Experimental Investigation and Optimization of PC/ABS Blend Composition in DGEBA Resin for Resin Infusion Moulding(RIM)

A PROJECT REPORT

submitted by

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to

the APJ Abdul Kalam Technological University
in partial fulfillment of the requirements for the award of the Degree

of

Master of Technology
in

Mechanical Engineering

with specialization in

Computer Integrated Manufacturing

Department of Mechanical Engineering

TKM College of Engineering Kollam
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DECLARATION

I undersigned hereby declare that the project report entitled "**EXPERIMENTAL INVESTIGATION AND OPTIMIZATION OF PC/ABS BLEND COMPOSITION IN DGEBA RESIN FOR RESIN INFUTION MOULDING (RIM)**", submitted for partial fulfillment of the requirements for the award of degree of Master of Technology in Mechanical Engineering with specialization in Computer Integrated Manufacturing, of the APJ Abdul Kalam Technological University, Kerala is a bonafide work done by me under the supervision of *Prof Dr. K.E. REBY ROY.*, Project Supervisor, Assistant Professor, Department of Mechanical Engineering. This submission represents my ideas in my own words and where ideas or words of others have been included. I have adequately and accurately cited and referenced the original sources. I also declare that I have adhered to ethics of academic honesty and integrity and have not misrepresented or fabricated any data or idea or fact or source in my submission. I understand that any violation of the above will be a cause for disciplinary action by the institute and/or the University and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission has not been obtained. This report has not been previously formed the basis for the award of any degree, diploma or similar title of any other University.

Kollam
July, 2023

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CERTIFICATE

This is to certify that the project report entitled " **EXPERIMENTAL INVESTIGATION AND OPTIMIZATION OF PC/ABS BLEND COMPOSITION IN DGEBA RESIN FOR RESIN INFUTION MOULDING (RIM)**" submitted by **ANUKRISHNA G S, (Reg. No. TKM21MECI03)** of fourth semester to the APJ Abdul Kalam Technological University in partial fulfillment of the requirements for the award of the Degree of Master of Technology in Mechanical Engineering Engineering with specialisation in Computer Integrated Manufacturing, is a bonafide record of the Project done by her under our guidance and supervision. This report in any form has not been submitted to any other University or Institute for any purpose.

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ANUKRISHNA G S

ABSTRACT

This research investigates the issue of brittleness in DGEBA resin, which limits its suitability for aerospace composite materials. The study explores the combined effects of polycarbonate (PC) and acrylonitrile butadiene styrene (ABS) in making DGEBA resin more ductile. By adjusting the composition of the PC/ABS blend, the researchers observed significant changes in the viscosity of modified DGEBA resins, with the 90/10 blend showing the least increase in viscosity.To confirm the effectiveness of the blend, the researchers compared various characteristics of the modified DGEBA (m-DGEBA) with the unmodified DGEBA (u-DGEBA). They analyzed the FTIR, DSC, cure properties, and cryo-toughening characteristics of m-DGEBA, finding that the 90/10 blend had the most pronounced modifying effect on DGEBA compared to PC100, ABS100, and the 10/90 compositions. Detailed optical images confirmed that the 90/10 blend improved the resistance of DGEBA resins to cryo-cracking. Furthermore, the researchers compared the thermal properties of m-DGEBA with those of modified carbon fiber-reinforced polymer (m-CFRP) composites. They discovered that m-CFRPs exhibited a significant decrease in thermal conductivity compared to both m-DGEBA and carbon fibre alone. This reduction in thermal conductivity may be attributed to the enhanced bonding between m-DGEBA resin and CF layers, which was not previously taken into account. Overall, this study offers valuable in- sights into a straightforward and cost-effective method of modifying DGEBA resins with mini- mal viscosity increase. It also highlights the potential of thermoplastic hybrid blends with low concentrations in the development of high-performance polymer composites.

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ABBREVIATIONS

m-DGEBA	Modified DGEBA
u-DGEBA	Unmodified DGEBA
m-CFRP	Modified carbon fiber-reinforced polymer
DGEBA	Diglycidyl Ether of Bisphenol A
CF	Carbon fibers
PEO	Polyethylene oxide
PVA	Polyvinyl alcohol
PAN	Polyacrylonitrile
CFRP	Carbon fiber-reinforced polymer
VOCs	Volatile organic compounds
HDPE	High-density polyethylene
LDPE	Low-density polyethylene
LLDPE	Linear Low-density polyethylene
PVC	Polyvinyl chloride
PP	Polypropylene
PS	Polystyrene

Chapter 1

INTRODUCTION

Thermoset epoxy resins are commonly used in aerospace, military, transportation, and space applications to develop high-performance polymer composites. These resins provide exceptional strength, stiffness, and durability, resulting in composites with a long service life. However, their brittleness, caused by extensive cross-linking, poses a significant challenge. Moreover, the low recyclability of thermoset-based composites makes them less desirable. To address these issues, researchers are exploring various modification techniques worldwide. Different approaches involve modifying the fibers, matrix, or both in order to reduce the brittleness and enhance the performance of thermoset resins under extreme conditions. These modification techniques include using various types of modifiers such as nanoparticles and surface-modified long fibers. By altering the fiber surface through chemical, mechanical, or electric deposition treatments, the surface area available for resin adhesion increases, resulting in improved toughness and fracture resistance. However, these modification methods are complex and costly. This study, however, focuses on the direct modification of thermoset resins, leaving fiber modification techniques for future research.

Direct modification of thermoset resins with thermoset or thermoplastic modifiers is favored due to its simplicity, cost-effectiveness, and ease of processing. Commercially, two commonly used techniques are solvent mixing and melt-mixing. Solvent mixing involves dissolving the modifier in specific solvents and adding it to the thermoset resin. However, this process is time-consuming, environmentally harmful, and potentially dangerous. Additionally, the presence of residual solvents can lead to void formation and material failure during curing.

In contrast, melt-mixing simplifies the process by directly melting the thermoplastic modifier and blending it with the thermoset resin at a temperature above the thermoplastic's glass transition temperature. This method offers a straightforward approach and allows for the combination of multiple thermoplastic modifiers with thermoset resins. When selecting a thermoplastic modifier, factors such as chemical structure similarity, modifier content, and the resulting morphology of the modified resin should be considered.

Common thermoplastic modifiers for Diglycidyl Ether of Bisphenol A (DGEBA) type thermoset resins include polyetherimide, polyimide, polyethylene, polycarbonate, polybutylene terephthalate, and acrylonitrile butadiene styrene. Incorporating a thermoplastic component into the thermoset resin results in semi-interpenetrating polymer networks (semi-IPNs), which have been reported to enhance fracture toughness and microcrack resistance in carbon fiber-reinforced polymer composites.

However, both solvent mixing and melt-mixing have limitations. The improvement achieved is constrained by the peak concentration of the thermoplastic modifier, which becomes especially critical at cryogenic temperatures. Moreover, the enhanced thermal and mechanical properties of modified thermoset resins lead to a significant increase in viscosity. This high viscosity makes them incompatible with resin infusion methods, which require lower viscosities for successful processing. To lower the viscosity, a higher concentration of hardener can be added, but this increases the brittleness of the cured resin, which may not be desirable for many applications. Therefore, careful determination of the modifier concentrations is crucial to control the viscosity increase of modified thermoset resins.

To further enhance the performance of thermoset resins, the combination of multiple thermoplastic modifiers can be explored. This approach, widely investigated in the manufacturing and transportation industries, aims to optimize the properties of machined parts. For example, the PC/ABS blend system exhibits superior performance compared to using either material alone. Previous studies have demonstrated the fracture and micro-crack resistance capabilities of PC/ABS/DGEBA-based carbon fiber-reinforced.

1.1 CARBON FIBER (CF)

Carbon fibers are produced by bonding carbon atoms together in a long chain, resulting in a material that is both incredibly strong and lightweight. These fibers typically have a diameter of 5 to 10 micrometers. They possess notable characteristics such as high stiffness, good tensile strength, low weight, high resistance to chemicals, ability to withstand high temperatures, and minimal thermal expansion. In comparison to steel, carbon fiber reinforced composites are approximately five times stronger, twice as rigid, and about two-thirds lighter. The carbon fiber strands are incredibly thin, even thinner than a human hair, and can be twisted into yarn or woven together to create lightweight garments. Depending on the specific application, carbon fibers can be reinforced in various ways, such as using thin yarn or tow, fabric with specific weave patterns like plain or twill weave, or as cloth.

While carbon fibers offer significant advantages, they are relatively expensive when compared to other fibers of a similar nature, such as glass or plastic. The formation of carbon fibers requires specific bonding and crystal alignment, with the long axis of the fiber parallel to the formed crystals, in order to achieve optimal strength. The atomic structures of carbon fibers and graphite share similarities, as they both consist of carbon atoms arranged in regular hexagonal patterns known as graphene sheets. However, the arrangement of these sheets differs, and it is the interlocking pattern of carbon fibers that contributes to their strength. When combined with other materials in composites, carbon fibers demonstrate their strength. Typically, resins are used to reinforce carbon fibers, and when cured, they result in a superior material with enhanced properties compared to the resin alone.

1.1.1 Structure and Properties of CF

Carbon fiber is often supplied in the form of a continuous tow wrapped onto a reel. This tow is composed of numerous small carbon filaments that are tightly bound together and coated with an organic size like polyethylene oxide (PEO) or polyvinyl alcohol (PVA) for protection. When needed, the tow can be easily unwound from the reel. Each individual carbon filament within the tow is a seamless cylinder with a diameter ranging from 5 to 10 micrometers, consisting almost entirely of carbon. In earlier generations, the filament diameters were larger, typically between 16 and 22 micrometers (e.g., T300, HTA, and AS4), but more recent fibers like IM6 or IM600 have a reduced diameter of approximately 5 micrometers.

Graphite and carbon fiber both consist of carbon atoms arranged in regular hexagonal patterns called graphene sheets. However, the arrangement of these sheets differs between the two materials. In graphite, the sheets are stacked parallel to each other, which gives graphite its characteristic softness and brittleness due to relatively weak intermolecular forces known as Van der Waals forces.

Carbon fiber can have different structures depending on the precursor used in its manufacturing process. It can be turbostratic, graphitic, or a hybrid structure with both graphitic and turbostratic components. Turbostratic carbon fiber is made from polyacrylonitrile (PAN) and has randomly folded or crumpled carbon atom sheets. On the other hand, graphitic carbon fiber is derived from mesophase pitch and undergoes high-temperature heat treatment above 2200 °C. Heat-treated mesophase-pitch-derived carbon fibers exhibit high Young's modulus and thermal conductivity, while turbostratic carbon fibers typically possess high ultimate tensile strength.

1.1.2 Patterns of CF

Fabrics made from carbon fiber spools are created using a weaving loom. Various weaving patterns can be employed, but the most commonly used weaves for carbon fiber fabrics are harness satin, twill, and plain weave.

1.1.3 Plain Wave CF

Carbon fiber cloth woven in a plain weave, also known as a 1x1 weave, exhibits a checkerboard-like symmetry, as depicted in Figure 1.1. The weaving technique used in this weave results in closely intertwined and highly stable fibers, thanks to the over/under pattern. Fabric stability refers to the material's ability to maintain its fiber orientation and weave angle. While plain weave carbon fiber cloth has excellent fabric stability, it lacks flexibility, making it less suitable for complex curves. However, it is easier to handle without causing fabric distortions. Therefore, it is commonly used for two-dimensional curves, tubes, and flat sheets. In a plain weave, each fiber in the weave exhibits crimp, which refers to the curvature of an individual fiber. Due to the tight interlacing in the tows of plain weave carbon fiber fabric, it has a pronounced crimp. This severe crimping can create stress points that may weaken the fabric overtime.

1.1.4 Twill Weave CF

The twill weave is the most popular type of carbon fiber fabric. It is distinguished by a pattern, such as 2x2 or 4x4, as shown in figure 1.2. In a 2x2 twill weave, each strand passes over two strands and then under two strands. Similarly, in a 4x4 twill weave, each strand crosses over four strands before going under another four. This weaving method creates a noticeable diagonal pattern by alternately going over and under. Compared to a plain weave, the twill

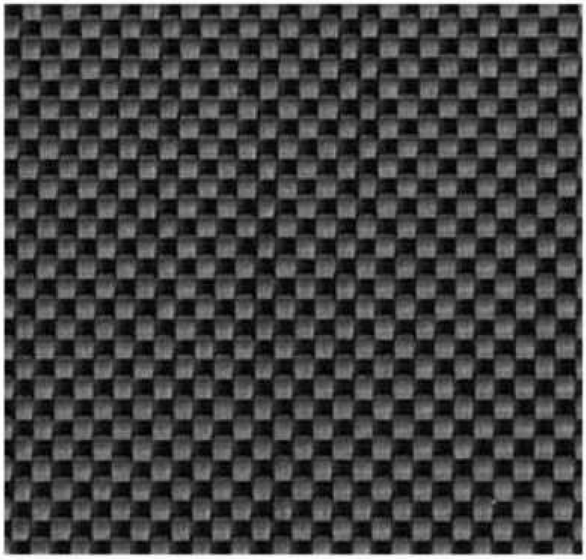


Figure 1.1: Plain weave CF

weave has a larger gap between interlacing points. As a result, there are fewer bends or folds in the fabric, reducing the chances of stress points forming.

1.1.5 Harness satin weave CF

Since ancient times, satin weaves have been employed to give silk fabric its lovely drape while still making the fabric smooth and seamless. Satin weaves translate to an ability to easily form around intricate curves when utilized for carbon fibre composites. This demonstrates that satin weaves are less stable than other weaves. Figure 1.3 shows the schematic structure of Satin weave carbon fiber.Harness satin weave CF is shown in figure 1.3.

1.1.6 Unidirectional CF

The fabric patterns mentioned, such as in figure 1.4, are classified as non-woven designs, where all the fibers are aligned in a single parallel direction. This results in a structure without any gaps or spaces between the fibers. This particular pattern offers notable advantages, including its exceptionally low weight and the ability to provide maximum strength in the direction of fiber alignment (known as isotropic strength). However, there are certain limitations associated with this pattern. It tends to have a less visually appealing appearance when used in finished product parts, and it cannot fulfill the requirements of applications that necessitate specific strength at-

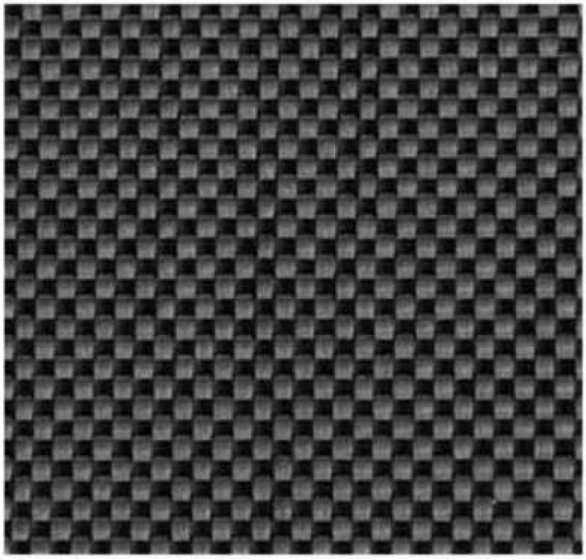


Figure 1.2: Twill weave CF

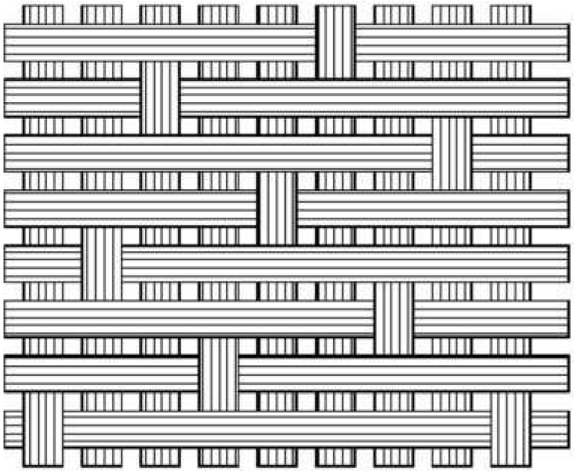


Figure 1.3: Harness Satin weave CF

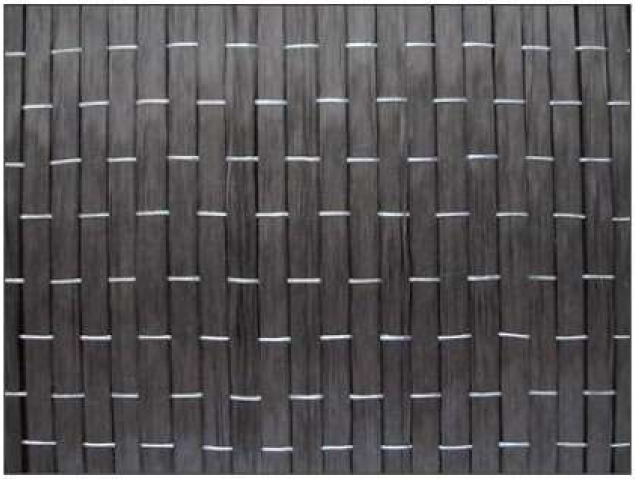


Figure 1.4: Unidirectional CF

tributes in different directions (anisotropic strength attributes).

