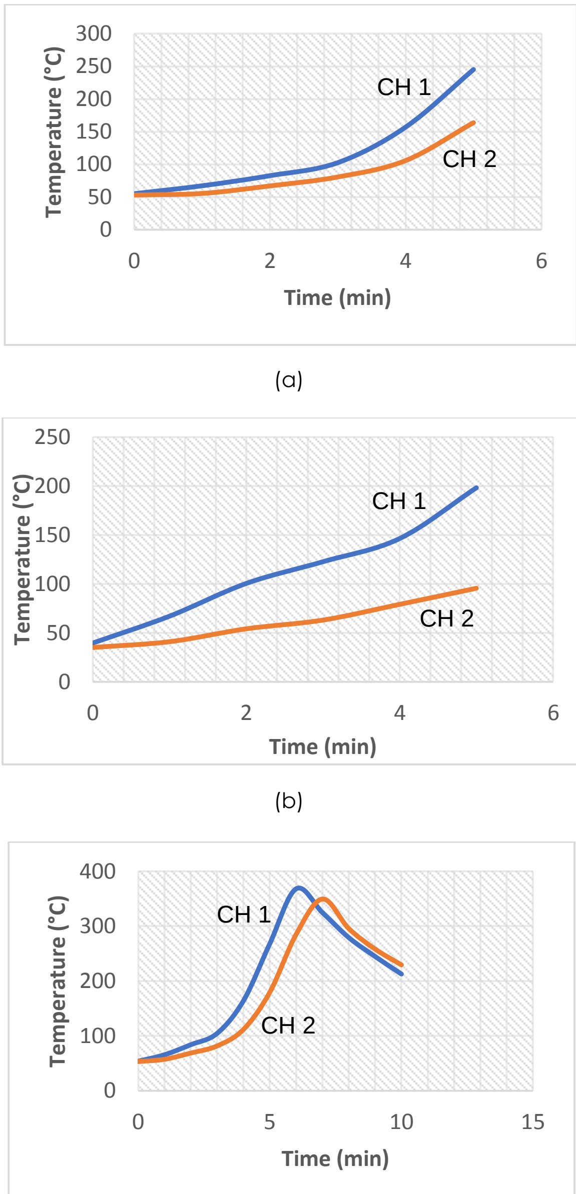
From Figure 3(b), the temperature at both channels increase steadily until 4 minutes. When entering the 4th minute, the temperature at channel 1 increase drastically but less than CSM sample while at channel 2, the temperature remains steady. This shows that WR sample conduct heat slower than CSM sample or a better insulator compared to CSM sample. For the 10 minutes fire test, the temperature pattern for CSM sample was totally different compared to the 5 minutes fire test as shown in Figure 3 (c). In the first 3 minutes, the temperatures steadily increase at channel 1 and channel 2, the same pattern as in 5 minutes fire test. But when entering the 3rd minute, the temperature at channel 1 rise significantly until the 6th minute, same goes at channel 2. After the 6th minute, the temperature starts to drop at channel 1 as well as at channel 2 but a bit slower. At a certain time, temperature at channel 2 seems to exceed temperature at channel 1. This can be seen in the 7th minute as the temperature at channel 2 is higher than at channel 1. This is due to the sample burned vigorously at the start of the 3rd minute and producing huge flame. That is why the temperature increase significantly which then propagate to the side of the sample and this clearly prove that why the temperature at channel 2 increase slower than at channel 1. After the 7th minute, the flame start to disappear since all the resin has been completely burned and the drop in temperature as shown in the graph indicates this situation. The experiment was repeated but the sample was changed to WR sample. When compared to CSM sample, WR sample indicates a different kind of temperature pattern as shown in Figure 3 (d).

It can be seen in the first 7 minutes, the temperature rise steadily at channel 1. After the 7th minute, the temperature starts to increase drastically but slower when compared to CSM sample. At channel 2, the temperature increase slowly and start to rise significantly at the 9th minute. Based on all of the experiment, the temperature pattern indicates that WR sample shows slower temperature increments which are from 39.7 °C to 198.3°C for the 5 minutes fire test at channel 1 compared to CSM sample which are from 55.2°C to 245.1°C. At channel 2, the temperature readings for WR sample are from 35.2°C to 95.7°C compared to CSM sample, from 53.3°C to 163.8°C. WR sample also shows a slower temperature increment during 10 minute fire test which are from 35.6°C to 321.1°C at channel 1 compared to CSM sample which are from 53.7°C to 212.7°C. At channel 2, the temperature readings for WR sample are from 33.3°C to 175.6°C compared to CSM sample, from 53.2°C to 229.4°C. These show that WR sample transfer heat slower than CSM sample which makes it a better heat insulator compare to CSM.

