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## **Laser treatment of textiles**

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## **Abstract**

Laser treatment of textile fabrics is a dry treatment of the surface of the material using the laser beam at 9.3 – 11.5 $\mu$ m wavelengths of infrared electromagnetic spectrum. The utilization of lasers in surface modifications is one of the new technologies being applied in recent years. Lasers are capable of changing the properties of fibers, when applied at certain intensities of laser beam. The fibers of treatment are Kevlar 49, Kevlar 149 and Glass fibres due to their high strengths and high thermal stabilities.

The treated fabrics are tested for absorbency test, Infrared Spectrophotometer, surface resistivity, Scan Electron Microscopy, abrasion and pilling tester, colour measurement and mechanical strength measurements and compared with the untreated samples of Glass, Kevlar 149 and Kevlar 49 fabrics. The water drop absorbency tests of the treated samples have shown different results as compared to the untreated substrates.

The influence of the laser light on the surface of the treated material show the carbonization of the chemical structure by the use of IR spectrophotometer. The treated materials tend to be rougher on the surface and the evidence was realized by Scan Electron Microscopy (SEM) to view the surface morphology. Abrasions of the samples were tested using abrasion tester and the results of the laser irradiated where compared with non – irradiated samples. The increase in laser's energy density reduced the abrasion resistance of the material.

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## **1. LASER TREATMENT ON TEXTILES**

High strength fibres such as Kevlar and glass fibres are utilized in manufacture of high performance products due to their special properties of high strength to weight ratio. The end uses, thus, high performance products such as bulletproof vests, ropes and cables, cut resistance products, fishing rods, protective apparel and tires among many other end uses. This many applications of high strength fibres leave them exposed to harsh environmental conditions, from high temperatures, strong chemicals, high-energy solar radiations, high pressures and tension forces. It is of high important to research more on the properties of high strength fibres under various electromagnetic radiations such as infrared and ultraviolet radiations and the effects of high strength fiber's surface when treated with infrared carbon dioxide laser beam at different intensity and duration of laser light [13].

The effect on dyeing properties by CO<sub>2</sub> laser modification of synthetic fibres have been studied whereby improvement on dye ability of treated sample were created by irradiation with carbon dioxide laser beam [5]. It is believed that laser treatment can increase absorbency and wettability of the material. Water drop absorbency will be researched further in this diploma work whereby treated samples will be compared with the untreated samples.

### **LITERATURE REVIEW:**

#### **1.1 Lasers:**

Lasers are generators of light, based on the amplification of light by means of stimulated radiation of atoms or molecules. The term laser basically mean: Light Amplification by Stimulated Emission of Radiation, which describes the key physical processes occurring in typical laser operation. Lasers technology is one of the best inventions to emerge from the 20<sup>th</sup> century. There are four categories of lasers divisions, namely, solid lasers, gas lasers, liquid lasers and semiconductor lasers. Lasers have variety of applications due to its special, unique light properties. Unlike many other light sources; lasers produce a highly directional and high intensity beam with a narrow frequency range. Lasers are coherent, meaning that they are highly organized and highly directional over relatively long distance and long periods of time, without

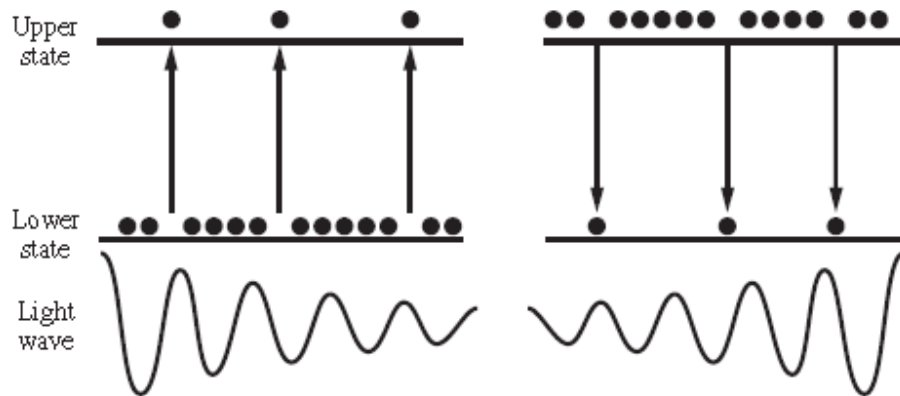
losing its energy. The laser light has high intensity beam, meaning that its energy is highly concentrated. One of lasers special property is that it is monochromatic, which implies that it is uni-colour. This is an interesting parameter of lasers because it is different from other light sources which change colour at different wavelengths. The crests and troughs line up with each other, meaning that all the light is exactly the same colour throughout [1-2].

The average intensity of visible light (sunlight) hitting the surface in the continental US at noon is approximately equal to  $200\text{Wm}^{-2}$ . A typical laser pointer produces  $5\text{mW}$  in  $1\text{mm}^2$  spot ( $5000\text{Wm}^{-2}$ ). At opposite extreme, commercially available “ultrafast laser systems” can readily produce  $100\text{mJ}$  pulses with  $100\text{fs}$  duration ( $10^{12}\text{W}$  peak power). This kind of peak power is roughly equal to the worldwide electrical generation capacity [20].

**Table 1: approximate regions of the electromagnetic spectrum [20]:**

<b>Region</b>	$\lambda$ (meters)	<b>Typical Sources</b>	<b>Molecular effects</b>
Low frequency	$> 10^3$	power lines ( $\nu = 60\text{ Hz}$ , $\lambda = 5000\text{ km}$ )	
Radio frequency	$10^3-1$	AM/FM radio; television	
Microwaves	$1-10^{-3}$	radar; microwave ovens	excites rotations
Infrared	$10^{-3}-10^{-6}$	heated objects	excites vibrations
Visible	$4-7 \times 10^{-7}$	sun	excites electrons in some molecules
Ultraviolet	$2-4 \times 10^{-7}$	sun	breaks bonds
X-rays	$10^{-7}-10^{-11}$	special sources	breaks bonds if absorbed
$\gamma$ -rays	$< 10^{-11}$	nuclear disintegrations	breaks bonds if absorbed

One of the most important phenomenons of lasers is the absorption and stimulated emission. At high intensities stimulated emission can be stronger than absorbed emission. If the population of the lower state is higher than population of the upper state, then there will be more absorption of photons than emission, and thus the energy of the light beam decreases. The opposite is the key process of lasers when the upper level is greater than the lower level (population inversion), thus energy of the laser beam increases as shown in figure below [20]:



**Figure 1: if the population on the left is higher on the lower level than the upper state, then absorption is stronger than emission. If the population is higher at the upper state, the situation on the right will create laser [20].**

## 1.2 History of lasers:

In 1917, Einstein predicted this kind of stimulated radiation. In 1952, Ch. Townes, J. Gordon and H. Zeiger in USA and N. Basov and A. Prokhorov in USSR suggested the principle of generating and amplifying of the microwave oscillations based on Einstein's concept. Masers (microwave amplification by stimulated emission of radiation) were later invented in 1954. The masers were using ammonia gas and microwave radiation and it was a two level system. In 1958, Townes, Schawlow and Prokhorov extended the maser concept by introducing the optical frequencies. Their new concept of optical amplifier, earned them a Nobel Prize. The masers were used to amplify radio signals and also as an ultrasensitive detector for space research. The first laser was produced for the first time in 1960 by Theodore Maiman of Hughes Research Laboratories. The laser used the ruby crystals as an amplifier and a flash lamp as an energy source. These ruby lasers emit a short pulse of laser light. The active centers in this type of laser are Chromium ions as they have a set of three energy levels suitable for lasing actions. A typical application of ruby lasers is in holography, metrology, medical applications and inorganic material processing.

A year after the invention of ruby laser, the gas laser was produced by A. Javan, W. Bennett and D. Herriott at Bell Telephone Laboratories, USA. This Helium and Neon gas laser is the first to operate using the principle of converting electrical energy to a laser light output. He-Ne laser is an atomic laser. This type of laser is widely used in laboratories as a monochromatic source, in

interferometry, bar code reading, in surveying, light pointers, length and velocity measurement, alignment devices [2].

Other important types of lasers were developed between 1962 and 1968 including: semiconductor, Carbon dioxide, Argon-Ion, He-Cd and dye lasers. During the mid 70s, the technology of laser application was realized and it found many of its applications in industries such as in welding, cutting, drilling and marking. Laser technology was explored by the 80s and 90s era, explorations were increased among applications such as heat treatment, cladding, alloying, glazing and thin film deposition [3]. The table below shows the detailed description about the types of lasers as well as the people who discovered them.

**Table 2: types of lasers, discoverers and year discovered [2]:**

<i>Year</i>	<i>Discoverer</i>	<i>Type of laser/principle</i>
1917	Albert Einstein	Stimulated emission process
1952	N.G Basov, A.M Prokhorov and Townes	Maser principle
1954	Townes, Gordon, Zeiger	Maser
1958	Townes, Schawlow, Basov, Prokhorov	Laser principle
1960	Theodore Maiman	Ruby laser
1961	A. Javan, W. Bennet and D. Harriott	Helium-Neon laser
1961	L.F. Johnson and K. Nassau	Neodymium laser
1962	R. Hall	Semiconductor laser
1963	C.K.N. Patel	Carbon dioxide laser
1964	W. Bridges	Argon Ion laser
1966	W. Silfvast, G.R. Fowles, and B.D Hopkins	He-Cd laser
1966	P.P. Sorokin and J.R. Lankard	Tunable dye laser
1975	J.J. Ewing and C. Brau	Excimer laser
1976	J.M.J. Madey and coworkers	Free-electron laser
1979	Walling and coworkers	Alexandrite laser
1985	D. Mathews and coworkers	X-ray laser

### 1.3 CO<sub>2</sub> laser:

In my part of research, a gas laser was used, i.e. CO<sub>2</sub> laser in the treatment of textiles. CO<sub>2</sub> lasers are one of the most powerful and efficient lasers which are used in industries applications. CO<sub>2</sub> lasers have average powers up to tens of kilowatts. This gas laser uses electric discharge for exciting of atoms. Energy is transferred from the discharge to the atoms by the form of collisions. The CO<sub>2</sub> laser ranges between 9.3 – 11.5µm wavelengths. This range of wavelength is in the invisible, infra-red part of the electromagnetic spectrum. This laser produces powers up to 100kW and pulsed energies of about 10kJ [2].

The CO<sub>2</sub> laser can be continuous wave or pulsed modes. It depends mainly on the required end product. Pulsed mode is more appropriate when heating is not desirable for specific application in textile treatment of textile, as compared to continuous wave mode. One of the advantages of carbon dioxide infrared lasers is their large beam size, high efficiency, easy operation, use non toxic gases and low costs of the equipment. The application of this type of lasers is of little in textile or polymer treatment likely due to the effect of infrared radiation which imparts thermal damage to the surface of the treated polymers. CO<sub>2</sub> pulsed lasers can be considered to be non-contact and environmentally friendly treatment for surface modification of polymers [5].

The mixture of carbon dioxide, nitrogen and helium are filled through the discharge tube which has a cross section of 1.5 cm<sup>2</sup> and a length of 26 cm. Carbon dioxide, nitrogen and helium gases are filled through the proportion 1:4:5 respectively. Light and electricity are the excitation mechanisms of choice for most lasers. In case of carbon dioxide lasers, electric discharge is used. A high voltage electric discharge is ignited into this mixture. The CO<sub>2</sub> molecule is being broken down during this process to form oxygen and carbon monoxide, thus small amount of vapour is added to the gas mixture for the regeneration of CO<sub>2</sub>.

The lasing mechanism of CO<sub>2</sub> is highly characterized by the vibration levels, whereby nitrogen is playing an important role. 10% - 30% of nitrogen is excited by the high voltage discharge. Nitrogen is homonuclear molecule and therefore it cannot lose energy by photon emission. CO<sub>2</sub> molecule undergoes vibrational oscillations known as vibrational modes, namely, stretching mode, the bending mode and the asymmetric stretching mode.

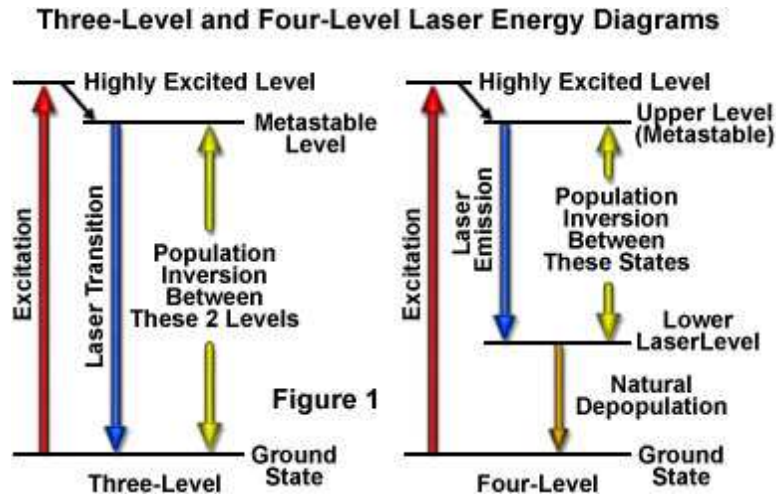


The molecules can only absorb infrared radiation if the dipole moments of that molecule changed by vibrations. The homonuclear diatomic molecule of  $N_2$  has no dipole moments, no matter how far the atoms are separated, thus it cannot be affected by infrared spectra. It can neither be affected by microwave spectra. All heteronuclear atoms (e.g. HCl and CO) and polyatomics (three or more atoms) absorb infrared radiation because they have dipole moments due to their vibrations. Thus  $CO_2$  is the used molecule in gas laser due to its bending mode of vibration which makes the molecule nonlinear, and thus creating dipole moments.

Nitrogen and carbon dioxide absorb energy from the discharge tube. The excited nitrogen molecule transfer energy to the carbon dioxide molecule through collisions. This results in carbon dioxide molecule being excited into highest energy level. Energy is then transferred to the lower energy level and population inversion is achieved [2], [6], [20].

#### **1.4 Laser energy levels:**

Two basic mechanisms can be achieved when population inversion occurs. It can either be creation of excess atoms or molecules in the higher energy state or reduction of the population of the lower energy state. The excited states commonly have the shortest lifetimes of only nanoseconds, a period which is not long enough to allow stimulation by another photon. Lasing mechanism depends on the longer stay of the excited atoms in the upper energy levels, appropriate ones being in the order of microsecond to a millisecond before spontaneous emission. With lifetime this long, excited atoms and molecules can produce significant amounts of stimulated emissions. Lasers action is only possible if the population builds up quicker than it decays in the upper energy level, maintaining a population larger than that of the lower energy level. This transition to the lower energy level produces infrared radiation at wavelength between 9.6 to 10.6  $\mu m$  [14]. The energy is transferred to the carbon dioxide molecule by the excited nitrogen molecules in resonant collisions. In this way carbon dioxide molecule is excited to the highly excited energy level. This is because nitrogen has nearly as much energy in its lowest vibrational level as the asymmetric stretching mode of carbon dioxide.



**Figure 2: three-level and four-level laser energy diagrams.**

### **1.5 Advantages of laser based technology over conventional processing technique:**

Laser treatments on textiles have greater advantages over both the chemical and physical methods. The technology of laser treatment have higher precision over surface treatment and has less damage on the surface of the material, they are easily controlled and environmentally friendly. Chemical treatment on textile has long been practiced to modify the surface layers of textile to improve some of the properties. This method of treatment requires precise process control and may lead to severe surface damage and undesirable roughness [1]. Laser technology is good for the ecological reasons. There are no harmful substances to the environment because of reduced chemical agents. Lasers can save us a lot of energy because it uses less water consumption. Process flexibility of lasers allows us to create new finish styles. The finish process can be applied on parts or assembled garments. The computerized technology of laser makes it simple to toggle from one finish to another without retooling. Special effects (logos, micrographics and characters) can be applied on the garment [4].

## **2. INFLUENCE OF LASER TREATMENT ON TEXTILE MATERIAL**

### **2.1 Introduction**

Most polymeric surfaces are inert, hydrophobic in nature and usually have a low surface energy. Lasers have found many uses in the textile industries due to its advanced properties. Surface modifications using new technologies have gained more interests among scientists and researchers in the past decade [1]. Laser irradiation can have huge influences on textile properties. These properties include chemical as well as physical properties. The surface morphology can easily be modified using laser light in which it can have some influences on dyeing and water absorption. The surface irradiation by laser on textiles can change some chemical groups in the chemical structure of polymers. The insertion of certain functional groups can thus have greater influence on textile properties. Laser treatment can increase the overall surface area of the material due to the increase in roughness of the material [5]. Usually hand-sanded or sand blasted methods are used to improve surface roughness [21]. Other properties that can be affected include: tensile strength, elongation, wettability, and printability, dye uptake, surface luster, air permeability, crystalline as well as abrasion [7].

Various modifications can be applied on the surface of textile material using laser beam. Type of modifications can be etching, ablation, deposition, evaporation, surface functionalization and many other treatments. It is always important when treating the material to consider the type of laser used, ambient conditions as well as type of material being treated. The properties of the material to be treated should be fully noted and fully considered when treating the surface of the material. The important properties are thermal and optical properties of the material. The thermal properties of main concern are specific heat and thermal diffusivity which need to be considered to reduce thermal damages on the material. In polymers, heat capacity increases steadily until glass transition temperature is reached.

Fibres with the rough surfaces are said to absorb more of the laser light as compared to the smooth surfaced ones. A rougher surface presents a greater surface area to the laser beam, thus causing light to be reflected several times, thereby increasing the total absorptivity. Materials with the higher absorption coefficients absorb more energy and therefore the bulk properties are not affected, because energy is absorbed on the surface. Every material absorbs energy at

different wavelengths so it is important to treat materials using specific required laser wavelength. If the material is not absorbing energy at the given wavelength, the power density of the laser can be increased accordingly so as to promote energy absorptivity of that material [1].

Surface modifications of polymers using longer wavelength carbon dioxide laser is found to be not so effective for the photochemical process. This is due to the large temperature increases during surface treatment. The molecules of the material can lead to dissociation by thermal means. The pulsed lasers are more appropriate for the textile treatment where heating is not desirable more than the continuous mode lasers.

## **2.2 Thermal and photochemical mechanisms:**

There are two basic mechanisms that can be realized by laser treatment of textiles surfaces, namely thermal and photochemical mechanisms. In the thermal modification, radiation is absorbed by the material so that the increased temperatures are high enough to make the reactions to occur. Both thermal and photochemical reactions can occur at the same time, it depends on certain parameters such as laser beam intensity, the wavelength, and mode of operation of the laser and on the properties of the material used.

The absorbed energy by the material induces atoms of the molecules to gain mobility and collisions of atoms with the lattice. This process therefore makes the atoms to gain the kinetic energy. The heat energy which is sufficient to activate the molecules of the material can take place without melting the surface of materials. In some cases, excess energy may be used to heat the surface of the substrate high enough to melt and vapourize the components of the surface layer which can also alter the properties of the material.

The main principle of the photochemical phenomena is guided by the Grotthus Draper law. This law states that only the absorbed radiation can be effective in producing a photophysical process (e.g. bond dissociation) or photochemical change (e.g. photo-rearrangement) in that molecule. Photochemical mechanism results in breaking of the chemical bonds especially the 3.5eV C-H bond, which is vital in bonding of many polymers and thus creating the bonding sites. The breaking of the chemical bonds is due to the absorbed light energy. The light excites atoms or molecules, making them reactive. Photon absorption by the material's molecule can lead to an

increase in energy from a ground state to an excited state. Chemical reactions that can occur due to absorption of light are crosslinking, chain scission, and radical formation.

Photo degradation can make alterations on polymer molecular weight by the scission of bonds. The molecular weight of the polymer decreases due to the chain scission reactions. This scission of bonds can substantially have influences on the mechanical properties of the fabric or fibres and also the chemical reactivity of the system can increase. Contrary to the chain scission, the cross-linking can have the different influence on the polymer molecular weight. Cross-linking results in an increase in molecular weight. Low level of cross-linking improve the mechanical properties, the high levels of cross-linking can further increase the strength and elasticity, only the disadvantages is that it makes the structure brittle and thus reducing the elongation at break.

There are three ranges of ultra violet radiations, namely UV-C which ranges from 280 – 100 nm, UV-B ranging from 315 – 280 nm and UV-A which ranges from 315 – 400 nm. The bond scissions can potentially be induced by UV-C whereas wavelengths along UV-B and UV-A lead to electrons excitation in the chemical bonds by the photochemical process.

