Mechanical property and fracture mechanism of glass fiber reinforced polymer and carbon fiber reinforced polymer

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Abstract. In the automotive field, most of the manufacturers are looking to replace the material steel, aluminium with lightweight material like carbon fiber or glass fiber composite. The purpose are due to their relatively high strength, higher chemical resistance, flexible usage temperature and higher stiffness than steel. In this study, mechanical properties of carbon fiber and glass fiber reinforced polymer were investigate. It was find that the tensile strength of carbon fiber composite is approximately 11% higher than that of glass fiber, almost twice in Young’s modulus than that of glass fiber. Carbon fiber is two times higher than glass fiber in both flexural stress and young modulus of flexural three points bending test. Image analysis of fracture and damage were detect by field emission scanning electron microscopy (FESEM) in microstructure scale to observe the fracture mechanism. Observed different failure mode in fiber and resin. Chemical composition of composite and fibers were investigated by using electron dispersive x-ray (EDX) spectroscopy that gave out in 88 wt % of carbon and 12 wt % in carbon fiber twill (CFT) composite. On the other hand, glass fiber woven (GFW) composite contained 72.7 wt % of C, 20.7 wt % of O₂, and the rest contained Si, Ca, Al, Mg and Cl.

Keywords: Carbon fiber, Glass Fiber, Fracture Mechanism, Mechanical Properties

1. Introduction
Nowadays, most of the automotive manufacturer deeply invested to make research on carbon fiber and glass fiber due to their lightweight properties. The purpose of lightweight vehicles is for future automotive fields [1]. Vanishing of CO₂ footprint and preventing the particles matters (PM) emission from vehicles in our environment are also one of the most important point. Carbon fiber and glass fiber are the most popular materials not only in the automotive field but also in the field of marine, aircraft, military vehicles, sports, rockets and etc [2]. The main properties are lightweight, high stiffness, high
temperature resistance and high strength compare to the same weight [3,4]. In composites, there are two main functions those are fiber and matrix. Fiber is the main product in the composite and matrix is one of the material that can create bonding strength between fibers [5]. Polymer matrix is the most widely used in the composite industry. There are two main matrix resins such as thermosetting and thermoplastic resins; those are the most useful resin in the composite field for laid up process laminar. Thermosetting resin is liquid form and it is irreversible resin [6]. After curing thermoset resin, the resin cannot turn back to the original liquid form and the resin can cured by chemical reaction at room temperature. Among several resin types in thermoset, epoxy is the most useful matrix because the matrix can lead composite to the best material of high bonding strength [7]. The composite need higher strength to resist the force and epoxy have to transfer stresses to fibers. Most of the composite starts to crack from matrix de-bonding, fibers delamination and pull out fibers from the matrix failure because matrix is not well enough to bond one to another fiber. Then matrix cannot distribute the load uniformly to the fibers [8]. Dany Arnoldo Hernandez [9] observed the main fracture of the composite is come from the interface zone (area between resin and fiber) which is affected by the tensile stress concentration on resin. It makes a crack initiation at the resin area, and then the force and crack are distribute to the fibers. Therefore, fiber is pull out then leads to break fibers. Issa A. Hakim [10] studied the porosity of the composite according to different vacuum poor, moderate and high vacuum. As the result, the poor vacuum composite has the highest quantity of porous that can make lower strength with faster crack then the toughness of fibers are decreasing. Energy absorptions are drop compare to moderate and high vacuum. From the view of an image, it is quite important to investigate the porous inside fiber and the structure of each fiber that can affect mechanical properties and fracture of composite. P. Karin [11] observed particle matters (PMs), average agglomerated particle diameter sizes are in the range of 50-500 nm size and average nanoparticle diameter size are in the range of 20-50 nm respectively. He used (TEM) transmission electron microscopy to investigate the size of PM. P. Karin [12] used TEM to observe particle matters size from biodiesel engine and diesel engine with different speed RPM. He investigated the average of nanoparticles size in approximately 48, 34 and 32 nm for carbon black for biodiesel and diesel engine’s PMs respectively. P. Karin [13] has investigated carbon black by using electron microscopy analysis. Therefore, electron microscopy is one of the most important tool to study fracture mechanism. However, in case of composite, micro and nanostructures are not understand well, it induces to investigate the properties and fracture mechanism of composite with different type of base material.

