



**EFFECT OF CARBON FIBER CONTENT ON THE  
MECHANICAL AND TRIBOLOGICAL  
BEHAVIORS OF POLYURETHANE FOAM  
MATRIX COMPOSITES**

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**EFFECT OF CARBON FIBER CONTENT ON THE MECHANICAL AND  
TRIBOLOGICAL BEHAVIORS OF POLYURETHANE FOAM MATRIX  
COMPOSITES**

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Wasim Amhemed Gliza KHALIFA

## **ABSTRACT**

**M. Sc. Thesis**

### **EFFECT OF CARBON FIBER CONTENT ON THE MECHANICAL AND TRIBOLOGICAL BEHAVIORS OF POLYURETHANE FOAM MATRIX COMPOSITES**

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In this study, the effect of short carbon fibers (SCFs) in different ratios (0.5%, 1% and 1.5%) on the mechanical and tribological properties of polyurethane foam (PU) composites was investigated. The samples were produced via hand lay-up process. A 3-point bending test was applied to examine the mechanical properties of pure polyurethane (PU) foam and composites (SCFs-PU). In addition, the wear resistance properties of the samples were applied under 5N load. The data obtained in this study reveal that the flexural strength of the PU foam-based composite containing 0.5% by weight SCFs is approximately 26.59% higher than the sample containing 1.5% by weight SCF. Therefore, it can be said that adding more SCF to the PU matrix may cause a decrease in the flexural properties of SCFs-PU foam composites. In addition, adding 1.5% by weight SCF to pure polyurethane improved the abrasion resistance property by an average of 43%. As a result, it was determined that the mechanical

properties of SCF-PU composites decreased as the SCFs content added to the PU foam material increased. However, the tribological properties of composites are significantly improved with the addition of SCFs.

**Keywords** : Short carbon fibers, polyurethane, flexural strength, wear.

**Science Code** : 91417

## ÖZET

Yüksek Lisans Tezi

### KARBON ELYAF İÇERİĞİNİN POLİÜRETAN KÖPÜK MATRİSLİ KOMPOZİTLERİN MEKANİK VE TRIBOLOJİK DAVRANIŞLARINA ETKİSİ

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Bu çalışma, değişik oranlarda (%0,5, %1 ve %1,5) kısa karbon elyafların (SCFs), poliüretan köpük (PU) kompozitlerin mekanik ve tribolojik özelliklerine etkisi incelenmeye çalışılmıştır. Numuneler el yatırması yöntemiyle imal edilmiştir. Saf poliüretan (PU) köpük ve kompozitlerin (SCFs-PU) mekanik özelliklerini incelemek için 3 nokta eğme testi uygulanmıştır. Ayrıca, numunelerin aşınma direnci özellikleri 5N yük altında uygulanmıştır. Bu çalışmada elde edilen veriler, ağırlıkça %0,5 SCFs ihtiva eden PU köpük bazlı kompozitin eğme mukavemetinin, ağırlıkça %1,5 SCF içeren numuneden takribi %26,59 daha yüksek olduğunu ortaya koymaktadır. Bu nedenle, PU matrise daha fazla miktarda SCF eklenmesinin, SCFs-PU köpük kompozitlerinin eğme özelliklerinde azalmaya sebep olabileceği söylenebilmektedir. Bunun yanısıra, saf poliüretana ağırlıkça %1,5 SCF ilave edilmesi, aşınma direnci özelliğini ortalama %43 oranında iyileştirmiştir. Sonuç olarak, PU köpük malzemeye

eklenen SCFs içeriđi fazlařtıđı SCF-PU kompozitlerinin mekanik zelliklerinin dıřtıđu tespit edilmiřtir. Bununla birlikte, SCFs ilavesi ile kompozitlerin tribolojik zellikleri nemli lde geliřmektedir.

**Anahtar Szckler** : Kırpılmıř karbon elyaf, poliretan, eđme mukavemeti, ařınma.

**Bilim Kodu** : 91417



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## **SYMBOLS AND ABBREVIATIONS INDEX**

### **SYMBOLS**

A : alkaline  
O : oxygen  
S : silicon  
mm : milimeter  
wt : weight

### **ABBREVIATIONS**

ABS : Acronitrile Butadiene Styrene  
CF : Carbon Fibers  
FRP : Fiber Reinforced Plastic  
HDPE : High-Density Polyethylene  
PE : Polyethylene  
PP : Polypropylene  
PU : Polyurethane  
RTM : Resin Transfer Method  
SEM : Scanning Electron Microscope

## **PART 1**

### **INTRODUCTION**

Composite materials have superior properties compared to the components that make them up. Composite materials have high modulus of elasticity, high specific strength and high toughness. More recently, they have had high strength-to-weight ratios. Fiber-added resin composites have gained important usage areas in applications where lightness is critical such as space and aircraft. Watercraft such as yachts and boats, which were made of wood or metal until yesterday, are now being replaced by composites made of polyester-glass fiber. Boats made of composite material are long-lasting and are preferred more than wooden or metal ones because they are lighter and faster. Recently, many components in the manufacturing industry are made of composite materials [1].

Within a few years, polyurethane (PU) and polystyrene foams have become powerful performance platforms to offer a variety of products in the flotation and packaging industries. Then furniture, food, construction, medicine, sports, automotive, aerospace, electronics, etc. started to be used in the sectors. Polymer foams are defined as materials containing gas voids surrounded by a dense polymer matrix, produced by the expansion of gaseous or liquid foamers that can turn into volatile gases. Polymer foams generally consist of at least two phases. The first of these is the solid polymeric matrix, and the other is the gas phase obtained with the foamer. While the voids in the polymer reduce the density of the material, they provide less raw material usage [2].

Polyurethane (PU) based composites are thermosetting polymer composite types that have a wide range of application areas including biomedical, aeronautical, sports, industries, and automotive, due to higher properties of chemical stability, specific strength, low relative density, strong, good stiffness, and outrageous wear resistance [3–7]. Bulk (rigid) or foam type PU matrixed composites are most popularly used as



construction material, because of their elevated durability, great strength to weight ratios, and inflated corrosion resistance [6].

In the literature, because PU materials have high elasticity, toughness and fast curing properties, today polyurethane matrix composites increase their application areas in industries more than ever, and it also mentions that it is responsible for some of the remedies in modern science. For this reason, the number of studies on polyurethane (PU) foam-based composite has greatly increased [6]. Despite the enormous applications of PU, its low mechanical properties have hindered its further applications in automobile body manufacturing and aerospace structures. For this reason, scientists are trying to improve the mechanical properties of polyurethane by adding organic and inorganic fillers to polyurethane matrices [6]. Many types of reinforcement have been used to improve the mechanical and physical capabilities of PU [6,8–10]. Carbon fibers are the most widely used inorganic fibers due to their low density, excellent chemical stability, high thermal resistance and good mechanical properties. For this reason, recently, carbon fiber-based (CF-based) composites offer a better alternative for a wide range of applications [6,11]. Previous studies suggest that shorter fibers do not exert a significant reinforcing effect on the composite due to the smaller contact area. However, the results obtained when long fibers, polyurethane agents and fillers were mixed were not good. Therefore, studies have shown that the optimum average length of carbon fibers reinforced with polyurethane matrix is 3-12 mm [12]. Also, in many cases, short carbon fibers have a stronger reaction on composites than very short or long carbon fibers [9].

There are some studies on chopped carbon fibers and their impacts on the mechanical properties of PU matrixed composites. In the study of Yakushin et al. [9], the result shows that the compression strength of the polyurethane foam was boosted by 20 % with the addition of 4 wt. % SCFs. Nevertheless, a significant decrease in the elongation at the break of the PU foams was ascertained as the carbon fiber subject matter develop to 8 wt. %. the other study [13], the effects of different kinds of fibers and fiber contents of 10 % to 20 % on the tensile max strength and bending performance of the polyurethane matrix composites were investigate. Accordingly test outcomes, higher flexural bending strength and higher energy absorption were

obtained for 20 % carbon fiber (CF) reinforced composites compared from the same content of Jute felt, Jute tablets, and Glass fiber reinforced composites. For polyurethane foamed CFRP composite tubes, the max force and doorstep force for PU foam-based CFRP composite tubes increased by approximately 132% over the pure CFRP polymer observed by Tamer A Sebaey et al. [14]. Suliman et al. investigated the effect of hardener on the mechanical properties of carbon fiber added phenolic resin composites [4]. The results revealed that composites containing 15% hardener (hexamine) exhibit increases in flexural strength due to the amount of hardener that improves the cross-links between phenolic resin and carbon fibers.

Past studies also reveal that few publications have been made on the effect of short carbon fiber content on the abrasion resistance properties of polyurethane foam-based composites. The study of Li and Cai [15] revealed that carbon fiber reinforced PP composite (CF/PP) showed superior tribological properties compared to pure PP. In another study, the wear rate and coefficient of friction of epoxy matrix composites were significantly reduced with increasing chopped carbon fiber content [16]. Zhao et al.[17], tested the tensile strength, abrasion and friction properties of rigid type polyurethane composite reinforced with carbon fiber. The test results revealed that chemically surface-treated carbon fibers improved the wear properties of PU composites. In addition, the tensile strength is increased by the addition of carbon fibers. In addition, the effect of different weight fractions of short carbon fiber on the efficiency of increasing the tribology resistance of high density polyethylene (HDPE) was investigated by Akgül et al. [18]. The result of this study indicates 10 by weight. % SCF composites show superior wear efficiency under SBF fluid conditions. The wear behavior of CF/PEEK under the influence of seawater lubrication was studied by Chen et al [19]. The result of this study indicates 10 by weight. % SCF composites show superior wear efficiency under SBF fluid conditions. The wear behavior of CF/PEEK under the influence of seawater lubrication was studied by Chen et al. In another study [20], the wear properties of using different synthetic and natural fibers of carbon, PU, jute, sugar cane, glass and banana were tested. According to the analysis results, the tribological properties of foam type sandwich materials improved when foam and natural fiber materials were combined.