1.1.7 Benefits of Carbon Fiber

Carbon fiber offers a range of benefits due to its unique properties and characteristics. Some of the key advantages of carbon fiber include:

- High Strength-to-Weight Ratio: Carbon fiber is renowned for its exceptional strength-to-weight ratio. It is significantly lighter than traditional materials like steel or aluminum while maintaining impressive strength and rigidity. This property makes carbon fiber ideal for applications where weight reduction is crucial, such as aerospace, automotive, and sports equipment.
- Stiffness and Rigidity: Carbon fiber exhibits excellent stiffness and rigidity, providing structural integrity and stability to components. It can resist deformation under heavy loads, ensuring enhanced performance and durability.
- Chemical Resistance: Carbon fiber is highly resistant to chemicals, including corrosive substances and solvents. This resistance makes it suitable for use in harsh environments, including chemical processing, marine applications, and automotive parts exposed to fluids or chemicals.
- Fatigue Resistance: Carbon fiber possesses remarkable fatigue resistance, allowing it to endure repeated stress and load cycles without weakening or breaking. This characteristic makes it suitable for applications that require long-term durability and reliability, such as aircraft com-

ponents and wind turbine blades.

- Thermal Conductivity: Carbon fiber has low thermal conductivity, meaning it can effectively resist heat transfer. This property makes it useful for applications where insulation or thermal management is essential, such as in aerospace, electronics, and energy sectors.
- Design Flexibility: Carbon fiber composites can be molded and shaped into complex forms, providing designers with greater flexibility in creating innovative and optimized structures. This versatility allows for the production of lightweight and intricately designed components.
- Electromagnetic Transparency: Carbon fiber is transparent to electromagnetic fields, making it ideal for applications requiring radiofrequency transparency, such as antennas, radomes, and aerospace structures.
- Environmental Benefits: Carbon fiber is considered more environmentally friendly than traditional materials due to its lighter weight, which can contribute to fuel efficiency and reduced emissions in transportation. Additionally, carbon fiber composites are recyclable and can be reused or repurposed, reducing waste.

Overall, the benefits of carbon fiber make it a highly sought-after material in various industries, offering advantages in terms of strength, weight reduction, durability, and design flexibility.

1.1.8 Applications of Carbon Fiber

Carbon fiber finds extensive applications across a wide range of industries due to its unique properties. Some of the key applications of carbon fiber include:

- Aerospace and Aviation: Carbon fiber is widely used in the aerospace industry for aircraft structures, including wings, fuselage components, and tail sections. Its high strength, low weight, and excellent fatigue resistance contribute to improved fuel efficiency and performance.
- Automotive: Carbon fiber is increasingly being used in the automotive sector to reduce weight and improve fuel efficiency. It is employed in the production of body panels, chassis components, interior trim, and suspension parts, enhancing performance and handling characteristics.
- Sports and Recreation: Carbon fiber is prevalent in sports and recreation equipment due to its lightweight and high strength. It is utilized in the construction of bicycles, tennis rackets, golf clubs, fishing rods, hockey sticks, and helmets, providing athletes with improved performance and durability.

• Wind Energy: Carbon fiber composites are utilized in wind turbine blades to enhance their strength, stiffness, and fatigue resistance. The lightweight nature of carbon fiber helps maximize energy efficiency and improve overall wind turbine performance.
• Marine: Carbon fiber is used in the marine industry for boat hulls, masts, and structural components. Its corrosion resistance, high strength, and low weight make it an ideal material for achieving faster speeds, improved fuel efficiency, and enhanced durability.
• Industrial and Infrastructure: Carbon fiber-reinforced polymer (CFRP) composites find applications in various industrial sectors, including construction, oil and gas, and infrastructure. It is used for reinforcing concrete structures, manufacturing pipes and tanks, and providing corrosion-resistant solutions.
• Medical and Prosthetics: Carbon fiber is employed in the medical field for manufacturing lightweight, strong, and customizable prosthetics, orthotics, and braces. Its biocompatibility and ability to be shaped into intricate designs make it a preferred material for medical applications.
• Electronics and Consumer Goods: Carbon fiber is utilized in electronics for shielding electromagnetic interference (EMI) and manufacturing lightweight and durable electronic enclosures. It is also found in high-end consumer goods like watches, wallets, and phone cases, adding a premium and stylish aesthetic.

These are just a few examples of the diverse applications of carbon fiber. The material's exceptional properties continue to drive innovation across industries, enabling the development of advanced and high-performance products.

1.2 EPOXY RESINS

Epoxy resins are a type of thermosetting polymer that consist of epoxy monomers. They are formed through the reaction of an epoxy resin (a polymeric precursor) with a curing agent (often referred to as a hardener). This chemical reaction, known as curing or crosslinking, transforms the liquid or semi-liquid epoxy resin into a rigid, three-dimensional network structure.Epoxy resins are known for their excellent adhesive properties, mechanical strength, chemical resistance, and electrical insulation capabilities. They offer strong bonding capabilities with various substrates and are widely used in applications such as adhesives, coatings, composites, electrical insulation, and protective coatings.The curing process of epoxy resins can be initiated by heat, catalysts, or a combination of both, allowing for control over the curing time and temperature. Once cured, epoxy resins exhibit high mechanical strength, chemical resistance, and dimensional stability.Due to their versatility, epoxy resins can be modified with additives and fillers to achieve specific properties and characteristics, such as increased flexibility, UV resistance, flame retardancy, or improved thermal stability. This flexibility in formulation makes epoxy resins suitable for a wide range of applications across various industries.

1.2.1 Properties of Epoxy Resins

Epoxy resins possess several properties that contribute to their wide range of applications. Here are some key properties of epoxy resins:

- Adhesive Strength: Epoxy resins exhibit excellent adhesive strength, allowing them to bond strongly to various materials, including metals, plastics, composites, and wood. This property makes epoxy resins widely used as structural adhesives.
- Mechanical Strength: Once cured, epoxy resins offer high mechanical strength, including good tensile strength, compressive strength, and impact resistance. They can withstand heavy loads and resist deformation, making them suitable for applications that require load-bearing capabilities and resistance to mechanical stress.
- Chemical Resistance: Epoxy resins display good resistance to a wide range of chemicals, such as acids, bases, solvents, and fuels. They can withstand exposure to harsh environments without significant degradation, making them suitable for applications requiring chemical resistance, such as coatings and chemical storage tanks.
- Electrical Insulation: Epoxy resins are excellent electrical insulators, providing insulation against electric current. They have a high dielectric strength and low electrical conductivity, making them widely used in electrical and electronic applications, including circuit boards and encapsulation of electronic components.
- Heat Resistance: Epoxy resins exhibit good heat resistance, allowing them to withstand elevated temperatures without significant degradation. They can retain their mechanical and adhesive properties at high temperatures, making them suitable for applications in thermal environments.
- Dimensional Stability: Once cured, epoxy resins offer good dimensional stability, meaning they maintain their shape and size over a wide range of temperatures and environmental con-

ditions. This property is important for applications where precise dimensions and stability are required.

- Low Shrinkage: Epoxy resins typically have low shrinkage during the curing process. This property minimizes internal stress and helps in achieving accurate and dimensionally stable final products.
- Versatility: Epoxy resins can be formulated and modified with various additives to achieve specific properties. They can be tailored to meet different application requirements, such as flexibility, UV resistance, flame retardancy, or specific curing times.

These properties make epoxy resins suitable for a wide range of applications, including adhesives, coatings, composites, encapsulation, casting, and more. Their combination of adhesive strength, mechanical properties, chemical resistance, and electrical insulation capabilities contributes to their popularity in various industries.

1.2.2 Types of Epoxy Resins

There are two primary types of epoxy resin: glycidyl and non-glycidyl resins. Glycidyl resins are widely used and are further divided into subclasses such as glycidyl-ether, glycidyl-ester, and glycidyl-amine. On the other hand, non-glycidyl resins can be classified as either aliphatic or cycloaliphatic. Among the glycidyl resins, glycidyl-ether epoxies, particularly those made from bisphenol and novolac, are the most popular.

1.2.3 Bisphenol Epoxy Resins

Bisphenol epoxy resins are a specific type of glycidyl resin that is widely used in various industries. They are derived from bisphenol compounds, which are reacted with epichlorohydrin to produce epoxy resins. Bisphenol epoxy resins offer excellent mechanical properties, high chemical resistance, and good adhesion strength. They are commonly used in applications such as coatings, adhesives, composites, and electrical insulation due to their versatility and reliability. These resins have a wide range of formulations and can be tailored to meet specific performance requirements.

1.2.4 Aliphatic Epoxy Resins

Aliphatic epoxy resins belong to the category of non-glycidyl resins. Unlike glycidyl resins, which have glycidyl functional groups, aliphatic epoxy resins do not contain these groups. Instead, they are composed of aliphatic chains. Aliphatic epoxy resins are characterized by their excellent UV resistance and color stability. They have a higher resistance to yellowing and degradation when exposed to sunlight compared to other types of epoxy resins. Due to their superior UV resistance, aliphatic epoxy resins are commonly used in outdoor applications where color retention and long-term durability are crucial. Some typical applications of aliphatic epoxy resins include outdoor coatings, automotive coatings, and decorative finishes where maintaining the appearance and color stability is essential.

1.2.5 Novolac Epoxy Resins

Novolac epoxy resins are another subclass of glycidyl epoxy resins. They are derived from phenolic compounds, specifically novolac resins, through a reaction with epichlorohydrin. Novolac epoxy resins are known for their exceptional chemical resistance and heat resistance. They exhibit high cross-linking density and have excellent mechanical properties, making them suitable for applications that require resistance to harsh chemicals, elevated temperatures, and mechanical stress.Novolac epoxy resins find applications in various industries, such as coatings, adhesives, electrical laminates, and chemical resistant linings. Their resistance to acids, solvents, and other corrosive substances makes them suitable for protective coatings in chemical processing plants, storage tanks, and industrial equipment. Additionally, their excellent heat resistance allows their use in electrical and electronic applications, such as encapsulation and insulation of electronic components. The unique properties of novolac epoxy resins make them a preferred choice in situations where high chemical resistance and thermal stability are crucial requirements.

1.2.6 Halogenated Epoxy Resins

However, it is worth noting that halogenated compounds can be incorporated into epoxy resins as additives or modifiers to enhance certain properties. For example, halogenated flame retardants can be added to epoxy resins to improve their fire resistance. These additives contain halogen elements such as chlorine, bromine, or fluorine, which contribute to the flame retardant properties of the resin. Halogenated epoxy resins, in this context, refer to epoxy resins that have been modified with halogen-containing additives for specific applications requiring flame retardancy.It’s important to understand that halogenated epoxy resins are not a distinct subclass within the epoxy resin classification, but rather a modified form of epoxy resins achieved by incorporating halogen-based additives.

1.2.7 Advantages of Epoxy Resins

Epoxy resins offer several advantages that make them a popular choice in various industries. Here are some key advantages of epoxy resins:

- Excellent Adhesion: Epoxy resins have exceptional adhesion properties, enabling them to bond well with a wide range of substrates, including metals, concrete, wood, and plastics. This strong adhesion enhances the durability and longevity of the bonded materials.
- High Mechanical Strength: Epoxy resins exhibit high mechanical strength, making them suitable for applications that require structural integrity and resistance to mechanical stress. They can withstand heavy loads, impacts, and vibrations without significant deformation or damage.
- Chemical Resistance: Epoxy resins possess excellent chemical resistance, making them highly resistant to a variety of chemicals, including acids, bases, solvents, and fuels. This property makes them well-suited for applications in corrosive environments and chemical processing industries.
- Versatility: Epoxy resins are highly versatile and can be formulated to meet specific application requirements. They can be modified with additives, fillers, or reinforcements to enhance properties such as thermal resistance, flame retardancy, electrical insulation, or UV resistance.
- Low Shrinkage: During the curing process, epoxy resins experience minimal shrinkage, resulting in reduced internal stresses and improved dimensional stability. This characteristic is particularly important in applications where precise tolerances and minimal distortion are required.
- Electrical Insulation: Epoxy resins exhibit excellent electrical insulation properties, making them widely used in electrical and electronic applications. They provide insulation against electrical currents and offer protection against electrical shocks, arcing, and short circuits.
- Durability and Longevity: Epoxy resins have exceptional durability and long-term stability. They are resistant to environmental factors such as moisture, temperature variations, and UV radiation, which helps maintain their performance and appearance over extended periods.

• Easy Application: Epoxy resins are available in various forms, including liquid, paste, and solid formulations. They can be easily applied by brush, roller, or spray, allowing for efficient and precise application on different surfaces.

These advantages make epoxy resins a preferred choice in a wide range of industries, including construction, automotive, aerospace, electronics, coatings, adhesives, and composites.

1.2.8 Disadvantages of Epoxy Resins

While epoxy resins offer numerous advantages, there are also some potential disadvantages that should be considered. Here are a few disadvantages of epoxy resins:

• Brittleness: Epoxy resins can be relatively brittle compared to other materials. They have a tendency to crack or fracture under high impact or sudden force, which can limit their use in applications that require high impact resistance or flexibility.

• Sensitivity to UV Radiation: Epoxy resins are susceptible to degradation and yellowing when exposed to prolonged or intense UV radiation. This can result in discoloration and reduced aesthetic appeal. However, this issue can be mitigated by incorporating UV stabilizers or using specialized epoxy formulations that are UV-resistant.

• Curing Process: Epoxy resins require proper curing to achieve their full strength and properties. The curing process often involves the use of curing agents or catalysts, and it requires precise control of temperature, humidity, and curing time. Improper curing can lead to inadequate bonding, reduced mechanical strength, or poor performance.

• Heat Sensitivity: While epoxy resins exhibit good heat resistance overall, they can soften or degrade at elevated temperatures. Different epoxy formulations have different temperature limits, and exceeding these limits can result in dimensional changes, reduced strength, or even complete failure of the resin.

• Health and Safety Concerns: Working with epoxy resins may involve exposure to harmful chemicals, such as uncured epoxy, curing agents, or volatile organic compounds (VOCs). Proper safety precautions, including the use of personal protective equipment and adequate ventilation, should be followed to minimize risks. Some individuals may also develop sensitivities or allergies to epoxy resins, requiring careful handling and avoidance in such cases.

• Cost: Epoxy resins can be relatively expensive compared to other types of resins or polymers. The cost of raw materials, manufacturing processes, and specialized formulations can contribute to higher overall costs in certain applications.

Despite these disadvantages, epoxy resins remain widely used and valued for their unique properties and versatility. Proper understanding, application techniques, and consideration of specific requirements can help mitigate or overcome these limitations in many cases.

1.2.9 Applications of Epoxy Resins

Epoxy resins find extensive use in various industries due to their wide range of properties and applications. Here are some common applications of epoxy resins:

- Coatings and Paints: Epoxy-based coatings and paints provide excellent protection against corrosion, chemicals, and wear. They are used in industrial flooring, automotive coatings, marine coatings, and protective coatings for metals, concrete, and wood.
- Adhesives and Sealants: Epoxy adhesives offer high bond strength and durability, making them suitable for bonding a wide range of materials, including metals, plastics, composites, and ceramics. They are used in construction, aerospace, automotive, and electronics industries for structural bonding and assembly.
- Electrical and Electronics: Epoxy resins are extensively used in electrical and electronic applications due to their excellent electrical insulation properties. They are used for encapsulating and potting electronic components, insulating electrical circuits, and manufacturing transformers, circuit boards, and semiconductors.
- Composites and Fiberglass: Epoxy resins are widely employed as matrix materials in composite materials, such as fiberglass-reinforced plastics (FRP). They provide strength, stiffness, and durability to composite structures used in aerospace, automotive, sporting goods, and construction industries.
- Construction and Civil Engineering: Epoxy resins are used in various construction applications, including concrete repair, flooring systems, waterproofing, and grouting. They enhance the strength, durability, and chemical resistance of concrete structures and are used for bonding, sealing, and protection in civil engineering projects.
- Casting and Molding: Epoxy resins are utilized in casting and molding applications for creating intricate shapes, prototypes, and decorative objects. They can be poured into molds and cured to form rigid, durable, and detailed replicas.
- Marine and Boat Building: Epoxy resins are extensively used in boat building and marine

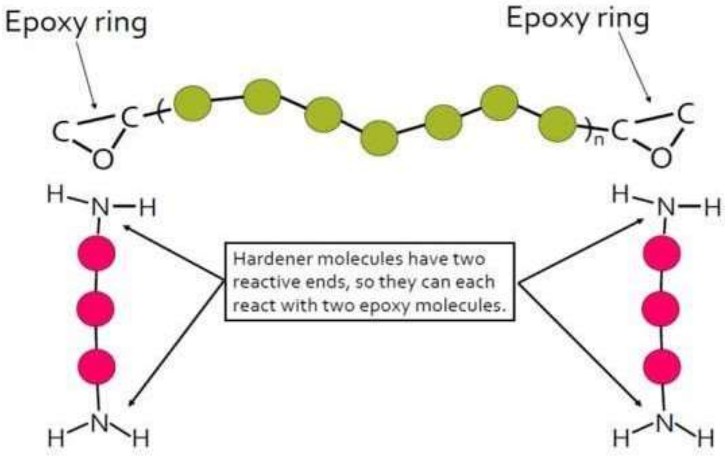


Figure 1.5: Curing of epoxy

applications. They are used for laminating hulls, decks, and other structural components, as well as for sealing and protecting against water penetration, osmosis, and marine organisms.