2. Materials and Methodology
2.1. Materials
In this research, two types of materials were used with epoxy resin matrix; carbon fiber (twill weave and plain weave) based on polyacrylonitride (PAN) [8, 9] and E-glass fiber (woven roving and fabrics). Epoxy YD 582 and hardener TH7253 are use as the matrix in this composite. Listed materials in table 1 are supply by concrete composite.

| No. | Material          | Prod name        | Composites name in this paper | Type     |
|-----|------------------|------------------|-------------------------------|----------|
| 1   | Carbon fiber twill | C135T            | CFT                           | Carbon   |
| 2   | Carbon fiber plain| PC6951500        | CFP                           |          |
| 3   | Glass fiber      | Woven roving N323 | GFW                          |          |
| 4   | Glass fabrics    | Glass cloth EW200 | GFF                          | Glass    |
| 5   | Epoxy (part: A)  | YD 582           |                               |          |
| 6   | Hardener (part: B)| TH 7253         |                               | Resin    |
2.2. Sample preparation

Orientation for all of the materials are bidirectional 0/90 degree. The fabrication process are wet lay up process based on the weave fibers pattern from manufacture. All of the fibers are lay up in the same orientation. In epoxy mixing ratio, there are two parts, part A: epoxy and part B: hardener are mix for 3:1 ratio based on fiber ratio and equations (1-3). The thickness of composite were control based on the fabric thickness of each layer. The same method is use for all composites with wet lay-up process. All of laid up conditions can see in table 2.

\[
\text{Hardener weight (g)} = \frac{\text{Weight of Fibers (g)}}{4} \tag{1}
\]

\[
\text{Epoxy weight (g)} = \text{weight of hardener (g)} \times 3 \tag{2}
\]

\[
\text{Epoxy and hardener ratio} = 3:1 \tag{3}
\]

Composite was cut by computer numerical control (CNC) machine Mazak FJV-20 with the situation of spindle speed 150 mm/min and feed speed 90-100mm/min. Samples are prepared according to ASTM 638 for tensile test and ASTM 790 for flexural test specimens. Fabricated composite information of composites.

**Table 2. Material ply and lay up status**

| No. | Material   | Fabric layers | Fabric thickness (mm) | Fibers w.t (g) | Composite size (mm) | Comp w.t (g) |
|-----|------------|---------------|----------------------|----------------|---------------------|--------------|
| 1   | CF twill   | 10            | 0.31                 | 261.1          | 320x320x3.2         | 512          |
| 2   | CF plain   | 9             | 0.3                  | 343.29         | 240x280x2.9         | 429          |
| 3   | GF woven   | 10            | 0.3                  | 408.1          | 320x320x3.2         | 636.06       |
| 4   | GF fabrics | 16            | 0.2                  | 343.62         | 320x320x3.2         | 574.167      |

2.3. Mechanical testing

The specimens were test on a tensile test machine INSTRON 8801 with load cell 95KN, test speed 5mm/min for all composite with the same testing function at temperature 24 degrees Celsius with 47% RH. Another mechanical flexural test (three-points bending) is perform at 24C temperature and 49% RH with INSTRON 55R4502 machine. Testing rate speed is 5.2mm/min with cell load 10KN.

3. Result and Discussion

3.1. Tensile test results with different materials CFT, CFP, GFW and GFF

Figure 1 shows the average value of each composite. CFT/CFP has the highest tensile strength than that of GFW/GFF. The tensile strain of glass fiber is two times longer than carbon fiber elongation. CFT is the peak tensile stress around 450MPa while CFP is around 420MPa at the same tensile strain 1.3%. Maximum strength of GFW and GFF are decrease particularly compare to CFT /CFP. The elongation at break point are 1.37% for CFT and 1.31% for CFP respectively, while GFW and GFF elongation are 2.85% and 2.91% respectively. Young modulus is the main important point in mechanical test and properties. Therefore, the highest young modulus is around 37 GPa from CFP and it is almost similar to CFT composite with the value of 36 GPa. The value of CFT and CFP are almost two times higher than that of GFW and GFF’s young modulus.

Tested materials data are summarize and compare to each sample properties in table 3. The specimens are not the same thickness, but the thickness will not affect to young modulus of materials
because material properties are not depends on the thickness of samples. Unlike steel or alumina, the samples are sensitive and break at several points. Therefore, strain gauge was not use in this experiment. The elongations are calculate from sample crosshead displacement because it was collect at maximum strength of sample.

Figure 1. Stress-strain relationship of tensile test data of CFT, CFP, GFW and GFF

The specimens were disintegrate to be several pieces immediately after the peak points of tensile stress for CFT. It leads to brittle behaviour, but higher stiffness. Composite breakage of CFT and CFP are almost linear. Figure 1 also shows that stresses are immediate drop. For glass fibers, the nature of glass are flexible and higher elongation. The fracture behaviour of GFW and GFF are tougher comparable to CFT and CFP behaviour. After the maximum load are applied, the specimens break immediately in the weakest point of the sample where the fillet of specimens are located for all types of specimens. The failure mode of composite are as shown in figure 2.