Therefore, although polymer-based composites are available in a wide variety of industries and technologies, this does not diminish the discovery of new polymer materials. Previous studies have focused on carbon fiber reinforced rigid polyurethane-based composites. However, within the scope of this research, the effects of different SCF contents (1.5 wt%, 1% wt% and 0.5 wt%) on SCFs-PU foam based composites were investigated. Flexural strength and abrasion resistance tests were carried out to analyze the mechanical (flexural strength) and wear behavior of SCFs-PU foam-based composites. In addition, the morphology of the fractured and worn surfaces of the pure polyurethane polymer foam and SCF-PU composites was describe by a scanning electron microscope (SEM).

## PART 2

### COMPOSITE MATERIALS

Since the second half of the 20th century, the rapid development of technique has accelerated the developments in materials and materials science, which is the basic input of the industry. With the innovations of the age, scientists have chosen the way to produce more suitable materials, both economically and technically, in accordance with the conditions and demands of the day, in parallel with the development of science, from the qualities of existing materials. " *Composite material* " refers to new materials formed by the combination of two or more materials that do not mix with each other. Most of the materials in nature consist of compound structured substances called as "composite" [1].

Composites can be classified in different ways according to matrix and reinforcement material. In the classification made according to the matrix material: polymer matrix composites, ceramic matrix composites and metal matrix composites are classified into three main groups. Classification according to the reinforcement material structure is divided into fiber-reinforced composites, particle reinforced composites, layered composites and mixed (hybrid) composites as shown in Figure 2.1 [21]. In some studies, a classification is made in terms of production method, and accordingly, there are two separate groups of composite structures as open molding and closed molding [22].

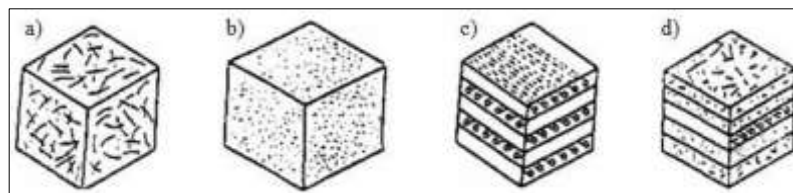


Figure 2.1. Classification of composites according to the reinforcing material structure: a) fiber reinforced, b) particle reinforced, c) layered, d) mixed (hybrid).

## 2.1. COMPOSITE MATERIALS WITH POLYMER MATRIX

It is a type of composite in which the matrix structure surrounding the reinforcement element is a polymer-based material. Polymers are compound structures obtained by the repetition of small molecular groups called monomers. The number of repetitions can be between  $10^3$  and  $10^6$  [23]. While the matrix material of polymer composites can be various polymers, the reinforcement materials can be carbon, glass, aramid, metallic, ceramic-based materials. Polymer matrix composites are among the most important structural engineering materials. This is not only due to the development of high-performance fibers such as aramid and carbon but also due to the development of new polymer matrices. The mechanical properties of polymers are generally insufficient for engineering applications. Especially their strength and rigidity are lower than ceramics and metals. For this reason, there are many studies on improving the mechanical properties of polymer materials with reinforcement elements. As a result, polymer matrix composites that can be easily produced with improved properties have emerged. Polymer matrix composites are more widely used than metals and ceramic matrix composites. Since high temperatures and pressure are not required to produce polymer matrix composites, parts with complex shapes are also easy to manufacture.

Problems related to the deterioration of the reinforcement during the production phase are not a problem since polymer composites are produced at low temperatures. In addition, the equipment required to produce such composites is simpler. As a result, the production and development of polymer matrix composites have taken place rapidly and have begun to be preferred for most structural applications [24].

Polymer matrix composites have many advantages such as making fiber combinations for optimum strength, lightness and rigidity, high corrosion resistance, improved fatigue life, low assembly cost because of using fewer parts and fasteners. Specific strength (strength/density) and specific modulus (modulus/density) values of high-strength fibers (especially carbon) are quite high compared to equivalent metallic alloys used in aerospace applications. Accordingly, a good degree of weight gain, i.e., lightness, can result in improvement in performance, longer range, higher

carrying capacity and fuel savings. Corrosion resistance is important in aircraft and marine vehicles, and in this respect, composites can provide savings. For example, in a situation where carbon fibers are directly in contact with the metal surface, galvanic corrosion occurs in aluminum, but the electrical insulation layer glass fibers added to the interface eliminates this problem. On the other hand, the fatigue life of composite materials is better than equivalent metal materials [25].

In addition to these advantages of polymer matrix composites, disadvantages are high production and assembly costs, high raw material cost, negative effects of temperature and humidity, low strength in case of out-of-plane loading in the parts where the matrix carries the main loads (for this reason, they should not be used in cases where the loading path is complex), susceptibility to delamination or delamination, impact damage, and repair are much more difficult compared to metals [25].

Polymer matrix composites are used in a wide range of areas, from aerospace, aerospace, automotive and construction industries to sports equipment. The usage area of glass fiber reinforced composite materials is quite wide. In the chemical industry, materials such as reaction vessels (with or without pressure), tanks, waste material and process pipes are mostly produced from glass fiber reinforced polyester resin composites. Walkways made of glass fiber composites and many structures on the sea have been manufactured with the pultrusion technique. Aramid and glass fiber reinforced polymer matrix composites are used in the floors and warehouses of aircraft used in civil aviation. Also, composite materials with polymer matrix are used in the coatings and doors of the aircraft. Some important parts of small airplanes and helicopters are produced from aramid fiber-reinforced composites. Aramid fibers can replace glass fibers in many applications but are more costly. Where performance is more important than costs, such as special boots and racing boots, aramid fiber can be used instead of glass fiber. Drumsticks (drumsticks) are produced as pultrusion filled aramid and thermoplastic coated. These drumsticks are lighter, less warped, longer-lasting and more durable than wooden ones. The use of polymer matrix composite materials in the military is spreading from helmets to rocket covers. It is recommended to use aramid fibers in components that contain shear, compression, or transverse tensile loads, it is recommended to use another fiber besides aramid fiber

in such components. Polymer composites are widely used in military and commercial helicopters for vehicle light-weighting [24].

## **2.2. STRENGTH COMPONENTS OF POLYMER MATRIX COMPOSITE MATERIALS**

The mechanical and physical properties of composite materials depend on various parameters. These parameters are type of matrix and reinforcement material, the mixing ratio of matrix and reinforcement material, direction of reinforcement material, the interface of matrix and reinforcement material, dimensions, and homogeneity within the composite system. For this reason, it is necessary to master these parameters to know how the strength of the composite will be affected in case of any loading [26].

### **2.2.1. Fiber/Resin Volumetric Ratio**

Increasing the amount of reinforcement material of the composite also increases its strength. The most distinctive features of polymer composites are the specific Young's modulus and high specific strength (strength/specific gravity). For example, the specific strength of steels is 110 Nm/gr, compared to 700 Nm/gr for carbon-epoxy, 620 Nm/gr for Glass fiber polyester, and 886 Nm/gr for Kevlar-epoxy [23].

### **2.2.2. Fiber Direction**

Continuous fibers used in composite materials can be positioned in different directions. These directions are divided into three main groups:

- Unidirectional ( $0^\circ$ ), all fibers are arranged in a single direction and direction. Composites made of unidirectional fibers show high resistance against loading in the fiber direction while exhibiting low resistance against forces perpendicular to the fiber direction. Such materials can be characterized as anisotropic.
- Bidirectional ( $0^\circ/90^\circ$ ), some of the fibers are positioned at  $90^\circ$  while the other part is positioned at  $0^\circ$ . Bidirectional composites are produced in two different forms; They are produced either by positioning the fibers in perpendicular

directions during production or by using knitted woven fibers. Such composites exhibit more isotropic properties. The strength of composites of this structure is high in both directions.

- The fibers can be positioned in different directions such as  $0^\circ/60^\circ$  or  $0^\circ/45^\circ$ . These composites show higher isotropic properties than the composites in the  $0^\circ/90^\circ$  array.

### **2.2.3. Fiber-Matrix Interface**

The properties and structure of the fiber-matrix interface play an important role in the mechanical properties of the composite. The strength of the composite material is related to the interfacial shear planes. The gaps in the matrix structure of the material will cause the interface to be weak and accordingly the load transfer mechanism will not work as desired. Again, the presence of different chemicals or moisture at the interface negatively affects the interface properties.

### **2.2.4. Fiber Diameter and Aspect Ratio**

The fiber diameter has a great influence on the strength of the material. It is more difficult for a large amount of fibers with small diameters to be wetted evenly and homogeneously by the resin. The success of the concept of wettability, in which the resin viscosity and the surface energy of the liquid play a critical role, is essential for achieving the desired high mechanical properties. The successful distribution of the force applied to the material depends on the interface formation and its effectiveness. As the diameter of the fiber increases, decreases are observed in the mechanical properties, on the contrary, as the fiber diameter decreases, the mechanical properties increase. This is due to the high specific surface area value added by the small diameter reinforcement. An increase in the surface area of the reinforcement means an increase in the interface. If the length/diameter ratio of the reinforcement material increases, the force applied to the system is transmitted to larger areas and damped. Under certain conditions, the fiber's high length/diameter ratio provides higher strength properties [27].