When polymer absorbs radiation, its energy is increased in the same proportion as the energy of the absorbed photon.

$$E = E_2 - E_1 = h\nu \dots\dots\dots (1)$$

Where  $E_2$  and  $E_1$  are energies of a single molecule in the excited and ground states, respectively,

$h$  = Plank's constant, and

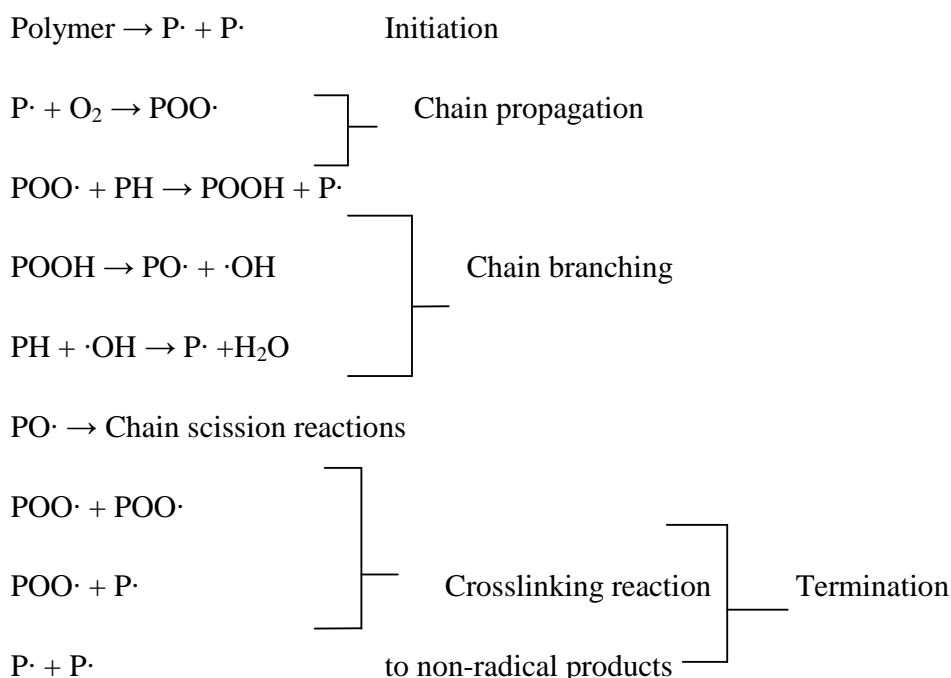
$\nu$  = frequency of radiation.

The excited molecule can then lose the absorbed energy by:

- a. Heat
- b. The emission of radiation energy in the form of fluorescence or phosphorescence,
- c. Undergoing a chemical change with the molecule,
- d. The breaking of chemical bonds (photolysis), or
- e. Transfer of energy to another atom or molecule.

The process of photochemistry is governed by the above mentioned principles. The 1<sup>st</sup> two principles are considered photophysical and the last three principles are considered photochemical processes. The fundamental principle governing this process is the Stark-Einstein law or the law of photochemical equivalence, which states that: one atom or molecule is activated for every photon that is absorbed. One other important principle of importance is the polymer photo oxidative degradation, which includes processes like chain scission, cross-linking and secondary oxidative reactions. This type of degradation occurs by the free radical mechanism which similar to thermal oxidation.

Polymer photo oxidative degradation occurs by the following steps:



Where: P· = polymer alkyl radical, POO· = polymer peroxy radical (polymer alkyl peroxy radical), PH = polymer, POOH = polymer hydro peroxide, PO· = polymer oxy radical (polymer alkoxy radical) and HO· = hydroxyl radical.

The above processes are the ones involved in the degradation of polymer, by both the thermal and photo oxidative degradation of polymers. The mechanism is the same for both degradation processes, however the mechanisms differ only in the initiation step, whereby in the thermal degradation, the initiation step is as a result of the thermal dissociation of chemical bonds; in

case of photo oxidative degradation, the mechanism is initiated by the formation of excited species. It can be also by the result of energy transfer processes or direct photodissociation of chemical bonds.

### **2.3 Factors affecting photo degradation:**

There are several factors that affect the photo degradation of polymers, for example, polymer morphology i.e. the molecular structure, the amounts of amorphous and crystalline regions, temperature, oxygen, moisture, and polymer manufacturing and processing.

#### **2.3.1 Polymer morphology:**

Polymer morphology, which constitutes amorphous and crystalline regions, plays an important role in the photo degradation of polymers. The amorphous region is the region of disorder, with chains being oriented in the random fashion, and it also acts as a boundary phase of the neighboring crystalline regions. During degradation, the molecules which connect the amorphous region and the crystalline region are cleaved and resulting in loss of mechanical properties of the polymer. Degradation reduces the amorphous content of the polymer and thus increases the crystallinity of the polymer.

Chain lengths of polymers also have a substantial influence on the degradation of polymers. The longer chains have the higher probability of oxidative attack and can rupture easily as compared to shorter chained polymers. This has greater effect on changes in weight average molecular weight than number weight molecular weight, thus having effect on mechanical properties, such as elongation.

#### **2.3.2 Role of polymer manufacturing and processing:**

The polymer is experiencing lot of impurities during manufacture, i.e. impurities present during polymerization, processing and storage. These impurities can be internal impurities, such as hydroperoxides, carbonyl and unsaturated bonds, catalysts residues and charge transfer complexes with oxygen. Impurities can also be external, which can be realized during processes

like weaving where sizing is used, traces of catalyst solvents, atmospheric pollutants, metals, metal salts and oil from the machinery used in the process. During processing, polymers are being exposed to high temperatures and oxygen, which make polymer more vulnerable to thermal oxidation. Also during processing (extrusion), the polymer are being processed under high shearing stress and thus makes chains to be under stress at certain points and weakening the covalent bonds, thus polymers become more vulnerable towards photo degradation.

### **2.3.3 Effect of moisture:**

During exposure of polymers to high – energy radiation, which uses elevated temperatures, the moisture content is reduced. Water can have at least three effects in the degradation of polymers, namely:

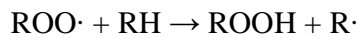
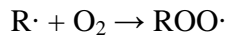
- Chemical: hydrolysis of the ester or amide bonds,
- Physical: loss of bond between the vehicle and the substrate or pigment, and
- Photochemical: generation of hydroxyl radicals or other chemical species.

### **2.3.4 Role of oxygen:**

In an oxygen environment, chain scission predominates over cross-linking and the latter predominates over the oxygen starved environment. The rate of degradation in an oxygen rich environment is faster, ultimately causing 100% weight loss over 700°C for heating rate of 10°C/min. the chain scission in materials upon exposure to UV and VIS light in the absence of oxygen is called photolysis, which is most commonly induced at low wavelengths of UV radiation.

At the presence of oxygen, thermal or photo degradation induced, oxidation takes place. The presence of oxygen commonly leads to the formation of hydroperoxides (ROOH) through a reaction with hydrocarbon free radicals. The equation can be represented in this way:





### 2.3.5 Influence of wavelength:

The ultra violet and the visible radiation have both the properties of a wave as well as of a particle. The infrared radiation which is the longer wavelength and low frequency, has no enough energy to induce the chemical reactions in the same manner that the ultraviolet and the visible does. However as the wavelength of radiation decreases through blue, violet and into the ultraviolet region, the energy of the photons increases. Thus it can be generalized that, the shorter the wavelength, the more energetic the photons, and therefore the more damaging the radiation.

Two terms of importance in understanding the role of wavelength in photo degradation are:

- Activation spectrum: which is the effect of wavelength on the extend of degradation, and
- Wavelength specificity: this is the influence of wavelength on the mechanism and the type of degradation.

### 2.4 Laser ablation:

Laser ablation is simply a method of removing small particles from the material without damaging the material itself. Laser ablation is the non-contact process because no wet chemistry is involved in the treatment of the material but it can be achieved in the presence of air. A process similar to ablation but treatment is under gas or liquid is called etching. Etching is whereby laser light is used to remove the foreign matter from the surface in the presence of an etchant [15].

Laser ablation process can occur under ultraviolet, visible and infrared radiation. Polymers induced by intense UV light have many applications in medications, packing industries, microelectronics, fundamental biological investigations, etc. The ultra violet light is not

thermally controlled as compared to infrared light and the invisible light, which are thermally controlled. The UV-light ablation process mainly involves photochemical mechanisms.

The other method which is similar to ablation is the laser desorption, which refers to the removal of adsorbed material. Laser ablation methods are said to be ‘self-developing’, which implies that wet chemistry is not necessary in order to remove the irradiated material. During the ablation process by the laser beam on the substrate, an overheated liquid is generated and it vaporizes instantaneously. The released energy,  $E_{ex}$  is converted completely into kinetic energy of the evaporating molecules. The molecules of the fragments will then have velocity of

$$v = \sqrt{\frac{2E_{ex}}{m}} \dots\dots\dots (2)$$

Where,  $m$  is the mass of the molecular fragments and

$$E_{ex} = E_{ph} - E_B \dots\dots\dots (3)$$

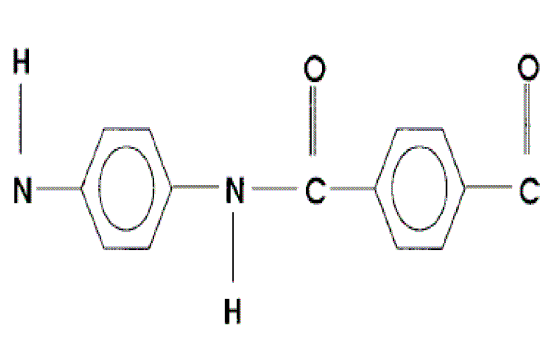
With photon energy =  $E_{ph}$  and binding energy =  $E_B$

### 3. KEVLAR FIBRES

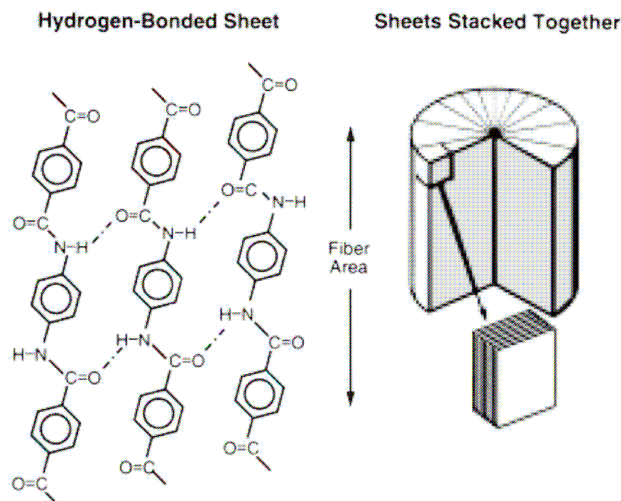
#### 3.1 Introduction

Kevlar is an organic fibre in the aromatic polyamide family with a chemical name, poly-p-phenyleneterephthalamine. It has a para orientation in its structural backbone of the benzene ring. There are two types of Kevlar, Kevlar 29 and Kevlar 49. They both have similar thermal properties, but differ slightly on tensile properties. Kevlar 49 has higher modulus, higher breaking tenacity, and thus, lower breaking strength and less elongation at break as compared to Kevlar 29. Another difference is that Kevlar 49 costs more than Kevlar 29. Kevlar is characterized by its unique properties of high strength, high modulus, toughness, high flexibility, low elongation, corrosion resistance and thermal stability.

Kevlar fibres have good fire resistance and it has a higher melting point. It is thus stable at elevated temperatures. Other property is that Kevlar has high electrical resistance. Although Kevlar has superior qualities, it is more susceptible to abrasion due to its poor abrasion resistance and the difficulty in dyeing. Kevlar is utilized more in technical textile due to its high strength both mechanical and chemical stability.



**Figure 3: primary structure of Kevlar.**



**Figure 4: hydrogen bonded sheet of Kevlar.**

**Table 3: typical properties of Kevlar 29 and Kevlar 49 yarns:**

Properties	Unit	Kevlar 29	Kevlar 49
Yarn type	Denier	1500	1140
	dtex	1670	1270
	# of filaments	1000	768
Density	lb/in <sup>3</sup>	0.052	0.052
	g/cm <sup>3</sup>	1.44	1.44
Tensile properties			
Breaking strength	lb	76.0	59.3
	N	338	264
Breaking tenacity	g/d	23.0	23.6
	cN/tex	203	208
	psi	424.000	435.000
	MPa	2.920	3.000
Tensile modulus	g/d	555	885
	cN/tex	4.900	7.810
	Psi	10.2x10 <sup>6</sup>	16.3x10 <sup>6</sup>
	Mpa	70.500	112.400
Elongation at break	%	3.6	2.4

Kevlar has twice the tenacity and 9 times the modulus of high strength nylon. Kevlar is much stronger than steel wire and stiffer than glass. The higher strength of Kevlar fibres is due to the highly structured polymer molecules interaction in their crystalline content. Stability of Kevlar

is also due to the symmetrical arrangement of the amide bridges which results to the linear polymer chain of high rigidity. Kevlar also have high resistance to tearing and cutting [9, 12].

### 3.2 Effects of chemical agents on Kevlar:

Kevlar has high chemical stability at variety of conditions; however, some chemicals can have an impact on the structure of the fibre. Aqueous acids such as formic acid and hydrochloric acid; bases such as sodium hydroxide and sodium hypochlorite can cause degradation on Kevlar, especially at elevated temperatures over a long period of time [9]. Kevlar remain stable under neutral conditions. The acidic medium contributes more to the loss in tenacity of Kevlar than the basic medium of the same range in the opposite side from the pH 7. Kevlar shows similar results under saturated steam at pH levels as shown in the figure 5 below:

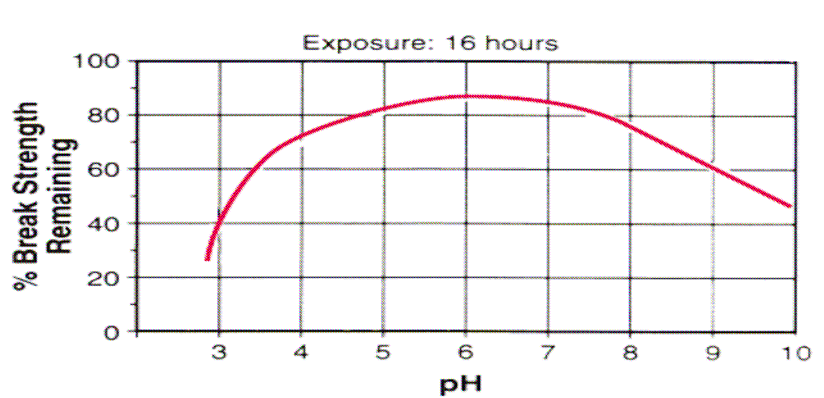
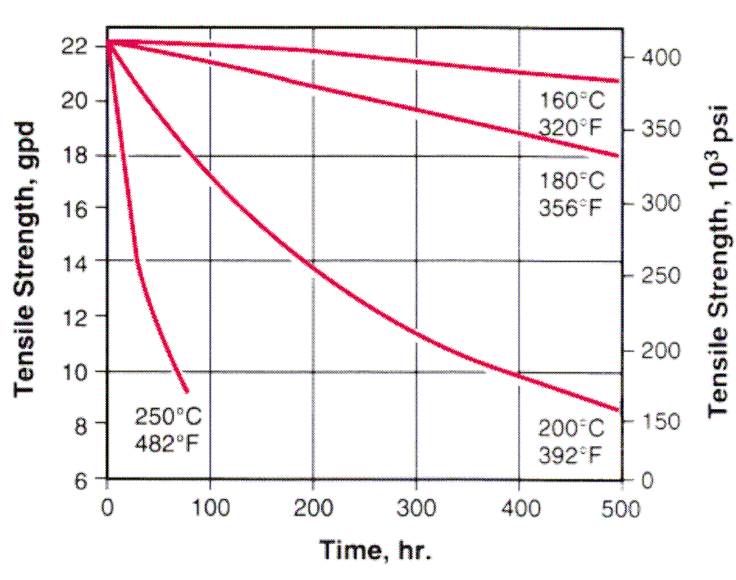


Figure 5: hydrolytic stability of Kevlar at 154°C at different pH levels.

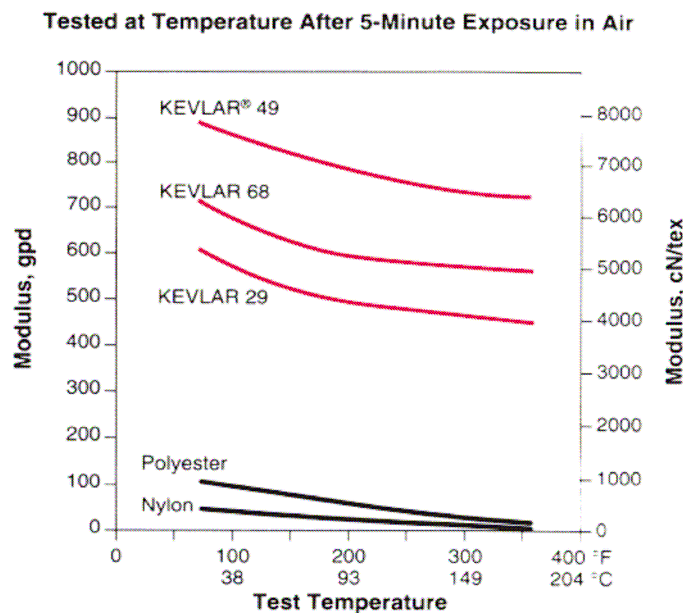
### 3.3 Thermal properties of Kevlar fibres:

The thermal properties are tabulated in the table 5 [9]. Kevlar when exposed to higher temperatures does not melt; it only decomposes at relatively high temperatures (427° C to 482° C) in air and to temperatures approximately 538 ° C in nitrogen, when tested with temperature rise of 10 ° C/minute. Kevlar can withstand high temperatures over a long time and yet not losing properties, this is due to extended chain morphology, high molar mass and excellent orientation. Thermal stability of Kevlar is from -46°C to 160°C. The decomposition temperature varies with the rate of temperature rise and the length of exposure. Increasing temperatures

reduce the modulus, tensile strength and break elongation of Kevlar yarns and other organic fibres. It is thus important when working with Kevlar at higher temperatures (149°C to 177°C) for long periods to consider the tensile properties with much caution. The figure 6 and 7 below show the behavior of Kevlar at elevated temperatures:

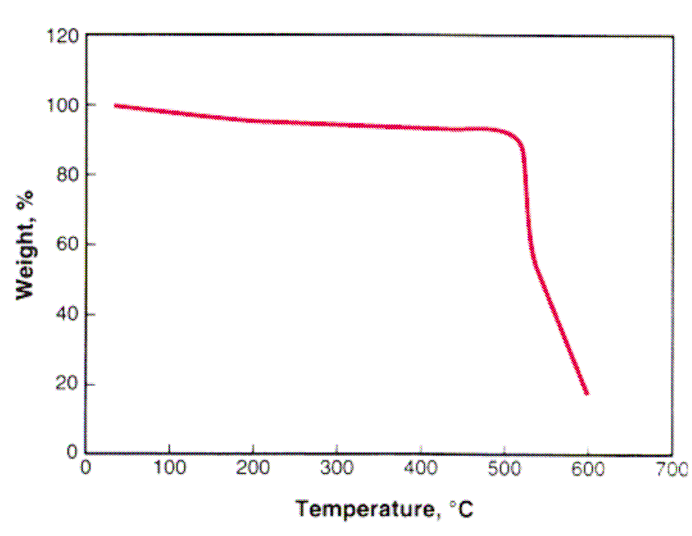


**Figure 6: effects of at elevated temperatures on textile strength.**



**Figure 7: effects of Kevlar at elevated temperatures on modulus.**

Kevlar does not shrink like other organic fibres when exposed to hot air or hot water. Most fibers experience shrinkage which irreversible when exposed to elevated temperatures. When exposed to higher temperatures, Kevlar experiences weight reduction due to water loss. As the temperature increases further, Kevlar will experience a significant weight loss where it starts decomposing, as shown on figure 8 below:



**Figure 8: Kevlar 49 at temperature rise of 10°C/min.**

Kevlar has a very small coefficient of thermal expansion (CTE) in the longitudinal direction. Kevlar reveals a negative axial coefficient of thermal expansion and a positive coefficient in the transverse plane. This unique feature of negative coefficient of thermal expansion can also be realized on polyethylene, carbon, PBO, technora, hinged polydiacetylene and some composites. The value of the coefficient of thermal expansion is dependent on several factors such as, measuring techniques, sample preparation and test method.

