INFLUENCE OF AVIATION AND BIOFUEL ABSOPRTION ON THE MECHANICAL AND POST-FIRE MECHANICAL PROPERTIES OF GFRP COMPOSITES

by

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LIST OF SYMBOLS

M	Moisture content
D	Diffusion coefficient
t	Conditioning time
Z	Length in the thickness direction
M_i	Moisture content at the initial stage
k	Constants
n	Constants
$M_{\%}$	Moisture content in percentage
W_i	Current mass of the specimen
W_o	Initial mass of the specimen before being immersed
V_{comp}	Volume of the composite
l	Length of the specimen
t_x	Specimen thickness
w	Width of the specimen
ρ_{comp}	Density of the composite
m_{comp}	Mass of the composite
V_f	Fiber volume faction
ρ_f	Density of the fibre
ρ_{matrix}	Density of the resin or matrix
m_f	Mass of the fibres
V_v	Void content
σ	Stress of the specimen
F	Force applied by Instron
A	Specimen area
ε	Strain of the specimen

L	Final length of the specimen
L_o	Initial length of the specimen before load is applied
E	Young’s modulus
$\Delta\sigma$	Change in stress
$\Delta\varepsilon$	Change in strain
T_g	Glass transition temperature
Cl	Chloride
Na	Sodium
SO_4	Sulfate
Mg	Magnesium
K	Potassium
Ca	Calcium
HCO_3	Bicarbonate
CO	Carbon Monoxide
CO_2	Carbon Dioxide

LIST OF ABBREVIATIONS

GFRP	Glass Fibre Reinforced Polymer
VARTM	Vacuum-Assisted Resin Transfer Moulding
WWII	World War Two
IATA	International Air Transport Association
ASTM	American Society for Testing and Materials
ECH	Epichlorohydrin
BPA	Bisphenol-A
GHG	Greenhouse Gas
SME	Methyl Soya Ester
FAEE	Fatty Acid Ethyl Ester
FAME	Fatty Acid Methyl Ester
SEM	Scanning Electron Microscopy
EDS	Energy Dispersive Spectroscopy
RTM	Resin Transfer Moulding
NI	National Instrument
UTM	Universal Testing Machine
GE	General Epoxy
IE	Infusion Epoxy
RT	Room Temperature
ATF	Aviation turbine fuel
AVG	Aviation gasoline

PENGARUH BAHAN API PENERBANGAN DAN BAHAN API BIO PADA SIFAT MEKANIKAL DAN SIFAT MEKANIKAL PASCA-API GFRP KOMPOSIT

ABSTRAK

Penurunan sifat mekanikal suhu bilik dan pasca-api bagi komposit epoksi bertetulang gentian kaca (GFRP) komposit setelah terdedah kepada ancaman bahan api telah dikaji secara eksperimen. Tiga jenis bahan api telah digunakan untuk penuaan kesan persekitaran bagi spesimen epoksi bertetulang gentian kaca komposit menggunakan teknik mandian rendaman. Bahan api yang digunakan adalah bahan penerbangan, bahan api alternatif yang merupakan biodiesel berasaskan minyak kelapa sawit dan campuran bahan api campuran terdiri dari 80% Jet-A dan 20% biodiesel yang di bancuh berdasarkan nisbah isi padu. GFRP specimen dibuat menggunakan teknik VARTM untuk mendapatkan specimen yg berkualiti. Semua graf erapan memaparkan lengkung Fickian klasik. Ujian tegangan dan mampatan dilakukan pada spesimen yang direndam selama 15 jam$^{0.5}$ untuk mengkaji pengaruh bahan-bahan api pada sifat mekanikal spesimen tersebut. Telah didapati bahawa terdapat sedikit pengurangan dalam sifat mekanikal spesimen yang direndam berbanding spesimen piawai. Walau bagaimanapun, spesimen tersebut mengekalkan sebahagian besar kekuatannya dengan pengurangan keseluruhan hanyalah kurang daripada 6% untuk tegasan tegangan, 18% untuk modulus tegangan, 12% untuk tegasan mampatan dan 14% untuk modulus mampatan. Sifat mekanikal pasca-api specimen yang direndam juga turut disiasat dalam kajian ini. Instrumen perolehan data digunakan untuk mendapatkan profil suhu spesimen bagi lebih memahami kesan suhu dan molekul bahan api pada sifat-sifat mekanikal. Data pasca-api menunjukkan bahawa dengan meningkatkan masa pendedahan terhadap haba, akan mengurangkan sifat-sifat mekanikal spesimen. Pendedahan sebanyak 60 saat bagi spesimen piawai dan 70 saat untuk spesimen yang direndam, didapati semua spesimen masih mengekalkan sebahagian besar sifat-sifat.

Kata Kunci-komponen; GFRP; sifat mekanikal; bahan api penerbangan; bahan api alternatif; bahan api campuran; sifat pasca-api.

INFLUENCE OF AVIATION AND BIOFUEL ABSORPTION ON THE MECHANICAL AND POST-FIRE MECHANICAL PROPERTIES OF GFRP COMPOSITES

ABSTRACT

The degradation of the mechanical room temperature and post-fire properties of Glass Fibre Reinforced Polymer (GFRP) composite due to fuel attack has been experimentally investigated. Three types of aviation fuel were used to environmentally age the GFRP specimens using an immersion bath technique. The fuels used are aviation fuels, an alternative fuel which was palm oil-based biodiesel and a blended fuel mixture consist of 80% kerosene and 20% biodiesel based on volume ratio. The GFRP were manufactured using vacuum assisted resin transfer moulding (VARTM) to obtain a high quality composite. All of the sorption behaviours obtained display a classic Fickian sorption curve. Tensile and compression test were conducted on the immersed specimens after being immersed for 15 hours$^{0.5}$ to study the influence of the fuel on the mechanical properties of the GFRP laminates. A slight decrement in the mechanical properties of the immersed specimens compared to the standard specimens was observed. However, the specimen retained most of its strength with on an overall reduction of less than 6% for tensile stress, 18% for tensile modulus, 12% for compressive stress and 14% for compressive modulus. In this research, the post-fire mechanical properties of the immersed GFRP laminates were also investigated. The post-fire experiment data shows that increasing the exposure time toward the heat will further decrease the mechanical properties. For an exposure of 60 seconds for standard specimens and 70 seconds for immersed specimens, all of the specimens retained most of their mechanical properties.

