EFFECT OF FERUM LOADING ON THE PROPERTIES OF GRAPHITE/CARBON BLACK/POLYPROPYLENE COMPOSITE AS BIPOLAR PLATE

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This report is submitted
in fulfillment of the requirement for the degree of
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DECLARATION

I declare that this project report entitled "Effect Of Ferum Loading On The Properties Of Graphite/Carbon Black/Polypropylene Composite As Bipolar Plate" is the result of my own work except as cited in the references

Signature	:	....
Name	:	....
Date	:	....

APPROVAL

I hereby declare that I have read this project report and in my opinion this report is sufficient in terms of scope and quality for the award of the degree of Bachelor of Mechanical Engineering (Structure & Materials).

Signature :. ....

Name of Supervisor : ....

Date : ....

DEDICATION

To my beloved parents

Mr.S.BASKARAN

Mrs.S.SELVI

My Supervisor,

DR. MOHD ZULKEFLI BIN SELAMAT

Other

Labratorory technician especially to Mr. Rizal, my friends and all people that had guided me throughout completion of this project.

ABSTRACT

Past few years, they are many processes has been conducting in understanding and improvement of Polymer Electrolyte Membrane Fuel Cell (PEMFC) The performance of PEMFC is relies upon the bipolar plates. This research is about the improvement of bipolar plate through multi-filler application by Ferum were fabricated through a selection of process. They are pre-mixing of raw materials, ball milling, pulverizing and compression molding. For electric conductivity the adding of 10wt% of Ferum plate demonstrates higher conductivity contrasted with other composition. Ferum 10 wt.% plate shows higher flexural strength when compared with others composition. With respect to density and shore hardness, 10wt% Ferum demonstrates unrivaled estimation of 1.489 g/cm³ and 70.8 individually. Therefore, the properties of adding 10 wt.% of Ferum to bipolar plate only composition exceed all target set by US-Department Of Energy.

ABSTRAK

Beberapa tahun yang lalu, mereka banyak proses yang sedang dijalankan dalam pemahaman dan peningkatan sel bahan bakar elektrolit elektrolit polimer (PEMFC) prestasi PEMFC bergantung kepada plat bipolar. Kajian ini adalah tentang peningkatan plat bipolar melalui aplikasi multi-filler oleh Ferum yang dibuat melalui proses pemilihan. Mereka adalah pra pencampuran bahan mentah, pengkompaunan, pemolesan dan pengacuan mampatan. Untuk kekonduksian elektrik penambahan 10wt% plat Ferum menunjukkan kekonduksian yang lebih tinggi berbanding dengan komposisi lain. Plat 10 gram ferum menunjukkan kekuatan lentur yang lebih tinggi apabila dibandingkan dengan komposisi yang lain. Berkenaan dengan ketumpatan dan kekerasan pantai, 10wt% Ferum menunjukkan taksiran yang tiada tandingannya 1.489 g / cm³ dan 70.8 secara individu. Oleh itu, sifat-sifat menambah 10% berat Ferum untuk plat bipolar hanya melebihi semua sasaran yang ditetapkan oleh US-DOE.

ACKNOWLEDGEMENT

First of all I would like to thank God for giving me strength to complete this report successfuly.

Secondly, I wish to express my sincere thanks to my supervisor, Dr. Mohd Zulkefli bin Selamat.I am extremely grateful and indebted to him for his expert, since and valueble guidance and encouragement extended to me.

I take this opportunity to record my sincere thanks to Faculty of Mechanical Engineering and also my fellow colleagues for their help and encourangement.

Lastly, I would like to thank my parents for unconditional love and support.

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LIST OF ABBEREVATIONS

PEMFC	Proton exchange membrane fuel cells
PEM	Proton exchange membrane
BPs	Bipolar Plates
GDL	Gas diffusion layer
CO	Carbon Monoxide
Pt-Ru	Platinum-Ruthenium
Fe	Ferum
CB	Carbon Black
Gr	Graphite
PP	Polypropylene
US-DOE	Unites States Department of Energy

CHAPTER 1

INTRODUCTION

1.1 Overview

The polymer electron membrane fuel cell (PEMFC) is current trending topic among researchers which is an electrochemical device that converts chemical energy into electrical energy. PEMFC is also not necessary for combustion process due to that it's considered to distributed portable electronics, power transportation and generation. Since that, PEMFC expected to play a major function in the world economy by decrease ecological issues. Bipolar plate (BP) is one of the fundamental parts of PEMFC, which takes haft portion of the total weight, cost and volume of the stack. The function of stack is to carry electric current away from each cell, it distributes anode with hydrogen and cathode with oxygen within individual cell and provides electron flow between the poles. In order to perform well the proper materials selecting is importance for devices has become serious research issues. Hence a materials selecting is most challenging things due to achieve the criteria of materials which established by United States Department of Energy (DOE) as shown in Table 1 [1].

Table 1: Requirement properties for the bipolar plate [2]

Property	Value
Electrical conductivity	>100 S/cm
Shore hardness	>50
Flexural strength	>25MPa
Bulk density	<5 [g/cm^3]

Pure graphite is one of the more conventional materials utilized to create bipolar plate because of their advantage of excellent chemical compatibility and great erosion safe. However, a few issues with pure graphite are during fabrication process is too expensive and time consuming, especially the machining procedure of gas stream channel into the plate surface and brittleness would cause the fuel stack to be overwhelming and huge.

For metal filler such as iron (Fe), stainless steel (SS), aluminum nickel, and titanium are commonly used Metal plates offer higher strength, toughness and shock resistance than graphite plates, and their unique mechanical properties allow for fabrication of thinner plates. However, there are also having some disadvantage by using metal filler such as high surface resistances and their helplessness to erosion.

Beside the type of fillers, thermoplastic or thermoset matrices could use to manufacture bipolar plates composites. There are a few models of thermoplastics lattices utilizing, for example, polypropylene (PP), polyphenylene sulfide (PPS), and polyvinylidene fluoride (PVDF). Polypropylene is promising materials lattice in regard to great mechanical properties and the expense however its primary chain does not contain polar gathering; in this way legitimate attachment can't be guarantee between the filler and framework.

Conducting polymer composite (CPC) as bipolar plates an appealing option in contrast to pure graphite and metal bipolar plates. Moreover, CPC is having capacity to give the important properties, for example, good mechanical strength, electrical and thermal conductivity. In other word, it necessary to do profound research on the blend of multi fillers bipolar plate materials to acquire the better properties of the composite. Therefore, graphite (G), carbon black (CB), carbon nanotubes (CNT) and carbon fillers (CF) are the a few materials utilized broadly in CPCs [2]. Furthermore, the thickness of the composite is exceedingly critical parameter in PEMFC considers. The mechanical quality relies upon the thickness of the composite. Low thickness in a composite advances a reduction in resistance and an expansion in the conductance of proton exchange membrane, which thus causes an increment in fuel cell execution.

The aim of the present work is to investigate the effect of Ferum (Fe) loading in multi filler Gr/CB/Fe/PP composite for bipolar plate PEMFC with the end goal to accomplish the necessity of the US DOE targets. The paper likewise investigates electrical conductivity and flexural quality properties of Gr/CB/Fe/PP composite were examined.

1.2 Problem statement

In this research, graphite is to be utilized as primary filler in view of high corrosion resistance, yet it is confronting primary debilitations which are weak and low conductivity. Additionally, the metal filler is ferum, which high conductivity however propensity to corrosive, and need to do good coating where it's exceptionally costly. Moreover, polypropylene is intense and adaptable, it's reasonable for cover to give awesome quality. Since, CPC is good corrosion resistance, lightweight, low cost and ease of machining or molding gas channels during processing. The main concept of utilizing multi filler, for example, Gr, CB and Fe is to decide the critical ratio of Fe which gives the best electrical conductivity and mechanical properties for G/CB/Fe/PP composite.

1.3 Objectives

- To study the effect of Ferum (Fe) loading on the electrical and mechanical properties of G/CB/Fe/PP composite.
- To determine the critical loading of Fe in G/CB/Fe/PP composite.

1.4 Scope

In this research, the study will cover the effect of Fe loading on the electrical and mechanical properties of G/CB/PP composite. The ratio of fillers (G/CB/Fe) and binder (PP) is fixed at 80:20. The adding small amount of Fe into G/CB/PP composite thus will give synergy effects on electrical conductivity and mechanical properties. The small amount of Fe which is 0 wt.% up to 15wt.% which is from the total weight of fillers 80% will be added into G/CB/Fe/PP composite and the CB has been fixed 25 wt%. All the fillers of G/CB/Fe will blend utilizing a ball mill process machine for one to accomplish homogenous blends. From that point forward, the G/CB/Fe will mix with PP through ball mill machine. After the intensifying procedure finished, the blends will gather and pummeled to additionally refine the examples as some of them agglomerate and frame bumps. This procedure will finish utilizing Retsch ZM200 Pulverizer. The following stage, the compression molding technique will mold the bipolar plate sample which will use Gotech (GT7014-A) hot press machine. Before the compression process begins, the temperature should be set to 180°C. From that point forward, the form will put in the hot press machine. The preheating procedure time takes around 10 minutes subsequent to a heating procedure is finish. At that point, the shape will expel from hot press space and place in cool press space. After 15 minutes the specimen will be expelled from the form. In order to determine the effect of loading Fe in G/CB/Fe/PP composite, the tests such as electrical conductivity, flexure test, density test, and hardness test will be performed. For determine the electrical conductivity properties, Jandel Multiheight Microposition Probe ware using for the test the plate. Lastly, the plate will be tried by utilizing Electronic Densimeter and Digital Tester to decide its density and hardness separately.

CHAPTER 2

LITERATURE REVIEW

2.1 Fuel cell

Fuel cell is a device that convert the chemical energy of a fuel straight forwardly into electricity by electrochemical process[3].Fuel cells work like batteries, yet they don't once-over or require recharging. They create power and heat insofar as fuel is provided. Thus, fuel cells have been utilized for a considerable length of time in transportation, material handling, stationary, convenient, and crisis reinforcement control applications.

Other than that, fuel cells have a few advantages over customary combustion-based innovations at present utilized in many power plants and traveler vehicles. Fuel cells can work at higher efficiencies than combustion engines and can change over the chemical energy in the fuel to electrical energy with efficiencies of up to 60%. Fuel cells have brought down outflows than combustion engines. Hydrogen fuel cells produce just water, so there are no carbon dioxide outflows and no air contaminations that make exhaust cloud and cause medical issues at the purpose of task.

A fuel cell comprises of two electrodes which is a negative electrode (anode) and a positive electrode (cathode). The anode which supplies electrons where the cathode retains electrons. The two electrodes must be immersed and isolated by an electrolyte which might be a fluid or solid, but which should in either case conduct ions between the electrodes with the end goal to finish the chemistry of the system. A fuel, for example, hydrogen is sustained to the anode and air is encouraged to the cathode. In a hydrogen fuel cell, a catalyst at the anode isolates hydrogen particles into protons and electrons, which take different ways to the cathode. The electrons experience an outer circuit, making a stream of electricity. The protons relocate through the electrolyte to the cathode, where they join with oxygen and the electrons to deliver water and heat. Figure 2.1 shows the fuel cell.

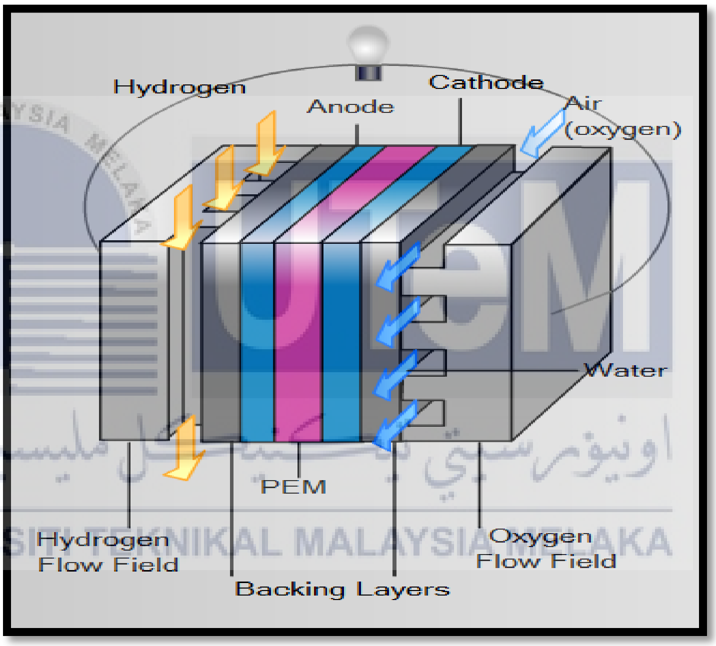


Figure 2.1: Fuel Cell [4]

2.2 Type of fuel cells

There are a few types of fuel cells right now a work in progress, each with its own advantages, constraints, and potential applications. The fuel cells classified by type of electrolyte they used. Polymer Electrolyte Membrane (PEM) Fuel Cells, Direct Methanol Fuel Cells (DMFCs), Alkaline Fuel Cells (AFCs), Phosphoric Acid Fuel Cells (PAFCs), Molten Carbonate Fuel Cells (MCFCs), and Solid Oxide Fuel Cells (SOFCs).

2.2.1 Direct methanol fuel cell

The direct methanol fuel cells (DMFCs) as shows in Figure 2.2 has been considered as the perfect fuel cell system since it produces electric power by the direct change of the methanol fuel at the fuel cell anode. Besides that, methanol offers a few points of interest as a fuel. It is reasonable however has a generally high energy density and can be effectively transported and saved. It tends to be provided to the fuel cell unit from a liquid repository which can be kept beaten up, or in cartridges which can be immediately changed out when spent. DMFCs is also will in general be utilized in applications with moderate power necessities such as in mobile electric gadgets and chargers[5]. Moreover, DMFCs work in the high pressure and temperature range from 60°C to 130°C which causes many losses in the system. The methanol traverses the membrane and sustained as a weak solution as it diffuses over the membrane without reacting. This condition lessen effectiveness to vast degree since the traversed methanol responds with air at cathode lastly causing decrease in cell voltage as the result.