**Table 4: Coefficient of thermal expansion of Kevlar 29 and Kevlar 49:**

Type of KEVLAR®	Denier	Temp. Range °F (°C)	CTE in./in./°F (cm/cm/°C)
KEVLAR 29	1500	77-302 (25-150)	-2.2 x 10 <sup>-6</sup> (-4.0 x 10 <sup>-6</sup> )
KEVLAR 49	1420	77-302 (25-150)	-2.7 x 10 <sup>-6</sup> (-4.9 x 10 <sup>-6</sup> )

\*Tested with zero twist and 0.2 gpd tension at 72°F (22°C), 65% RH.

The negative axial CTE in Kevlar fibres is due to its structural characteristics. Molecules of poly-p-phenyleneterephthalamine (PPTA) of which Kevlar is made include inherently planar phenyl groups and amide segments. The PPTA chains assume a fully extended all-trans conformation. The chemical as well as crystallographic structural characteristics endow or contribute to the PPTA chains with a rigid rod-like character. The specific heat of Kevlar is influenced by temperature. It more than doubles when temperature is raised from 0° C to 200° C, further increases of temperatures are more gradual [9, 10]. The negative axial expansion of Kevlar 49 fibres has been giving more problems to users of Kevlar fibre reinforced composites at higher temperatures. In a composite material, if there is an anisotropic shrinkage in the volume of the fibre at elevated temperatures, the properties of the components made of the composite can deviate from the initial values and eventually affecting the anticipated performance [11].

**Table 5: thermal properties of Kevlar 49 and Kevlar 29:**

Property	Unit	Kevlar29	Kevlar49
Shrinkage in water at 100° C	%	<0.1	<0.1
In dry air at 117° C	%	<0.1	<0.1

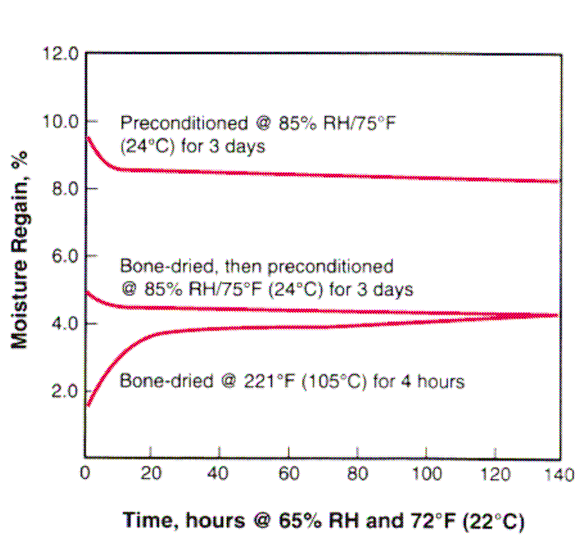


Shrinkage tension in dry air at 117 °C	G/D  cN/tex	<0.1  0.88	<0.2  1.77
Specific heat at 25 °C	Cal/g x °C	0.34	0.34
	J/kg x °K	1.420	1.420
Specific heat at 100 °C	Cal/g x °C	0.48	0.48
	J/kg x °K	2.010	2.010
Specific heat at 180 °C	Cal/g x °C	0.60	0.60
	J/kg x °K	2.515	2.515
Thermal conductivity	[W/(m x K)]	0.04	0.04
Decomposition temperature in air	°F	800 – 900	800 – 900
	°C	427 – 482	427 – 482
Recommended max. temperature range for long- term use in air	°F	300 – 350	300 – 350
	°C	149 – 177	149 – 177
Heat of combustion	Joule/kg	35x10 <sup>6</sup>	35x 10 <sup>6</sup>

### 3.4 Effect of moisture on Kevlar 29 and Kevlar 49:

Most fibres have a tendency of giving up or picking up ambient atmospheric moisture until they reach equilibrium moisture content at a given temperature and moisture level, this is known as moisture regain. Unlike other fibres, Kevlar filaments are hygroscopic and can sorp up to 3.5 – 4.5 wt% moisture at ambient temperature at 100% relative humidity. The rate of moisture absorption and equilibrium level reached on Kevlar is influenced by relative humidity. The higher the relative humidity, the faster Kevlar absorbs moisture during the initial stage of moisture gain and the higher the equilibrium moisture level. The moisture content does not affect the tensile properties of Kevlar. However, Kevlar exposure to high temperatures, superheated steam can cause permanent fibre damage, resulting in fibers that can absorb 10 wt% of moisture.

Moisture is more likely to absorb into the system of microvoids within the filament. Moisture diffuses more rapidly in the network of microvoids in the interfibrillar regions where hygroscopic  $\text{Na}_2\text{SO}_4$  impurities reside, although it is sterically possible that water molecules can penetrate the molecular holes in the PPTA crystals. Moisture can presumably inhibited from penetrating the Kevlar 49 fibres by forming croslinks across the crystal holes by oxidation or plasma surface treatment and/or filling the holes with hydrophobic agents.



**Figure 9: moisture regain of Kevlar.**

### 3.5 Flammability properties of Kevlar:

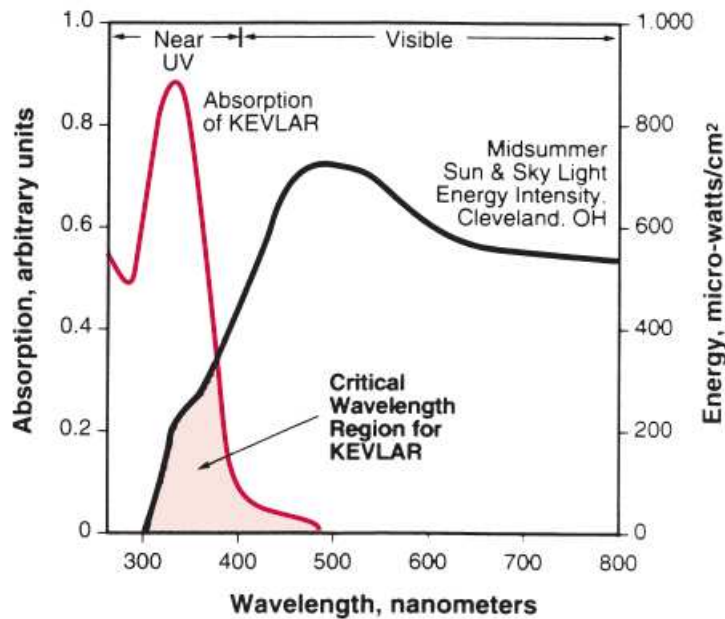
Kevlar is flame resistance with the limiting oxygen index (LOI) of 29. Although it is resistance to flame, Kevlar can ignite and cease burning when the ignition source is removed from it. Kevlar produces hazardous gases when burned, the most produced being CO<sub>2</sub> followed by CO, HCN, NO<sub>2</sub>, C<sub>2</sub>H<sub>2</sub>, and NH<sub>3</sub> which are similar to those produced by wool. All of these produced gases depend on the burning conditions.

**Table 6: composition of released gases of Kevlar compared with other fibres:**

	Combustion Products in mg/g of Sample									
	CO <sub>2</sub>	CO	C <sub>2</sub> H <sub>4</sub>	C <sub>2</sub> H <sub>2</sub>	CH <sub>4</sub>	N <sub>2</sub> O	HCN	NH <sub>3</sub>	HCl	SO <sub>2</sub>
KEVLAR®	1,850	50	—	1	—	10	14	0.5	—	—
Acrylic	1,300	170	5	2	17	45	40	3	—	—
Acrylic/Modacrylic (70/30)	1,100	110	10	1	18	17	50	5	20	—
66 Nylon	1,200	250	50	5	25	20	30	—	—	—
Wool	1,100	120	7	1	10	30	17	—	—	3
Polyester	1,000	300	6	5	10	—	—	—	—	—

### 3.6 Effect of ultra violet (UV) light on Kevlar:

Kevlar is degradable by UV light. Fluorescent lighting will cause discolouration of Kevlar from its original gold colour to brownish colour after a prolonged exposure. Mechanical property can be affected after exposure in a long time but it depends on wavelength, radiation intensity and exposure time. Moisture has no effect on the degradation of the Kevlar by UV light; it only degrades in the presence of oxygen. Kevlar absorbs light strongly around the 300 – 450 nm wavelengths which includes the near-UV and part of visible region. UV increases stability with size – the denier of a yarn, the thickness of the fabric or diameter of rope [9].



**Figure 10: overlap of the absorption spectrum of Kevlar with solar spectrum.**

## **4. GLASS FIBRES**

### **4.1 Introduction:**

Glass fibre is a man-made fibre which can be used in many applications which can be divided into four main categories, namely: insulations, reinforcements, optical fibres and filtration media. Glass fibres are made of silicon dioxide and some small amounts of other oxides. They have small diameters, ranging from 10 – 20  $\mu\text{m}$ , and they have small ratio of surface cracks, thus the brittle property of glass. The special properties of glass fibre includes its low density and its low thermal conductivity in wooly fibres, thus it is used in insulations and filtrations to provide the supporting structure. The other form of glass fibres are the continuous strands of filaments. The continuous strands are used mainly in the reinforcement of thermosetting and thermoplasts resins. Typical examples of glass composites are glass reinforced phenol composites, glass reinforced epoxy resin and glass reinforced UP resin composites. The composites are used in many productions, e.g. in automotives, sports equipments, etc.

There are two main types of glass fibres, namely, E-glass and S-glass. E-glass is the most widely used and has high electrical conductivity. The S-glass is very strong, stiff and temperature resistant, used in areas where tensile strength is an important or required property. In S-glass and R-glass, the tensile strength of glass fibre is determined by the structure connectivity of silica networks and the absence of alkali oxides, which are not readily integrated into the structure. S-glass and R-glass have the ability to withstand higher in-use temperatures than E-glass.

S-glass has appreciably higher amount of silica oxide, aluminium oxide and magnesium oxide than E-glass and it is 40 – 70 % stronger than E-glass. The other types being, A-glass (alkali-lime glass), E-CR-glass (alumino-lime silicate) which is highly resistant to acid, C-glass (alkali-lime) used for glass staple fibres, D-glass (borosilicate), R-glass (alumino-silicate) and pure silica or quartz fibres, which can be used at ultrahigh temperatures.

**Table 7: specific properties of glass and aramid fibres:**

	E (GPa)	$\sigma_u$ (GPa)	$\rho$ (g/cm <sup>3</sup> )	E/ $\rho$ (Mm)	$\sigma_{fu}/\rho$ (Km)	$\epsilon_u$ (%)	$d_f/(\mu\text{m})$
E – glass	72	1.5 – 3.0	2.55	2.8 – 4.8	58 – 117	1.8 – 3.2	10 – 20
S – glass	87	3.5	2.5	3.5	140	4.0	12
S2 – glass	86	4.0	2.49	3.5	161	5.4	10
Aramid	60 – 180	2.65 – 3.54	1.44 – 1.47	4.0 – 12.2	180 – 235	1.9 - 4	12
Bulk glass	60	0.05 – 0.07	2.6	2.3	1.9 – 2.7	0.08 – 0.12	-

Where  $E$  (GPa) is the Young's modulus,  $\sigma_u$  (GPa) is the tensile strength,  $\rho$  ( $\text{g/cm}^3$ ) is density,  $E/\rho$  (Mm) is specific stiffness,  $\sigma_{fu}/\rho$  (Km) is the specific strength,  $\epsilon_u$  (%) is the failure strain, and  $d_f$  ( $\mu\text{m}$ ) is the diameter of the fibre.

The specific strengths of glass fibres are much higher than other conventional bulk materials. This is the reason glass fibre is used as an important reinforcing material in composites, especially in structural application, where high strength, high stiffness and low weight properties are utilized in the design of composites. The modulus of glass fibre (70 – 80GPa) is due to the chemical forces operating in the amorphous inorganic glass. Higher modulus can be realized with crystallization into ceramic or glass – ceramic. Glass fibres are dimensionally stable.

Fiber glass wool is lighter in weight, flexible, and thermal insulation material used to provide the ultimate noise reduction. This type of wool fiber is formed from resin bounded borosilicate glass fibres. It is resistant to fire and water with a low density of combustion gas and low toxicity. It reduces transport to heat and sounds. [15].

Humidity plays an important role in the tensile strength of glass fibre. Fibre glass can easily absorb moisture, and this can result in worsened microscopic cracks and surface defects. The fibre does not shrink nor stretch when exposed to higher temperatures and retains its strength at temperatures up to 540°C. E-glass decomposes at 730°C and S-glass at 850°C.

The glass fibre are chemically stable, they may be affected by hot phosphoric acid, hydrofluoric acid and alkaline substances. Although glass fibres are chemically stable, they can be eroded by leaching action when exposed to water. For example, E-glass filament of 10 microns of diameter typically loses 0.7 percent of its weight when exposed to hot water for 24 hours. To slow the erosion, fibre is coated with moisture resistant compound such as silane, applied during manufacture.

Fibre glass has low coefficient of thermal expansion and high thermal conductivity thus it is a highly dimensionally stable and it rapidly dissipate heat as compared to other organic fibres and asbestos [17], [18]. Fibre glass wool has thermal conductivity is 0.03 – 0.04  $\text{W}\cdot\text{m}^{-2}\text{K}^{-1}$  in 10°C. The mobility of the sodium and potassium ions contributes to the electrical conductivity of glass. The bulk conductivity is realized at high temperatures as compared to the surface conductivity which is achieved in ambient conditions [15].

## 4.2 Types of fibre glass:

### E-glass:

More than 99% of continuous glass fibres are spun from the E-glass formulation. E-glass fibres are most commonly used fibres due to their prices and good technical properties. The E – glass (calcium aluminoborosilicate glass) is significantly stronger and stiffer, has very low sodium oxide content with good chemical durability and good electrical conductivity ( $10^{15}\Omega\text{m}$ ). Although can be susceptible to acid attack, E-glass fibres are more resistant to alkaline agents. Chloride ions will also attack and dissolve E-glass surface. The maximum elongation at break for E-glass is 4.8% and recovers by 100% elastically when stressed close to point of rupture.

**Table 8: composition in weight % of typical glasses for fibres and some of their properties [15]:**

Constituent or property	E	ECR	C	A	S	R	Cemfil <sup>11</sup>	AR <sup>12</sup>	AR
SiO <sub>2</sub>	55.2	58.4	65	71.8	65.0	60	71	60.7	61
Al <sub>2</sub> O <sub>3</sub>	14.8	11.0	4	1.0	25.0	25	1	—	0.5
B <sub>2</sub> O <sub>3</sub>	7.3	0.09	5	—	—	—	—	—	—
ZrO <sub>2</sub>	—	—	—	—	—	—	16	21.5	13.0
MgO	3.3	2.2	3	3.8	10.0	6	—	—	0.05
CaO	18.7	22.0	14	8.8	—	9	—	—	5.0
ZnO	—	3.0	—	—	—	—	—	—	—
TiO <sub>2</sub>	—	2.1	—	—	—	—	—	—	5.5
Na <sub>2</sub> O	0.3	—	8.5	13.6	—	—	11	14.5	—
K <sub>2</sub> O	0.2	0.9	—	0.6	—	—	—	2.0	14.0
Li <sub>2</sub> O	—	—	—	—	—	—	—	1.3	—
Fe <sub>2</sub> O <sub>3</sub>	0.3	0.26	0.3	0.5	tr	—	tr	tr	—
F <sub>2</sub>	0.3	—	—	—	—	—	—	—	—
Liquidus temp. <sup>a</sup> (°C)	1140	—	—	1010	—	—	1201	1172	—
Fiberising temp. <sup>b</sup> (°C)	1200	—	—	1280	4.7	4.5	1470	1290	—
Single fibre tensile strength at 25°C, (GPa)	3.7	3.4	3.4	3.1	—	—	2.9	—	2.5
Single fibre tensile modulus (GPa)	76.0	73.0	—	72.0	86.0	85.0	—	—	80
Density, (g/cm <sup>3</sup> )	2.53	2.6	2.49	2.46	2.48	2.55	—	2.74	2.74
Refractive index $n_D$	1.550	—	—	1.541	1.523	—	—	—	1.561
Coefficient of linear thermal expansion (10 K)	5.0	—	7.1	9	2.85	4.10	—	—	—
Volume resistivity ( $\Omega\text{cm}$ )	$10^{15}$	—	—	$10^{10}$	$10^{16}$	—	—	—	—
Dielectric constant at 25°C and $10^{10}\text{Hz}$	6.11	—	—	—	—	6.2 <sup>c</sup>	5.21	—	—
Loss tangent at 25°C and $10^{10}\text{Hz}$ ( $10^{-3}$ )	3.9	—	—	—	—	1.5 <sup>c</sup>	6.8	—	—

<sup>a</sup>The liquidus temperature is the highest temperature at which a glass, if held there sufficiently long, will develop crystals. The greater the difference between this and fiberising temperature, the more stable the fibre-forming process.

<sup>b</sup>Indicates temperature at which the viscosity of the glass is  $10^3\text{P}$ .

<sup>c</sup>Measured at  $10^6\text{Hz}$ .

### ECR:

This type of glass fibre is highly resistant to corrosion. ECR have enhanced long term acid

resistance and short term alkali resistance. This fiber glass is formulated by addition of high levels of ZnO and TiO<sub>2</sub> to the boron-free E-glass system enhances further corrosion resistance of the resulting ECR glass fibre while at the same time reduces the fiberisation temperature.

**C-glass:**

C-glass is chemically resistant and it is often used where acid conditions are met [16]. C-glass loses much less of its weight when exposed to acids than does E-glass.

**A-glass:**

A-glass fibres contain high proportion of boric acid and aluminates, thus they are sensitive to alkaline attack (corrosion). The volume resistivity of A-glass is 10<sup>10</sup>Ωm. A-glass has half the strength of E-glass fibre. It is the economically conservative product because it is produced from the remelt process rather than the direct melt process.

**S-glass:**

S-glass has the same formulation as R-glass. This type of glass fibres are used in high strength composites. The prices of these fibres's manufacturing are very high, thus it is being utilized in sectors like aerospace, military and sports equipments.

**D-glass:**

D-glass was mainly developed to meet the requirements of the fast-response of the electronic circuits. It has the lower dielectric constant than E-glass. D-glass has high content of B<sub>2</sub>O<sub>3</sub> and thus has lower dielectric constant [15].

**Silica/quartz glass:**

These are high silica content glass fibres which are mainly characterized by high in-temperature. High silica fibres (95% SiO<sub>2</sub>) are amorphous glass fibres. They are obtained by leaching of borosilicate E-glass fabrics by acid, which are in turn used as insulation blankets at temperatures up to 1040°C. The other type is the pure silica (99% SiO<sub>2</sub>), also known as "Silfa", which is made from dry spinning of aqueous water-glass solutions. They are used as yarns, for example, in wire insulation at temperatures up to 1090°C. The ultrapure silica fibres or quartz are 99.99% SiO<sub>2</sub> and are produced by down-drawn from performs under container-less process. These types of



fibers are also amorphous and possess good optical properties, with superior transparency to ultra-violet (UV) and longer wavelengths [19].

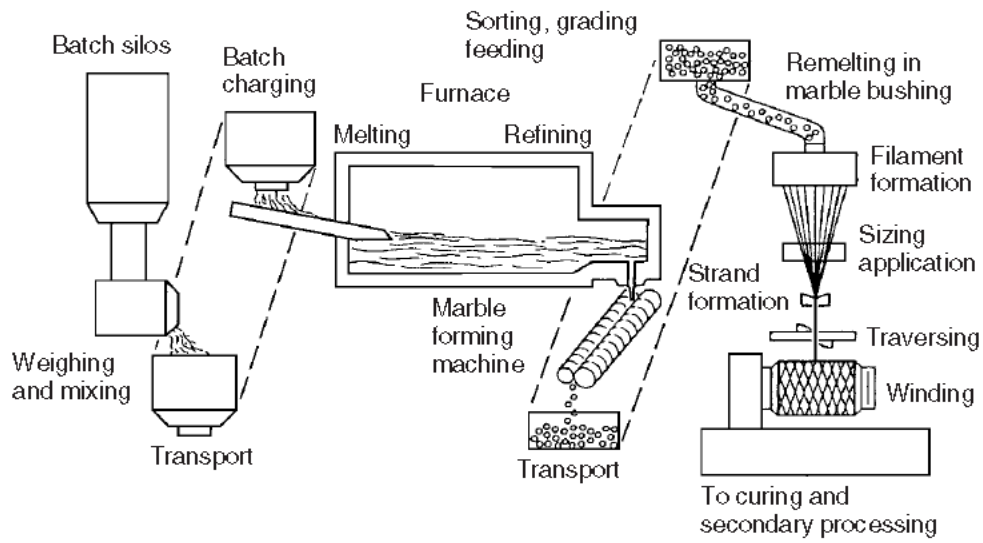
### 4.3 Manufacturing of glass fibre:

Glass fibres can be manufactured in two processes, by preparation of marbles, which are remelted in the fiberization stage; the other process is the direct melting route, where the furnace is continuously charged with raw materials which are melted and refined in the forehearth above a set of platinum-rhodium bushings where the fibres are drawn. Type of process used in the manufacture is based on the special purpose. The marble melt process, for example, is for high strength fibres. In this process the raw materials are melted and solid glass marbles (2-3 cm in diameter) are formed from the melt. The marbles are then remelted and formed into glass fibres. The fibres are produced by rapid attenuation exuding through the nozzles by gravity. The rate of attenuation, the bushing temperature, glass viscosity and the pressure head above the bushing determine the final diameter of the fibers, whereas the rate of flow determines the fibre production rate at the nozzles.