Keywords-component; GFRP; mechanical properties; aviation fuel; alternative fuel; blended fuel; post-fire properties.

CHAPTER 1

INTRODUCTION

1.1 Overview

In this chapter, the inclusive overview of the research was presented. The research background provides a general understanding of the research carried out, the problem statement, the research's objective and its scope. In the final sub-section of this chapter, the thesis overview was presented.

1.2 Research Background

1.2.1 Composite Material

Amazing progress had been made in the field of material science. From the Stone Age, where the crude and unrefined stone was used in daily life to the modern age of material science, where materials that can withstand very high temperature without being incinerated or have a high strength to weight ratio are being produced daily (Callister *et al.*, 2000). The materials available can be classified into several categories which are metals, ceramics, inorganic materials, and polymers. Each one of this material class has their advantages and drawbacks. For example, elevated temperature will cause the metal to lose its strength (Kodur *et al.*, 2012). Despite the fact that ceramics have prevalent mechanical properties at elevated temperature compared to metals and polymers, its weak structure makes it unsuitable to be utilized as a structural material (Shackelford *et al.*, 2008). With the advancement of technologies, there have been demands by the industries for better materials that can improve the performance and efficiency of a product while reducing the production cost. This is where composite materials come into the big picture due to having better mechanical properties compared to traditional materials. The combination of two or more material is called a composite material (Hull *et al.*, 1996; Pourang, 2018).

Composite materials are generally utilized as a part of the aviation components. The advancement of the aerospace industry is mainly due to the unique properties of composite materials where more advanced structure design can be manufactured and fabricated (Soutis, 2005). The usage of composite material dated all the way back to 1909 where the fuselage of deHavilland Albatross transport aircraft was manufactured using sandwich composite structure. This lead to the development of deHavilland Mosquito, a combat aircraft that was used during the world war two (WWII). During that time, balsawood was used as the reinforcement material. Only during 1950's glass and carbon fibres were developed, and this skyrocketed the aerospace industries to what we know now (Potter, 1996).

Since the aerospace industry is a multi-billion dollar industry, materials have to meet the specific requirement in order to be used as an aerospace structure (Nayak, 2014). A couple of cases of necessity and its relevance in the avionics business are presented in Table 1.1. Typical fibres used in the aerospace application are as shown in Table 1.2.

Table 1.1 Requirement for different aerospace applications needs (Nayak, 2014)

Requirement	**Usage**
Lightweight	All aerospace structure/application
High reliability	All space application
High durability and fatigue resistance	Aircraft and spacecraft
Functionality	All aerospace application
Multi weather operations	Aircraft

Table 1.2 Fibres used in aerospace application (Nayak, 2014)

Fibres	**Application**
Glass	Aircraft interiors Aircraft secondary structures; radomes, fairing, rocker motor casings Small passenger aircraft
Aramid	Aircraft fairings
Carbon	Primary structures in aircraft and spacecraft Widely used in many different parts such as satellites, antenna dishes, aircraft

Currently, the two biggest aircraft manufacturer Boeing and Airbus are competing with each other to increase the overall percentage of composite material used in an aircraft structure. Based on Figure 1.1, the measure of composite material utilized as a part of assembling aeroplane has a consistant increment from the 70’s (C., 2014; Ching Hao *et al.*, 2014; Slayton *et al.*, 2015). This is due to composite materials being lighter than metal while having similar strength as a metal. This will lead to the aircraft being lighter which increase its fuel efficiency and performances. Besides that, large and complex parts of the aircraft can be manufactured using composite material which in turn reduce the total number of parts used to assemble an aircraft. Moreover, this will reduce the need for fasteners and joints on the aircraft.

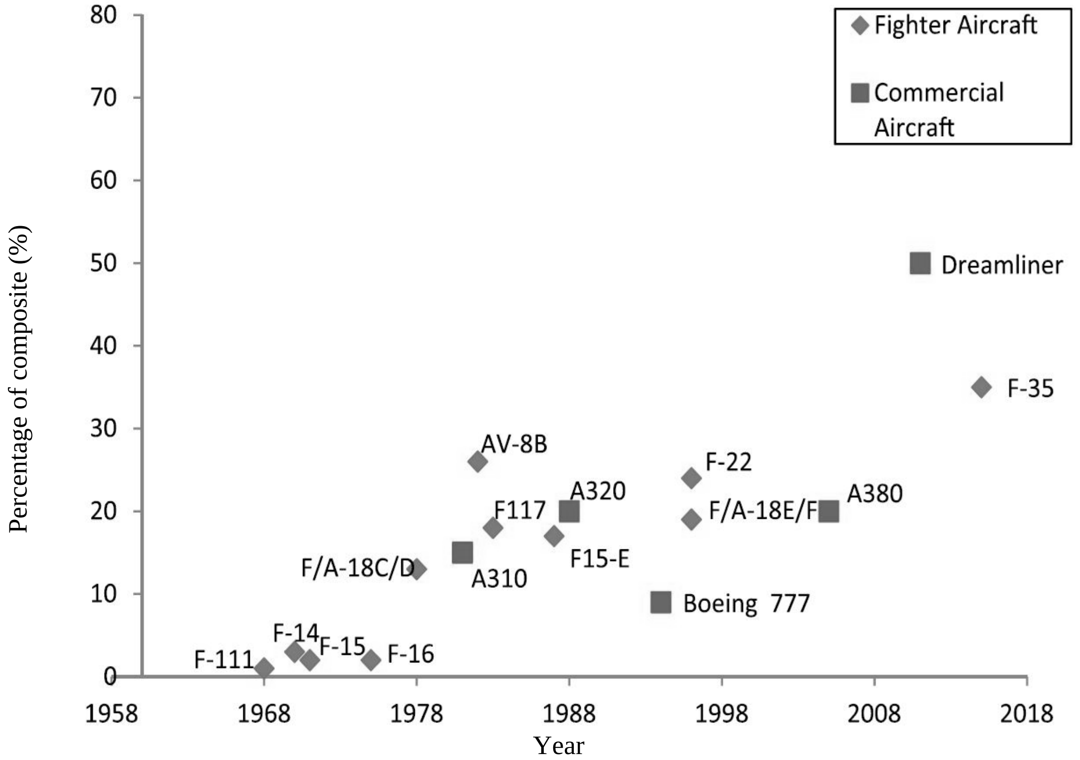

Figure 1.1 Percentage of composite material in aircraft (Slayton *et al.*, 2015).

