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**National Engineering School of Monastir**

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# Graduation Project

Presented to obtain

## Engineering degree

**Specialty: Textile Engineering**

**By**

**Dalel DRIRA**

**Born on: 07/04/1996 in Monastir**

Study of the mechanical and comfort properties of a ballistic Kevlar/epoxy composite manufactured with different methods

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## *Content*

Abstract .....	1
General Introduction .....	2
Chapter 1: State of the Art.....	4
I. Composite Material .....	4
1. Historical brief .....	4
2. Polymer matrix.....	5
3. Reinforcements .....	6
4. Composite manufacturing techniques .....	6
5. Composite applications .....	12
II. Kevlar fabric .....	15
1. Invention of Kevlar .....	15
2. Chemical structure .....	16
3. Dry-jet-wet spinning process of Kevlar .....	19
4. Properties of Kevlar .....	20
5. Uses & Applications .....	22
6. Comparison with E Glass and Carbon Fiber.....	26
III. Epoxy resin .....	29
1. Introduction.....	29
2. Epoxy Resin Manufacture and Characterization .....	29
3. Properties .....	30
4. Application fields.....	31
IV. Important parameters .....	33
1. Thermal conductivity .....	33
2. Relative Water vapor permeability .....	34
3. Air permeability .....	34
4. Tensile Strength .....	35
5. Stiffness or Modulus of Elasticity.....	35
6. Stab resistance.....	35
V. Conclusion .....	36
Chapter 2: Materials and methods.....	37
I. Equipment used .....	37
1. Laboratory and technical equipment.....	37

2.	Equipment .....	37
II.	Materials used.....	39
1.	Reinforcement .....	40
2.	Matrix.....	42
III.	Experimental method.....	47
1.	Preparation of specimens .....	47
2.	Matrix preparation .....	47
3.	Composite fabrication .....	49
IV.	Test Methods .....	54
1.	Determination of composite structural and physical properties .....	54
2.	Determination of Thermophysiological comfort properties .....	57
3.	Determination of mechanical properties .....	59
V.	Conclusion .....	64
	Chapter 3: Results and Discussion .....	65
I.	Experimental samples .....	65
1.	Results of Coating method.....	65
2.	Results of dropping Method.....	69
3.	Results of Printing Method .....	71
II.	Structural and physical properties .....	75
III.	Comfort properties.....	76
1.	Air permeability .....	76
2.	Thermal conductivity .....	77
3.	Water Vapor Resistance.....	79
IV.	Mechanical properties.....	81
1.	Tensile performance.....	81
2.	Stab resistance test .....	83
V.	Conclusion .....	87
	General Conclusion .....	89
	References .....	89

## **Tables List**

Table 1: Differences in material properties among the different grades of Kevlar.....	20
Table 2: Tensile Strength of E Glass, Carbon Fiber and Kevlar [48] .....	26
Table 3: Density and strength to Weight Ratio of E Glass, Carbon Fiber and Kevlar.....	26
Table 4: Modulus of Elasticity of E Glass, Carbon Fiber and Kevlar .....	27
Table 5: Analysis equipment.....	37
Table 6: Fabric Structure.....	40
Table 7: Product data of plain-woven Kevlar fabrics.....	41
Table 8: Characteristics of epoxy resin L285.....	42
Table 9: Specifications of Laminating resin LR 285 .....	43
Table 10: Specifications of Hardener LH 285 .....	43
Table 11: Processing details .....	44
Table 12: Mixing ratios .....	44
Table 13: Gel Time .....	45
Table 14: Glass transition temperature (T <sub>g</sub> ).....	45
Table 15: Mechanical data of unreinforced resin .....	46
Table 16: Initial weight of Kevlar samples and final weight of composites .....	67
Table 17: Structural parameters of composites under study .....	75

## **Figures List**

Figure 1: Open contact molding .....	7
Figure 2: Schematic of the RTM process .....	8
Figure 3: Schematic of the compression molding process .....	9
Figure 4: injection molding .....	9
Figure 5: Filament winding Method.....	10
Figure 6: Schematic of the pultrusion process .....	11
Figure 7: Automated fiber placement (AFP) method.....	12
Figure 8: Registered Kevlar Fiber Logo .....	15
Figure 9: Polymeric Structure of Twaron® (poly-para-Phenylene-terephthalamide) (PPTA)	16
Figure 10: The figure shows the condensation reaction and how the para-aramid is formed..	17
Figure 11: a section of an individual Kevlar chain .....	17
Figure 12: Molecular structure of Kevlar (bold represents a monomer unit, dashed lines indicate hydrogen bonds.) .....	18
Figure 13: Sheets stacked together .....	18
Figure 14: Figure 14: Kevlar fiber production process [5]. .....	19
Figure 15: (a) Kevlar reinforced hoses (b) Kevlar reinforced belts (c) Kevlar in Aircraft .....	23
Figure 16: Kevlar reinforced (a) Bicycle Tire (b) Car Tire.....	23
Figure 17: Kevlar in Some sports equipment .....	24
Figure 18: iPhone Cover Carbon Fiber Kevlar .....	24
Figure 19: Personal safety equipment .....	25
Figure 20: Military Equipments .....	26
Figure 21: reaction between diphenylol propane (DPP) and epichlorhydrin (ECH) .....	29
Figure 22: Commercial grades of resin .....	30
Figure 23: Photos of epoxy resins used in paints and coatings .....	31
Figure 24: Photos of epoxy resins used in Adhesives .....	32
Figure 25: Photos of epoxy resins used in aerospace industry .....	32
Figure 26: Photos of epoxy resins used in electronic materials .....	33
Figure 27: Optical image of K706 plain woven Kevlar fabric .....	40
Figure 28: Optical images of five styles of plain-woven Kevlar fabrics. ....	41
Figure 29: (a) 1Kg of hardener 285 (MGS) (b) 3Kg of epoxy resin L285.....	42
Figure 30: Temperature rise .....	45
Figure 31: Rise of glass transition temperature (T <sub>g</sub> ).....	46
Figure 32: The Geometry of the specimens .....	47
Figure 33: The stages of preparation of the resin coating (1 – resin, 2 – addition of hardener, 3 – mixing of components).....	48
Figure 34: Manual coating method of resin .....	50
Figure 35: Spreading of resin .....	51
Figure 36: Dropping Method.....	51

Figure 37: Triangular shape of 3 spots .....	52
Figure 38: Different films for printing .....	53
Figure 39: Printing Method .....	54
Figure 40: The measuring balance .....	55
Figure 41: TEXTTEST Principle and Design .....	55
Figure 42: Thickness tester .....	56
Figure 43: Optical microscope .....	56
Figure 44: The ALAMBETA instrument [13] .....	57
Figure 45: The Permetest apparatus design and principle [65] .....	58
Figure 46: (a) Universal Testing Machine (TESTOMETIC M350-10CT), (b) Cross-head installed with knife and (c) Geometry of CKB-2 (K1) .....	61
Figure 47: Illustration of different Knife Penetration Angles .....	62
Figure 48: Illustration of knife cutting axis.....	62
Figure 49: Tensile Test [48] .....	63
Figure 50: specimen dimensions for tensile test .....	64
Figure 51: 4 samples prepared by different coating ratios .....	65
Figure 52: Microscopic view of samples 1, 2, 3 and 4.....	68
Figure 53: 2 samples prepared by dropping method .....	69
Figure 54: Microscopic view of sample 5 and 6 .....	70
Figure 55: Intersection of 3 spots .....	71
Figure 56: 4 samples prepared by printing method.....	72
Figure 57: Microscopic View of sample 7 .....	73
Figure 58: Microscopic View of sample 8 .....	73
Figure 59: Microscopic View of sample 9 .....	74
Figure 60: Microscopic View of sample 10 .....	74
Figure 61: Influence of matrix mass fraction on air permeability.....	76
Figure 62: Fundamental mechanism of thermal conductivity by particle collision .....	77
Figure 63: Effect of matrix mass fraction on thermal conductivity .....	78
Figure 64: Effect of thickness on thermal conductivity .....	78
Figure 65: Effect of matrix mass fraction on water vapor resistance.....	80
Figure 66: Photographs of the tensile fracture of (a) Kevlar fabric (b) composites prepared by coating methods.....	81
Figure 67: Photographs of the tensile fracture specimens of (a) the composites prepared by dropping method (b) the composites prepared by printing method .....	81
Figure 68: Tensile Load–displacement curves of Kevlar/Epoxy composites prepared by coating methods.....	82
Figure 69: Tensile Load–displacement curves of Kevlar/Epoxy composites prepared by dropping and printing methods .....	82
Figure 70: Effect of matrix mass fraction on knife penetration depth .....	83
Figure 71: Picture sequence of the stab penetration of a Kevlar fabric .....	84
Figure 72: Damaged Kevlar fabric by knife impactor type 1.....	84
Figure 73: Damaged composites prepared by coating method penetrated with knife impactor type 1 .....	85
Figure 74: Damaged composites prepared by dropping and printing methods penetrated with knife impactor type 1.....	86

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# Dedication

I humbly dedicate this piece of work to the soul of my father **Taher** who taught me the meaning of life, to my mother **Hamida** the origin of my success whose words of encouragement and push for tenacity ring in my ears. My sisters **Nawel**, **Malek** and my brothers-in-law **Housseem** and **Mohamed Salah** have never left my side and are very special. I also dedicate this dissertation to my many friends who have supported me throughout the process. I will always appreciate all they have done, especially **Oussama Ghali** for helping. I dedicate this work and give special thanks to **Kamel** and my besties **Nedra**, **Zeineb** and **Balkis** for being there for me throughout the entire project. All of you have been my best cheerleaders. Above all, to almighty God who always give me strength, knowledge, and wisdom in everything I do.



## Abstract

*Impact resistance and weight are important features for ballistic materials. Kevlar fibers are the most widely reinforcement for military and civil systems due to its excellent impact resistance and high strength-to-weight ratio. Kevlar fibers or spectra fiber composites are used for designing personal body armor to avoid human injury from aggressive action by knife, sharp, spike, broken glass, and needle. So, wearer's comfort also becomes a pre-requisite of armor design to produce light-weight and comfortable armor.*

*In this study, the comfort properties of Kevlar/epoxy matrix are investigated. Two innovative methods were used for the preparation of a Kevlar/epoxy composite by using Kevlar fabric as reinforcement and epoxy resin as matrix in order to maintain the ballistic impact performance of Kevlar-epoxy composite and to increase the comfort properties at lower weight.*

# General Introduction

## General Introduction

Protective textiles have become an important branch of technical textiles. Textiles are playing a major role in wearables that assure life safety in various types of critical applications. The introduction of gunpowder has changed the requirement of body armor. The old solutions for body protection using metal and leather, silk or flak jacket armor became ineffective. Those solutions were no guarantee of life-saving against high-velocity gunfire or were bulky enough to restrict comfortable use. The soft body light-weight armor became possible only after the birth of Kevlar® by DuPont™ in 1970s.

In search of the best system of protection against ballistic threats, last few decades have produced considerable research on body protection armor. These armors are lighter than metallic armor solutions and easier to wear and carry. The solution was found in use of polymer-fiber composites, with synthetic fibers of high strength and high module like Dyneema®, Twaron®, and Kevlar® and thermoset polymer matrix. These solutions have better bulk properties and distribute the localized energy of impacting bullet to a larger area and dissipate its penetrating energy. The latest requirement imposed on body protection armor is protection against sharp objects. Personal protection, against the attacks of sharp objects like the knife, has become increasingly important especially for police personnel. The design of bullet resistant protection is different from the armor protecting against sharp objects like a knife or spike. In various condition of body protection against sharp objects and spikes is required. Such kinds of attacks are evident where access to gunpowder and firearms is restricted by territory law.

Normally, the bullet attacks are for army personals in some critical situation or in the battlefield, where the attack is expected. In contrast, sharp objects' attacks are unexpected, and the required period of protection is incessant and extended. So, wearer's comfort also becomes a pre-requisite of armor design to produce light-weight and comfortable armor.

In this scenario, it becomes important to find a way for designing comfortable personal body armor.

Generally, classical methods of resin coating allow obtaining composites with good mechanical properties. These composites have a continuous structure of matrix which covers

all the area of the reinforcement leading to a compact structure. We can use these composites in several fields unless in clothing because of the absence of comfort properties.

The work carried out aims to prepare some composites with utilizing two innovative methods of resin deposition in order to minimize the area density of matrix to improve the comfort properties of composites and then to study the mechanical and comfort properties of those soft Kevlar/epoxy innovative composites.

This work has three main parts:

- In bibliographical part essential concepts will be presented in order to approach this work, namely the characteristics of a composite material, Kevlar fiber and epoxy resin as well as the important parameters and their effect on the comfort and impact resistance of Kevlar/epoxy composite.
- The second part deals with the material, methods and processes used for the experimental work.
- The last chapter will be devoted to the experimental results.

Finally, the report concludes with a general conclusion, which includes the main obtained results and the perspectives that can be opened in future works.

## **Chapter 1: State of the Art**

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This first chapter sets out basic concepts for a good understanding of the work done during this end of studies project. Its elaboration would therefore have the objective of introducing a composite material, Kevlar fiber and Epoxy resin by presenting its structures, properties and the fields of its applications.

It discusses the parameters which should be studied to obtain a comfortable Kevlar/Epoxy composite with a high tensile strength.

---

## **I. Composite Material**

### **1. Historical brief**

Composite materials are formed by combining two or more materials that have quite different properties, and they do not dissolve or blend into each other. In general, a composite consists of three components: (i) the matrix as the continuous phase; (ii) the reinforcements as the discontinuous or dispersed phase, including fiber and particles; and (iii) the fine interphase region, also known as the interface. The different materials in the composite work together to give the composite unique properties. Humans have been using composite materials for thousands of years in different areas.

In 3400 B.C the first composites were engineered by the Mesopotamians in Iraq. The ancient society glued wood strips on top of each other at different angles to create plywood. Following this, in around 2181 B.C the Egyptians started to make death masks out of linen or papyrus soaked in plaster. Later on, both of these societies started to reinforce their materials with straw to strengthen mud bricks, pottery and boats.

In 1200 A.D, the Mongols began to engineer composite bows which were incredibly effective at the time. These were made out of wood, bamboo, bone, cattle tendons, horn and silk bonded with pine resin.

Following the industrial revolution, synthetic resins started to take a solid form by using polymerization. In the 1900s this new-found knowledge about chemicals laid to the creation of various plastics such as polyester, phenolic and vinyl. Synthetics then started to be developed; Bakelite was created by the chemist Leo Baekeland. The fact that it did not conduct electricity and was heat resistant meant it could be widely used across many industries.

The 1930s was an incredibly important time for the advancement of composites. Glass fiber was introduced by Owens Corning who also started the first fiber reinforced polymer (FRP) industry. The resins engineered during this era are still used to this day and, in 1936, unsaturated polyester resins were patented. Two years later, higher performance resin systems became accessible.

The first carbon fiber was patented in 1961 and then became commercially available. Then, in the mid-1990s, composites were starting to become increasingly common in manufacturing

and construction due to their relatively cheap cost compared to materials that had been used previously.

The composites on a Boeing 787 Dreamliner in the mid-2000s substantiated their use for high strength applications [50].

Today, composites research attracts grants from governments, manufacturers and universities. These investments allow innovation to accelerate. Specialized companies, such as aerospace composite companies, will find a place in the industry. Two applications that continue to experience innovative growth are airplane composite materials and composite sheets for marine use.

Other materials such as environmentally-friendly resins incorporating recycled plastics and bio-based polymers meet the demand for stronger, lighter and environmentally friendly products. Looking ahead, still to be developed fibers and resins will create even more applications for everyday and specialized use.

## **2. Polymer matrix**

Matrix materials are generally ceramics, metals, and polymers. In reality, the majority of matrix materials that exist on the composites market are polymer. There are several different polymer matrices which can be utilized in composite materials. Among the polymer matrix composites, thermoset matrix composites are more predominant than thermoplastic composites. Though thermoset and thermoplastics sound similar, they have very different properties and applications. Understanding the performance differences can help to make better sourcing decisions and the product designs as composites. Thermosets are materials that undergo a chemical reaction or curing and normally transform from a liquid to a solid. In its uncured form, the material has small, unlinked molecules known as monomers. The addition of a second material as a cross-linker, curing agent, catalyst, and/or the presence of heat or some other activating influences will initiate the chemical reaction or curing reaction. During this reaction, the molecules cross-link and form significantly longer molecular chains and cross-link network, causing the material to solidify. The change of the thermoset state is permanent and irreversible. Subsequently, exposure to high heat after solidifying will cause the material to degrade, not melt. This is because these materials typically degrade at a temperature below where it would be able to melt. Thermoplastics are melt-process able plastics. The thermoplastic materials are processed with heat. When enough heat is added to bring the temperature of the plastic above its melting point, the plastic melts, liquefies, or

softens enough to be processed. When the heat source is removed and the temperature of the plastic drops below its melting point, the plastic solidifies back into a glasslike solid. This process can be repeated, with the plastic melting and solidifying as the temperature climbs above and drops below the melting temperature, respectively. However, the material can be increasingly subject to deterioration in its molten state, so there is a practical limit to the number of times that this reprocessing can take place before the material properties begin to suffer. Many thermoplastic polymers are addition type, capable of yielding very long molecular chain lengths or very high molecular weights. Both thermoset and thermoplastic materials have its place in the market. In broad generalities, thermosets tend to have been around for a long time and have a well-established place in the market, frequently have lower raw material costs, and often provide easy wetting of reinforcing fiber and easy forming to final part geometries. In other words, thermosets are often easier to process than thermoplastic. Thermoplastics tend to be tougher or less brittle than thermoset. They can have better chemical resistance, do not need refrigeration as uncured thermosets frequently do, and can be more easily recycled and repaired [51].

### **3. Reinforcements**

Composite reinforcements can be in various forms such as fibers, flakes, or particles. Each of these has its own properties which can be contributed to the composites, and therefore, each has its own area of applications. Among the forms, fibers are the most commonly used in composite applications, and they have the most influence on the properties of the composite materials. These reasons are that the fibers have the high aspect ratio between length and diameter, which can provide effective shear stress transfer between the matrix and the fibers, and the ability to process and manufacture the composites part in various shapes using different techniques [51].

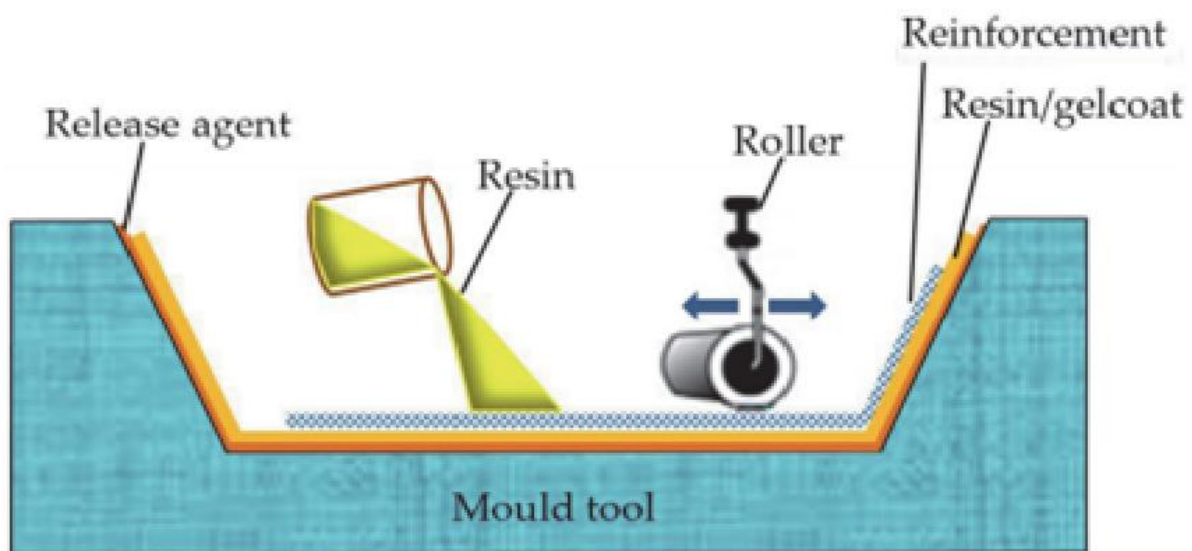
### **4. Composite manufacturing techniques**

There are several methods for fabricating composite materials. The selection of a method for a part will depend on the materials, the part design, the performance, and the end-use or application.



### a. Open contact molding

Hand lay-up is an open contact molding technique for fabricating composite materials. Resins are impregnated by the hand into fibers which are in the form of woven, knitted, stitched, or bonded fabrics. In this technique, the mould is first treated with mould release, dry fibers or dry fabrics are laid on a mould, and liquid resin is then poured and spread onto the fiber beds. This is usually accomplished by rollers or brushes, with an increasing use of nip-roller-type impregnators for forcing resin into the fabrics by means of rotating rollers and a bath of resin. A roller or brush is used to wet the fibers and remove air trapped into the lay-ups. A few layers of fibers are wetted, and laminates are left to cure under standard atmospheric conditions. After these layers are cured, more layers are added, as shown in Figure 1.

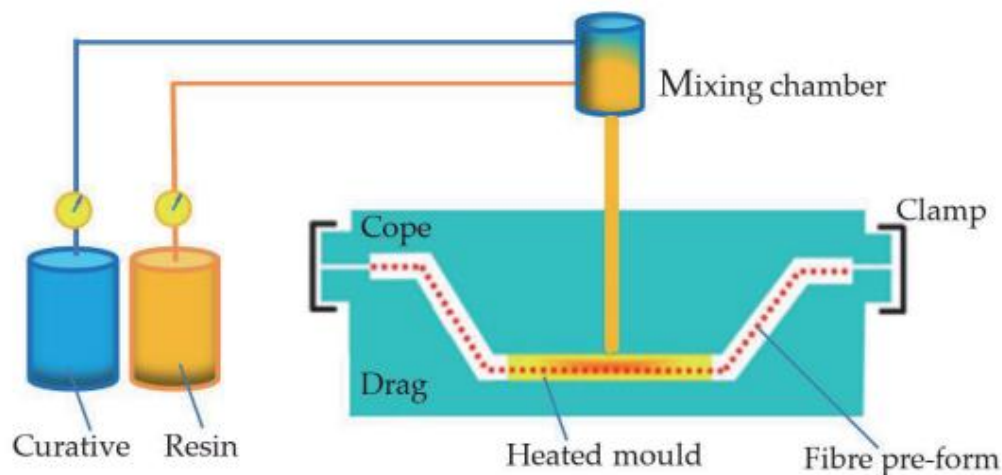


**Figure 1:** Open contact molding

### b. Resin infusion processes

With the ever-increasing demand for faster production rates, the industry has used alternative fabrication processes to replace hand lay-up as well as encouraged fabricators to automate those processes wherever possible. Resin transfer molding (RTM), sometimes referred to as liquid molding, is a fairly simple process. In this technique, the mould is first treated with mould release. The dry reinforcement, typically a preform, is then placed into the mould and the mould is closed. Low viscosity resin and catalyst are metered and mixed and then pumped into the mould under low-to-moderate pressure through injection ports, following predesigned

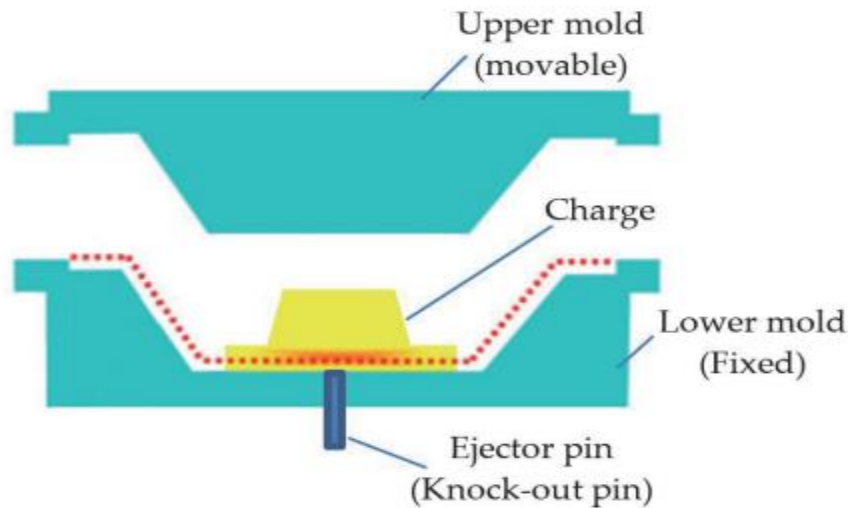
paths through the preform. Low-viscosity resin is used in RTM technique to ensure that the resin permeates through the preform quickly and thoroughly before gel and cure, especially with thick composite parts. Reaction injection molding (RIM) injects a rapid cure resin and a catalyst into the mould in two separate streams. Mixing and chemical reaction occur in the mould instead of in a dispensing head. Automotive industry suppliers have combined structural RIM (SRIM) with rapid preforming methods to fabricate structural parts that do not require a class A finish. Figure 2 describes the schematic of the RTM process.



**Figure 2:** Schematic of the RTM process

### c. Compression molding

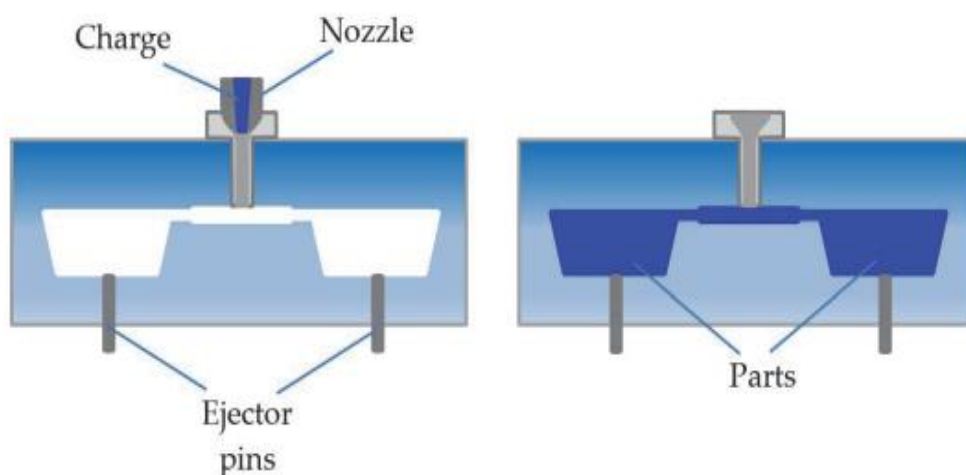
Compression molding is a precise and potentially rapid process for producing high-quality composite parts in a wide range of volumes. The material is manually or robotically placed in the mould. The mould halves are closed, and pressure is applied using hydraulic presses. Cycle time ranges depending on the part size and thickness. This process produces high-strength, complex parts in a wide variety of sizes. The composites are commonly processed by compression molding and include thermosetting prepregs, fiber-reinforced thermoplastic, molding compounds such as sheet molding compound (SMC), bulk molding compounds (BMC), and chopped thermoplastic tapes. Figure 3 shows the schematic of the compression molding process.