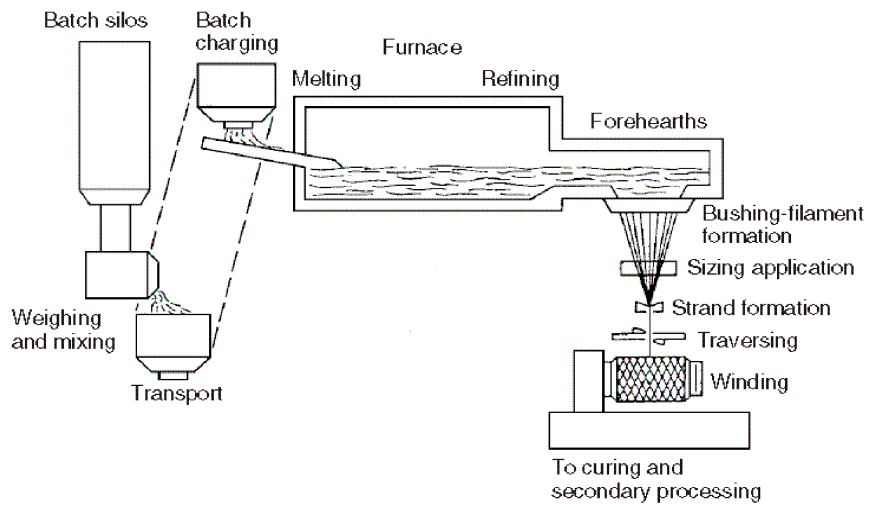
The flow of glass melt through the nozzles can be determined according to the Poiseuille's equation:

$$F = \frac{r^4 h}{l \eta} \dots\dots\dots (4)$$

Where F is the rate of flow, r is the radius of the nozzles at its narrowest cylindrical section, h is the height of glass above the nozzle, l is the length of the cylindrical section and  $\eta$  is the viscosity of the glass. The platinum – rhodium alloy (standard bushing) can produce up to 200 – 204 fibres. But as production increases, the usage of soft alloys is no longer applicable, as the stiffness of the bushing needs to be increased also. Typically this can be achieved by using composite alloys dispersed with zirconia, yttria, or thoria. With this type of bushing, up to 4000 filaments can be spun. Direct roving is also possible to be formed into final package immediately with this nozzle bushing [15, 19].



**Figure 11: schematic representation of melt marble process of continuous filaments [15].**



**Figure 12: schematic of direct melt process of continuous filaments [15].**

## 5. EXPERIMENTAL PART

### 5.1 MATERIALS:

The used specimen was satin 1/4 weaved Kevlar 49 fabric of 240 tex linear density with a fibre density of  $1.45 \text{ g/cm}^3$  and plain weaved glass fabric with linear density of 272 tex. For surface resistivity measurements, remission, colour and spectroscopic measurements, and absorbency test, the (11x11) cm dimensions were used for both Kevlar and glass fabrics. In case of mechanical testing, 30x6 cm was used and the materials were cleaned with dichloromethane prior to irradiation with laser beam.

### 5.2 METHOD

#### 5.2.1 Laser irradiation on Glass, Kevlar 49 and Kevlar 149 fabrics:

The Kevlar and glass fabrics were irradiated with the Marcatex 150/250 Flexi CO<sub>2</sub> laser of the infrared wavelength ranging from  $9.3\mu\text{m}$  –  $11.5\mu\text{m}$ . The irradiation of the substrate was done at different laser energy densities. The irradiation of the substrates was done at the pixel times as shown in the table 3.1. The irradiated samples were all irradiated only in the one side of the fabric, on the specific marked area on the substrates.



**Figure 13: Marcatex 150 Flexi CO<sub>2</sub> LASER (infrared).**

Laser's parameters:

- Energy density [ $\text{mJ}/\text{cm}^2$ ]
- Pixel time [ $\mu\text{s}$ ] – time used to mark each pixel of the image (in microseconds).
- Frequency = 5KHz
- Laser power = 100W
- Beam diameter =  $0.08\text{cm}^2$

### **5.2.2 Scanning Electron Microscopy (SEM):**

The untreated and treated glass, Kevlar 49 and Kevlar 149 samples were analyzed for the surface morphology with the Scan Electron Microscopy SEM (TS5130), operating at 30.0 kV. The samples were analyzed at different magnifications (30x, 500x, 1000x and 5000x).

### **5.2.3 Colour measurement on irradiated samples as compared to the untreated samples:**

Colour differences on the laser treated samples were measured using Spectraflash SF600 spectrophotometer. The samples dimensions were 11x11cm of glass, Kevlar 49 and Kevlar 149 fabrics. The samples were measured and results were taken from four measurement readings in different areas of the fabrics. The four reads were automatically averaged stored and by the software of the spectrophotometer. The data was recorded from the spectrophotometer. And the results were analyzed using CIE  $L^*a^*b^*$ . Delta L, a, b ( $\Delta L^*$ ,  $\Delta a^*$ , and  $\Delta b^*$ ) are values associated with the CIE  $L^*a^*b^*$  colour scale.

$\Delta E$  is the total colour difference and all the delta values are calculated from the data produced by the spectrophotometer. The values of a and b of the CIE  $L^*a^*b^*$  axes have no specific numerical limits as compared to the L value, which is the vertical axis of the CIE  $L^*a^*b^*$  running from top to bottom of the cube form of the CIE colour space. With the results obtained, the colour changes of the treated samples were being compared with the original, non-irradiated sample. Differences

were compared according to the used laser energy densities, wavelengths, the total colour difference, spectral reflectance values and K/S values.

**5.2.4 Abrasion and piling test:**

The laser-irradiated Kevlar and glass samples were tested for abrasion, using Martindale Abrasion/pilling Tester by JAMES H. HEAL & Co. Ltd. England. The abradant fabric used was plain wool fabric. The abrasion tester used 10 cycles for abrasion. The materials were tested at standard atmospheric conditions. The tested materials were then weighed and changes in mass were calculated using the equation:

$$((A - B)/A) \times 100 \dots\dots\dots (5)$$

Where A = mass 1,

And B = mass 2.

**5.2.5 Test for mechanical properties:**

The tensile strength and elongation at break of Kevlar 49, Kevlar 149 and glass fibres were measured using Instron Tensile Tester. The samples were cut into required dimensions: 30x5cm<sup>2</sup>. The test for mechanical properties was done on weft direction only. It is to be highly noted that, the test was being done only for orientation. The non-irradiated samples were tested as well as irradiated samples to check the effect of laser treatment on mechanical properties. The results of strength, modulus and elongation at break were recorded and the results and discussion section 6.3.4.



**Figure 14: Instron tensile tester.**

#### **5.2.6 Absorbency test:**

Absorbency was tested on glass, Kevlar 49 and Kevlar 149 fabrics. The test was done using water drop test on the surface of material. Testing was done on the laser irradiated and non-irradiated samples and the results were compared. The size of the water drop was 100  $\mu\text{L}$  and 3 - 4 drops were allowed to dissolve on the material and time taken for the drop to absorb was taken and the average was calculated. The cleaned sample and un-cleaned samples were also compared, the absorbency for laser irradiated and non-irradiated samples and comparison were made thereof.

### 5.2.7 Infrared spectrophotometer:

Infrared spectrophotometer was used to check the changes or detection of the reactive groups of the laser irradiated Kevlar types and glass samples. Comparisons were made with the non-irradiated samples.

### 5.2.8 Surface resistivity test:

Surface resistivity of treated samples was measured using Professional Digital Multimeter. The materials being tested were tested at standard atmospheric conditions. The resistivity measuring equipment uses double electrodes. Kevlar material was measured in different directions, i.e. both warp and weft directions. Several measurements were taken and the average was taken thereof. The results are tabulated in the results and discussions section.

## 5.3 RESULTS AND DISCUSSIONS

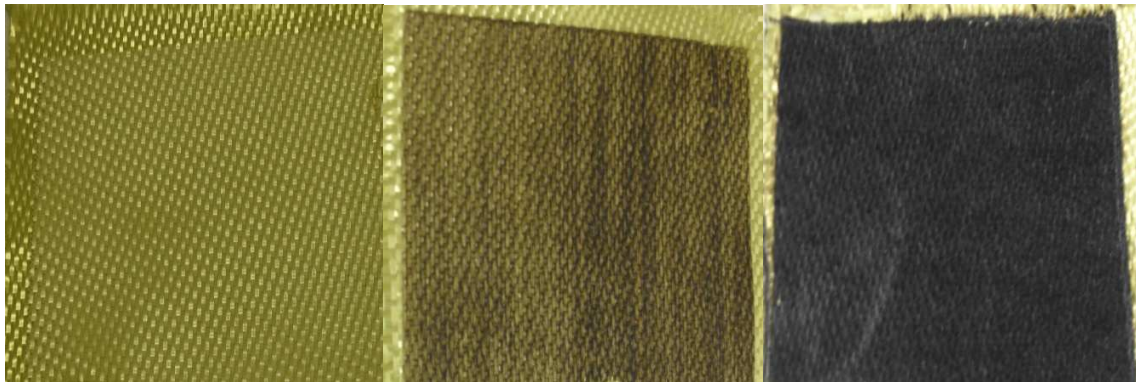
### 5.3.1 Laser Irradiation

The irradiated samples were varied according to different laser intensities. Laser parameters that were variable were energy densities in  $\text{mJ}/\text{cm}^2$ . At the fluency of  $2.62 \text{ mJ}/\text{cm}^2$ , the intensity is small and the highest intensity is at  $101.37 \text{ mJ}/\text{cm}^2$ .

**Table 9: laser parameters:**

Pixel time [ $\mu\text{s}$ ]	Marking time [s]	Energy density [ $\text{mJ}/\text{cm}^2$ ]
200	2.093	2.62
150	2.781	3.48
100	4.125	5.16
50	8.188	10.24
40	10.203	12.75
30	13.578	16.97
25	16.282	20.35
20	20.312	25.39
15	27.078	33.85
5	81.094	101.4

The highest intensity at  $101.37 \text{ mJ/cm}^2$ , damaged fibres completely and the lowest intensity revealed absence of damage on the fibres. Different kinds of damages were visually observed (like darkening to charring and possible hole making) according to laser intensity and type of fabric treated. Kevlar fabrics remained stable at higher intensity ( $101.37 \text{ mJ/cm}^2$ ), whereas glass was completely destroyed at  $20.35 \text{ mJ/cm}^2$ . The figures below show the effect of different laser intensities on Kevlar 49, Kevlar 149 and glass samples. At lowest intensity of laser, there is only small change on surface of material, with Kevlar 49 having a slightly lighter marked (irradiated) area, Kevlar 149 slightly yellowish-brown marked area and glass slightly darker. Darkening and damage on the surface increases as the laser intensity is increased. Glass is not stable at very high laser intensities and was completely damaged to almost ashes at  $101.37 \text{ mJ/cm}^2$  as compared to Kevlar samples. Kevlar 149 was the most stable at higher laser irradiations.



**Figure 15: Kevlar 49 samples irradiated at  $2.62 \text{ mJ/cm}^2$ ,  $16.97 \text{ mJ/cm}^2$  and  $101.37 \text{ mJ/cm}^2$  respectively.**



**Figure 16: Kevlar 149 sample irradiated at  $2.62 \text{ mJ/cm}^2$ ,  $16.97 \text{ mJ/cm}^2$  and  $101.37 \text{ mJ/cm}^2$  respectively.**

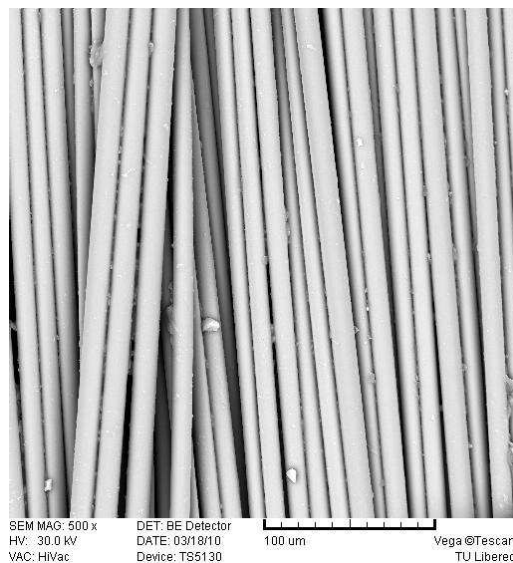




**Figure 17: Glass samples irradiated at  $2.62\text{mJ}/\text{cm}^2$ ,  $10.24\text{mJ}/\text{cm}^2$  and  $16.97\text{mJ}/\text{cm}^2$  respectively.**

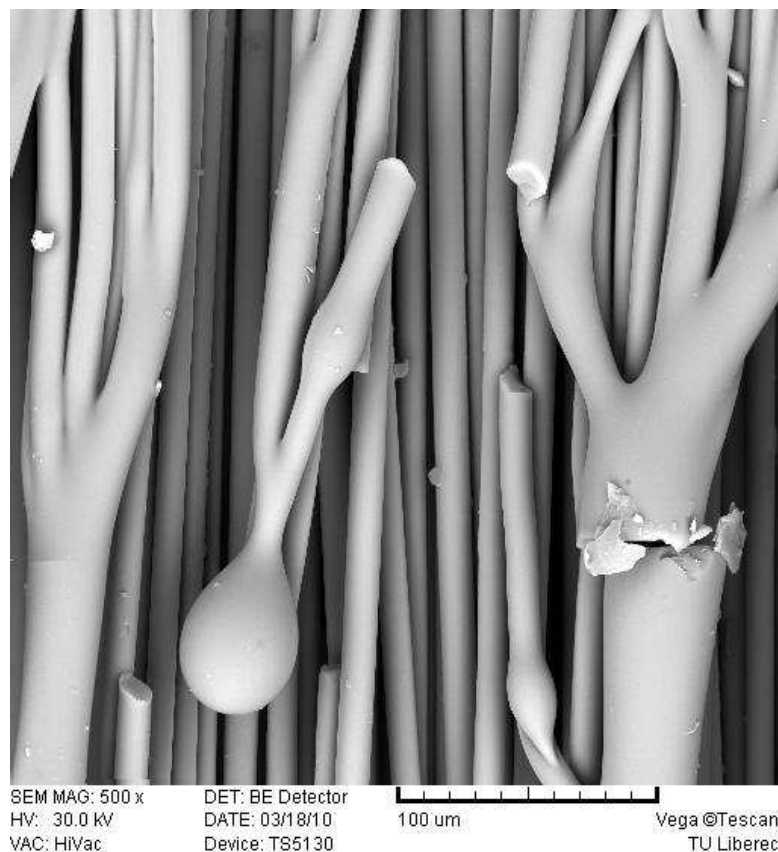
### **5.3.2 Scanning Electron Microscopy:**

Surface modifications of glass and two types of Kevlar (Kevlar 49 and Kevlar 149) treated and untreated samples were done using Scanning Electron Microscopy (SEM). The treated samples surface morphology was compared with the untreated samples at different magnifications. The results show laser beam has significant influence on samples surface. There are visible roughness created on the laser treated samples, the roughness on the surface of treated samples are due to the thermal effect of the infrared beam on the surface of the fabrics. Examples of the untreated and treated glass fabric are shown on the figures below, where magnification of 5000x was used on a Scanning Electron Microscopy.



**Figure 18: SEM image of the untreated glass.**

The irradiated fibres show different effect of laser beam on the surface morphology. On the treated sample, it is visible on the surface of fibres some modifications. The roughness on the surface is due to thermal treatment of the IR laser, as the intensity of laser energy increase, the roughness increases due to charring on the surface morphology. The highest intensity revealed some damage to the glass and Kevlar fibres, with Kevlar 149 being stable at higher intensities. Kevlar 49 is least stable as compared to Kevlar 149, but is more stable than glass fibres. This is due to the high thermal stability of Kevlar fibres, thus it is used in fire resistance applications. The Kevlar fibres are recommended for use up to 250° – 300°C. Kevlar fibres and glass fibres did not melt under high thermal treatment of laser intensity, but they rather form round ripple – like structures on the surface as it is shown on the figure below. The fibres decompose at higher intensities.



**Figure 19: SEM image of glass irradiated at 2.62mJ/cm<sup>2</sup>.**

There was no enlargement of dimensions as it is commonly known on heating of most materials. This is due to the negative axial coefficient of thermal effect on the axial and a positive coefficient in transverse plane of Kevlar. This dimensional stability is highly related to its structural characteristics. The stability of Kevlar is because of planar phenyl groups and amide segments in the PPTA molecule.

**5.3.3 Colour measurement:**

The reflected light on the untreated glass, Kevlar 149 and Kevlar 49 was measured using the remission Spectraflash SF600 spectrophotometer at different light spectrum. The remission was measured at the visible spectrum of the electromagnetic wavelength ranging from 400 – 700nm. The total colour differences, delta E values were calculated from the equation:

$$\Delta E = \sqrt{\Delta L^2 + \Delta a^2 + \Delta b^2} \dots\dots\dots (6)$$

Where:

$$\Delta L = L_{\text{sample}} - L_{\text{standard}} \dots\dots\dots (7)$$

$$\Delta a = a_{\text{sample}} - a_{\text{standard}} \dots\dots\dots (8)$$

$$\Delta b = b_{\text{sample}} - b_{\text{standard}} \dots\dots\dots (9)$$

The results of ΔE, ΔL, Δa and Δb are tabulated in the table 3.2 below.

**Table 10: colour quality measurement of glass fabric**

Laser's Energy Density	L	a	b	ΔL	Δa	Δb	DE	Intensity
Untreated	91.13705	-1.06949	4.73248	-	-	-	-	476.534
2.62	86.82423	-0.15375	5.45808	-4.31282	0.91574	0.7256	4.468276	423.2976
5.16	75.83293	2.2662	10.81314	-15.3041	3.33569	6.08066	16.8023	303.25
10.24	59.70065	1.70377	6.07456	-31.4364	2.77326	1.34208	31.58701	171.8946
12.75	61.0954	1.04836	4.55604	-30.0417	2.11785	-0.17644	30.11673	180.9716
16.97	68.11433	0.4777	4.05309	-23.0227	1.54719	-0.67939	23.08465	233.7673
20.35	69.75207	0.80538	5.69479	-21.385	1.87487	0.96231	21.48857	246.9691

**Table 11: colour quality measurement of Kevlar 49**

Laser's Energy Density	L	a	b	$\Delta L$	$\Delta a$	$\Delta b$	DE	Intensity
Untreated	<b>86.26788</b>	<b>-5.37607</b>	<b>44.20061</b>	-	-	-	-	<b>368.5477</b>
2.62	82.64318	-3.09631	36.075	-3.6247	2.27976	-8.12561	9.18484	339.3207
5.16	83.54961	-3.85207	42.25322	-2.71827	1.524	-1.94739	3.674765	342.2646
10.24	83.47261	-4.99547	41.79978	-2.79527	0.3806	-2.40083	3.704372	340.3348
12.75	83.84842	-5.83285	42.14862	-2.41946	-0.45678	-2.05199	3.205167	342.3595
16.97	82.72563	-6.11794	41.19927	-3.54225	-0.74187	-3.00134	4.701696	330.7356
20.35	80.85424	-5.73641	40.0978	-5.41364	-0.36034	-0.36034	6.802234	313.0169
25.39	81.05163	-6.07008	39.49347	-5.21625	-0.69401	-4.70714	7.060317	314.9402
33.85	72.53191	-3.59318	34.58493	-13.736	1.78289	-9.61568	16.8617	243.8374
101.37	64.18024	-1.17037	28.85165	-22.0876	4.2057	-15.349	27.22393	186.2293

**Table 12: colour quality measurement of Kevlar 149:**

Laser's Energy Density	L	a	b	$\Delta L$	$\Delta a$	$\Delta b$	DE	Intensity
Untreated	<b>87.87061</b>	<b>-7.18996</b>	<b>35.8084</b>	-	-	-	-	<b>387.2554</b>
2.62	82.62881	-3.15142	35.91267	-5.2418	4.03854	0.10427	6.617941	339.0722
5.16	57.35151	3.87347	31.70678	-30.5191	11.06343	-4.10162	32.72061	149.2355
10.24	38.66874	3.64512	17.90593	-49.2019	10.83508	-17.9025	53.46701	63.94337
12.75	37.87546	3.81878	17.35907	-49.9952	11.00874	-18.4493	54.41585	61.53831
16.97	28.88972	1.91288	7.25833	-58.9809	9.10284	-28.5501	66.15673	35.84723

20.35	26.38662	1.09395	3.98911	-61.484	8.28391	-31.8193	69.72354	30.20513
25.39	23.16812	0.67064	2.23629	-64.7025	7.8606	-33.5721	73.31635	23.87925
33.85	19.97997	0.41386	0.92696	-67.8906	7.60382	-34.8814	76.7051	18.57071
101.37	17.48936	0.38037	1.03222	-70.3813	7.57033	-34.7762	78.86833	14.95955

Where L, a, b are CIE L\*a\*b\* colour space.