Figure 1.2 shows the different parts of B787 and A350 which use composite as its material selection. 50% of Boeing B787 structure is made from the composite material (Freissinet *et al.*, 2018; Ghobadi, 2017). On the other hand, Airbus A350's structure is 52% composite material (McConnell, 2011).

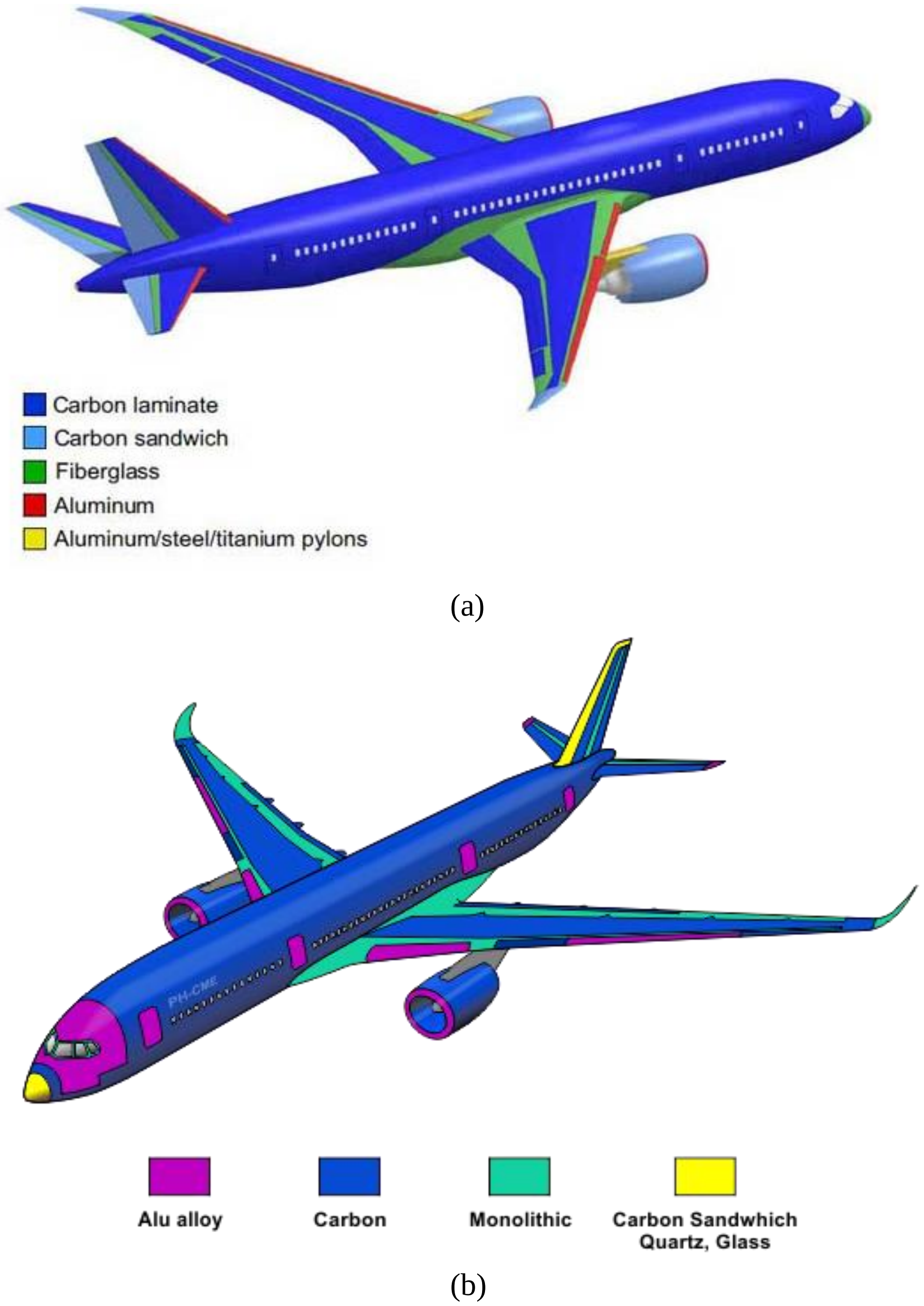

Figure 1.2 Type of material used in aircraft structure a) Boeing B787 and b) Airbus A350 (Freissinet *et al.*, 2018; McConnell, 2011).

Besides that, composite materials are also being utilized as a part of different ventures from automotive to marine as well as aerospace industries. This is due to its unique properties that are beneficial in this modern-day age compared to traditional materials. In the automotive industry, for example, the usage of glass fibre epoxy composite and carbon fibre epoxy composite instead of conventional steel as the composite material are superior in terms of stiffness and strength, and comparatively lighter than steel, not only saves cost but also fuel efficient (Beardmore *et al.*, 1986). In addition, composite material does not rust or corrode (Mallinson, 1987). Furthermore, multiple layers of composite material can provide a better safety during impact compared to a single layer of steel.

In the marine industry, the construction of boats, ships, and even yachts are done using the composite material (Shenoi *et al.*, 2011). It has a higher strength to weight proportion than traditional wood or steel structure, in addition to having a lower maintenance cost. In addition, composite materials have high corrosion resistance. It is generally utilized as a part of the body of the watercraft, where it minimizes the risk of failure in extreme condition. Racing yachts and powerboats are built using composite material where it is lighter, faster, and durable. A company, Fothergill Composites Inc., Bennington, has outlined a security cell cockpit from carbon and aramid filaments with aramid honeycomb centre to ensure the driver safety in all conditions, especially in a rapid crash (Eric Greene, 1999). This structure can endure a 100-foot drop test without any significant damage. It was built for racing powerboats.

1.2.2 Fibreglass Tanks

One of the critical parts that are normally manufactured using fibreglass composite is tanks. These tanks are ranging from normal storage tanks to fuel tanks that are used in aircraft (Cheremisinoff *et al.*, 1995a). Fibreglass tanks are utilized to replace steel tanks due to its chemical properties. Fibreglass has a high corrosion resistance to chemicals compared to steels (Cheremisinoff *et al.*, 1995b). Fibreglass tanks are also much lighter than steel tanks which ease the manufacturing and installation process which directly reduce the overall costing.