**Figure 3:** Schematic of the compression molding process

#### d. Injection molding

Injection molding is a closed process as shown in Figure 4. This is fast, high volume, low-pressure, and most commonly used for filled thermoplastics, such as nylon with chopped glass fiber. The injection-molding process has been in use for nearly 150 years. Reciprocating screw injection-molding machines were introduced in the 1960s and are still used today. Injection speeds are typically one to a few seconds, and many parts can be produced per hour in some multiple cavity moulds.

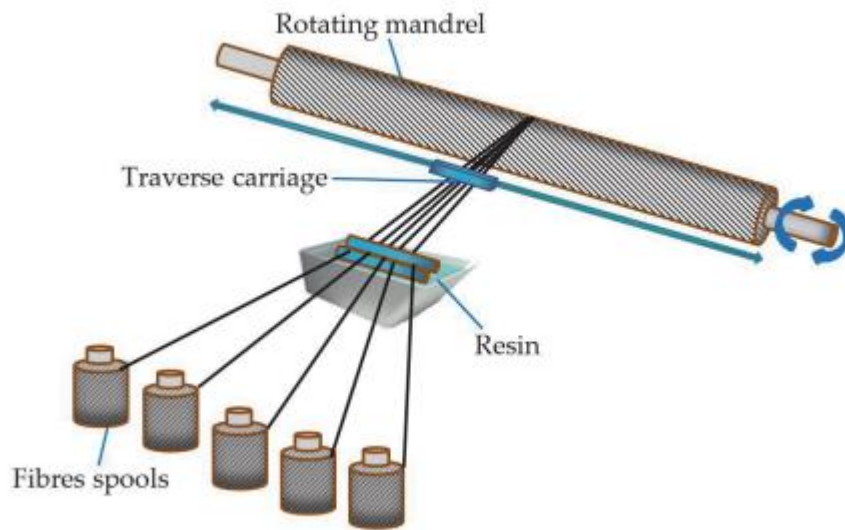


**Figure 4:** injection molding

#### e. Filament winding

Filament winding is a continuous fabrication method that can be highly automated and repeatable, with relatively low material costs as shown in Figure 5. A long, cylindrical tool

called a mandrel is suspended horizontally between end supports. Dry fibers are run through a bath of resin to be wetted. The fiber application instrument moves back and forth along the length of a rotating mandrel with the traverse carriage, placing fiber onto the tool in a predetermined configuration. Computer-controlled filament-winding machines are used to arrange the axes of motion [52], [53], [54]. Filament winding is one example of aerospace composite materials.

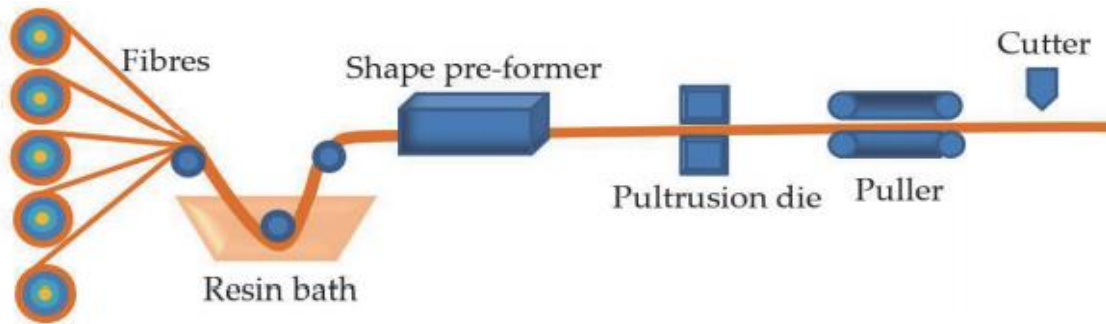


**Figure 5:** Filament winding Method

#### **f. Pultrusion process**

Composite pultrusion is a processing method for producing continuous lengths of fiber-reinforced polymer structural shapes with constant cross-sections. This is a continuous fabrication method that can be highly automated. In this process, a continuous bundle of dry fiber is pulled through a heated resin-wetting station.

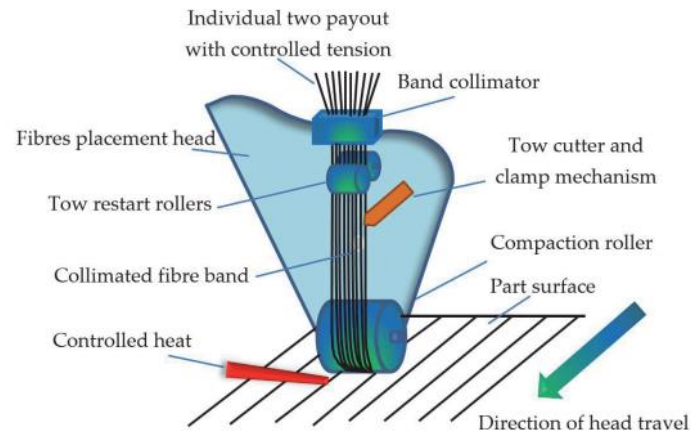
The wetted bundle is pulled into heated dies, and the cross-sectional shape of the pulled fiber is formed by these dies. The resin is cured, and the composites are formed. Parts are then made by slicing the long-cured piece. This process is limited to straight parts with a constant cross-section, such as I-beams, T-beams, or frame sections and ladder rails. Figure 6 shows the schematic of the pultrusion process [55], [56]. Pultrusion is used in the manufacture of linear components such as ladders and moldings.



**Figure 6:** Schematic of the pultrusion process

#### **g. Automated fiber placement**

Automated fiber placement (AFP) is one of the most advanced methods for fabricating and manufacturing of composite materials as presented in Figure 7. This method is used almost exclusively with continuous fiber-reinforced tape. A robot is utilized to place fiber-reinforced tape and build a structure one ply (layer) at a time. A band of material comprised of multiple narrow strips of tape (tows) is placed where these tows are commonly 0.125 and 0.25 inches wide. The use of robotics gives the operator active control over all the processes critical variables, making the process highly controllable and repeatable. This method allows the fabrication of highly customized parts as each ply can be placed at different angles to best carry the required loads [57], [58]. Advantages of fiber placement are processing speed and reduced material scrap and labor costs. Often, the process is utilized to fabricate large thermoset parts with complex shapes. Similar to ATP process, automated tape laying (ATL) is an even speedier automated process in which prepreg tape, rather than single tows, is laid down continuously to form parts.



**Figure 7:** Automated fiber placement (AFP) method

## 5. Composite applications

The most widely used form of fiber-reinforced polymer is a laminar structure, made by stacking and bonding thin layers of fiber and polymer until the desired thickness is obtained. By changing the fiber orientation among layers in the laminate structures, a specified level of anisotropy in composite properties can be achieved. Composites offer many benefits such as corrosion resistance, light weight, strength, lower material costs, improved productivity, design flexibility, and durability. Therefore, the wide range of industries uses composite materials and some of their common applications.

### a. Aerospace

The major original equipment manufacturers (OEMs) such as Airbus and Boeing have shown the potential of using composite materials for large-scale applications in aviation. NASA is continually looking to composite manufacturers for innovative approaches and space solutions for rockets and other spacecrafts. Composites with thermoset are being specified for bulkheads, fuselages, wings, and other applications in commercial, civilian, and military aerospace applications. There are several other applications of composites in the areas such as air-foil surfaces, antenna structures, compressor blades, engine bay doors, fan blades, flywheels, helicopter transmission structures, jet engines, radar, rocket engines, solar reflectors, satellite structures, turbine blades, turbine shafts, rotor shafts in helicopters, wing box structures, etc.

**b. Appliance/business**

Composite materials offer flexibility in design and processing; therefore, composite materials can be used as alternatives for metal alloys in appliances. Unlike most other industries, trends within the appliance segment move quite quickly. In addition, design and function are subject to both technology advancements and changing consumer taste. Composite materials are being used in appliance and business equipment such as equipment panels, frames, handles and trims in appliances, power tools, and many other applications. Composites are being utilized for the appliance industry in dishwashers, dryers, freezers, ovens, ranges, refrigerators, and washers. The components in the equipment that were utilized composites include consoles, control panels, handles, kick plates, knobs, motor housings, shelf brackets, side trims, vent trims, and many others.

**c. Architecture**

With their aesthetic qualities, functionality, and versatility, the composite materials are becoming the material of choice for architectural applications.

Composite materials allow architects to create designs that are impractical or impossible with traditional materials, improve thermal performance and energy efficiency of building materials, and meet building code requirements. Composite materials also offer design flexibility and can be molded into complex shapes. They can be corrugated, curved, ribbed, or contoured in a variety of ways with varying thickness. Further, a traditional look such as copper, chrome or gold, marble, and stone can be achieved at a fraction of the cost using composite materials. Therefore, the architecture community is experiencing substantial growth in the understanding and use of composites in commercial and residential buildings.

**d. Automotive and transportation**

The automotive industry is no stranger to composites. This is one of the largest markets for composite materials. Weight reduction is the greatest advantage of composite material usage. A lower-weight vehicle or truck is more fuel-efficient because it requires less fuel to propel itself forward. In addition to enabling groundbreaking vehicle designs, composites help make vehicles lighter and more fuel efficient. The composite materials are used in bearing materials, bodies, connecting rod, crankshafts, cylinder, engines, piston, etc. While fiber-reinforced polymers such as CFRP in cars get most of the attention, composites also play a big role in increasing fuel efficiency in trucks and transport systems. A number of US state

Departments of Transportation are also using composite to reinforce the bridges those trucks travel on.

#### **e. Construction and infrastructure**

Construction is one of the largest markets for composites globally. The composites can be made to have a very high strength and ideal construction materials. Thermoset composites are replacing many traditional materials for home and offices' architectural components including doors, fixtures, molding, roofing, shower stalls, swimming pools, vanity sinks, wall panels, and window frames. Composites are used all over the world to help construct and repair a wide variety of infrastructure applications, from buildings and bridges to roads, railways, and pilings.

#### **f. Energy**

Material technology has grown from the early days of glass fibers as major reinforcements for composite material to carbon fibers which are lighter and stronger. The advancements in composites, particularly those from the US Department of Energy, are redefining the energy industry. Composites help enable the use of wind and solar power and improve the efficiency of traditional energy suppliers. Composite materials offer wind manufacturers strength and flexibility in processing with the added benefit of a lightweight components and products [3], [60]. The wind industry has set installation records over the last couple years. According to the Global Wind Energy Council, the trend for this industry may continue with global wind capacity predicted to double in the next few years. Composites play a vital role in the manufacture of structures such as wind turbine blades [59], [60].

#### **g. Marine**

Just like in the other engineering areas, the main struggle of naval architecture is to achieve a structure as light as possible. The marine industry uses composites to help make hulls lighter and more damage-resistant. With their corrosion resistance and light-weighting attributes, marine composite applications include boat hulls, bulkheads, deck, mast, propeller, and other components for military, commercial, and recreational boats and ships. Composites can be found in many more areas of a maritime vessel, including interior moldings and furniture on super yachts [59], [61], [62].

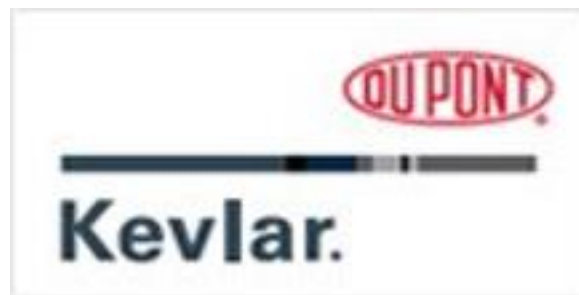


## h. Sports and recreation

The fiber-reinforced composite materials possess some excellent characteristics, including easy molding, high elastic modulus, high strength, light in weight, good corrosion resistance, and so on. Therefore, fiber-reinforced composite materials have extensive applications in production the manufacturing of sports equipment. From bicycle frames, bobsleds fishing poles, football helmets, hockey sticks, horizontal bars, jumping board, kayaks, parallel bars, props, tennis rackets, to rowing, carbon fibers, and fiberglass composite materials help athletes reach their highest performance capabilities and provide durable and lightweight equipment [59], [60], [61], [62] .

## II. Kevlar fabric

### 1. Invention of Kevlar



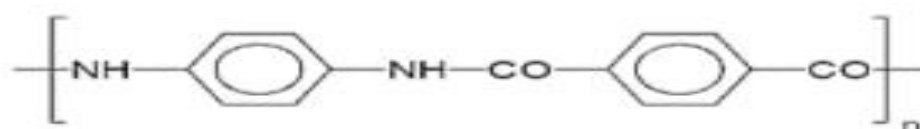
**Figure 8:** Registered Kevlar Fiber Logo

Kevlar® is a manmade fiber developed in 1965 by two research scientists, Stephanie Kwolek and Herbert Blades. The two scientists worked for the DuPont Company. Their product offered a number of benefits that led to its commercial introduction in the early 1970's. While working for DuPont in their Wilmington labs. In anticipation of a gas shortage, in 1964 the DuPont research group led by Kwolek began searching for a new lightweight but strong fiber to use for tires. One day in 1965, while trying to dissolve one of her polymers, something strange happened. Stephanie Kwolek reported: "Ordinarily a polymer solution sort of reminds you of molasses, although it may not be as thick. And it's generally transparent. This polymer solution poured almost like water, and it was cloudy. I thought, 'There's something different about this. This may be very useful.'" Normally such a "cloudy, opalescent, and low viscosity" solution would just be thrown away. However, the technician Charles Smullen who ran the "spinneret" persuaded Kwolek to test her solution. When spun into a fiber, they were amazed to find that, unlike the other well-known fiber of the time, nylon, this new fiber did not break.

Both her supervisor and laboratory director understood the significance of her discovery and a new field of aramid polymer chemistry were born. It then took six years to produce Kevlar commercially, finally reaching the market in 1971 [11].

## 2. Chemical structure

Kevlar is an aromatic polyamide known as Aramid. It is gel spun from liquid crystalline solution, with a known structure as shown in Figure 9.



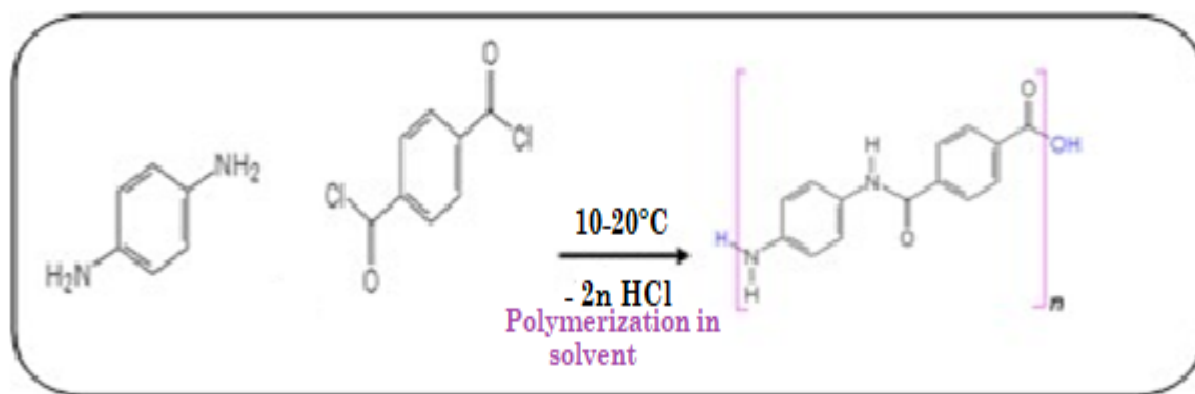
**Figure 9:** Polymeric Structure of Twaron® (poly-para-Phenylene-terephthalamide) (PPTA)

Kevlar is synthesized in solution from the monomers paraphenylenediamine (PPD) and terephthaloyl chloride (TCl) in a condensation reaction in which molecules of HCl are terminated as a byproduct [2].

Hexamethylphosphoramide was the solvent initially used for the synthesis, but for safety reasons DuPont replaced it by a solution of N-methyl pyrrolidone and CaCl<sub>2</sub>.

The resultant aromatic polyamide contains at least 85% of the amide (–CO–NH–) linkages which are attached directly to two aromatic rings. The aramid ring gives Kevlar thermal stability.

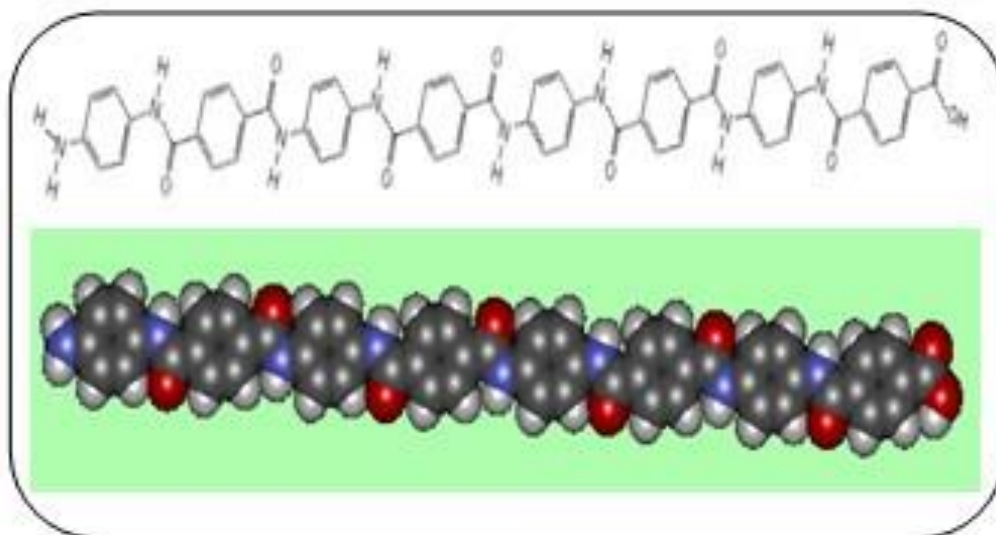
This fiber is properly known as a para-aramid thanks to its para-structure which makes it strong and increases the modulus [3].



**Figure 10:** The figure shows the condensation reaction and how the para-aramid is formed

Kevlar fiber is an array of molecules orientated parallel to each other. The orderly, untangled arrangement of molecules is described as the crystalline structure. The crystallinity is obtained by the spinning manufacturing process. This process involves the extrusion of molten polymer solution through small holes.

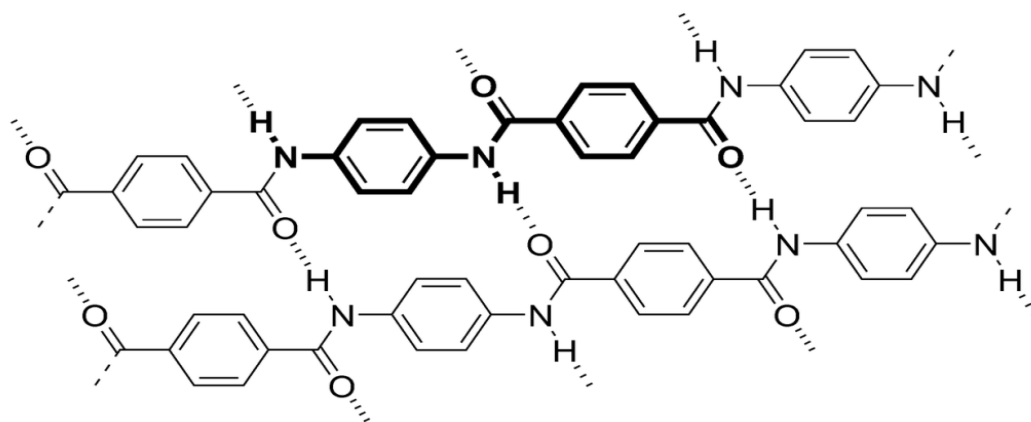
When the PPD-T solutions are extruded the liquid crystalline domains orient and align in the flow direction. Kevlar can acquire a high-degree of long, straight polymer chains parallel to the fiber axis.



**Figure 11:** a section of an individual Kevlar chain

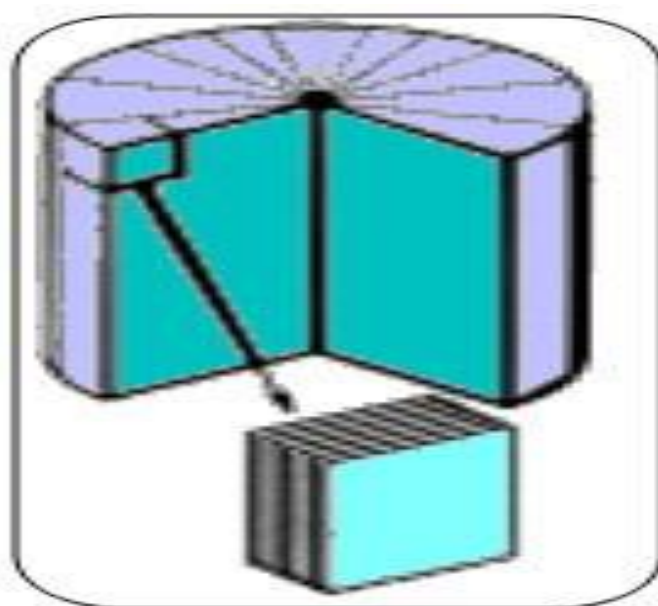
The structure has anisotropic properties, which means the fiber has higher strength in the longitudinal direction than in the axial direction. The extruded material has a fibrile structure, causing it to have poor shear and compression properties. Hydrogen bonds form between the

polar amide groups and on adjacent chains. These hydrogen bonds hold the individual Kevlar polymer chains together.



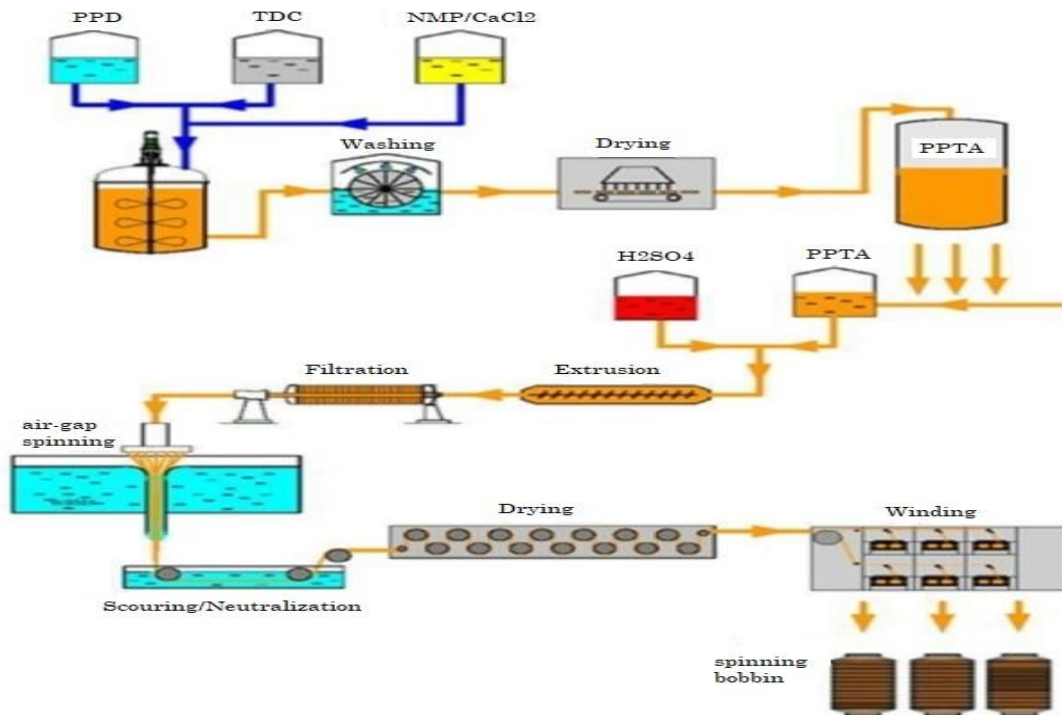
**Figure 12:** Molecular structure of Kevlar (bold represents a monomer unit, dashed lines indicate hydrogen bonds.)

A single rod- like fiber structure of Kevlar is shown in the figure 13[4].



**Figure 13:** Sheets stacked together

### 3. Dry-jet-wet spinning process of Kevlar



**Figure 14:** Figure 14: Kevlar fiber production process [5].

The resulting polymer obtained in the laboratory is pulverized, washed, and dried [6]. It is turned into fibers by a process called dry-jet-wet spinning because Kevlar decomposes at around 450 °C before it melts [7].

This is mixed with a highly concentrated sulphuric acid which is used to keep the crystalline Kevlar in the solution while it spins in the spinneret. It is very difficult to use highly concentrated sulphuric acid but it's a necessary process, that's why it is one of the most expensive steps of production. The anisotropic solution (liquid crystal domains) extruded through spinnerets at 100 °C through about 1-cm air layer is to cold water (0-4 °C). The dissolved polymer is fed out of the spinneret on an air gap to drive off the solvent where the fiber precipitates and then goes into a coagulation bath where the acid is removed, and the fiber is solidified. The spinneret capillary and air gap cause rotation and alignment of the domains resulting in highly crystalline and oriented as-spun fibers [6].

The final stages of the spinning process for the coagulated filaments consist of washing, neutralizing and drying. During the drying process a light tension is applied. This tension does not make significant stretching. The resulting fiber has a fibrillar texture, but it is highly oriented and has the necessary high crystallinity and the chain-extended structure to give it

high modulus and high strength greater than those of the flexible semi-crystalline polymer fibers [8].

## 4. Properties of Kevlar

### a. Mechanical Properties

Kevlar derives its strength from inter-molecular hydrogen bonds and aromatic stacking interactions between aromatic groups in neighboring strands. These interactions are much stronger than the Van Der Waals interaction found in other synthetic polymers and fibers. Kevlar consists of relatively rigid molecules, which form a planar sheet-like structure similar to silk protein. These properties result in its high mechanical strength [11].

The tensile strength of Kevlar ranges from about 2.6 to 4.1 GPa. This is more than twice that for conventional fibers like Nylon 66. Tensile failure initiates at the fibril ends and propagates via shear failure between the fibrils. The table below shows the differences in material properties among the different grades. Kevlar cloth is most likely to be Kevlar 49.

**Table 1: Differences in material properties among the different grades of Kevlar**

Grade	Density g/cm <sup>3</sup>	Tensile Modulus GPa	Tensile Strength GPa	Tensile Elongation %
29	1.44	83	3.6	4.0
49	1.44	131	3.6--4.1	2.8
149	1.47	186	3.4	2.0

The tensile modulus and strength of Kevlar 29 is roughly comparable to that of glass (S or E), yet its density is almost half that of glass. Thus, to a first approximation, Kevlar can be substituted for glass where lighter weight is desired. Kevlar 49 or 149 can cut the weight even further if the higher strength is accounted for. Of course, Kevlar's weight savings does come at a price: Kevlar is significantly more expensive than glass [9].

Kevlar behaves elastically in tension. In compression, it shows nonlinear, ductile behavior. It exhibits yield at compression strains of 0.3 to 0.5%. This corresponds to formation of structural defects known as kink bands. These bands are related to compressive buckling of the aramid molecules. Aramid fibers are noted for toughness and general damage tolerance. Kevlar 29 has the lowest modulus and highest toughness, and the tensile elongation of Kevlar 29 is about 4%. The fibrillar structure and compression behavior contribute to composites that

are less notch-sensitive and which fail in a ductile, non-catastrophic manner, as opposed to glass and carbon [3].