### **2.2.5. Production method and microstructure defects**

The production method of the composite should be determined according to parameters such as reinforcement material, matrix material, place of use of the composite, and structural properties. Failure of the composite product may occur due to errors in production parameters. Temperature and pressure parameters directly affect the performance of the curing composite. In order not to encounter production related errors such as non-homogeneous wetting, insufficient wetting, and insufficient vacuum, the parameters must be determined before production. The porosity (porosity) and foreign residues in the structure of the composite material have a great effect on the mechanical properties of the composites. Especially the high number of pores facilitates the formation of cracks in the composite structure and the propagation of this crack. In this case, it means that the strength of the material decreases.

## PART 3

### TYPES OF MATRIXES IN POLYMER COMPOSITES

The selection of the types of reinforcement and matrix materials that make up the composite, the production method, the strength and structural properties required from the composite for use of the composite are directly related. The desired success of the composite depends on the appropriate selection of the matrix and reinforcement element. The main task of the matrix; reinforcement the corrosion material to isolate from external influences such as oxidation, the applied force to convey the reinforcing material is to distribute and protect the loads directly. For this reason, the mechanical properties of the material such as impact and rupture are very important in the selection of matrix material. Since most of the matrix materials are in liquid form, their viscosity should not be ignored. The curing (physical and chemical transformation) time of the matrix material, the curing environment, and the curing temperature are important factors that play a role in the selection of the matrix. The materials used as polymer matrices are divided into two as thermoset and thermoplastic. Their molecular structures are shown schematically in Figure 3.1 [28].

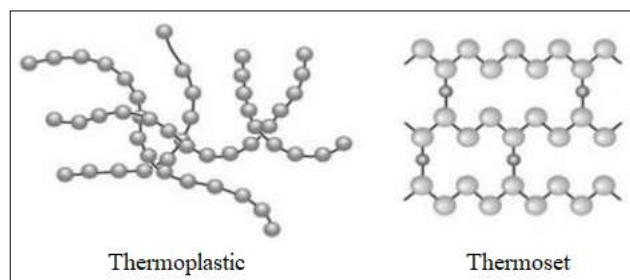


Figure 3.1. Molecular structures of thermoplastic and thermoset.

#### 3.1. THERMOPLASTIC MATRICES

Thermoplastics consist of long hydrocarbon molecules linked by Van der Waals bonds. Due to the weak bond strength, when thermoplastics are heated, they first

soften and then melt. When they are cooled, they solidify again [23]. When thermoplastics are melted or solidified, there is no change in their chemical properties, only a physical change. Thermoplastic materials are recyclable materials that can be reused. The forming operations of thermoplastic matrices are very short in relation to their softening time. For example, the injection molding process is completed in a few seconds to a few minutes [22]. For this reason, they are prone to mass production and a high amount of parts production. However, it is necessary to have the necessary technical infrastructure and equipment to be able to produce and apply the necessary temperature and pressure for their shaping. Production equipment is costly and complex. In some cases, it may be necessary to go through more than one production operation in order to improve their structural properties [29].

The most used polymers that make up the thermoplastic matrix group are: Acronitrile Butadiene Styrene (ABS), Acrylic, Poly Tetra Fluor Ethylene (PTFE-Teflon), Polyethylene Derivatives (PE), Poly Amide Derivatives (PA), Poly Vinyl Chloride (PVC), Polypropylene (PP) [30]. Although thermoplastic resins have many superior properties, thermosets are not used in composite production for reasons such as processing under high heat and pressure, sensitivity to solvents of some amorphous thermoplastics due to their high viscosity, and difficulty in manufacturing fiber-reinforced composites.

### **3.2. THERMOSET MATRIXES**

Thermoset materials, unlike thermoplastics, chemical changes occur in their structures when heated. For this reason, they cannot regain their former shape. In general, they are the most used matrix materials in the production of composite materials. Due to the good adhesion of thermosets and their resistance to chemicals, their usage areas are increasing. Thermoset materials are linked by covalent bonds that is the most important difference between thermoplastics and thermosets. For this reason, thermosets exhibit more rigid and less ductile behavior compared to thermoplastics [31].

### **3.2.1. Epoxy Resins**

Depending on the production method and molar mass, epoxy resins are obtained as solid or liquid polymers. Epoxy resins are generally preferred in the production of polymeric composites. Epoxy resins are plastic materials with high bonding strength and are in the thermoset polymer class. They are highly preferred as matrix phase. Epoxy resins are low viscosity resins. They can often be molded under pressure and at room temperature and do not produce by-products. Resins that can be used at low pressures are commonly preferred for glass fiber reinforced plastic (FRP) molding [32]. Epoxy matrix has many advantages such as high adhesion, rapid hardening in wide temperature ranges, and being able to be used in a short time after application. They are resistant to most chemicals compared to other resins. They are resistant to moisture and corrosion, have high mechanical properties. The shrinkage tendency of epoxy resins is low during the curing, so the formation of internal stress is minimized.

### **3.2.2. Polyurethanes**

Polyurethanes are condensation polymers. While these polymers are forming, cascading and slow reactions occur. Polyurethanes are obtained from the reaction of multi-hydroxyl compounds with isocyanate (Figure 3.2). Polyurethanes are produced from one or more polyhydroxyl compounds and one or more diisocyanates or polyisocyanates. The raw materials are obtained from petroleum in a few steps and thus have a large commercial volume. In addition, studies on the physical and chemical recovery of polyurethane wastes have been carried out recently [33].

In the mechanism of the polyurethane reaction, a proton from the H-active compound is transferred to the nitrogen atom in the isocyanate. These reactions are autocatalytic. The free electron pairs on the nitrogen in the urethane group act as or catalyze the catalytic species. In the production of polyurethane, N,N-dimethyl cyclohexyl amine, N,N-dimethylpiperazine, N,N'-dimethyl ethanoamine, diazabicyclo octane (DABCO), N,N,N',N'-tetramethyl butane diamine, dibutyl tin dilaurate, organic titanium compounds, bismuth, lead catalysts are used [33].

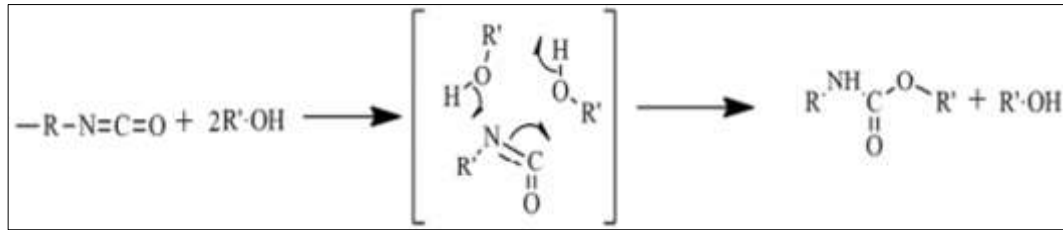


Figure 3.2. Polyurethane reaction mechanism [33].

Polyol groups determine the properties of polyurethane. These properties are primarily selected according to application temperature and elasticity. The flexibility or rigidity of polyurethanes depends on the bond length of the polyols, the aromatic or aliphatic structure, the ester or ether groups, and the functionality of the hydroxyl groups. Polyurethanes can show similar properties even if they are made from completely different raw materials. Long-chain polyols - polyester polyols, polyether polyols, polycaprolactones, polycarbonate polyols - are used in the production of flexible polyurethanes. They are also used in the preparation of flexible foams, elastomers, cellular elastomers, or solid foams [33].

Thanks to the very good adhesion of polyurethanes, it is easy to add different additives and fillers into it. The combustion behavior, thermal properties and mechanical properties of the material change with the added additives and fillers. In addition, the material can be obtained in a porous structure by adding blowing agents to the medium. In this case, polyurethane foam materials that can reach up to tens of times their initial volume emerge [34].

### 3.2.2.1. Polyurethane Foams

Foams have been used for a long time as a useful product to make our lives better. II. Before World War II, the low-density foam was obtained and then it began to be used in civilian applications. Within a few years, polyurethane (PU) and polystyrene foams have become powerful performance platforms to offer a variety of products in the flotation and packaging industries. Then furniture, food, construction, medicine, sports, automotive, aerospace, electronics, etc. started to be used in the sectors.

Polymer foams are defined as materials containing gas voids surrounded by a dense polymer matrix, produced by the expansion of gaseous or liquid foamers that can turn into volatile gases. Polymer foams generally consist of at least two phases. The first of these is the solid polymeric matrix, and the other is the gas phase obtained with the foamer. While the voids in the polymer reduce the density of the material, they provide less raw material usage [2].

The most preferred types of foam polymers are polyurethane (PU), polystyrene (PS), polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), and polycarbonate (PC). Approximately 70-80% of the total polymer foam production is based on polyurethane (Figure 3.3), polystyrene and polyvinyl chloride. Total polyurethane foam consumption is more than 50% in this share. In recent years, the use of polypropylene foam material has increased compared to polyethylene and polystyrene polymers. These materials show higher impact resistance, higher melting temperature and better thermal stability [35].



Figure 3.3. Example of polyurethane foam.

Rigid plastic foams are used as structural materials in a variety of forms and densities. Low-density foams are mostly used as core materials in sandwich structures, while high-density foams are used as the main load-bearing materials in structures designed for low-stress applications [36].

Polyurethane (PU) foams can be rigid or flexible. While rigid foams are used for thermal insulation, flexible foams are used as cushioning materials in furniture, transport, and packaging applications [37].