In aircraft, there are multiple configurations of fibreglass fuel tank layouts. Commonly used are the integral tanks and rigid removable tanks. Most commercial aircraft uses integral tanks or better known as 'wet wing' layout and the layout is as shown in Figure 1.3. While rigid removable tanks are typically used in small aircraft and military aircraft as well as in helicopters (Whitford, 2004). Besides aircraft, other vehicles such as motorcycles, automobiles and boats are starting to use fibreglass fuel tanks.

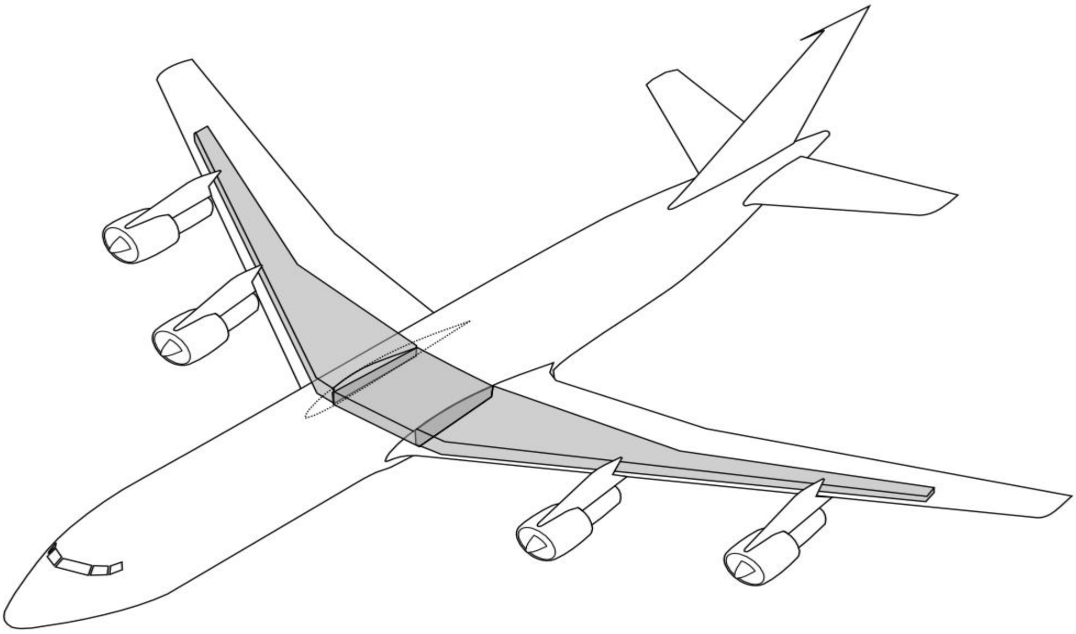

Figure 1.3 Main fuel tank layout in a typical aircraft (Tosaka, 2010).

1.2.3 Aviation Fuel

The current source of aviation fuel is originated from the middle fractional distillation of crude oil (Korres *et al.*, 2008). Since crude oil is a type of unrenewable fuel source, other alternative fuel source are been look upon (Yilmaz *et al.*, 2017). One emerging alternative fuel source which is promising to reduce the usage on kerosene is biodiesel. Besides that, usage of biodiesel can reduce the carbon footprint left by the aircraft which is a huge environment concern (Chuck *et al.*, 2014). Due to this, several researcher have started to study blends between aviation fuel and biodiesel. This could reduce the dependency on crude oil as it will be depleted in the near future (Nygren *et al.*, 2009).

1.2.4 Post-Fire GFRP Properties

Composite materials have many key advantages over traditional materials such as lighter, high corrosion resistance, and low thermal expansion but like all material, composite materials have its downside and one of their major drawbacks is their high flammability. The expanding utilization of polymer composite material in an extensive variety of ventures and applications, could, truth be told, be a potential fire danger. This is a serious problem especially in the aerospace business as they are the major player in polymer composite materials. There were several aircraft incidents over the years that involved a fire accident that cause serious damages as well as some fatalities (Fry, 1965). Based on the data collected by the Flight Safety Foundation, within a period from 1990 to 2010, there were 423 fatalities that involved fire accidents ("Flight Safety Foundation," 2014). At high temperature, GFRP will lose its strength making it unable to support the load or structure which can cause serious damage (Hajiloo *et al.*, 2016). At high temperature the resin become rubbery which cause the GFRP to lose its strength and eventually the resin will decomposed and release harmful substances (Ji *et al.*, 2008; Lau *et al.*, 2016; Y. C. Wang *et al.*, 2007).

1.3 Problem Statement

With the current world fossil fuel being depleted there is a called for renewable alternative fuel that can reduce the dependence on fossil fuel if not replace the fossil fuel entirely. One emerging renewable fuel that is currently looking upon is biodiesel fuel (Hassan *et al.*, 2013). Biodiesel fuels usually are a blend of fatty acid alcohol esters. Biodiesel likewise has a lower ozone-harming substance outflow which can help in diminishing the measure of air contamination for the future. Because of this, the International Air Transport Association (IATA) has started to increase research in kerosene and biodiesel blends to achieve its target of reducing the greenhouse gas production by 50% (IATA, 2013). There are already several big-name airlines such as Virgin Atlantic, Air New Zealand, and Lufthansa has already performed real-time flight testing using this blends (G. Dunn, 2008; Kanter, 2008; Nichols, 2011). More flight test with passengers has been conducted after getting approval from the American Society for Testing and Materials (ASTM) in 2011 (Downing, 2011).

Biodiesel fuels are normally non-corrosive but when it is subjected to humidity, it becomes corrosive due to the formation of the acidic compound. The alcohol content in the fuel is directly proportional to its corrosivity level (Matějovský *et al.*, 2017). With higher alcohol content in the biodiesel, the more amount of water it can absorb from the environment to become more acidic (Christiansen, 1921). This component can react with metal and corrode it. This could be a potential hazard if there were any leakage in the tank. Also, the fuel tanks are an essential piece of a framework or vehicle which could cause a disastrous failure to the overall system. Since fibreglass tanks have gained popularity to replace commercial steel tanks, this behaviour of fuel could pose a serious drawback if the acidic compound attacks the fibreglass and corrode it.