Table 3. Comparison of composite material and their properties of tensile test

| Samples | Thickness (mm) | Width (mm) | Grip distant (mm) | Maximum load (N) | Tensile strength (MPa) | Young modulus (MPa) | Elongation at break (%) |
|---------|----------------|------------|------------------|------------------|------------------------|---------------------|------------------------|
| CFT     | 3.5            | 13.35      | 115              | 21,332.87        | 452.98                 | 36,204              | 1.37                   |
| CFP     | 2.85           | 13.6       | 115              | 16,328.60        | 430.73                 | 36,604              | 1.31                   |
| GFW     | 3.3            | 13.6       | 115              | 18,182.37        | 399.85                 | 18,620              | 2.85                   |
| GFF     | 3.2            | 13.7       | 115              | 15,582.11        | 358.99                 | 15,860              | 2.91                   |
Figure 2. Fracture sample of tensile test a) CFT, b) CFP, c) GFW and d) GFF

3.2. Flexural Test

Three points bending flexural test condition are as mentioned; six pieces of each type are tested. The average flexural strength of all specimens are as shown in figure 3. Each type of samples are much different not only in flexure stress at maximum load but also in young modulus. The summary and properties of all flexural tested conditions are show in table 4. CFT and CFP have a big gap in maximum stress but almost the same flexure strain in elongation. GFW/GFF in this flexural test are drop gradually without breaking immediately. After the maximum load are applied, the fibers breaks unstably and tends to more elongation. In young modulus, CFT is the best one with the highest value of 47 GPa and the next follow by CFP with 42 GPa. Young modulus for GFW and GFF are lesser more than compare to CFT. On the other hand, glass fiber are very good in elongation that lead to the good toughness behaviour. The failure behaviour are also quite different in each type as shown in figure 4. Tension side of surface starts to crack first due to tension load and compression side are crack.

| Name | Maximum flexure load (N) | Flexure Stress at max load (MPa) | Modulus (automatic young's) MPa | Flexure strains at max flexure stress (%) | Thickness (mm) | Width (mm) |
|------|--------------------------|---------------------------------|-------------------------------|------------------------------------------|----------------|------------|
| CFT  | 655.69                   | 675.37                          | 46,975                        | 1.55                                     | 3.35           | 13.34      |
| CFP  | 425.35                   | 598.26                          | 41,945                        | 1.53                                     | 2.88           | 13.63      |
| GFW  | 329.04                   | 327.15                          | 20,720                        | 2.21                                     | 3.32           | 13.67      |
| GFF  | 229.33                   | 246.18                          | 18,603                        | 1.72                                     | 3.2            | 13.66      |
Figure 3. Flexural stress-strain curve for all composites

Figure 4. a) CFT, b) CFP, c) GFW and d) GFF specimens after the flexural test

3.3. FESEM image Analysis

Fracture mechanism of materials is very important role to improve the property or strength because it is extremely depend on the microstructure of interface. In this paper, the microstructure is describe based on tensile test specimens for all four types of composite. Firstly, the main fracture of all samples are come from the smallest and the weakest area of the specimens. The fracture mechanism of glass and carbon are quite different in crack area. Small area for CFT/CFF and quite a large area for
GFW/GFF with complex breakage. CFP fracture breakage shows 0 degree (the same direction with tension load) laid fiber are break almost linearly while 90 degrees across lay up fiber are break by each strand delamination in figure 5 a) and b). The main tension force of CFT and CFP are come from vertical direction laid up fibers, it lead to break resin and fiber. Longitudinal tension force pulls the fiber yarn to separate each filament that make each fiber delamination from bonding. As shown in figure 5 a), CFT is disintegrating into several pieces in the middle, but still hold together matrix and fiber on both edge sides. GFW/GFF is difficult to detect the breakage area because of breakage filament are complicated and breakage area of fibers is longer than that of carbon fibers. The main fracture behavior of GFW/GFF is delamination and pullout the fibers from the bonding matrix as shown in figure 5 c) and d). The matrix bond tightly, but the fibers are delaminate and pull out due to external from through fibers. Delamination of fiber will bring to stand alone each filament, therefore each filament are very easy to break. The middle filament are break first and the breakage are distribute to the both side of fibers, it is the main breakage of fiber in GFW and GFF. Additionally, voids can see in matrix area that comes from the fabricated process through air bubbles that didn’t remove very well while lay up process are performed, it becomes voids in composite. Those voids are also one of the weak points to initiate crack in the matrix.