Polyurethane foams are obtained as a result of mixing suitable polyol and isocyanate components in the presence of blowing agents under appropriate conditions and proportions. The stage that the material is prepared to swell after the mixing process passes until the reaction starts is called the creaming time. Currently, the mixture changes from dark brown to creamy. When the crosslinks and urethane network begin to form with the onset of the reaction, the gelation time and the time elapsed until the sticky property of the material ends and its surface becomes non-stick after the swelling is over is also called the touch time. The gases released at the beginning of the reaction or physically applied from the outside provide the formation of foam material with millions of small cells. These materials form cross-links depending on the materials used and depending on the high or low level of these bonds, they become open or closed-celled. The rigidity of rigid polyurethane foam materials can vary depending on the material that makes up their components. In the polyurethane structure, polyols form the soft segment, while diisocyanates form the hard segments [38,39].

Polyurethane foams are generally classified as flexible, semi-rigid or rigid depending on their mechanical performance and core density. The applications of these foams are largely dependent on the cellular structure of the resulting foam [40].

#### **3.2.2.2. Components of Polyurethane Foams**

##### **Polyols**

For rigid polyurethane foams, polyols are liquid oligomers or polymeric compounds with at least two hydroxyl groups. Such polyols include polyether polyols, polyester polyols, hydroxyl-terminated polyolefins, and hydroxyl-containing vegetable oils [41]. Polyol systems used in the production of polyurethane contain chemicals such

as chain extenders, catalysts, embossing agents, surfactants, flame retardants. These substances are added to the polyol system either before or during application. The advantages of polyether polyols over polyester polyols are:

- Equivalent weight can be varied widely.
- Viscosities are lower than those of polyesters.
- Production costs are cheaper than aliphatic polyesters.
- The foams formed are resistant to hydrolysis.
- The functionality and equivalent weight of polyether polyols can vary widely.

This is a major advantage of polyether polyols over polyester polyols and therefore polyether polyols are widely used to produce various polyurethanes such as elastomers, coatings, adhesives, sealants, resins, flexible, semi-flexible and rigid foams [41].

### **Isocyanates**

Isocyanates, especially polyisocyanates, are identified by polyurethane chemistry. Although isocyanates are involved in many reactions, the most important of these is usually the polymerization of polyurethane and its relationship with its structure. Isocyanates represent a class of chemicals characterized by high reactivity and versatility. The combination of these positive properties has contributed greatly to the wide application of polyurethane materials. The most important chemical feature of isocyanate chemistry is its reactivity with molecules with active hydrogen. Such active hydrogens are typically found on molecules with alcohol and amine functionality as well as water [42]. Aromatic polyisocyanates are used in the preparation of isocyanate-based foams. Aliphatic isocyanates were not used as foaming reactions require high reactivity. Aliphatic polyisocyanates react slowly with OH groups. The main polyisocyanates used are toluene diisocyanate (TDI) and diphenylmethane diisocyanate (MDI) of the oligomeric type. The chemical structures of TDI and MDI are shown in Figure 3.4 and Figure 3.5, respectively [41].



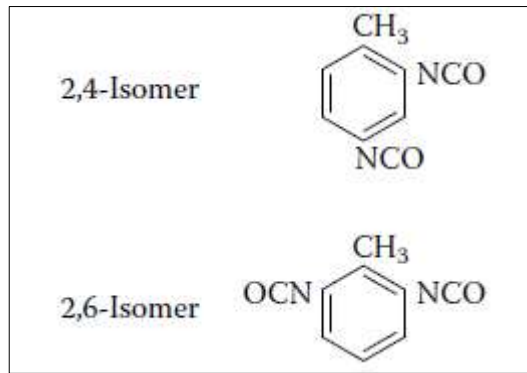


Figure 3.4. Chemical structure of toluene diisocyanate (TDI) [41].

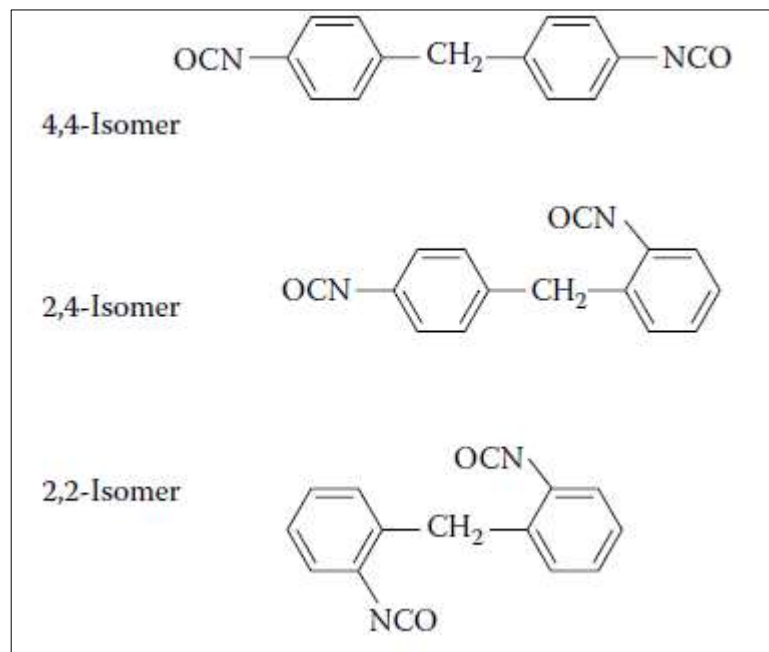


Figure 3.5. Chemical structure of diphenylmethane diisocyanate (MDI) [41].

## **PART 4**

### **REINFORCEMENTS IN POLYMER COMPOSITES**

General classification of reinforcement elements used in polymer composite materials; It is made under three headings as continuous fibers, discontinuous fibers and particles. Considering that the discontinuous fibers are derived from the shearing or fragmentation of the continuous fibers, it is understood that the basis of the reinforcement elements is composed of particles and fibers. Particle-reinforced composites are easier to produce than fiber-reinforced composites, but they are weaker in terms of strength. The biggest limitation in the incorporation of particles into the composite structure is that the particles are difficult to distribute homogeneously in relation to their size and to be wetted by the matrix. As long as the particles are distributed evenly and homogeneously in the composite, the isotropic property of the structure increases. It is the feature that gives the actual strength to the bonding material system at the interface of the reinforcement and the matrix element. Particles added to the composite system can also be named as filling material. Many fiber types are used as a reinforcement element in applications. Fibers can be classified according to their lengths as long, short or continuous, according to their stiffness and strength as low, medium and high, according to their very high modulus or according to their inorganic or organic chemical components. The most well-known inorganic fibers are carbon, glass and aramid. Fiber selection can be made according to the effectiveness of cost, mechanical and environmental properties in practice [43].

#### **4.1. GLASS FIBERS**

In terms of production and consumption amounts in the composite industry, the most widely the used reinforcement material is glass fiber. Glass fibers can be produced according to many parameters such as physical strength, purity, electrical strength and chemical resistance. Glass fiber is an amorphous material and has a

molecular structure in which 1 silicon atom is surrounded by 4 oxygen atoms. Silicon, the basic building block of glass, is a light, non-metallic material and is usually found in nature in the form of SiO<sub>2</sub> with oxygen. The silica sand used to obtain the glass is heated up to around 1260 °C with various additives, and after the glass is melted at this temperature is left to cool, it hardens and a solid structure is obtained [44]. Some of the prominent features of glass fibers are:

- They are resistant to chemicals.
- Tensile strength is very high.
- Thermal resistance is quite low. They do not burn but soften at high temperatures.
- They do not have electrical conductivity except those with high alkaline content.
- They do not absorb moisture.

Although there are many types of glass fibers, the 4 most common types can be listed as follows [44]:

1. A (Alkaline) Glass: Due to its high alkali content, its electrical insulation is bad. It has high resistance to chemicals and is the most common type of glass.
2. C (Corrosion) Glass: It has very high resistance against corrosive environments and chemical solutions.
3. E (Electric) Glass: With its low alkali rate, its electrical insulators are very good. It has very good water resistance and high strength.
4. S (Strength) Glass: It is high-strength glass. They are preferred in the aerospace and aviation industry due to their high fatigue strength.

Although the fibers lose 50% of their strength during processing, they are extremely strong. Glass fiber still has higher durability properties than carbon and aramid fibers. Fiber fabrics are generally produced with fibers of continuous glass fiber. Different types of glass fibers can be produced with the addition of different chemicals during the processes and some special production methods [1]. The glass fiber fabric produced is shown in Figure 4.1.



Figure 4.1. Fiberglass woven fabric.

#### **4.2. ARAMID FIBERS**

Although aramid fibers are organic, their strength and stiffness are between glass and carbon fiber. These aromatic polyamides are a member of the nylon type. Aramid fibers are based on the amide bond formed as a result of the reaction between the carboxylic acid and the amine group. Kevlar (Dupont) fiber is known as the most common of this type and is called Kevlar 29 and Kevlar 40. Aramid fibers contain highly crystalline ordered polymer chains. However, due to weak hydrogen bonds between the chains, they suffer defibrillation damage under tension and can form bending strips under pressure. When the system is under compressive stress, the elongation at break is 25% of that at tensile stress. Therefore, their use in applications involving compression stress is limited. Due to their high toughness, aramid fibers are frequently used in ballistic application areas. The biggest known advantage of aramid fibers is that they absorb high amounts of energy during breakage due to plastic deformation. The structure of Kevlar fiber and its behavior in compressive stress reduce the notch sensitivity of composites, and unlike carbon and glass fibers, it exhibits a brittle and sudden behavior in case of damage [25]. An example of aramid fiber is shown in Figure 4.2.



Figure 4.2. Aramid fiber woven fabric.