- Automotive and Aerospace: Epoxy resins are utilized in the automotive and aerospace industries for various applications, including composite parts, structural bonding, corrosion protection, and surface coatings.
- Art and Crafts: Epoxy resins are popular in art and craft applications, such as creating resin jewelry, coatings on artwork, and resin-based crafts. They provide a clear, glossy, and durable finish to various artistic creations.

These are just a few examples of the wide-ranging applications of epoxy resins. Their versatility, adhesive properties, chemical resistance, and durability make them valuable in numerous industries and creative endeavors.

1.2.10 Curing of Epoxies

Instead of initiators, hardeners are commonly used for the curing process of epoxy resins. Hardeners are molecules capable of undergoing a reaction with the epoxy functional groups found in the resin. This reaction leads to the formation of cross-links and the solidification of the epoxy, resulting in a cured and hardened material.

1.3 PLASTICS

Plastics derive their name from the Latin word "plasticus," meaning capable of molding. Alexander Parkes is credited with the invention of plastics in 1862. Plastics are defined as synthetic materials composed of various organic polymers, including polyethylene, PVC, PC, ABS, PET, PEI, PP, and more. They have high molecular weight and can be molded into soft, rigid, or slightly elastic forms as needed. Plastics are widely used in our daily lives, from household items like utensils, tables, and chairs to electronic devices such as mobiles and laptops. They are also utilized in industries like automotive, construction, healthcare, and textiles.

The properties of plastics make them highly desirable. They possess high strength, toughness, moisture resistance, flexibility, cost-effectiveness, durability, reusability, optical clarity, and insulation characteristics. These properties make them suitable for a wide range of applications. Plastics are formed through polymerization reactions, where monomer molecules react chemically to create polymer chains or three-dimensional networks. Plastics can be shaped by applying heat, pressure, or other forms of energy. They are commonly categorized into commodity plastics, standard plastics, and engineering plastics based on their application areas.However, it is important to note that plastics have negative impacts on the environment. To mitigate these effects, proper management and utilization of plastic waste are necessary. By establishing efficient waste management systems, we can reduce the adverse effects of plastics to some extent.

1.3.1 Types of plastics

1.3.2 Polyethylene (PE)

Polyethylene (PE) is a type of plastic that is widely used due to its versatility, durability, and cost-effectiveness. It belongs to the family of polyolefins and is produced through the polymerization of ethylene monomers. PE is classified into different types based on its density and branching, including high-density polyethylene (HDPE), low-density polyethylene (LDPE), and linear low-density polyethylene (LLDPE).Polyethylene is known for its excellent chemical resistance, electrical insulation properties, and low moisture absorption. It is lightweight, flexible, and has high impact strength, making it suitable for a wide range of applications. Some common uses of polyethylene include:

- Packaging: PE is extensively used in packaging materials, such as plastic bags, films, and containers. It provides excellent barrier properties, protecting products from moisture, chemicals, and contaminants.

- Pipes and Fittings: PE pipes are widely used in water supply, irrigation, and gas distribution systems due to their corrosion resistance, flexibility, and long service life. PE fittings are also used for joining and connecting pipes in plumbing applications.

- Automotive Components: Polyethylene is employed in various automotive components, such as fuel tanks, bumpers, interior trim, and electrical insulation. Its lightweight nature helps improve fuel efficiency.

- Construction: PE is used in construction applications, including insulation materials, geomembranes, roofing membranes, and pipes for drainage and sewage systems. Its resistance to chemicals and UV radiation makes it suitable for outdoor use.

- Electrical and Electronics: PE is used as an insulating material in electrical cables, wire coatings, and electrical connectors due to its excellent dielectric properties and thermal stability.

- Agriculture: PE films and sheets are used in agriculture for greenhouse coverings, mulching, and soil protection. They help regulate temperature, conserve water, and prevent weed growth.

- Consumer Goods: Polyethylene is utilized in the production of various consumer goods, such as toys, containers, household items, and furniture. Its durability and ease of molding allow for the creation of a wide range of products.

  Polyethylene's versatility and wide-ranging applications make it one of the most commonly used plastics worldwide. Its properties, including chemical resistance, flexibility, and durability, contribute to its extensive use in diverse industries.Polyethylene (PE) is a translucent plastic that is derived from ethylene. It can be classified into two main types:

- (a). Low-density polyethylene (LDPE): LDPE is a form of PE that has a lower density. It is known for its toughness, affordability, and good resistance to chemicals. LDPE is commonly used for molding applications such as bottles and garment bags.

- (b). High-density polyethylene (HDPE): HDPE is a form of PE that has a higher density. It is stiffer, stronger, and less translucent compared to LDPE. HDPE is commonly used in packaging, piping, and car fuel tanks.
  In summary, LDPE and HDPE are different forms of polyethylene with distinct properties and applications. LDPE is favored for its toughness and chemical resistance, while HDPE is valued for its stiffness and strength in various industries.

1.3.3 Polyvinyl chloride (PVC)

Polyvinyl chloride (PVC) is a widely used thermoplastic polymer known for its versatility and durability. It is derived from vinyl chloride monomers through polymerization. PVC is classified as a vinyl polymer and is one of the most commonly produced and used plastics globally.PVC has a range of properties that make it highly suitable for numerous applications. Some key characteristics of PVC include:

- Rigidity and Strength: PVC exhibits excellent rigidity and mechanical strength, making it suitable for applications that require structural integrity and resistance to impact or deformation.

- Chemical Resistance: PVC is highly resistant to chemicals, acids, bases, and salts, making it suitable for applications in corrosive environments.

- Electrical Insulation: PVC possesses good electrical insulation properties, making it widely used in electrical cables, wiring, and insulation for various applications.

- Fire Resistance: PVC has inherent fire-resistant properties and can be further enhanced with additives, making it suitable for fire safety applications.

- Weather Resistance: PVC demonstrates good weather ability, with excellent resistance to sunlight, UV radiation, and weathering effects, making it suitable for outdoor applications.

- Cost-Effectiveness: PVC is a cost-effective material, making it attractive for various applications where affordability is a factor.

- PVC finds extensive use in various industries and applications, including:

- Construction: PVC is widely used in the construction industry for applications such as pipes, fittings, window profiles, siding, roofing membranes, flooring, and insulation materials.

- Electrical and Electronics: PVC is used in electrical cables, wire coatings, connectors, and insulation for electrical and electronic applications.

- Automotive: PVC is utilized in automotive applications such as interior trims, door panels, dashboards, wire harnesses, and gaskets.

- Packaging: PVC is used for packaging applications such as blister packs, shrink films, and bottles.

- Healthcare: PVC is employed in the healthcare industry for applications including medical tubing, intravenous bags, and components for medical devices.

While PVC offers many advantages, it is important to note that its production and disposal can have environmental considerations due to the release of chlorine-based substances. Proper management and recycling of PVC can help mitigate its environmental impact and promote sustainability.

1.3.4 Polypropylene (PP)

Polypropylene (PP) is a versatile thermoplastic polymer that is widely used in various industries due to its excellent combination of properties. It is derived from the polymerization of propylene monomers. PP is known for its high strength, durability, and resistance to chemical solvents, acids, and bases.

Some key characteristics of polypropylene include:

- Lightweight: PP is a lightweight material, making it suitable for applications where weight reduction is desired.

- High Strength and Toughness: PP exhibits high tensile strength, impact resistance, and toughness, allowing it to withstand demanding conditions.

- Chemical Resistance: PP is highly resistant to many chemicals, making it suitable for applications that involve exposure to corrosive substances.
- Heat Resistance: PP has a high melting point, allowing it to maintain its structural integrity at elevated temperatures. It has good thermal stability and can withstand sterilization processes.
- Flexibility: PP has good flexibility, allowing it to be molded into different shapes and sizes.
- Low Moisture Absorption: PP has low moisture absorption, making it resistant to water and moisture-related damage.

The versatility and desirable properties of PP make it widely used in various applications, including:

- Packaging: PP is extensively used in packaging materials such as films, containers, and bottles due to its excellent barrier properties and resistance to moisture and chemicals.
- Automotive: PP is used in automotive applications, including interior and exterior parts, battery cases, bumpers, and fuel systems, due to its strength, impact resistance, and lightweight nature.
- Consumer Goods: PP is used in the manufacturing of consumer goods such as appliances, furniture, toys, and household items due to its durability, versatility, and cost-effectiveness.
- Medical and Healthcare: PP is used in medical applications such as syringes, medical devices, laboratory equipment, and packaging for pharmaceutical products due to its sterilizability, chemical resistance, and safety.
- Textiles: PP is used in the textile industry for applications such as non-woven fabrics, ropes, carpets, and upholstery due to its resistance to moisture, mildew, and abrasion.

Polypropylene is a widely adopted plastic due to its favorable properties and versatility across multiple industries. Its strength, chemical resistance, heat resistance, and flexibility contribute to its extensive range of applications.

1.3.5 Polystyrene (PS)

Polystyrene (PS) is a versatile and widely used thermoplastic polymer known for its rigidity, insulation properties, and affordability. It is derived from the polymerization of styrene monomers. PS can exist in two main forms: a solid, rigid form known as "crystal" or "general-purpose" polystyrene (GPPS), and a foamed form known as expanded polystyrene (EPS).
Key characteristics of polystyrene include:

- Rigidity: PS is rigid and provides excellent structural support, making it suitable for applications where stiffness and stability are required.
- Thermal Insulation: EPS, in its foamed form, offers excellent thermal insulation properties, making it commonly used in packaging and construction applications.
- Transparency: GPPS is transparent, allowing for clarity and visibility in applications such as packaging, disposable cups, and optical components.
- Lightweight: Both GPPS and EPS are lightweight materials, making them convenient for various applications and reducing transportation costs.
- Chemical Resistance: PS has good resistance to chemicals, oils, and greases, making it suitable for packaging applications that involve contact with such substances.
- Electrical Insulation: PS exhibits good electrical insulation properties, making it suitable for applications in the electrical and electronics industry.
- Polystyrene finds widespread use in various industries and applications, including:
- Packaging: PS is commonly used in packaging materials, including food containers, disposable cups, trays, and protective packaging for fragile items.
- Construction: EPS foam is used for insulation in buildings, as well as for void-fill and lightweight concrete applications.
- Consumer Goods: PS is utilized in the production of a wide range of consumer goods, such as household appliances, electronic casings, toys, and stationery items.
- Medical and Healthcare: PS is used in medical applications, including laboratory ware, petri dishes, test tubes, and disposable medical devices.

- Insulation and Building Materials: EPS foam is used in insulation boards, roofing insulation, and other construction materials to enhance energy efficiency.

It is important to note that while polystyrene offers several benefits, its disposal and environmental impact have raised concerns. Proper recycling and waste management practices can help mitigate these concerns and promote sustainability in the use of polystyrene.

1.3.6 Polyethylene Terephthalate (PET)

Polyethylene terephthalate (PET) is a versatile thermoplastic polymer known for its excellent combination of properties, including clarity, strength, and recyclability. It is derived from the polymerization of ethylene glycol and terephthalic acid or its derivatives. PET is commonly recognized for its use in the production of plastic bottles for beverages.

Key characteristics of polyethylene terephthalate include:

- Transparency: PET has excellent clarity and transparency, making it suitable for applications where visibility of the contents is desired.
- Strength: PET exhibits high tensile strength, making it strong and durable. It can withstand rigorous handling and transport.
- Chemical Resistance: PET is resistant to many chemicals, acids, and alkalis, making it suitable for packaging applications that involve contact with various substances.
- Barrier Properties: PET has good barrier properties against oxygen, carbon dioxide, and moisture, making it effective for preserving the freshness and integrity of packaged products.
- Lightweight: PET is lightweight, which contributes to its popularity in packaging applications, as it reduces transportation costs and energy consumption.
- Recyclability: PET is highly recyclable and can be used to produce new PET bottles or converted into other products such as fibers for textiles.
- Polyethylene terephthalate finds extensive use in various industries and applications, including:

- Beverage Bottles: PET is widely used for the production of beverage bottles, including water bottles, soda bottles, and juice containers, due to its clarity, strength, and ability to preserve the flavor and quality of the contents.
- Food Packaging: PET is utilized in food packaging applications such as trays, containers, and films, providing excellent product visibility and protection.
- Textiles: PET can be processed into polyester fibers used in textiles, including clothing, upholstery, carpets, and non-woven fabrics.
- Electrical and Electronics: PET is employed in electrical insulation films, connectors, and components for electronic devices due to its electrical insulation properties.
- Industrial Applications: PET is used in various industrial applications, including automotive parts, industrial fibers, films for solar panels, and thermal insulation materials.

PET's versatility, strength, transparency, and recyclability make it a widely adopted material in the packaging industry and other sectors. Its lightweight nature and compatibility with recycling processes contribute to its popularity as a sustainable choice in plastic packaging.

1.3.7 Polycarbonate (PC)

Polycarbonate (PC) is a durable and versatile thermoplastic polymer known for its exceptional impact resistance, transparency, and heat resistance. It is derived from the polymerization of bisphenol A and phosgene or its derivatives. Polycarbonate is commonly used in applications that require a combination of strength and optical clarity.

Key characteristics of polycarbonate include:

- Impact Resistance: PC exhibits high impact resistance, making it highly suitable for applications where protection against impacts is crucial. It can withstand strong forces without shattering or breaking.
- Transparency: Polycarbonate offers excellent optical clarity, with a glass-like appearance. It allows for high light transmission, making it ideal for applications that require visibility or transparency.
- Heat Resistance: PC has a high melting point and good heat resistance, enabling it to withstand high temperatures without deformation or melting. It is also flame retardant.

- Strength and Durability: Polycarbonate is known for its strength and durability, making it resistant to breakage, cracking, and chemical degradation.
- Lightweight: Despite its strength, PC is relatively lightweight, making it suitable for applications that require both strength and reduced weight.
- Electrical Insulation: Polycarbonate exhibits excellent electrical insulation properties, making it widely used in electrical and electronic applications.

Polycarbonate is utilized in various industries and applications, including:

- Construction: PC is used in construction for applications such as skylights, roofing materials, safety windows, and architectural glazing, due to its impact resistance and transparency.
- Electrical and Electronics: Polycarbonate is employed in electrical components, connectors, switches, and electronic device casings due to its electrical insulation properties and durability.
- Automotive: PC is used in automotive applications such as headlamp lenses, instrument panels, interior trims, and protective covers due to its impact resistance and heat resistance.
- Optical and Medical Devices: Polycarbonate is utilized in the production of eyewear lenses, safety goggles, medical devices, and optical discs due to its optical clarity and impact resistance.
- Consumer Goods: PC is used in the manufacturing of consumer goods such as household appliances, sports equipment, mobile phone casings, and protective gear due to its strength and impact resistance.

Polycarbonate's combination of impact resistance, transparency, heat resistance, and durability makes it a preferred choice for applications that require strength, optical clarity, and protection. Its versatility and performance have led to its extensive use in a wide range of industries.

1.3.8 Polyetherimide (PEI)

Polyetherimide (PEI) is a high-performance engineering thermoplastic known for its exceptional heat resistance, mechanical strength, and electrical properties. It is derived from the polymerization of bisphenol-A and 4,4’-diaminodiphenyl ether. PEI is commonly used in applications that require a combination of high temperature resistance and mechanical integrity.

Key characteristics of polyetherimide include:

- High Heat Resistance: PEI exhibits excellent heat resistance and can withstand continuous use at high temperatures up to around 180°C (356°F) without significant deformation or degradation.
- Mechanical Strength: PEI offers exceptional mechanical strength, including high tensile strength, flexural strength, and impact resistance. It is known for its stiffness and dimensional stability.
- Electrical Insulation: PEI has excellent electrical insulation properties, making it suitable for applications that require high voltage resistance and insulation.
- Flame Retardancy: PEI has inherent flame retardant properties, making it self-extinguishing and meeting stringent fire safety requirements.
- Chemical Resistance: PEI demonstrates good resistance to a wide range of chemicals, including acids, bases, and solvents, enhancing its suitability for various demanding environments.
- Dimensional Stability: PEI exhibits minimal creep and low coefficient of thermal expansion, resulting in excellent dimensional stability even under varying temperature conditions.