Flaming fibreglass composite can cause a serious health hazard as its by-product can consists of a mixture of toxic gasses, fibres and soot particles (A. P. Mouritz *et al.*, 2006b). Fibres that were airborne after being released from burning can severely affect the respiratory system of anyone that inhale it (Anderson, 2001). Thus, there is a need to grasp the fire resistance of GFRP that were subjected to fuel solution. In addition to that, in order to have a better understanding on the structure integrity of GFRP after being exposed to fire, the post-fire mechanical properties of GFRP were investigated.

There are wide arrays of researchers that study the moisture sorption in fibreglass. Those researchers had reported the effect on the mechanical properties of fibreglass due to moisture uptake. Nevertheless, most of the studies conducted used water or seawater as the solution where the fibreglass composite is immersed. Apart from that, several studies uses polyester resin as the matrix for the composite while in aviation applications epoxy resin are typically utilized as a result of its better mechanical properties contrasted with polyester resin. Most of the past studies only took into account the mechanical properties at room temperature while currently there is limited test being conducted on the post-fire environment. Hence, there is a need to investigate how these different type of fuel mixtures may affect the mechanical properties of fibreglass epoxy laminate as well as its post-fire mechanical properties.

1.4 Research Objectives

The general reason for this research is to contemplate the impact of various fuel on the mechanical properties of glass fibre epoxy using a sustainable manufacturing method. The objectives of this research are as follows:

1) To define the sorption curve of Jet-A fuel, biodiesel fuel and fuel blends between Jet-A and biodiesel fuel.
2) To investigate the effect of aviation fuel and biodiesel uptake on the tensile and compressive properties of GFRP composites at room temperature.
3) To determine the post-fire mechanical properties of GFRP composites.

1.5 Research Scope

For this research, GFRP specimens were manufactured using VARTM method and the raw materials are 800gsm E-glass with two type of epoxy resin. There were five different environmental conditions with two of those environments were set as control. The GFRP specimens were immersed in five different solutions which were Jet-A kerosene fuel, biodiesel fuel, a mixture of Jet-A kerosene and biodiesel fuel, distilled water and seawater. The control specimens will be immersed in distilled water and seawater. The specimens will be immersed in that solution for a period of time until saturation to obtain the absorption curve. The immersion will be done using immersion bath technique without any control in the surrounding environment. The high-temperature experimental analysis was performed on the fuel immersed GFRP specimens to determine whether the absorption affect the post-fire GFRP mechanical properties. Fire torch with wind guard was used to burn the specimen concentrating on the middle of the specimen. Data acquisition were used to obtain the temperature profile of the burnt specimens. The tensile and compression test were conducted on the fuel immersed specimen as well as the post-fire specimens to investigate the influence of the fuel solution on the mechanical properties of GFRP. Due to limitation on the equipment used to carry out compression test, the composite's Young's modulus could not be obtained. Besides that, compression test could not be carried out for post-fire specimens due to its small gauge length.

1.6 Thesis Outline

This thesis consists of five chapter that will give a detail explanation of the research conducted. The five chapter included in the thesis are the introduction, literature review, methodology, result and discussion, and a conclusion. Chapter 1 gives an outline of the study done for this thesis. It gives a concise prologue to the composite material and its application particularly in the aviation field.

The next chapter which is the literature review, present the previous studies that have been performed on the GFRP composite which give an idea of the gaps and novelty of the topic. Moreover, a comprehensive immersion and post-fire method for GFRP laminate are discussed in this chapter.

Chapter 3 describe the procedure and technique throughout the research period from the manufacturing process of the specimens to the mechanical testing of the specimens. The method used for immersion as well as for the testing were based on the ASTM standards available.

For chapter 4, there will be four main sections. The first section present and discuss the specimen's void content and fibre volume fraction. The next section will discuss the specimen's absorption curve based on Fickian fitting. The room temperature mechanical properties of the GFRP specimen undergo tensile and compression load were discussed in the third section. The final section will be on the GFRP post-fire mechanical properties.

The final chapter summarizes the research and provides a few recommendations for future work. After the final chapter, the reference, the appendices and list of publications are presented.

CHAPTER 2

LITERATURE REVIEW

2.1 Manufacturing Method

There are various method for fabricating composite materials. The most widely recognized manufacturing technique is the hand lay-up technique. This method is the least complex and commonly utilized for manufacturing composite materials. Other commonly used techniques include resin infusion and resin transfer moulding (RTM). Unlike the hand layup method, both of this method requires preparation to be done such as mould before the process can be carried out. In this research, a few techniques were studied and performed to determine the most suitable fabrication method. The following sections discussed the details of the fabrication method used in this research

2.1.1 Hand Layup

As mention in the previous section, this technique is the most basic fabrication method for a composite (Elkington *et al.*, 2015). It has a low-cost tooling, as the only tool required for this method is a roller. Depending on the shape and complexity of the part fabricate, a mould may or may not be used. A simple structure like a rectangular panel will not require a mould when utilizing this technique. The fabricating process is simple and the schematic is shown in Figure 2.1 (FiberGlass Coatings, 2016; Fong *et al.*, 2015). This kind of method is generally used in fabricating large and small components in various industries such as aircraft, automotive, marine and space.

Due to its simplicity, the capital cost for this method is quite low. However, because of its fully manual process, it has a low production rate and is not suitable to be used for mass production parts. Besides that, a high volume fraction of fibre will be difficult to achieve. The quality of the part produce will be based on the skills of the worker.

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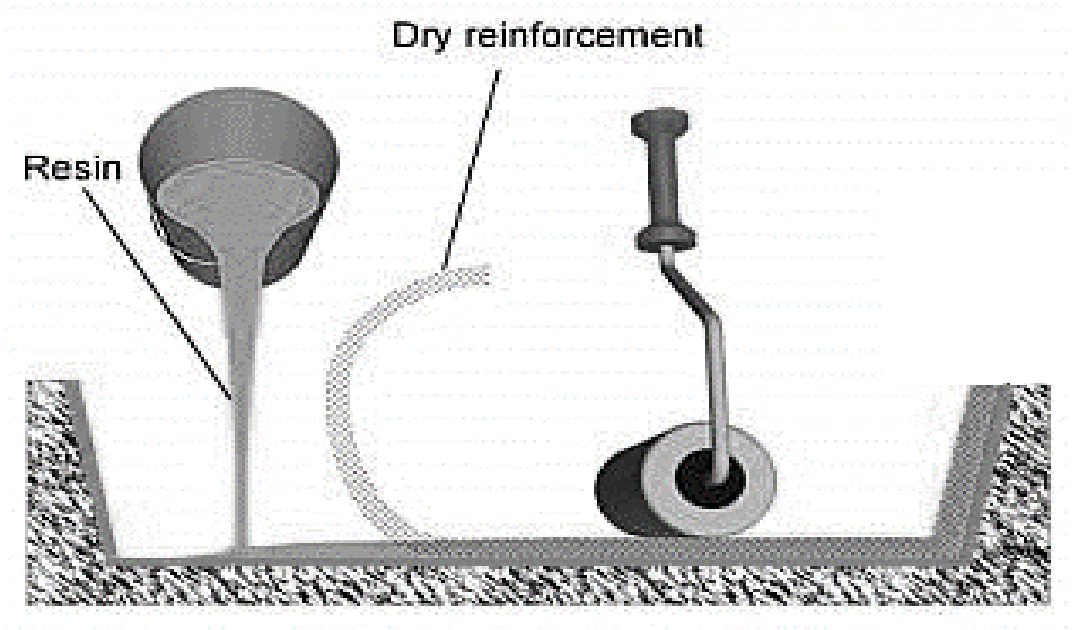