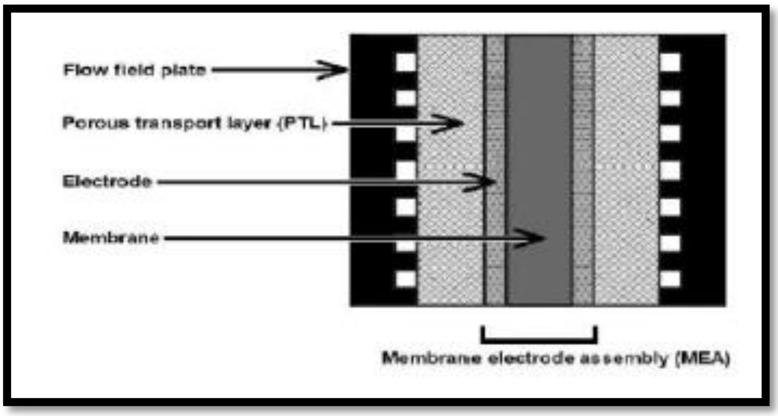


Figure 2.2: Direct Methanol Fuel Cell [5]

2.2.2 Alkaline fuel cell

Alkaline Fuel Cells (AFCs) uses watery solution of potassium hydroxide as the electrolyte. The fuel is work on compacted hydrogen and oxygen. The primary AFCs worked at somewhere in the range of 100ºC and 250ºC, yet common working temperatures are presently around 70ºC. Furthermore, AFCs were one of the primary energy component advances to be created and were initially utilized by NASA in the space program to deliver both power and water. Other than that, these types of fuel cell are easily harmed by carbon dioxide. Even the little measure of carbon dioxide in the air can affect this fuel cell task so that making it important to clean both the hydrogen and oxygen use in the cell. This refinement procedure is expensive to fuel cells. Since it is helplessness to harming additionally influences the cell's lifetime to further adding to cost. Figure 2.3 shows the alkaline fuel cell.

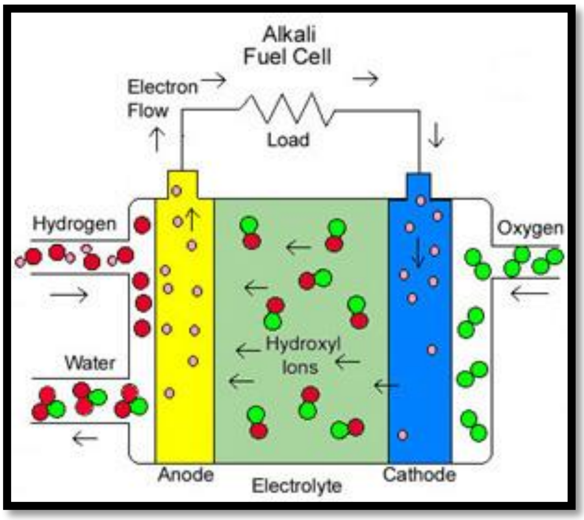


Figure 2.3: Alkaline Fuel Cell [6]

2.2.3 Phosphoric acid fuel cell

Phosphoric Acid Fuel Cells (PAFCs) as shown in Figure 2.4 is utilize phosphoric acid as the electrolyte. They are very resistant to harming by carbon monoxide however will in general have bring down efficiency than other fuel cell types in creating electricity. However, these cells work at reasonably high temperatures of around 180ºC and in general efficiency can be over 80% if this procedure heat is bridled for cogeneration. They are utilized in stationary power generators with output in the 100 kW to 400 kW range to power.

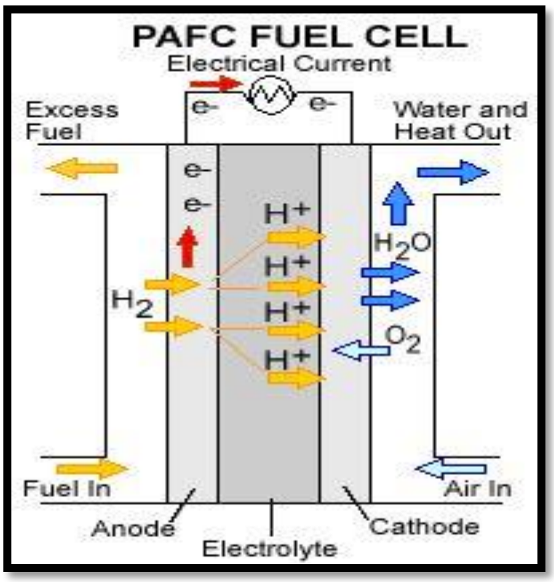


Figure 2.4: Phosphoric Acid Fuel Cells [7]

2.2.4 Molten carbonate fuel cells

Molten Carbonate Fuel Cells (MCFCs) as shown in Figure 2.5 is utilize a molten carbonate salt suspended in a permeable ceramic matrix as the electrolyte. They work at high temperature, around 650ºC and there are a few focal points related with this. Initially, the high working temperature significantly enhances kinetics energy and consequently it is not important to support these with good metal catalyst. The higher temperature additionally makes the cell less inclined to carbon monoxide harming than lower temperature systems. Moreover, MCFC systems can work on a wide range of fuels, including coal-inferred fuel gas and methane gas. The main impediments related with MCFC innovation is toughness. The high temperatures at which these cells work, and the destructive electrolyte utilized quicken segment breakdown and consumption, reduce cell life.

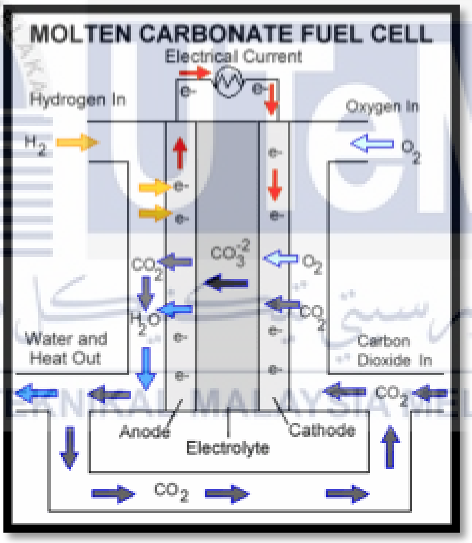


Figure 2.5: Molten Carbonate Fuel Cells [8]

2.2.5 Solid oxide fuel cell

Solid Oxide Fuel Cells (SOFCs) as shows in Figure 2.6 is utilize a hard-ceramic compound of metal such like calcium or zirconium oxides as electrolyte. A SOFC cell is a high temperature device, ordinarily working somewhere in the range of 700 and 800C which is highest compared among all type of fuel cell. Other than that, they can have efficiencies of over 60% while changing over fuel to electricity. Besides that, if the heat they delivered is likewise bridled then their general efficiency in changing over fuel to energy can be over 80%. The interest point of this type fuel cells incorporates high efficiency, long haul security, fuel adaptability, low discharges, and very low cost. However, SOFCs work high temperature these cells take more time to fire up and achieve working temperature, they should be built of hearty, heat-safe materials, and they should be protected to forestall heat loss. Finally, SOFCs are being considered for an extensive variety of utilizations in functioning as power systems for trains, boats and vehicles.

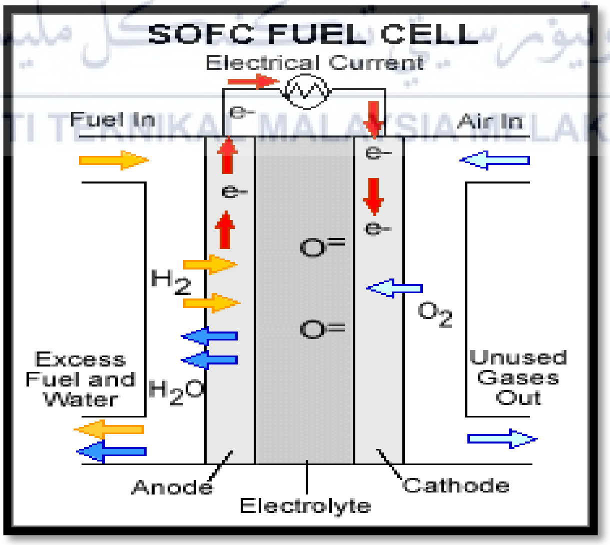


Figure 2.6: Solid Oxide Fuel Cells [9]

2.3 Proton exchange membrane fuel cells (PEMFC)

Proton exchange membrane fuel cells (PEMFC) is additionally called as polymer electrolyte membrane fuel cells which utilize a solid polymer as an electrolyte and porous carbon cathodes containing a platinum catalyst. They require just hydrogen, oxygen from the air, and water to work and don't require destructive fluid like some fuel cells. They are regularly fueled with pure hydrogen provided from capacity tanks.

PEMFC work at generally low temperatures which its procedure temperature is 50˚C - 100˚C and their weight is light [10]. This low temperature task enables them to begin rapidly and results in less wear on systems segments, bringing about better strength. Moreover, the fixing of PEMFC electrode is less demanding than other kinds of fuel cells. PEMFC has longer lifetime than the other fuel cell and it is less expensive for the manufacture.

Other than that, PEMFC utilize a to a very thin solid polymer layer as a electrolyte. This membrane is sandwiched between two electrodes which is the hydrogen electrode and the oxygen electrode. A thin layer of catalyst is clung to either side of the membrane. This membrane electrode assembly (MEA) is sandwiched between separators to create one cell. Two bipolar plates are situated against the electrodes, one on each side of the MEA. The response in a fuel cell delivers just about 0.7 volts, so a few fuel cells are associated in an arrangement to accomplish a helpful output. Fuel cells associated together are known as a fuel cell stack. To acquire a fuel cell stack, different fuel cells and bipolar plates are consecutively gathered in arrangement in a measured setup.

Besides that, PEMFC are the main type of fuel cell being created for transportation applications. Their improvement time table is basic for convenient organization of fuel cell vehicles to empower the real component of the hydrogen economy. Because of their quick startup time, low affect ability to introduction, and positive capacity to-weight proportion, PEM fuel cells would be especially suited for use in traveler vehicles. The Figure 2.7 shows PEM fuel cell.

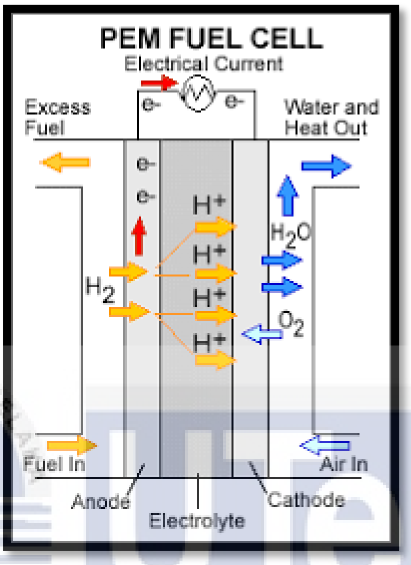


Figure 2.7: Proton Exchange Membrane Fuel Cell [11]

2.4 Pem fuel cell components

There are for major components in a PEMFC as shows in Figure 2.8. They are:

1. Membranes
2. Electrodes
3. Gas diffusion layer (GDL)
4. Bipolar plates

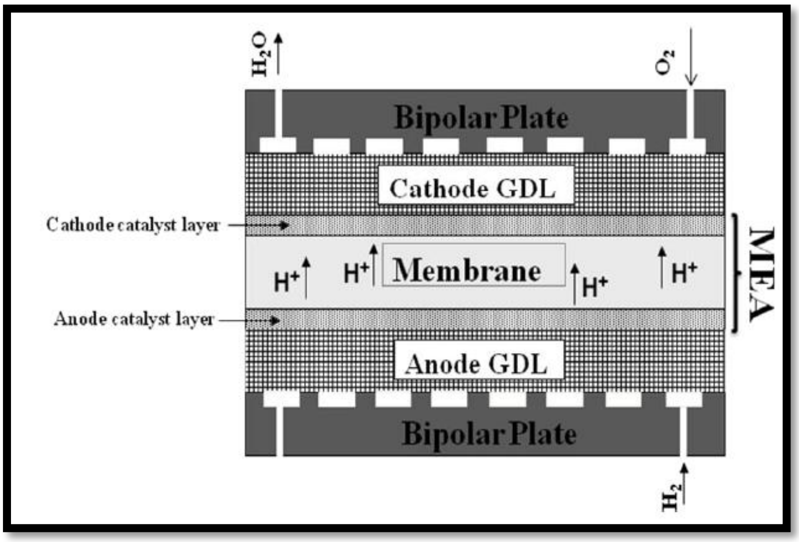


Figure 2.8: Basic schematic of a PEM fuel cells [3]

2.4.1 Membranes

For a PEM fuel cell to work, a proton exchange membrane is required that will convey the hydrogen particles, proton, from the anode to the cathode without passing the electrons that were expelled from the hydrogen molecules. These polymer membranes that lead proton through the membrane yet are sensibly impermeable to the gases, fill in as solid electrolytes for assortment of electrochemical applications. These membranes have been distinguished as one of the key parts for different purchaser related applications for fuel cells, such as in vehicles, back-up power, versatile power. Besides that, because of this some purchaser advertises continues developing to make these membranes appropriate for longer length, and even high temperature activities.