Polyetherimide finds applications in various industries and sectors, including:

- Aerospace and Defense: PEI is used in aerospace and defense applications such as aircraft components, connectors, electrical insulation, and structural parts due to its high heat resistance, mechanical strength, and flame retardancy.
- Electronics and Electrical Engineering: PEI is utilized in electrical connectors, insulators, printed circuit boards, and coil bobbins due to its excellent electrical properties and dimensional stability.

- Automotive: PEI is used in automotive applications such as connectors, sensors, electrical housings, and under-the-hood components due to its high heat resistance, strength, and chemical resistance.
- Medical and Healthcare: PEI is employed in medical devices, sterilization trays, surgical instruments, and diagnostic equipment due to its biocompatibility, high heat resistance, and dimensional stability.
- Industrial and Manufacturing: PEI is used in various industrial applications, including jigs and fixtures, pump components, gaskets, and manifolds, due to its strength, chemical resistance, and thermal stability.

  Polyetherimide's exceptional heat resistance, mechanical strength, and electrical properties make it a valuable material for applications that require performance under extreme conditions. Its wide range of applications across different industries demonstrates its versatility and reliability.

1.4 Acrylonitrile Butadiene Styrene (ABS)

Acrylonitrile Butadiene Styrene (ABS) is a versatile thermoplastic polymer known for its toughness, impact resistance, and excellent mechanical properties. It is a copolymer composed of three main monomers: acrylonitrile, butadiene, and styrene. ABS is widely used in various industries due to its balanced combination of strength, rigidity, and ease of processing[1].

Key characteristics of acrylonitrile butadiene styrene include:

- Impact Resistance: ABS offers exceptional impact resistance, making it highly suitable for applications that require durability and resistance to sudden impacts or shocks.
- Strength and Rigidity: ABS exhibits good tensile strength and stiffness, providing structural integrity and stability to the finished products.
- Chemical Resistance: ABS demonstrates resistance to a wide range of chemicals, oils, and greases, making it suitable for applications in harsh environments.
- Heat Resistance: ABS has moderate heat resistance, allowing it to withstand relatively high temperatures without significant deformation or melting.

- Processability: ABS is easily processed through various manufacturing methods such as injection molding, extrusion, and 3D printing, making it a popular choice for producing complex shapes and intricate designs.
- Surface Finish and Aesthetic Appeal: ABS can be easily molded to achieve smooth surfaces and can be readily painted or coated, providing versatility in terms of aesthetic customization.

Acrylonitrile butadiene styrene finds applications in numerous industries and sectors, including:

- Automotive: ABS is commonly used in automotive applications such as interior trims, dashboard components, door panels, and exterior parts due to its impact resistance, strength, and ability to withstand temperature variations.
- Consumer Goods: ABS is utilized in the production of various consumer goods, including household appliances, toys, electronic enclosures, luggage, and sporting equipment, due to its toughness and aesthetic appeal.
- Electronics and Electrical Equipment: ABS is employed in electronic housings, computer and communication equipment, electrical enclosures, and components due to its electrical insulation properties and dimensional stability.
- Construction and Building Materials: ABS is used in construction applications such as pipes, fittings, profiles, and panels due to its strength, chemical resistance, and durability.
- Medical and Healthcare: ABS is used in medical devices, equipment housings, trays, and storage containers due to its biocompatibility, impact resistance, and ease of sterilization.

The versatility, impact resistance, and ease of processing of ABS make it a popular choice for a wide range of applications across different industries. Its combination of strength, rigidity, and chemical resistance ensures reliable performance and durability in various environments.

1.4.1 Polycarbonate and Acrylonitrile Butadiene Styrene (PC/ABS)

Polycarbonate and Acrylonitrile Butadiene Styrene (PC/ABS) is a blend of two thermoplastic polymers, combining the characteristics of both materials. It is a copolymer blend composed of polycarbonate (PC) and acrylonitrile butadiene styrene (ABS). The combination of these polymers results in a material with enhanced properties compared to each individual component.

Key characteristics of Polycarbonate and Acrylonitrile Butadiene Styrene (PC/ABS) blend include:

- Impact Resistance: PC/ABS blend offers excellent impact resistance, surpassing the impact strength of both PC and ABS alone. It provides improved toughness and durability.
- Strength and Rigidity: The blend exhibits good tensile strength and rigidity, ensuring structural integrity and dimensional stability in various applications.
- Heat Resistance: PC/ABS blend has moderate heat resistance, allowing it to withstand higher temperatures compared to ABS alone. It can endure elevated temperatures without significant deformation or degradation.
- Chemical Resistance: The blend demonstrates resistance to a wide range of chemicals, oils, and solvents, making it suitable for applications that require resistance to chemical exposure.
- Processability: PC/ABS blend is easily processed through various manufacturing techniques, including injection molding and extrusion, providing versatility in terms of shaping and forming complex designs.
- Aesthetic Appeal: The blend combines the aesthetic qualities of both PC and ABS, allowing for smooth surfaces, good colorability, and the ability to achieve different textures and finishes.

  Polycarbonate and Acrylonitrile Butadiene Styrene (PC/ABS) blend finds applications in diverse industries, including:

- Automotive: PC/ABS blend is commonly used in automotive applications such as interior trims, dashboards, door panels, and exterior components due to its excellent impact resistance, strength, and heat resistance.
- Electronics and Electrical Equipment: The blend is utilized in electronic enclosures, computer and communication equipment, consumer electronics, and electrical components due to its mechanical strength, electrical insulation properties, and processability.

- Appliances and Household Goods: PC/ABS blend is employed in the production of appliances, home goods, and consumer products such as housings for kitchen appliances, vacuum cleaners, power tools, and personal care devices due to its durability, impact resistance, and aesthetic appeal.

- Medical Devices and Equipment: The blend is used in medical device housings, equipment enclosures, and components that require a combination of strength, impact resistance, and resistance to harsh chemicals.

  The combination of polycarbonate and acrylonitrile butadiene styrene in PC/ABS blend results in a material that offers enhanced properties, making it suitable for a wide range of applications where impact resistance, strength, and heat resistance are crucial. Its versatility and processability make it a preferred choice in industries requiring durable and aesthetically pleasing components.

1.4.2 CARBON FIBER REINFORCED POLYMER (CFRP)

Carbon Fiber Reinforced Polymer (CFRP) is a composite material consisting of carbon fibers embedded in a polymer matrix. It is a high-performance material known for its exceptional strength, stiffness, and light weight. The carbon fibers provide the material with high tensile strength and rigidity, while the polymer matrix acts as a binder and provides versatility in shaping and processing. CFRP is widely used in industries such as aerospace, automotive, sports, and construction, where lightweight yet strong materials are required for various applications.

1.4.3 Carbon Fiber/Epoxy (CF/EP) Composite Modification using Thermoplastic

The objective of this research is to create a new composite material by incorporating carbon fibers into a matrix. Composites are formed by combining materials with distinct physical and chemical properties to create a specialized material tailored for specific tasks. By doing so, the resulting material can exhibit improved characteristics such as increased strength, reduced weight, enhanced electrical resistance, and greater stiffness. This makes composites a preferred choice over conventional materials, as they can enhance the properties of the constituent materials and find applications in various fields.

Chapter 2

LITERATURE REVIEW

Natalia Romanova and colleagues (2019)[1]conducted a study on the thermal properties of ABS and ABS/PC blends using the DSC method. The research focused on analyzing the influence of different blend ratios (75/25, 60/40, 50/50, and 30/70) on the glass transition temperature (Tg) and delta Cp values. The results indicated that as the proportion of ABS decreased in ABS/PC blends, the Tg value for SAN/PC (Styrene Acrylonitrile/Polycarbonate) increased. However, further increasing the PC content in the ABS/PC blend (30/70) led to a decrease in Tg values for both ABS and PC. These thermal studies on ABS/PC compositions provide valuable insights for assessing the quality of materials used in automotive components based on their composite composition.

Jong H. Eun et al. in 2021[2] studied The impact resistance and fracture toughness of carbon/epoxy composites were improved through the application of a polyamide coating at different weight percentages (5 wt., 10 wt., 15 wt., and 20 wt.). The chemical reaction between the polyamide and epoxy resin was examined using techniques such as Fourier transform infrared spectroscopy, differential scanning calorimetry, and X-ray photoelectron spectroscopy. The mechanical properties and fracture toughness of the composites were analyzed through various tests including transverse flexural tests, longitudinal flexural tests, impact tests, and mode I tests. Ultrasonic C-scan imaging was performed after the impact tests to evaluate the internal damage area. The results showed a significant increase of 77percent in the critical energy release rates compared to the carbon/epoxy composites without the polyamide coating. The surface morphology of the fractured surfaces was observed, and a toughening mechanism for the carbon/epoxy composites was proposed based on the experimental data obtained in the study.

Vijay Parashar et al . (2014) [3] studied the blending of diglycidyl ether of bisphenol-A (DGEBA) and low molecular weight Novolac epoxy resin at different concentrations. They observed that as the Novolac Epoxy resin content increased, the viscosity of the blends decreased. The curing behavior of the blends was examined using differential scanning calorimetry. The study also evaluated the water vapor permeability, tensile strength, damping factor, and storage modulus of the blends. It was found that, except for the blend containing 10percent Novolac epoxy, the water vapor permeability and tensile strength decreased with increasing Novolac Epoxy resin content. However, the blend with 10percent Novolac epoxy exhibited superior mechanical properties, as indicated by its higher damping factor and storage modulus, as analyzed using a dynamic mechanical thermal analyzer.

Stefan Caha et al . (2016) [4] studied The drive to reduce costs in the production of fiber reinforced composite parts, specifically through processes like Resin Transfer Molding (RTM), emphasizes the need for shorter cycle times. These processes involve injection and curing of the resin, which are directly influenced by the properties of the resin itself. During the injection phase, resin viscosity plays a critical role in determining the flow rate and influencing factors such as fiber wetting and void formation. The curing phase is the most time-consuming part of the process. This paper introduces a novel model that describes the viscosity development of the resin during the injection phase using the cumulative Weibull distribution function. The model has been validated through a study of the isothermal viscosity behavior of various resins across a wide temperature range. The findings demonstrate the potential for advanced resin selection and more accurate modeling of void formation during the injection phase of the RTM process, highlighting the benefits of this new model.

Muralidhara B et al . (2020)[5]studied to enhance our understanding of the mechanical properties of carbon fabric reinforced epoxy (CF/Ep) composites. Specifically, the study examines the mechanical behavior of CF/Ep composites with different fiber architectures (T300CF/Ep, T700CF/Ep, and T800CF/Ep) under various loads such as indentation, in-plane, tensile, and bending. The composites were fabricated using a consistent weight percentage of carbon fiber and a similar consolidation process involving hand layup followed by compression molding.

The experimental results highlight the influence of fiber weave structure on the mechanical properties of CF/Ep composites, which is more pronounced compared to neat epoxy. The use of high-strength carbon fiber (T800) contributes significantly to improving the tensile and bending load response of the CF/Ep composites. The fiber architecture has a moderate impact on the composite density but has a more significant effect on strength and deformation. The T300CF/Ep and T800CF/Ep composites exhibit nearly linear behavior up to brittle fracture, while the T700CF/Ep system shows non-linearity prior to failure. Moreover, the weaving pattern of the composites, despite the presence of fiber flaws and stress concentrations, proves advantageous by reducing sensitivity to flaws. These characteristics are systematically analyzed, taking into account numerical aspects of fiber strength and the formation of critical defects. Scanning electron microscopy is employed to provide further insights into the significant improvements observed in the mechanical properties of the composite systems.

H.A. Aisyah et al . (2021)[6]studied the increasing adoption of natural fibers in polymer composites has played a crucial role in mitigating environmental concerns. A notable trend is the utilization of woven natural fiber materials derived from lignocellulosic sources, which find applications in a wide range of industries including construction, consumer goods, automotive, aerospace, and defense. Woven materials offer unique advantages in the production of natural fiber polymer composites (NFPCs), as they provide flexibility, tailored properties, and improved mechanical performance due to their inherent weaving structures. This paper aims to provide a comprehensive review of studies on woven materials in NFPCs, discussing various factors that influence the properties of woven NFPCs, such as yarn characteristics, fabric properties, and manufacturing parameters. Furthermore, it compiles previous and ongoing research efforts on woven NFPCs using different polymer matrices, including polypropylene, polylactic acid, epoxy, and polyester, along with an analysis of the resulting composite properties. Finally, the paper highlights the applications, challenges, and future prospects in the field of woven NFPCs.

Na Ning et al . (2022)[7] investigated Enhancing the interlaminar fracture toughness of carbon fiber reinforced thermoset polymer composites has been a persistent issue. Resin matrix modification is a direct and effective method to address this challenge. In this research, the focus is on the incorporation of nanoparticles (NPs) into epoxy resins and evaluating the extent to which the improved toughness of the matrix is transferred to the resulting composites. The

NPs utilized in the study exhibit different particle morphologies, including homogeneous and core/shell structures, with an equal percentage of soft and hard polymer composition. The findings indicate that core/shell particles, particularly with the soft polymer as the core and rigid polymer as the shell, significantly enhance the fracture toughness of the epoxy resin by 851 percent, as well as the fracture toughness of the composite by 185percent (GIC) and 43percent (GIIC) compared to the control sample. In contrast, homogeneous particles show lesser effectiveness. The analysis of fracture surface morphology reveals that achieving effective toughening in the composite requires a combination of well-dispersed particles with strong particle-resin and resin matrix-fiber interfaces. This study provides valuable insights for selecting highly efficient toughening particles and offers comprehensive data on the transfer of toughness from the neat resin to the corresponding composites.

Hiranori Nishida et al . (2018) [8] investigate that Thermoplastic resins offer several advantages over thermoset resins, such as enhanced toughness, improved recyclability, and faster manufacturing processes. However, their higher melt viscosity can pose challenges during the infusion process, leading to insufficient impregnation of fiber bundles. To address this issue, a thermoplastic epoxy resin (TP-EP) has been developed, combining the workability of thermoset resins with the formability and recyclability of thermoplastics. This research aims to compare the mechanical properties of thermoplastic and thermoset epoxy carbon textile composites. The findings indicate that the composite incorporating highly polymerized thermoplastic epoxy exhibits superior mechanical performance compared to conventional thermoset epoxy textile composites.

Heru Sukanto et al . (2021)[9] studied the comprehensive overview of epoxy resins and their applications as composite matrices. It covers the different types of epoxy resins and curing agents commonly used, as well as the process of cross-linking formation and degradation through pyrolysis and solvolysis. The article emphasizes the importance of selecting the appropriate epoxy resin and curing agent combination to achieve desired mechanical properties in composite materials.Engineers can benefit from the wide range of epoxy resin options available, allowing them to tailor composite materials to specific application requirements. The advantages of using epoxy resin as a matrix in composites can be maximized by carefully selecting the resin type and optimizing the curing agent dosage.The article also addresses the growing demand for fiber-reinforced epoxy composites, especially those reinforced with carbon fiber (CF). However, the disposal of these composites after their useful life can be challenging. The article suggests that recycling strategies such as pyrolysis or solvolysis methods have the potential to reclaim and reuse carbon fiber and processed epoxy resin, thus addressing the waste management issue.

Jyotishkumar et al. (2011)[10]studied how the curing process influences the stress relaxation in ABS/epoxy composites. Specifically, the researchers focus on the thermomechanical behavior of the epoxy and ABS blends under different cure schedules. Various compositions of the blends were prepared by incorporating 3.6, 6.9, 10, and 12.9 wt percent of epoxy, resulting in different ABS concentrations. The thermal, mechanical, and morphological properties of the epoxy/ABS mixes were analyzed. The findings indicate that increasing the ABS content leads to larger domain sizes and greater interparticle distances. The domain size serves as an indicator of the effectiveness of an energy-absorbing mechanism. Moreover, the study reveals that higher ABS concentrations result in increased inter-particle distances due to substantial coalescence effects. Among the compositions tested, the epoxy blend containing 3.6 wtpercent ABS exhibits superior qualities. The presence of internal stress affects the dimensional stability of the system, which can be alleviated by employing a two-stage healing process instead of a single step. Regardless of the curing schedule employed, the thermal and mechanical properties remain comparable. However, the incorporation of the thermoplastic ABS, which is inherently heterogeneous, alters the mechanical and morphological characteristics of the composites.

Chapter 3

METHODOLOGY

3.1 SYNTHESIS FOR EPOXY MODIFICATION

The synthesis of epoxy modification consists of several essential stages, as described below:

- Cryo-grinding
- Melt-mixing
- Degassing

Figure 3.1 illustrates the overall setup employed for the synthesis of epoxy modification.

3.1.1 Cryo-Grinding

Cryogenic grinding, also referred to as freezer milling, cryo-milling, or freezer grinding, involves the cooling or chilling of a substance followed by the reduction of its particle size. This method is commonly employed when processing thermoplastics that tend to become lumpy or clog screens when ground at room temperature. By chilling the material using dry ice, liquid carbon dioxide, or liquid nitrogen, it becomes easier to crush the thermoplastics into coarse powders suitable for various applications, such as electrostatic spraying and other powder operations. The cryogenic grinding process utilizes a mechanical grinder in which liquid nitrogen is introduced to chill PC and ABS pellets, causing them to be coarsely crushed into powder form.