Based on Equation 1, the thermal conductivity of the chopped strand mat (CSM) glass fibre samples and woven roving (WR) glass fibre samples were calculated (Table 1) and the specific heat capacity were calculated using Equation 4 (Table 1). Based on the experiment, the temperature pattern indicates that WR sample shows slower temperature increments compared to CSM sample. This shows that WR sample transfer heat slower than CSM sample which makes it a better heat insulator compare to CSM. The thermal conductivity reported by Berardi and Dembsey [13] is 0.15 to 0.04 W/mK for wood and 46.55 W/mK for steel, which shows the both sample is the high durability and much more stable behaviour in terms of thermal conductivity and do not suffer aging and weathering.

Table 1 Thermal conductivity and specific heat capacity for the samples

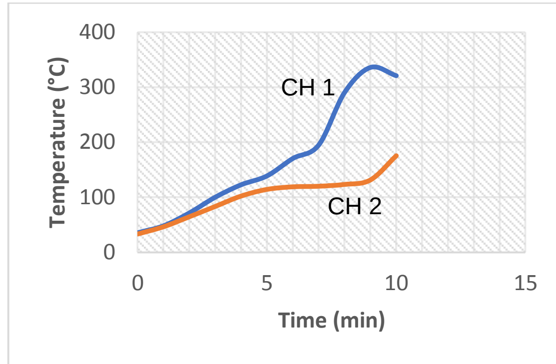
Samples	Thermal Conductivity(W/mK)	Specific Heat Capacity(J/kgK)
CSM 1	0.239	514.4
CSM 2	0.232	528.8
WR 1	0.205	593.1
WR 2	0.204	585.8



(a)

(b)

(c)



(d)

Figure 3 Fire Test Graph; (a) CSM in 5 minute period; (b) WR in 5 minute period; (c) CSM in 10 minute period; (d) WR in 10 minute period

3.2 Failure

Based on the fire test gathered, there are several composites failure that can be observed through naked eyes. The most common failure occurs in fire environment include delamination and charring due to decompose of the matrix. The failures of the samples were shown as in Figure 4 and 5. The charring of vinyl ester matrix and delamination cracking can be seen and this is the main type of failure for composite material in fire condition. The blackened material shows the combustion of vinyl ester resin that produced small amount of residual carbonaceous char. Delamination cracks produced within the unburned section of the material and were probably formed by pressure of volatile gases during resin's decomposition or by induced strains because of thermal gradient throughout the plate.

Figure 4 Delamination of fibres

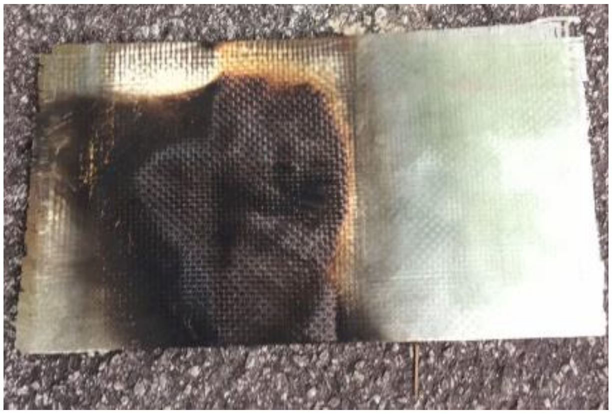
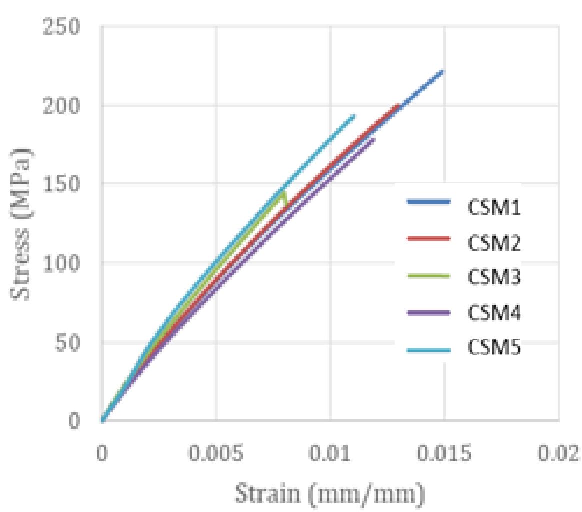