The untreated glass fabric has the highest value of L, the lightness. This highest value of L is closer to 100, which implies that there is high level of whiteness as compared to the laser treated glass fabrics. The glass fabric is also having highest value of L as compared to Kevlar fabrics. This is due to a general white colour of glass fabric. As the laser intensity increases the value of L decreases in the Kevlar 149. The Kevlar 149 treated at highest intensity of laser light has the lowest value of L. this implies that lightness approaches zero, which is the minimum value for L, which means the colour of the laser irradiated sample became black (darkness) as shown on the graph below. The black colour on the Kevlar fabric irradiated with highest intensity is due to charring of the Kevlar fabric under high thermal treatment. Kevlar 49 lightness decreased sharply as compared to Kevlar 149.

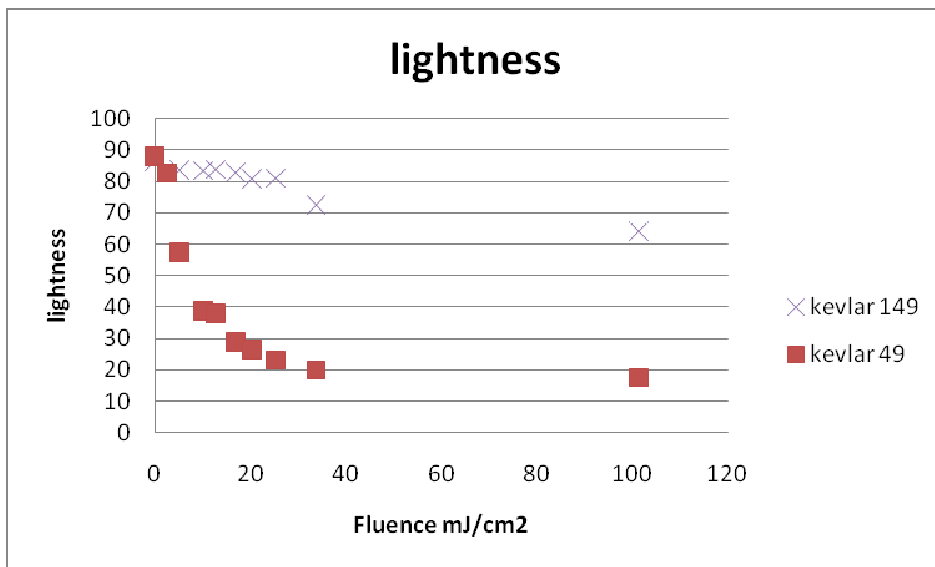
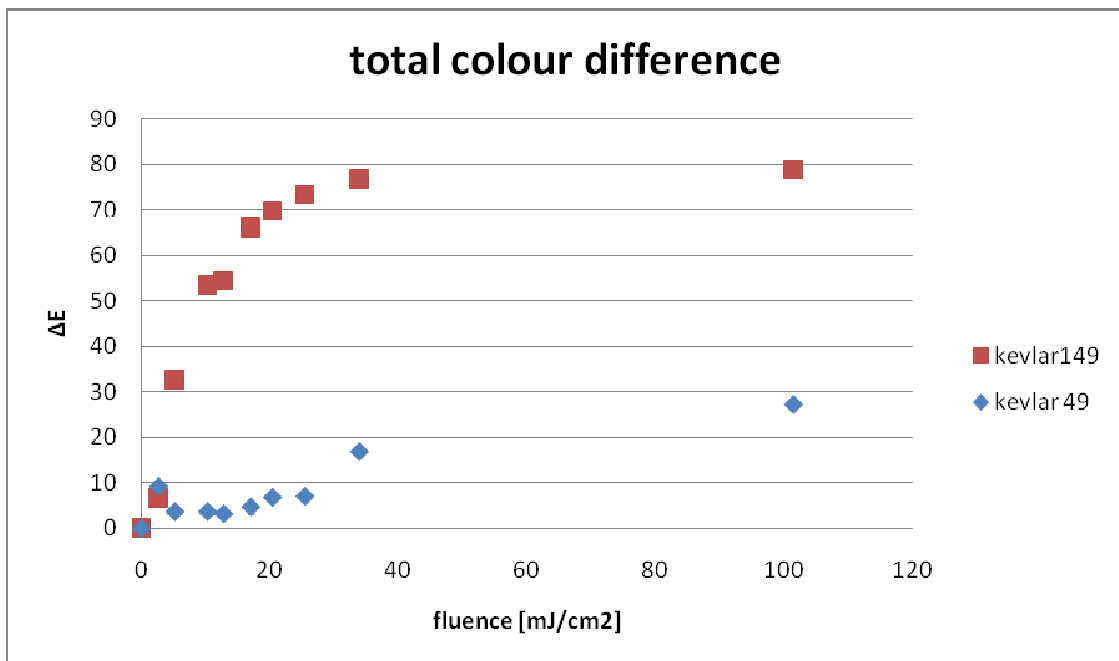


Figure 20: graph of lightness of kevlar 49 and kevlar 149 with laser fluence.

The delta values of  $L^*a^*b^*$ , show how the colour of the laser treated samples differ from the untreated samples using equations (7), (8) and (9) respectively. The delta L values of the treated samples are all negative; this means the treated samples are darker than the untreated samples. This shows the impact of laser beam treatment on the surface of the material. The delta L values increase (samples become darker) as the intensity of laser increases. This implies that the sample irradiated with the highest intensity is the darkest.

The total colour difference,  $\Delta E$ , of the laser irradiated samples as compared to the untreated Kevlar 149 sample shows in the graph that the total colour difference increase as the energy density of laser increases. This changes in overall colour differences are due to thermal treatment of laser beam, and thus at higher energies the overall colour difference is huge. At lower laser energy, the colour difference is almost zero, and at higher laser energy, the colour difference is closer to 80. These results are also showing same trends with Kevlar 49 and also for glass fibre but in general, Kevlar 149 has the highest colour difference than Kevlar 49 and glass fabrics.



**Figure 21: graph of laser fluence vs. total colour difference.**

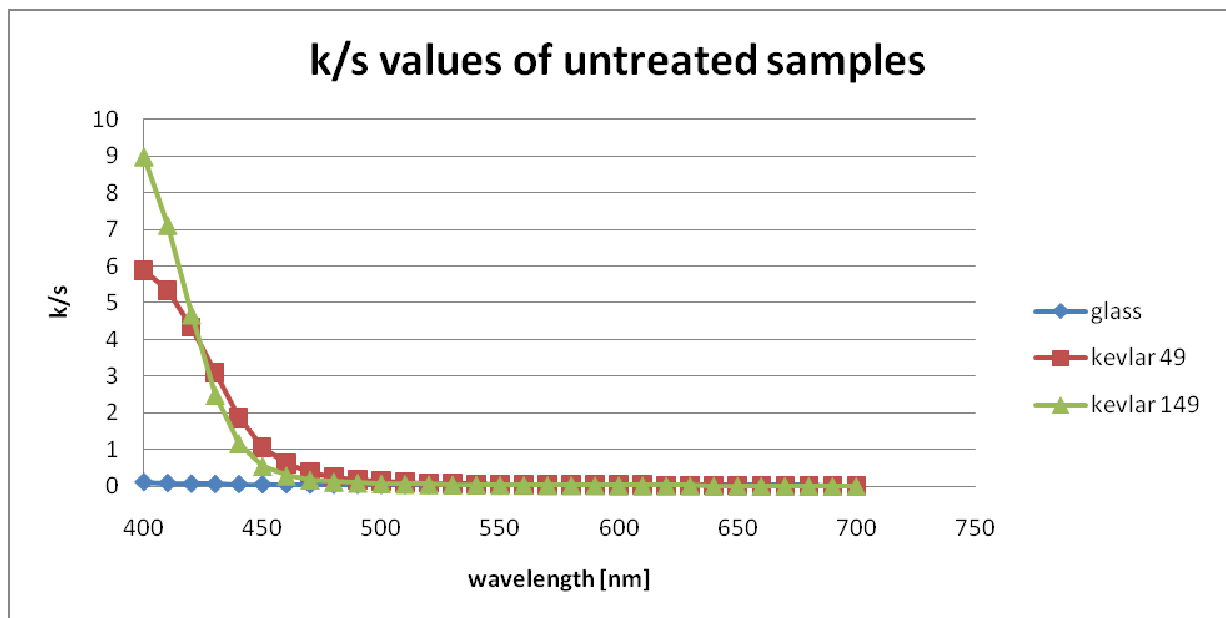
The Kubelka Munk equation was used to evaluate the colour of the laser treated samples as well as non-irradiated samples. The Kubelka – Munch equation:

$$K / S = \frac{(1-R)^2}{2R} \dots\dots\dots (10)$$

Where K is the absorption constant,

S – Scattering constant and

R – Spectral reflectance.



**Figure 22: graph of R values of untreated samples with the change in wavelength.**

In the graph above, the intensity of colour can be described by the K/S value. The untreated Kevlar reveal a high K/S at 400nm. This is the yellow region of the visible spectrum. The intensity of colour is not visible or is very low at wavelength above 450 and above. In general, the energy density of laser beam has significant influence on the k/s value. Laser treated Kevlar has higher k/s values. The treated glass have same k/s value as untreated samples as the wavelength increased in the visible spectrum. Kevlar 149 is mostly affected, to almost in the

visible spectrum when irradiated at  $20.35\text{mJ}/\text{cm}^2$ . The remission values of glass and both kevalr fabrics increase with the increase of wavelength in the visible spectrum. The non-irradiated samples higher remission values as compared to the irradiated samples.

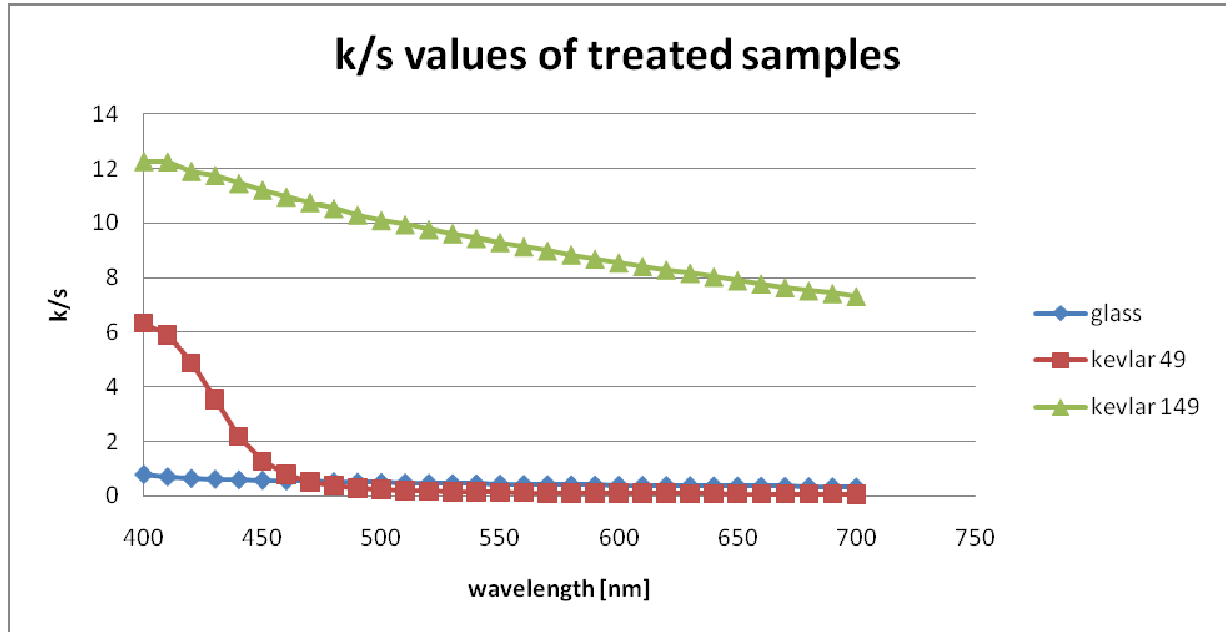


Figure 23: graph of k/s values of treated samples at  $20.35\text{mJ}/\text{cm}^2$ .

### 5.3.4 Abrasion/pilling test:

The abrasion of glass, kevlar 49 and kevlar 149 were subjected to abrasion using Martindale Abrasion Tester at ambient conditions. The changes in weighed were calculated by using equations (5) and the results were tabulated in table 13, 14 and 15 for glass, kevlar 49 and kevlar 149 respectively.

Table 13: glass fabric mass difference:

Laser's Energy Density	mass(1)[g]	Mass(2)[g]	Change in mass[g]	Percentage change [%]
untreated	165.9124	165.9123	0.0001	6.02728E-05
2.62	165.866	165.8468	0.0192	0.011575609



5.16	165.9492	165.9132	0.036	0.021693386
10.24	165.8664	165.7903	0.0761	0.045880299
12.75	165.9834	165.8851	0.0983	0.05922279
16.97	165.86	165.7304	0.1296	0.078138189

**Table 14: Kevlar 49 fabric mass difference:**

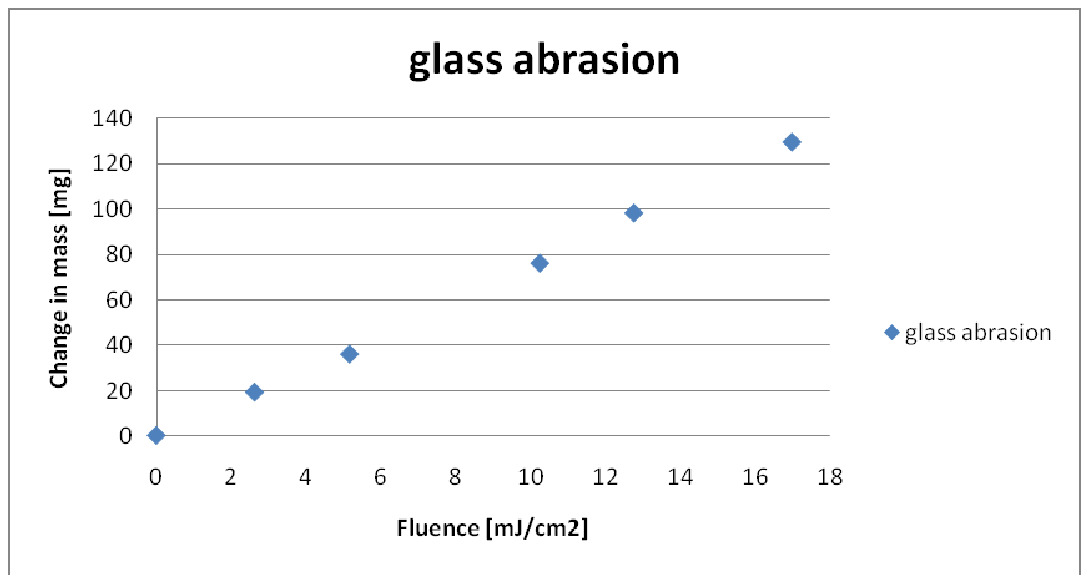
Pixel time	mass(1)[g]	Mass(2)[g]	Change in mass[g]	Percentage change
untreated	165.8586	165.8585	0.0001	6.02923E-05
2.62	165.8395	165.8391	0.0004	0.000241197
5.16	165.8419	165.8393	0.0026	0.001567758
10.24	165.8085	165.8067	0.0018	0.00108559
12.75	165.81	165.8065	0.0035	0.00211085
16.97	165.7989	165.7949	0.004	0.002412561
20.35	165.7682	165.7606	0.0076	0.004584715
25.39	165.7379	165.7221	0.0158	0.009533124
33.85	165.5951	165.5763	0.0188	0.011352993
101.37	165.6498	165.6279	0.0219	0.013220662

**Table 15: Kevlar 149 fabric mass differences:**

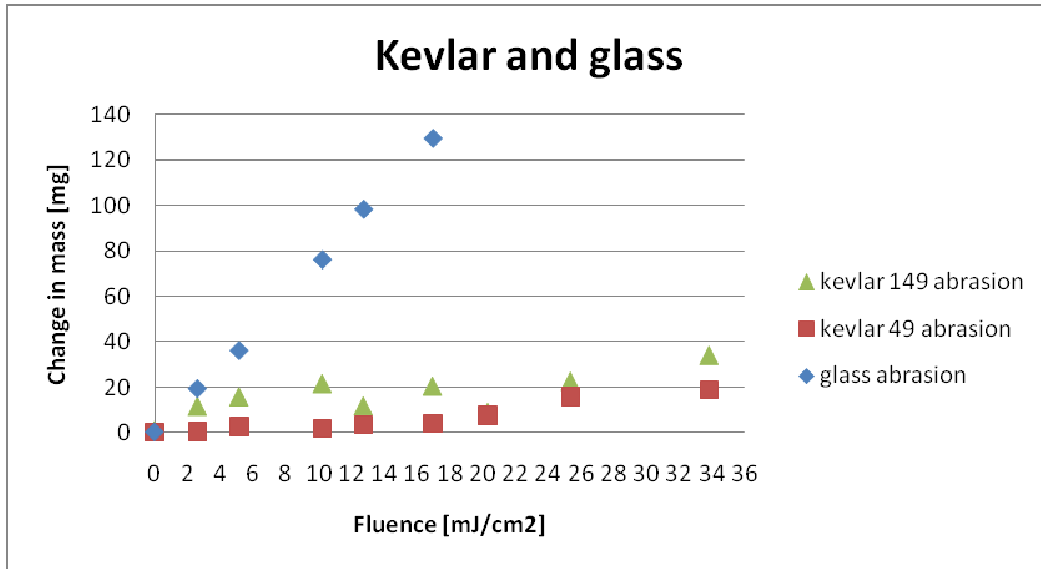
Pixel time	Mass(1)[g]	Mass(2)[g]	Change in mass[g]	Percentage change
untreated	165.9573	165.9562	0.0011	0.000662821
2.62	165.9696	165.9578	0.0118	0.007109736
5.16	165.9268	165.9109	0.0159	0.009582539

10.24	165.9633	165.9416	0.0217	0.01307518
12.75	165.9084	165.8965	0.0119	0.007172633
16.97	165.872	165.8514	0.0206	0.012419215
20.35	165.821	165.8119	0.0091	0.005487845
25.39	165.856	165.8333	0.0227	0.013686571
33.85	165.8763	165.8422	0.0341	0.020557488
101.37	165.768	165.7218	0.0462	0.027870277

In the graph below, it shows the effect of laser's energy density on the overall weight changes of abraded fabric. The mass change on abraded glass fabric increases linearly with the increase in energy density of laser. The non-irradiated glass fabric has almost no loss of mass after it was subjected to abrasion. The high energy irradiation of laser on glass made it more prone to abrasion due to the roughness created by laser beam on the surface of glass. The surface is more subjected to damage by highest intensity beam, making the fabric unstable at highest irradiation energy densities. The rough surface of the irradiated fabric will thus be easily abraded than smooth dimensionally stable non-irradiated fabric.



**Figure 24: graph of laser fluence vs. change in mass of abraded glass.**



**Figure 25: graph of laser fluence vs. change in mass of abraded Kevlar.**

Kevlar samples remained stable under abrasion. Kevlar experienced only small change in mass after abrasion, although the samples were irradiated at higher intensities of laser beam. Kevlar 49 revealed the good resistance to abrasion compared to Kevlar 149 sample.

### 5.3.5 Mechanical properties:

The results obtained in the test for mechanical properties of irradiated samples and non-irradiated samples are tabulated in the table below.