Figure 2.1 Hand Layup Process (Fong *et al.*, 2015).

2.1.2 Resin Infusion

Resin infusion is a technique where the resin is forced to flow into a laminate using vacuum pressure. The resin will solidify and bind the matrix with the fibre to form a composite material. The basic tool requirement needed for resin infusion are two ports for an inlet and an outlet, a catch pot or a resin trap, a vacuum pump, vacuum beg, sealant tape and mould . The general setup for this technique is shown in Figure 2.2 (Corporation, 2003). The resin will flow into the mould through the inlet by the vacuum pressure created by the vacuum pump. Excess resin will flow out through the outlet and into the catch pot.

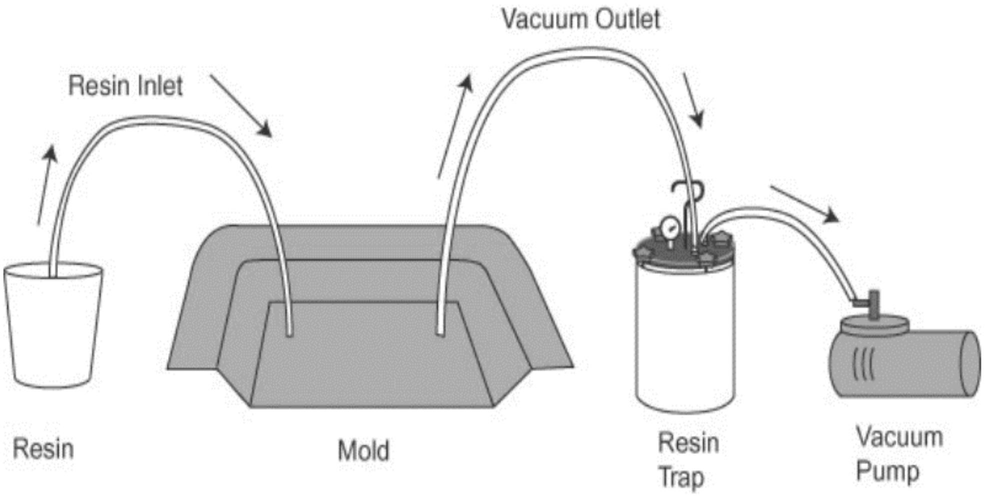

Figure 2.2 Resin infusion setup (Corporation, 2003).

Resin infusion provides several improvements over hand lay-up process as reported by Yuhazri *et al.* (2010) such as; reducing the wastage of resin, the consistency of the finished product and a cleaner set-up. After several repetitions using this method, the amount of resin required for a certain product can be predictable thus reducing the amount of resin used. Compared to hand lay-up process, the consistency of the resin consumed could not be achieved since slight human error might occur and this parameter varies every time. The product made using resin infusion will also have a higher consistency in the thickness as the vacuum pump will have a constant suction force each time it is used. In addition, the finished product will have a high fibre volume faction. Since resin infusion is partially automated, roller or brush is not needed which will create a cleaner workspace without any spattering. Epoxy resin will release styrene which is a harmful volatile fume. Constant exposure to styrene emission can pose a number of health concerns (Di Tomasso *et al.*, 2014). Challenor *et al.* (2000) have reported various symptoms such as fatigue, headaches and depression due to exposure of styrene. There were cases where overexposure could lead to mental disorder. A research on styrene emissions was investigated by Di

Tomasso *et al.* (2014) and it was found that styrene emission can be reduced by using a closed mould system. Thus creating a friendlier and healthier workspace.

Like any process, resin infusion does have its drawbacks (One, 2013). The major setback is the setup process can be quite complicated for a beginner and needed time to master it as there are several steps to be performed before the composite can be fabricated. This lead to another problem, where a little misconduct or error can ruin the product and there is little to none that can be done to correct that error once the infusion begins. Since the vacuum bagging tape, hose and bagging film are not reusable, this will increase the overall cost of using resin infusion compared to hand lay-up. For a larger and a new part, a thorough and comprehensive study using resin infusion method is required beforehand to ensure the effectiveness of the process and the quality of the finished product.

2.1.3 Resin Transfer Moulding (RTM)

Resin transfer moulding or better known as RTM is a typical alternative to resin infusion as this method is less tedious than using resin infusion (Kruckenberg *et al.*, 2012). The obvious contrast between resin infusion and RTM is that RTM is two-sided closed mould process while resin infusion is a single-sided closed mould process. The schematic of an RTM is shown in Figure 2.3. This method consists of a closed mould; a female lower mould and a male top mould, vent port, inlet port and pump unit. The pump unit will pump resin and hardener into the mould. Before entering the mould, both resin and hardener will be mixed together in the mixing head.