3.1.2 Melt-mixing

Melt mixing is utilized in this study to combine the DGEBA epoxy resin YD-128 with the desired thermoplastics, namely PC and ABS.

Among various methods, melt mixing and solvent mixing are commonly employed for creating epoxy/thermoplastic mixtures. However, solvent mixing is time-consuming, chemically unclean, and less environmentally friendly [9]. Moreover, it increases the risk of void development during the curing process, leading to unexpected failures [8]. In this research, melt mixing is chosen because it does not involve any residual chemicals that may interfere with the curing of the product. Additionally, it is considered one of the simplest and cleanest methods for modifying epoxy and achieving void-free samples [9].

To initiate the melt mixing process, 200g of epoxy is accurately weighed and placed in a silica mold. For optimal mechanical properties, the total weight of the thermoplastics added should be 1.5 wt percent [6]. Cryo-ground PC and ABS powders are then introduced into the epoxy after heating it to approximately 180°C in a sand bath. The mixture is swirled for 60 minutes, resulting in a slight yellowing of the modified epoxy. The temperature for melt-mixing PC, ABS, and PC/ABS into DGEBA is determined through a trial-and-error approach, using the color change of DGEBA during modification as a control parameter. Continuous agitation and thorough mixing are crucial to achieve the best possible blending of the epoxy and thermoplastic components. The temperature is closely monitored and maintained between 180°C and 190°C to prevent overheating. Once the modified resins have cooled to room temperature, 100g of TH7301 is added and thoroughly mixed. A temperature-controlled sand bath, as depicted in figure 3.1, is employed for the melt-mixing process of PC, ABS, and PC/ABS into DGEBA.

Figure 3.2 illustrates the specific setup used for the temperature-controlled sand bath during the melt-mixing process.

3.1.3 Degassing (Stabilizing of Resin/Hardener in vacuum degassing chamber)

The hardener and thermoplastic-modified epoxy are mixed in a 2:1 ratio, and it is necessary to remove any trapped bubbles from the mixture through a process called degassing before proceeding with fabrication. Degassing is crucial because trapped bubbles can lead to the formation of voids within the cured epoxy, which can cause the composite to fail unexpectedly under

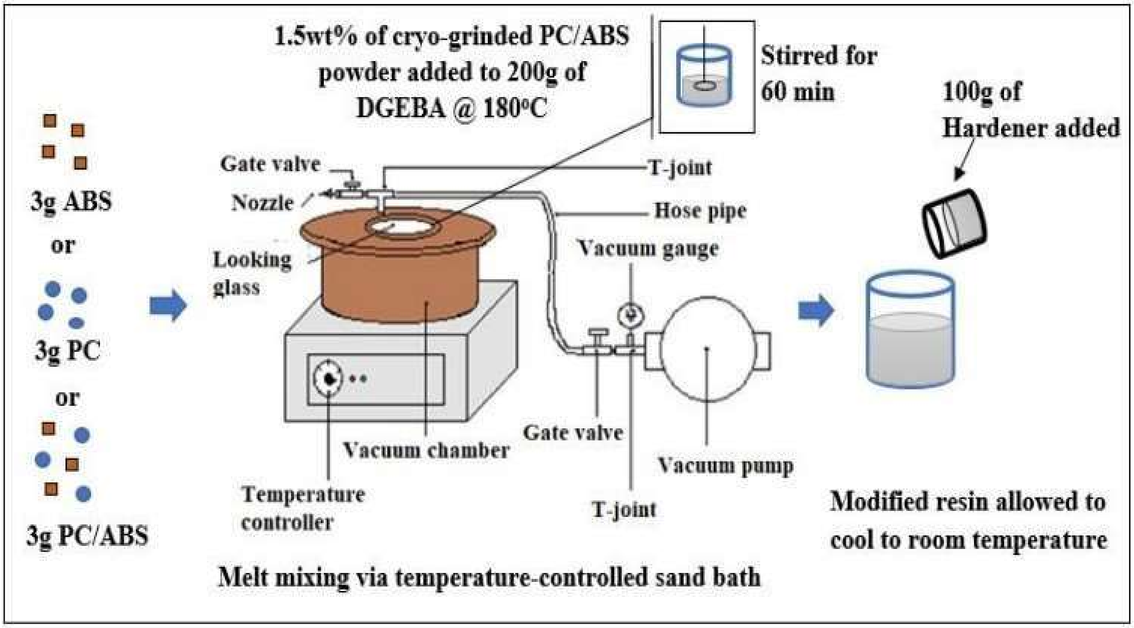


Figure 3.1: Epoxy Modification

mechanical stress [2]. The laboratory setup depicted in Figure 3.2 is used for the degassing process, which involves the following steps:

- Ensure the vacuum chamber and top lid are free from dust and solid debris to prevent contamination of the epoxy.
- Fill the chamber with the thoroughly mixed epoxy/hardener mixture and securely fasten the top lid.
- Ensure a tight seal by checking that the top lid is properly seated and the gaskets are fully sealed.
- Connect the inlet port of the chamber to the suction side of the vacuum pump using a hose pipe.
- Close the exhaust valve and open the inlet valve, then activate the vacuum pump.
- Monitor the vacuum gauge and close the inlet valve once the desired vacuum levels are reached.
- Maintain the vacuum to a certain extent while allowing trapped air to rise to the surface and burst by closing the valves.

Figure 3.2: Laboratory setup of Vacuum degassing unit

- Open the exhaust valve to release any remaining unnecessary air from the chamber.
- Periodically repeat the stages to ensure a clear and stabilized resin, as well as to eliminate all trapped bubbles.
- Turn off the vacuum pump, remove the top lid, and retrieve the resin for fabrication. By following this degassing process, the epoxy mixture can be effectively freed from trapped air and ensure a quality resin for further fabrication steps.

3.2 SPECIMEN PREPARATION

3.2.1 Vacuum-assisted resin transfer molding (VARTM)

The VARTM (Vacuum Assisted Resin Transfer Molding) process is employed to fabricate composite materials using both neat epoxy and thermoplastic-modified epoxy. In order to achieve a superior surface finish for the cast composite, a glass plate with dimensions of 30cm × 30cm × 1cm is carefully selected. To prevent the mesh and carbon fiber from sticking to the glass plate, a layer of wax is applied. The injection of an 8cm × 8cm mesh is positioned at the center of the glass surface. A peel-ply cloth of appropriate dimensions is placed over the mesh to ensure

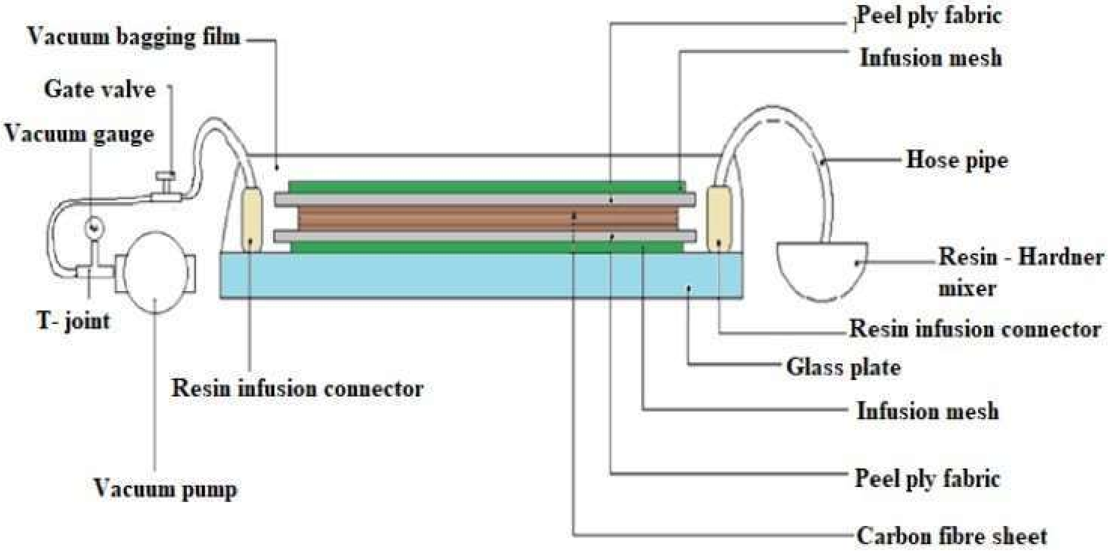


Figure 3.3: VARTM

proper wetting of the epoxy throughout the composite. Next, a twill weave carbon fiber sheet measuring 7.5cm × 7.5cm is cut into 15 layers, stacked together, and positioned on top of the peel-ply cloth. Once again, the peel-ply fabric and infusion mesh are placed over the stacked carbon fiber sheets. This arrangement, as depicted in figures 3.3 to 3.5, results in the carbon fiber sheets being sandwiched between the layers of mesh and peel-ply fabric.

Connectors for resin infusion are placed in appropriate locations to facilitate the flow of resin into and out of the mold. An inlet connector is used for resin entry, while an outlet connector allows the resin to exit the mold. A vacuum bagging film is then applied over the entire setup, ensuring a tight seal. Sealant tapes are used to secure the vacuum bagging sheet to the glass surface, ensuring proper vacuum sealing. The resin pot and infusion connector are connected through hose pipes to facilitate resin flow into the mold. A vacuum pump is connected to the second infusion connector through hose tubing to create a vacuum inside the sealed bag. The vacuum pump is briefly turned on and off to check for any potential leaks. Once a leak-free setup is confirmed, the resin is allowed to flow by submerging the inlet pipes into the resin. The resin flow rate is regulated by adjusting the gate valves on the outflow line to ensure thorough wetting of the carbon fiber sheets. Once the carbon sheets are completely wetted, the resin flow is redirected to the outlet pipes, and the gate valve is closed. Clamps are applied to the inlet and outlet ports to prevent gas leakage, and the vacuum pump is switched off. After curing overnight, the fabricated composite is removed from the mold.

Chapter 4

TESTING AND CHARACTERIZATION

4.1 MATERIAL USED

The epoxy matrix selected for this research is a thermoset polymer that has an epoxide equivalent weight (EEW) between 185 and 194 g/eq. It is known as YD 128 and is manufactured by Aditya Birla Chemicals Ltd., located in Thailand.For the curing process of the epoxy, a cycloaliphatic amine called Modified TH 7301, produced by Aditya Birla Chemicals Limited in Thailand, is utilized.To modify the matrix of the epoxy, a technique called melt mixing is employed, where thermoplastics such as polycarbonate (PC) and poly(acrylonitrile butadiene styrene) (ABS) are mixed with the epoxy. The specific thermoplastics used are Makrolon 2856 from Covestro AG in Germany for PC and Cycolac MG 47F from Sabic in Saudi Arabia for ABS.Additionally, the composite material is reinforced with carbon fiber. The carbon fiber used is a 3K genuine carbon fiber fabric cloth with a weight of 220g/m2 and a 2x2 twill weave pattern. The manufacturer of the carbon fiber cloth is Carbon Black Composites in India, and the product is identified by the Manufacturer Part No. CBC24030.

Table 4.2. presents details regarding the epoxy YD 128, which is based on DGEBA (Digly- cidyl Ether of Bisphenol A), as provided by the manufacturer, Aditya Birla Chemicals Ltd. located in Thailand.

Table 4.1: Properties of carbon fiber

No.	Parameters	Specifications
1	Fabric type	3K genuine carbon fiber fabric cloth
2	Weave pattern	2 × 2 twill weave
3	Dimension	100cm × 30cm
4	Weight of the fabric	220 g/m^2
6	Izod impact strength	612 J/m

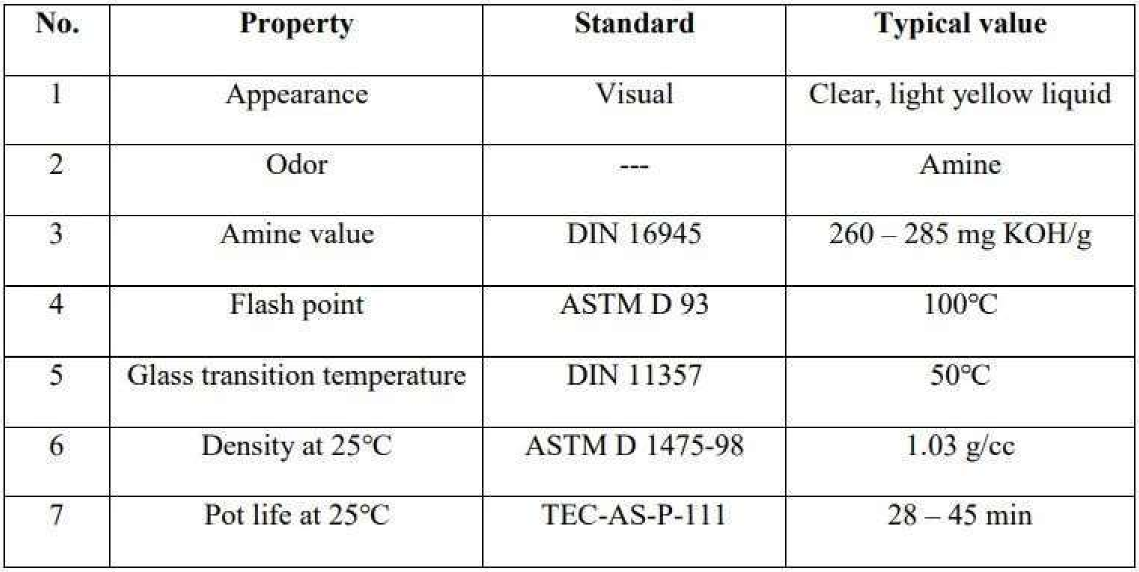
Figure 4.1: Twill weave carbon fiber

Table 4.2: Properties of epoxy (YD-128)

No.	Property	Standard	Typical value
1	Appearance	Visual	Clear, colorless to light yellow liquid
2	Epoxy equivalent weight	ASTM D 1652-04	185 - 194 g/eq
3	Epoxide value	ASTM D 1652-04	5.15 – 5.40
4	Hydrolyzable chlorine	ASTM D 1726-03	0.05 max
5	Flash point	ASTM D 93	252°C
6	Density at 25°C	ASTM D 1475-98	1.16 g/ml
7	Viscosity at 25°C	ASTM D 2196-05	11,000 – 14,000 cPs

Figure 4.2: epoxy YD-128

Table 4.3: Properties of Hardener (TH 7301)



No.	Property	Standard	Typical value
1	Appearance	Visual	Clear, light yellow liquid
2	Odor	---	Amine
3	Amine value	DIN 16945	260 – 285 mg KOH/g
4	Flash point	ASTM D 93	100°C
5	Glass transition temperature	DIN 11357	50°C
6	Density at 25°C	ASTM D 1475-98	1.03 g/cc
7	Pot life at 25°C	TEC-AS-P-111	28 – 45 min

4.1.1 Hardener: TH 7301

Table 4.3 listing the properties of TH 7301 from Aditya Birla Chemicals Ltd. in Thailand. To obtain the desired information, I recommend referring to the manufacturer’s documentation or reaching out to Aditya Birla Chemicals Ltd. directly.

4.1.2 Polyacrylonitrile butadiene styrene (ABS)

Table 4.4 or the specific properties of ABS (Cycolac MG47F resin) as provided by Sabic in Saudi Arabia.

4.1.3 Polycarbonate (PC)

Table 4.4 or the specific properties of PC (Makrolon 2856) provided by Covestro in Germany.

4.1.4 Vacuum bagging film

A vacuum bag is used to cover the preform, and the resin is injected into the mold cavity with the aid of vacuum pressure. The vacuum bags are prepared by attaching the glass mold to the vacuum bagging film, allowing the application of vacuum to create a tight seal. This process facilitates the removal of air and ensures proper resin consolidation during the injection process.

Figure 4.3: Hardener TH 7301

Table 4.4: Properties of ABS

No.	Property	Standard	Typical value
1	Specific gravity	ASTM D 792	1.04
2	Coefficient of thermal expansion	ASTM E 831	8.82E – 05 /°C
3	Notched Izod impact strength	ASTM D 256	320 J/m
4	Vicat softening temperature	ISO 306	98°C
5	Tensile stress at yield	ISO 527	47 MPa
6	Tensile strain at break	ASTM D 638	25 %
7	Melt temperature	---	220 - 260°C

Figure 4.4: ABS

Table 4.5: Properties of PC

No.	Property	Standard	Typical value
1	Specific gravity	ASTM D 792	1200 kg/m^3
2	Coefficient of thermal expansion	ISO 11359-1, -2	0.65×10^{-4}/°C
3	Notched Izod impact strength	ISO 7391/b.o. ISO 180-A	70P KJ/m^2
4	Glass transition temperature	ISO 11357-1, -2	145°C
5	Tensile stress at yield	ISO 527-1,-2	65 MPa
6	Tensile strain at break	b.o. ISO 527-1,-2	130 %
7	Flexural stress	ISO 178	97 MPa
8	Melt temperature	---	280 - 320°C

Figure 4.5: PC

Table 4.6: Details of vacuum bagging film

No.	Parameters	Specification
1	Provider	CF Composites, Delhi, India
2	Material	Modified nylon resin film
3	Thickness	75 micron
4	Width	1000 mm

The details of Vacuum bagging film are given in Table 4.6

4.1.5 Sealant tape

Using sealant tape is essential for achieving a superior airtight seal when applying vacuum to adhere the vacuum bagging sheets to the mold surface. This step is crucial as even the smallest leaks can lead to voids in the composite material. Table 4.7 provides a description of the specific sealant tape utilized in this study for the VARTM process.