Other than that, for PEM fuel cell and electrolyze applications, a polymer electrolyte membrane is sandwiched between an anode electrode and a cathode electrode. When electrochemical process, oxidation reaction at the anode produces protons and electrons decrease reaction at the cathode consolidates protons and electrons with oxidants to generate water. To finish the electrochemical process, the proton exchange membrane assumes a basic job that conducts protons from anode to cathode through the membrane. The proton exchange membrane additionally executes as a separator for isolating anode and cathode reactants in fuel cells and electrolyzes.

The most ordinarily for PEM fuel cells which work at temperatures under 100 C, sulfonated polymers, for example, Nafion are the most utilized material. The sulfonated polymers are involved perfluorinated spines and sulfonated side-chains. The perfluoroether oversee the chemical steadiness while the capacity of sulfonated side-binds is to combine and facilitate water as schematically appeared in Figure 2.9 (left). Other than that, at DTU were they are working with another kind of membranes dependent on phosphoric acid doped polybenzimidazoles (PBI), see Figure 2.9 (right).

This membrane includes an alternate component of proton conduction and has high proton conductivity even with low water content. Therefore, PEMFC dependent on this type of membranes can work at temperatures up to 200°C with no gas humidification. The high working temperature considers a CO resistance of up to a few percent. A lifetime of task for more than 5000 hours at 150°C and shutdown-restart thermal cycling test for in excess of 200 cycles has been accomplished.

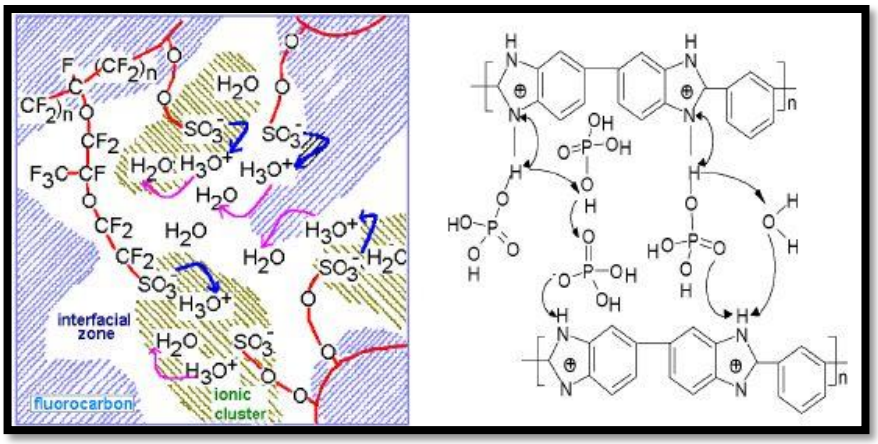


Figure 2.9: Schematic introduction of proton conduction in perfluoro sulfonic acid (left) and acid-doped polybenzimidazole (right) membranes [12].

2.4.2 Electro-catalyst layer (Electrodes)

The electrochemical reaction of PEM fuel cell happens at electrodes which specifically fabricated by Membrane Electrode Assembly (MEA). The function of electro-catalyst layer is to start the separation of the hydrogen, on the anode side, and for quickening the oxygen reduction reaction (ORR) on the cathode side. The electrons which delivered on the anode side, travel through an external circuit to deliver the current while the protons cross the membrane to the cathode side of the membrane and joint with the oxygen while the electrons process from the external circuit to deliver water and heat.

Generally, in PEM fuel cell the platinum is considered as the best catalyst for both anode and cathode energy component reactions regardless of a substantial distinction between the ORR and the hydrogen oxidation reaction (HOR). Moreover, the platinum-based catalyst layers are very good for fuel cell with relatively clean reactants. However, the major problems of the platinum-based catalyst emerge when the hydrogen fuel contains remain carbon monoxide (CO). The CO harms the platinum catalyst layer by weaken the fuel cell performance. Since that, the platinum-ruthenium (Pt-Ru) catalyst is recommended for avoid the CO harming issue. Many other Pt-alloy catalysts were explored however none of them was good Pt-Ru compound because of insecurity amid the electrochemical reaction. Decreasing the amount of platinum in the electro-catalyst layer will lessen the general expense of the PEMFC innovation and manufacturing.

Basically, the platinum substance can be diminished either by alloying it with minimal effort metals as pointed out previously or using core shell catalysts which is covered by low cost platinum shell. Currently the sum of platinum loading in electrode are around 0.4-0.8 mg platinum/cm². The US Department of Energy (DOE) has set the objectives of 0.2 mg/cm² for 2015 and 0.125mg/cm² for 2017 [13]. Figure 2.10 shows the structure of catalyst layers.

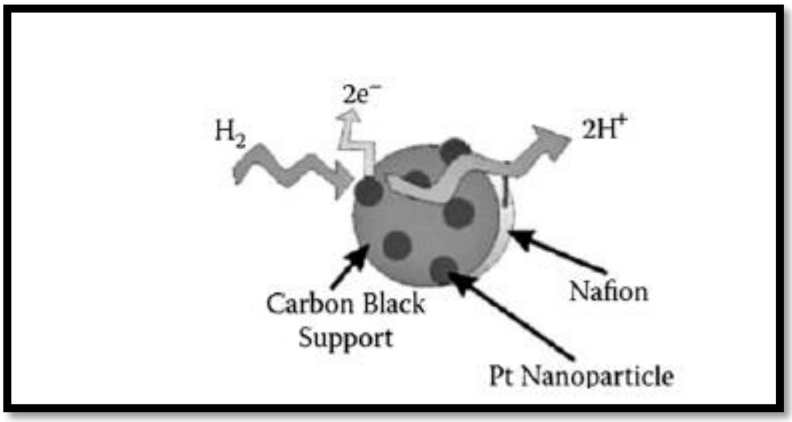


Figure 2.10: Structure of catalyst layers [13]

2.4.3 Gas Diffusion Layer (GDL)

Gas Diffusion Layers (GDL) are the key components of PEM fuel cell. The GDL is the external layer of the membrane electrode assembly (MEA) and thicker than the catalyst layer. There are many functions of GDL in the PEMFC:

1. Give mechanical help for the catalyst structure and membrane.
2. Lead electrons between the bipolar plate and the electrode.
3. Shield the catalyst layer from erosion caused by flow.
4. Add to heat and water expulsion.
5. Spread the reactant from the flow plates over the catalyst layer.

To satisfy most of the above capacities, the GDL must to have high electronic and heat conductivity also thicker than the catalyst and hydrophilic. The most famous materials utilized as GDL in PEMFC are carbon fiber paper and carbon cloth as shown in Figure 2.11. The GDL could be covered with a hydrophobic material, for example, Polytetrafluoroethylene (PTFE) since because of that the water may hinder the permeable of the GDL which are extremely important for reactant transports. PTFE also can call as Teflon. A hydrophobic treatment to GDL empowers enhanced water transport. In PEM fuel cells, especially water reservation can result in lower power generation[3]. Moreover, these GDLs are treated with Teflon in order to make the material hydrophobic and enhance water transport.

The flow inside the GDL can be sorted as multi-stage flow especially at the cathode side where the water is produced. A Micro-Porous Layer (MPL) can be coordinated with GDL at the catalyst layer to enhance the stream qualities of the multi-stage and improve the fluid expulsion. The motivation behind the carbon Micro-Porous Layer (MPL) is to limit the contact opposition between the GDL and catalyst layer, limit the loss of catalyst to the GDL inside and help to enhance water the executives as it gives successful water transport. MPL treatment is particularly prescribed for use with CCM (Catalyst Covered Membrane).

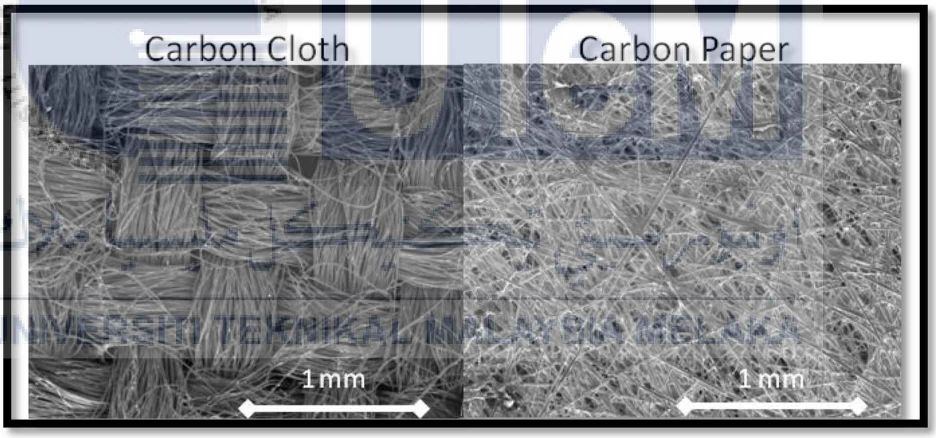


Figure 2.11: Microscope image of carbon cloth and carbon fiber paper used as GDL in PEMFC [14].

2.5 Bipolar plates

Bipolar plates (BPs) is an important component of the PEM fuel cell stack which represent about 80% of aggregate weight and 45% of stack cost [1]**.** They various function of BPs in fuel cell. Bipolar plates have reactant flow channels on the two sides, shaping the anode and cathode compartments of the unit cells on the restricting sides of the bipolar plate. They not just disseminate fuel and oxidant inside the cell, yet they likewise separate the individual cells in the stack, convey current from cell to cell, divert water from every cell, humidify gases, and keep the cells cool. Moreover, the plates must be of economical, lightweight materials and must be effectively and cheaply fabricated.

The materials of the bipolar plate must have specific properties due to its different obligations and the testing condition in which the fuel cell works. Material's properties must be considered for reachable design for a fuel cell application, explicitly, high electrical and thermal conductivity, gas penetrability, good mechanical quality, erosion obstruction and low weight. A perfect material should join the accompanying qualities that are characterized by Department of Energy (DOE) as shown in Table 2.1.

Table 2.1: Requirement properties for the bipolar plate [2].

Property	Value
Electrical conductivity	>100 S/cm
Shore hardness	>50
Flexural strength	>25MPa
Bulk density	<5 [g/cm^3]

2.6 Type Of Bipolar Plate

A few kinds of materials are right now utilized in bipolar plates, including non-porous graphite plates, metallic plates with or without coating and conductive polymer composite plates (CPC).

2.6.1 Graphite Bipolar Plates

Bipolar plates in the PEMFC have regularly been produced using graphite, since graphite has excellent chemical steadiness to endure the fuel cell condition. Pure graphite-based bipolar plates offer the benefits of excellent chemical obstruction, great thermal and electrical conductivity joined with a lower thickness than metal plates.

The disadvantages of graphite plates are its staggering expenses, the trouble of machining it, its porosity, and its weak and permeable. Bipolar plates have generally been made from graphite carbon impregnated with a resin or subject to pyrolytic impregnation. A thermal treatment is utilized in the process to seal the pores. They must be covered to be made impermeable to the fuel and oxygen. Moreover, graphite plates utilized in fuel cell stacks should ordinarily be a few millimeters thick, which add to the weight of the stack due to brittle of graphite [15].

Besides that, to overcome this issue, flexible graphite was viewed as the material of decision for bipolar plates in PEMFC. Flexible graphite is produced using a polymer/graphite composite, in which the polymer goes about as a binder. The graphite utilized for the composite is extended graphite (EG), created from graphite flakes inserted with exceedingly concentrated acid. The flakes can be extended up to a couple of multiple times their volume created from graphite flakes insert with very concentrated acid. This layered structure gives higher electrical and thermal conductivity. The extended form is then packed to the coveted thickness and squeezed to shape the bipolar plate.

2.6.2 Metallic Bipolar Plates

Metals, as sheets, are potential contender for bipolar plate material since they have great mechanical properties, gas impermeability, electrical and thermal conductivity. Likely the most imperative advantage is that the resultant stack can he littler and lighter than graphite bipolar plates. Two points of interest to metallic plates that they can be stepped to oblige flow channels and that the resultant plate can be fluctuated thick.

However, the main disadvantages is BPs are presented to a working situation with a pH of 2-3 at temperatures of around 80>C°, metal plates are inclined to erosion or disintegration[1]. The dissolved metal particles may prompt harming of PEM membrane and thus bringing down of ionic conductivity. In addition, an erosion layer on the surface of a BP expands the electrical resistance and declines the output of the cell.

To solve these issues, researchers have considered of non-coated metal composites and coated metals with a defensive layer. In conclusion, coated metal bipolar plates appear to have accomplished erosion security for the moderately short activity times of car applications [16]. A few vehicle producers are at present utilizing metallic bipolar plates in their car PEMFC stacks.

2.6.3 Conductive Polymer Composites Plates (CPCS)

Conductive polymer composites reasonable for building bipolar plates are set up by admixture and molding technique. The evolution of conductive polymer composites (CPCs) is a promising and developing field of research. Moreover, CPCs is composite materials for bipolar plates can be classify as metal or carbon-based. CPCs are lightweight, minimal effort and simplicity of machining, and can be formed into any shape and size, which makes them allure for PEM fuel stacks [17].

CPCs are commonly made of a polymer such as thermoplastic or thermoset. Moreover, CPCs is also made up of an electrically conductive added substance for example graphite, carbon black, carbon nanotubes and graphene. CPCs are handled very influences their conductivity since preparing straightforwardly influences the diffusion of the conductive fillers in the polymer matrices. Furthermore, the type and polarity of the matrix material additionally influences the conductivity of the CPC. The more polar the matrix, the better the association between the matrix and filler. Given this mind-boggling relationship, picking the perfect polymer and filler is hard to satisfy the prerequisites of good electrical conductivity, vigorous mechanical properties, and simple process capacity for PEM fuel cell development.

The advantages of thermoset composites are good strength and creep obstruction than the thermoplastic composites. On under other conditions, thermoplastic BPs can be reused, not at all like thermosets. Thermosets resin such as epoxy resins, phenolic resin and vinylesters are most usually for creation of BPs, while instances of thermoplastics resin that have been used for BPs is such as polypropylene (PP), polyvinylidene fluoride (PVDF), polymethylmethacrylate, polyethylene, and polyphenylene sulfide (PPS).