Figure 5. FESEM image a) CFW, b) CFP, c) GFW and d) GFF

3.4. EDS Analysis

FE-SEM machine with EDS system observed the element composition on the composite CFT and GFW with 60 CPS in figure 6. a) and b). CFT composite spectrum 1 proved that 88% w.t of
carbon, 11.7% of O₂ and 0.3% of calcium containing in composite. Therefore, especially carbon and oxygen are the most important element in this material to play at the main role of carbon composite. GFW has observed 72.7% w.t of C, 20.7% of O₂, 3.1% of Si, 2.2% of Ca, and a few of AL, Cl and Mg respectively in spectrum 1. Thus, element composition of epoxy can be assumed as C, O₂, Ca and Cl. Table 5 is the summary of EDS chemical composite in each GFT and GFW. On the other hand, breakage of CFT prove that it have brittle behaviour due to tension force to the fibers as shown in figure 5. Au containing percent is due to gold spray on sample for electron conductive purpose. Therefore, Au data was ignore in figure 6. A) and b). Al (Alumina) also EDS scanner may count from the stub, which use to stick the sample.

**Figure 6.** Element composition of a) CFT and b) GFW composite by using electron dispersive x-ray spectroscopy (FESEM-EDS)
4. Conclusion

The composite of carbon fiber and glass fiber reinforced polymer with an epoxy matrix were test in tensile testing machine, the results show carbon fiber composite (CFT/CFP) was the highest modulus and tensile strength. Approximately 11% of tensile strength are higher than that of GFW/GFF and almost double modulus are achieve in CFT and CFP with 36, 204MPa and 36,604MPa respectively.

Fracture test shows higher modulus than a tensile test with value 46,975 MPa and 41,945MPa for CFT and CFP respectively, meanwhile GFW and GFF are lower than CFT and CFP almost half.

Fracture surface shows, the main character of CFT/CFP are peel off fiber by each bundles and break therefore the breakage area are almost linear in each bundles. This experiments show that CFT/CFP have brittle behaviour. As a contrast, GFW and GFF are delaminate in each filament then each filament are crack after matrix transfer the load. Then the whole fibers are leads to failure. GFW/GFF has a lesser brittle deformation behaviour than CFT/CFP.

Acknowledgement

The author would like to thank and acknowledge to International College, KMITL for supporting research fund, National Science and Technology Development Agency (MTEC) for providing facilities and their big support, Somboon Advance Technology Co., Ltd. for providing Materials and Polyplastics for supporting equipment.

References

[1] Wulfsberg J, Herrmann A, Ziegmann G, Lonsdorfer G, Stöß N and Fette M 2014 Procedia Eng. 81 1601-1607.
[2] Huang X 2009 Materials (Basel) 2 2369-2403.
[3] Chawla KK 2016 Glass Fibers, Ref. Modul. Mater. Sci. Mater Eng, pp. 1-5.
[4] Shide S and Salve AV 2015 Int. J. Eng. Res. 4 446–449.
[5] Patel A, Kravchenko O and Manas-Zloczower I 2018 Polymers (Basel) 10 125.
[6] Enns JH 1993 Creep and mechanical properties of carbon fibre reinforced PEEK composite material.
[7] Acatay K, Akdeniz Kimya San. ve Tic. AS, Kemalpasa, Izmir, Turkey. 2017 Fiber Technol Fiber-Reinforced Compos, pp. 123.
[8] Sood M and Dwivedi G 2018 Egypt J Pet. 7 75-783.
[9] Hernandez DA, Soufen CA and Orlandi MO 2017 Mater. Res. 20 951–961.
[10] Hakim IA, Donaldson SL, Meyendorf NG and Browning CE 2017 Mater. Sci. Appl. 8 170.
[11] Karin P, Watanawongskorn P, Boonsakda J, Saenkhumvong E, Rungsritanapaian S, Srivarocha S. 2017. Impact of Biodiesel on Small CI Engine Combustion Behavior and Particle Emission Characteristic, SAE Technical Paper 2017-32-0094.
[12] Karin. P, Boonsakda J, Stricholatham K, Saenkhumvong E, Charoenphonphanich C and Hanamura K 2017 Int. J. Automot. Technol. 18 31-40.
[13] Karin. P, Supanamok C and Hanamura K 2016 J. Res. Appl. Mech. Eng. 4 126-134.