**Table 16: mechanical properties of glass:**

Energy density	$\epsilon_u$ max	Fmax	W	E	$\epsilon_u$ max
mJ/cm2	mm	N	J	MPa	%
0	5.2	882	27.59	2108	2.61
2.62	5.9	765	9.97	1495	2.99
5.16	3.9	308	2.62	870	1.96
10.24	2.4	56	0.046	157	1.19
12.75	1.7	52	0.17	215	0.86

**Table 17: mechanical properties of Kevlar 49:**

Energy density	$\epsilon_u$ max	Fmax	W	E	$\epsilon_u$ max
mJ/cm <sup>2</sup>	mm	N	J	MPa	%
0	6.4	3714	141.9	565.96	3.2
2.62	5.1	3217	136.8	585.61	2.56
5.16	6.7	1660	57.5	364.72	3.35
10.24	5.9	970	12	303.34	2.96
12.75	5.7	804	7.7	263.38	2.85
16.97	5	213	2.3	199.63	2.5
20.35	2.4	73	2	256.49	1.19
25.39	0.6	6.5	0.02	80.96	0.3
33.85	0.5	0.8	0.003	12.2	0.27

**Table 18: mechanical properties of Kevlar 149:**

Energy density	$\epsilon_u$ max	Fmax	W	E	$\epsilon_u$ max
mJ/cm <sup>2</sup>	mm	N	J	MPa	%
0	15.04	1079.25	6.97747	863.75	7.52
2.62	14.21	1086.73	7.65948	840.08	7.1
5.16	14.6	969.64	6.96562	762.23	7.3
10.24	11.72	621.23	4.30577	584.97	5.86
12.75	10.46	523.12	3.71457	512.56	5.23
16.97	9.66	103.05	1.0189	100.8	4.83
20.35	8.58	51.68	0.57945	34.92	4.29
25.39	8.69	74.43	0.76714	57.8	4.34
33.85	9.19	113.23	1.74314	53.95	4.6

Where  $\epsilon_u$  max – is the elongation at break [in % and mm],

Fmax – is the breaking strength [N],

E – Young's Modulus [MPa], and

W – the work done (energy) [J].

Laser irradiation on textile has some influences on mechanical properties of textiles. The strength of the material tends to decrease due to thermal damage by the Infrared laser irradiation. The high order of decrease of strength was seen at Kevlar 49 as compared to Kevlar 149 when the energy density of laser was increased. Kevlar 149 maintained its strength more than Kevlar 49, at the initial (lowest) irradiation energy density, only less than 1% change in strength was experienced in Kevlar 149, at the same initial irradiation energy as compared to Kevlar 49, which suffered 13.4% loss in strength.

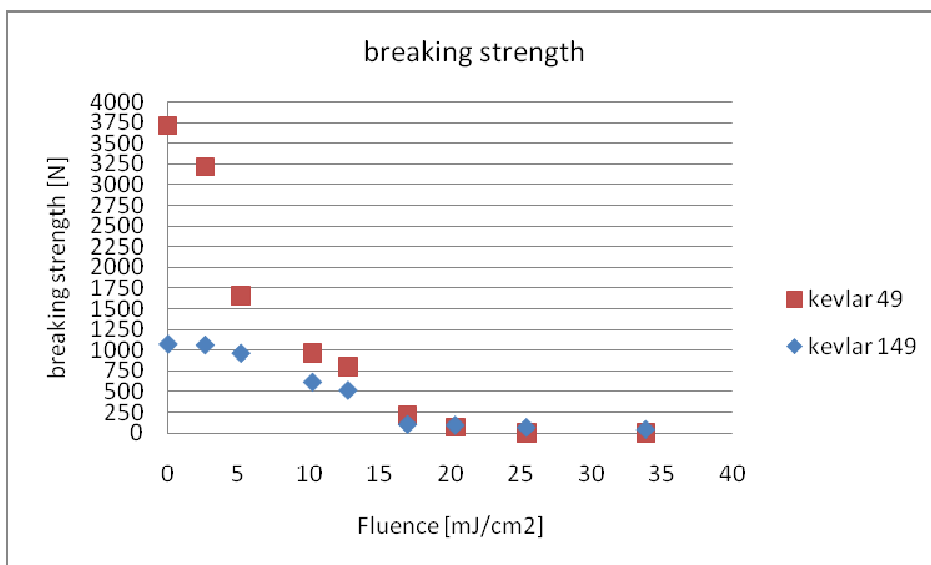
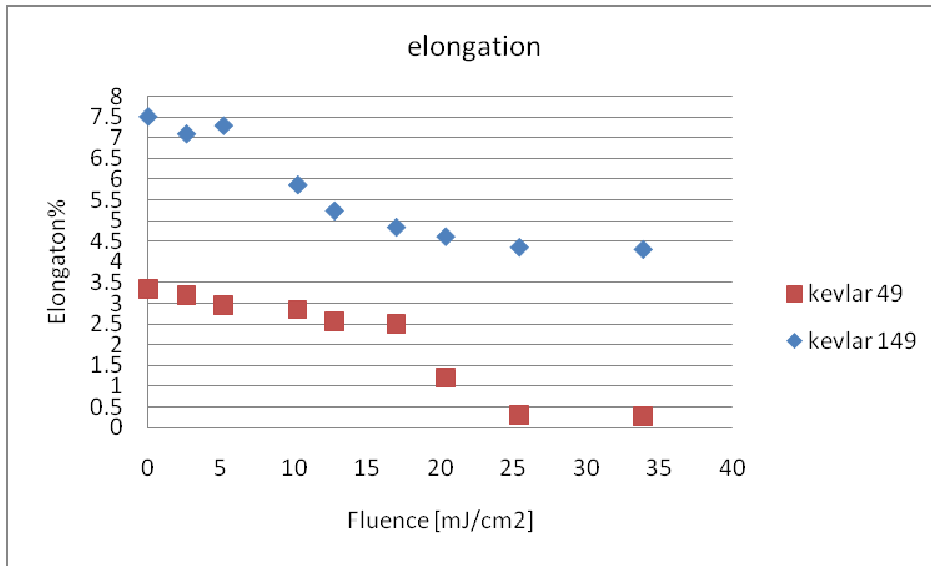


Figure 26 strength of fabric vs. energy density of laser in Kevlar 149 and Kevlar 49.



**Figure 27: elongation of fabric vs. energy density of laser in two types of Kevlars.**

Elongation as well as modulus is also affected by laser beam irradiation. Kevlar 49 untreated elongates up to 3.35%, whereas Kevlar 149 elongated up to 7.52%. Elongation of Kevlar 49 was reduced to 0.27% at energy density of 33.58mJ/cm<sup>2</sup>. The decrease in tensile strength and elongation are decreased due to the fact that the ripples which are found to be perpendicular to the fibrillar orientation of the fibre created more weak points in the fibre, leading to deductions in strength.

### 5.3.6 Absorbency test:

The results were recorded and tabulated in the table 19 below. Water drop test was initially done with a size of 50µL and the results were not clear and there was no correlation in the results. After careful considerations the size of the drop was changed to 100µL in which the results were much clearer. Both cleaned samples then irradiated and un-cleaned then irradiated yielded different results. Same applies to cleaned non-irradiated and un-cleaned non-irradiated samples.

**Table 19: Absorbency time of cleaned laser treated glass fabric with 100 $\mu$ L:**

Laser's Energy Density [mJ/cm <sup>2</sup> ]	Absorbency time of glass fabric [s]			Average	Standard deviation
2.62	161	176	163	166.6667	8.144528
5.16	58	145	146	116.3333	50.52062
10.24	36	31	38	35	3.605551
12.75	15	15	20	16.66667	2.886751
16.97	15	20	24	19.66667	4.50925
20.35	24	12	24	20	6.928203

**Table 20: Absorbency time of cleaned laser treated Kevlar 49 fabric:**

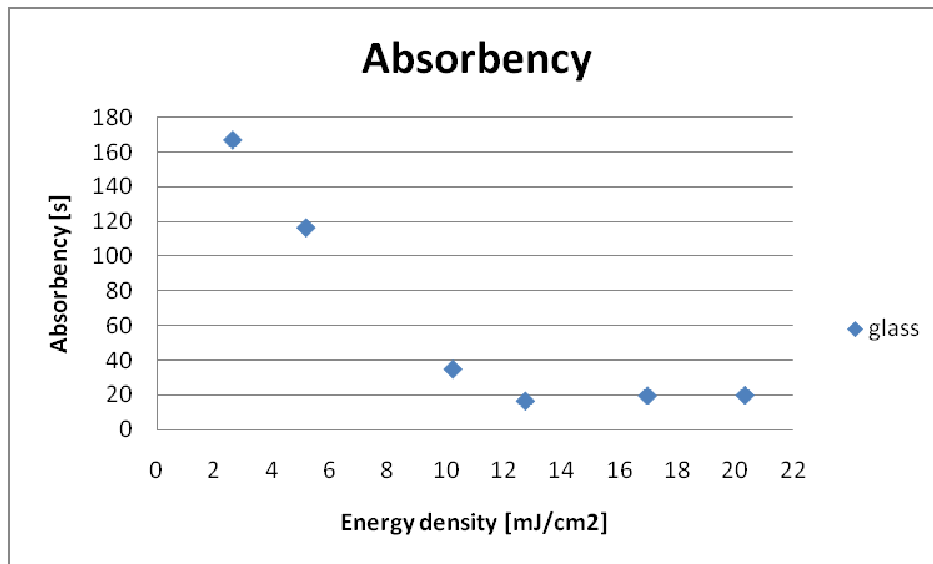
Laser's Energy Density [mJ/cm <sup>2</sup> ]	Absorbency time of glass fabric [s]			Average	Standard deviation
2.62	24	21	21	22	1.73
5.16	31	32	35	32.67	2.08
10.24	22	23	24	23	1
12.75	36	32	36	34.67	2.31
16.97	56	51	49	52	3.60
20.35	40	55	56	50.33	8.96
25.39	45	48	45	46	1.7
33.85	126	57	52	78.33	41.4

**Table 21: absorbency time of Kevlar 149 fabric:**

Laser's Energy Density [mJ/cm <sup>2</sup> ]	Absorbency time of glass fabric [s]			Average	Standard deviation
0	36.6	35.9	42.9	38.5	3.855299
2.62	106.4	54.3	138.3	99.7	42.40287
5.15	134.9	38.5	89.2	87.5	48.22161
10.24	18.5	5.6	21.5	15.2	8.448077
12.75	8.3	23.4	7.6	13.1	8.926926
16.97	3.7	1.1	1	1.9	1.530795
20.35	1.4	1.3	1	1.2	0.208167
25.39	1	1	1	1	0
33.85	2.5	1.1	1.7	1.7	0.702377

The untreated glass samples are hydrophobic and drop of water took long time to absorb on the surface. It took approximately more than 7200 seconds with 100 $\mu$ L drop of distilled water. All the tests were performed at standard atmospheric conditions. The plot of laser's energy density against absorbency time show that the laser treated glass sample increased absorbency. This is due to laser's cleaning properties making glass sample to have an increased wettability. The

absorbency time were decreased from 167 seconds to 16.7 seconds and remained almost constant at higher laser irradiation energy. Clean glass samples have higher absorbency as compared to un-cleaned glass samples after irradiation.



**Figure 28: Absorbency of cleaned glass sample vs. Energy density of laser.**

Kevlar 49 absorbency is opposite to glass absorbency. Kevlar instead it has reduced wettability after laser irradiation. Both cleaned and un-cleaned samples have absorbency of water drop on the 1<sup>st</sup> second. This is due to the weave structure of Kevlar 49, which is not closely weaved (satin 1/4). The laser beam on the surface of Kevlar was able to glue the structure together due to carbonization on surface and roughness created by thermal treatment created on the surface of Kevlar by laser beam. This behavior of Kevlar post-treatment is due to the reduced contact area between the water and the solid. At highest intensity of laser light, the drop of water took 78.3 seconds to absorb as compared to non-irradiated, which only took 1 second to absorb.

Cleaned Kevlar 49 when irradiated at lower irradiation intensity (energy density) of 2.62mJ/cm<sup>2</sup> has lowest absorbency time of 1.3 second, whereas un-cleaned sample is at 22 seconds at same energy density of 2.62mJ/cm<sup>2</sup>. Kevlar 149 is affected by laser in the same way as glass, i.e. laser treatment increases absorbency of Kevlar 149. The absorbency time was reduced from 100 seconds in the lowest energy density to only one second absorbency time at highest energy



density. The graph of mean value vs. standard deviation shows that the absorbance values are not widely dispersed from the mean value as the energy density increased from 10.24 up to 33.85mJ/cm<sup>2</sup>.

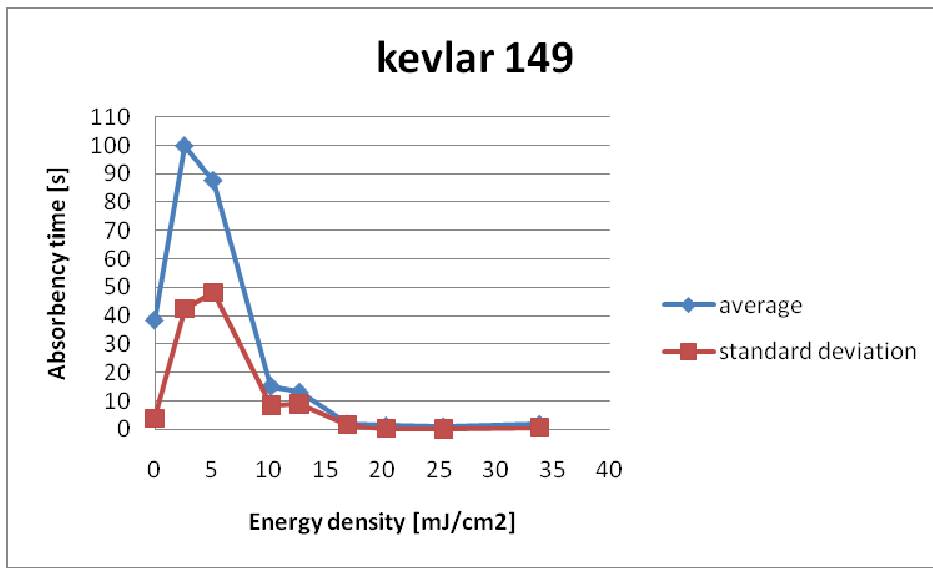


Figure 29: Absorbency time of Kevlar 149.

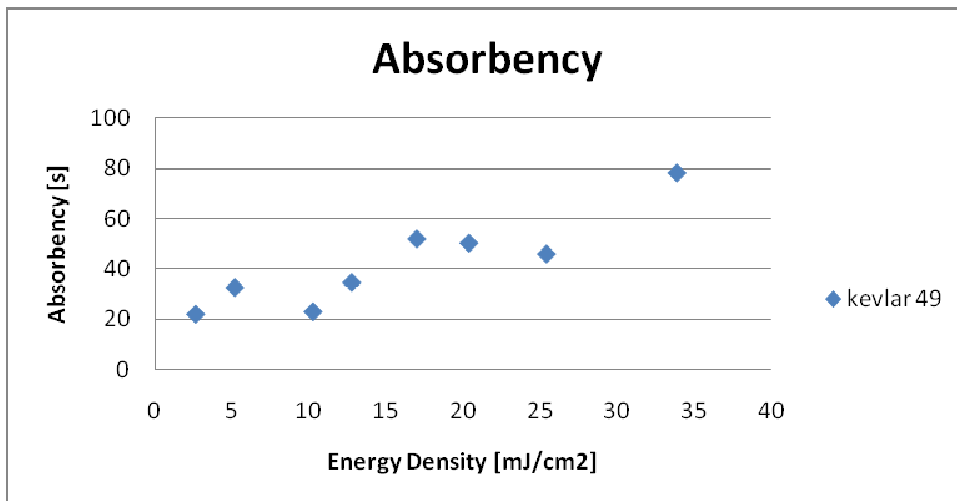


Figure 30: Absorbency of cleaned Kevlar 49 sample vs. Energy density of laser.

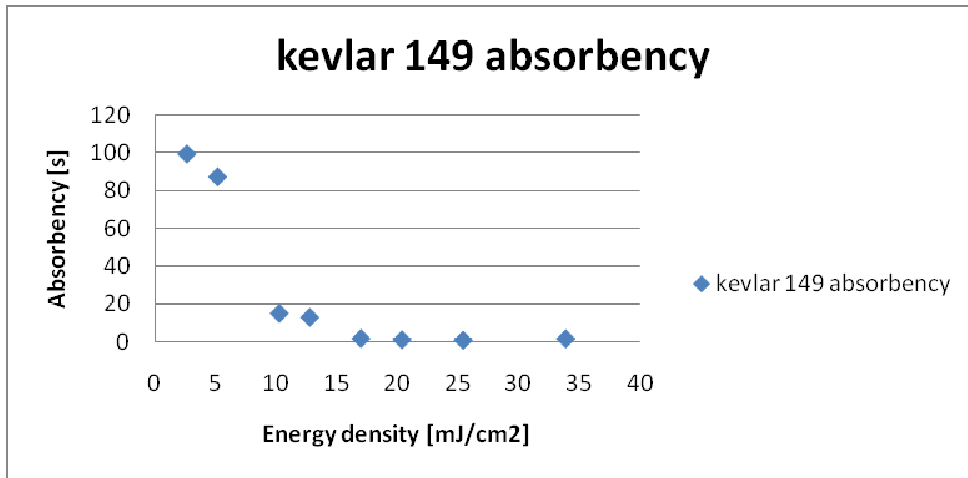


Figure 31: Absorbency of cleaned Kevlar 149 sample vs. Energy density of laser.

### 5.3.7 Infrared spectra:

The results of infrared spectrophotometer show no possible changes in the reactive groups of the treated material. The only change which was observed was carbonization. The generation of amorphous carbon is due to high thermal treatment of infrared laser beam. There are no chemical reactions such as chain scission, crosslinking, etc. this is because, energy of photons in the infrared region is not enough to induce this reactions.

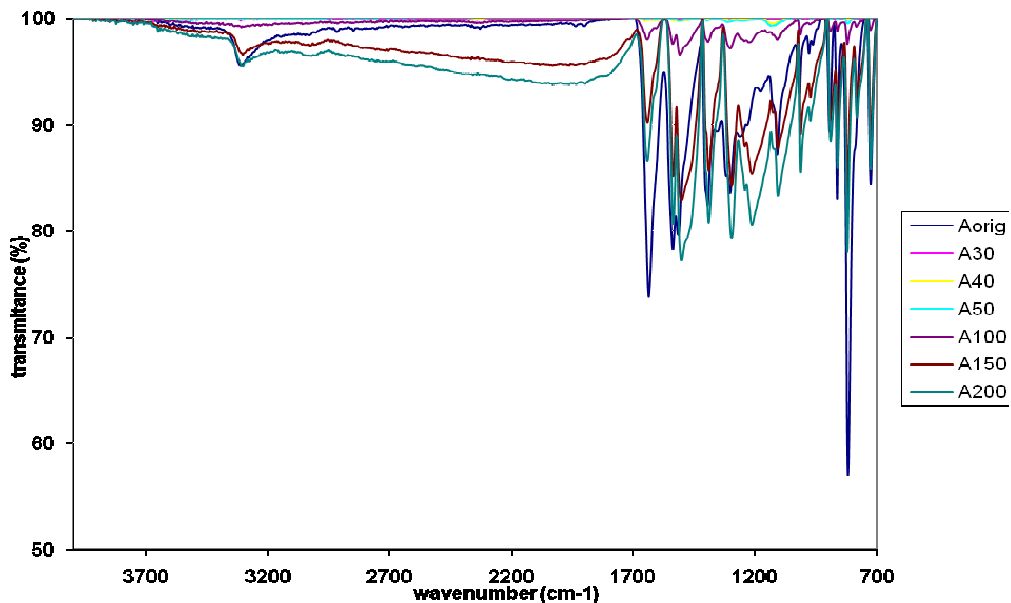


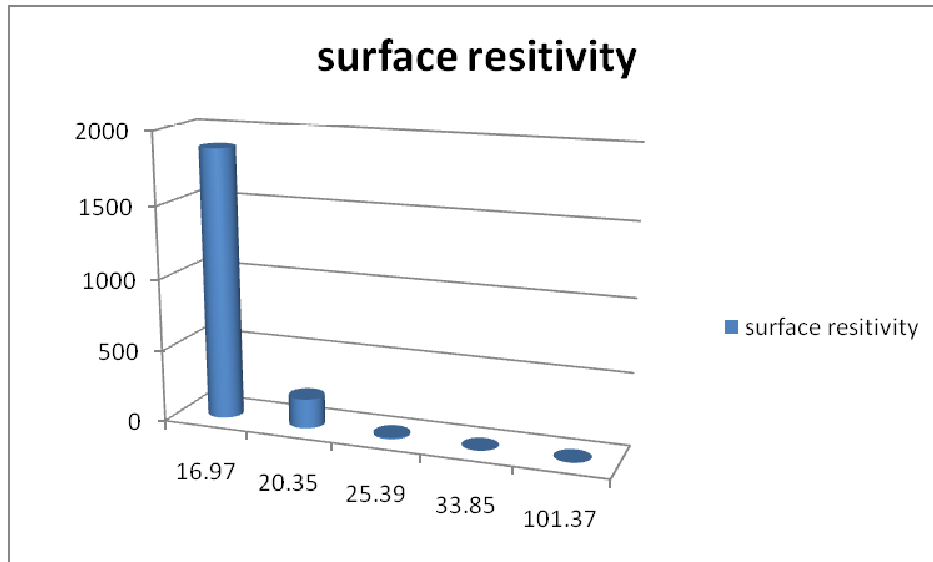
Figure 32: Infrared spectrum of Kevlar.