2.7 Percolation threshold theory

The conduction system of CPCs is clarified by the traditional percolation theory. It is expected that the composite carries on as an insulator when the volume fraction of the conductive filler is underneath a value, known as the percolation threshold (ϕc). Over this basic substance, a huge conductive bunch is formed, and the composite ends up as a conductive. Figure 2.6 shows the systematic graph of conductivity verse filler volume content. The higher the filler volume friction in a composite the higher electrical conductivity that can be produced by the bipolar plates [18].

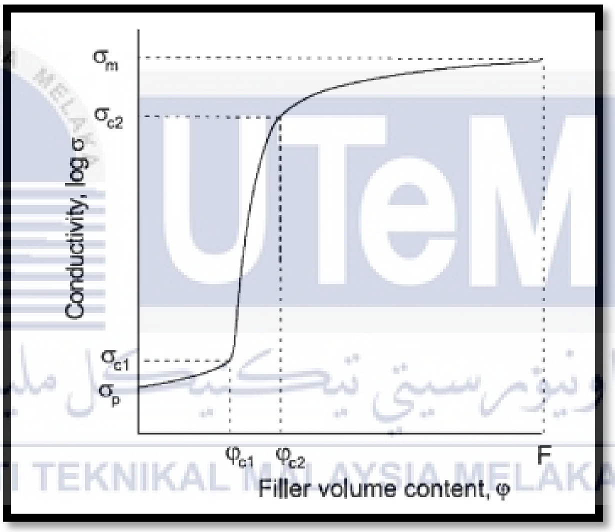


Figure 2.12: Shows the systematic graph of conductivity verse filler volume Content [29].

2.8 Materials

These parts are dedicated to the introduction of the materials, it will initially concern the conductive fillers and the polymer matrix.

Table 2.2 Properties Of materials [2]

Materials	Graphite	Carbon black	Ferum	Polypropylene
Grade	3243	5303	316SS	Titans
Density (g/cm^3)	1.74	1.79~ 1.9	7.874	0.91~0.92
Thermal Density	350-400	3000		175~220
(°C)	3500-4000	121	1500-1600	180~220
Size	59.022µm	< µm	43.281	Flake
Resistivity	1295 (10^{-8} Ωm)	0.14Ωcm	~100 mΩcm^2	1(1014 Ωm)

2.8.1 Conductive Fillers

Polymers are ordinarily electrical protectors; however, some conductivity might be gotten by the added substance fillers. Most composites bipolar plates have electrical conductivity which is far beneath the DOE focus of 100 S/cm[19]. Two type of fillers might be considered, either dependent on metal or nonmetal (carbon filler). Although the metallic conduction might be high, most concentrates in the writing are concerned with carbon fillers. There are many types of conductive filler such as graphite, carbon black, carbon fiber, carbon nanotubes, ferum, standard steel, silver, etc. Around 80% of bipolar plates weight based on this filler which have good mechanical and electrical conductivity.

2.8.1.1 Graphite

In this research, the most broadly utilized material for bipolar plates is graphite on the grounds that it gives great erosion opposition, low mass thickness and high electrical conductivity. Graphite as a sub-metal, is gotten from carbon stones shakes that are transformed. It is inferred in a flaky frame from these stones and has a hexagonal crystal structure. Graphite is one of the mildest metals, also making a good lubricant and it's the steadiest type of carbon under standard conditions.

Moreover, graphite is utilized in thermochemistry as the standard state for characterizing the heat of arrangement of carbon mixes. The conductivity of graphite relies upon a few components, such as on the crystallinity, explicit surface region. granular size and shape circulation of the material and on its manufactured. The conductivity of pure graphite can be higher than that of manufactured graphite, as its level of crystallinity is generally higher, contingent upon the place of inception [20].

Moreover, conductivity of graphite is not only depending on the crystallinity as well as on the state of its particles. Other than that, graphite has an amazing property of standing even hot condition, because of its high dissolving point, this makes it more helpful in specific regions of high temperatures. The properties for Gr are shown in Table 2.2.

2.8.1.2 Carbon black

The other widely used filler for bipolar plates is carbon black. Carbon black is a material delivered by the fragmented burning of overwhelming petroleum products, for example, FCC tar, coal tar, ethylene splitting tar, and a little sum from vegetable oil. Carbon black is a type of shapeless carbon that has a high surface territory to volume proportion, although its surface zone to volume proportion is low contrasted with activated carbon. The properties for CB are shown in Table 2.2.

Carbon black also a filler which increase conductivity of bipolar plates. Due to its higher explicit surface region carbon black can be included littler adds up to the matrix material. The saturation level on account of carbon blacks may fluctuate unequivocally contingent upon the explicit surface territory of the material utilized. Moreover, carbon black particles could go about as extensions between graphite particles for the most part because of their littler size bringing about better conductivity.

2.8.1.3 Ferum

In this research, iron goes about as second filler for bipolar plate to expand the efficiency of fuel cell. Iron is a glistening, strong, bendable, moldable, and silver-gray metal. Iron is bendable equipped for being drawn into thin wires and flexible equipped for being pounded into thin sheets. It is one of only three normally occurring magnetic component.

Iron is a metal substance component and known as Ferum (Fe). Fe has atomic number 26, atomic weight 55.85, and stable isotopes in periodic table. It is known to exist in four unmistakable crystalline structures. Iron rusts in moist air, however not in dry air. It breaks down promptly in weaken acids. Iron is synthetically dynamic, and structures two noteworthy arrangement of substance intensifies, the bivalent iron (II), or ferrous, mixes and the trivalent iron (III), or ferric, mixes. The properties for Fe are shown in Table 2.2.

Its surface is normally stained by corrosion, since it joins promptly with the oxygen of the air within the sight of dampness. In completely dry air, it doesn't rust. The oxide that is created is brittle and delicate, giving no protection to the base metal, which inevitably rusts away. It is found in nature as the metal just in shooting stars and in extremely uncommon conditions where iron minerals have been lessened by environmental factors.

Iron has an exceptionally high tensile strength, where it may be extended without breaking. Iron is generally work with a metal to get it into an ideal shape or thickness. The melting and boiling point of pure iron is 1,536°C (2,797°F) and 3,000°C (5,400°F) respectively. Its thickness is 7.87 grams per cubic centimeter.

Iron containing from 2.1% to about 4% carbon and from 1% to 3% silicon. This composition makes them good enough as casting metals. Tonnage of cast iron castings is a few times that of all other cast metal parts consolidated, barring cast ingots in steel-production that are hence folded into bars, plates, and comparative stock.

Moreover, pure iron has a body-centered cubic crystal structure at room temperature, called α-iron or ferrite. At 910°C the structure changes to face centered cubic (FCC), and this material is called γ-iron or austenite. At 1394°C, the structure returns to body centered cubic (BCC), and the material is called δ-iron, however it is extremely equivalent to α-iron. At 1535°C, the iron melts. Austenite is a softer and more effectively worked than ferrite, which clarifies the metalworker's heating of iron to red heat for working it. Figure 2.13 shows low-pressure phase diagrams of pure iron.

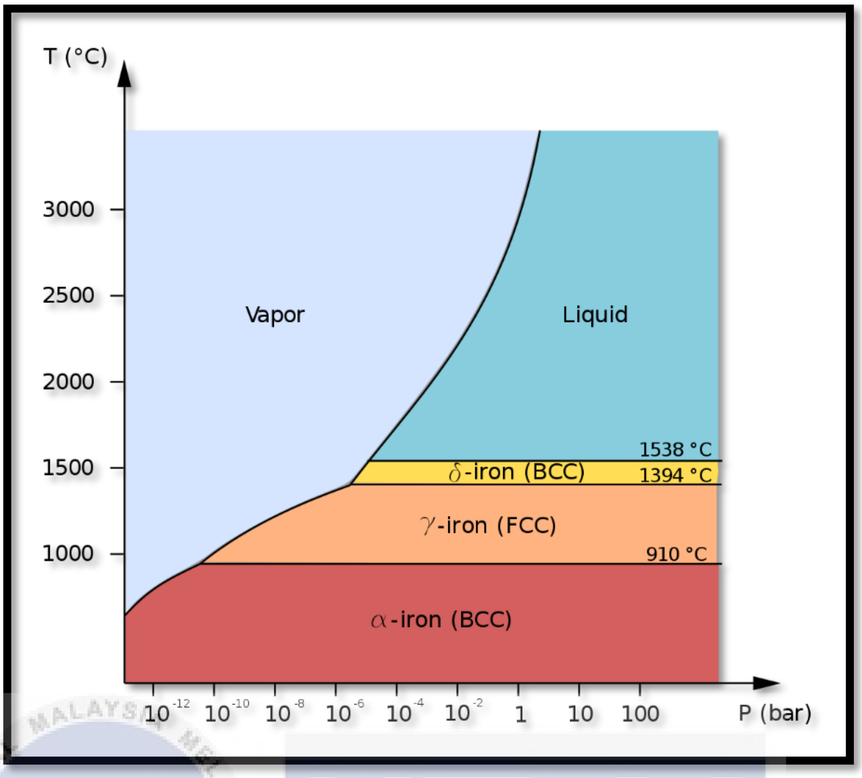


Figure 2.13: Low-pressure phase diagrams of pure iron [21].

2.8.2 Polymer matrix

The polymer matrix also impacts the electrical conduct of the composite. In polymers both thermoplastic and thermosetting resins might be utilized. In any case of the idea of the polymer, the readiness of BP requires a genuinely take large percentage of fillers and it will end cause wetting problem. If the distinction in the surface energies between the polymer and the fillers is low, at that point the polymer should effectively wet the fillers, permitting an expansion in the filler concentration, before porosity shows up in the composite. The most thermoplastic used in BPs is polypropylene (PP) since have good mechanical properties and low cost. Furthermore, they also three type of thermoset resin commonly used in BPs fabrications which is epoxy, phenolic and vinylester [22].

2.8.2.1 Polypropylene

The most polymer matrix used in bipolar plates is polypropylene (PP) which was act as a binder. PP is also called as polypropene, is a thermoplastic polymer utilized in a wide range of application. It is delivered by chain-development polymerization from the monomer propylene. Polypropylene has a place at polyolefins group and in form of crystalline and non-polar. Its properties are like polyethylene, yet it is marginally harder and heat resistant. Furthermore, PP is also cheaper, have great preparing conditions and mechanical properties of materials [2]. Polypropylene has been utilized as a matrix base due to lessen the weight and the delicacy of created plate. Moreover, polypropylene holds its shape after a ton of torsion, twisting, as well as flexing. This property is particularly profitable for making living pivots. Figure 2.14 shows the polypropylene.

Figure 2.14: Polypropylene [23]

2.9 Manufacturing process

Two major manufacturing processes are new technology that can manufacture economical bipolar plate that is compression moulding and injection moulding. As shown in Figure 2.12 the process.

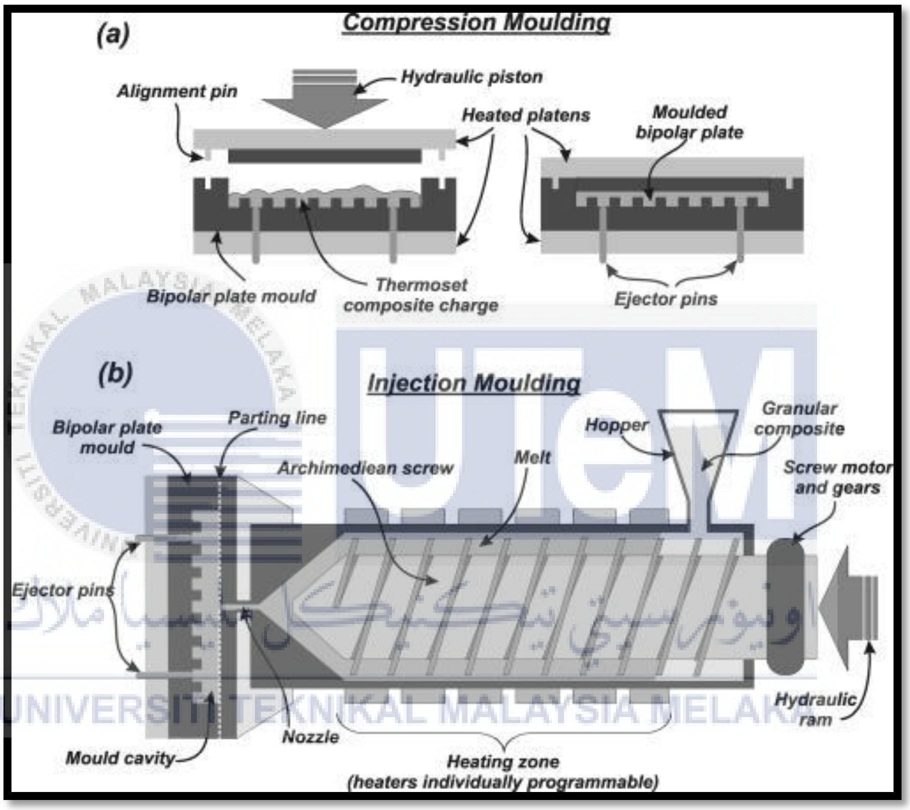


Figure 2.15: Compression moulding & Injection moulding [24]

2.9.1 Injection mould

Injection molding is a method of producing a product by injecting the product into shape, recognized as die-casting. It can improve the efficiency required in this method and decrease the expense of production.

To push the molten injection material into a mold cavity, use a ram or screw-type plunger in the injection molding. Injection molding of raw material elevated pressure injection to create a required shape. Mold or die are common devices that are used in the process of injection. Typical mold is produced of elevated melting point material such as hardened steel, aluminum, and tool steel. Because of its mechanical characteristics, aluminum content and stainless steel are more appropriate for producing a big amount of products and are more likely to harm and distortion during injection [25].