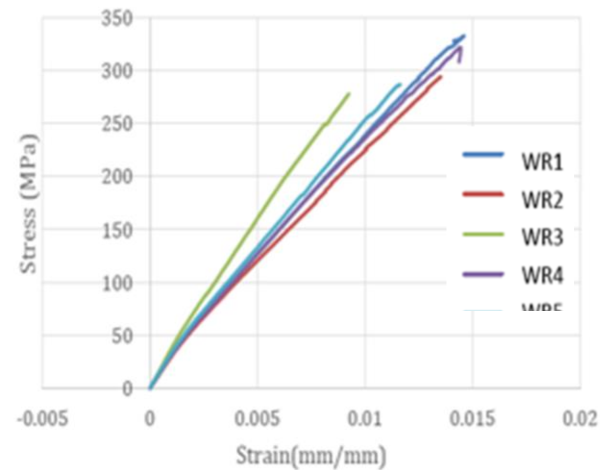
Figure 5 Charring of matrix system

3.3 Tensile Properties

Based on stress strain curve in Figure 6, CSM samples, Figure 6(a) has the lowest stress value compared to WR samples while WR samples, Figure 6(b) has the highest stress value among all the samples. This shows that CSM samples failed at the lowest load compared to WR samples failed at the highest load. By finding the slope of the stress strain graph, the Modulus Young, Ec of each sample was calculated. CSM sample give an average value of 16.1 GPa and WR sample with 24.2 GPa. WR sample has the highest value of Modulus Young among other samples which is 24.2 GPa. From the stress strain graph, percent elongation of the samples was also calculated. CSM sample give an average value of 2.8% and WR sample with 3.0%. WR sample has the highest value of Modulus Young and percent elongation among other samples which is 24.2 GPa and 3.0% respectively.



(a)



(b)

Figure 6 Stress strain graph; (a) CSM sample; (b) WR sample

3.4 Microstructure Analysis

For the microstructure analysis, Scanning Electron Microscope (SEM) was used as the instrument to illustrate the images of the samples which are chopped strand mat (CSM) glass fibre and woven roving (WR) glass fibre after the tensile test was conducted. The results are as shown in Figure 7and 8. For all the samples, the failure due to tensile test resulting the fibres separation and matrix cracking. As in the microstructures, the fibres tend to break from their original orientation and the cracking of the matrix results in the fibres behaviour. When the matrix system that hold the fibres in their orientation crack, that is why the fibres were separated from their original orientation [14]. Based on the fire and tensile test conducted, the failure occurred on the samples are quite the same which are the cracking of matrix and delamination of fibres. This is because the main components of the samples are the reinforcement and the matrix. Arina Modrea *et al.* show the delamination presents a more spectacular effect for glass reinforce polyester resin laminates [15]. For the fire test conducted, WR sample shows better thermal properties compared to CSM in terms of its thermal conductivity and specific heat capacity. Furthermore, the failure occurred on WR sample is less than CSM sample. The burnt region of CSM sample is larger as well as the fibres and matrix burnt completely compared to WR sample. For tensile test, WR shows the best mechanical properties in terms of its tensile modulus compared to CSM sample. Based on the microstructure analysis, the fibres orientation of for both CSM and WR samples has a greater damage where its fibres and matrix disoriented and cracked completely.0

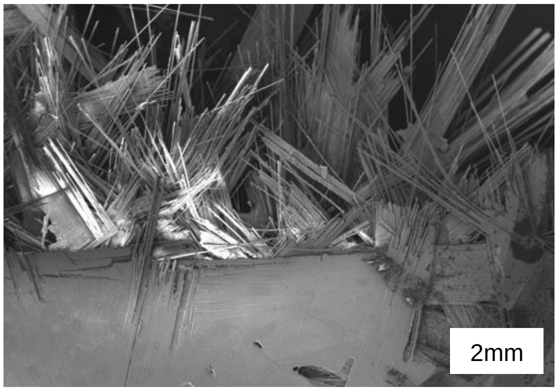


Figure 7 SEM micrograph for CSM sample

Figure 8 SEM micrograph for WR sample

4.0 CONCLUSION

The fire test conducted function as to identify the thermal properties of both chopped strand mat (CSM) glass fiber and woven roving (WR) glass fiber which were fabricated with vinyl ester resin. WR sample transfer heat slower than CSM sample which makes it a better heat insulator compare to CSM because WR show lower thermal conductivity (0.205 W/mK) and higher specific heat capacity (589.5 J/KgK). CSM sample tend to burn faster compared to WR sample, WR sample has better strength and stiffness compared to CSM sample because of the high value of Modulus Young (24.2 GPa) and percent elongation (3.0%). SEM micrograph shows the failures microstructure which was due to the fibers separation and the cracking of the matrix system due to the tension load that applied to the samples. From the fire and tensile test conducted, the damage occurred on the samples were quite the same with the failure of the reinforcement and matrix.

Acknowledgements

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