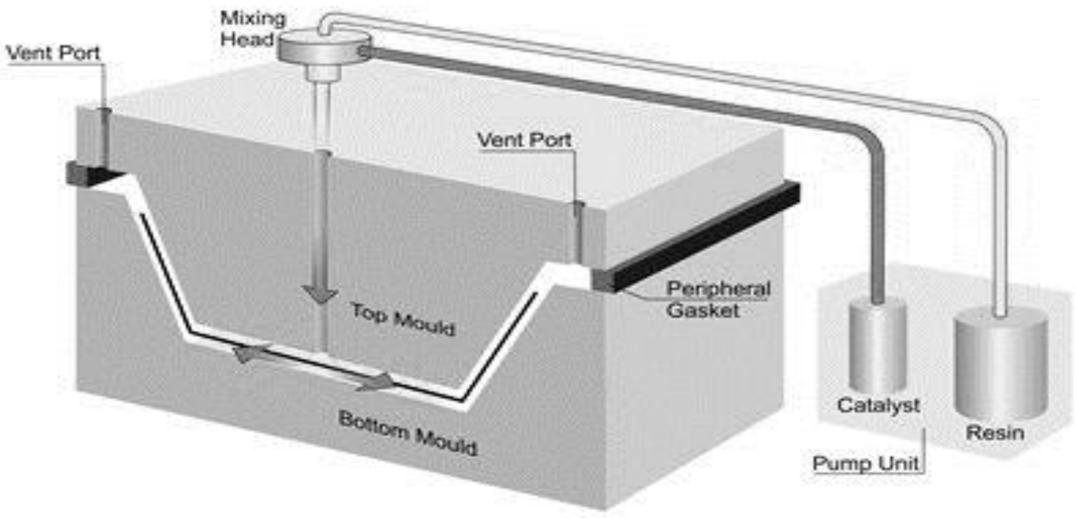

Figure 2.3 RTM setup (Allnex, 2018).

RTM process can produce a thick and near net shape part which eliminate post-fabrication work (Kruckenberg *et al.*, 2012; Lee *et al.*, 1998). The finished product will have a high surface finish and detail as well as produce parts that are dimensionally accurate. Moreover, this is consistent with every product made by using the RTM process. The finished product will also have a high fibre volume fraction similar to resin infusion process. RTM is also simpler and takes less time to set up compared to resin infusion. Complex components can be manufactured using RTM. Since RTM uses a closed mould, this eliminates the need of bagging film or vacuum bag, sealant tape, peel-ply as well as wire mesh which cut the overall expenses. RTM process can be used for mass production as it can produce a consistent and repeatable product using the mould. Similar to resin infusion, RTM provides a cleaner and safer workspace.

However, RTM has an expensive overall cost which means that it is not suitable for low production as the total expenses will be high. The dimension especially the thickness of the part is limited by the mould and changing the parameter will need a new mould. This lead to a high tooling cost.

2.1.4 Vacuum-assisted Resin Transfer Moulding (VARTM)

Another type of RTM that is becoming popular in the industries is vacuum assisted resin transfer moulding (VARTM) (A. Mouritz, 2012b). The obvious difference between VARTM and RTM is that VARTM uses a vacuum to draw resin into the mould compared to RTM where it uses a pump to create pressure which pushes the resin into the mould. Because of this VARTM does not require an expensive high-pressure pump. Thus, reducing the tooling cost which makes it suitable to mass produce large, complex parts in one go. A closed mould is used in this process. The general setup of a VARTM is shown as in Figure 2.4. The mould is typically made from composite but there are aluminium and steel mould used as well.

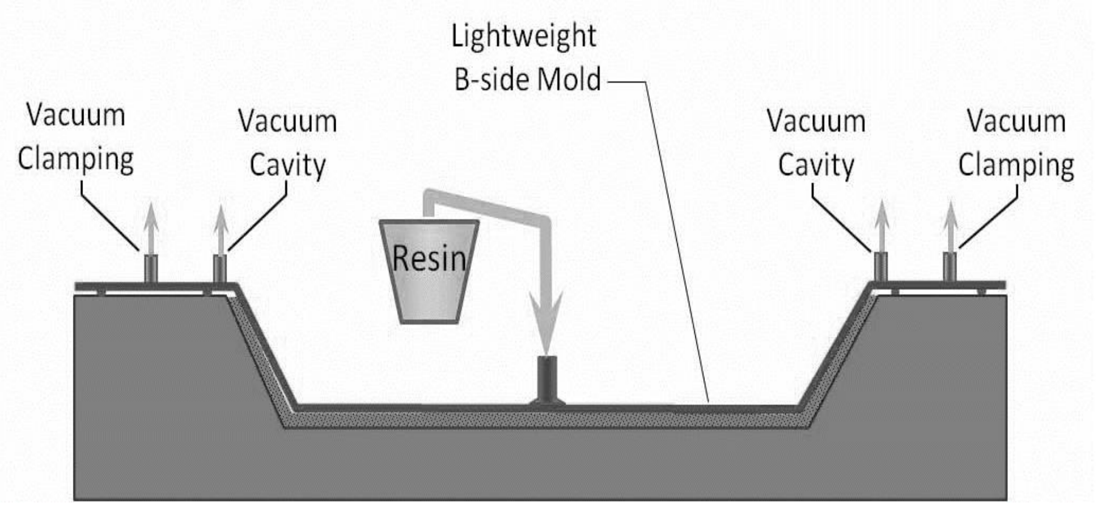

Figure 2.4 VARTM schematic diagram (Companies, 2017).

The B-side mould will have several outlet ports and one inlet port. The resin will be drawn into the mould by the vacuum through the inlet port. There will be one outlet port where the catch-pot will be located and it is then connected to a vacuum port. Normally there will be only one outlet port for the vacuum but this is dependent on the size of the mould and the strength of the vacuum.

VARTM is more cost efficient than RTM since VARTM does not need a RTM machine to operate and uses a vacuum pump to draw the resin into the mould (Steve, 2001; Takeda *et al.*, 2005). The finished product has a high fibre volume fraction as well as high surface finish due to its gel coating on the mould. VARTM can be used to manufacture large-scale parts at a lower cost than RTM. The setup is similar to RTM and simpler compared to resin infusion. Since VARTM uses a closed mould, the dimension especially the thickness of the finished product cannot be control and a new mould is required to alter the dimension of the product.

2.1.5 Summary

A comparison of each method was tabulated in Table 2.1. Based on this comparison, VARTM manufacturing method was chosen to manufacture the GFRP laminate for this research.