The aromatic structure gives the fibers a high degree of thermal stability. They decompose in air at about 425°C and are inherently flame resistant. Aramids have a slight negative longitudinal coefficient of thermal expansion of about  $-2 \times 10^{-6}/\text{K}$  and a positive transverse expansion of  $60 \times 10^{-6}/\text{K}$ . They also have a low thermal conductivity that varies by about an order of magnitude in the longitudinal versus transverse direction [3].

#### **b. Effect of Chemical agents on Kevlar**

Kevlar® is chemically stable under a wide variety of exposure conditions; however, certain strong aqueous acids, bases and sodium hypochlorite can cause degradation, particularly over long periods of time and at elevated temperatures [11].

#### **c. Effect of PH on Kevlar**

PH Stability Degradation can occur when Kevlar® is exposed to strong acids and bases. At neutral pH (pH 7), the filament tenacity remains virtually unchanged after exposure at 65°C for more than 200 days. The further the pH deviates from pH 7, the greater the loss in tenacity. Acidic conditions cause more severe degradation than basic conditions at pH levels equidistant from neutral [11].

#### **d. Effect of water on Kevlar**

Kevlar molecules have polar groups accessible for hydrogen bonding. Water that enters the interior of the fiber can take the place of bonding between molecules and reduce the material's strength, while the available groups at the surface lead to good wetting properties [1].

#### **e. Thermal properties**

##### **i. Effect of Elevated Temperatures on Tensile Properties**

Kevlar® does not melt; it decomposes at relatively high temperatures 427°C to 482°C in air and approximately 538°C in nitrogen.

Kevlar maintains its strength and resilience down to cryogenic temperatures ( $-196^\circ\text{C}$ ). In fact, it is slightly stronger at low temperatures. At higher temperatures the tensile strength is

immediately reduced by about 10–20%, and after some hours the strength progressively reduces further [12].

## **ii. Effect of Elevated Temperatures on Dimensional Stability**

Kevlar® does not shrink like other organic fibers when exposed to hot air or hot water. Most other fibers suffer significant, irreversible shrinkage.

Kevlar® has a very small, negative coefficient of thermal expansion (CTE) in the longitudinal direction [11].

## **f. Flammability of Kevlar:**

Because it is highly unsaturated, as the ratio of carbon to hydrogen atoms is quite high, it has a low flammability [1].

Kevlar® is inherently flame resistant but can it be ignited (limiting oxygen index of 29). Burning usually stops when the ignition source is removed; however, pulp or dust, once ignited, may continue to smolder.

## **g. Effect of UV Light on Kevlar**

Like other polymeric materials, Kevlar® is sensitive to UV (ultraviolet) light. Unprotected yarn tends to discolor from yellow to brown after prolonged exposure. Extended exposure to UV can also cause loss of mechanical properties, depending on wavelength, exposure time, radiation intensity and product geometry [11].

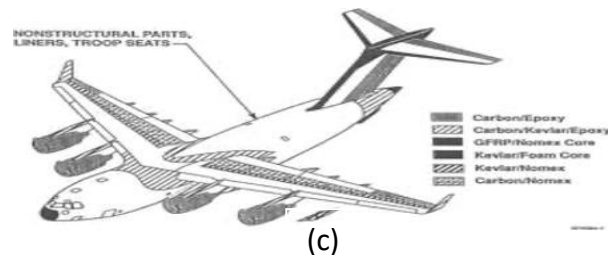
# **5. Uses & Applications**

## **a. Industrial applications**

Kevlar is used to make industrial equipment such as hoses, belts, reinforcement materials. It is used to make parts of aircrafts, ship hulls and reinforce tires [2].

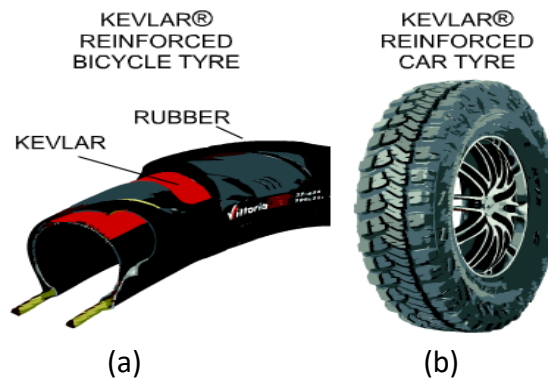






**Figure 15:** (a) Kevlar reinforced hoses (b) Kevlar reinforced belts (c) Kevlar in Aircraft

In fast racing cars and bikes, excessive friction on tires causes burning and overheating. The tire is composed of steel wires wrapped in rubber. These steel wires are insufficient to absorb all heat. Nowadays racing car tires have KEVLAR as their essential ingredient because it is good heat resistant material with the ability to work in high tension situations [13].



**Figure 16:** Kevlar reinforced (a) Bicycle Tire (b) Car Tire

## b. Sports Equipment

Kevlar is used in making of various sports equipment due to light weight and strength. It is used in both snowboards and skis for their core material. The combination of being both lightweight, as well as incredibly strong makes the chances of the board or skis breaking on a crash significantly less likely [14]. Kevlar is also used for the interior of ping pong paddles, table tennis, badminton, squash rackets, cricket bats and hockey sticks, sport shoes, gloves, motor sport helmets etc [2].



**Figure 17:** Kevlar in Some sports equipment

### c. Technology

Even the phone could possibly have Kevlar within it. Phone companies are now using Kevlar in their back panels. This helps to protect the inner workings of the phone in case it is dropped or damaged [14].



**Figure 18:** iPhone Cover Carbon Fiber Kevlar

### d. Musical Instruments

#### i. Audio equipment

Kevlar has also been found to have useful acoustic properties for loudspeaker cones, specifically for bass and mid-range drive units [1]. Additionally, Kevlar has been used as a strength member in fiber optic cables such as the ones used for audio data transmissions [1].

#### ii. Bowed string instruments

Kevlar can be used as an acoustic core on bows for string instruments [17]. Kevlar's physical properties provide strength, flexibility, and stability for the bow's user. To date, the only manufacturer of this type of bow is Coda Bow [15]. Kevlar is also presently used as a material

for tailcords (a.k.a. tailpiece adjusters), which connect the tailpiece to the endpin of bowed string instruments.

### iii. Drumheads

Kevlar is sometimes used as a material on marching snare drums. It allows for an extremely high amount of tension, resulting in a cleaner sound. There is usually a resin poured onto the Kevlar to make the head airtight, and a nylon top layer to provide a flat striking surface. This is one of the primary types of marching snare drumheads. Remo's Falam Slam patch is made with Kevlar and is used to reinforce bass drumheads where the beater strikes [16].

### iv. Woodwind reeds

Kevlar is used in the woodwind reeds of Fibracell. The material of these reeds is a composite of aerospace materials designed to duplicate the way nature constructs cane reed. Very stiff but sound absorbing Kevlar fibers are suspended in a lightweight resin formulation.

### e. Personal safety equipment

Kevlar is used in production of various personal protection gears such as riding shoe, helmets, industrial gloves, firefighting apparel, body pads etc [2].



**Figure 19:** Personal safety equipment

### f. In manufacturing of Military Equipments

Because of its light weight and high tensile strength Kevlar is used in production of various Army gear such as Military helmets, Vehicle Armors, Body Armors, Tactical Vests, Fighter Plane's Wings and other parts etc [2].



**Figure 20:** Military Equipments

## 6. Comparison with E Glass and Carbon Fiber

### a. Tensile Strength

The following Table presents the Tensile Strength comparison of E Glass, Carbon Fiber and Kevlar®.

**Table 2: Tensile Strength of E Glass, Carbon Fiber and Kevlar [48]**

	Fiber Strength (MPa)	Laminate Strength (MPa)
E Glass	3450	1500
Carbon Fiber	4127	1600
Kevlar®	2757	1430

### b. Density and Strength to Weight Ratio

**Table 3: Density and strength to Weight Ratio of E Glass, Carbon Fiber and Kevlar**

	Density of Laminate grams/cc	Strength-to-Weight (kN.m/kg)
E Glass	2.66	564
Carbon Fiber	1.58	1013
Kevlar	1.44	993

When we compare the density of the 3 materials, we see a significant difference. If we make up 3 samples exactly the same size and weight them, we quickly see that Kevlar® fiber is much lighter, Carbon Fiber is next, and the E Glass is the heaviest.

In other words, any structure, where we require a given strength, can be smaller or thinner if made out of carbon fiber or Kevlar® composite than if made out of glass.

Kevlar® (Aramid) and Carbon Fibers have a high strength-to-weight ratio when tested unidirectionally in direction of the fibers, while e glass has a lower strength-to-weight ratio. Glass is still quite high, just not as good as Kevlar® or Carbon [48].

### c. Compression Strength

Whereas Carbon and Glass are only slightly less strong and stiff in compression than in tension, Kevlar® is much less stiff and strong when compressed. In fact, in some tests the Kevlar® was failing before the resin matrix. According to Researchers at Rowan University, pdf document, "The compressive strength of Kevlar® is 1/10 of its ultimate tensile strength". Kevlar® is strong but does not like to be hit sideways which causes a compression strain, and often a crack [48].

### d. Modulus of Elasticity

**Table 4: Modulus of Elasticity of E Glass, Carbon Fiber and Kevlar**

Material	Young's Modulus
E Glass	30-40
Carbon Fiber	125-181
Kevlar®	70.5-112.4

The stiffness of Carbon Fiber, Kevlar® and Glass are very different. Carbon Fiber is by far the stiffer of the composite materials. It is twice as stiff as Kevlar, and about 5 times stiffer than glass.

### e. Flammability and Thermal Degradation

Both Kevlar® and Carbon Fiber are resistant to elevated temperatures. Neither have a melting point. Both Materials have been used for protective clothing and fabrics used near fire.

Glass eventually melts but is also highly resistant to high temperatures. For this reason, fiberglass is sometimes used for curtains in areas where fire resistance is important. Matted glass fiber of course is used in buildings to improve fire resistance [48].

**f. Electrical Conductivity**

While carbon fiber is very definitely conductive, Kevlar® and Glass do not conduct electricity.

Kevlar® is used for guy lines in transmission towers. Although it is not conductive, it can absorb water and the water does conduct electricity (or rather minerals in the water make it conductive.) so in such applications a waterproof coating is applied to the Kevlar.

Because Carbon Fiber does conduct electricity, galvanic corrosion is a concern when it is in contact with other metallic parts. [48]

**g. UV Degradation**

Aramid fibers will degrade in Sunlight and high UV environment.

Carbon Fiber or glass are not very sensitive to UV radiation.

If you anticipate using these fibers as reinforcement of a composite which will be utilized outside you need to protect this composite from UV. Some resins are available [48].

**h. Fatigue Resistance**

Carbon fiber is somewhat sensitive to fatigue and tends to fail catastrophically without showing many signs of distress, Kevlar® is more resistant to fatigue. Glass is somewhere in between and can be quite fatigue resistant depending on the type of glass and the setup.

**i. Abrasion Resistance**

Kevlar® has a strong abrasion resistance. This makes it difficult to cut. Suppliers often sell special shears and extra strong scissors for Kevlar® cloth. One of the common uses of Kevlar® is as a protective glove for use in areas where the hand might be cut by glass, or while using sharp blades. Carbon fiber and Glass are less resistant.

**j. Chemical Resistance**

Aramids are sensitive to strong acids, bases, and some oxidizers, like chlorine bleach (sodium hypochlorite). These cause degradation of the fiber. Regular chlorine bleach and hydrogen peroxide cannot be used with Kevlar®, oxygen bleaches such as sodium perborate can be used without damaging the Aramid fiber.

Carbon Fiber is very stable and is not sensitive to chemical degradation [48].

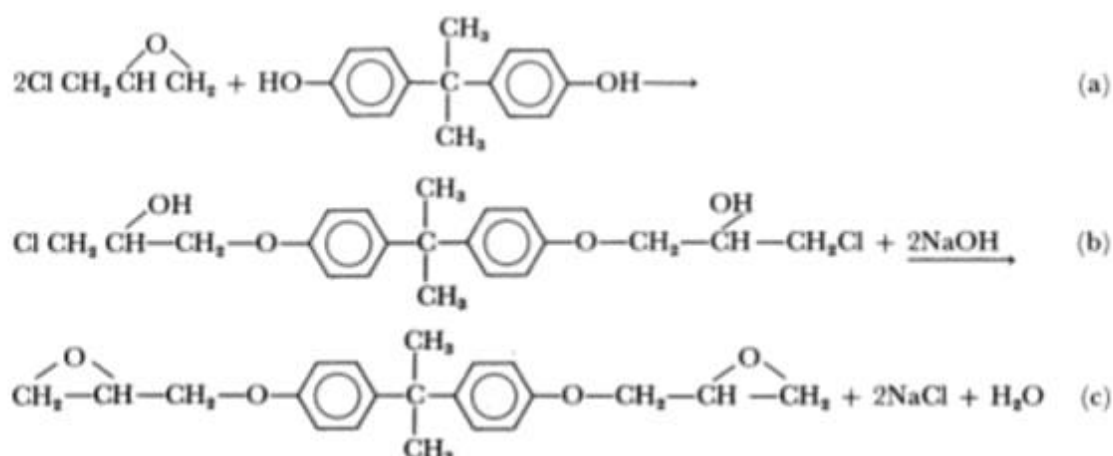
### III. Epoxy resin

#### 1. Introduction

Aramid fibers are widely used for reinforcing composite materials, often in combination with carbon fiber and glass fiber. The matrix for high performance composites is usually epoxy resin. It comes under the category of “thermoset” family of resins. Once cured it cannot be melted by the application of heat. The diglycidyl ether of bisphenol A (DGEBA) is the most commonly used synthetic epoxy resin. The epoxy resins used in adhesive formulations vary from aliphatic resins having simple, low molecular weight to aromatic resins which are complex and multifunctional. These can be produced by chemical reaction and by incorporating preformed filler in the liquid system [15] to produce laminated epoxy insulations. Sheets of woven glass, paper, and polyaramid fabric or cotton preprinted with the B-stage epoxy resins are laminated in large multiple patterns presses to make hard and rigid materials in the form of sheets, rods, and tubes.

#### 2. Epoxy Resin Manufacture and Characterization

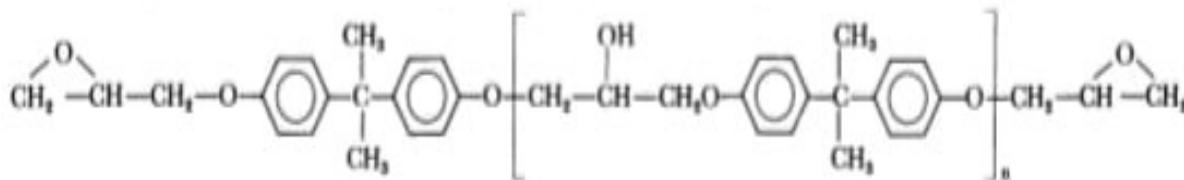
By far the most important class of epoxy resins used at present on a large scale commercially is that based upon the reaction between diphenylol propane (DPP) and epichlorhydrin (ECH) in the presence of alkali. The basic reactions are shown in Figure 13.



**Figure 21:** reaction between diphenylol propane (DPP) and epichlorhydrin (ECH)

The basic reaction is formation under alkaline conditions of a chlorohydrin ether of DPP (b) followed by dehydrochlorination of the chlorohydrin group by alkali to form an epoxy group,

thus giving the diglycidyl ether of DPP (c). An excess of ECH will favor a high proportion of the simple diglycidyl ether of DPP; higher DPP ratios will give higher molecular weight polymers. Commercial grades of resin can be represented by the following formula:



**Figure 22:** Commercial grades of resin

The pure diglycidyl ether of DPP with  $n=0$  is a crystalline solid. The commercial low viscosity liquid resins are rich in this compound and the average  $n$  is approximately 0.2. Viscosity can be further reduced by addition of monoepoxide compounds such as aliphatic glycidyl ethers. In low melting point solid resins average  $n$  is approximately 2. The common commercial high molecular weight resins have average  $n$  up to 13. There are also very high molecular weight resins with molecular weights up to 200000. These resins have mainly hydroxy groups and practically no epoxy groups and are used as thermoplastic resins for non-convertible coatings [17].

### 3. Properties

Epoxy resins are highly reticulated thermosetting polymers which are easy to process, with high-performance, containing at least two epoxy groups per molecule. Due to the high reactivity of epoxy ring (polar groups), Epoxy resins have good adhesion to a wide range of materials, including metals, wood, concrete, glass, ceramic, Kevlar and many plastics.

They cure without splitting off any volatile matter, with negligible shrinkage, and without requiring the application of pressure. When cured, they have excellent mechanical and electrical properties, outstanding stability, and excellent resistance to atmospheric and chemical attack. This unique combination of properties makes epoxy resins extremely versatile and, since the resins are available in many forms, some curing at room temperature and others at elevated temperatures, their field of use is expanding rapidly [18].

Epoxy resins are flexible, highly resistant to chemical solvents, and ambient moisture due to their long hydrophobic chains, excellent electrical insulating properties, and minimum



shrinkage on curing which provides good dimensional stability. They are well known for high tensile, flexural, and modulus properties [16].

## 4. Application fields

### a. Paints and coatings

Epoxy resins are widely used as heavy-duty anticorrosion coatings because of their exceptional properties, such as easy processing, high safety, excellent solvent and chemical resistance, toughness, low shrinkage on cure, mechanical and corrosion resistance, and excellent adhesion to many substrates. Metal cans and containers are often coated with epoxy resins to prevent rusting, especially when packaging acidic foods like tomatoes. Epoxy resins are also used for high performance and decorative flooring applications such as terrazzo, chip, and colored aggregate flooring [19], [21] et [22].



**Figure 23:** Photos of epoxy resins used in paints and coatings

### b. Adhesives

Epoxy adhesives are a major part of the class of adhesives called “structural adhesives”. These high-performance adhesives are used in the construction of aircraft, automobiles, bicycles, boats, golf clubs, skis, snowboards, and other applications where high strength bonds are required. When used as adhesives in cryogenic engineering applications, it is necessary to optimize the epoxy shear strength at both cryogenic and room temperatures. Commercial epoxy adhesives are engineered for optimal toughness by incorporating phase-separated thermoplastics, rubber particles, or rigid inorganic particles into the matrix. Typically, the adhesives are cured at elevated temperatures to increase their strength and activate chemical bonding at the substrate/adhesive interface [22], [23], [24], [25] et [26].



**Figure 24:** Photos of epoxy resins used in Adhesives

### **c. Industrial tooling**

Epoxy systems are used in industrial tooling applications to produce molds, master models, laminates, castings, fixtures, and other industrial production aids. This “plastic tooling” replaces metal, wood, and other traditional materials, and generally improves the process efficiency while either lowering the overall cost or shortening the lead-time for many industrial processes. Fiber-reinforced epoxy composites have proven effective in repairing metallic components and tubular pipes. The composites also act as load-bearing units in hydrogen storage cylinders [29], [28], [29] et [30].

### **d. Aerospace industry**

Epoxy resins have been extensively used for structural adhesive applications in the aerospace industry because of their high adhesive properties and low cost. Epoxy resins reinforced with high strength glass, carbon, Kevlar, or boron fibers have the greatest potential for use in the aerospace industry



**Figure 25:** Photos of epoxy resins used in aerospace industry

### **e. Electronic materials**

Epoxy resin formulations are important in the electronics industry, and are employed in motors, generators, transformers, switchgear, bushings, and insulators. Epoxy resins are excellent electrical insulators and protect electrical components from short circuiting, dust, and moisture. Metal-filled polymers are extensively used for electromagnetic interference

shielding [31]. Epoxy molding compounds (EMCs) are popularly used as encapsulation materials for semiconductor devices protect the integrated circuit devices from moisture, mobile-ion contaminants, and adverse environmental conditions such as temperature, radiation, humidity, and mechanical and physical damage [32], [33]. Epoxy composites containing particulate fillers, such as fused silica, glass powder, and mineral silica have been used as substrate materials in electronic packaging applications [34], [35].



**Figure 26:** Photos of epoxy resins used in electronic materials

#### **f. Biomedical systems**

Epoxy resins are widely used in biomedical applications. Collagen-based materials have been used in human clinical applications as wound dressings, vascular grafts, and aortic heart valves [36]. Shape memory polymer foams have significant potential for biomedical applications such as embolic sponges [37]. Nanodiamond-epoxy derivatives have found considerable application in biomedical systems because they exhibit a combination of extreme hardness, outstanding chemical inertness, low electrical and high thermal conductivities, wide optical transparency, and other unique properties [38], [39].

### ***IV. Important parameters***

#### **1. Thermal conductivity**

It presents the total heat transmitted through composite. It can be expressed using this equation:

$$K = (Q/A) / (\Delta T / \Delta L) \quad (1)$$

**Where**

- **K** is the thermal conductivity (W /m-K),
- **Q** is the Heat Flux (W),
- **A** is the cross-sectional area of the specimen (m<sup>2</sup> ),
- **ΔT** is the Temperature difference (K),
- **ΔL** is the overall distance (m).

Thus, the thermal conductivity of a material can be defined as a rate at which heat is transferred by conduction through a given unit area of a given material, when the temperature gradient is normal to the cross-sectional area. The thermal conductivity of a composite material depends on the fiber, resin materials, fiber volume fraction, orientation of the fiber, direction of heat flow and operating temperature [40].

## 2. Relative Water vapor permeability

It represents the resistance of a composite to the transfer of water vapor also known as insensible perspiration, released by human body. Relative water vapor permeability is the percentage of water vapor transmitted through the composite sample compared with the percentage of water vapor transmitted through an equivalent thickness of air. It can be expressed by this equation:

$$p = 100 \times (q_s / q_0) \quad (2)$$

**Where:**

- **q<sub>s</sub>**: presents the heat flow value with a sample (w/m<sup>2</sup>);
- **q<sub>0</sub>**: presents the heat flow value without a sample (w/m<sup>2</sup>).

A Kevlar/epoxy composite with a low moisture vapor permeability value is unable to pass sufficient perspiration and this causes sweat accumulation in the composite.

## 3. Air permeability

The air permeability is a very important factor in the performance of some textile materials. It is a parameter which can characterize certain component of physiological comfort of many

textile products, such as industrial curtains, sails, body armor, airbags and parachutes. The air permeability is mainly dependent upon the material weight and construction (thickness and porosity) [41].

The standard measure of air permeability is the speed of air passing perpendicularly through the sample depending on its surface area and pressure drop.

#### **4. Tensile Strength**

Tensile Strength is the maximum stress a material subjected to a stretching load can withstand without tearing [42].

Tensile strength varies by material. Some non-brittle material distorts before breaking, but Kevlar, Carbon Fiber and E glass are brittle and fail with almost no distortion. Tensile Strength is measured in Force per unit area: Pa or Pascals. Ultimate tensile strength (UTS) or ultimate strength is terms also used.

#### **5. Stiffness or Modulus of Elasticity**

Young's modulus is a measure of the stiffness of an elastic material which is defined by a linear relationship between the normal stress  $\sigma$  acting on the surface of a particle and the strain  $\epsilon$  measured in the same direction as the stress acts. Normally, these variables are determined by a uniaxial tensile or compression test.

The stiffness of the material is then defined by the relationship

$$E = \sigma / \epsilon \quad (3)$$

Where the Modulus of elasticity E (YOUNGS modulus) functions as the “Material stiffness”. This law is well known as HOOKE’S law of elasticity [43].

In other words, materials with a high Youngs Modulus are stiffer than materials with lower Youngs Modulus.

#### **6. Stab resistance**

The stab resistance is the resistance of a material to the penetration of the knife to a certain depth. The cutting width and the penetration depth depend mainly on nature, shape, size of knife and operating parameters such as speed, depth and working conditions.

## **V. Conclusion**

The purpose of this chapter was to explore the field of Kevlar fibers, epoxy resin and their new applications. The study of chemical, physical and mechanical of Kevlar fibers will guide us in the mechanical characterization of Kevlar reinforced epoxy resin composites which will be described in the next chapter.

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## **Chapter 2: Materials and methods**

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This chapter will be devoted first of all to the presentation of the textile materials and equipment used in this work. Secondly, to the different processes followed for the fabrication of composites and the determination of its mechanical and comfort parameters.

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## I. Equipment used

### 1. Laboratory and technical equipment

This project took place in the chemistry laboratory located in the department of Material Engineering in Technical university of Liberec.

The tasks that were completed there are:



- Preparation of specimens
- Preparation of matrix
- Preparation of composite

The mechanical and comfort properties tests were done in Department of Textile Evaluation.

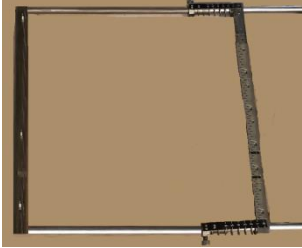

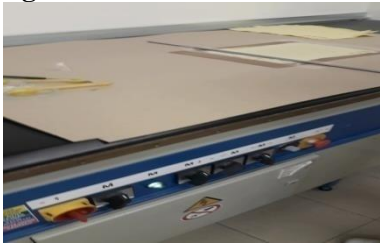


### 2. Equipment





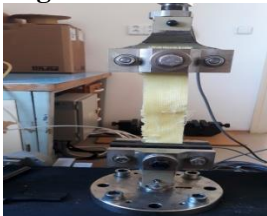

The Laboratory equipment used in this study is presented in table 5:

**Table 5: Analysis equipment**

Process	Equipment	Use
Fabrication of Composites	<b>General Purpose Electronic Balance :</b> 	Used to measure the quantity of resin mixed with the quantity of hardener.
	<b>Plastic pipette:</b> 	Used in the deposition of resin on composite.



	<b>Support garnished with needles:</b> 	Used for specimen fixation.
	<b>Forced Ventilation Conditioning Oven:</b> 	Used for the resin curing.
	<b>Printing Machine:</b> 	Used in the deposition of resin on composite.
<b>Structural and physical testing</b>	<b>Analytic balance Weighing capacity:</b> 	Used to measure the weight of specimens by using a beaker to obtain precise values.
	<b>Thickness-Lab:</b> 	Used to measure the thickness of specimens.

<b>Mechanical and comfort testing</b>	<b>ALAMBETA Test Instrument:</b> 	Used to measure the thermal conductivity of composites.
	<b>PERMETEST Instrument:</b> 	Used to measure the relative water vapor of composites.
	<b>Air Permeability Tester:</b> 	Used to measure the air permeability of composites.
	<b>Microscope:</b> 	Used to get photos of the enlarged structure of composites in order to measure certain parameters.
	<b>Tensile strength Tester:</b> 	Used to measure the Tensile strength of composites.
	<b>Knife Tester:</b> 	Used to measure the stab resistance of composites.

## II. Materials used

Materials of the following specifications were used in the fabrication of our composites.

## 1. Reinforcement

### a. Used fabric and its characteristics

In this project, one basic textile fiber was used: the Kevlar® KM2. Then, one weaving concept is utilized for the preparation of composites and the evaluation of its mechanical and comfort properties. This weave is the plain weave which consists of yarns interlaced in an alternating fashion one over and one under every other yarn as shown in table 3.