### **4.3. CARBON FIBERS**

Carbon fiber was the first produced because carbon was known to be a very good conductor of electricity. Since the hardness of glass fiber is very low compared to metal, it was an obvious goal to increase the hardness by 3-5 times. When very high heat treatment is applied to carbon fibers, these fibers become completely carbonized and these fibers are called graphite fibers. Today, this difference disappears, so both carbon fiber and graphite fiber describe the same material. Combining carbon fiber with epoxy matrices results in exceptional durability and rigidity properties. Since carbon fiber manufacturers work in continuous development, the types of carbon fibers are constantly changing. Since the production of carbon fiber is very expensive, it is used in sports equipment, where the cost is in the background, in the aircraft industry or high-value applications of medical materials. The most important advantage of carbon fiber compared to all other fibers is its high modulus feature. Carbon fiber is the hardest material when compared equally with all known materials [1]. Figure 4.3 shows an example of carbon fiber fabric.



Figure 4.3. Carbon fiber woven fabric.

## **PART 5**

### **PRODUCTION METHODS OF THERMOSET COMPOSITES**

How the production method is selected depends on the type of matrix and fiber to be used in the system, the temperature required to form the system and cure the matrix, and the cost. In general, choosing the production method for the composite material to be produced is one of the first steps. The reason for this is that the adequacy of the production method to be determined to produce the desired structure, production cost, production volume and rate. Because each production method has its limitations. For this reason, selecting according to the material to be produced is one of the stages to be considered. The production of polymer matrix layered composite materials is in the form of applying the final processes such as saturating the fibers with the resin, placing the fibers in the desired order, freeing the resin from bubbles and volatile substances, solidifying, or curing the polymer, removing it from the mold and cutting the remaining parts after production [43]. The methods used to produce layered composite materials can be listed as follows; vacuum bagging, hand laying, pultrusion, filament winding, autoclave, resin infusion methods, press molding.

#### **5.1. HAND LAY UP METHOD**

The hand lay-up method is widely used in the production of glass fiber reinforced composite materials. With this method, it is used in many areas such as body panels in vehicles such as trucks, cars, boats, tank bodies used for storage in the building sector, channels of ventilation systems, pools. This method is an open molding method used in the production of polymer matrix composite materials. The low cost of this method is primarily due to the cheapness of the tools used in its production. If mass production will not be produced, that is, if prototype or model production is mentioned, the hand lay-up method maybe preferred. The hand layup method has several advantages. Considering its advantages such as no limitation in the size of

the parts to be produced, low mold costs, and the ability to produce molds in different shapes, it is a highly preferred method [45].

This method also has some disadvantages; these are in connection with the professionalism of the person applying the hand layup method; There may be differences in material thickness in areas where the fiber distribution is uneven or where the resin is not homogeneously distributed. There may be various deviations in the dimensions of the produced composite material, in addition, there may be changes that will adversely affect the mechanical properties of the material due to the presence of air bubbles during the process, the fibers not being properly placed during lamination [45]. In this method, the adhesion of the resin to the mold surface is prevented by using materials such as polyvinyl alcohol, mineral oils, silicone, and wax. Thus, the composite material can be easily removed from the mold. In this method, materials such as fiber, felt, and weaving are generally chosen as reinforcement elements. The hand layup method is applied as shown in Figure 5.1. After the mold release material is applied, the fiber is laminated and applied to it with the help of a resin roller brush without any air bubbles. The process is terminated by continuing this repetition until the desired thickness is achieved. In addition, the fiber volume ratio in the hand lay-up method is around 25-35%.

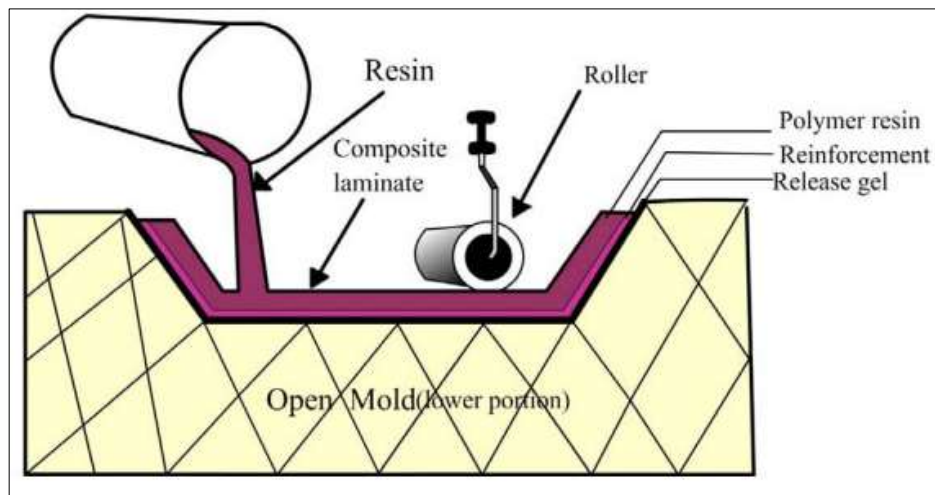


Figure 5.1. Hand lay-up method [45].



## 5.2. SPRAY METHOD

The spraying method is a production method in which the reinforcement material used is used in clipped form and is mostly used in vehicles such as automobile body, boat, boat, tank. In the spraying method, as shown in Figure 5.2, the continuous fibers, which are clipped and become small particles, are sprayed into the mold with the resin and hardener mixture at an appropriate speed with the help of a special gun. When the desired thickness is reached, the spraying process is terminated. Air bubbles that may occur in this method are removed with the help of a roller. Thus, the rate of wetting the fibers of the resin increases. It is an advantageous method in that the tools used in this production method are cheap, there is no size limitation in the parts to be produced, the labor costs are low, and complex shaped parts can be produced with this method [45].

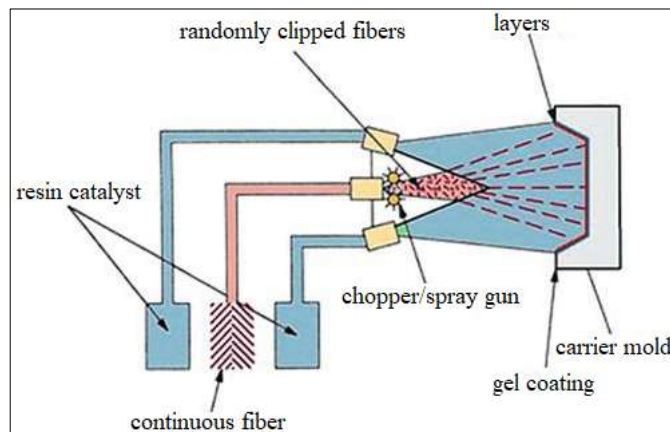


Figure 5.2. Spraying method [45].

## 5.3. RESIN TRANSFER MOLDING METHOD

In this composite production method, although it is faster and longer-lasting than the manual lay-up method, it is necessary to use a two-piece mold. Making the mold from composite material causes it to be lower than the steel mold cost. RTM (resin transfer method) is mostly used on parts with or without gel jeans where both surfaces are required to be smooth. Dry felt, fabric or a combination of both are used as reinforcement material. The reinforcement material is placed in the mold beforehand to fill the mold cavity and the mold is closed. It is coated with late-

dissolving resins in the matrix to prevent the fibers from drifting in the mold. The resin is pumped into the mold under pressure. This production the process takes more time. RTM is implemented as shown in Figure 5.3. Matrix injection can be applied in warm, cold, or heated containers to a maximum of 80 °C. In this method, a vacuum can be used to expel the air inside and to penetrate the resin into the fiber well. Due to the need to place the fiber in the mold, it requires a long labor process. Since the mold is closed, harmful gases are reduced, and a porous product can be obtained. With this method, complex parts can be produced [1].

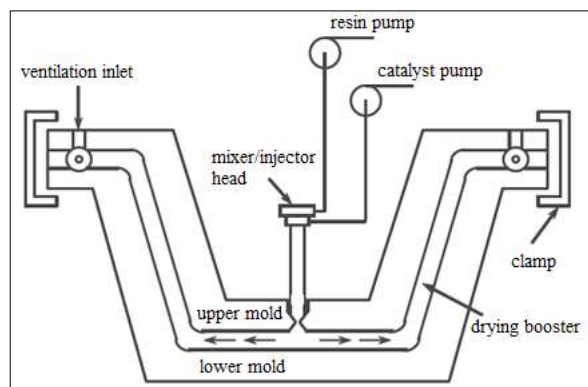


Figure 5.3. Resin transfer molding method [45].

#### 5.4. FILAMENT WINDING METHOD

It is an open mold method in which cylindrical parts such as pipes, rocket bodies, pressure tanks, poles are produced by the fiber winding method. This method usually uses a rotating steel shaft. Inflatable and deflatable flexible shafts can also be used for some special applications. In this method, as shown in Figure 5.4, the continuous fibers passed through a chamber with resin are arranged at the angles we want and wound on the shaft, and the winding process continues until the desired thickness is reached at a certain tension with the help of a car that moves the shaft continuously back and forth. After the resin hardens, the material is removed from the spindle and the production process is terminated.

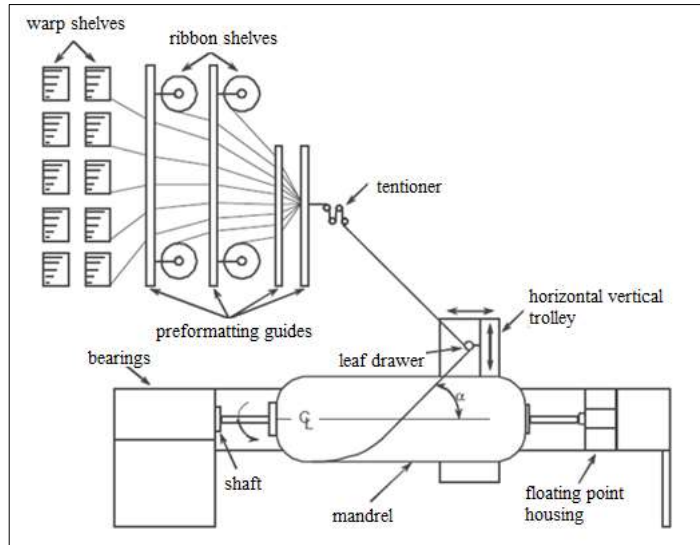


Figure 5.4. Filament winding method [45].