Figure 4.6: vacuum bagging film

Table 4.7: Details of Sealant tape

No	Parameters	Specifications
1	Provider	CF Composites, Delhi, India
2	Material	Butyl-sealant tape
3	Dimension	3 mm × 15 mm × 15 m

Figure 4.7: Sealant tape

4.1.6 Vacuum pump

A vacuum is generated within the vacuum bagging system using a vacuum pump, enabling the infusion of resin into the mold. Table 4.8 provides relevant information regarding the specific vacuum pump employed in the process.

4.1.7 Mechanical grinder

A cryo-grinding setup involves the use of a mechanical grinder. The detailed specifications of the mechanical grinder can be found in Table 4.9.

4.2 Materials and Methods

4.2.1 Materials

For this research, virgin PC and ABS are selected as modifiers for the DGEBA resin. The specific materials and their respective sources are provided in Table 4.19, which have been previously utilized in our published works [8, 3, 4].

Table 4.8: Details of vacuum pump

No	Parameters	Specifications
1	Manufacturer	Truvac
2	Capacity	2.5 CFM
3	Weight	12.6 Kg
4	Dimension	336 mm × 123 mm × 255 mm
5	Displacement	113 L/min
6	Voltage	220 V
7	Frequency	50 Hz
8	Oil Capacity	220 ml
9	Stage	Double
10	Ultimate vacuum	50 microns

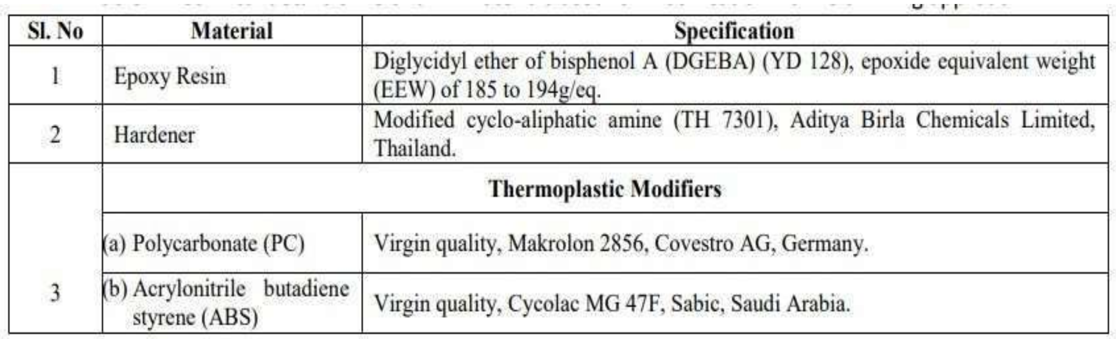
Figure 4.8: Vacuum pump

Table 4.9: Details of Mechanical grinder

No	Parameters	Specifications
1	Brand	NILSAN
2	Color	Silver
3	Model	NSG100A
4	Material	Stainless steel
5	Power	650 W
6	Voltage	220 V
7	Rotate Speed	28000 RPM

Figure 4.9: Mechanical grinder

Table 4.10: Technical details of TS and TP materials used for modification via melt-mixing approach



Sl. No	Material	Specification
1	Epoxy Resin	Diglycidyl ether of bisphenol A (DGEBA) (YD 128), epoxide equivalent weight (EEW) of 185 to 194g/eq.
2	Hardener	Modified cyclo-aliphatic amine (TH 7301), Aditya Birla Chemicals Limited, Thailand.
3	**Thermoplastic Modifiers**	
	(a) Polycarbonate (PC)	Virgin quality, Makrolon 2856, Covestro AG, Germany.
	(b) Acrylonitrile butadiene styrene (ABS)	Virgin quality, Cycolac MG 47F, Sabic, Saudi Arabia.

4.2.2 Methods

4.2.3 Resin Modification using melt-mixing

The DGEBA modification process involves a melt-mixing procedure conducted in a temperature-controlled sand bath developed in our Space Technology Laboratory [6]. The DGEBA resin, maintained at 180°C, is mixed with a 1.5wt percent TP modifier. Continuous stirring ensures complete melting and thorough blending of the TP component with the hot resin. Figure 1 depicts the resulting m-DGEBA and u-DGEBA resins. The observed light-yellow coloration is attributed to the phase separation phenomenon previously reported in related studies [9].

Various compositions of PC/ABS blends (PC100, 90/10, 10/90 and ABS100) were selected for modifying DEGBA resins via melt-mixing. The composition of PC/ABS ranges from 100percent PC, 90percent PC and 10 percentABS, 10percent PC and 90percent ABS and 100percent ABS concentrations in the 1.5wtpercent of TP modifier content. The compositions and processing time for modification of DGEBA is represented in Table 2. The TP modifiers, PC and ABS are available as 2mm to 3mm pellets that, when directly melt-mixed with DGEBA, require approximately 45-60 minutes [7].

In order to streamline the procedure, the pellets were transformed into flakes by applying constant temperature and mechanical compression at 200°C. This conversion process reduces the thickness of the pellets and increases the surface area, enabling faster melting and mixing of the TP content into the DGEBA resin at 180°C within a time frame of less than 20 minutes. To maintain a minimal increase in viscosity of the m-DGEBA resins after melt-mixing, the maximum TP modifier content allowed for the resin is set at 1.5wt percent of the DGEBA

Figure 4.10: u-DEGBA and m-DGEBA resins after melt-mixing of PC/ABS blends into DGEBA at 180oC.

Table 4.11: PC/ABS hybrid blend composition and observed modified DEGBA colour change.

Sl.No.	Specimen	DGEBA (g)	PC (g)	ABS (g)	Processing Time	Colour
1	u-DEGBA	100	0	0	0	Transparent
2	PC100 m-DGEBA		1.5	0	20	Slight Yellow
3	90/10 m-DGEBA		1.35	0.15		Moderate Yellow
4	10/90 m-DGEBA		0.15	1.35		Moderate Yellow
5	ABS100 m-DEGBA		0	1.5		Moderate Yellow

portion. This concentration ensures an improvement in mechanical properties, as reported in previous studies [1,3].

4.2.4 Characterisation Studies to determine the synergistic effect of hybrid TP blend in DGEBA

The objective of this study is to modify DGEBA resins using a hybrid PC/ABS blend with minimal modifier content. The m-DGEBA resins underwent several tests including FTIR, DSC, rheology, cure, and cryo-toughening to assess the synergistic effect of the hybrid blend. FTIR and DSC measurements were conducted on cured m-DGEBA samples to examine the chemical effects compared to the unmodified DGEBA (u-DGEBA). Rheology properties were determined by testing uncured m-DGEBA and u-DGEBA using an Anton-Paar Rheometer. Curing reactions and times were evaluated by mixing m-DGEBA and u-DGEBA with a hardener and monitoring the curing process in insulated acrylic molds under vacuum. Cryo-crack resistance was determined by subjecting 5mm thick, 5cm diameter disc specimens of m-DGEBA to cryo-cycling in liquid nitrogen. High-resolution images were captured before and after cryo-cycling to assess the severity of cryo-cracks.

To determine the strength characteristics of cured m-DGEBA, a total of five specimens measuring 10cm x 1.5cm x 1cm were prepared for each modification and subjected to Charpy testing. In order to assess the resistance of m-DGEBA to cracking after cryo-treatment, the specimens were cryo-treated in LN2 for a duration of 2 hours prior to conducting the Charpy test. The fracture surfaces of the specimens were thoroughly examined to evaluate any discernible changes or effects.

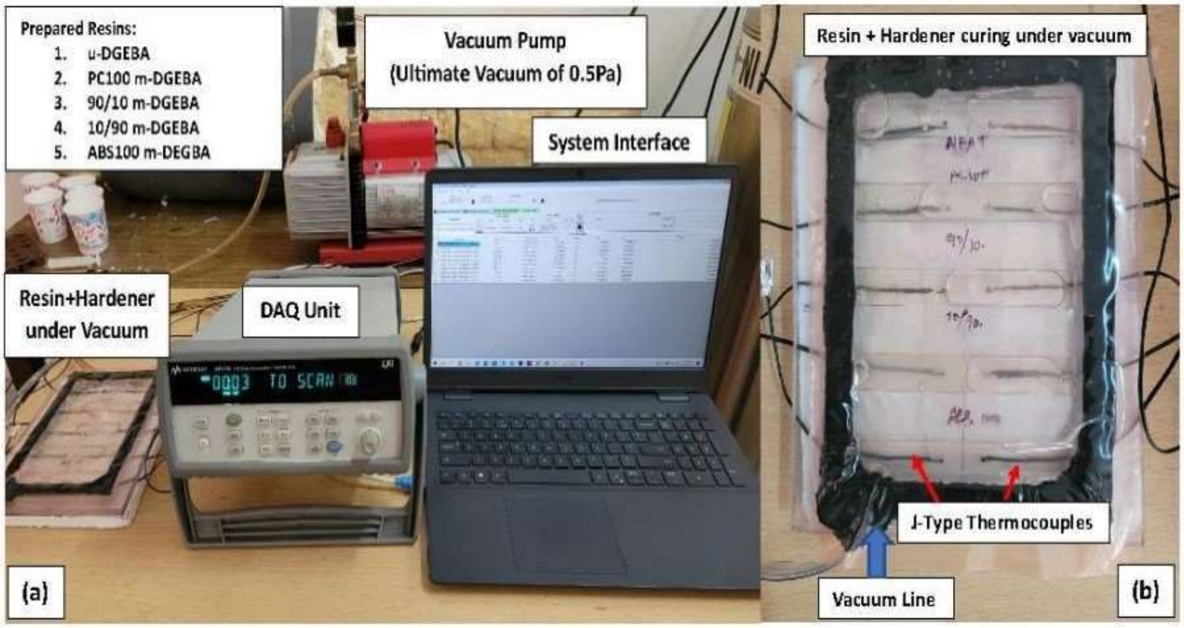


Figure 4.11: (a) Set-up for the investigation of cure characteristics of m-DEGBA/Hardener system and (b) prepared acrylic mould housing J-type thermocouple filled with m-resin + hardener for recording curing temperature.

Chapter 5

RESULTS AND DISCUSSIONS

5.1 Identification of FTIR peaks for bond confirmation

This work involves modifying DGEBA resins to reduce their brittleness at room temperature (RT) and cryogenic temperatures (CT). To improve the fracture toughness characteristics of DGEBA, the flakes of TP modifiers PC, ABS and PC/ABS are melted with DGEBA at 180°C. As depicted in Figure 3, FTIR spectroscopy of m-DGEBA and u-DGEBA is compared to confirm the nature of the modification scheme (chemical or physical) involved. The u-DGEBA exhibits characteristics between 3300cm^{-1} and 3570cm^{-1} that confirm -OH stretching, whereas a slight peak between 2750cm^{-1} and 2910cm^{-1} may be attributed to -CH stretching[3]. Melt-mixing of PC into DGEBA at all PC/ABS hybrid blend compositions exhibits higher peak intensities at 2850cm^{-1} to 2910cm^{-1} [2,1], whereas ABS100 composition does not exhibit this trend.

Additionally, a decrease in the intensities of the characteristic peaks in the range of 650cm^{-1}to 1450cm^{-1} can be observed in PC100 m-DGEBA as the concentration of PC in the PC/ABS blend decreases. Conversely, a significant characteristic peak confirming the presence of ABS in DGEBA is observed at 1603cm^{-1} and 2205^{-1}, indicating the stretching of -C=C in butadiene and -CN in acrylonitrile, respectively. This confirms the chemical composition of the hybrid blend.

Furthermore, the absence of a peak at 913^{-1} in all m-DGEBA samples suggests that the epoxide groups have fully participated in the curing reaction with the chosen hardener. This confirms the achievement of complete cross-linking, ensuring maximum strength after the

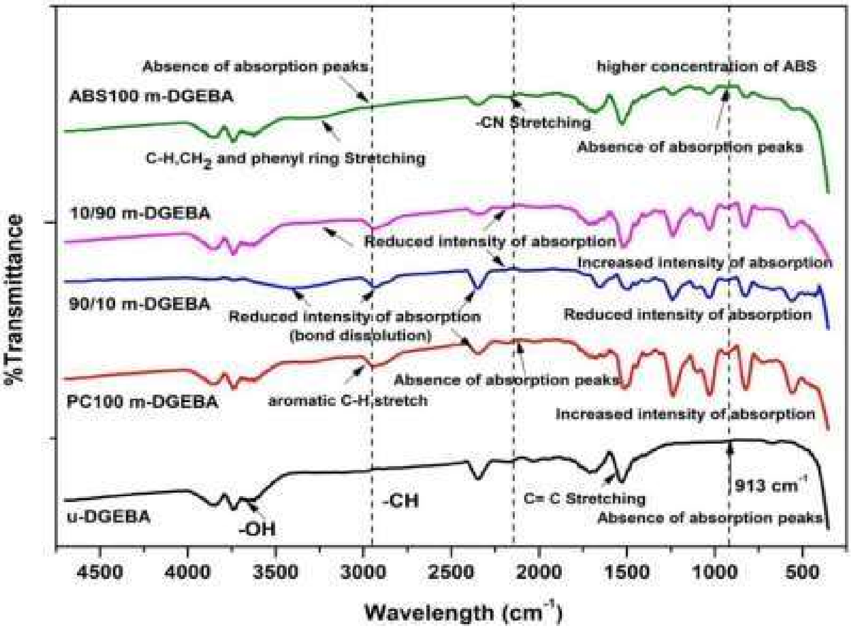


Figure 5.1: FTIR curves to determine bonds in cured m-DEGBA samples.

curing process. It also indicates that the modification does not interfere with the curing process and allows m-DGEBAs to undergo a complete curing reaction for optimal strength and stiffness.

Among the hybrid blend compositions, 90/10 m-DGEBA exhibits the greatest decrease in peak intensities, indicating a stronger role in chemically modifying DGEBA resins through bond dissolution or formation compared to other blend compositions. The partial miscibility of PC in DGEBA observed in previous studies may contribute to the pronounced chemical modification observed in this study, particularly with the 90/10 hybrid blend system.

To further confirm the chemical modification and reactive effects of the hybrid blends, DSC analysis is performed, which will be discussed in the following section.

5.2 DSC curve analysis of m-DGEBA samples

Figure 5.2(a) and 4(b) display the heat flow and reaction rate characteristics of the m-DGEBA samples, respectively. The heat flow curves of the virgin PC (v-PC) and virgin ABS (v-ABS) in the literature show typical endothermic peaks at their respective melting temperatures (Tm) of 149°C and 107°C[2,5]. However, due to the lower concentration of PC/ABS in the DGEBA

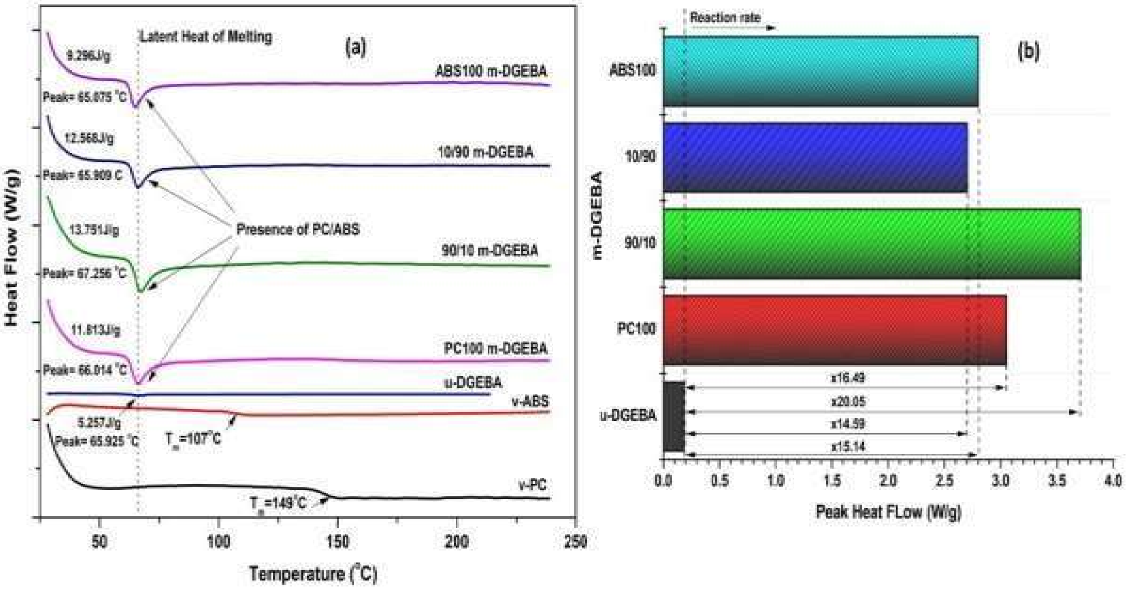


Figure 5.2: (a) DSC characteristics and (b) Reaction rate of DGEBA/Hybrid TP blend system.

matrix (1.5wt percent DGEBA content), the endothermic peaks are not clearly visible in the selected compositions. This observation suggests the possibility of chemical reactions occurring during the melt-mixing process, which is further supported by the FTIR analysis.