**Table 6: Fabric Structure**

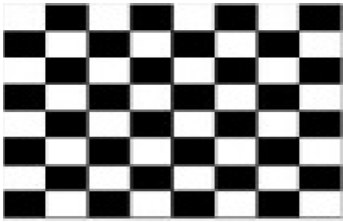
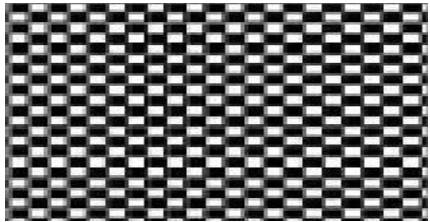
Weave	Weave Design	
Plain		

Figure 27 shows the plane texture of our fabric which is imaged by an optical Microscope. K706 is the style of our plain-woven Kevlar fabric used in this study.



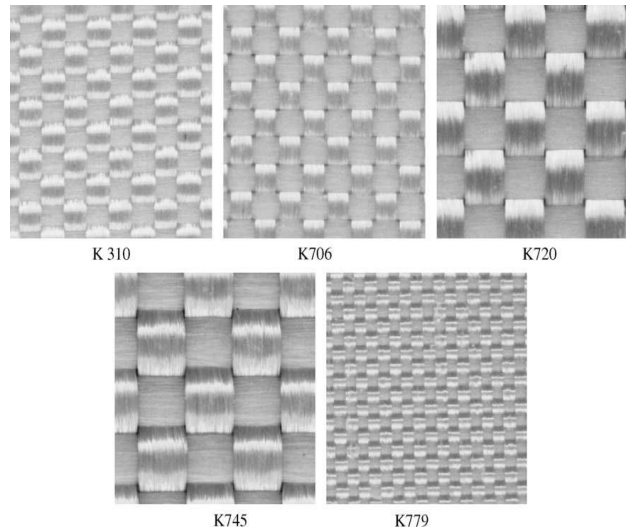
**Figure 27:** Optical image of K706 plain woven Kevlar fabric

**b. Comparative study of five styles of plain-woven Kevlar fabrics on their property's specifications**

Five styles of plain-woven Kevlar fabrics are shown in Figure 28. The property specifications given by the manufacture are listed in Table 4. These fabrics are quite different in fiber type, yarn size, fabric counts, thickness and weight. They can be easily classified into three groups: fabrics K310 and K706 are thin and have a medium weave; fabrics K720 and K745 are thick, heavy, and have a coarse weave; fabric K779 is thin and has a fine and tight weave.

**Table 7: Product data of plain-woven Kevlar fabrics**

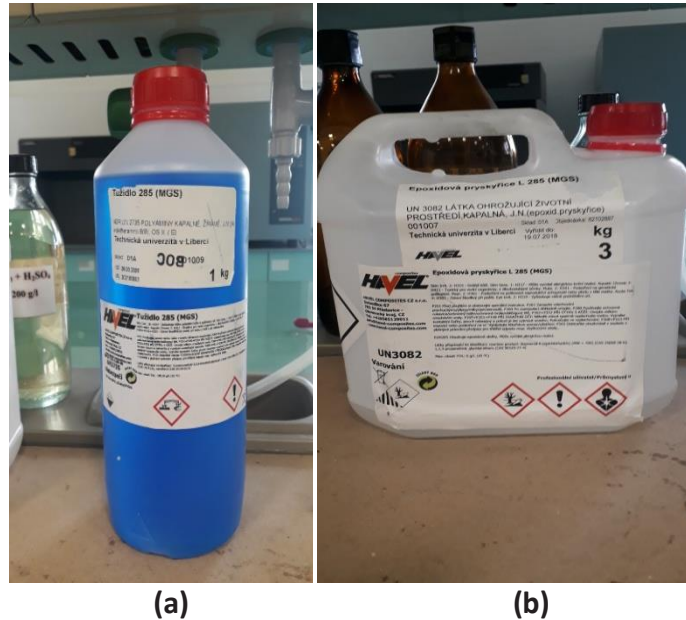
Fabric Style	K310	K706	K720	K745	K779
Fiber Type	<b>Comfort</b>	<b>KM-2</b>	<b>129</b>	<b>29</b>	<b>159</b>
Fiber modulus(GPa)	<b>87.0</b>	<b>80.0</b>	<b>99.7</b>	<b>73.0</b>	<b>97.2</b>
Yarn Size (Denier)	<b>400</b>	<b>600</b>	<b>1420</b>	<b>3000</b>	<b>200</b>
Weight (g/m <sup>2</sup> )	<b>122</b>	<b>180</b>	<b>258</b>	<b>475</b>	<b>132</b>
Warp count (yarns/in.)	<b>35.5</b>	<b>34</b>	<b>20</b>	<b>17</b>	<b>70</b>
Weft count (yarns/in.)	<b>35.5</b>	<b>34</b>	<b>20</b>	<b>17</b>	<b>70</b>
Warp Strength (lbs/in.)	<b>530</b>	<b>775</b>	<b>978</b>	<b>1600</b>	<b>385</b>
Weft Strength (lbs/in.)	<b>530</b>	<b>880</b>	<b>992</b>	<b>1800</b>	<b>530</b>
Thickness(mm)	<b>0.18</b>	<b>0.23</b>	<b>0.36</b>	<b>0.61</b>	<b>0.18</b>



**Figure 28:** Optical images of five styles of plain-woven Kevlar fabrics.

## 2. Matrix

In this project, L285 epoxy resin is selected as matrix for its good features as mechanical and thermal properties and a wide operating temperature range. This resin can be mixed with one of 3 types of hardeners LH 285, 286, 287. But, for the preparation of our composite, we mixed the epoxy resin with LH 285.



**Figure 29:** (a) 1Kg of hardener 285 (MGS) (b) 3Kg of epoxy resin L285

### a. Characteristics

The following table shows the different characteristics of epoxy resin L285.

**Table 8: Characteristics of epoxy resin L285**

<b>Approval</b>	German Federal Aviation Authority
<b>Application</b>	production of gliders, motor gliders and motor planes, boat and shipbuilding, sports equipment, model airplanes, moulds and tools
<b>Operational temperature</b>	-60 °C up to +50 °C (-76 °F up to 122 °F) without heat treatment -60 °C up to +80 °C (-76 °F up to 176 °F) after heat treatment
<b>Processing</b>	at temperatures between 10 °C and 50 °C (50-122 °F) all usual processing methods
<b>Features</b>	extremely good physiological compatibility, good mechanic and thermal properties, pot life of approx. 45 min. to approx. 4 hours

<b>Special modifications</b>	LR 285T: thixotropic LR 285W: white
<b>Storage</b>	shelf life of 24 month in originally sealed containers

## b. Specifications

This section describes the Specifications of Laminating resin LR 285 (Table 6) and Hardener LH 285 (Table 7) at a measuring condition: 25 °C / 77 °F.

**Table 9: Specifications of Laminating resin LR 285**

	<b>Laminating resin LR 285</b>
<b>Density [g/cm<sup>3</sup>]</b>	1,18 - 1,23
<b>Viscosity [mPas]</b>	600 - 900
<b>Epoxy equivalent [g/equivalent]</b>	155 - 170
<b>Epoxy value [equivalent/100g]</b>	0,59 - 0,65
<b>Refractory index</b>	1,525 -1,5300

**Table 10: Specifications of Hardener LH 285**

	<b>Hardener LH 285</b>
<b>Density [g/cm<sup>3</sup>]</b>	0,94 - 0,97
<b>Viscosity [mPas]</b>	50 - 100
<b>Amine value [mg KOH/g]</b>	480 - 550
<b>Refractory index</b>	1,5020 - 1,5500

### Where:

- The density of a substance is its mass per unit volume. It is defined as mass divided by volume:  
$$\rho = m/v \quad (4)$$
- The viscosity is a measure of a fluid's resistance to flow. It describes the internal friction of a moving fluid. A fluid with large viscosity resists motion because its molecular makeup gives it a lot of internal friction. A fluid with low viscosity flows easily because its molecular makeup results in very little friction when it is in motion.

- The epoxy equivalent represents the weight of resin that has one reactive group.
- The amine value represents the weight of amine reactive group on 1g of epoxy resin.
- The refractive index of a material is a dimensionless number that describes how fast light travels through the material. It is equal to the velocity of light  $c$  of a given wavelength in empty space divided by its velocity  $v$  in a substance:  $n = c/v$  (5)

### c. Processing details + mixing ratios

Processing details and mixing ratios used in the experimental part are presented in table 8 and table 9.

**Table 11: Processing details**

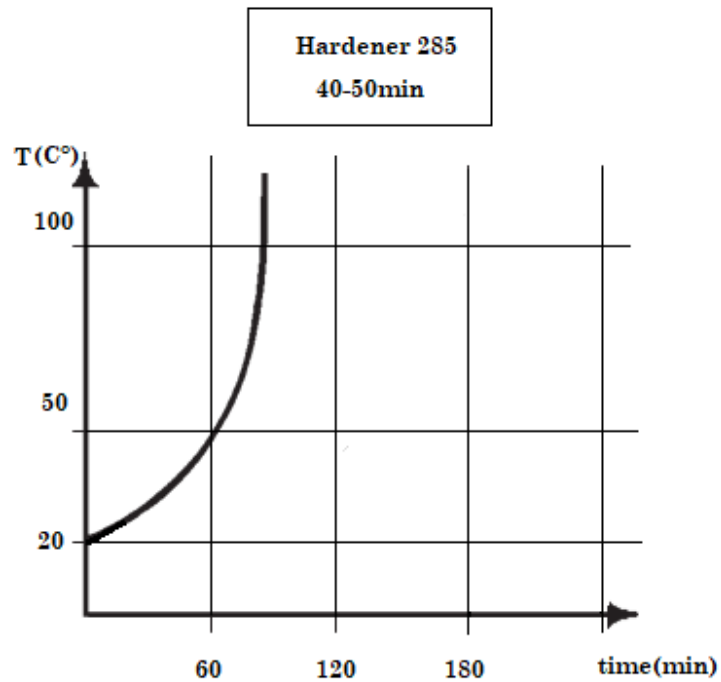
	Resin L285	Hardener285
Average EP -Value	0,62	--
Average amine equivalent	--	64

**Table 12: Mixing ratios**

	ResinL285:Hardener285
Parts by weight	100:40(+/-2)
Parts by volume	100:50(+/-2)

### d. Temperature rise

The curve below represents the rise in temperature of 100g of Laminating resin L285 mixed with Hardener 285 at 20 °C.

**Figure 30:** Temperature rise**e. Gel Time**

This table shows the gel time at different temperatures.

**Table 13: Gel Time**

	Hardener 285
20 -25 $^{\circ}\text{C}$	app.2-3hours
40 -45 $^{\circ}\text{C}$	app.45-60min.

**f. Glass transition temperature ( $T_G$ )**

The following table represents the glass transition temperature (TG) in unconditioned state and in conditioned state at 40 $^{\circ}\text{C}$  and 90% of Relative Humidity.

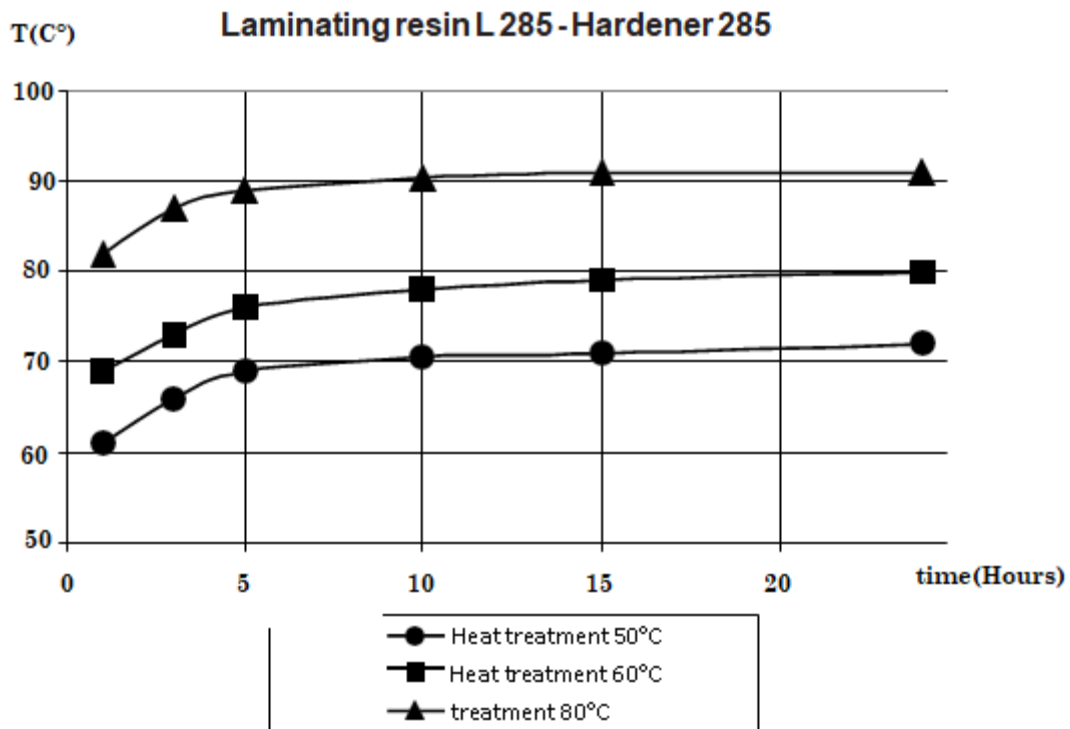
**Table 14: Glass transition temperature ( $T_g$ )**

24 h. 25 $^{\circ}\text{C}$ + 15 h. 60 $^{\circ}\text{C}$	Hardener 285
Unconditioned	75 -80 $^{\circ}\text{C}$
Conditioned	65 -70 $^{\circ}\text{C}$



### g. Rise of glass transition temperature ( $T_G$ )

The rise of glass transition temperature in different states of heat treatment is presented in the following figure.



**Figure 31:** Rise of glass transition temperature ( $T_g$ )

### h. Mechanical data of unreinforced resin

The mechanical data of unreinforced resin is represented in the table 15.

**Table 15: Mechanical data of unreinforced resin**

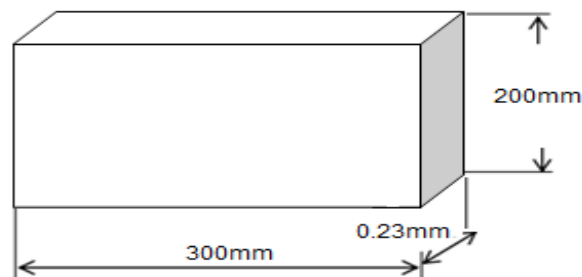
Density ( g/cm <sup>3</sup> )	1,18 - 1,20
Flexural strength (N/mm <sup>2</sup> )	110 - 120
Modulus of elasticity (kN/mm <sup>2</sup> )	3,0 - 3,3
Tensile strength ( N/mm <sup>2</sup> )	70 - 80
Compressive strength (N/mm <sup>2</sup> )	120 - 140
Elongation (%)	5 - 6,5
Impact strength (Nmm/mm <sup>2</sup> )	45 - 55
Shore hardness D	80 - 85
Water absorption %	0,20 - 0,30
Curing: 24 h at 23°C	+ 15 h at 60°C (140°F)

### III. Experimental method

#### 1. Preparation of specimens

10 specimens are prepared to be used in the fabrication of composites.

Specimens took a rectangular shape with dimensions equal to 200 mm x 300 mm (figure 32).

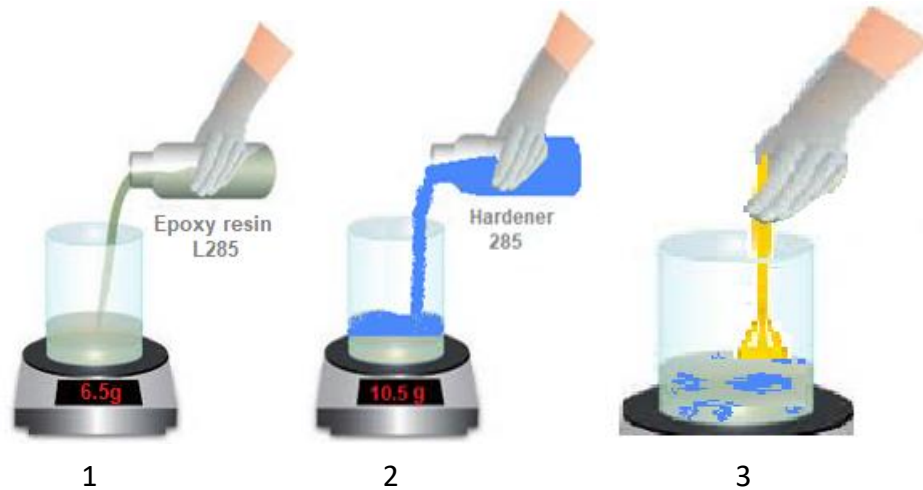


**Figure 32:** The Geometry of the specimens

#### 2. Matrix preparation

##### a. Process

The components used to make the resin coating have a liquid consistency and a different color at first. Hardener 285 was added to the epoxy resin L285, and then thoroughly mixed until a homogeneous consistency and color was obtained throughout the entire mass. Mixing the ingredients took two minutes and was performed using a plastic spoon (Figure 33). The ratio (by weight) of resin to hardener was 100:40.



**Figure 33:** The stages of preparation of the resin coating (1 – resin, 2 – addition of hardener, 3 – mixing of components)

#### **b. Tips**

**Tip 1:** The correct mixing ratio

If you do not follow the correct proportions resin + hardener, the resin may not work as desired or may not cure in the end. If you add more hardener to the mixture, the material is often less hard and robust after curing. If you add too much resin, the surface may become sticky or the material may not cure at all.

**Tip 2:** Observe ambient temperature

Casting resin is a very heat-sensitive material. Therefore, you should also keep an eye on the ambient temperature when mixing the resin.

At ambient temperatures below 20° C, the resin cures much slower. If the temperature drops significantly below 20° C, it is also possible that the resin begins to crystallize.

At ambient temperatures above 20 ° C., the reaction time of the resin increases significantly. And this applies not only to the time of curing, but also to the time in which the material is to be further processed.

**Tip 3:** The role of humidity in processing

Just as sensitive as the resin is to temperatures, the hardener also reacts to contact with air. Therefore, if the humidity in the air is above 65% you should leave the bottle containing the hardener closed. If you do not use the material immediately, the quality will suffer.

This effect also occurs when the bottle is opened and closed again and again, as oxygen enters the bottle each time and reacts with the hardener. For the same reason, the two components resin and hardener should only be handled with absolutely clean tools. Only in this way can a reaction within the container be prevented.

**Tip 4:** Careful mixing of the components

The resin has a point called Pot life which is the lifetime in the pot. This time is too short, so we need to mix the components very well (2 minutes) until they have a homogeneous consistency than apply the mixture as fast as possible.

The thorough mixing of the resin and hardener is essential to obtain an attractive, useful result later on. If you do not work carefully enough, there is a risk that incompletely cured, sticky spots may appear in the resin or that the hardness levels within a work piece may vary.

When mixing the components, note that often a lot of material sticks to the edge of the mixing container. Since this can affect the mixing ratio, you should not mix very small amounts of resin and hardener in order to have enough material available.

**Tip 5:** The right tool for mixing the components

The optimal tool for mixing resin and hardener must have straight sides. This will enable you to thoroughly mix even the material that sticks to the bottom and sides of the mixing container. For small quantities of epoxy resin, a flat spatula has proved to be a good choice.

**3. Composite fabrication**

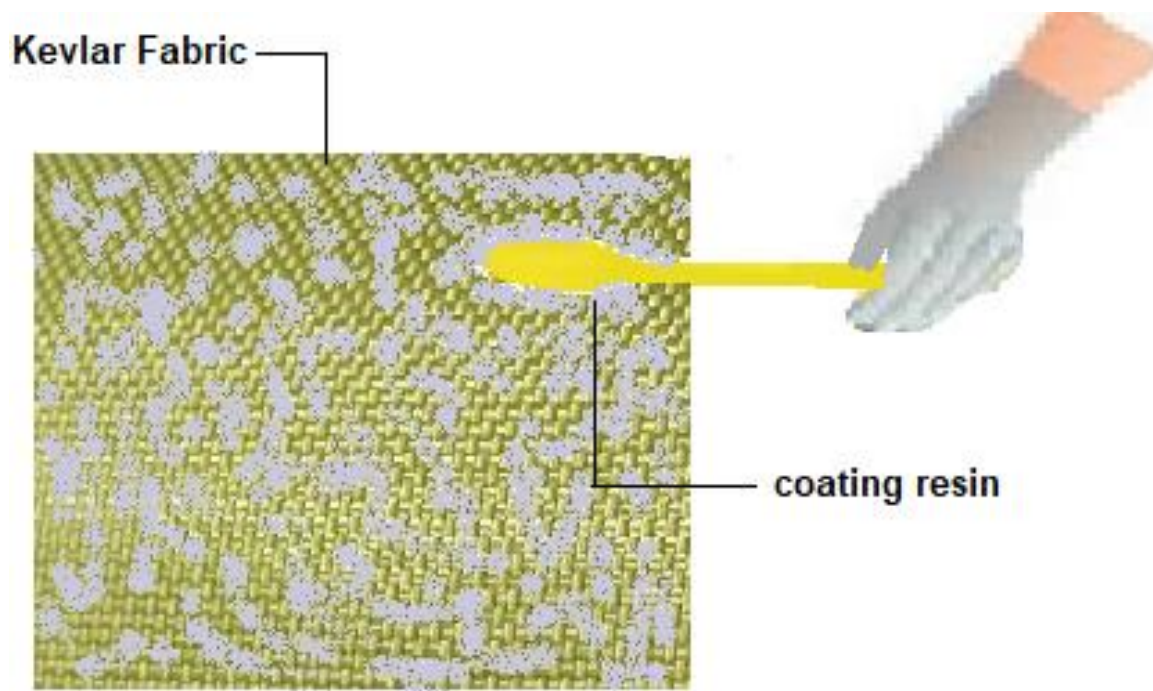
In this part, we will discuss the experimental methods done in the chemical lab to obtain different forms of Kevlar/epoxy composites with different area density of matrix in order to obtain a lightweight composite but strong.

### a. Coating Method

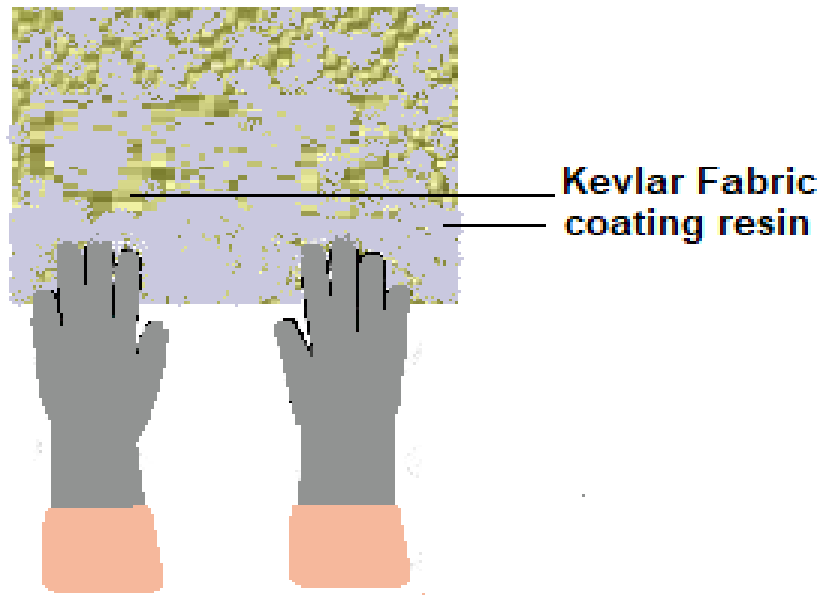
The finished mixture of resin and hardener was spread on the surface of specimen manually by a plastic spoon (Figure 34). So that the mixture reaches all the areas of the sample, we folded the fabric and we made back and forth movements with fingers (Figure 35). After that, the system was placed between two pieces of Teflon and a load of 0.07 kN was applied during 24 h in order to obtain a homogeneous structure and to maintain a constant fiber volume fraction and uniform composite thickness.

The post cure was followed according to manufacturer datasheet of epoxy resin L285 in an oven at 60 °C during 13 h.

This process was repeated 3 times with different coating ratios of resin: hardener (10:04; 10:06 and 10:14) in order to discover the optimum concentration that is enough for a homogeneous structure and a good mechanical and comfort properties.



**Figure 34:** Manual coating method of resin



**Figure 35:** Spreading of resin

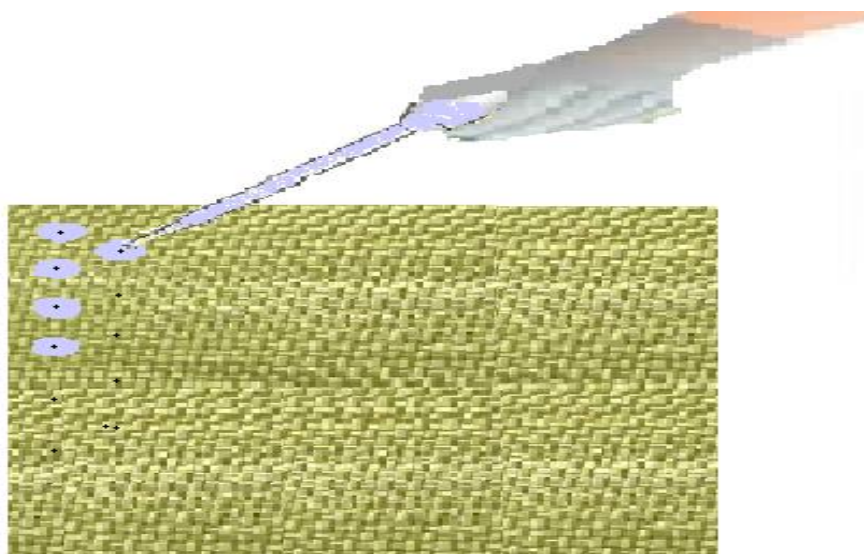
#### **b. Dropping Method**

First of all, we marked the positions of the drops in such a way that each point differs from the others on each side of 2 cm.