### 5.3.8 Resistivity measurements:

Measurements were done on Kevlar fabric on only one side of the fabric. Surface resistivity is related to conductivity because of they are inversely proportional. The results are in the following table:

**Table 22: resistivity measurements of Kevlar:**

Laser's energy density [mJ/cm <sup>2</sup> ]	resistivity [kΩ] <sup>-1</sup>						Average	Standard deviation
16.97	1340	1500	1345	1471	3197	2407	1876.667	761.7949
20.35	425	334	292	57	59	59	204.3333	165.616
25.39	4.2	17.5	17.4	17.3	4.18	4.19	10.795	7.235694
33.85	0.135	0.135	0.135	0.188	0.187	0.186	0.161	0.028489
101.37	0.027	0.028	0.018	0.003	0.003	0.004	0.013833	0.012024

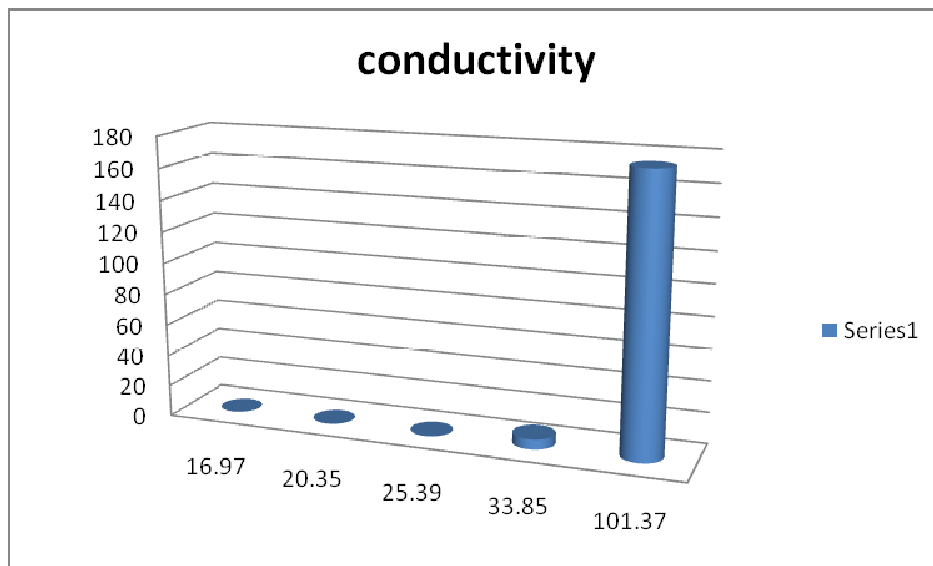


**Figure 33: Surface resistivity of Kevlar**

The graphs of resistivity show us that laser irradiation of Kevlar, reduce its surface resistivity and increase its conductivity. Thermal treatment has influence on the resistivity of the material.

**Table 23: Table of resistivity values of Kevlar 49:**

Laser's energy density [mJ/cm <sup>2</sup> ]	conductivity [kΩ]						Average	Standard deviation
16.97	0.000746	0.000667	0.00074	0.00068	0.000313	0.00042	0.000594	0.000168
20.35	0.00235	0.00299	0.0034	0.0175	0.0169	0.01695	0.0100	0.007
25.39	0.2381	0.057	0.0575	0.0578	0.2392	0.2387	0.1480	0.091
33.85	7.4075	7.4074	7.4074	5.319	5.3476	5.376	6.377	1.030
101.37	37.0371	35.714	55.5556	333.33	333.33	250.0	174.0	134.5



**Figure 34: graph of conductivity of Kevlar**

In overall results, of resistivity, laser treated sample decreased the resistivity as the laser intensity increases.

## **5.4 FUTURE PERSPECTIVES AND CONCLUSIONS:**

In conclusions, laser treatment on textile has shown some potential use, in the surface modifications of textiles. Special fibres, with their good thermal properties are found to be well treatable with the use of infrared laser. Surface modifications of polymers using longer wavelength carbon dioxide laser is found to be not so effective for the photochemical process. This is due to the large temperature increases during surface treatment. The molecules of the material can lead to dissociation by thermal means. The pulsed lasers are more appropriate for the textile treatment where heating is not desirable more than the continuous mode lasers.

Laser's thermal treatment has shown carbonization of chemical groups as it was shown by the infrared spectrophotometer. The absorbency of glass was increased by the laser treatment and in Kevlar 49 it was the opposite results. Surfaces that are rough on a nanoscale tend to be more hydrophobic because of the reduced contact area between the water and material. The formation of ripple-like structures was seen via SEM especially in glass and this made the surfaces of the treated material to be rough.

At highest laser intensities textile cannot withstand the mechanical properties. The tensile strength Kevlar revealed better thermal stability when was compared with glass fibres. Kevlar and glass fabrics suffered a loss of mechanical properties. The decrease in mechanical properties was subject to higher irradiation of laser beam on special fibres. The ripples on the surface of the irradiated samples are also a cause for reduction in strength due to creation of weak points in the fibre. Abrasion resistance of the laser treated samples was also affected, at lower irradiation intensities, the effects are very small, whereas at high intensities, the change in mass was very high after being exposed to abrasion by abrasion tester.

Colour of the treated samples changed due to the thermal effects of laser beam. The total colour difference is huge on the high intensity irradiated beam. The Kevlar turned brownish and then turned black as the intensity of laser increased. This is due to charring and carbonization. No cross linking reactions occurred in the molecules of the material, this is due to the use of infrared which cannot cause some chemical reactions, but only causes carbonization.

Surface resistivity results were not very clear, and not much can be concluded from it. Better results can be improved to see the effect over different laser energy densities. The most important factors to be taken into consideration when measuring resistivity are the relative humidity, air temperature and thickness of the material. A lot can be improved in the future, to check how many other properties are being affected by infrared laser. In most literature, ultraviolet lasers are used. More research needs to be done especially on special fibres because of their excellent thermal and mechanical properties.

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## 7. GLOSSARY:

- CO<sub>2</sub> = Carbon dioxide.
- LASER = Light Amplification by Stimulated Emission of Radiation.
- MASERS = Microwave Amplification by Stimulated Emission of Radiation.
- Wm<sup>-2</sup> – Watts per square meter. Units for power density, where W = watts and m = meter.
- mJ – milli-Joule. Units for laser energy, where m = milli and J = Joule.
- Pulse – the time duration the laser is on. Units μs or fs. Where μs = microsecond (1 millionth of a second) and fs = femtosecond (1 quadrillionth of a second).
- λ – wavelength [m]
- ν – frequency [Hz]
- He-Ne laser – Helium Neon laser
- He-Cd laser – Helium Cadmium laser
- HCl – Hydrochloric acid
- CO – Carbon Dioxide
- N<sub>2</sub> – Nitrogen
- $E = E_2 - E_1 = h\nu$ , where E = total energy, E<sub>2</sub> = energy of the upper state, E<sub>1</sub> = Energy of the lower state, h = Planck's constant and ν = radiation frequency.
- UV – Ultraviolet radiation
- IR – Infrared radiation
- VIS – visible radiation
- LOI = limiting oxygen index

- PPTA = poly-p-phenyleneterephthalamine
- $P\cdot$  = polymer alkyl radical,  $POO\cdot$  = polymer peroxy radical (polymer alkyl peroxy radical),  $PH$  = polymer,  $POOH$  = polymer hydro peroxide,  $PO\cdot$  = polymer oxy radical (polymer alkoxy radical) and  $HO\cdot$  = hydroxyl radical.

- $v = \sqrt{\frac{2E_{ex}}{m}}$ , where  $E_{ex}$  = released energy,  $m$  = mass

- $E_{ex} = E_{ph} - E_B$ , where  $E_{ph}$  = photon energy, and  $E_B$  = binding energy.

- dtex = dencitex
- $lb/in^3$  = pounds per cubic inch
- $g/cm^3$  = grams per cubic centimeter
- N – newton
- g/d = grams per denier
- cN/tex = centinewton per tex
- psi = per square inch
- Mpa = megapascal
- E (GPa) is the Young's modulus
- $\sigma_u$  (GPa) is the tensile strength
- $\rho$  ( $g/cm^3$ ) is density
- $E/\rho$  (Mm) is specific stiffness
- $\sigma_{fu}/\rho$  (Km) is the specific strength
- $\epsilon_u$  (%) is the failure strain
- $d_f$  ( $\mu m$ ) is the diameter of the fibre.
- CTE = coefficient of thermal expansion [ $W \cdot m^{-2} K^{-1}$ ], where Watts, m = meter and K = Kelvin.

$$F = \frac{r^4 h}{l \eta} \quad \text{where } F = \text{rate of flow, } r = \text{radius of the nozzles, } l = \text{length of the cylinder and } \eta = \text{viscosity}$$

## 8. APPENDICES:

### 8.1 Appendix A: laser irradiated samples:

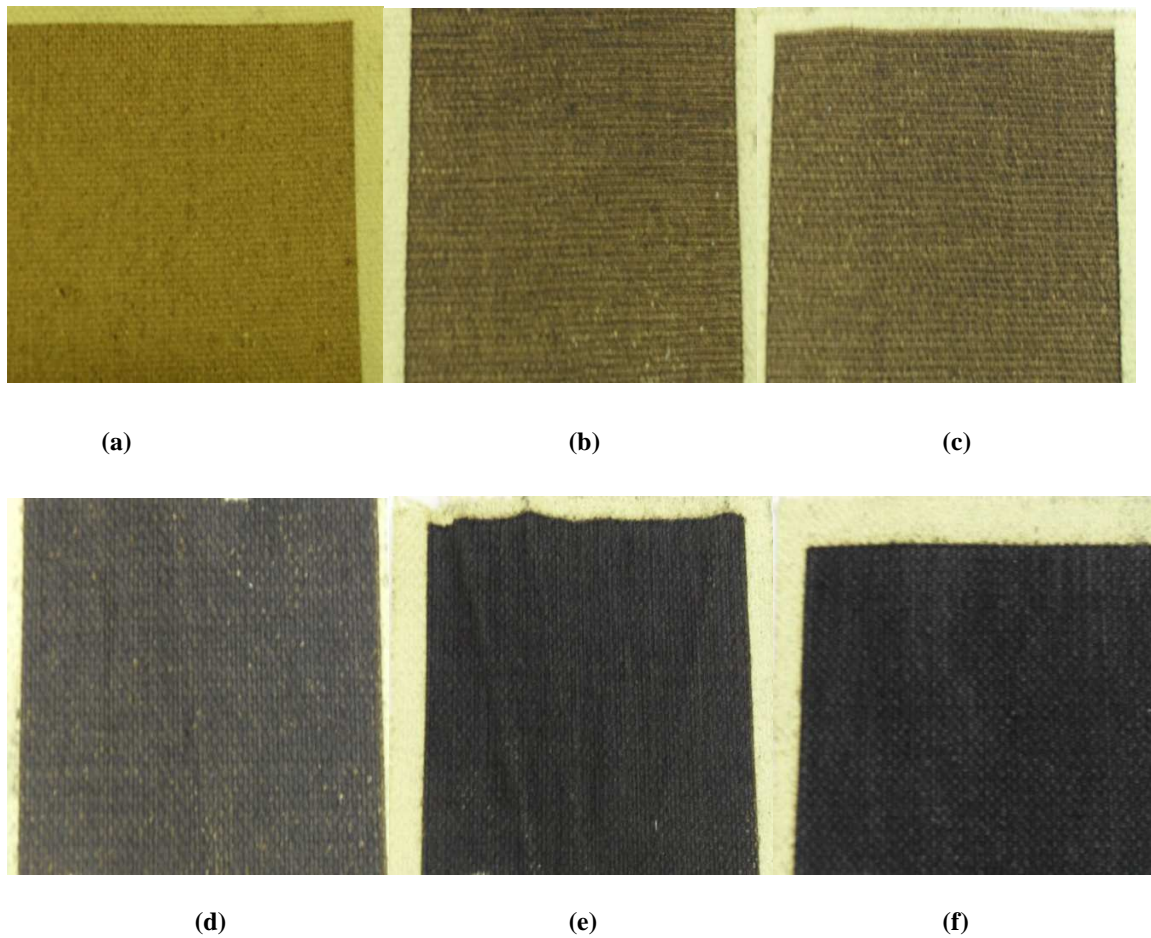
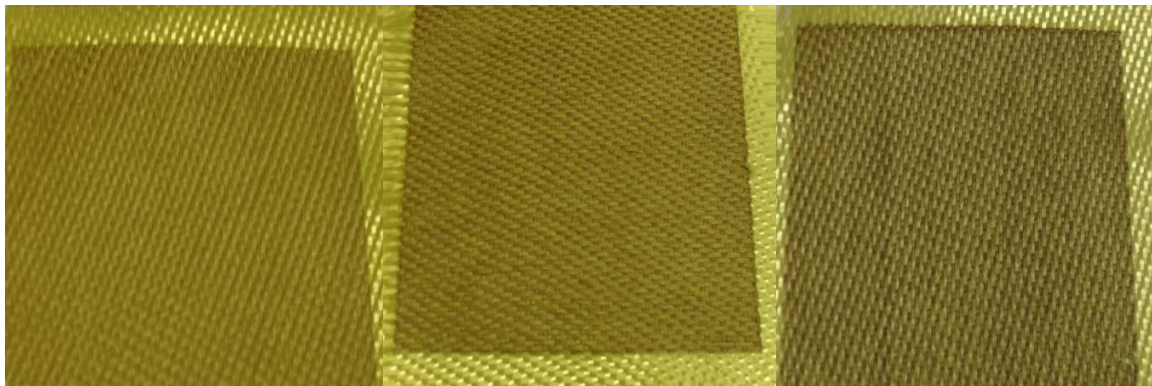


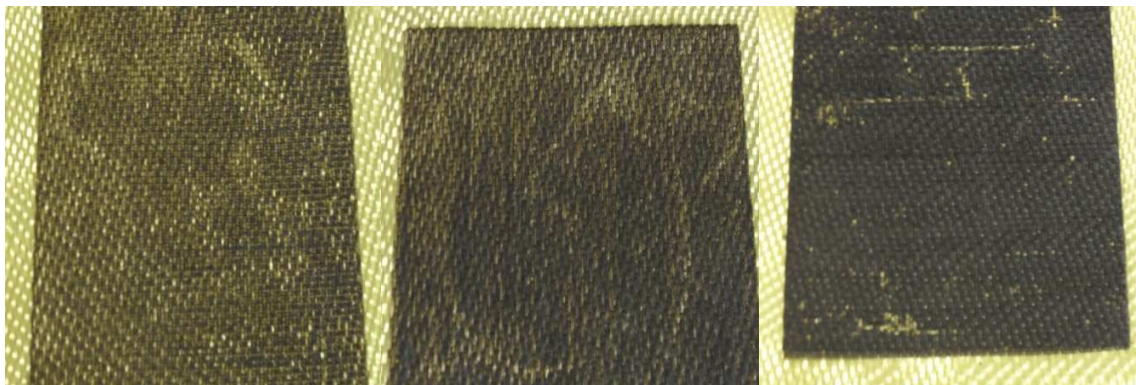
Figure 35: Kevlar 149 laser irradiated from top at (a) 5.16mJ/cm<sup>2</sup>, (b) 10.24mJ/cm<sup>2</sup>, (c) 12.75mJ/cm<sup>2</sup>, (d) 20.35mJ/cm<sup>2</sup>, (e) 25.39mJ/cm<sup>2</sup> and (f) 33.85mJ/cm<sup>2</sup> laser energy densities.



(a)

(b)

(c)



(d)

(e)

(f)

**Figure 36: Kevlar 49: laser irradiated from top at (a)  $5.16\text{mJ}/\text{cm}^2$ , (b)  $10.24\text{mJ}/\text{cm}^2$ , (c)  $12.75\text{mJ}/\text{cm}^2$ , (d)  $20.35\text{mJ}/\text{cm}^2$ , (e)  $25.39\text{mJ}/\text{cm}^2$  and (f)  $33.85\text{mJ}/\text{cm}^2$  laser energy densities.**



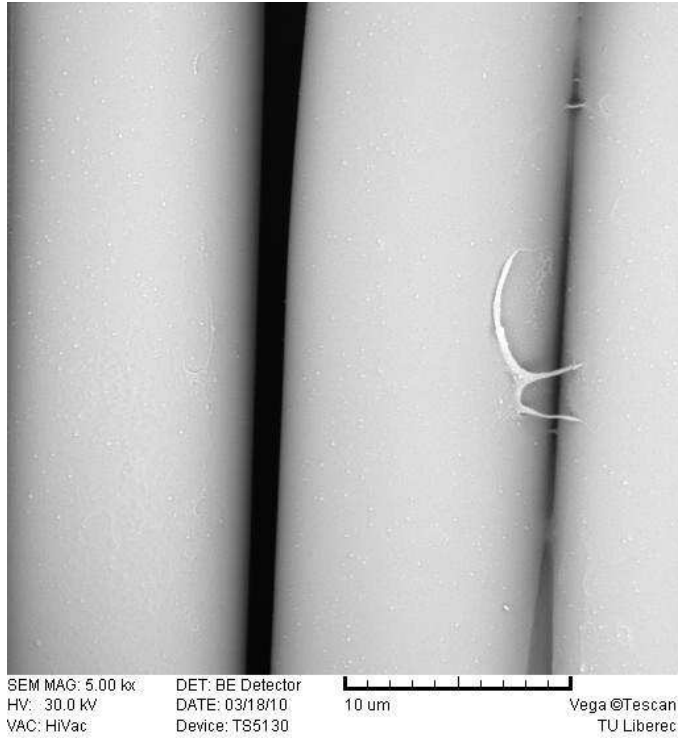
(a)

(b)

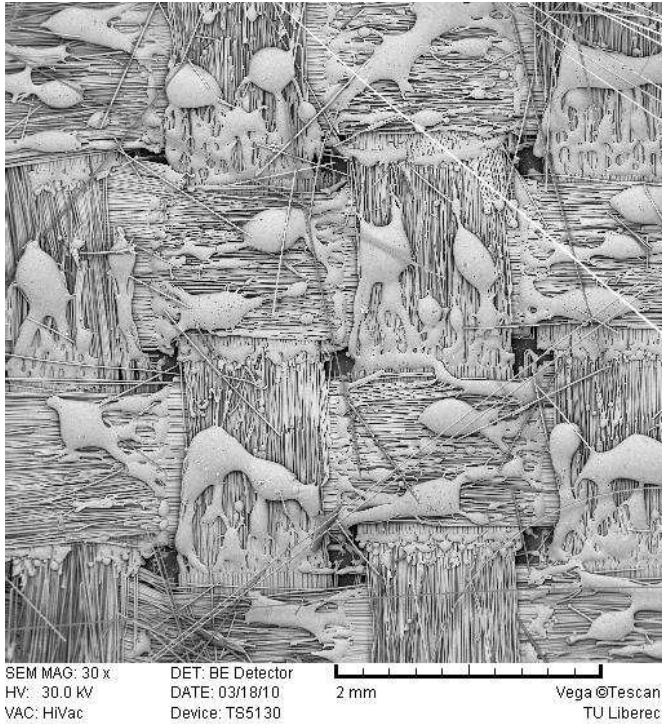
(c)

**Figure 37: Glass: laser (a) irradiated at  $5.16\text{mJ}/\text{cm}^2$ , (b)  $12.75\text{mJ}/\text{cm}^2$  and (c)  $20.35\text{mJ}/\text{cm}^2$ .**