These machines all perform certain essential function such as :

- Plasticizing
- Injection
- Post-filling
- Cooling
- Molded-part release

2.9.2 Compression mould

The moulding of compression enables for cost-effective, large-scale production of bipolar plate. During the operation when it is hot, the healed sheet is removed from the mould so that its size and precision will not alter. Thus, the method is easy because after moulding it did not need a lengthy moment to cool down. In the moulding, the mould stress preferred to apply 40MPa to obtain a thick and low-porosity plate.

There are methods such as tableting, extrusion moulding, pre-forming and then feeding the prototype or billet into moulding device for obtaining bipolar plate for enhanced efficiency. Furthermore, the compression moulded thermoset composite can be cured comfortably in less than 10 minutes by using the compression method, resulting in less than the cycle time required for thermoplastics.

Compression moulding can also improve the surface strength of the bipolar plate owing to applied stress, increasing inter connectivity and contact between the reinforcing components

2.10 Performance criteria

There are a few parameters considered in BP material choice shown in Table 2.3. However, in the different innovative work on BPs more consideration has been given to enhancement of electrical conductivity, mechanical quality, corrosion resistance and interracial contact resistance. Most investigates on metallic BPs center more around erosion resistance and contact resistance, while studies on CPC BPs have concentrated more on accomplishing a balance between electrical conductivity and mechanical quality. This is because of the test looked in the improvement of a material that agreeably consolidate these properties to meet the condition for BP application.

Table 2.3: DOE targets for PEM fuel cell BPs [2]

Property	Value
Electrical conductivity	>100 S/cm
Thermal conductivity	>10 W/(mk)
Flexural strength	>25MPa
Flexibility	3-5 deflection at mid-span
Corrosion resistance	<1µAcm^{-2}
Bulk density	<5 [g/cm^3]
Weight	<0.4 kg/kW

2.10.1 Electrical conductivity

High electrical conductivity is not an issue with graphite and metals as these materials have conductivity esteems which an adequacy sufficiently high for BP applications. Maybe, with polymer composites, accomplishing high electrical conductivity is a basic thought because of the way that the polymer patterns for the most part have low conductivity, and high conductivity must be accomplished through stacking with high filler substance. The electrical conductivity of CPC BPs relies upon variables, for example, type of matrix, type of filler, molecule size, scattering and preparing strategy [26].

2.10.2 Mechanical strength

In order to give the required structural help to the fuel cell stack and withstand impacts, the BPs must have satisfactory mechanical strength. Mechanical test that are generally completed on BPs incorporate tensile test, pressure test, and flexural test. Anyhow, there has been more concentration on the flexural strength which is normally estimated utilizing the three-point bending test. This is because of the high bending pressure which the BPs are exposed to during stacking of the fuel cell.

Metals like stainless steels, ferum and aluminum, satisfying mechanical properties for BP applications however on CPC a main problem is failure or break down in mechanical strength when the filler content is raised to levels required to grant sufficient electrical conductivity. Hence, with CPC BPs, there is dependably a deal between mechanical strength and conductivity. Moreover, mechanical strength of CPC' BPs compared with metallic ones makes them less impervious to mechanical stuns, vibrations and less favored for transportation applications.

CHAPTER 3

METHODOLOGY

3.1 Experimental overview

This section will bargain about the method utilized through this project. Detailed explanation for the fabrication of bipolar plate using different composition will be given. Figure 3.1 demonstrates the flow chart for this project from Final Year Project 1 and Final Year Project 2.

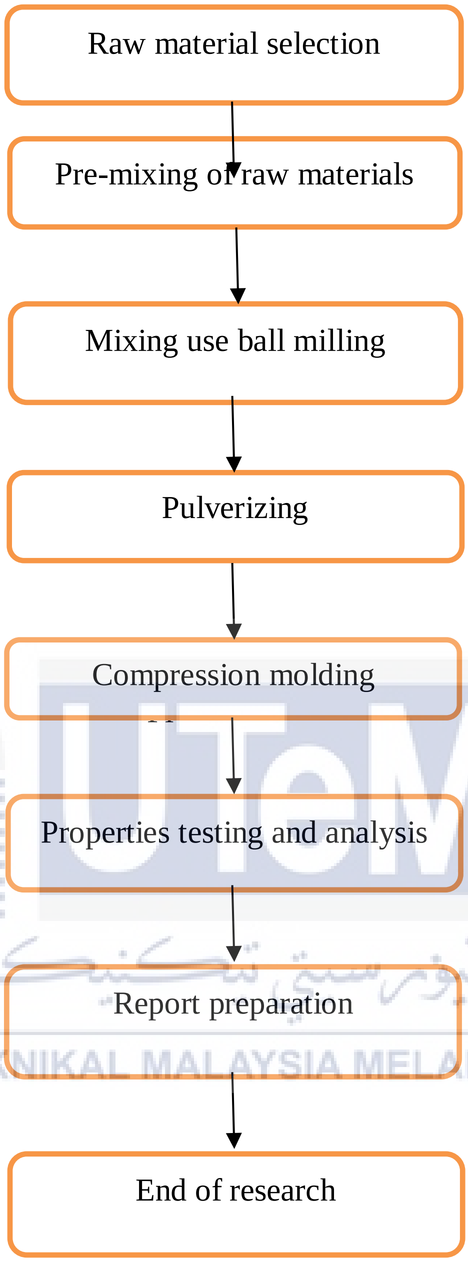


Figure 3.1: Flow chart of project

3.2 Material selection

The main raw material used in this project is Graphite, Carbon Black, Ferum and Polypropylene. The Graphite, Carbon Black, and Ferum will act as conductive filler while Polypropylene act as a binder. The materials shown in Figure 3.2. These materials will be mixed to produce four different materials compositions for create bipolar plate as shown in Table 3.1.

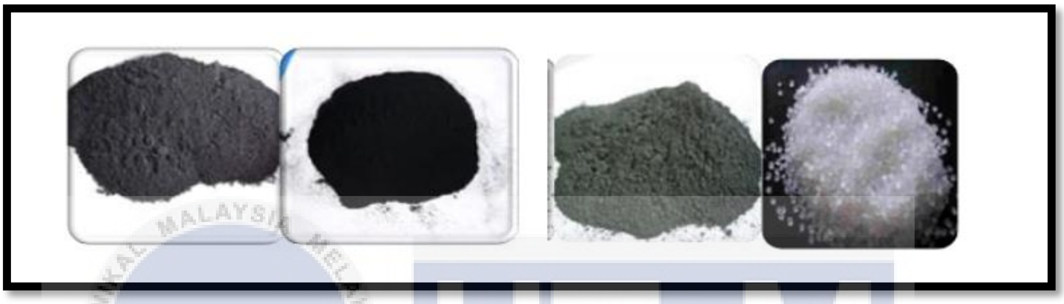


Figure 3.2: From left – Graphite, Carbon black, Ferum and Polypropylene[27].

Table 3.1: Composition based on weight percentage

Composition	Filler			Binder
	Graphite (wt.%)	Carbon Black (wt.%)	Ferum (wt.%)	Polypropylene (wt.%)
1	55	25	0	20
2	50	25	5	20
3	45	25	10	20
4	40	25	15	20

3.3 Pre Mixing

The reasons behind the pre-mixing process are the confirmation of a homogeneous mix between the filler materials. Graphite and Carbon Black are placed in a plastic bottle of 500 ml for the primary composition. For better mixing between Graphite and Carbon Black, they will insert 20 ball bearings into the plastic bottle. The device used for this pre-mixing process is the Ball Mill Model 2VS. The bottle will spin at a speed of 300 rpm and the process will take about 3 hours to complete the appropriate mixing [24]. For each run, two bottles can be placed. In addition, Graphite, Ferum and Carbon Black are used this process repeatedly to mix well for create composition two, three and four. Figure 3.3 shows the 500ml bottle, ball bearings and mixing process.

Figure 3.3: The 500ml bottle, mixing process, and ball bearings

3.4 Pulverizing

The main aim of pulverizing process is to make the binder materials in fine powder form. This process using Pulverizer- High Manganese Grinding Bowl machine. The speed of machine setup to 500 rpm and this procedure will took around 10 to 15 minutes. Figure 3.4 shows the size of PP before crush and pulverized and after pulverized.

The primary purpose of the process of pulverization is to produce the binder in fine powder form. Pulverizer- High Manganese Grinding Bowl machine used in this process. Moreover, machine setup speed to 500 rpm and this procedure will take about 10 to 15 minutes. Figure 3.4 shows the size of PP before and after pulverizing.

Figure 3.4: The size of PP before and after pulverized.

3.5 Mixing use ball milling

The main goal of this process is to mix the filler with binder materials. The com position of Gr, CB, Fe must be mixed with PP. This process can be done by the ball milling, the mixing,time is about 1 to 2 hours. Figure 3.5 shows that composition of Gr, CB, Fe with PP.

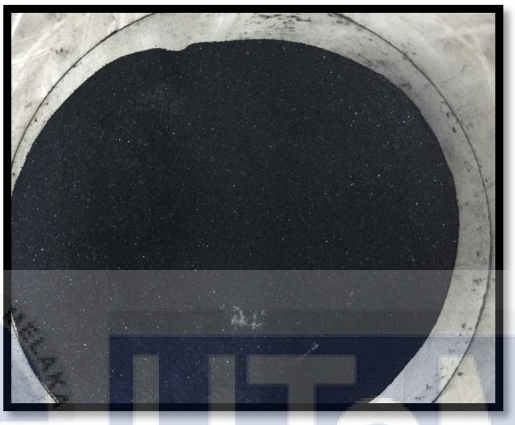


Figure 3.5: Composition of Gr, CB, Fe with PP

3.6 Compression molding

After the mixing between fillers and binder has been completed, the mixture will be set in a 140 mm x 60 mm rectangular mold. The mold will be placed for compression molding purposes on 200 Ton High Speed Hot Press Hydraulic as shown in Figure 3.6. Parameters are set for the compositions of Gr/CB/PP and G/CB/Fe/PP are shown in Table 3.2.

Table 3.2: Parameters of compression molding

Parameter	Gr/CB/PP	Gr/CB/Fe/PP
Amount of mixture (g)	40	40
Temperature (°C)	180	180
Load (tonne)	80	80
Pre-heating (min)	3	2
Pressing time (min)	10	9
Curing temperature (°C)	100 and below	70 and below

Figure 3.6: 200 Ton High Speed Hot Press Hydraulic machines

The formed bipolar plate is removed from the mold once the mold has cooled down. Figure 3.7, and 3.8 show the compression molding product, i.e. the bipolar plate made from compositions Gr/CB/PP and Gr/CB/Fe/PP respectively. The plate made of both compositions has the same dimensions of 140 mm x 60 mm.

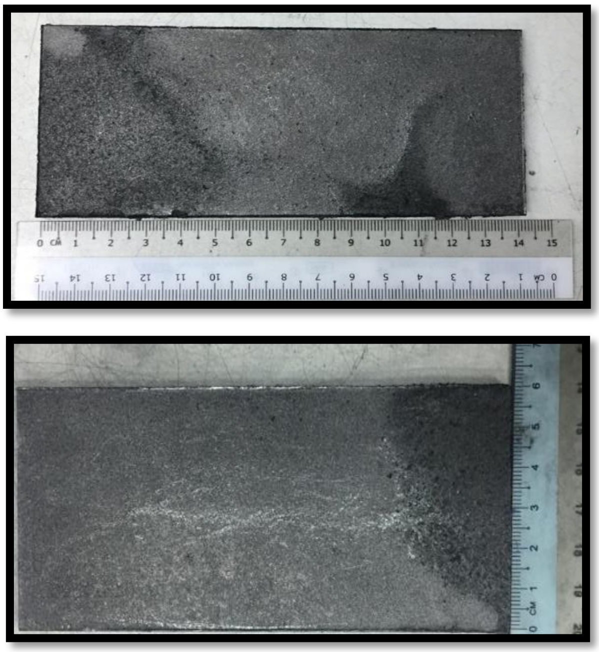


Figure 3.7: Bipolar plates made of G/CB/PP composition

Figure 3.8: Bipolar plates made of G/CB/Fe/PP composition

3.7 Properties testing and analysis

After the molding of bipolar plates has been completed, they must verify that they meet US-DOE requirements for bipolar plates. There are few tests performed to study the properties of bipolar plates made using compositions of Gr/CB/Fe/PP. The test incorporates electrical conductivity, shore hardness and flexural strength.

3.7.1 Electrical conductivity

This test was performed to determine the electrical conductivity of bipolar plates. It was carried out using the Jandel Multiheight Microposition probe. The sample conductivity measurement was performed using four-point probe technique using Jandel four-point probe head. First, the sample has been placed on the jig. Then the probe was brought down and placed on the front and back surface of the sample at nine different points. Reading has been taken for every point. The electrical conductivity must be more than 100 S/cm according to US-DOE targets. This test was referred to as the Standard Test Method for Electrical Conductivity Using the Electromagnetic (Eddy Current) (ASTM E1004). Figure 3.9 shows the measurement device and method[28].