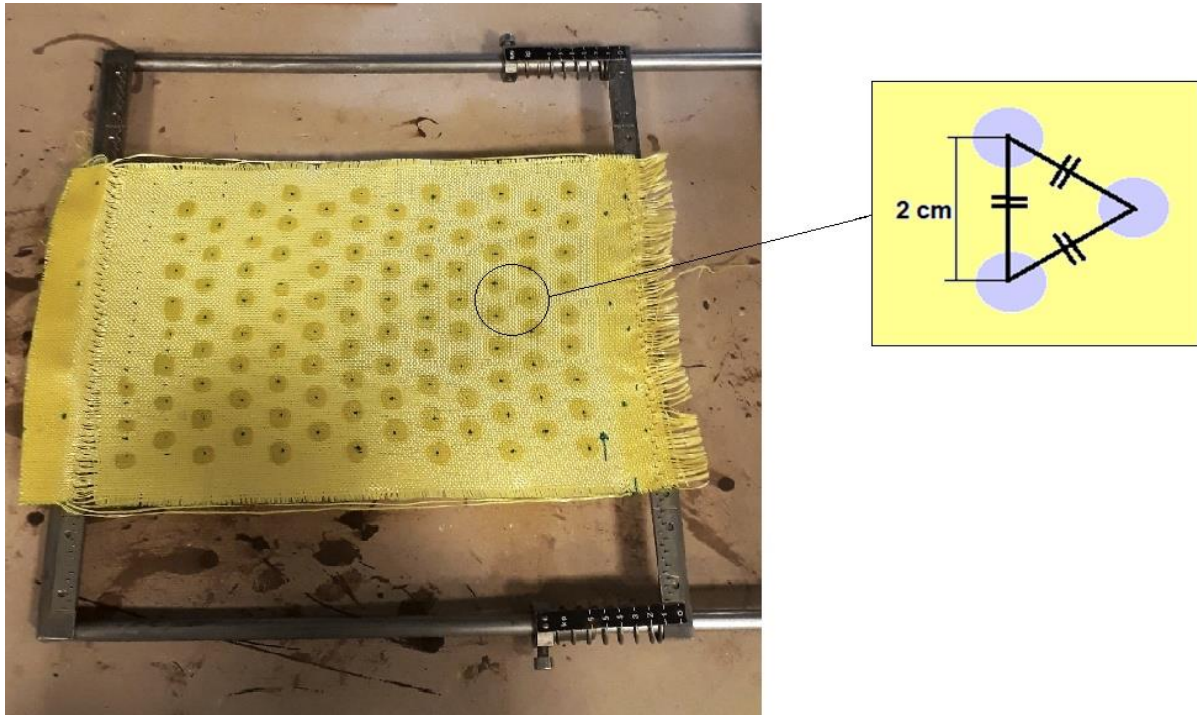
To stabilize the structure on the edges of the sample we spread it with glue. Secondly, we fixed the specimen on a support garnished with needles.

Finally, we putted the mixture of resin + hardener on a plastic pipette and we formed a drop on each marked point in such a way that every 3 spots form a triangle. (Figures 36, 37)

This process was repeated with a different distance between the spots which is equal to 3 cm.



**Figure 36:** Dropping Method



**Figure 37:** Triangular shape of 3 spots

### c. Printing Method

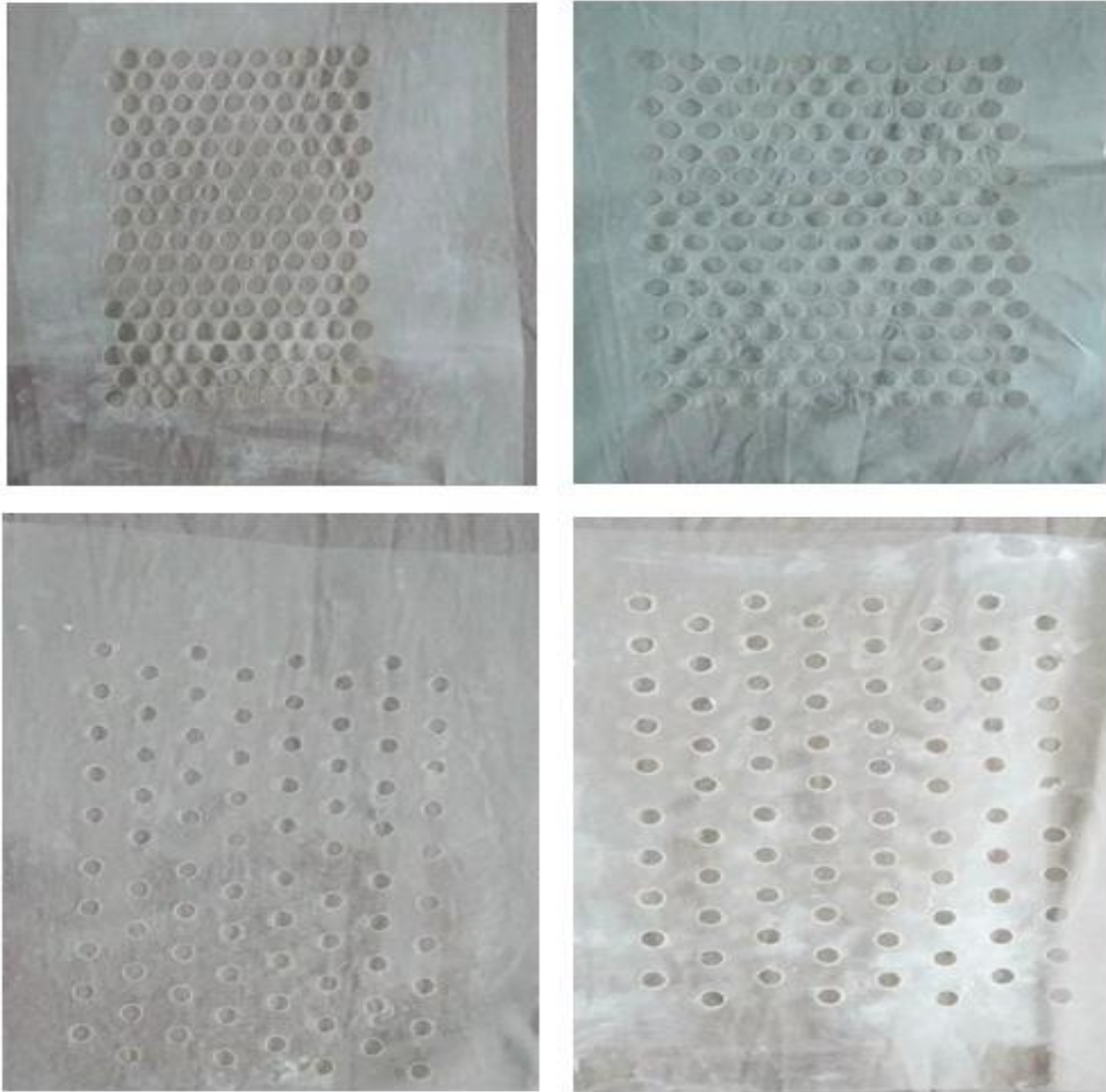
Firstly, we have prepared transparent films with holes in a circular shape and each time we changed the diameter and the distance between the holes as shown in figure 38.

After that, we adjusted the cylinder made of steel on the magnetic field of the printing machine.

We have placed the system composed of the specimen and the film on the machine mat and then we disposed the mixture of resin and hardener in front of the cylinder.

Finally, the machine gets started and a layer of resin is spread over the film and passes through the holes to form spots on the sample. (Figure 39)





**Figure 38:** Different films for printing





**Figure 39:** Printing Method

## IV. Test Methods

All of the experimental studies in this section were conducted in the textile laboratories at the technical university of Liberec, Czech Republic, Faculty of textile engineering, Department of textile evaluation.

### 1. Determination of composite structural and physical properties

Composite structural and physical properties were tested since these properties would influence composite mechanical and comfort properties.

In this study, composite weight (mass per unit area), thickness, air permeability are the physical and structural properties that were tested.

#### a. Mass per unit area

Nine specimens of 50mm x 50mm from the composites were conditioned and tested in a standard atmosphere. Each of specimens was weighed by a measuring balance (Figure 40).

The mass per unit area was calculated using the following formula:

$$M = m/a \quad (6)$$

**Where:**

- **M:** Mass per unit area (g/m<sup>2</sup>);
- **m:** The mass of the specimen(g);
- **a:** The area of the specimen(m<sup>2</sup>).



**Figure 40:** The measuring balance

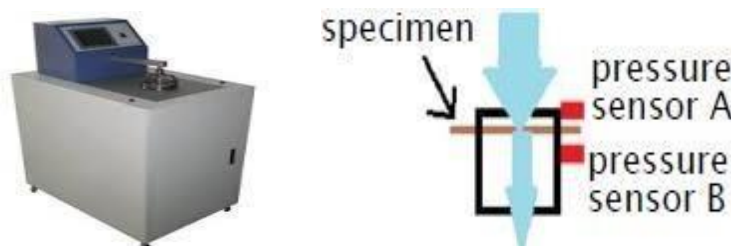
### b. Air permeability

TEXTTEST Air permeability Tester (FX3300) was used to measure the air permeability according to standard ISO 9237: 1995 (F).

The device used produces a constant airflow that travels vertically through the specimen. The surface area tested is  $20 \text{ cm}^2$  and the air pressure differential applied between the two surfaces of the composite was 200 Pa.

The airflow is gradually adjusted until the flow meter indicator is stabilized (see figure 41). The displayed value is noted, and the test repeated at least 5 times in different places of the fabric.

The main components of the air permeability tester are: Test head for positioning the test sample, clamping system for securing the test specimen to the test head without any distortion, air pump to draw a steady flow of air perpendicularly through the test fabric and pressure gauge or manometer connected to the test head below the test sample to measure pressure drop across test sample in Pascals.



**Figure 41:** TEXTTEST Principle and Design

**c. Thickness Test**

The thickness of composite was measured as the distance between the reference plate and parallel presser foot (AS 2001.2.15-198).

Test specimens was conditioned and tested in the standard atmosphere. After that the thickness tester was prepared.

After the presser foot was lifted, the specimen was positioned on the thickness tester reference plate, and then the presser foot was gently lowered to apply pressure to the specimen. The indicator reading was recorded (Figure 42).



**Figure 42:** Thickness tester

**d. The optical microscope**

This microscope uses visible light and a system of lenses to magnify the images of textile materials. Those images can be captured by normal, photosensitive cameras to generate a micrograph.

It works on 1X to 10X magnification, but we have used 1X magnification.



**Figure 43:** Optical microscope

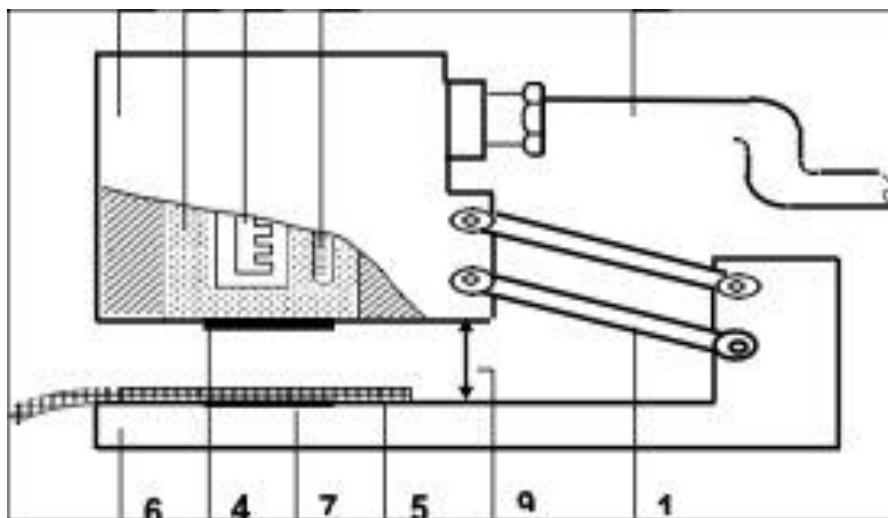
## 2. Determination of Thermophysiological comfort properties

### a. Thermal properties: The ALAMBETA instrument

#### The principle of the test method and apparatus design [65]:

The principle of this instrument (figure 44) depends on the application of an ultra-thin heat flow sensor (4) which is attached to a metal block (2) with constant temperature which differs from the sample temperature. When the specimen is inserted, the measuring head (1) containing the mentioned heat flow sensor drops down and touches the planar measured sample (5), which is located on the instrument base (6) under the measuring head. At this moment, the surface temperature of the specimen suddenly changes, and the instrument computer registers the heat flow course. Simultaneously, a photoelectric sensor measures the sample thickness. All the data are then processed in the computer according to an original program, which involves the mathematical model characterizing the transient temperature field in thin slab subjected to different boundary conditions. To simulate the dry human skin and the real conditions of warm-cool feeling evaluation, the instrument measuring head is heated to 32°C (the heater (3) and the thermometer (8)), which correspond to the average human skin temperature, while the sample is kept at the room temperature 22°C.

The measurement lasts for several minutes only, the evaluation of humid samples is reliable too since they don't turn dry during the measurement.



**Figure 44:** The ALAMBETA instrument [13]

ALAMBETA measuring device was used for the measurement of the following thermal properties: Thermal conductivity.

An average of three readings was taken for each sample. The contact pressure was 200 Pa for all cases.

## b. Water vapor permeability: The Permetest

### Principle of the test method and apparatus design:

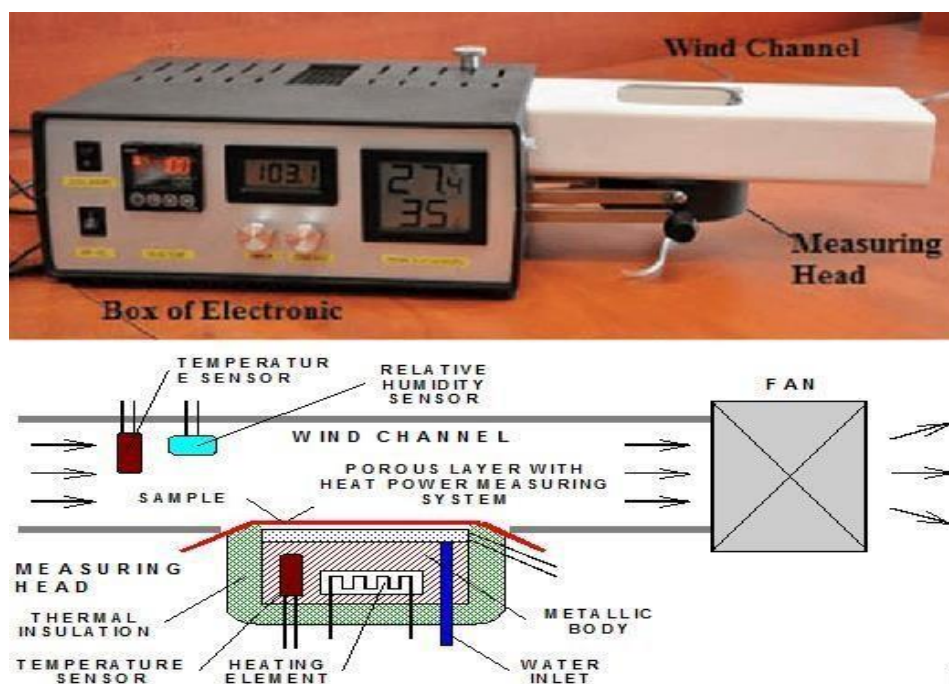
The Permetest is a measuring instrument (skin model) for the non-destructive determination of water-vapor and thermal resistance of textile materials (figure 45).

The porous sweating surface of the device simulates the skin and records the cooling heat flow caused by perspiration. The composite sample to be measured is placed on a measuring head over a semi-permeable foil and exposed to parallel air flow at a velocity of 1m/s.

As with all the skin model systems, the measurements are carried out under isothermal conditions ( $23^{\circ}\text{C} \pm 0.5$ ). This isothermal principle involves the temperature of the skin model surface, the air temperature and composite temperature, when the composite is kept in direct thermal contact with the skin model surface.

The computer connected to the apparatus determines the evaporative resistance ( $R_{et}$ ) and the thermal resistance ( $R_{ct}$ ) of composites in a similar way to that described in standard ISO 11092, as well as the RWVP (or relative negative heat flow responsible for the cooling of the body). These values serve to reflect the Thermophysiological properties of composites.

The higher the RWVP, the lower the  $R_{et}$ , and the better the thermal comfort of the composite. Due to the very short measuring time which normally does not exceed 3 minutes, the composite mass remains mostly unchanged during the measurements.



**Figure 45:** The Permetest apparatus design and principle [65]

Relative water vapor permeability of the textile sample RWVP (%) can be determined from the relation:

$$RWVP\% = (q/q_0)/100 \quad (7)$$

Where:

- **q<sub>0</sub>**: it means the instrument reading without a sample (heat losses of the free wet surface in W/m<sup>2</sup>);
- **q<sub>v</sub>**: it presents the heat losses of the wet measuring head (skin model) with a sample (W/m<sup>2</sup>).

Water vapor resistance **Ret** when expressed in terms of the according to the ISO 11092 standard (Textiles-physiological effects-Measurement of the thermal and water vapor resistance) is as the following relationship:

$$Re = (P_m - P_a) (q_v - q_0^{-1}) \quad (8)$$

Where:

- **Ret**: presents the water vapor resistance (m<sup>2</sup> Pa/W);
- **P<sub>m</sub>**: is the saturation water vapor partial pressure at the surface of the measuring unit (Pa);
- **P<sub>a</sub>**: is the water vapor partial pressure of the air in the test chamber (Pa).

All samples were put in the testing laboratory where relative humidity was between 20 and 22% and temperature was in the range of 24-26°C.

Each sample was tested three times to calculate the mean values.

### 3. Determination of mechanical properties

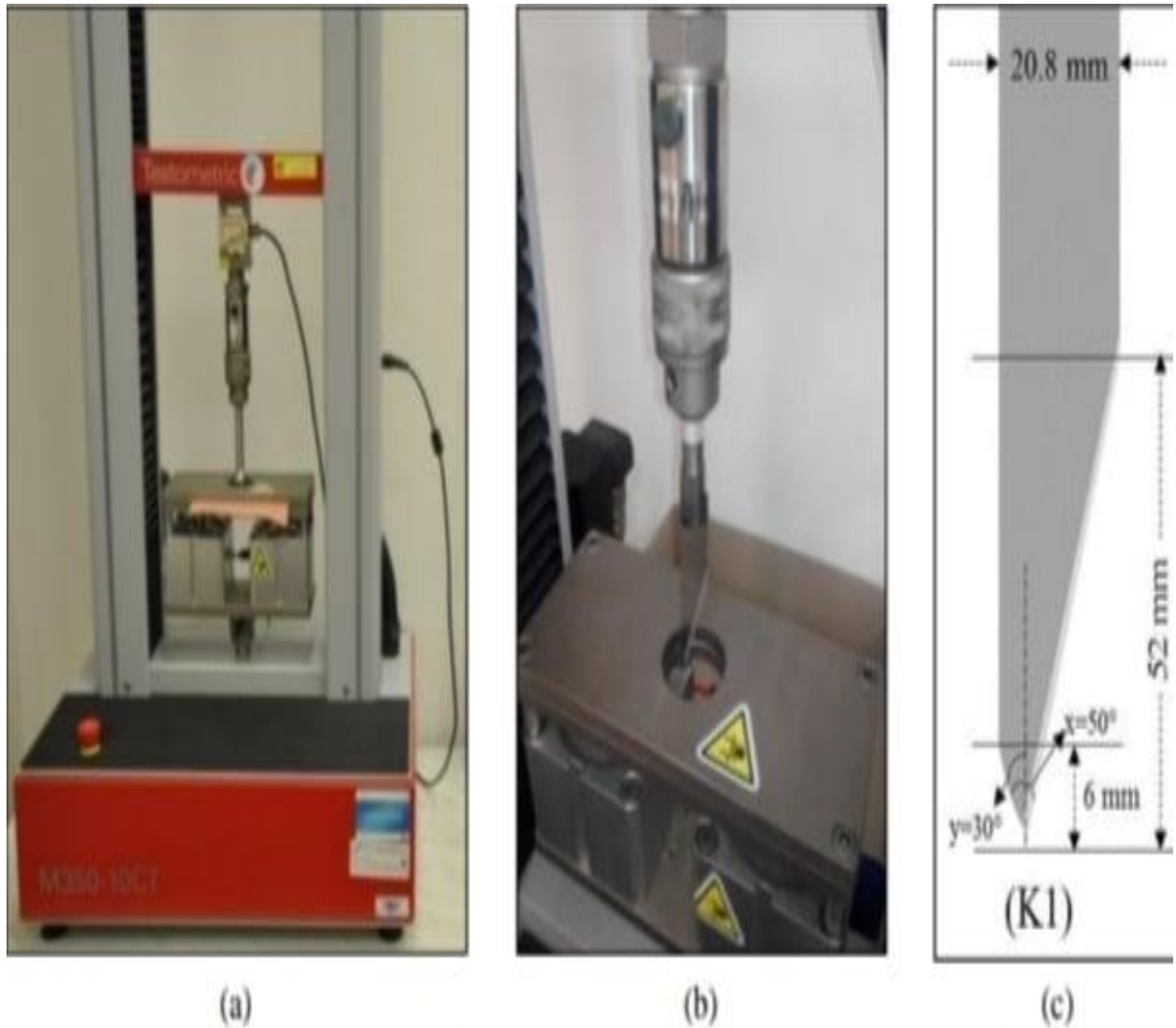
#### a. Quasi-Static Knife Penetration Resistance (QSKPR) measurement

The QSKPR testing was done in accordance with recently reported method followed by various researchers. [44], [45], [46], [47].

The universal testing machine TESTOMETIC M350-10CT, shown in Figure 46(a), was used to penetrate the composite samples quasi-statically at the constant penetration speed of 8.33 mm/s. The specimen was held in a pneumatically gripped platform at 7.5 bars with the inner diameter of a circular hole of 45.55 mm. The composite samples were pre-tensioned at 1 N

force. The sample size was 100 mm x 100 mm  $\pm$ 5 mm. The knife was held in cross-head with 1000 N load cell and was vertically penetrated the specimen.

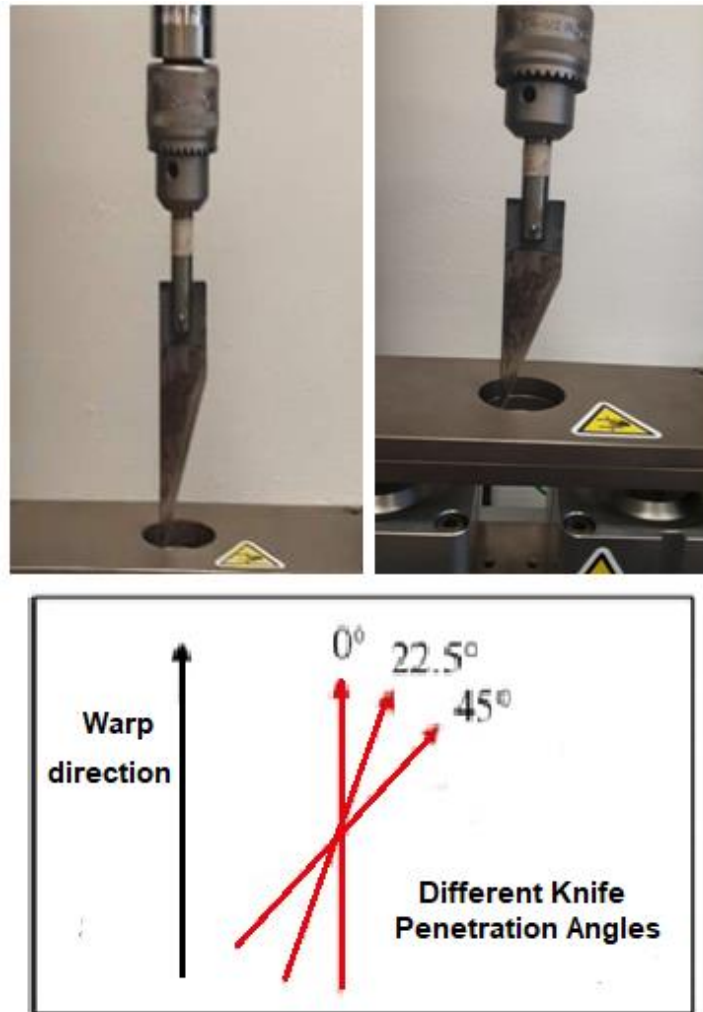
The knife material, shape and sharpness directly affect the response of the composite. [48],[49], [50], [51], [52] Owing to this important factor the knife used in this procedure, was wood crafting stainless steel knife, namely CKB-2 of OLFA Japan. To obtain consistent shape and sharpness for different measurements, commercially available knives were utilized. The shape of knife can be observed, as K1, in Figure 46 (c). It is visible that one edge of knife is sharp and other side is blunt. The first 6 mm of the tip of knife profile has inclination on both directions with 50° angles while after this tip the blunt side is parallel to the length of knife. While sharp edge has 15° inclination for a maximum vertical length of 52 mm. Maximum width of knife is 20.8 mm and thickness of 1.2 mm. One important observation must be noted here that width of the knife (that causes cut in the fabric) increases rapidly for first 6 mm due to both-sided inclinations, however, after that knife profile width increases in single-side corresponding to 20° angle of inclination.



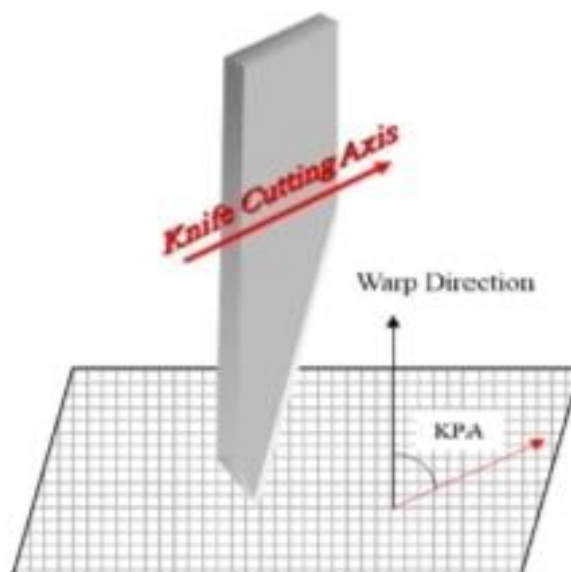
**Figure 46:** (a) Universal Testing Machine (TESTOMETIC M350-10CT), (b) Cross-head installed with knife and (c) Geometry of CKB-2 (K1)

The QSKPR was tested for five different Knife Penetration Angles ( $KPA = 22.5^\circ, 45^\circ$ ), as illustrated in Figure 47. KPA here refers to the angle made between axis of warp yarn length and blade cutting axis, while blade penetrates the composite vertically downwards, as illustrated in Figure 48. For each KPA at least 10 samples were tested.