Table 2.1 Summary of different technique

Summary	
Tooling cost	
Hand layup	Low tooling cost which consists of brushes and roller.
Resin infusion	Medium tooling cost which consists of sealant tape, vacuum bag, mesh, peel-ply and tube.
RTM	High cost because of equipment needs to set up this method.
VARTM	Low to the medium cost which consists of a tube and once in a while rubber seal needs to be replaced.
Product quality	
Hand layup	Low product quality.
Resin infusion	Medium to high quality but an only single surface that has good finishing.
RTM	High quality with good surface finishing on both side.
VARTM	High quality with good surface finishing on both side.
Safety and Health	
Hand layup	High exposure to styrene emission. Exposure period start from mixing process till end of lay-up process.
Resin infusion	Low exposure to styrene emission. Exposed mainly during mixing process.
RTM	Low exposure to styrene emission. Exposed only during adding epoxy into the epoxy pot.
VARTM	Low exposure to styrene emission. Mainly exposed during mixing process.
Void content	
Hand layup	High void content. Required skill worker to decrease the void formation
Resin infusion	Low to the medium void formation
RTM	Low void formation
VARTM	Low void formation

2.2 Characteristic of Composite

As mention in the previous chapter, there are three main classifications of composite material and this research will be focusing on fibre reinforced polymer composite. Usually, in a polymer composite, the fibre constitute 40-70 % of the composite volume. The most popular type of fibres that are utilized in the aerospace industry are carbon and glass fibre. Thus, the reinforcing material that was selected for this research was E-glass woven roving fibre.

Another vital element or substance that is needed to manufacture a composite material is the matrix or generally known as the resin. There is two type of resin available which is thermoplastic and thermoset resins (Tsai *et al.*, 2011). Table 2.2 shows the comparison between thermoplastics and thermosets resins in term of their strengths and weakness.

Table 2.2 Comparison between thermoplastics and thermosets resins

	Thermosets	**Thermoplastics**
Advantages	Stronger than thermoplastics	High impact strength
	Have higher heat resistance	Recyclable and reversible process
	Low cost	Shaped by applying heat
Disadvantages	Release emissions	Soften when heated
	Non-recyclable	Short workable pot life

Based on the advantages listed in Table 2.2, thermoset resins are more suitable for application that require high strength materials (G. Gibson, 2017). Example of thermoset resins are polyester, vinyl ester, and epoxy. A. Mouritz (2012a) has stated that epoxy resins are commonly used in the aerospace industry due to its chemical and mechanical properties such as high strength and low shrinkage during the curing process. Due to this, epoxy resin will be used in this study.

2.2.1 Glass Fibre

The reinforcement material that was utilized as a part of this investigation was fibreglass, more specifically E-glass woven roving fibre. Currently, glass fibres have been used intensively in multiple industries such as aerospace, automotive, oil and gas, and civil construction to name a few (Daniel *et al.*, 2006). In the aerospace industry, glass fibre is commonly used as reinforcement material as secondary structures (Toozandehjani *et al.*, 2018). Some of its advantages that cause it to be widely accepted in the current market are it can be easily processed or manufactured at low cost and can be easily obtained. Besides that, fibreglass also has high durability and a high strength to weight ratio which is suitable for structural parts.

Glass fibres typically are white and are available in the market as dry fabric or prepreg (K. Mallick, 2007). Some example of fibreglass are woven mat, chopped fibre, unidirectional fibre and glass tissue (Sathishkumar *et al.*, 2014). Usually, for aerospace structures, woven fabric is used as this type of fabric will minimize void content, reduce weight while maintaining its orientation (FAA, 2014). As mention in the previous section, E-glass woven fabric was selected as the reinforcement form in this research. E-glass woven roving has a bidirectional construction (0 degrees and 90 degrees). The distinction in the layout of a bidirectional and unidirectional fabric is shown in Figure 2.5. Bidirectional have strength in two bearings or both directions while unidirectional fabrics have strength only in the fibre direction. Table 2.3 shows the compositions of E-glass fibre.

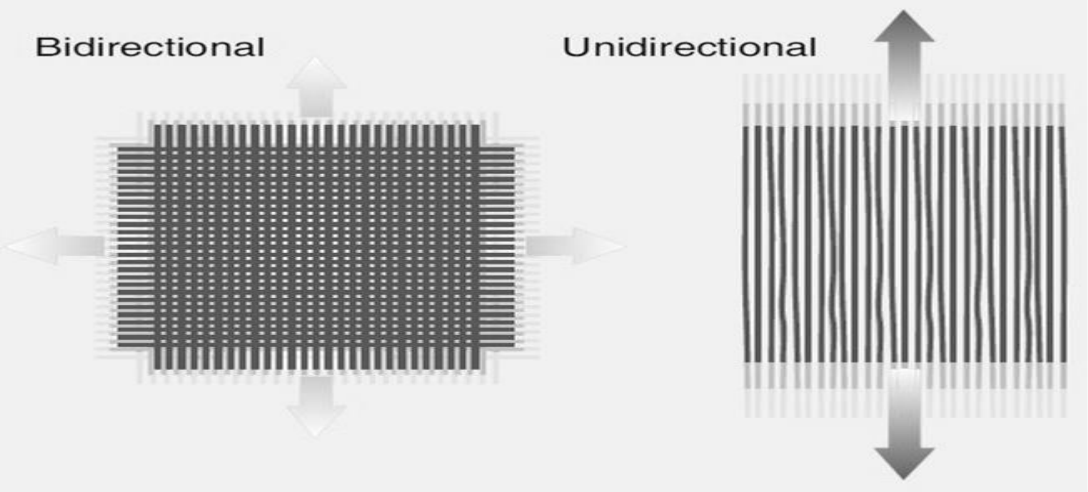

Figure 2.5 Comparison between bidirectional and unidirectional fabric (FAA, 2014).

Table 2.3 E-glass compositions (Reinhart *et al.*, 1987)

Components	**E-glass compositions (wt %)**
Silicon dioxide	52-56
Calcium oxide	16-25
Aluminium oxide	12-16
Boric oxide	5-10
Magnesium oxide	0-5
Sodium oxide and potassium oxide	0-2
Titanium dioxide	0-1.5
Iron	0-1
Iron oxide	0-0.8

2.2.2 Epoxy Resin

Most generally utilized thermoset resin in a polymer-based matrix composite for aerospace application are epoxy resins. This is due to its inert properties upon curing and having low cure shrinkage. Epoxy resins are made of a polymer that has two or more epoxy group rings in its molecular structure. Epichlorohydrin (ECH) and bisphenol-A (BPA) are the two main component required in the manufacturing of epoxy resins. The reaction between those two will result in the forming of epoxy. Distinctive kind of epoxy resin can be produced by shifting the proportion between