## 5.5. PULTRUSION METHOD

Products to be produced by pultrusion method with constant and continuous cross-section; It is used in designs such as construction sector, building, furniture to be used in open areas and greenhouse cultivation. In this method, felt and glass fibers are used as reinforcement elements. The reinforcing element is first passed through a chamber containing resin for a pre-wetting, and after this process, it is passed through molds with a heating feature to give the desired shape. After the product, in which the desired shape is given, is brought to the desired size in the drawing unit, it is cut into certain lengths and finalized. It is a widely used method due to its low investment cost and large application area. This method is applied as shown in Figure 5.5 [45].

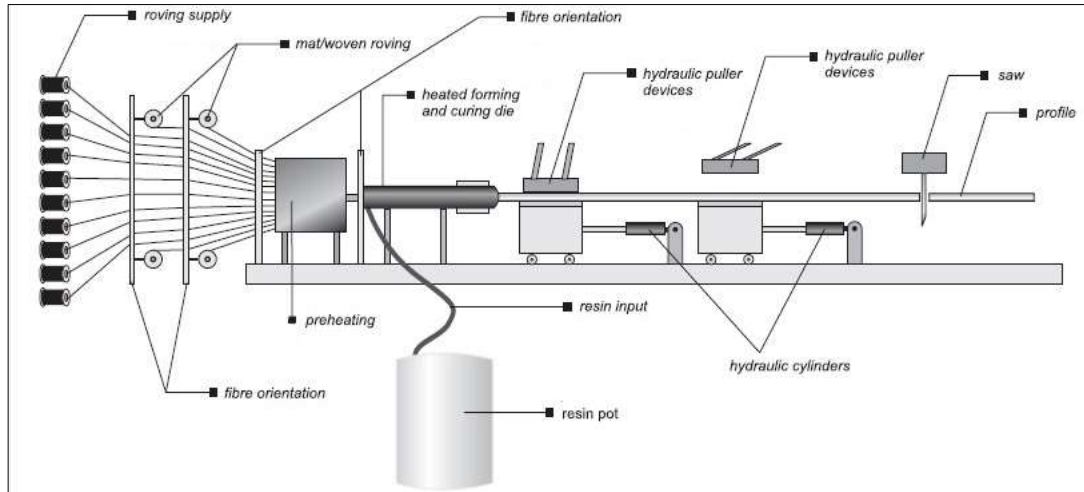


Figure 5.5. Pultrusion method [45].

## 5.6. VACUUM BAGGING METHOD

In the vacuum bag molding method, which is an alternative to the hand lay-up method, the mold is covered with a flexible vacuum bag after the fiber fabrics are laminated and resin impregnated. To prevent the bag and the sheet from sticking to each other, a peeling fabric is placed between these two, and a dispersing fabric is also added to ensure regular distribution of the resin. After the piece is thoroughly isolated by the bag, it is aimed to obtain a flat surface with the help of vacuum pressure. In addition, with the help of vacuum pressure; Air trapped in the structure and harmful volatile gases are also thrown out of the system. The vacuum bagging method is applied as shown in Figure 5.6. As in other methods, when curing occurs, the vacuum process is terminated, and the material is removed from the mold. Vacuum bagging allows the production of high quality, large size, low-cost composites. The main advantage is that the curing equipment and vacuuming can be used on different parts. But the quality of the part depends on the skill of the manufacturer. Fewer pores and air bubbles are formed in the composites produced by vacuum bagging. The dispersion rate of the resin between the fibers increases and the formation of the resin pool is prevented with the excess resin discharged from the system so that the weight of the product can be kept under control. In vacuum bagging composite production method, where toxic gases are less dispersed to the environment, labor is more than spray production and manual layering. Although thermosets and thermoplastics are produced in the same way, the vacuum bag to be

used in thermoplastics must be able to withstand high temperatures. In addition, the high-pressure requirements and high viscosities of thermoplastics complicate the process. High-quality thermoplastic matrix composites are generally used in areas where cost is not so important, such as aerospace and medical materials [43].

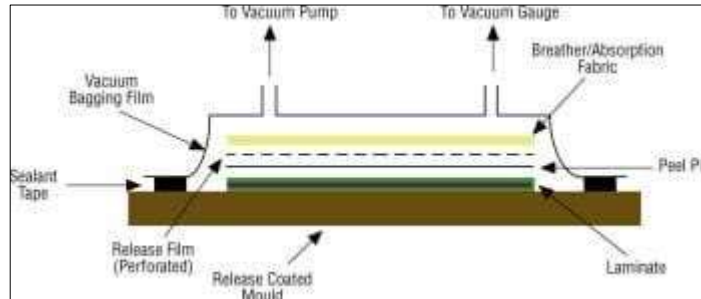


Figure 5.6. Vacuum bagging method [46].

## PART 6

### EXPERIMENTAL STUDIES

#### 6.1. MATERIALS

Short carbon fibers were purchased from KO-Faktor Technology (Turkey) with an average length of 6-12 mm. The polyol and isocyanate used were supplied from Kimteks Polyurethane, Turkey. The chemical content of PU and SCFs are as indicated in Table 6.1.

Table 6.1. Composite compositions.

Experiment No	Short Carbon Fiber (SCFs)	Polyurethane (PU)
	Percentage (wt. %)	
1	1.5	98.5
2	1	99
3	0.5	99.5
4	×	100

#### 6.2. FABRICATION OF COMPOSITES AND HYBRID SAMPLES

Different proportions of SCFs (1.5 wt%, 1 wt% and 0.5 wt%) were mixed homogeneously with 49.25 wt% polymeric isocyanate in a beaker. Then another 49.25 wt% polyol is added to the homogeneous mixture of SCFs and isocyanate. There is very little time between homogeneous mixing and casting of the polyol. Therefore, the liquid composite mixture is poured directly into the mold after rapid mixing. Then the samples are divided equally into the casting mold. After curing, a foaming reaction begins to occur and an increase in volume occurs. After the reaction is over, the samples are taken from the mold and sanded with 240 grit sandpaper. Samples were

prepared according to ASTM D790-03 standards. Figure 6.1 contains fabrication examples of composites and pure PU materials. Figure 6.1 (a)-1(c) shows PU foam-based composites with 1.5, 1, and 0.5 wt. % SCFs, respectively. A pure foam-based PU polymer sample was indicated in Figure 6. 1(d).



Figure 6.1. SCFs-PU foam-based composites and pure polyurethane polymer.

### 6.3. CHARACTERIZATION

To make the characterization of mechanical properties easier, samples were fabricated with dimensions measured with a 158mm x 13mm x 4.5mm sliding Vernier caliper. According to Figure 6.2(a), flexural strength tests were performed on a Zwick Roell 600KN testing machine at a constant speed of 2 mm/min, with at least three acceptable tests per sample. Abrasion tests were tested with the UTS Tribometer T10/20 in dry sliding conditions as shown in Figure 6.2(b). During the wear test, an abrasive 6 mm stainless steel ball diameter, 25 m total sliding distance, 40 mm/s sliding speed and 10 mm stroke with 5N applied load were used. In addition, a scanning electron microscope (Zeiss Ultra Plus) was used to analyze the structure of the damaged (broken and corroded) surfaces of the samples after coating with gold using a sputter coating device (Quorum, Q150R ES Plus).

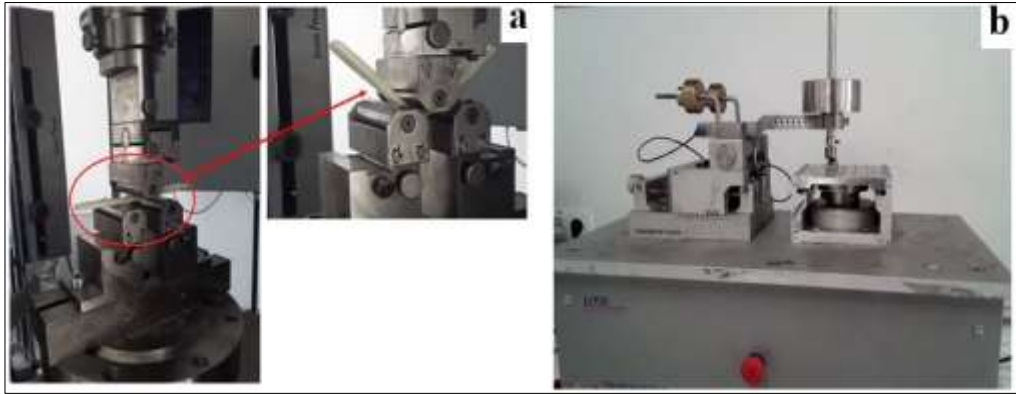


Figure 6.2. (a) Zwick Roell flexural (bending) strength tester and (b) UTS T10/20 Tribometer wear test machine.