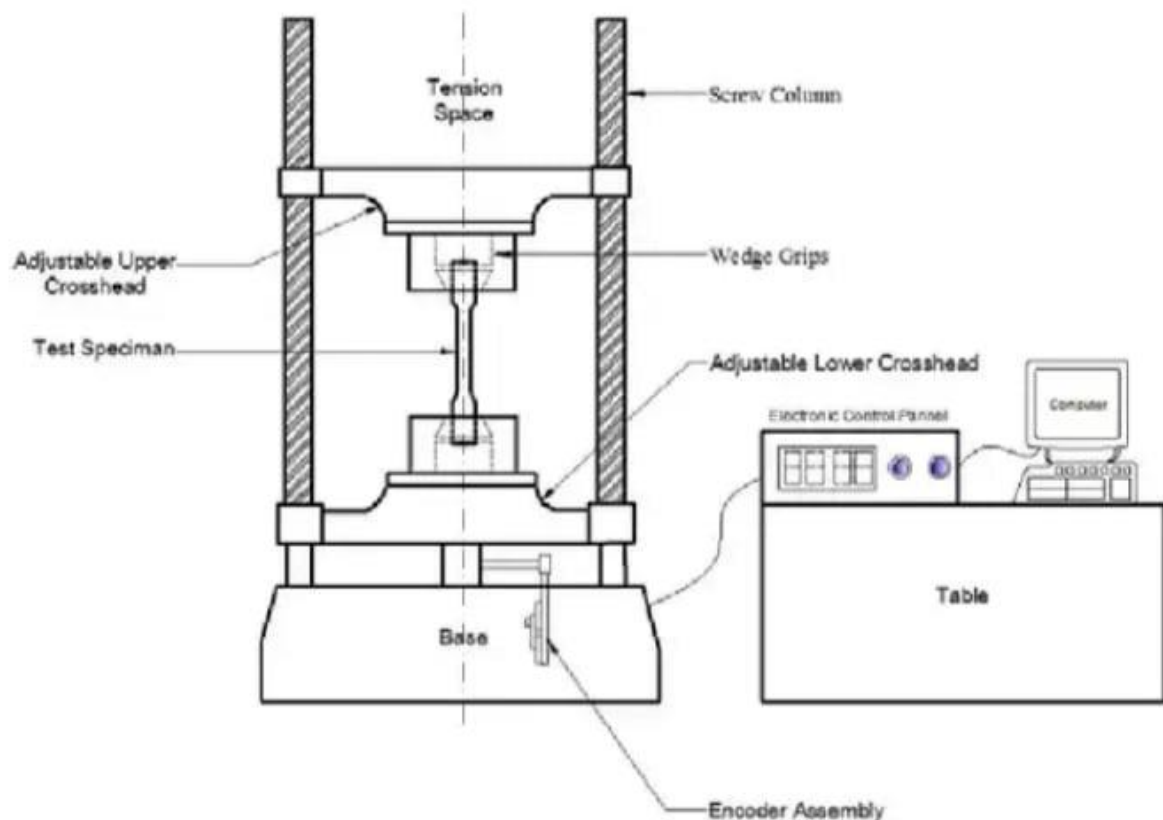
**Figure 47:** Illustration of different Knife Penetration Angles



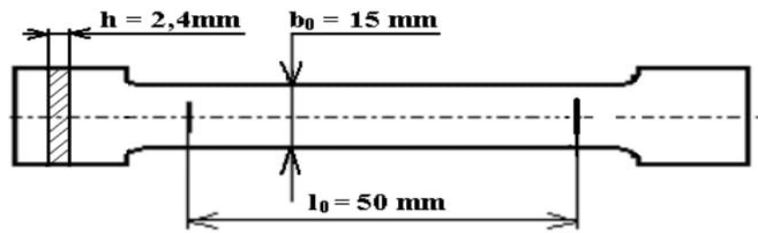
**Figure 48:** Illustration of knife cutting axis

### b. Tensile Strength

The specimen's dimensions for tensile test are shown in Figure 50. The specimens were subjected to a standard tensile test. The tensile tests were conducted on Instron 5582, a universal tensile testing machine (Figure 49). The loading rate of the specimens in the tensile test was 2 mm/min. The results of the tensile tests were the load-elongation curves. The load-elongation curves were determined by breaking force specimens. Subsequently, the stress was calculated at breaking point, i.e., tensile strength of the composite. The load-elongation curves from a tensile test were converted to the stress-strain curves. The stress-strain curves were determined by the mechanical properties of the composites as a whole. Other mechanical properties of composites that were determined were the relative strain and Young's modulus.



**Figure 49:** Tensile Test [48]



**Figure 50:** specimen dimensions for tensile test

## V. Conclusion

In this chapter, we have seen the different materials and equipment that will be used during this research. We have also presented the different methodology followed to prepare our composites and to perform the mechanical and comfort testing. Next part will concern the description, of obtained results as well as discussion section.

## **Chapter 3: Results and Discussion**

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This chapter discusses the outcome of the present work according to the experiments carried out. It includes results covering the structural properties of modern and classical composites, their mechanical and comfort properties in relation with their matrix mass fraction and thickness. The goal was to obtain a comfortable Kevlar/epoxy composite with compromising good mechanical properties. In this part, we will compare between mechanical and comfort properties of classical composites and that of modern composites prepared by dropping and printing methods by studying the variation of matrix mass fraction and sometimes the thickness.

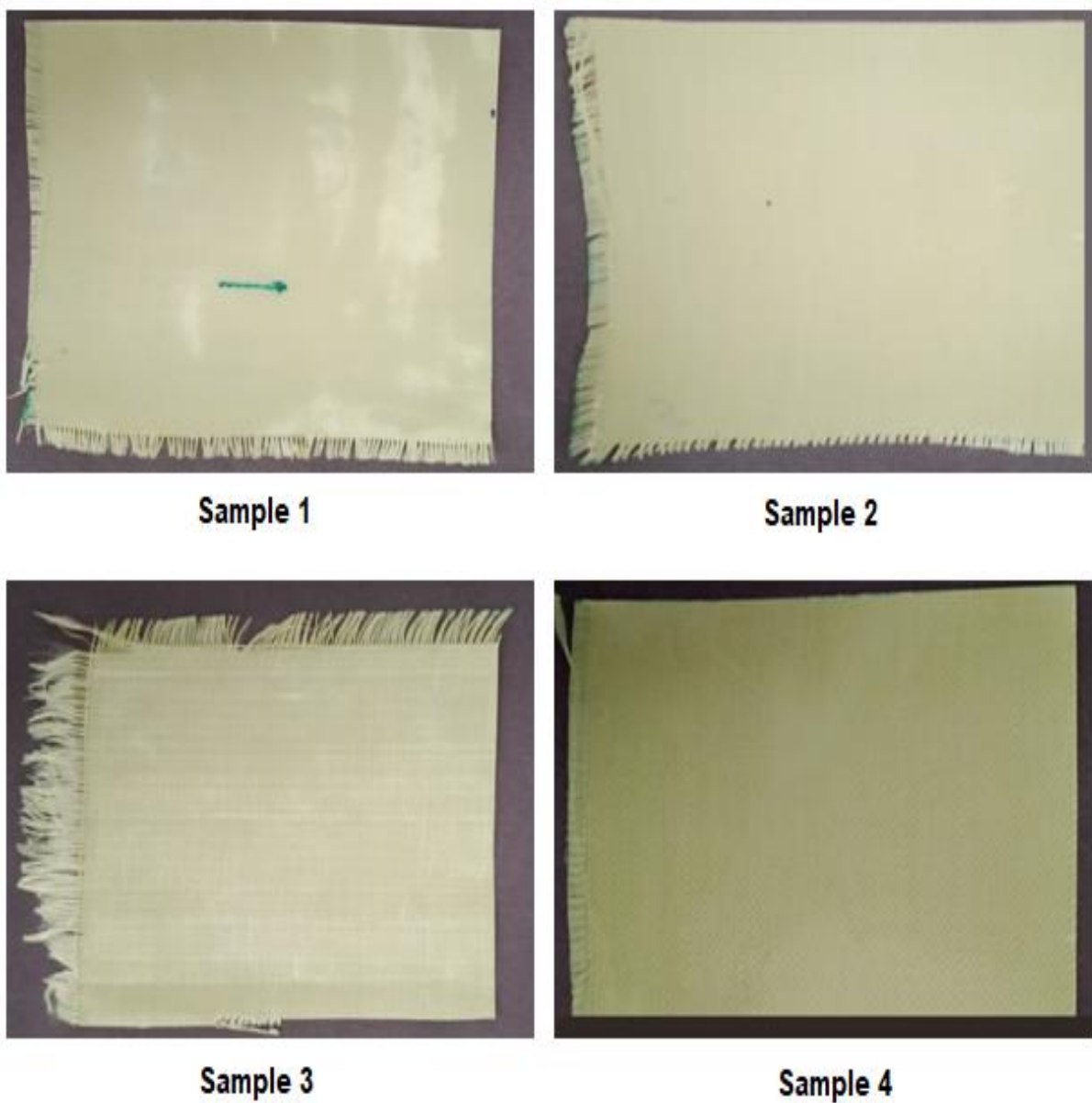
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## I. Experimental samples

All the samples prepared were tested to find out their physical, structural, comfort and mechanical properties.

### 1. Results of Coating method

The following figure (Figure 51) shows the 4 samples of the Kevlar/epoxy composites prepared by different coating ratios.



**Figure 51:** 4 samples prepared by different coating ratios

➤ **Sample 1 & sample 4:**

The samples number 1 and number 4 take the coating ratio 10:04 as shown in table 16:

$$10\text{g} \rightarrow 4\text{g}$$

$$10.7\text{g} \rightarrow \text{weight of matrix} = (10.7 \times 4) / 10 = 4.3\text{g}$$

The Mixing ratio of resin is 100:40 (parts by weight) as presented in table 12 in chapter 2:

$$100\text{g} \rightarrow 40\text{g}$$

$$4.3\text{g} \rightarrow \text{weight of hardener} = (4.3 \times 40) / 100 = 1.7\text{g}$$

$$\rightarrow \text{Weight of resin} = 4.3\text{g} - 1.7\text{g} = 2.6\text{g}$$

➤ **Sample 2:**

The sample number 2 takes the coating ratio 10:06 as shown in table 16:

$$10\text{g} \rightarrow 6\text{g}$$

$$10.7\text{g} \rightarrow \text{weight of matrix} = (10.7 \times 6) / 10 = 6.4\text{g}$$

The Mixing ratio of resin is 100:40 (parts by weight) as presented in table 12 in chapter 2:

$$100\text{g} \rightarrow 40\text{g}$$

$$6.4\text{g} \rightarrow \text{weight of hardener} = (6.4 \times 40) / 100 = 2.6\text{g}$$

$$\rightarrow \text{Weight of resin} = 6.4\text{g} - 2.6\text{g} = 3.8\text{g}$$

➤ **Sample 3:**

The sample number 3 takes the coating ratio 10:14 as shown in table 16:

$$10\text{g} \rightarrow 14\text{g}$$

$$10.7\text{g} \rightarrow \text{weight of matrix} = (10.7 \times 14) / 10 = 15\text{g}$$

The Mixing ratio of resin is 100:40 (parts by weight) as presented in table 12 in chapter 2:

$$100\text{g} \rightarrow 40\text{g}$$

$$15\text{g} \rightarrow \text{weight of hardener} = (15 \times 40) / 100 = 6\text{g}$$

$$\rightarrow \text{Weight of resin} = 15\text{g} - 6\text{g} = 9\text{g}$$

The table below presents the results obtained:

**Table 16: Initial weight of Kevlar samples and final weight of composites**

Number of Sample	Sample1	Sample2	Sample3	Sample4
Coating Method	Manually			Printing Machine
Coating ratios	10:04	10:06	10:14	10:04
Weight of Kevlar samples (g)	10,7			
Weight of the mixture (resin + hardener) (g)	4,3	6,4	15	4.3
Weight of composite	13,8	15,9	18,9	14,9
weight of the remaining mixture	1.2	1.2	6.8	0.1

Sample number 1 is prepared by using 10.7g of Kevlar fabric which is coated manually by adding 4.3g of resin + hardener on specimen as shown in table 16.

According to figure 51, sample 1 shows some areas which are not impregnated with the mixture.

- Sample 1 presented a non-homogeneous structure caused by using a small quantity of resin + hardener. Therefore, the coating ratio 10:04 is insufficient to coat 10.7g of Kevlar fabric.

Sample number 3 is prepared by using 10.7g of Kevlar fabric which is coated manually by adding 15g of resin + hardener on specimen as shown in table 16.

The final weight of composite is equal to 18.9g which mean that the weight of remaining mixture is equal to  $(10.7+15) - 18.9 = 6.8$  g which is a large quantity.

- The coating ratio 10:14 is too large to coat 10.7g of Kevlar fabric. It allows losing huge quantities of resin and hardener throughout our process.

Sample number 2 is prepared by using 10.7g of Kevlar fabric which is coated manually by adding 6.4 g of resin + hardener on specimen as shown in table 16.

According to figure 51, the spreading of the mixture is seen uniform over all areas of the sample 2.

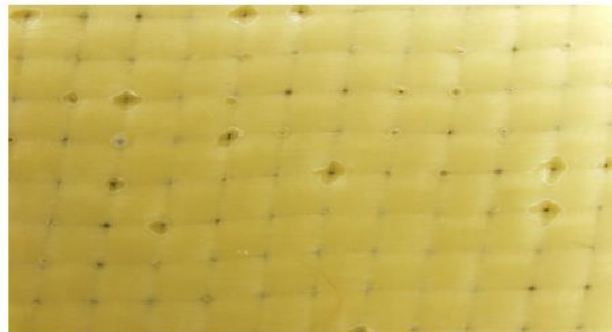
- Therefore, 10:06 is the optimal ratio that can be used to cover 10.7g of Kevlar fabric manually with a plastic spoon.



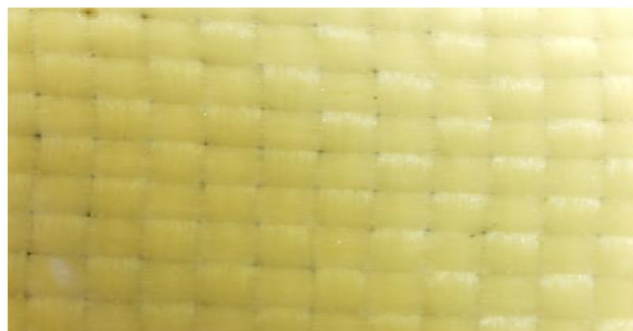
**Sample 1**



**Sample 2**



**Sample 3**



**Sample 4**

**Figure 52:** Microscopic view of samples 1, 2, 3 and 4



Sample number 4 is prepared by using 10.7g of Kevlar fabric which is coated by adding 4.3g of resin + hardener on specimen. The method used to obtain this composite is the printing machine as shown in table 16.

According to figure 52, the microscopic view of sample 4 shows the best homogeneous structure by comparing it with the other samples.

- Therefore, the printing machine method is more efficient to obtain a good homogeneous structure.

## 2. Results of dropping Method

The results of dropping method are shown in the figures below

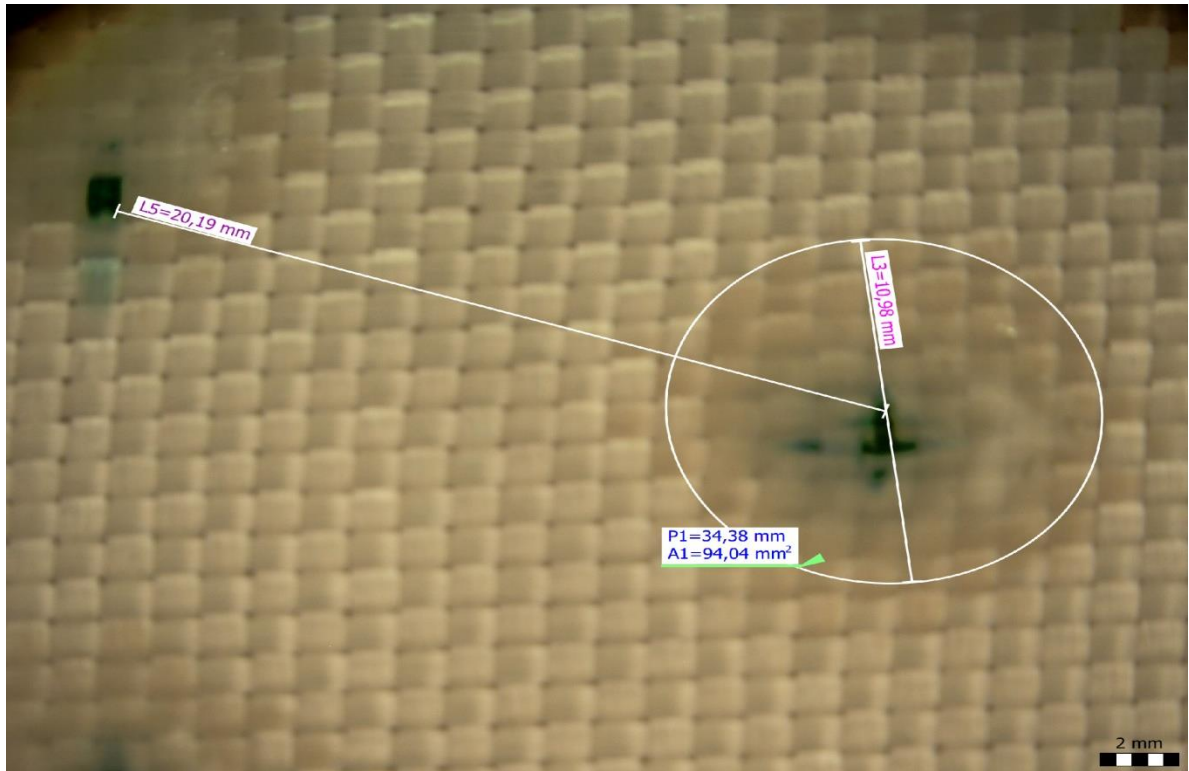


**Sample 5**

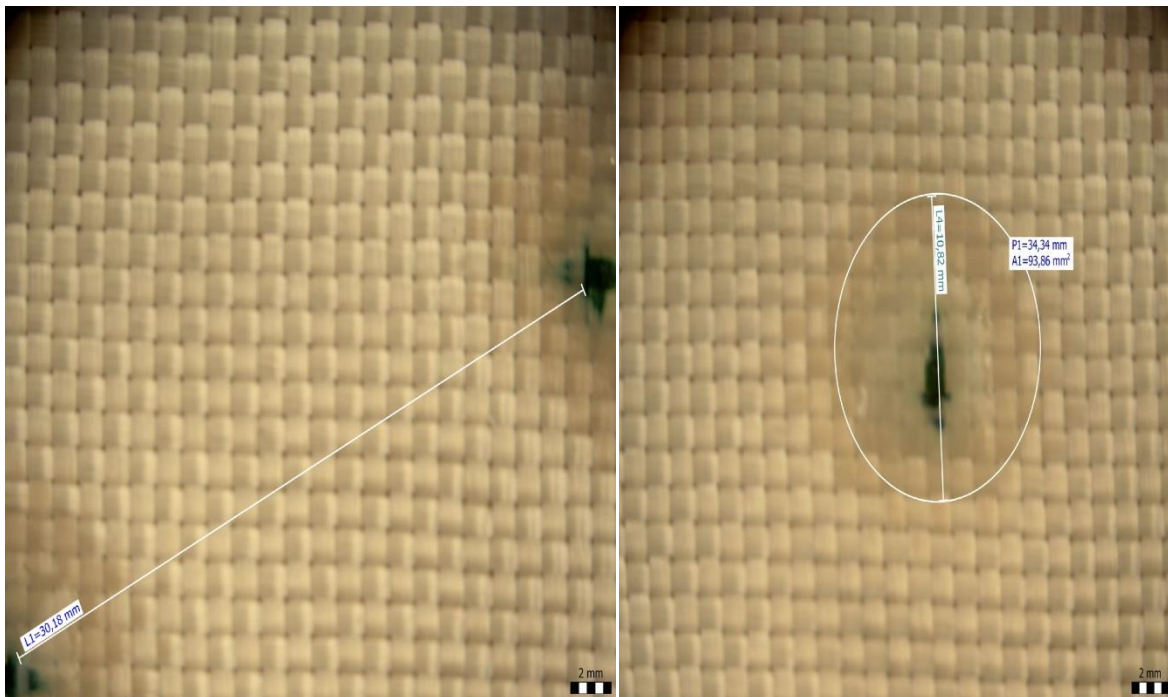


**Sample 6**

**Figure 53:** 2 samples prepared by dropping method



Sample 5



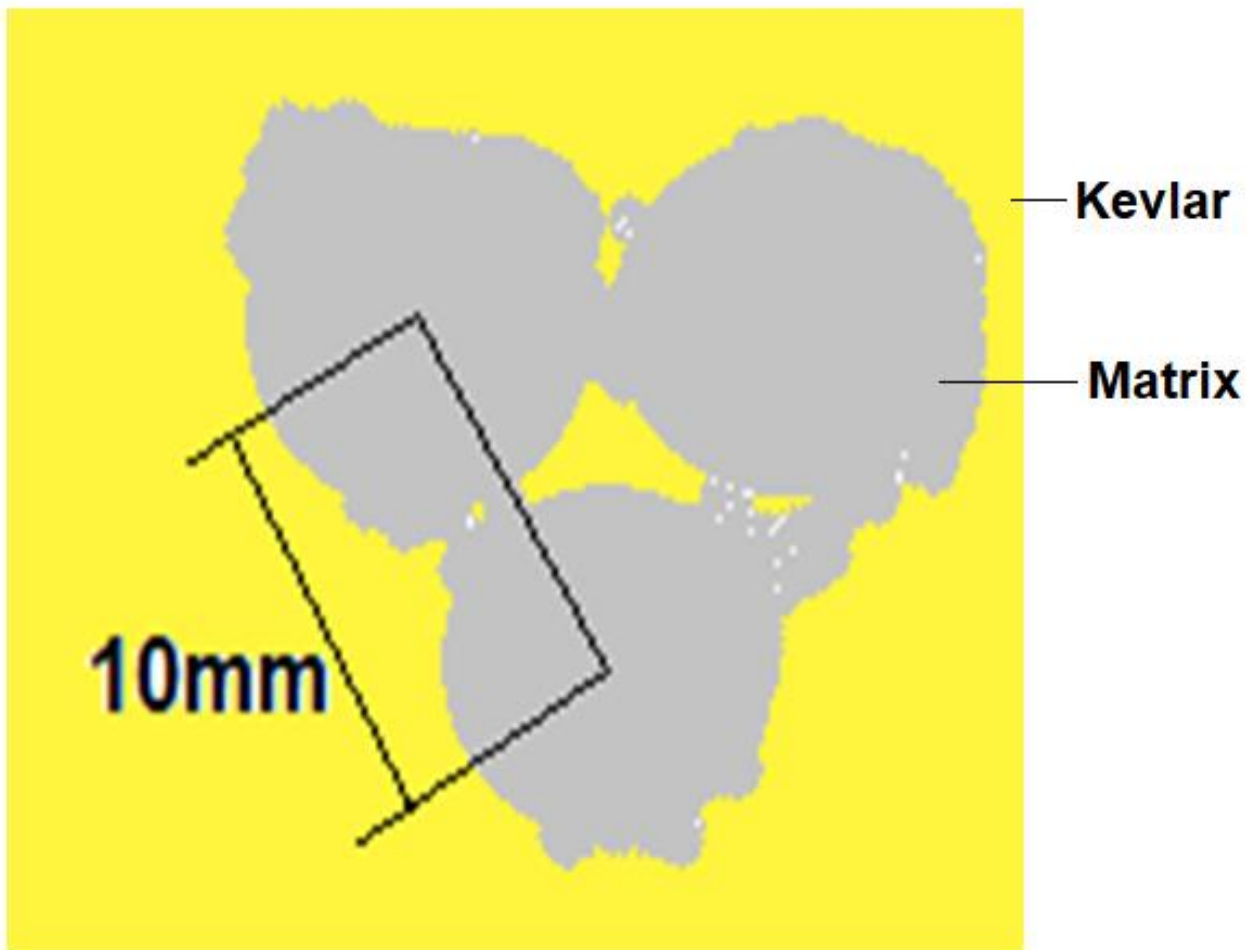
Sample 6

**Figure 54:** Microscopic view of sample 5 and 6

Sample 5 shows a distance between two spots equal to 20.19mm as shown in figure 54.

Sample 6 shows a distance between two spots equal to 30.18 mm as shown in figure 54.

- These different distances allow to obtain a circular shape of spots but if we decrease more and more this distance, we risk losing this circular shape because spots can intersect as shown in figure 55.



**Figure 55:** Intersection of 3 spots

### 3. Results of Printing Method

The results of printing method are shown in the figures below.