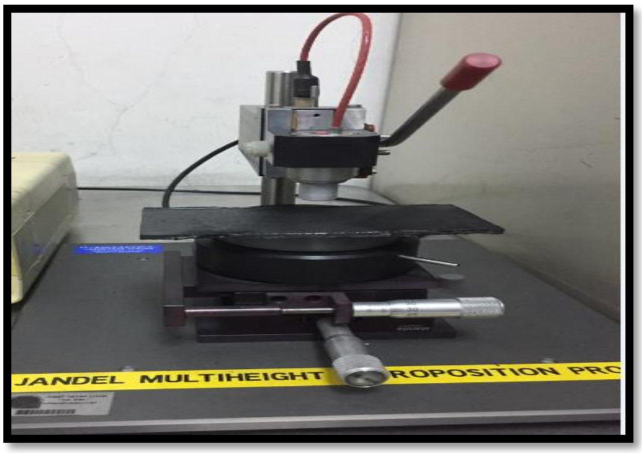


Figure 3.9: Jandel Multiheight Microposition Probe

3.7.2 Density Testing

Density test is essential to ensure that BP is lightweight as could be allowed. This test completed utilizing electronic densimeter. Firstly, the weight of sample was taken by setting it on densimeter. The sample fully submerged in water inside the densimeter then the reading was taken. As indicated by US-DOE targets, density must be less 5 g/cm^3. This test was referred to as the Standard Test Methods for Density and the Specific Gravity (Relative Density) of Plastics by Displacement (ASTM D792)[29]. Figure 3.10 shows electronic densimeter.

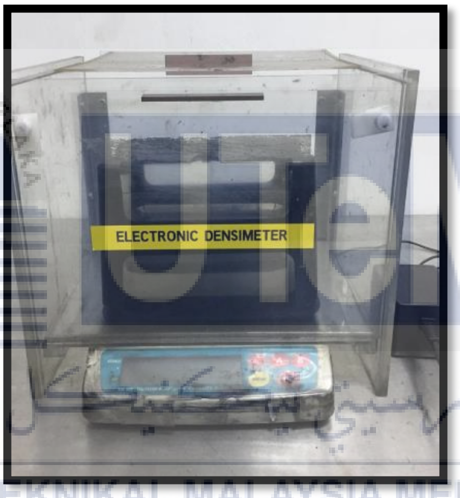


Figure 3.10: Electronic Densimeter

3.7.3 Flexural strength

The flexural test is one of the essential tests to be done as the flexural strength defines the bipolar plate's failure limits. The test was carried out using the INSTRON Universal Testing Machine. Before being placed for testing, the plates were cut in 140 mm x 13 mm. Set the speed 1mm/1min once the sample is placed on the machines and the support span between two points around 50 mm. Then start the machine to operate automatically and stop the machine when the graph value decreases. The reading of the flexural strength has been taken. Figure 3.13 shows the machine and method. This test was referred to Unreinforced and Reinforced Plastics and Electrical Insulating Materials (ASTM D 790-03) Standard Test Methods for Flexural Properties[29].

Figure 3.11: INSTRON Universal Testing Machine

3.7.4 Shore Hardness

Shore hardness is a measure of material hardness. This test was performed using an analog TECLOCK GS-720 G SHORE-D Durometer. The analog Durometer is shown in Figure 3.12. First, it must be set to zero for the longer dial. The durometer was then pressed onto the sample by which a needle extends and penetrates the sample. The longer dial shows hardness reading afterwards. This test was referred to Standard Test Method for rubber property – Durometer hardness (ASTM D2240D) [29].

Figure 3.12: Durometer

3.7.5 Scanning electrical microscopic

A specimen can be imaged and analysed by Scanning Electron Microscopy (SEM). It is possible to physically examine the sample structure and determine its elementary composition. It also generates many kinds of signals that can be used to obtain surface geometry and structure data.

CHAPTER 4

RESULTS AND ANALYSIS

After the fabrication of bipolar plates made from Gr/CB/Fe/PP compositions a few tests were performed for determination of their properties. In this chapter the tests results are described and analyzed.

4.1 Electrical conductivity

The conductivity was taken on the sample surface at nine different points shown in Figure 4.1 in order to obtain a similar average reading. The measurement was taken about 18 readings, at each point on the top and bottom of the plates and calculated the average.

Figure 4.1: Nine different points on surface of sample

The reading shown in millivolts (mV). Thus, to calculate the conductivity in Siemens Per Centimeter (S/cm), the formula below was used.

$$\text{Scm}^{-1} = \frac{1}{2\pi(data\ ave)(0.6336)}$$

Where, S = 0.1 cm (distance from Jandel Multi Height Four Point Probe)
0.6336 = factor of thickness per diameter of specimen.

The electrical conductivity of each sample for bipolar plates was shown in Table 4.1.

Table 4.1: Electrical conductivity for bipolar plates made of Gr/CB/Fe/PP composition.

Sample	Gr (wt.%)	CB (wt.%)	Fe (wt.%)	PP (wt.%)	Average σ (S/cm)
1	55	25	0	20	118.834
2	50	25	5	20	101.32
3	45	25	10	20	125.50
4	40	25	15	20	119.94

*Note: The full results are shown in Appendix A

It is clear from Tables 4.1 that the bipolar plate made from the addition of Fe 10 wt.% composition showed the higher electrical conductivity compared to other compositions. The Unites States Department of Energy (US-DOE) has set the standard for bipolar plates electrical conductivity to be higher than 100 S/cm. The bipolar plate made from all compositions therefore exceeds the minimum standards established by the US-DOE.

4.2 Flexural test (3-point bending)

Figures 4.2 show respectively the placement of the specimen on the INSTRON machine and the result after the test. Three specimens of each sample were cut and calculated on average.

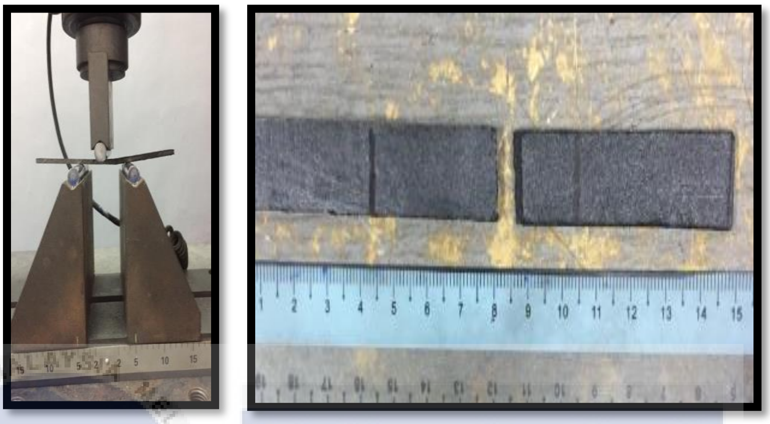


Figure 4.2: Proper placement and results of the specimen.

Table 4.2 shows the results of the flexural test carried out on bipolar plate specimens made of the different Fe wt.% composition.

Table 4.2: Flexural strength of bipolar plates.

Fe Weight (%)	1st specimen (MPa)	2nd specimen (MPa)	3rd specimen (MPa)	Average (MPa)
0	18.57	21.42	23.84	21.28
5	24.96	23.88	25.13	24.66
10	25.05	23.35	28.93	25.78
15	13.06	15.00	14.50	14.19

*Note: The full results are shown in Appendix A

It can be concluded from Table 4.2 that the plate made from adding 10 wt.% Fe shows a higher flexural strength compared to the plate made from other compositions. Other than that, the addition of 15 wt.% of Fe among other bipolar plate is the lowest flexural strength. The United States Department of Energy (US-DOE) has set the standard for flexural strength of bipolar plates that must exceed 25MPa. The bipolar plate made from adding 10 wt.% of Fe is only composition that exceeds the minimum standards set by the US-DOE.

4.3 Density Test

The measurement of density for each sample was taken three times and calculated on average. The density of bipolar plates made from different compositions of Gr/CB/Fe/PP is shown in Table 4.3.

Table 4.3 Density of Gr/CB/Fe/PP composition bipolar plates.

Fe Weight (%)	Reading 1 (g/cm^3)	Reading 2 (g/cm^3)	Reading 3 (g/cm^3)	Average (g/cm^3)
0	1.166	1.265	1.216	1.216
5	1.242	1.475	1.639	1.452
10	1.604	1.429	1.437	1.489
15	1.606	1.598	1.596	1.600

The bipolar plate from the Gr/CB/PP compositions, meaning no addition of Fe, is lighter and has a lower density compared to other bipolar plate, based on Table 4.4.The Unites States Department of Energy (US-DOE) has set the standard for bipolar plates density to be less than 5 g/cm^3. The density of the bipolar plate made of all the compositions complies with the US-DOE standards.

4.4 Shore Hardness Test (Shore-D)

The measurement of the hardness was taken at 3 different points on the plate and the average has been calculated. Figure 4.4 shows the points from which the measurement was taken. Table 4.3 shows the result of the hardness of the plates made from Gr/CB/Fe/PP compositions.

Figure 4.3: Point of the measurement was taken.

Table 4.4: Hardness measurement of Gr/CB/Fe/PP bipolar plates.

Fe Weight (%)	Point 1	Point 2	Point 3	Average
0	69.3	72.0	65.0	68.77
5	66.4	62.0	67.0	65.13
10	70.4	72.0	70.0	70.80
15	68.2	69.1	68.0	68.43

Table 4.5 shows that the bipolar plate made from the addition of 10 wt.% of the Fe composition shows a higher hardness value of 70.80 compared to the other three compositions. The Unites States Department of Energy (US-DOE) has set the standard for shore hardness of bipolar plates must be 50 or higher. The shore hardness of the bipolar plate made of all the compositions meets the standards of the US-DOE.

CHAPTER 5

DISCUSSION

Based on tests conducted, the results were determined and analyzed. The bipolar plates made of Gr/CB/Fe/PP composition exceed the standards set by US-DOE for electrical conductivity, density, flexural strength, and shore hardness.

5.1 Electrical Conductivity

Initially, the electrical conductivity of Gr/CB/Fe/PP composites decreased with the increase in Fe content from 0 wt.% to 5 wt.% as shown in Figure 5.1. Finding thus provides evidence that using Fe as a filler there still has the complication of agglomeration that forms during fabricating, although Fe's particle size has been reduced[30]. Therefore, a weak conducting network was formed between the fillers Gr/Fe/CB and PP matrix. However, as the concentration of Fe filler loading increased, the electrical conductivity of Gr/CB/Fe/PP composites has been slightly increased. The present finding was also made in line with research which concludes based on threshold percolation theory, the electrical conductivity of the bipolar plate also increases when the filler content is increased [29].This is because Fe is as highly conductive as we know it. While the electrical conductivity value of all bipolar plates made from the composition of Gr/CB/Fe/PP is not consistent, it still considers acceptable as it must be at 100 S/cm between the targeted values set by US-DOE. The maximum electrical conductivity value is 10 wt.% of Fe at loading with a value of 125.50 S/cm.

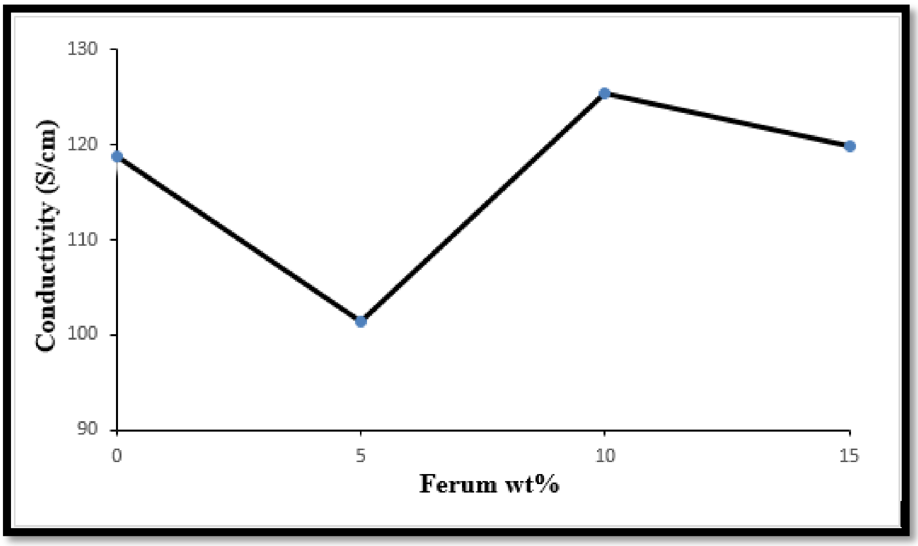


Figure 5.1: Graph of conductivity versus Fe wt.%

5.2 Flexural Test

The graph flexural strength against weight percentage of the Fe has been plotted as shown in Figure 5.2. With increased Fe content, the flexural strength of the G/CB/Fe/PP composite gradually increases. The optimal value of the flexural strength obtained was 25.78 MPa at 10 wt.% of Fe. This showed increased flexural strength with increasing filler content[29]. The reduction of flexural strength after adding Ferum loading at 15 wt.% can be attributed to the poor mixing of filler with binder [27]. Adding 10 wt.% Ferum to the bipolar plate is the only composition that meets the flexural strength requirement set by US-DOE, which states that the flexural strength must exceed 25 MPa.