## PART 7

### RESULTS AND DISCUSSIONS

#### 7.1. MECHANICAL PROPERTIES

Figure 7.1(a)-1(c) shows fracture surface views of polyurethane foam composites with additions of various SCF contents (1.5 wt%, 1 wt% and 1 wt% and 0.5 wt%). The fracture surface view of pure polyurethane polymer foam is as in Figure 7.1(d). The reason for the fracture was the presence of high stress concentration around many porosities and the consequent onset of crack formation in the polyurethane matrix. It is stated in the literature that the primary damage mechanism is the initiation of cracks in the matrix [14]. These micro-polyurethane matrix cracks, which contain micropores that occur during curing, tend to spread and bond with the applied load, causing SCF breakage and ultimately composite damage [47].

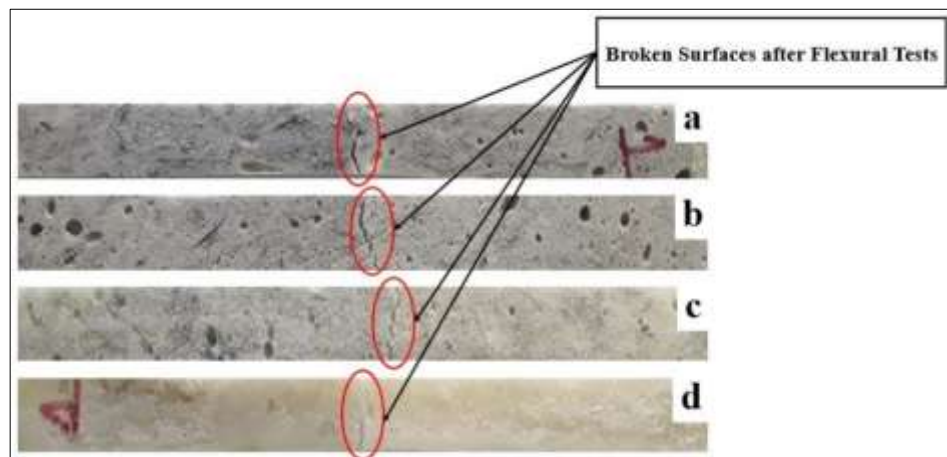


Figure 7.1. Flexural test results of pure Polyurethane foam and SCFs-PU composites.

Figures 7.2(a)-4(c) show force-deformation graph plots of composites with different SCF content (1.5 wt%, 1 wt% and 0.5 wt%, respectively). As can be seen in the figures, not all force-deformation curves of composites are linear until the force max value is reached. After reaching the maximum load point, the force-deformation curve of the

short carbon fiber added polyurethane foam composite begins to decrease significantly. This is because the presence of higher stress concentration and crack propagation effects around the pores caused by an increase in the proportion of short carbon fibers results in a drastic decrease in the mechanical behavior of the composites [48]. The presence of non-strong interfacial bonds may be a reason for the reduced load bearing capabilities of SCFs-PU composites compared to pure polyurethane foam. Moreover, the formation of the non-strong interfacial bond between the SCFs and the polyurethane matrix causes much lower deformation for short carbon fiber reinforced composites than for pure polyurethane foam [14]. Therefore, among all the samples in Figure 7.2, the highest deformation was seen for pure polyurethane foam with a max load of about 18N.

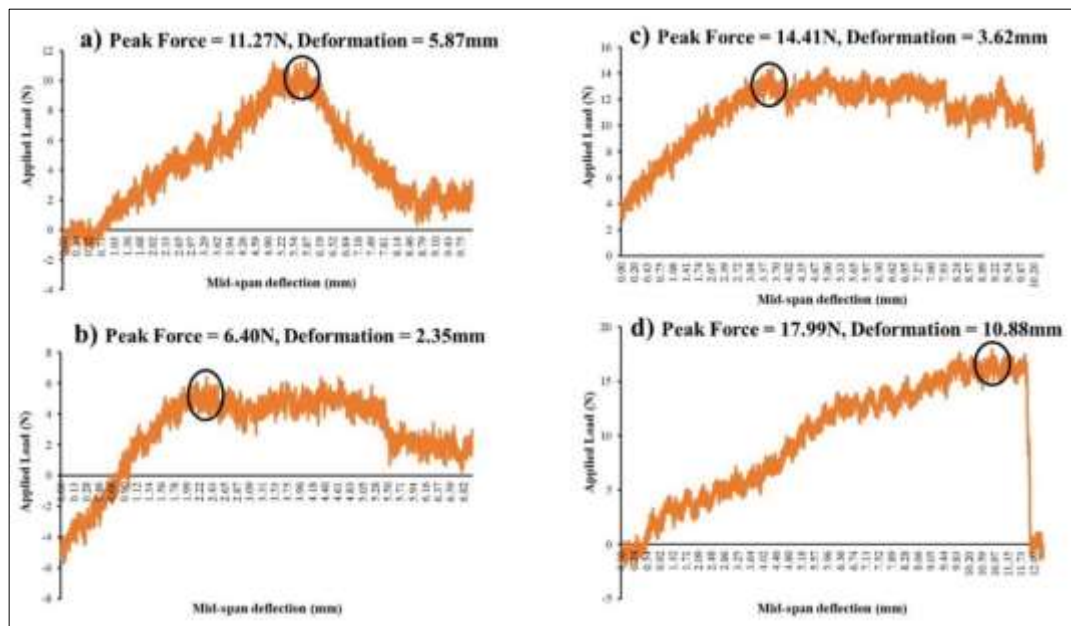


Figure 7.2. Load-deflection curves in bending for pure PU foam and SCFs-PU composites.

SEM observations of failed surfaces were applied to confirm the failure mechanism of the samples. For pure polyurethane foam, Figure 7.3(a) shows the crushed polyurethane matrix cells, pores, and polyurethane matrix cracks. This is due to the vertical displacement of the polymer structure during bending tests. Figure 7.4 and Figure 7.5 show the broken surfaces of 1 by weight. % SCF-PU and 1.5 wt. Composites based on SCF-PU foam, respectively. In these samples, polyurethane matrix cracks and broken composite parts were observed after bending tests.

Therefore, it can be said to be 0.5 by weight. The % SCF-PU foam composite (Fig. 7.3(b)) both has relatively better interfacial bonding compared to 1% by weight. % SCF-PU and 1.5 wt. % SCF-PU composites. This can be attributed to the difficulty of mixing with the polyurethane matrix due to the increase in viscosity as the amount of chopped carbon fibers increases. In addition, as seen in Figure 7.5, higher rates of unreacted compounds and free spaces (voids) were formed in the composite [48]. These defects (voids) caused the mechanical properties of the composites to decrease. Also, the lower the fiber content, the higher the probability of SCFs diffusing through the polyurethane matrix. Therefore, the probability of interfacial bond formation between fiber and matrix increases [47].

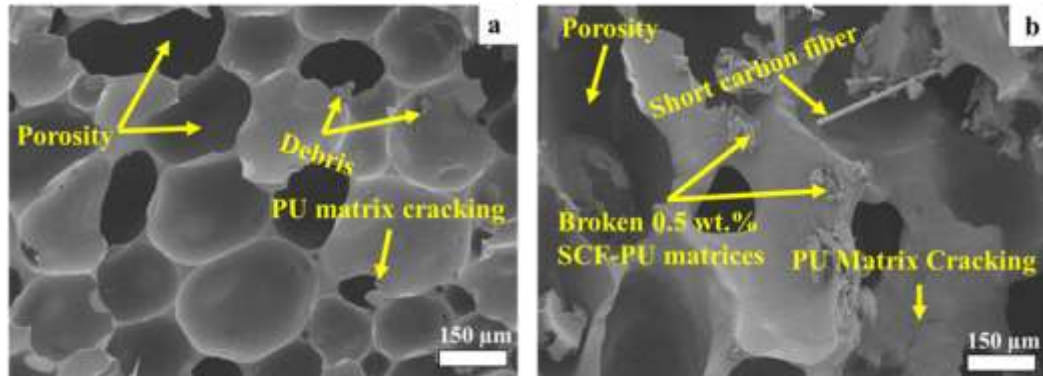


Figure 7.3. SEM images (a) Pure polyurethane polymer foam and (b) 0.5 wt. % SCF-PU foam composite.

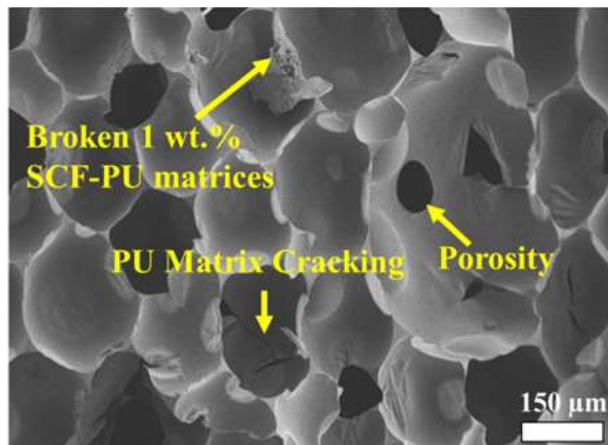


Figure 7.4. SEM image of 1 wt. % SCF-PU foam composite.