**Sample 7**



**Sample 8**



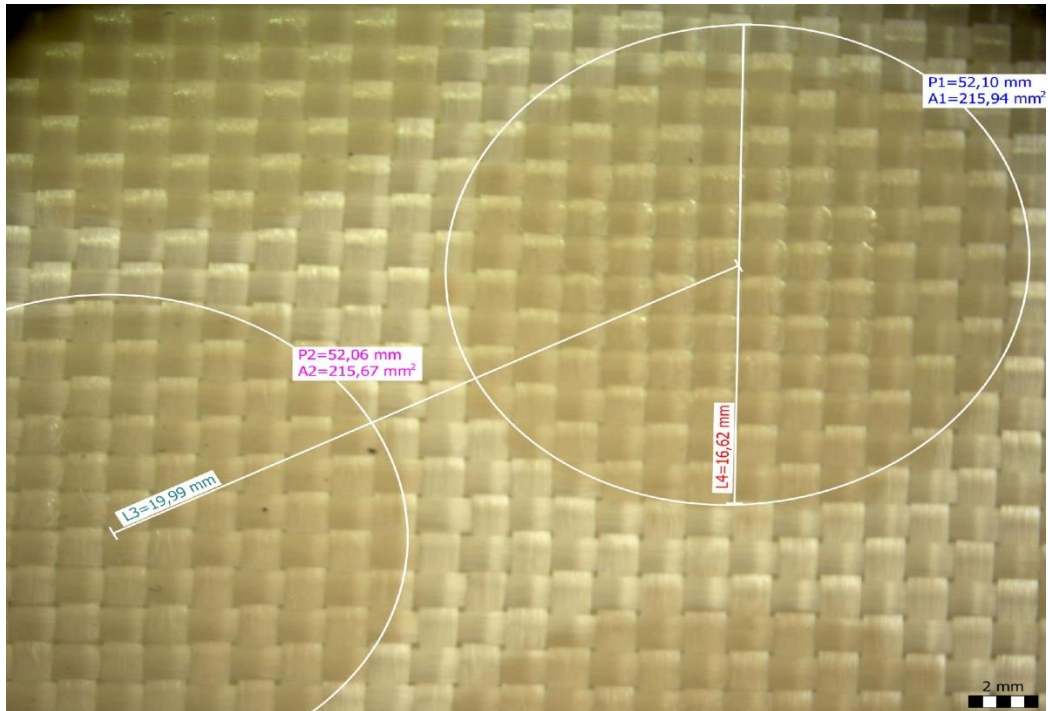
**Sample 9**



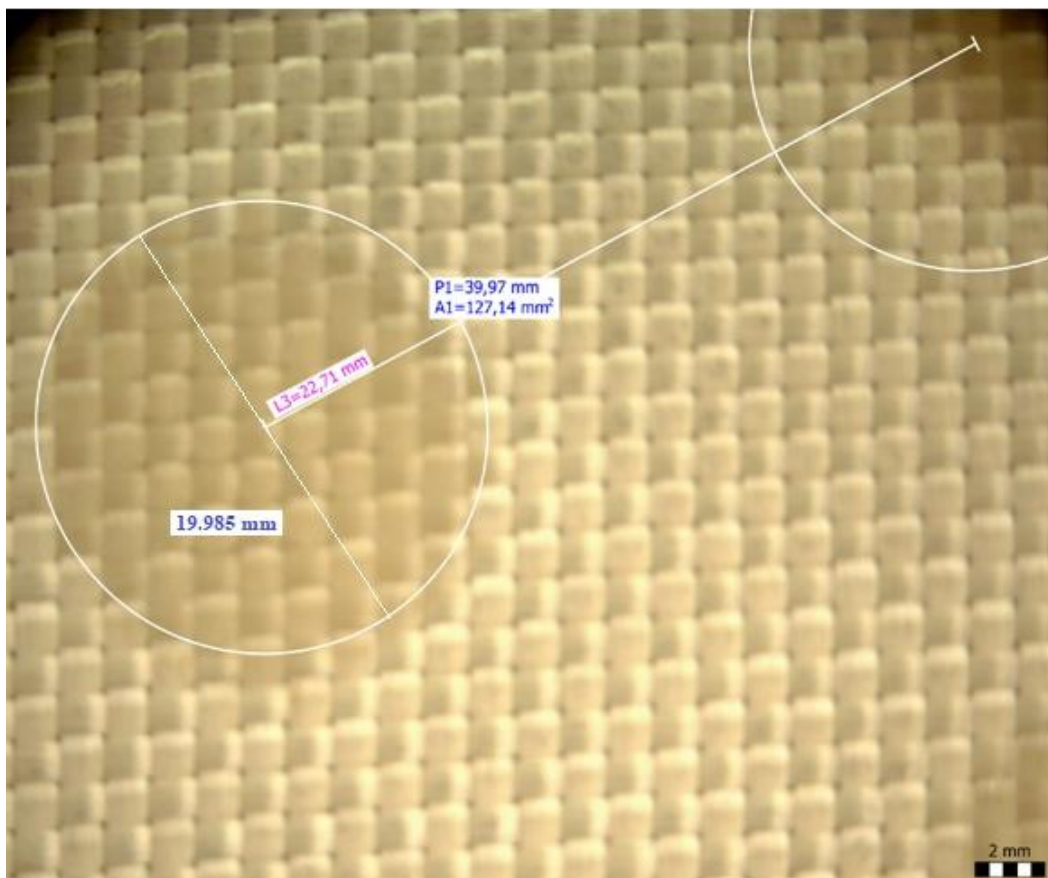
**Sample 10**

**Figure 56:** 4 samples prepared by printing method

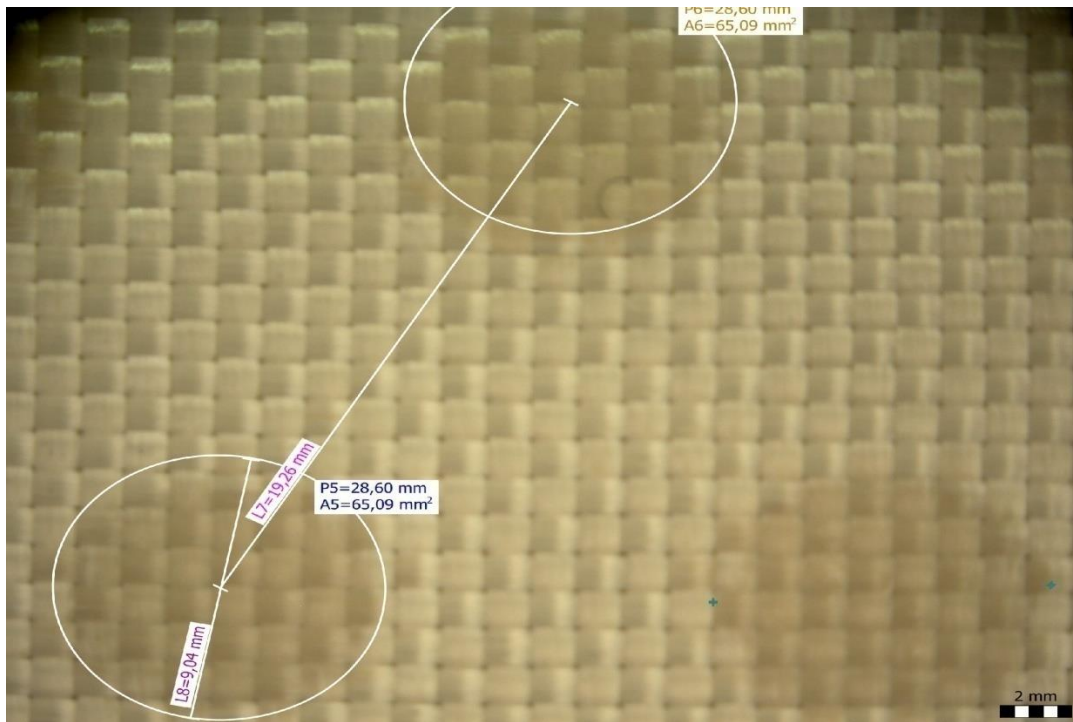




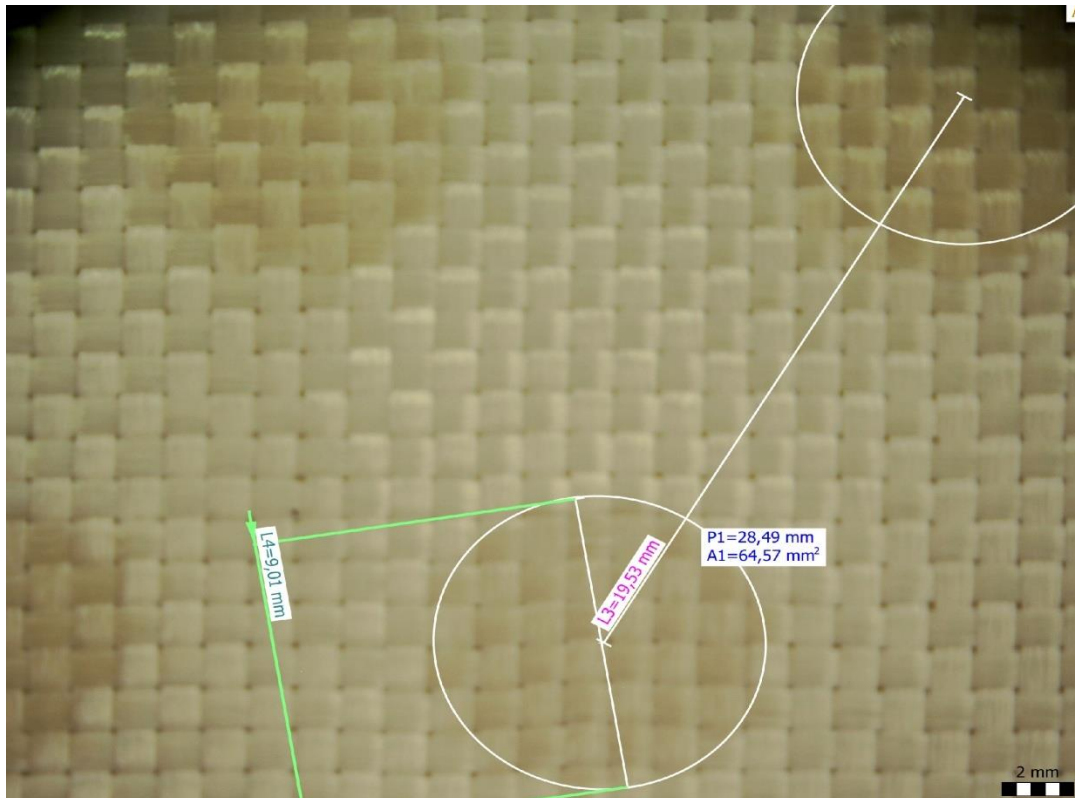
**Figure 57:** Microscopic View of sample 7



**Figure 58:** Microscopic View of sample 8



**Figure 59:** Microscopic View of sample 9



**Figure 60:** Microscopic View of sample 10

The samples 7, 8, 9 and 10 have a different size of spots and a non-identical distance between two spots.

Sample 7 shows a distance between two spots equal to 19.99mm and a diameter of one spot equal to 16.62mm as shown in figure 57.

Sample 8 shows a distance between two spots equal to 22.71 mm and a diameter of one spot equal to 19.985 mm as shown in figure 58.

Sample 9 shows a distance between two spots equal to 19.26 mm and a diameter of one spot equal to 9.04 mm as shown in figure 59.

Sample 10 shows a distance between two spots equal to 19.53 mm and a diameter of one spot equal to 9.01 mm as shown in figure 60.

## II. Structural and physical properties

The results of structural and physical properties of composites are given in table 17.

**Table 17: Structural parameters of composites under study**

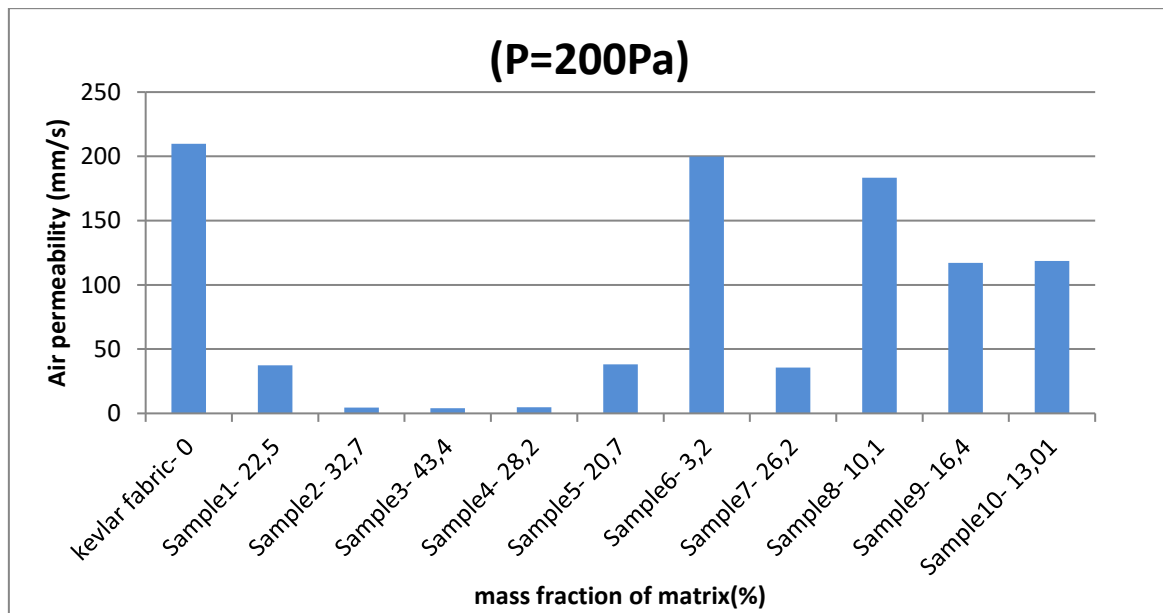
	Area density of composite (g/mm <sup>2</sup> )	Area density of matrix (g/mm <sup>2</sup> )	Homogeneity	Size of spots (Ø mm)	Methods of preparation	Thickness (mm)
<b>Standard fabric</b>	-	-	-	-	-	0.23
<b>Sample1</b>	0.00023	5.16667E-05	-	-	coating	0.26
<b>Sample2</b>	0.000265	8.66667E-05	+	-	coating	0.32
<b>Sample3</b>	0.000315	0.000136667	+	-	coating	0.35
<b>Sample4</b>	0.000248333	0.00007	+	-	coating with printing machine	0.30
<b>Sample5</b>	0.000225	4.66667E-05	-	10.98	dropping	0.88
<b>Sample6</b>	0.000184167	5.83333E-06	-	10.82	dropping	0.84
<b>Sample7</b>	0.000241667	6.33333E-05	-	16.62	printing	0.58
<b>Sample8</b>	0.000198333	0.00002	-	19.985	printing	0.29
<b>Sample9</b>	0.00021333	0.000035	-	9.04	printing	0.32
<b>Sample10</b>	0.000205	2.66667E-05	-	9.01	printing	0.31

### III. Comfort properties

#### 1. Air permeability

The air permeability of a composite is a measure of how well it allows the passage of air through it and is defined as the volume of air passed in one second through 100 sq.mm of the specimen at a pressure equal to 200 Pa. It is often used in evaluating the breathability characteristic and the porosity of the composite.

The obtained results are presented in the following chart.



**Figure 61:** Influence of matrix mass fraction on air permeability

The figure above shows that Kevlar fabric exhibits the higher air permeability value (209.75 mm/s) whereas Sample 3 exhibits the lower air permeability value (3.98 mm/s) as compare to other samples; meanwhile, as shown in figure 27 “Optical image of K706 plain woven Kevlar fabric”, There are voids between weft and warp yarns in the fabric. The void volume within this textile fabric makes it a porous structure which allows the passage of air through it. However, sample 3 is covered totally with the mixture resin + hardener as shown in figure52«Microscopic view of samples 1, 2, 3 and 4 », the layer of resin does not allow the passage of air through composite which become a non-permeable structure. The results indicate that specimen air permeability and porosity are related to each other. A sample that has a high porous structure is more likely to have high air permeability.

As shown in figure 61, Sample 6 which has the lower matrix mass fraction (3.2%) exhibits the

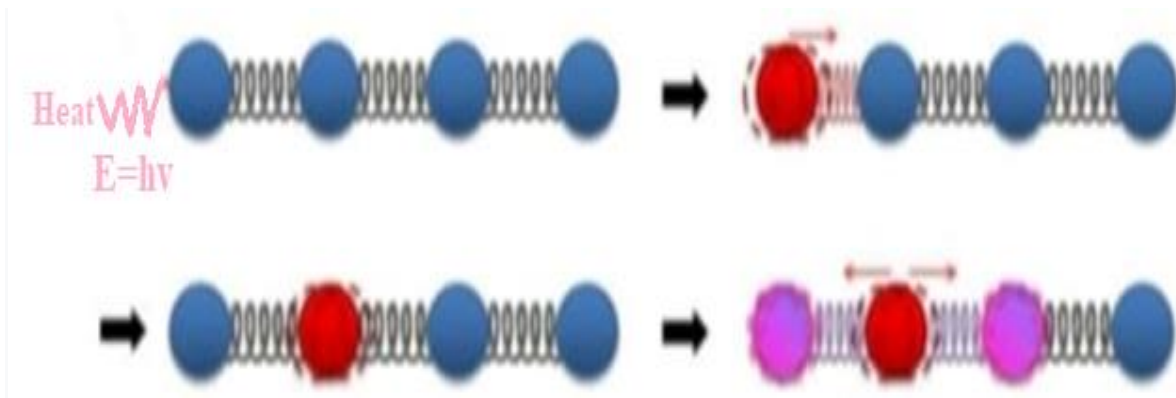


higher air permeability value (199.75 mm/s) whereas Sample 3 which has the higher mass fraction of matrix (43.4%) exhibits the lower air permeability value (3.98 mm/s) as compare to other composites.

That can be explained by the fact that when increasing the mass fraction of matrix, composite will have a compact structure which presents a barrier in front of the passage of air flow.

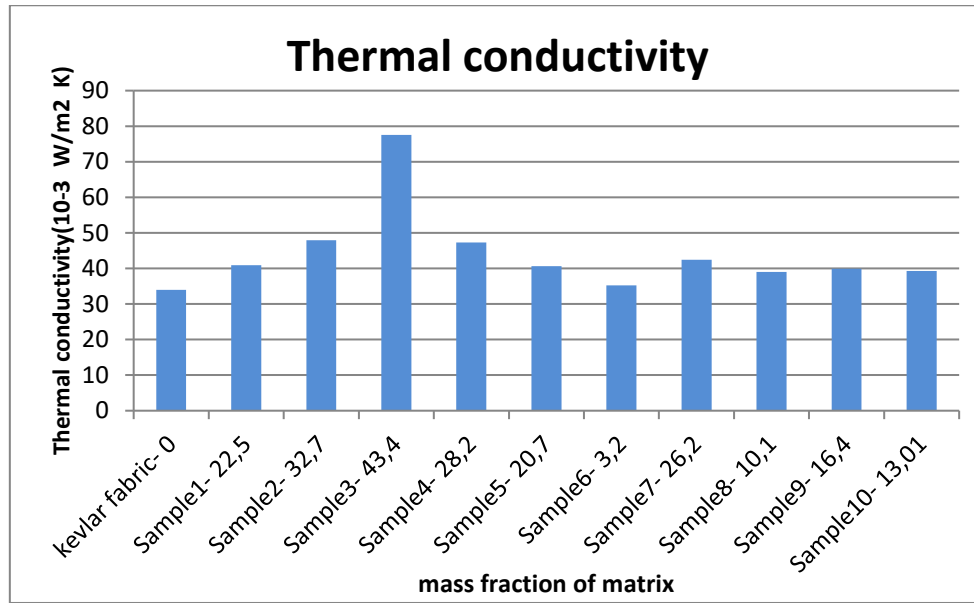
## 2. Thermal conductivity

Thermal conductivity is an intrinsic property of any material that indicates its ability to conduct heat. It is the flux of heat (energy per unit area per unit time) divided by the temperature gradient. From a fundamental point of view, it is the transfer of vibrational energy from a particle to its adjacent particles by collision, without movement of material as shown in figure 61. Thermal conductivity of a structure is a very important property for determining the thermal insulation properties of the structure. It is known that lower thermal conductivity leads to better thermal insulation function.

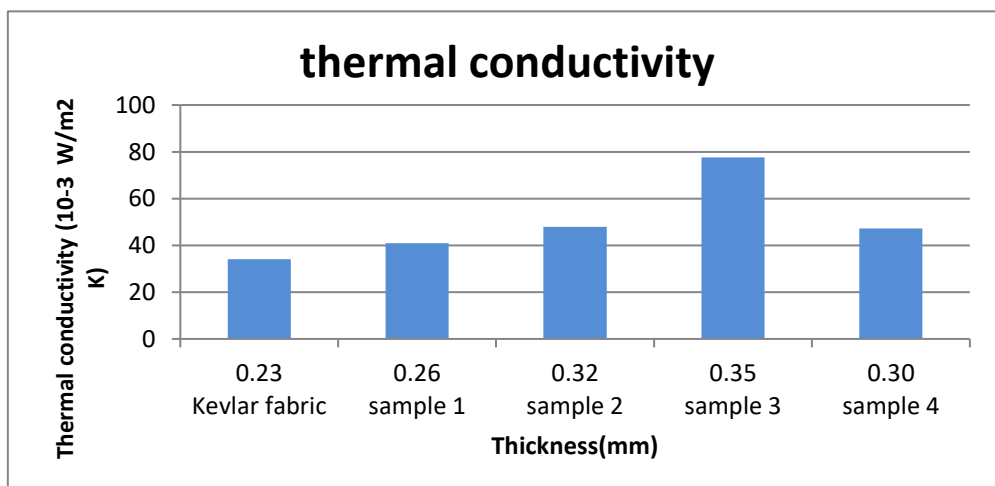


**Figure 62:** Fundamental mechanism of thermal conductivity by particle collision

The obtained results are presented in the following figures.



**Figure 63:** Effect of matrix mass fraction on thermal conductivity



**Figure 64:** Effect of thickness on thermal conductivity

If we compare the thermal conductivity of composites 1, 2, 3 and 4 prepared by coating method with using different coating ratios, we observe that thermal conductivity of sample 3 ( $77.55 \cdot 10^{-3} \text{ W/m}^2 \cdot \text{K}$ ) is higher than thermal conductivity of other composites.

As shown in Figure 64, sample 3 has the higher thickness (0.35 mm) than that of composites 1, 2 and 4.

In fact, thermal conductivity properties of composites depend on the specimen thickness because still air trapped between the components of composite material has lower thermal conductivity value compared to all materials ( $0,0262 \text{ W/m}^2 \cdot \text{K}$ ). It is observed also that while

the composite thickness increased, the composite volume increased, and the composite weight increased. With the increasing of the composite weight, the amount of air layer decreased. Therefore, the heavier composites that contain less still air have higher thermal conductivity values.

Figure 63 shows that Kevlar fabric has the lower thermal conductivity ( $34.02 \cdot 10^{-3} \text{W/m}^2\cdot\text{K}$ ); meanwhile, composite 3 which has the higher mass fraction of matrix (43.4%) has the higher thermal conductivity ( $77.55 \cdot 10^{-3} \text{W/m}^2\cdot\text{K}$ ).

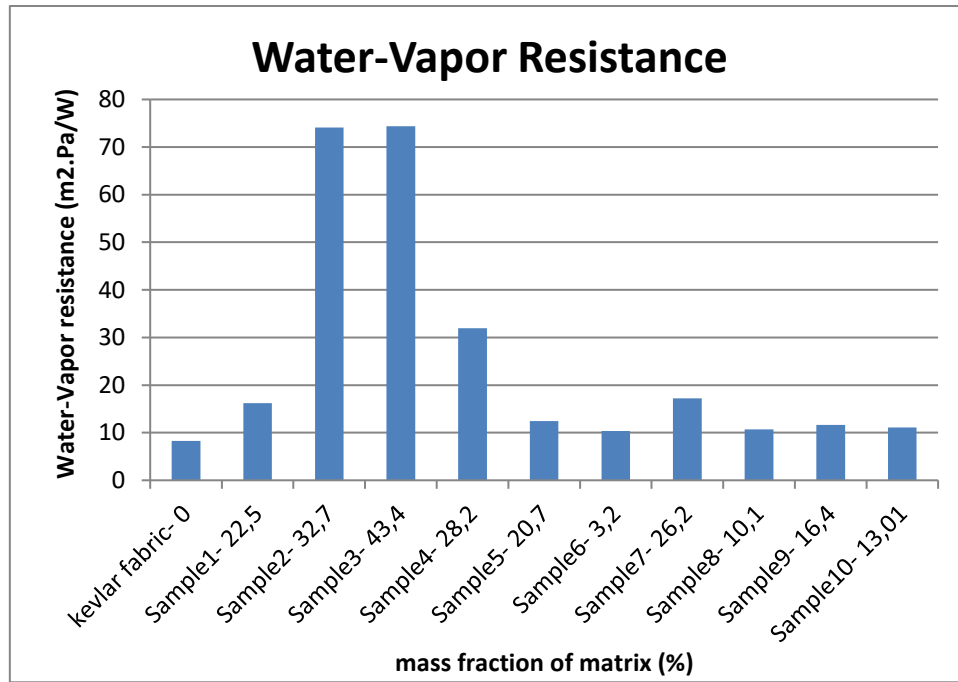
If we compare the thermal conductivity of composites 5, 6, 7, 8, 9 and 10 prepared by dropping and printing methods, we observe that thermal conductivity of sample 7 ( $77.55 \cdot 10^{-3} \text{W/m}^2\cdot\text{K}$ ) which has the higher mass fraction (26.2%) is higher than thermal conductivity of other composites.

This could be explained by the very low thermal conductivity of Kevlar which can be improved by the application of epoxy resin which contains thermal conductive fillers. The thermal conductivity of Kevlar/Epoxy composites increases with the increasing content of epoxy.

### **3. Water Vapor Resistance**

Vapor resistance determines the ability of a composite to resist and/or transfer water-vapor from the fabric to the atmosphere. Higher moisture resistance with high thermal resistance of composites produces more heat storage on body skin causes uncomfortable sensation.

The following figure shows water vapor resistance values of the experimental samples.



**Figure 65:** Effect of matrix mass fraction on water vapor resistance

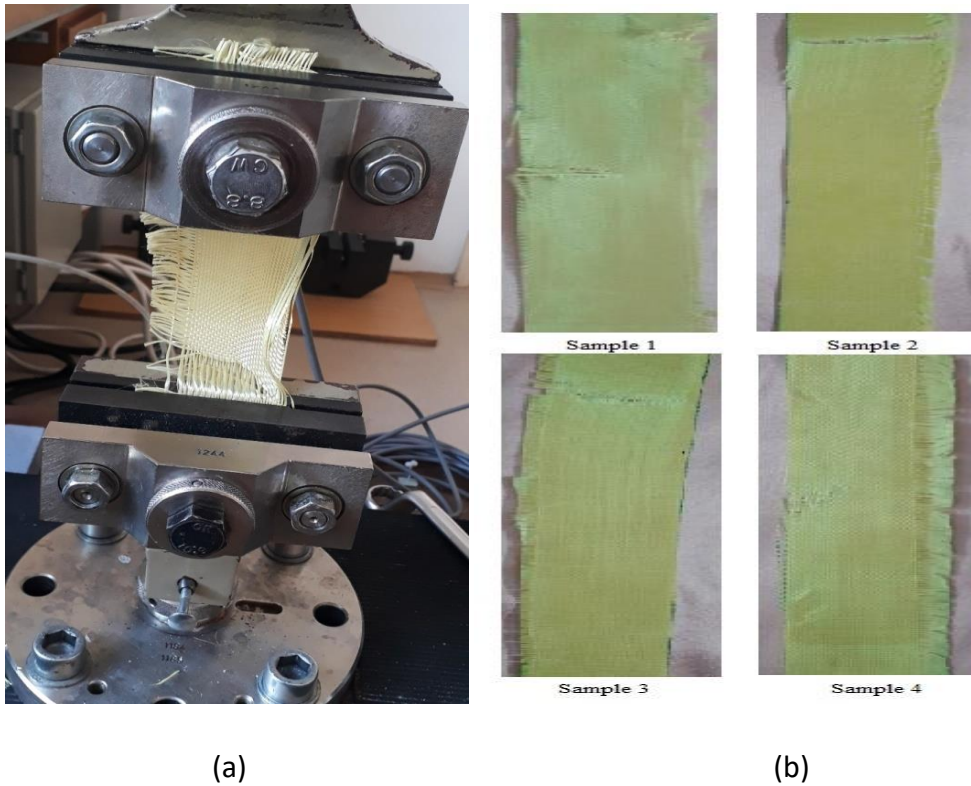
Figure 65 shows that the water-vapor resistance for Kevlar fabric is 8.2 m<sup>2</sup>Pa/W, which is lower than that for the other samples which are prepared by depositing epoxy resin on Kevlar fabric. This indicates that uncoated ballistic fabrics offer good breathability. In contrast, plastic-coated fabrics have very low breathability. These materials could cause discernable discomfort if worn in warm climates.

As shown in Figure 65, the water-vapor resistance for sample 3 is 74.4m<sup>2</sup> Pa/W, which is higher than that for samples 2, 4, 7, 1, 5, 9, 10, 8 and 6, 74.075 m<sup>2</sup> Pa/W, 31.9 m<sup>2</sup> Pa/W, 17.2 m<sup>2</sup> Pa/W, 16.17 m<sup>2</sup> Pa/W, 12.4 m<sup>2</sup> Pa/W, 11.6 m<sup>2</sup> Pa/W, 11.07 m<sup>2</sup> Pa/W, 10.7 m<sup>2</sup> Pa/W and 10.35 m<sup>2</sup> Pa/W respectively. This indicates that sample 3 is more applicable in low-temperature environments because of its high vapor resistance. According to Horrocks and Anand, protective clothing with water-vapor resistance that is less than 20 m<sup>2</sup> Pa/W can perform best breathability and comfortable to wear when the humidity is low [64]. In other words, composites prepared by dropping and printing methods have lower water-vapor resistance to moisture transfer and therefore higher breathability.

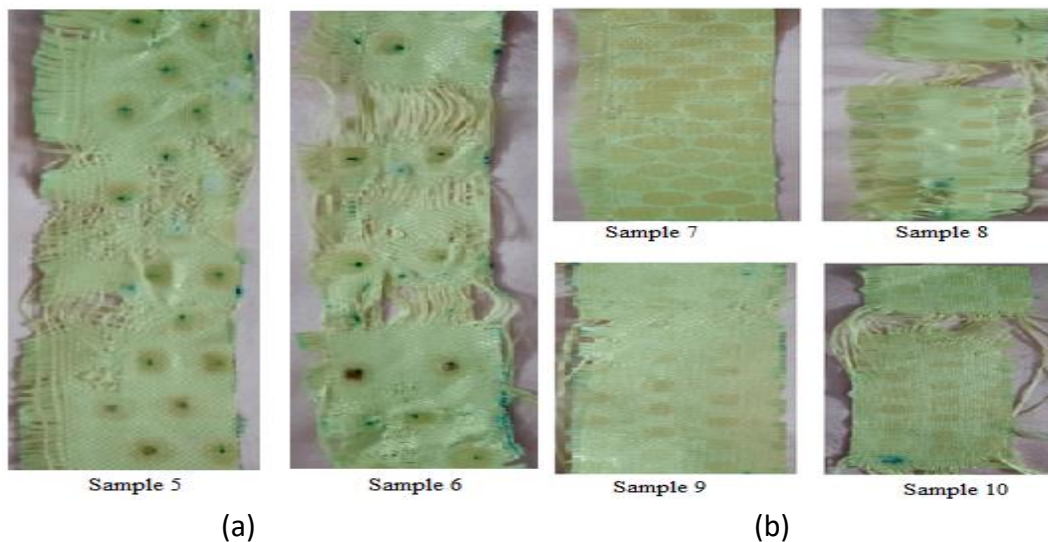
These composites can absorb a lot of vapor and release it away from the body to the atmosphere. Therefore, they have better breathability and improved comfort properties compared to classical coated composites when the humidity inside the garment is high.