Figure 5.2(a) illustrates that the 90/10 m-DGEBA composition exhibits the highest heat flow and peak temperature, indicating its superior stability in modifying DGEBA. The steepness of the peaks in the heat flow curves of all m-DGEBA samples confirms the presence of PC/ABS in the DGEBA blend. Furthermore, the absence of multiple endothermic peaks in the heat flow characteristics confirms the excellent compatibility of the low concentration hybrid PC/ABS blend with DGEBA.

The steepness of the enthalpy peak on the DSC graph corresponds to the reaction rate, which determines the compatibility of modifiers with the base material (DGEBA). A higher reaction rate indicates better cooperation between the hybrid molecules and the DGEBA base material. Figure 5.2(b) illustrates the reaction rate of m-DGEBA based on the data from Figure 5.2(a). It demonstrates that the 90/10 m-DGEBA composition exhibits an approximately 20-fold higher reaction rate compared to unmodified DGEBA. This indicates the strong cooperative nature of the 90/10 hybrid blend with DGEBA. On the other hand, the 10/90 hybrid blend shows a diminished reaction rate compared to both PC100 and ABS100 as individual modifiers,

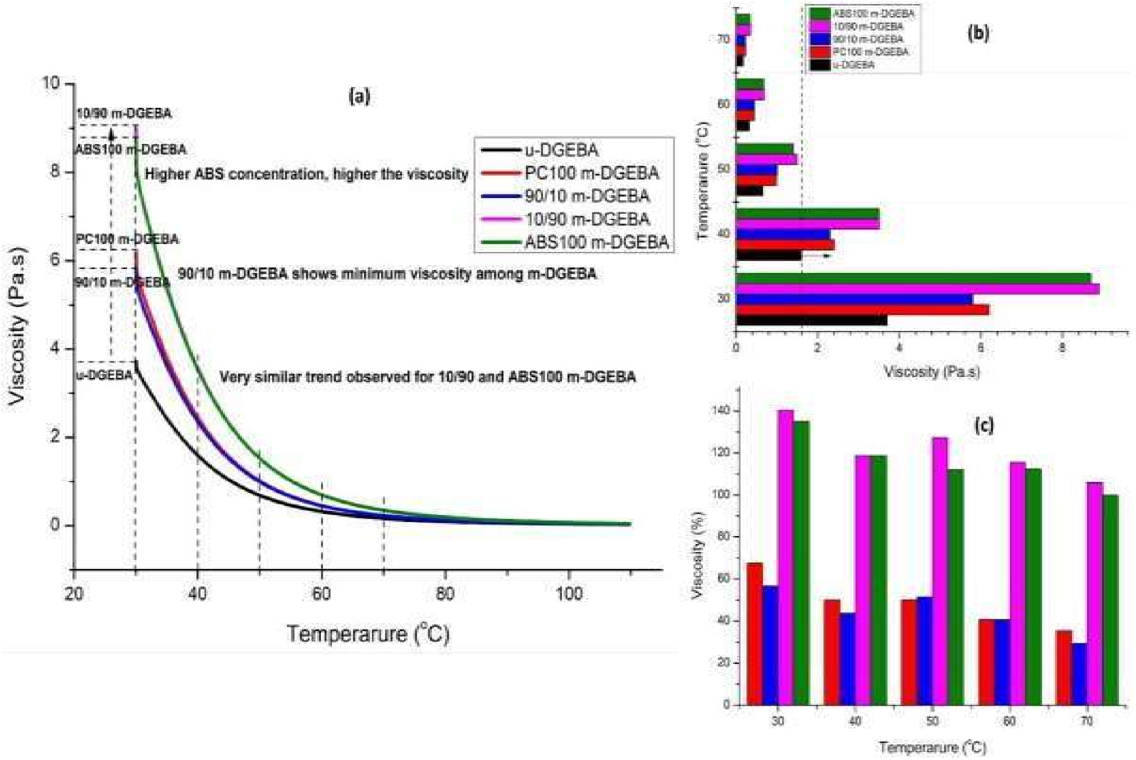


Figure 5.3: (a) Viscosity vs temperature, (b) viscosity and (c) percentage increase in viscosity observed for m-DGEBA at specific temperatures.

making it a less preferred composition for this study. The solubility of PC in DGEBA may contribute to the enhanced reaction rate and chemical modification of the system. Additionally, the higher concentration of ABS in the 10/90 blend may lead to increased agglomeration tendencies and the formation of voids, resulting in negative synergistic effects and poorer cooperation with DGEBA.

5.3 Viscosity vs temperature characteristics of m-DEGBA

The resistance to flow of m-DGEBA resins, obtained by melt-mixing the PC/ABS hybrid into DGEBA and cooling it to room temperature, was significantly greater than that of u-DGEBA resins. The extent of flow resistance varied among the different modifier compositions tested. Therefore, it was important to assess the impact of PC and/or ABS concentration on the viscosity of m-DGEBA resins modified with the PC/ABS blend. Figure 5(a) presents the viscosity versus temperature characteristics obtained from rheological measurements. It was observed that all m-DGEBA resins showed a higher increase in viscosity compared to u-DGEBA resins, with the difference being most pronounced at lower temperatures. As the temperature increased, the viscosity difference between u-DGEBA and m-DGEBA resins diminished, and they exhibited similar viscosity values in the range of 2 Pa.s to 4 Pa.s. Within the temperature range of 40°C to 50°C, the viscosity of the resins ranged from 1.8 Pa.s to 4 Pa.s. These results indicate that m-DGEBA resins can be effectively processed at temperatures between 40°C and 50°C due to their favorable flow properties at higher temperatures.

According to previous research, the 90/10 hybrid blend (90 percent PC concentration and 10 percent ABS concentration) exhibits exceptional synergistic effects by combining the strength and stiffness of PC with the flowability and processability of ABS. In Figure 5 (a), it can be observed that the 90/10 m-DGEBA resin shows the lowest increase in viscosity compared to PC100 m-DGEBA. The 10 percent ABS concentration in the hybrid blend improves the flow properties of m-DGEBA, resulting in a lower viscosity increase and enhanced flow capabilities. On the other hand, an increase in ABS concentration leads to a higher viscosity increase in m-DGEBA. However, in the case of the 10/90 hybrid blend, the viscosity observed is slightly higher than that of ABS100 m-DGEBA. This can be attributed to the tendency of immiscible ABS portions dispersed in the continuous phase of DGEBA to form larger discontinuities and voids within the PC co-continuous phase. This heterogeneous morphology negatively affects the flow properties of the 10/90 blend, resulting in higher resistance to flow . In contrast, ABS100 m-DGEBA, despite exhibiting coalescence tendencies and a heterogeneous morphology, does not significantly impede flow compared to the 10/90 blend.

Figure 5.3(b) presents the viscosity of m-DGEBA resins at different temperatures (30°C, 40°C, 50°C, 60°C, and 70°C). The viscosity characteristics of the resin/hardener mixture required for the RIM process fall within the range of 0.2 Pa.s to 0.5 Pa.s at temperatures between 30°C and 40°C. Among the tested m-DGEBA resins, the 90/10 hybrid blend exhibited the least increase in viscosity within this temperature range, making it suitable for RIM processing. The viscosity values for 90/10 and PC100 m-DGEBA/hardener mixtures ranged from 0.25 Pa.s to 0.48 Pa.s, respectively. These viscosity values are within the acceptable range for RIM. The 90/10 hybrid blend, known for its strength and processability, carries over these characteristics to DGEBA resins, resulting in minimal viscosity increase compared to other modifiers. Therefore, the 90/10 hybrid TP modifier is the most suitable modification for the selected DGEBA resin system, as it exhibits the least increase

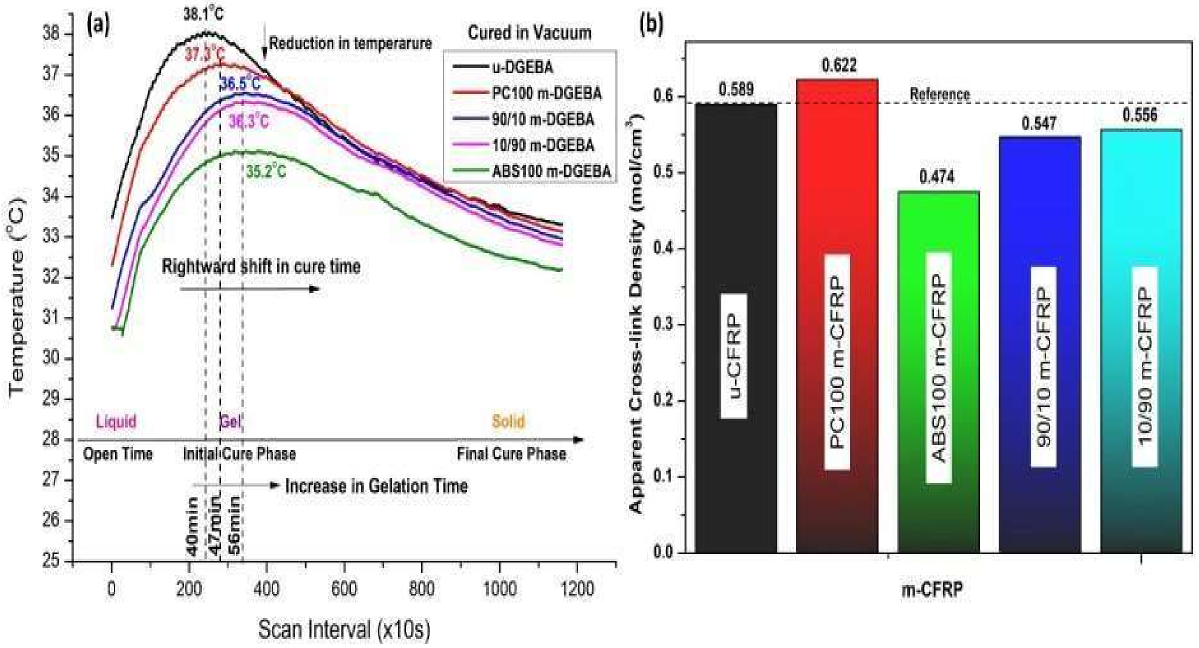


Figure 5.4: (a) Cure characteristics and (b) apparent cross-linking density for m-DGEBAs.

5.4 Cure Characteristics vs time of m-DEGBA

In order to assess the curing time and reaction temperature, a specific investigation was carried out to evaluate any potential changes in these parameters for the m-DGEBA resins. This study aimed to determine if the curing process was affected by the modifications made to the resin system.

In this section, we investigated and analyzed the curing time and reaction temperature properties, as shown in Figure 5.4(a). The figure displays the average curing temperature obtained using a J-type thermocouple housed within acrylic molds. The curing reaction progresses through three stages: liquid phase, gel phase, and solid phase, as depicted in Figure 5.4(a). Notably, the cure characteristics shift towards higher temperatures, which is directly influenced by the ABS content in the hybrid PC/ABS blend modifiers. Additionally, the peak temperature observed during the curing reaction decreases and shifts towards higher temperatures as the ABS concentration increases. The highest curing temperature is observed for the u-DGEBA resin (38.1°C), and it gradually decreases with increasing ABS concentration, reaching a minimum of 35.2°C for the ABS100 m-DGEBA system. This study suggests that ABS has the ability to reduce the curing temperature, which is indirectly related to the chemical reaction rate. Interestingly, the curing temperatures for the hybrid blends 90/10 and 10/90 are very close (36.5°C and 36.3°C, respectively).

Furthermore, the peak curing temperature, indicating complete participation of epoxy monomers in the curing reaction, exhibits a rightward shift. This shift is attributed to the decreased concentration of effective monomers involved in the curing reaction. Consequently, the time required to reach the peak cure temperature varies from 40 minutes for u-DGEBA to 57 minutes for ABS100 m-DGEBA. This extended curing time provides users with more flexibility to work with the m-resin/hardener system, making it suitable for complex projects. The chemical reactions shown in Figure 3, which result in bond dissolution during the modification of DGEBA, support the reduction in cure temperature and increased cure time. The phenomenon of bond dissolution may have reduced the effective epoxy monomer content available for participation in the curing reaction, thereby decreasing the degree of cross-linking. Higher cross-linking is typically associated with increased brittleness of epoxy. The decreased temperature of the curing reaction further confirms the ability of the hybrid TP modifiers to reduce the cross-linking rate of m-DGEBAs, potentially enabling the development of high-performance composites for aerospace applications.

Figure 5.4(b) illustrates the apparent cross-linking density observed in m-DGEBA-based CFRPs. It is evident from the graph that the hybrid PC/ABS blend modifier can moderately decrease the apparent cross-linking density of m-DGEBA. The hybrid blends 90/10 and 10/90 exhibit a moderate decrease in cross-linking density, while ABS100 shows the greatest decrease. This is consistent with the temperature of the curing reaction observed in Figure 5.4(a). On the other hand, the PC100 modifier increases the cross-linking density of the polymer. FTIR analysis revealed that the addition of more bonds to DGEBA has minimal effect on the peak intensities of PC100 m-DGEBA. In contrast, the dissolution of bonds in DGEBA is more pronounced with the 90/10 and 10/90 hybrid blend modifiers. By harnessing the synergy between 90 percent PC and 10percent ABS with DEGBA (90/10 m-DGEBA), which reduces the effective reactive groups in m-DGEBA, the 90/10 hybrid blend demonstrates exceptional bond dissolution capabilities with DGEBA, as observed in FTIR studies. The closely aligned values of apparent cross-linking density observed for 90/10 and 10/90 m-DGEBA are supported by the nearly identical increase in cure reaction temperature, as shown in Figure 5.4(a). PC100 m-DGEBA, with its higher observed cross-linking density and reported brittle characteristics below -40°C, exhibits diminished fracture toughness.

5.5 Crack resistance capabilities of m-DGEBA under Cryo-conditions

The primary objective of this research is to evaluate how hybrid PC/ABS blend modifiers enhance the fracture toughness and crack resistance of DEGBA at both room temperature (RT) and cryogenic temperatures (CT). The toughness characteristics of the hybrid PC/ABS m-DGEBAs at RT and CT are illustrated in Figures 5.5(a) to 5.7(c). Figure 5.5(a) shows the fractured m-DEGBA specimens after Charpy impact testing at RT and CT. Special attention was given to maintaining the specimens at cryogenic temperatures during testing to account for the effects of low temperatures on their behavior, as reported in previous studies conducted by Yuxin et al. When examining the fractured m-DGEBA specimens at RT, similar trends to those of u-DEGBA can be observed. However, PC100 m-DEGBA exhibits multiple fractured failures, possibly due to the higher cross-linking density observed in Figure 5.6(b), resulting in increased brittleness of m-DGEBA. Therefore, PC100 m-DGEBA tends to demonstrate greater brittleness compared to u-DGEBA. On the other hand, the fracture characteristics of m-DGEBA differ from those of u-DGEBA when evaluated at CT. Fractured surfaces of u-DGEBA show clean, non-deviating crack paths, with cracks forming perpendicular to the direction of impact, indicating a low resistance to crack path deviation and confirming the dominant brittle nature of u-DGEBA. In the case of PC100 m-DGEBA, critical fractures and deviating crack paths are observed. The presence of multiple fractures can be attributed to the brittle nature of PC below -40°C. However, slight deviations in crack paths are still observed, potentially due to the inherent low degree of plasticity of DGEBA influenced by the PC modifier.

The addition of 10 percent ABS (a hybrid blend consisting of 90 percent one component and 10 percent another) to PC (polycarbonate) can greatly decrease its tendency to be brittle. As a result, when examining the fractured profiles using CT scans, it was observed that there was only one fractured specimen for the 90/10 m-DGEBA (a specific type of epoxy resin). This finding further validates the effectiveness of the 90/10 modifier in improving the fracture toughness properties of m-DGEBA during CT analysis.

Figure 5.5: (a) Impact samples retrieved after Charpy test.