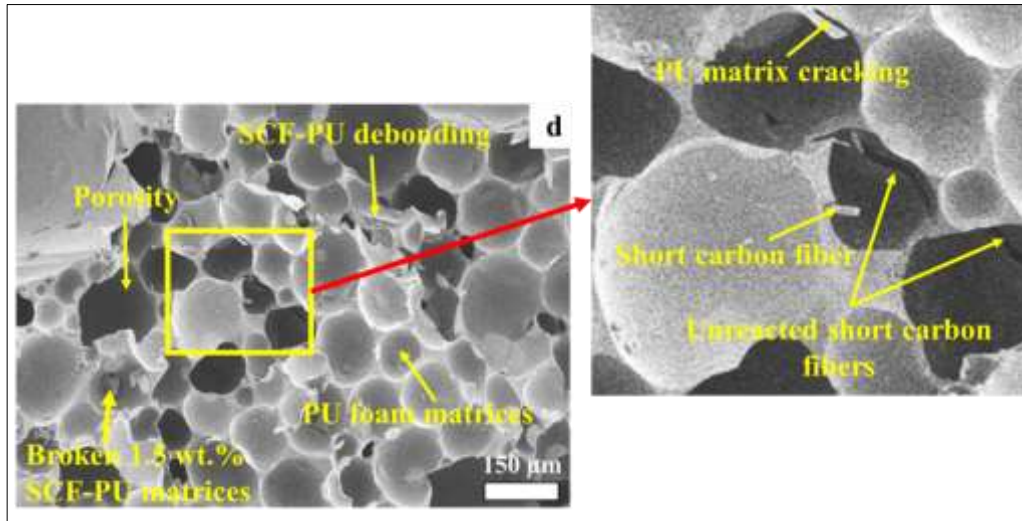


Figure 7.5. SEM image of 1.5 wt. % SCF-PU foam composite.

Figure 7.6 shows the flexural strength of composites based on pure polyurethane foam and SCFs-PU foam. The flexural (bending) strength of pure polyurethane foam is better compared to 1 by weight. 63.85% SCFs-PU composite. In addition, it is 16.42% more by weight than 0.5. % SCF-PU composite. This is because the application of carbon fibers as reinforcement in polyurethane foam-based composites leads to defects such as separation and extra voids (void spaces) that reduce the load-carrying capacity of the composites [14,48].

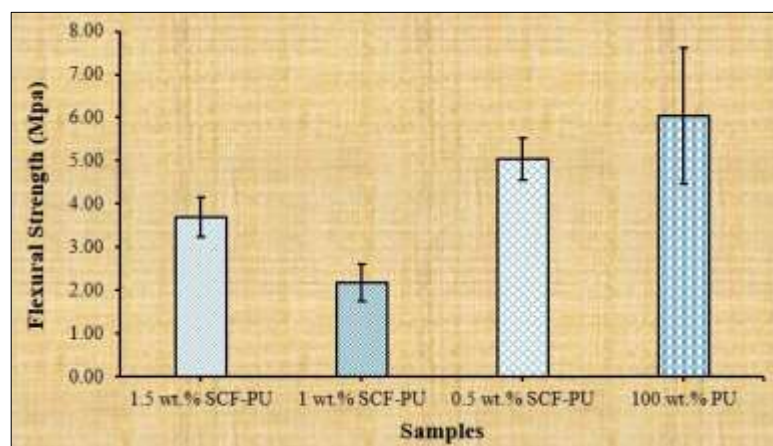


Figure 7.6. Flexural strength versus samples.

## 7.2. TRIBOLOGICAL PROPERTIES

Figure 7.7 shows the abrasion test results of pure polyurethane foam and short carbon fibers reinforced with different weight fractions of SCFs-PU composites. Judging by the test results, the highest wear resistance properties were observed at 1.5 wt. % SCF was added to the pure polyurethane matrix. This is due to the self-lubricating properties of short carbon fibers [16,18]. However, when the short carbon fiber content drops to 0.5 by weight. A remarkable decrease of % in wear resistance properties was observed. It can be said that as the amount of carbon fiber decreases, more surfaces are in contact and thus the wear rate increases significantly.

Worn surfaces of pure polyurethane foam and SCFs-Polyurethane composites were analyzed using a scanning electron microscope. 1.5 wt worn surface. The % SCF-Polyurethane composite was relatively smooth as shown in Figure 7.9(b). This can prove to have higher wear resistance. Therefore, when 1.5 wt. SCF added to pure polyurethane polymer foam; This led to an improvement of approximately 43% in the wear resistance property. Figure 7.9(a) shows the eroded surface of 1 wt. % SCFs-Polyurethane composite material. Delamination, wear residues and broken short carbon fibers were observed. Figure 10(a), shown below, shows the worn surface of pure polyurethane foam material. As can be seen, the wear residue size is small compared to the wear residue size of the composites observed in Figure 7.8(b) and Figure 7.9(a). 0.5 wt worn surfaces. The % SCF-Polyurethane composite is shown in Figure 7.8(b). 0.5 weight. % SCFs were added to the polyurethane matrix, resulting in a composite with the lowest abrasion resistance characteristic (highest abrasion rate value 0.18 mm<sup>3</sup>/m) as seen in Figure 9.

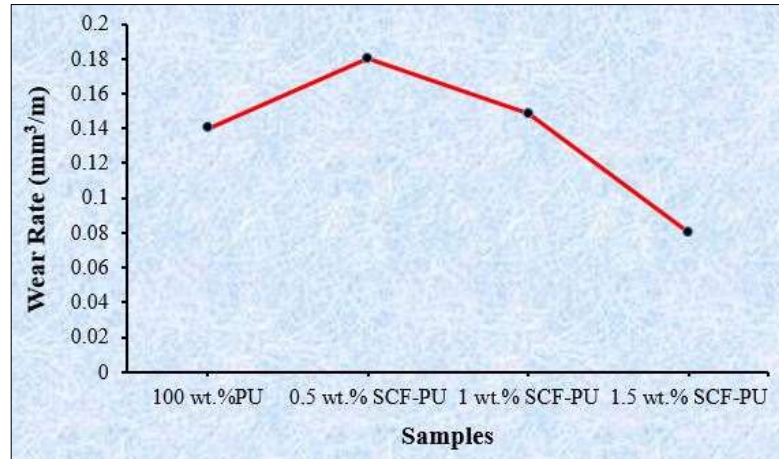


Figure 7.7. Wear rate versus samples.

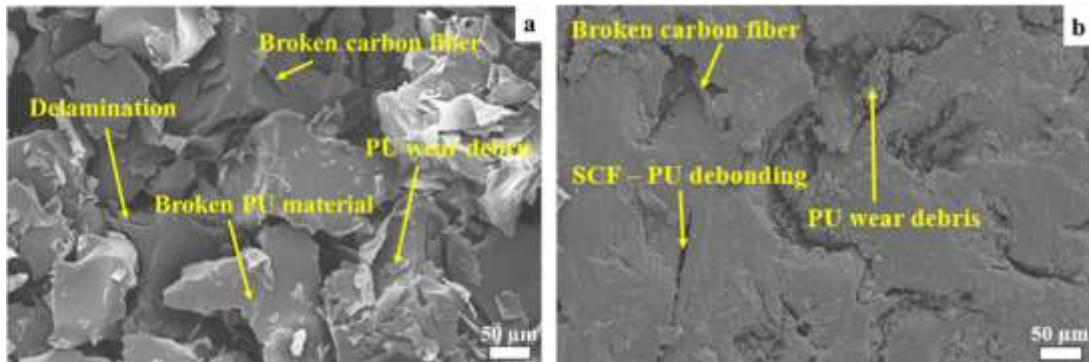


Figure 7.8. SEM worn surface images (a) 100 wt. % PU and (b) 0.5 wt. % SCF-PU.

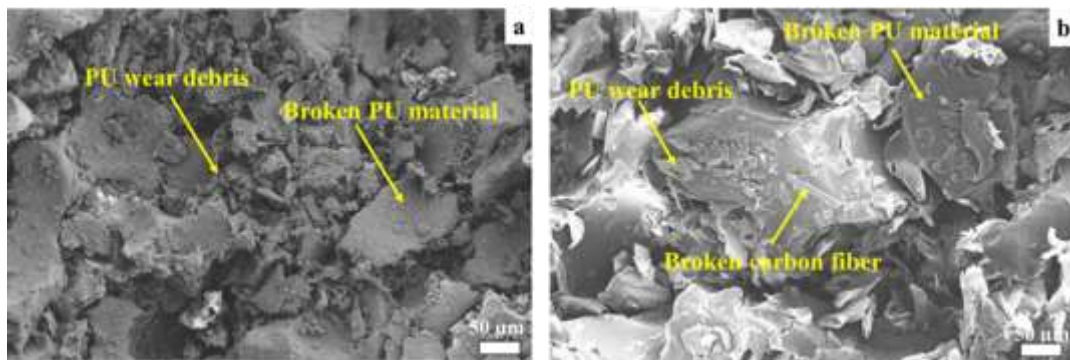


Figure 7.9. SEM worn surface images (a) 1 wt. % SCF-PU and (b) 1.5 wt. % SCF-PU.

## **PART 8**

### **CONCLUSIONS**

This study revealed that the increase of short carbon fibers (SCFs) (0.5-1.5% by weight) leads to a decrease in flexural strength of PU foam matrix composites reinforced with SCFs. 0.5 weight addition. The % SCFs on the pure polyurethane foam matrix resulted in greater than 1% wt flexural strength. % and 1.5 by weight. SCF reinforced polyurethane foam composites. This was explained by the stress concentration and interfacial bonding factors. In addition, this study found that short carbon fiber content has significant effects on the tribological properties of PU foam-based composites. The abrasion resistance of the composites increased by approximately 43% with the addition of 1.5 wt. Chopped carbon fibers on a pure polyurethane foam matrix. Thus, a superior improvement in abrasion resistance property was observed for 1.5 wt. % SCF-Polyurethane composite. However, the lowest wear resistance was recorded for 0.5wt. % SCF-Polyurethane composite. Plus, 1.5 short carbon fiber content by weight. The % reinforced pure polyurethane foam matrix had smoother worn surfaces compared to the worn surfaces of both pure PU foam (100% by weight of PU) and composite materials (0.5% by weight of SCF-Polyurethane and 1% by weight of SCF-PU).

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## **RESUME**

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