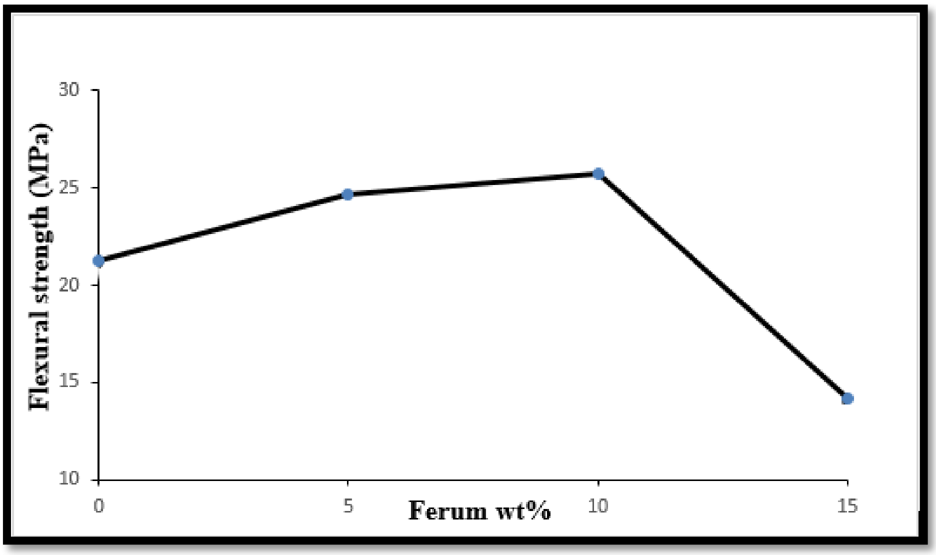


Figure 5.2: Graph of flexural strength versus Fe wt.%

5.3 Density Test

The graph bulk density against weight percentage of the Fe has been plotted as shown in Figure 5.3. Bulk density is increased by increasing the presence of Fe as a filler. Bulk density of all samples generally affected by particle weight and size. The density of the Gr/CB/Fe/PP bipolar plate meets the standard set by US-DOE, which states that the density of a bipolar plate must be less than 5 g/cm^3.

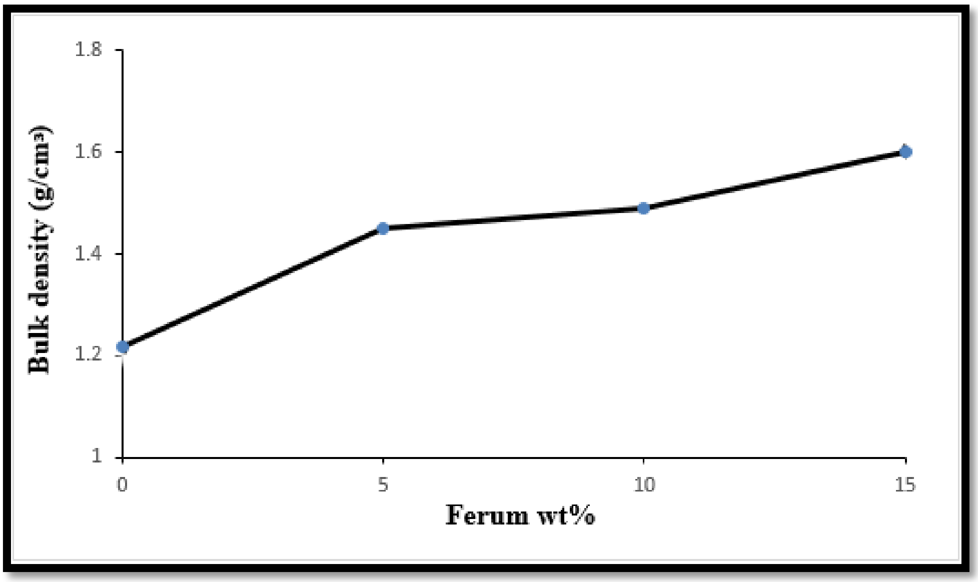


Figure 5.3: Graph of bulk density versus Fe wt.%

5.4 Shore Hardness Test

The shore hardness value dropped from 68.77 at 0 wt.% to 65.13 at 5 wt.% Fe content. The reduction in the composite's hardness may be attributed to the poor bonding of Fe content with other fillers in the composite [27]. The addition of Fe 10 wt.%, based on Figure 5.4, shows a 70.8 higher harness value compared to other compositions. All bipolar plates made from the Gr/ CB/Fe/PP composition are still considered acceptable as the targeted values set by US-DOE must be 50 or higher.

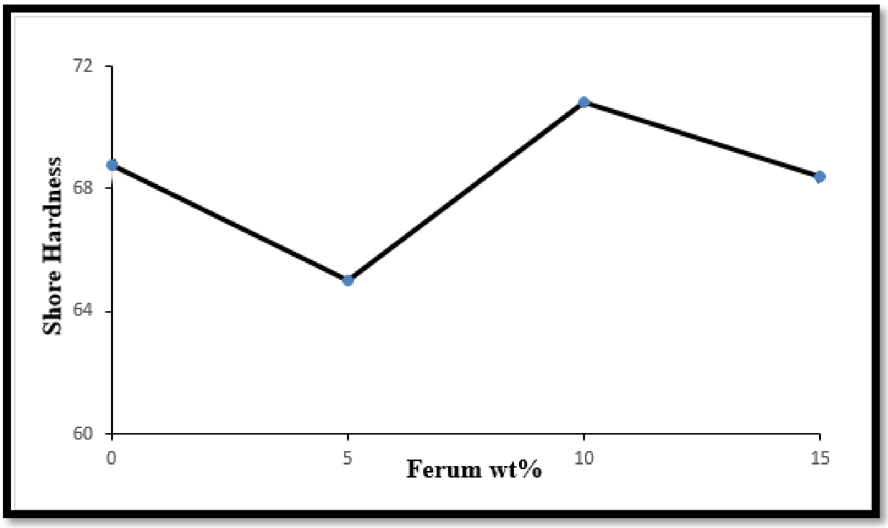
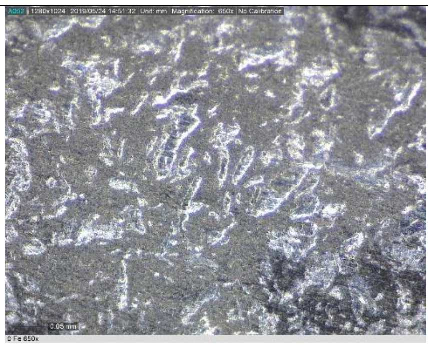
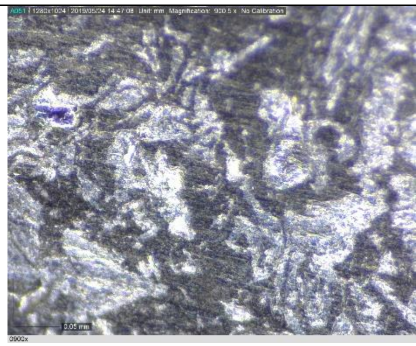
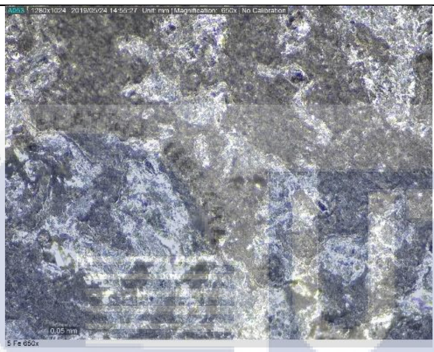
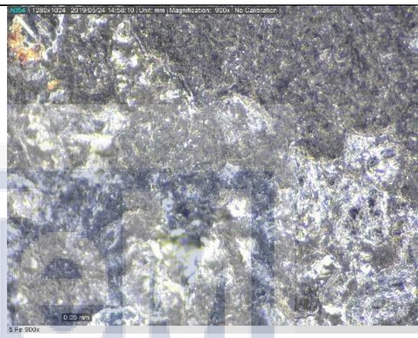
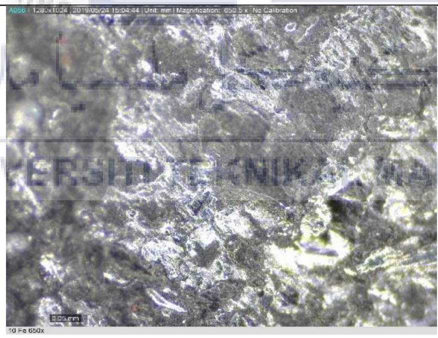
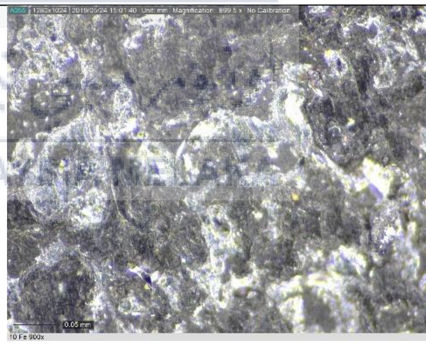
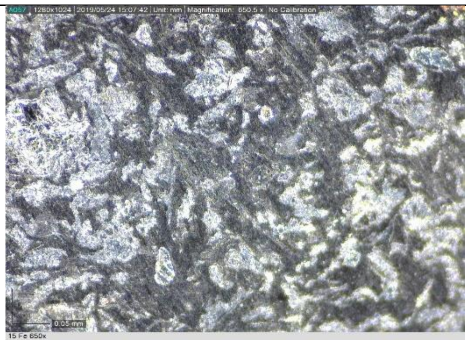
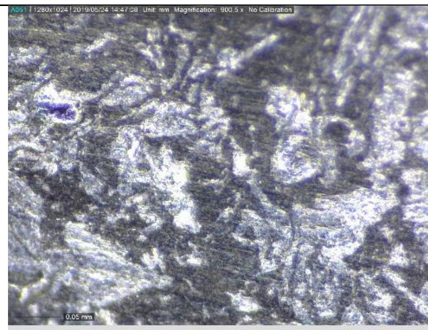


Figure 5.4: Graph of shore hardness versus Fe wt.%

5.5 Microstructure results

Figure 5.1 shows the SEM image (650x and 900x) on the 0,5,10 and 15 wt. percent of Fe surface.

Table 5.1: Microstructure

Fe (wt%)	Maginification 650x	Maginification 900x
0		
5		
10		
15		

5.6 Result validation

All the obtained results are validated in accordance with the US-DOE standard. Table 5.2 shows the overall characteristics of various Fe loadings in the composite Gr/Fe/CB/PP.

Table 5.2: Overall properties of different Fe loading in Gr/Fe/CB/PP composite

Characteristics	Fe weight (%)				US-DOE standard
	0	5	10	15	
Electrical conductivity (S/cm)	118.83	101.32	125.50	119.94	>100
Flexural strength (MPa)	21.28	24.66	25.78	14.19	>25
Density (g/cm^3)	1.216	1.452	1.489	1.600	<5
Hardness (shore D)	68.77	65.13	70.8	68.43	>50

CHAPTER 6

CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

As for the conclusion, there is two main objectives for this project. The first is to study the effect of Fe loading on the electrical and mechanical properties of Gr/CB/Fe/PP composite. This objective has been achieved since the successful fabricate of the bipolar plates of all composition with different amount of Fe. Their properties were studied by conducting four tests that are electrical conductivity, flexural strength, shore hardness, and density.

The second objective is to determine the critical loading of Fe in Gr/CB/Fe/PP composite. This objective has also been achieved. Based on the result, all US-DOE requirements have been successfully met by bipolar plate made from Fe 10 wt.% composition.

6.2 Recommendations

From this research, adding Fe as filler material in this project demonstrates good electrical conductivity and hardness value. Therefore, other conductive filler materials such as Stanum, Nickel and Copper are highly recommended in the future. In addition, due to some improper mixing of filler with binder, some compositions may have negative results. Improvement in the process of mixing filler with binder should be significant to well mixed for this purpose. Other than that, for better performance of fuel cell make a complete bipolar plate with flow and cooling channel.

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APPENDIX A

Electrical conductivity

A) FRONT

Sample 1 Gr/Fe/CB/PP :55/0/25/20

I (mA)	V (mA)	σ (S/m)
1	0.019	132.27
1	0.019	132.27
1	0.018	139.62
1	0.025	100.53
1	0.018	139.62
1	0.02	125.66
1	0.025	100.53
1	0.021	119.68
1	0.022	114.24
Average		122.7124

B) BACK

Sample 1 Gr/Fe/CB/PP :55/0/25/20

I (mA)	V (mA)	σ (S/m)
1	0.021	119.68
1	0.019	132.27
1	0.022	114.24
1	0.025	100.53
1	0.024	104.72
1	0.025	100.53
1	0.024	104.72
1	0.019	132.27
1	0.02	125.66
Average		114.9556

A) FRONT

Sample 2 Gr/Fe/CB/PP :50/5/25/20

I (mA)	V (mA)	σ (S/m)
1	0.024	104.72
1	0.021	119.68
1	0.022	114.24
1	0.025	100.53
1	0.022	114.24
1	0.02	125.66
1	0.027	93.08
1	0.024	104.72
1	0.022	114.24
Average		110.12

B) BACK

Sample 2 Gr/Fe/CB/PP :50/5/25/20

I (mA)	V (mA)	σ (S/m)
1	0.025	100.53
1	0.024	104.72
1	0.022	114.24
1	0.026	96.66
1	0.032	78.54
1	0.03	83.77
1	0.027	93.08
1	0.025	100.53
1	0.026	96.66
Average		96.52

A) FRONT

Sample 3 Gr/Fe/CB/PP :45/10/25/20

I (mA)	V (mA)	σ (S/m)
1	0.014	179.51
1	0.014	179.51
1	0.016	157.07
1	0.014	179.51
1	0.021	119.68
1	0.016	157.07
1	0.013	193.32
1	0.015	167.55
1	0.013	193.32
Average		127.21

B) BACK

Sample 3 Gr/Fe/CB/PP :45/10/25/20

I (mA)	V (mA)	σ (S/m)
1	0.013	193.32
1	0.02	125.66
1	0.018	139.62
1	0.015	167.55
1	0.013	193.32
1	0.014	179.51
1	0.02	125.66
1	0.013	193.32
1	0.015	167.55
Average		123.79

A) FRONT

Sample 4 Gr/Fe/CB/PP :40/15/25/20

I (mA)	V (mA)	σ (S/m)
1	0.021	119.68
1	0.025	100.53
1	0.022	114.24
1	0.02	125.66
1	0.021	119.68
1	0.019	132.27
1	0.018	139.62
1	0.021	119.68
1	0.023	109.27
Average		120.07