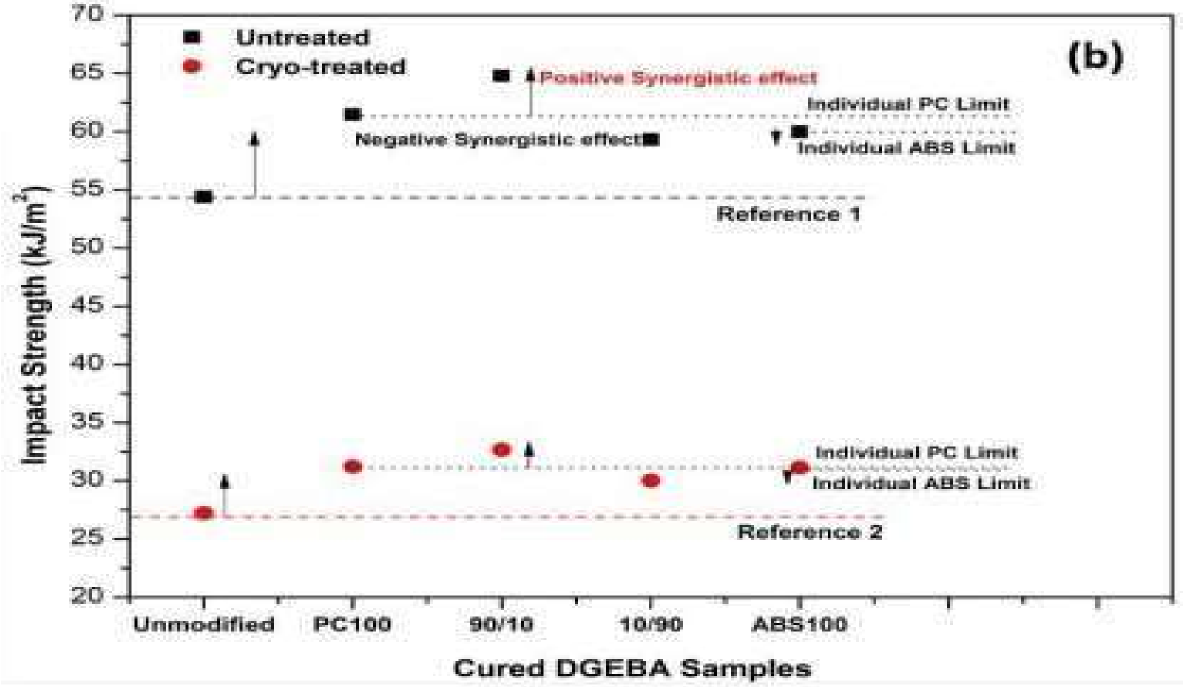


Figure 5.6: (a) Impact strength

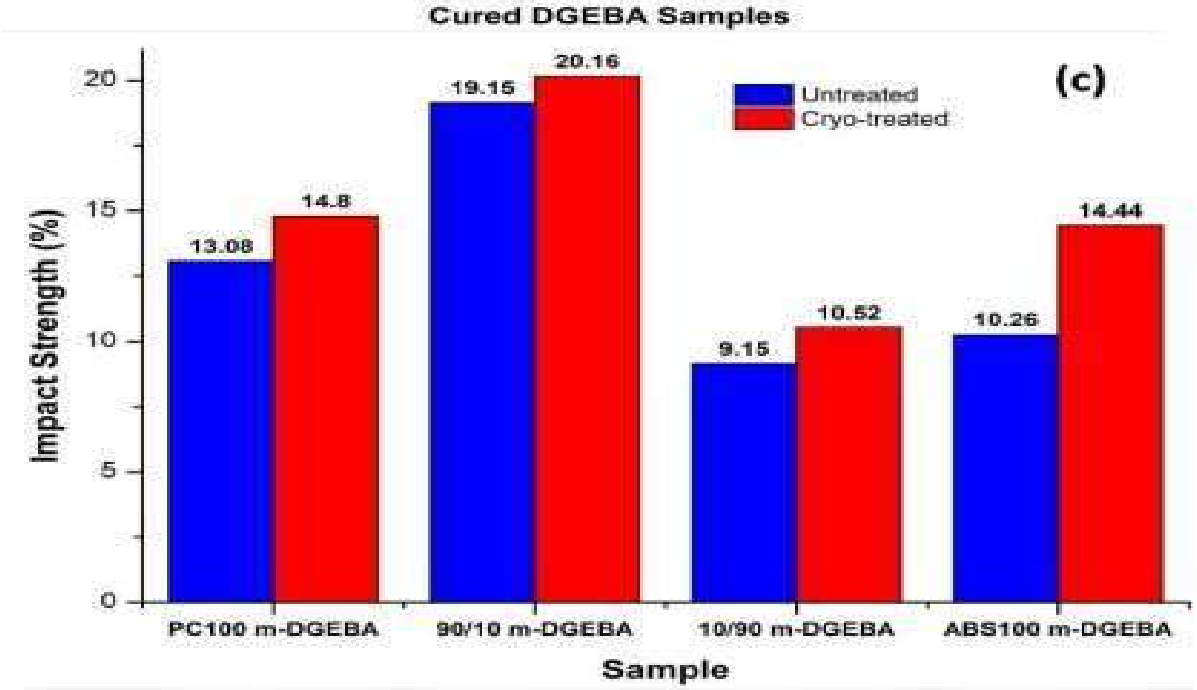


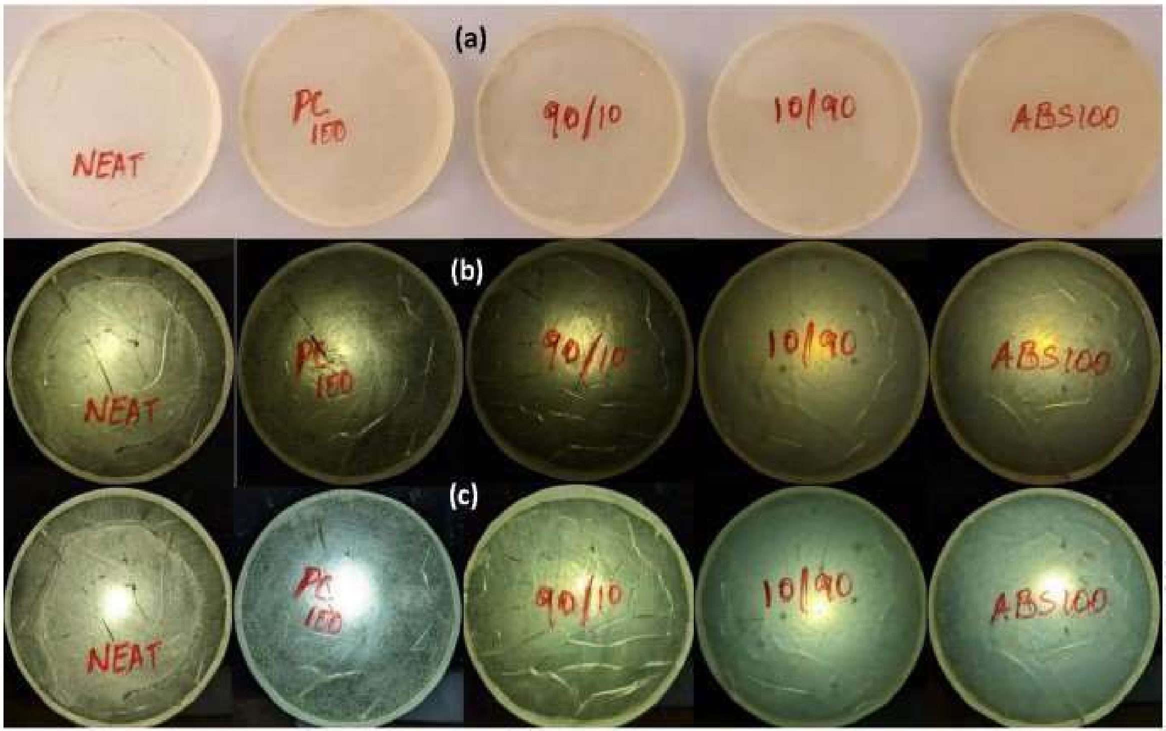
Figure 5.7: (C) percentage increase in impact strength observed for m-DGEBA before and after cryo-treatment

After cryo-treatment, changes were observed in the m-DGEBA (a type of epoxy resin) samples. These changes included the formation of cacks and deviation in crack paths, which could have a significant impact on the strength characteristics of m-DGEBA during CT. The samples containing 10/90 and ABS100 m-DGEBA showed multiple fractured samples, while PC100 m-DGEBA samples exhibited deviated crack paths. In contrast, the 90/10 m-DGEBA samples were different, with cracks showing interruptions in their paths and a lower concentration overall. This unique behavior could be attributed to the 90/10 modifier, which has the ability to resist cracking and increase the fracture toughness of m-DGEBA under CT conditions, while also enhancing its strength. The other modifiers also showed the ability to increase impact potency at both room temperature (RT) and CT, but the 90/10 m-DGEBA exhibited the best results. The synergistic effect of the 90/10 blend with DGEBA was evident in the improved strength capabilities depicted in Figure 7(b), surpassing the performance of PC100. The cooperative behavior of the 90/10 blend with DGEBA, as confirmed by DSC (differential scanning calorimetry), contributed to these results. On the other hand, the decrease in strength observed in the 10/90 and ABS100 samples confirms the negative synergistic effect of the hybrid blend with DEGBA. In this study, PC-dominant hybrid blends were found to provide the greatest increase in strength and fracture resistance for DGEBA under RT and CT conditions, making them more suitable modifiers compared to ABS-dominant o nes. In comparison to u-DGEBA, the 90/10 m-DGEBA showed a maximum strength enhancement of approximately 20 percent at both RT and CT. The presence of a lower concentration of ABS in the 90/10 blend resulted in a distributed droplet morphology within a continuous (DGEBA) and co-continuous (PC) phase. These ABS droplet portions acted as load damping zones, contributing to the enhanced strength characteristics of 90/10 m-DGEBA at RT and CT. However, when the size of the distributed droplets increased due to nucleation effects, the formation of voids in the morphology became more prominent, resulting in reduced performance in the ABS-dominant m-DGEBAs (ABS100 and 10/90). The longer gel time and decreased apparent cross-linking density could be the reasons for the lower impact strength observed in ABS100 m-DGEBA at both RT and CT. To further confirm the cryo-crack resistance mechanism, additional cryo-cycles were performed on m-DGEBA specimens, and the resulting cracks were analyzed in detail, as shown in Figure 8.

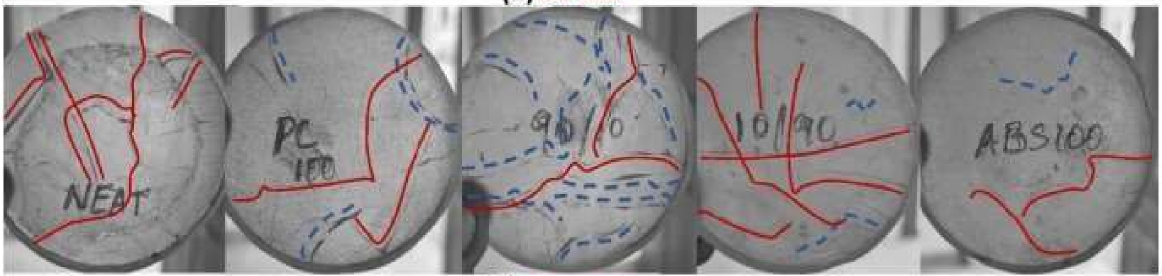
Figures 5.8(a) to (c) present a visual depiction of the different stages observed in the m-DGEBA samples throughout the cryo-cycling experiment. Specifically, Figures 8(b) and 8(c) illustrate the samples after the first and fifth cryo-cycles, re spectively. It is clear from Figure 5.8(b) that the specimens display cryo-cracking following the initial cryo-cycle and exhibit further growth by the end of the fifth cryo-cycle. The cracks demonstrate a deviation in their growth pattern and criticality, confirming that the dominant brittleness of the matrix has undergone a change.

Figures 5.8(d) and (e) provide high-resolution monochromatic images of the upper and lower surfaces of the specimens after the fifth cryo-cycling. These images are used to examine the crack paths and their criticality, allowing for a thorough analysis of the cryo-crack resistance capabilities of hybrid TP modifiers in DGEBA. In Figure 5.8(d) and (e), the red lines represent continuous crack profiles, while the blue lines represent discontinuous crack profiles. The yellow highlighted sections indicate the severity of cracks within the samples.

The analysis reveals that the u-DGEBA matrix exhibits fractures in a continuous pattern without any deviations in the crack paths. This aligns with the inherent brittleness of the u-DGEBA matrix, which lacks adequate fracture resistance properties. In the case of PC100



(d) TOP VIEW



(e) BOTTOM VIEW

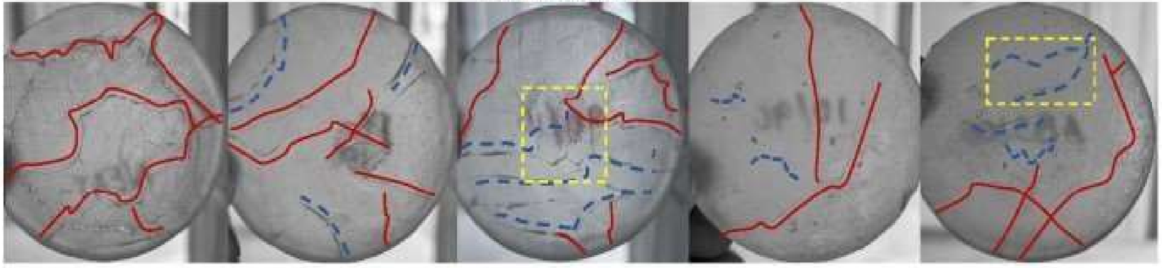


Figure 5.8: Specimens (a) for cryo-treatment, (b) after 1 cryo-cycling, (c) after 5 cryo-cycling, (d) top view after 5 cryo-cycling and (e) bottom view after 5 cryo-cycling for m-DEGBAs.

m-DGEBA, there are minimal deviations in crack paths, although fewer discontinuities are observed. This can be attributed to the brittleness of the PC component at temperatures below -40°C.

ABS100 m-DGEBA displays smoother crack paths with fewer discontinuities compared to u-DGEBA. However, this indicates that ABS100 m-DGEBA may not be suitable for cryo- genic applications. On the other hand, the 90/10 hybrid PC/ABS blend modifier exhibits the most significant improvement in cryo-crack resistance properties, likely due to a reduced cross- linking density. This is supported by the presence of numerous discontinuous crack paths. The cooperative behavior of molecules in the 90/10 m-DGEBA, as evidenced by DSC results, combined with the inherent ductility of DGEBA, contributes to its enhanced crack resistance capabilities. The higher cooperation of molecules in 90/10 m-DGEBA allows the modified ma- trix to effectively handle the transfer of thermal stresses, resulting in lower stress concentrations and limited crack initiation energy. The observed crack path deviations and discontinuities are a consequence of ductile tearing and crack path deviation occurring within plastic zones dispersed throughout the brittle matrix.

In contrast, the crack paths of 10/90 m-DGEBA resemble those of ABS100 m-DGEBA, but with fewer discontinuities. The presence of phase-inverted morphologies, commonly ob- served in ABS-dominant concentrations, is responsible for this behavior. Higher ABS concen- tration leads to nucleation and the formation of larger droplets in the morphology, which, in turn, results in the formation of voids and discontinuities within the matrix. These voids serve as crack initiation zones and provide pathways for crack propagation.

Based on these findings, the 90/10 hybrid blend demonstrates sufficient cryo-crack resistance characteristics in DGEBA, making it suitable for the development of high-performance hybrid polymer composites in space and cryogenic applications.

Chapter 6

CONCLUSION

This study provides insights into the synergistic effect of the hybrid PC/ABS modifier in enhancing the fracture resistance properties of the DGEBA matrix. The incorporation of the 90/10 blend chemically modifies the DGEBA matrix by reducing the effective reaction groups through melt-mixing at 180°C. The dispersed 90/10 phase exhibits strong cooperation with the DGEBA matrix, resulting in a synergistic increase in strength at both room temperature and cryogenic conditions. The impact strength of the modified m-DGEBA matrix is enhanced by up to 20 percent at RT and CT, while the curing characteristics show a longer peak curing time, making the modified resins more suitable for specific processes like RIM (Reaction Injection Molding). Moreover, the viscosity increase of the 90/10 m-DGEBA is the lowest among other modified resins, ensuring optimal viscosity range for infusion applications. These modifications allow for longer infusion times and controlled viscosity, facilitating the use of complex designs and reducing the presence of voids in the prepared composites. The inherent plastic zones within the predominantly brittle DGEBA matrix contribute to the deviation of crack paths and higher fracture energies, resulting in cryo-toughening. The 90/10 hybrid blend m-DGEBA exhibits enhanced toughening properties, including increased resistance to crack propagation and induced discontinuities in crack paths. The higher reaction rate, reduced cross-linking density, increased fracture toughness, and improved cryo-crack resistance of the 90/10 m-DGEBA confirm the efficacy of melt-mixing in synergistically modifying DGEBA.

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