## IV. Mechanical properties

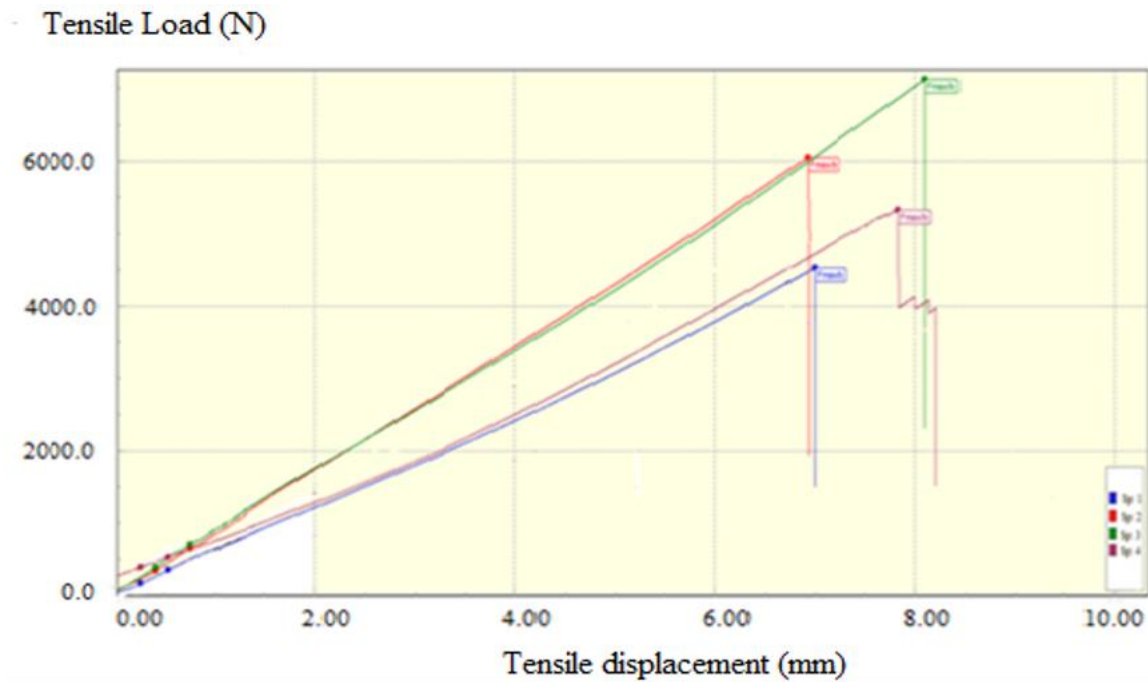
### 1. Tensile performance



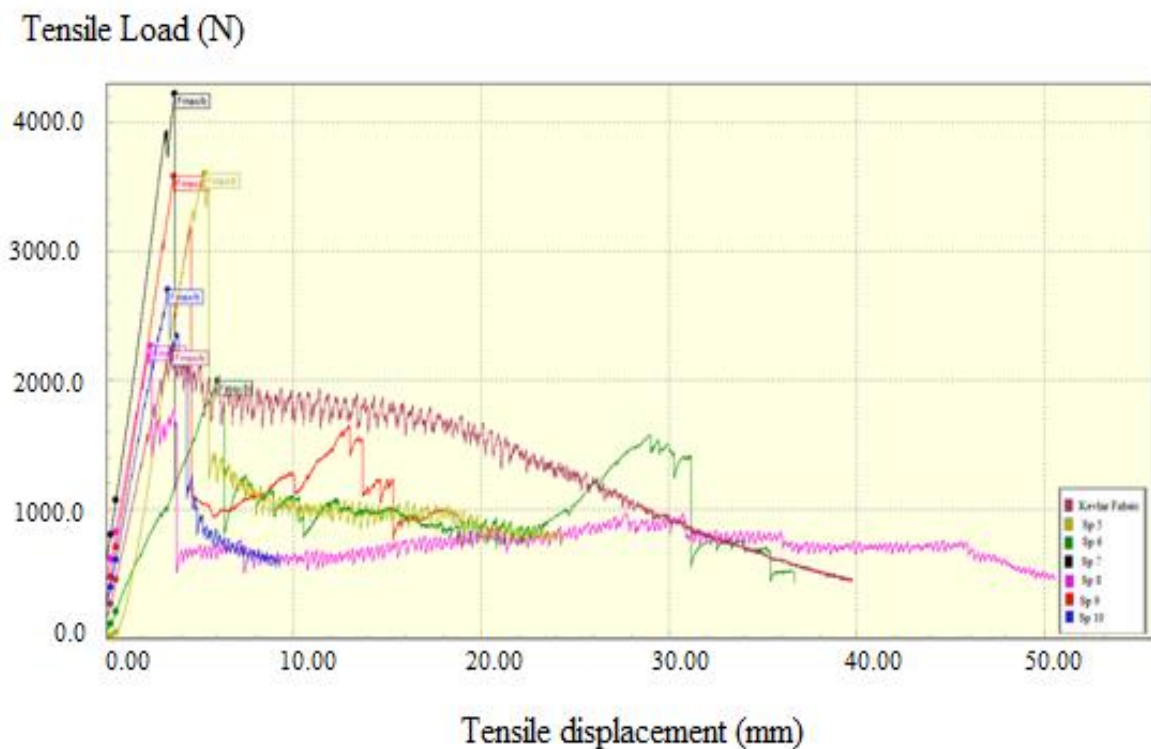
**Figure 66:** Photographs of the tensile fracture of (a) Kevlar fabric (b) composites prepared by coating methods



**Figure 67:** Photographs of the tensile fracture specimens of (a) the composites prepared by dropping method (b) the composites prepared by printing method



**Figure 68:** Tensile Load–displacement curves of Kevlar/Epoxy composites prepared by coating methods



**Figure 69:** Tensile Load–displacement curves of Kevlar/Epoxy composites prepared by dropping and printing methods

Figures 68 and 69 show the tensile Load–displacement curves of Kevlar/Epoxy composites fabricated with using different mass fraction of matrix which is deposited by coating,

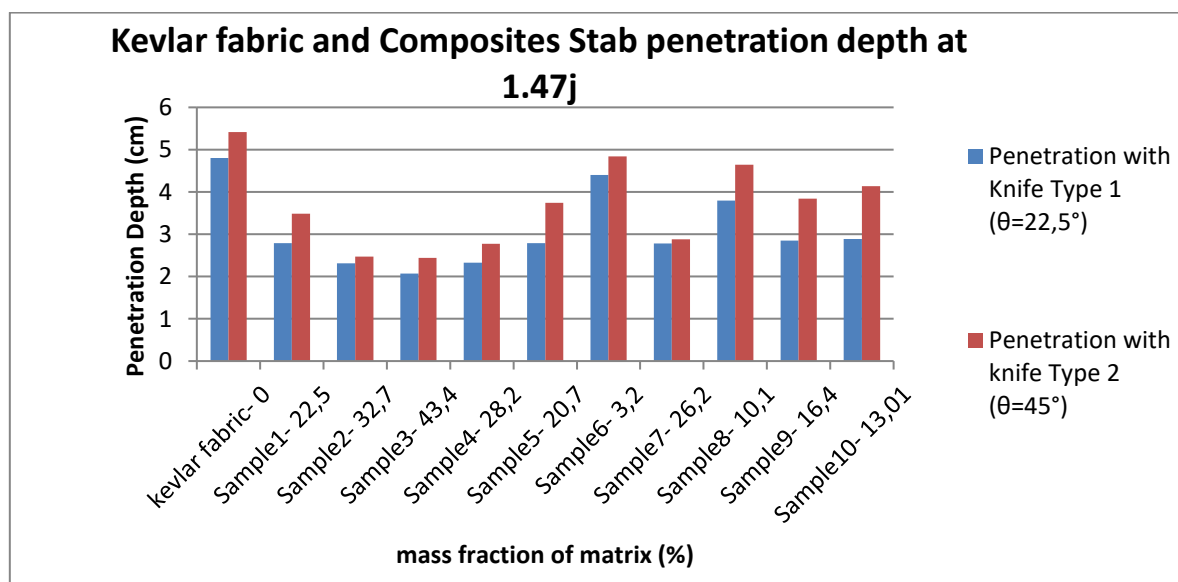
dropping or printing methods. The tensile Load of all composites increased linearly with displacement until the fracture occurred, after which the tensile Load decreased drastically. Moreover, with increase in the mass fraction of matrix, the composite showed fracture at higher tensile Load. The composite number 6 fabricated with utilizing the lower matrix mass fraction (3.2%) had the lower tensile Load of 2266.05 N as shown in figure 69. Whereas, composite number 3 fabricated with utilizing the higher matrix mass fraction (43.4%) had the higher tensile Load of 7125.01 N. However, sample 7 shows the higher tensile Load as to compare with modern composites because of its higher matrix mass fraction. The increase of matrix mass fraction leads to the significantly increase of tensile Load. This indicated that matrix mass fraction had a greater influence on the tensile Load of the composites.

At lower matrix weight, the resin chains are loosely bonded by weak van der Waals forces and the chains can move easily, responsible for low strength of composite, although crystallinity is present.

At higher matrix weight, the resin chains become large and hence are cross-linked. The cross-linking restricts the motion of the chains and increases polymer strength which is transmitted to the composite.

## 2. Stab resistance test

Following the mean values of the stab resistance tests series are presented in Figures below.

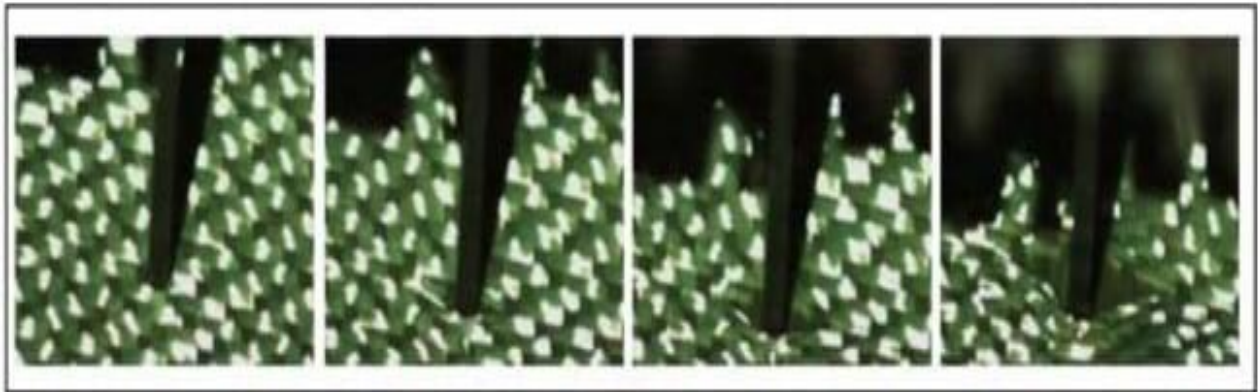


**Figure 70:** Effect of matrix mass fraction on knife penetration depth



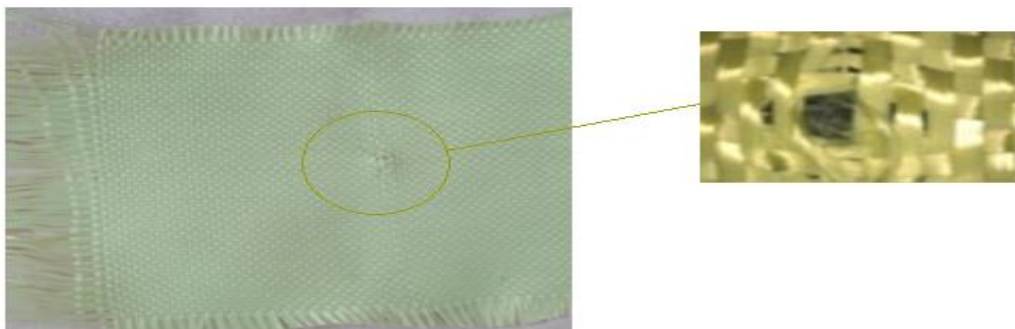
The test series showed a significant influence of the epoxy resin onto the stab depth of the samples. While the pure Kevlar fabric is penetrated 4.803 cm with the knife type 1 and 5.416 cm with the knife type 2, the Kevlar/Epoxy composites prepared by coating, dropping or printing methods presented results lower than 4.803 cm depth with the knife type 1 and lower than 5.416 cm depth with the knife type 2 as shown in figure 70.

The picture sequence (Figure 71) shows the moment when the blade type 1 penetrates the Kevlar fabric: the blade depresses the fabric and the primary filaments, which are in direct contact to the knife, migrate away from this impact area. In this case, the filaments are not cut, but sliding apart. It is assumed, that the low friction between the yarns lead to a high yarn slippage and the blade can ingress deeper.



**Figure 71:** Picture sequence of the stab penetration of a Kevlar fabric

Figure 72 presents the holes in the Kevlar fabric after the stabbing. It can be observed that the yarns in the pure Kevlar fabric are cut, but mostly slide apart.

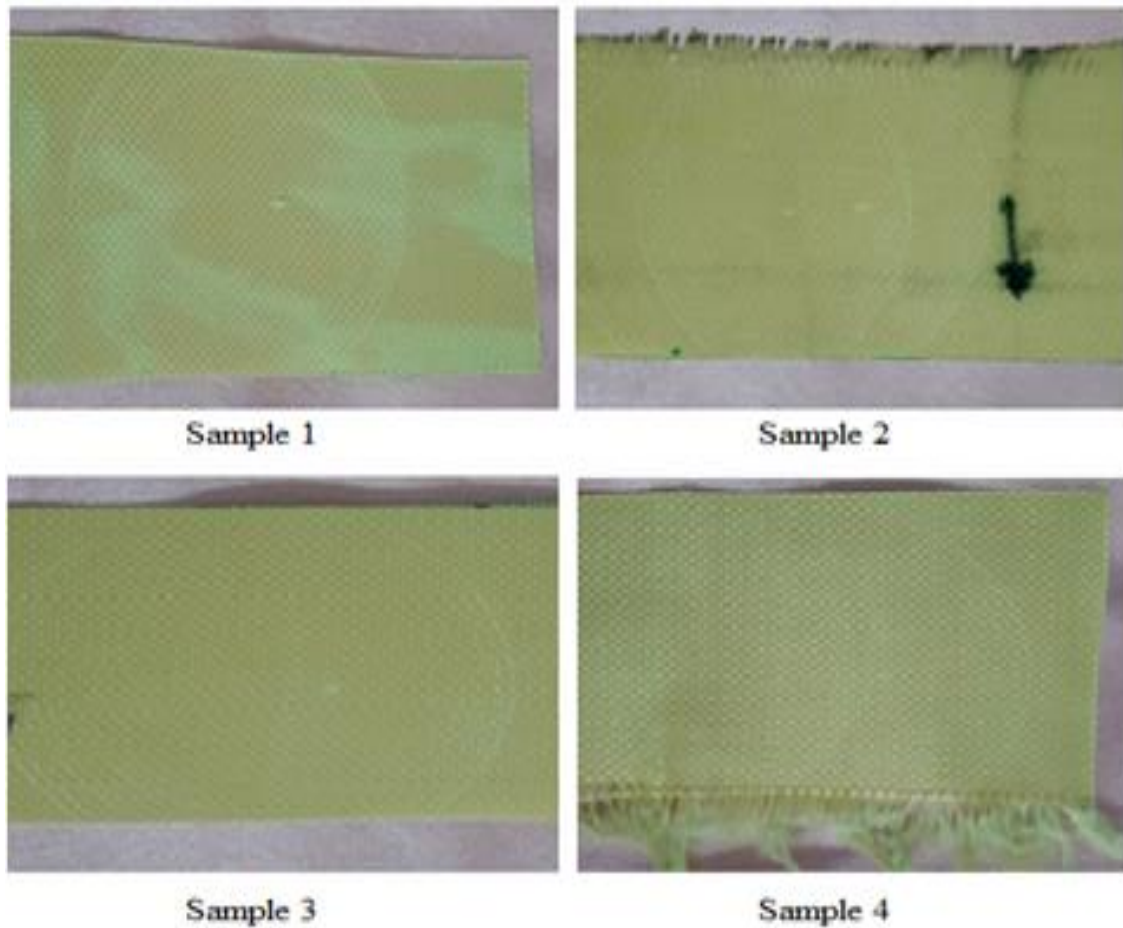


**Figure 72:** Damaged Kevlar fabric by knife impactor type 1

While, as shown in figure 73 the yarns in the Kevlar/epoxy composites prepared by coating method are cut.



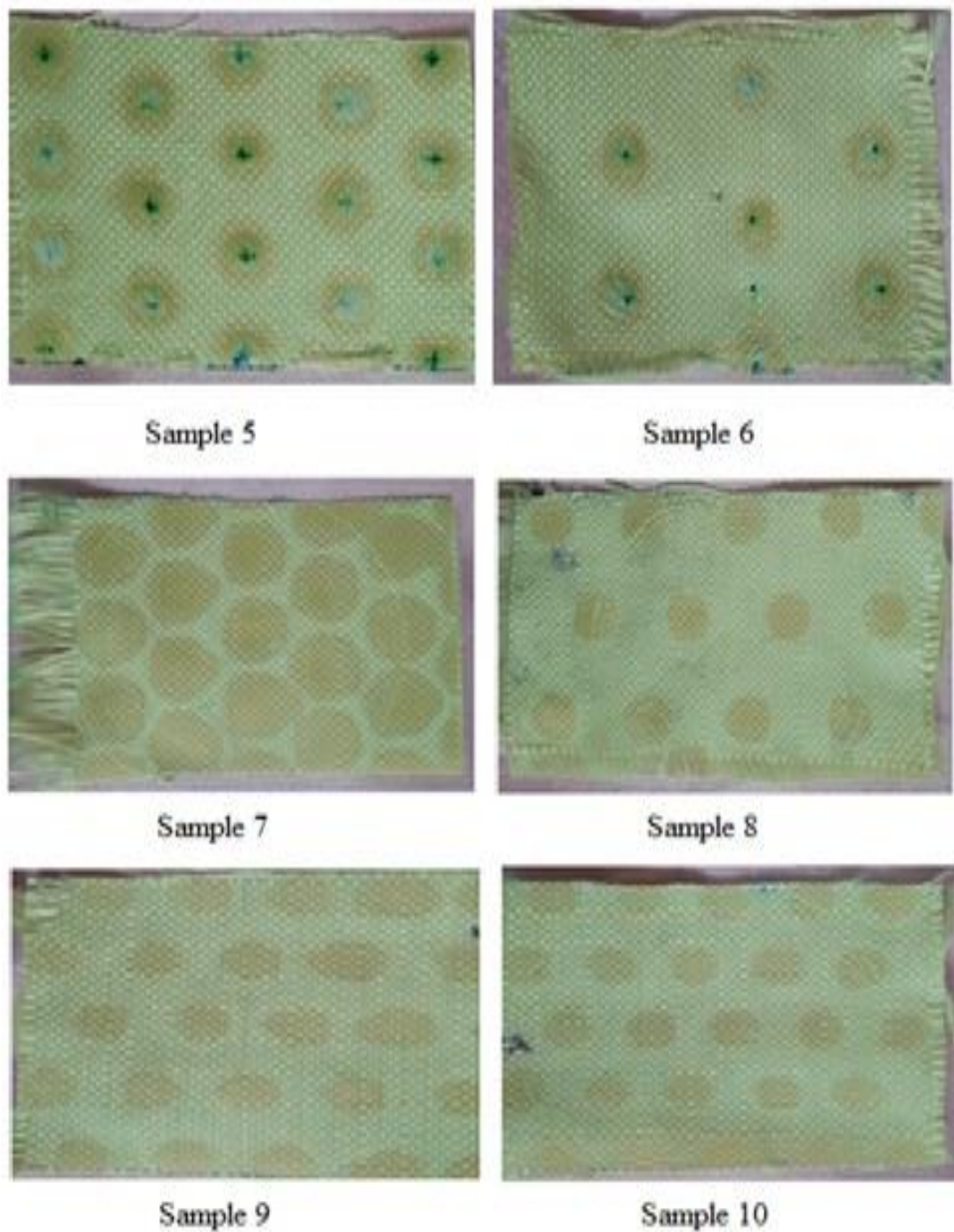
Therefore, more energy is required to cut the Kevlar/epoxy composite structure than to penetrate the Kevlar fabric. Moreover, with increase in the mass fraction of matrix, the composite showed a low penetration depth which explains the improvement of mechanical properties.



**Figure 73:** Damaged composites prepared by coating method penetrated with knife impactor type 1

Figure 74 shows that if the knife impactor depresses the area between the spots (Kevlar fabric), the yarns in this zone are cut, but mostly slide apart. While, if the knife depresses the resin spot, the yarns in the Kevlar/epoxy composites are cut.

However, in the two cases the penetration depth of composites prepared by dropping or printing methods is lower than that of Kevlar fabric. As shown in figure 70, sample 7 which has the higher matrix mass fraction reveals the lower penetration depth as compare to modern Kevlar/epoxy composites. Therefore, sample 7 exhibits the best mechanical properties.



**Figure 74:** Damaged composites prepared by dropping and printing methods penetrated with knife impactor type 1

Also, we can observe that the increase in Knife Penetration angles leads to the increase of penetration depth as shown in figure 70. It may be associated with the increase in friction and knife load distribution to the sample structure.

## V. Conclusion

This research aimed to develop and improve the comfort properties of the ballistic Kevlar/epoxy composite without overly compromising its mechanical properties. Therefore, after preparing the classical and modern samples, a series of examination were conducted to test the difference and changes that occurred.

The results indicate that Sample 3 which has the higher mass fraction of matrix exhibits the lower air permeability value. Therefore, when decreasing the mass fraction of matrix, the structure of the sample becomes more porous, this allows the passage of air through it. That can explain the fact that Kevlar/epoxy composites prepared by dropping or printing methods by using less of matrix mass fraction exhibit the higher air permeability.

For thermal conductivity, we have found that composite number 3 has the heavier structure that contains less still air that's why it has the higher thermal conductivity value as to compare to other samples. However, sample 7 exhibits the higher thermal conductivity value as to compare with the other modern composites because it shows the higher mass fraction of matrix which contains thermal conductive fillers.

For water-vapor resistance, we have found that composites prepared by dropping and printing methods have lower water-vapor resistance to moisture transfer and therefore they have better breathability and improved comfort properties compared to classical coated composites when the humidity inside the garment is high.

For tensile performance, the increase of matrix mass fraction leads to the significantly increase of tensile Load. Sample 3 which has the higher mass fraction shows the higher tensile load as to compare with samples. However, sample 7 exhibits the higher tensile load as to compare with the other modern composites.

For stab resistance test, we have found that Sample 3 which has the higher mass fraction shows the lower penetration depth as to compare with samples. However, sample 7 exhibits the lower penetration depth as to compare with the other modern composites. Therefore, with increase in the mass fraction of matrix, the composite showed a low penetration depth which explains the improvement of mechanical properties.

All of the developed composites successfully met and enhanced the properties and characteristics required for the intended applications. But sample 7 which exhibits improved

comfort properties has the best mechanical properties as to compare with modern Kevlar/epoxy composites.

# General Conclusion

## General conclusion

The aim of this study is the comfort and mechanical characterization of ballistic Kevlar/epoxy composite through different tests, depending on different parameters.

In the first part, a literature review was conducted on the characteristics of a composite material, its composition, manufacturing methods and different fields of application. Then, we have presented Kevlar fabric and epoxy resin characteristics, its chemical compositions, its properties and different fields of application.

In the second part, we presented the material and equipment used. Besides, we mentioned the composite manufacturing process and the followed experimental methodology.

The last chapter focused on studying comfort and mechanical properties of ballistic Kevlar/epoxy composites prepared by coating, dropping and printing methods. To characterize comfort and mechanical properties some physical properties were determined. In fact, the Permetest was used to determine the resistance to water vapor. The ALAMBETA was used to characterize thermal properties by evaluating thermal conductivity. The air permeability tester was used to determine the air permeability values. To evaluate mechanical properties of composites, tensile tester and stab resistance tester were used.

The characterization of the composites reveals the importance of matrix mass fraction in having a significant effect on the mechanical properties of composites. In fact, increasing the mechanical properties is due to increasing the mass fraction of matrix.

Tensile load and stab resistance behavior of composites show better properties in composite processing by using huge quantity of resin. Moreover, composite number 3 fabricated by coating method with utilizing the higher matrix mass fraction (43.4%) had the higher tensile load of 7125.01 N; meanwhile, it presents the lower penetration depth value of knife type 1 (2.067 mm) and also the lower depth penetration value of knife type 2 (2.44 mm) throughout stab resistance testing. While sample 7 prepared by printing method which have the higher mass fraction of matrix (26.2%) as to compare to modern composites shows the higher tensile load of 4217,79 N. In stab resistance testing, sample 7 exhibits the lower penetration depth for knife type 1 and knife type 2; 2.78 mm, 2.876 m, respectively.

The estimation of the effect of matrix mass fraction and thickness of Kevlar/epoxy composite on the comfort properties of all samples allows revealing that for air permeability; thermal conductivity and water-vapor resistance results have showed that matrix mass fraction and thickness of composites have a significant effect on them. Results show that sample 1 prepared by coating method with utilizing the lower mass fraction of matrix (22.5%) which

leads to the lower thickness (0.26mm) as to compare to classical composites shows the higher air permeability value (37,4mm/s) and the lower water-vapor resistance value (16,175Pa.m<sup>2</sup>/W). While sample 3 which has the higher mass fraction and thickness (0.35mm) exhibits the higher thermal conductivity value (77.55 10<sup>-3</sup> W/m K) as to compare to classical composites. For the modern composites prepared by dropping and printing methods, sample 6 presents the higher air permeability value (199, 75 mm/s) and the lower water-vapor resistance value (10.35Pa.m<sup>2</sup>/W) because of its lower matrix mass fraction. While sample 7 presents the higher thermal conductivity value (42,410<sup>-3</sup> W/m K) because of its higher matrix mass fraction.

At the end of our research, the best composite having a good mechanical and comfort properties was revealed.

This research was a first approach to improve the comfort properties of a ballistic Kevlar/epoxy composite with different methods of matrix deposition. Nevertheless, it would be appropriate to improve this study by:

- Studying the behavior of n composite layers in stab resistance and tensile performance tests.
- Studying the behavior of modern composite in shearing and bending testing.
- Studying the surface treatment of composite in order to decrease the hardness and improve the touch.

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