B) BACK

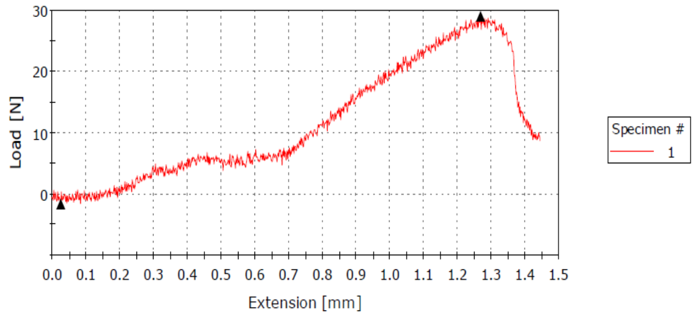
Sample 4 Gr/Fe/CB/PP :40/15/25/20

I (mA)	V (mA)	σ (S/m)
1	0.02	125.66
1	0.019	132.27
1	0.018	139.62
1	0.024	104.72
1	0.022	114.24
1	0.021	119.68
1	0.025	100.53
1	0.023	109.27
1	0.019	132.27
Average		119.81

APPENDIX B

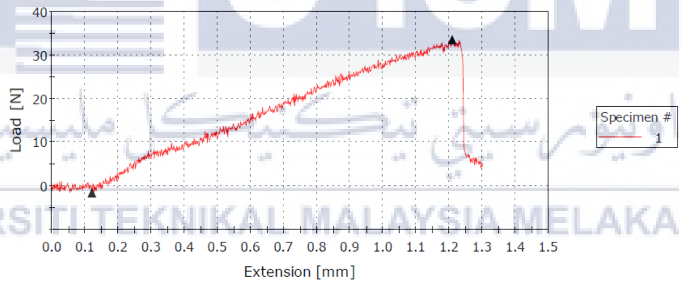
Flexural result

Sample 1



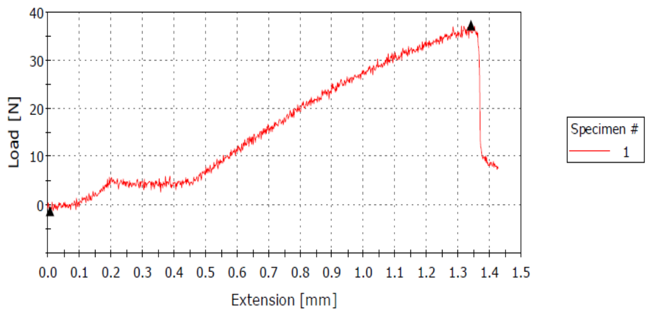
	Maximum Load [N]	Flexure stress at Maximum Load [MPa]	Extension at Maximum Load [mm]	Energy at Maximum Load [J]
1	28.96	18.57	1.27	0.01

Sample 1 A1 Gr/Fe/CB/PP :55/0/25/20



	Maximum Load [N]	Flexure stress at Maximum Load [MPa]	Extension at Maximum Load [mm]	Energy at Maximum Load [J]
1	33.42	21.42	1.21	0.02

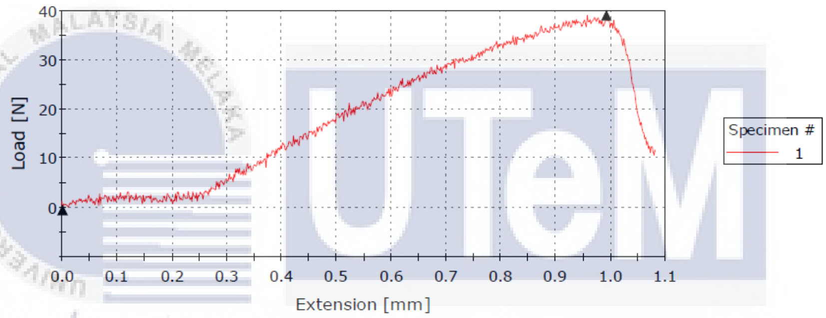
Sample 1 A2 Gr/Fe/CB/PP :55/0/25/20



	Maximum Load [N]	Flexure stress at Maximum Load [MPa]	Extension at Maximum Load [mm]	Energy at Maximum Load [J]
1	37.19	23.84	1.34	0.02

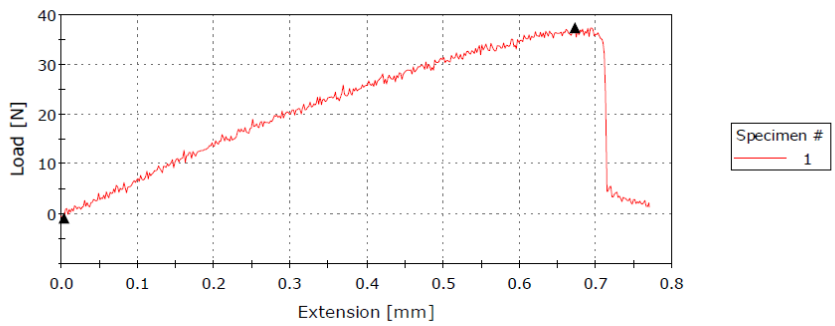
Sample 1 A3 Gr/Fe/CB/PP :55/0/25/20

Sample 2



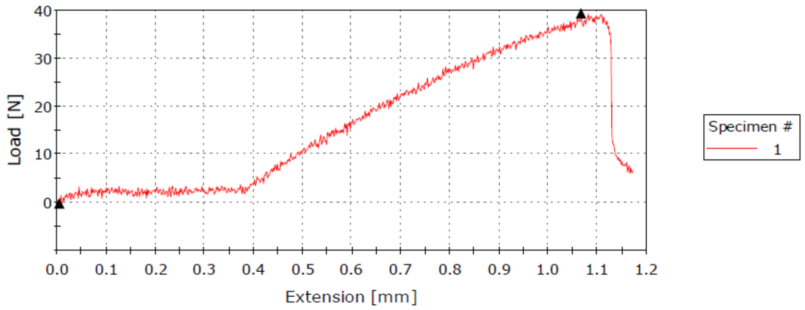
	Maximum Load [N]	Flexure stress at Maximum Load [MPa]	Extension at Maximum Load [mm]	Energy at Maximum Load [J]
1	38.94	24.96	0.99	0.02

Sample 2 A1 Gr/Fe/CB/PP :50/5/25/20



	Maximum Load [N]	Flexure stress at Maximum Load [MPa]	Extension at Maximum Load [mm]	Energy at Maximum Load [J]
1	37.25	23.88	0.67	0.01

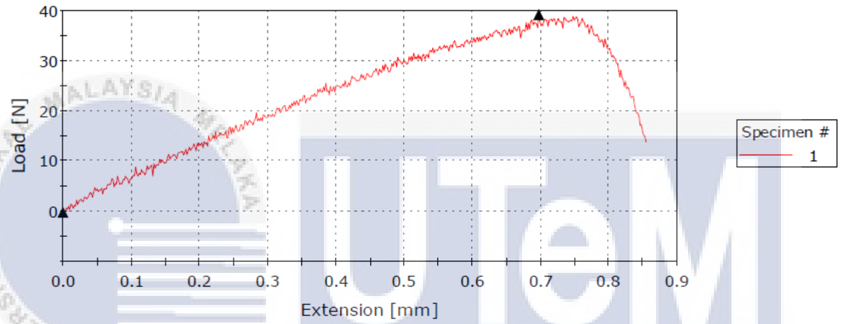
Sample 2 A2 Gr/Fe/CB/PP :50/5/25/20



	Maximum Load [N]	Flexure stress at Maximum Load [MPa]	Extension at Maximum Load [mm]	Energy at Maximum Load [J]
1	39.20	25.13	1.06	0.02

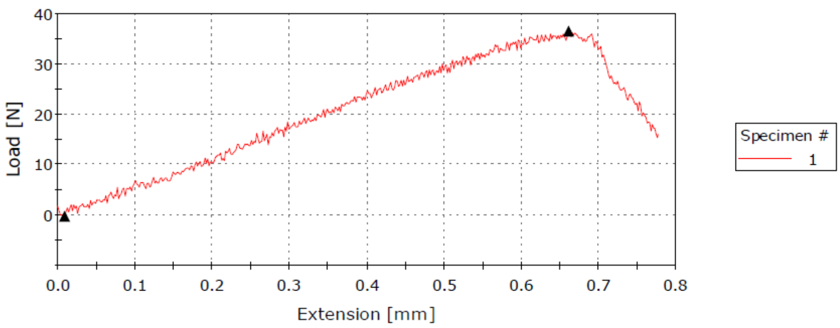
Sample 2 A3 Gr/Fe/CB/PP :50/5/25/20

Sample 3



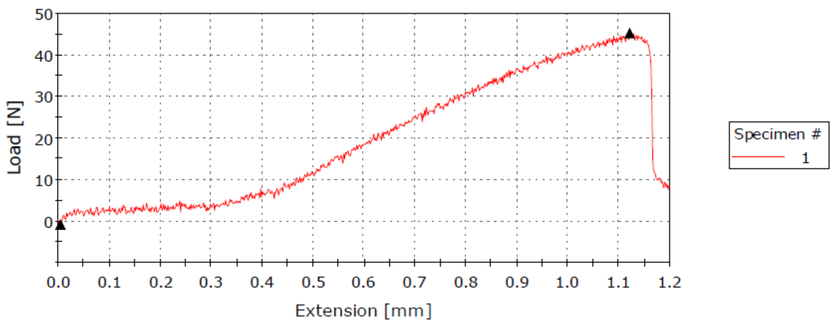
	Maximum Load [N]	Flexure stress at Maximum Load [MPa]	Extension at Maximum Load [mm]	Energy at Maximum Load [J]
1	39.08	25.05	0.70	0.01

Sample 3 A1 Gr/Fe/CB/PP :45/10/25/20



	Maximum Load [N]	Flexure stress at Maximum Load [MPa]	Extension at Maximum Load [mm]	Energy at Maximum Load [J]
1	36.43	23.35	0.66	0.01

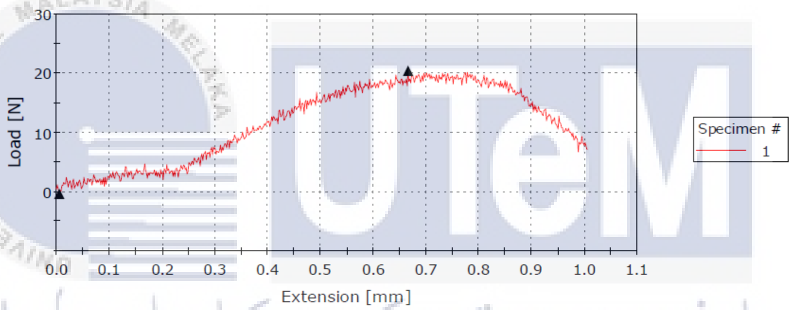
Sample 3 A2 Gr/Fe/CB/PP :45/10/25/20



	Maximum Load [N]	Flexure stress at Maximum Load [MPa]	Extension at Maximum Load [mm]	Energy at Maximum Load [J]
1	45.13	28.93	1.12	0.02

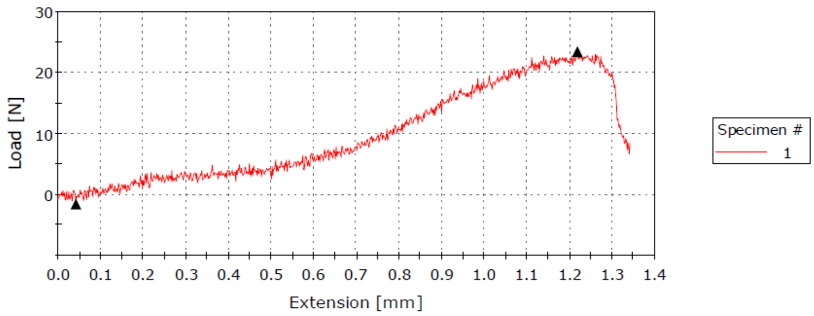
Sample 3 A3 Gr/Fe/CB/PP :45/10/25/20

Sample 4



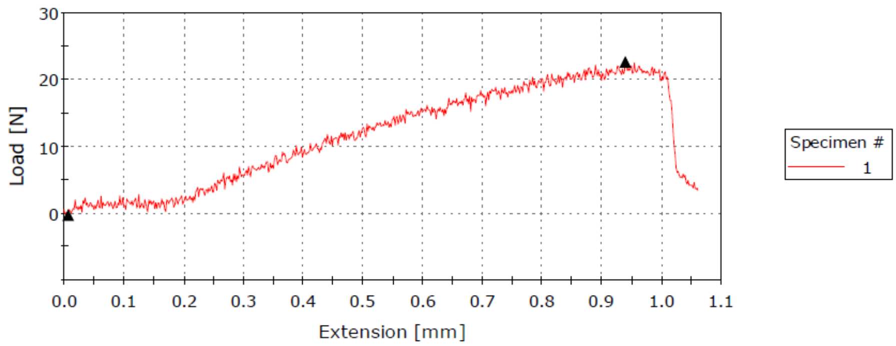
	Maximum Load [N]	Flexure stress at Maximum Load [MPa]	Extension at Maximum Load [mm]	Energy at Maximum Load [J]
1	20.38	13.06	0.67	0.01

Sample 4 A1 Gr/Fe/CB/PP :40/15/25/20



	Maximum Load [N]	Flexure stress at Maximum Load [MPa]	Extension at Maximum Load [mm]	Energy at Maximum Load [J]
1	23.40	15.00	1.22	0.01

Sample 4 A2 Gr/Fe/CB/PP :40/15/25/20



	Maximum Load [N]	Flexure stress at Maximum Load [MPa]	Extension at Maximum Load [mm]	Energy at Maximum Load [J]
1	22.62	14.50	0.94	0.01

Sample 4 A3 Gr/Fe/CB/PP :40/15/25/20