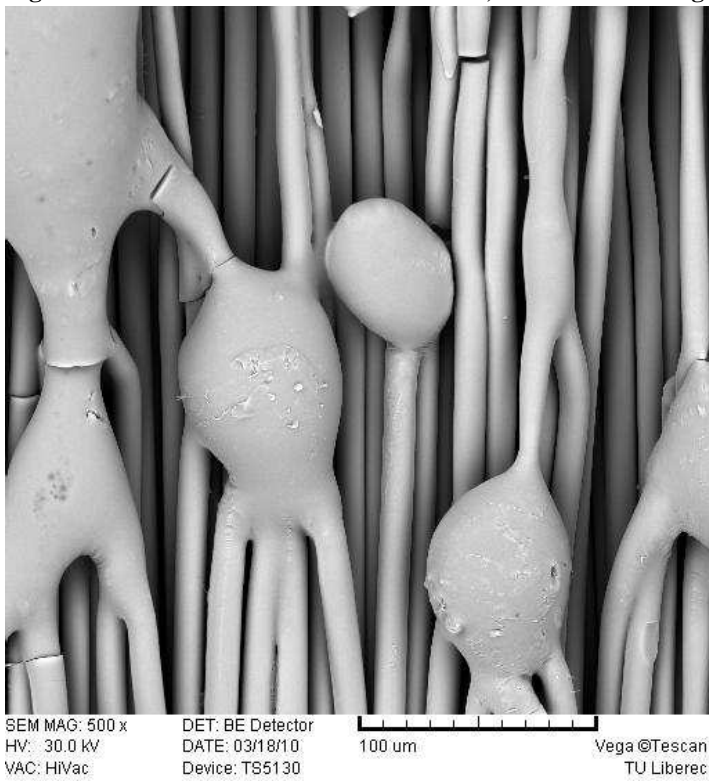
## 8.2 Appendix B: Microscope images



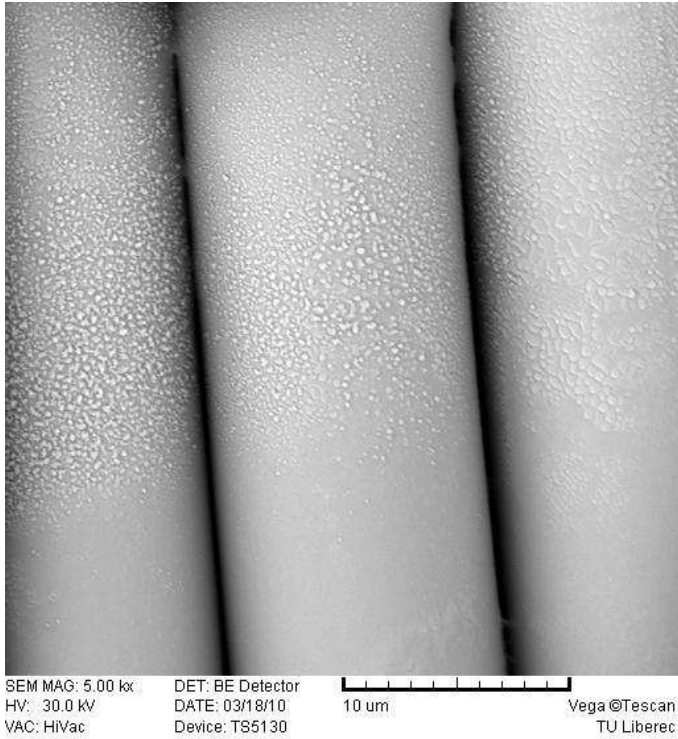
**Figure 38: Glass irradiated at  $5.16\text{mJ}/\text{cm}^2$  viewed at 5000x magnification of SEM.**



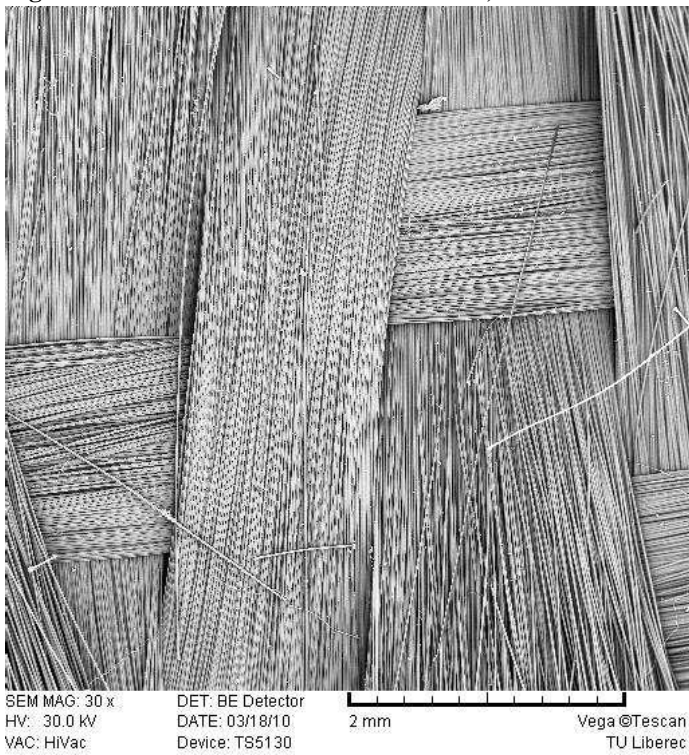
**Figure 39: Glass irradiated at 10.24mJ/cm<sup>2</sup>, viewed at 30x magnification of SEM.**



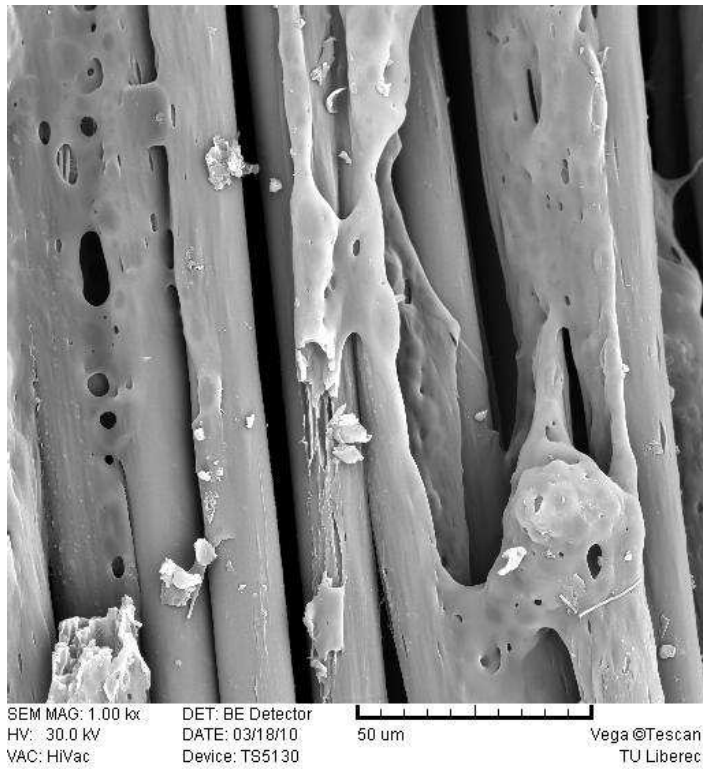
**Figure 40: Glass irradiated at 12.75mJ/cm<sup>2</sup>, viewed under 500x magnification of SEM.**



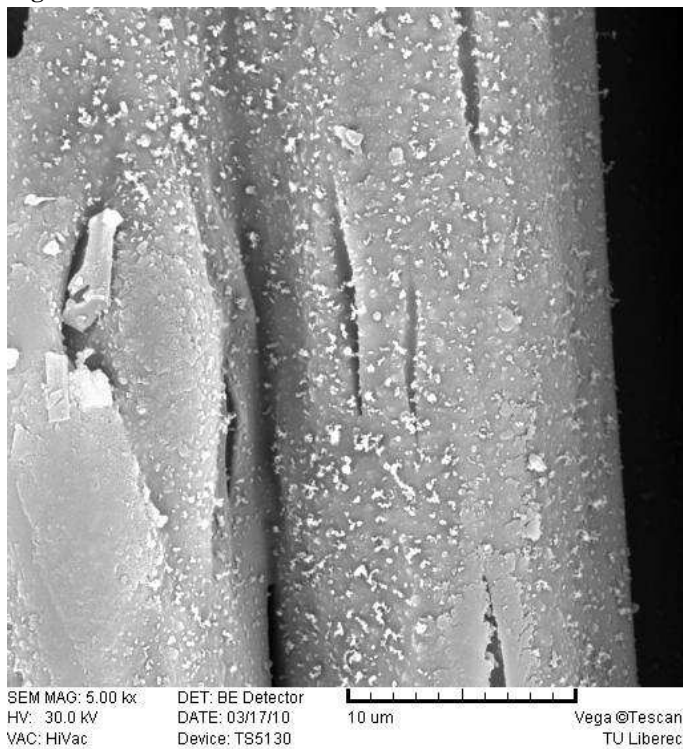
**Figure 41: Glass irradiated at 16.97mJ/cm<sup>2</sup>, viewed under 5000x magnification of SEM.**



**Figure 42: Kevlar 49 irradiated at 2.62mJ/cm<sup>2</sup> viewed under 30x magnification of SEM.**

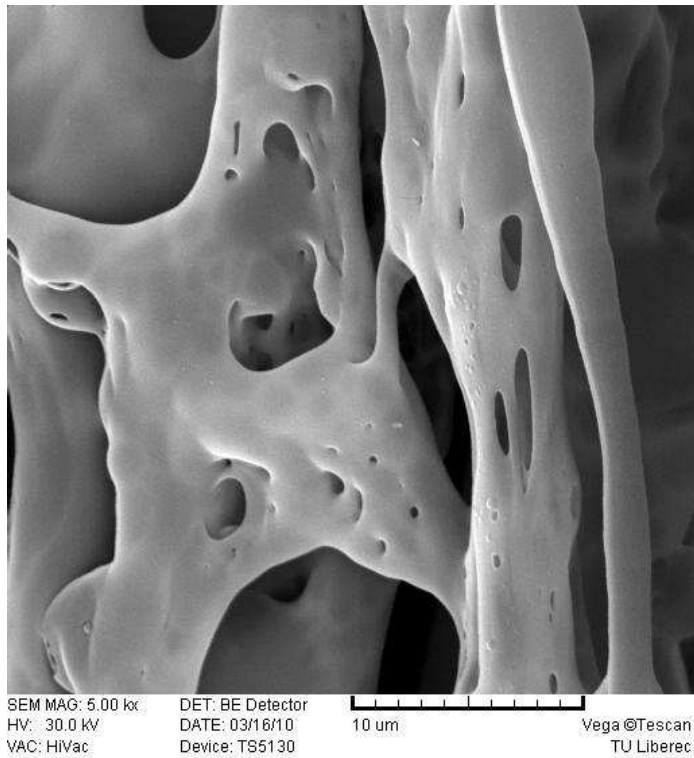


**Figure 43: Kevlar 49 irradiated at  $5.16\text{mJ}/\text{cm}^2$  viewed under 1000x magnification of SEM.**

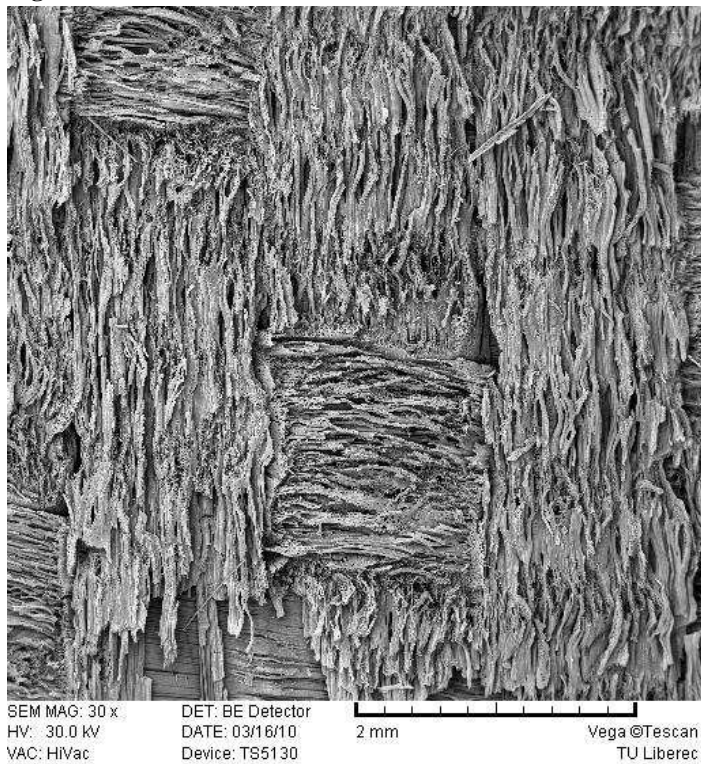


**Figure 44: Kevlar 49 irradiated at  $10.24\text{mJ}/\text{cm}^2$  viewed under 500x magnification of SEM.**

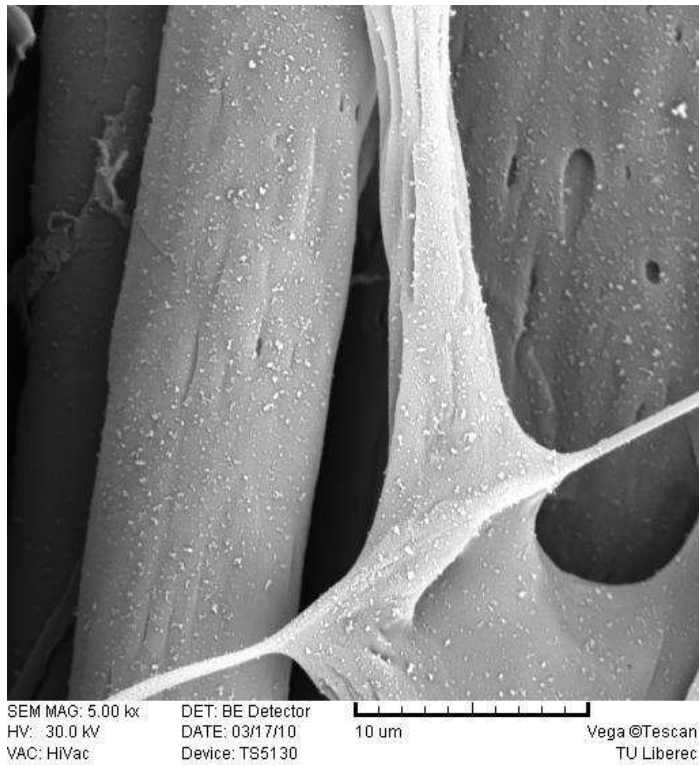




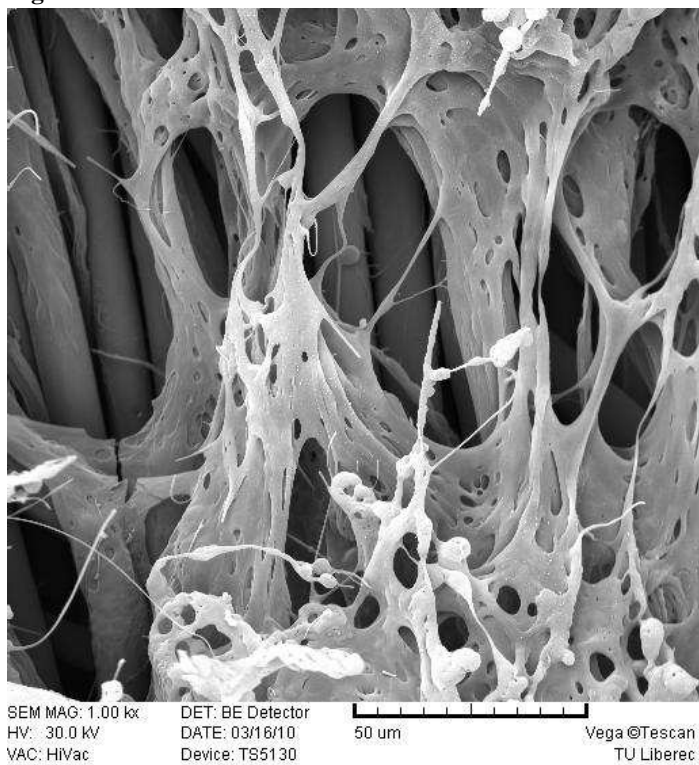
**Figure 45: Kevlar 49 irradiated at 25.39mJ/cm<sup>2</sup> viewed under 5000x magnification of SEM.**



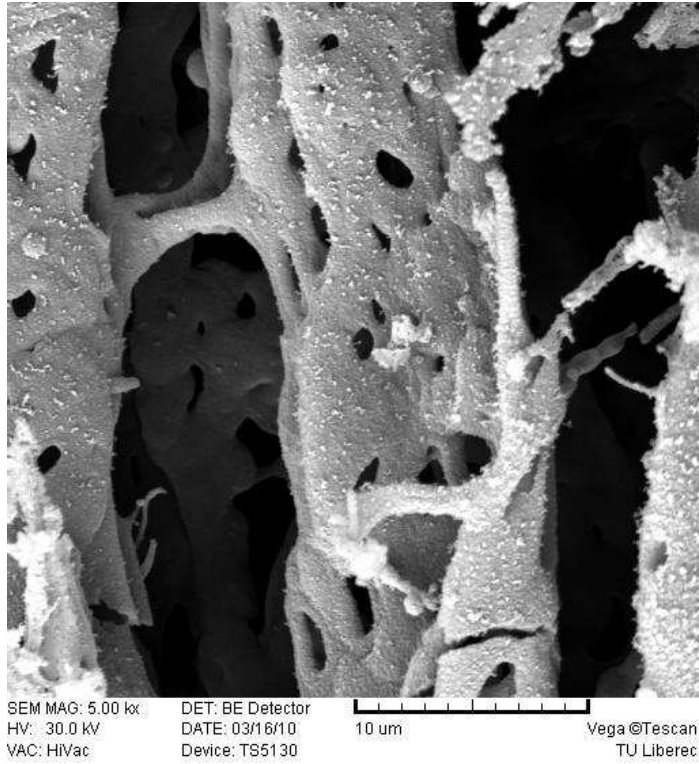
**Figure 46: Kevlar 49 irradiated at 101.37mJ/cm<sup>2</sup> viewed under 30x magnification of SEM.**



**Figure 47: Kevlar 149 irradiated at 10.24mJ/cm<sup>2</sup> viewed under 5000x magnification of SEM.**



**Figure 48: Kevlar 149 irradiated at 25.39mJ/cm<sup>2</sup> viewed under 1000x magnification of SEM.**



**Figure 49: Kevlar 149 irradiated at  $101.37\text{mJ}/\text{cm}^2$  viewed under 5000x magnification of SEM**

### 8.3 Appendix C: Colour testing:

Table 24: remission values and wavelngths of laser treated glass samples:

Wavelength [nm]	Energy Density [mJ/cm <sup>2</sup> ]							
	0	2.62	5.16	10.24	12.75	16.97	20.35	
400	0.62313	0.556012	0.341065	0.21882	0.242898	0.316819	0.306401	Remission values
410	0.662395	0.583335	0.354876	0.224339	0.249233	0.329198	0.325927	
420	0.691286	0.602341	0.367333	0.229208	0.254681	0.337932	0.339914	
430	0.707988	0.614784	0.37827	0.232691	0.257791	0.342488	0.347366	
440	0.718715	0.624132	0.388237	0.236043	0.260298	0.345897	0.353122	
450	0.728553	0.63333	0.39896	0.240034	0.263638	0.349474	0.358554	
460	0.738258	0.641983	0.409517	0.243572	0.266727	0.353067	0.363819	
470	0.747998	0.650862	0.419643	0.247357	0.270037	0.3569	0.369187	
480	0.757224	0.659345	0.430198	0.25142	0.273304	0.360913	0.374506	
490	0.765159	0.666552	0.44006	0.255077	0.27619	0.364127	0.379164	
500	0.773083	0.674257	0.450281	0.259102	0.27946	0.367917	0.384135	
510	0.77902	0.680496	0.459981	0.262795	0.28244	0.371032	0.388566	
520	0.784352	0.686502	0.469561	0.266501	0.285331	0.374063	0.39291	
530	0.789136	0.692316	0.479214	0.270366	0.288294	0.377234	0.397393	
540	0.79267	0.697045	0.488429	0.27403	0.291054	0.379919	0.401506	
550	0.795266	0.701428	0.49759	0.277767	0.293859	0.382739	0.405436	
560	0.797241	0.705149	0.506473	0.281327	0.296625	0.385029	0.409198	
570	0.79857	0.708336	0.51496	0.285025	0.299229	0.387401	0.412871	
580	0.79888	0.711136	0.523174	0.288707	0.301727	0.389438	0.416102	
590	0.798166	0.713034	0.531128	0.292236	0.304222	0.391314	0.419024	
600	0.797157	0.714565	0.538769	0.295807	0.30675	0.393244	0.421912	
610	0.796102	0.716141	0.546398	0.299513	0.309298	0.39489	0.424681	
620	0.795277	0.71745	0.553592	0.303043	0.311566	0.396442	0.42733	
630	0.794756	0.718886	0.56057	0.306648	0.313985	0.398154	0.429966	
640	0.794874	0.72076	0.567628	0.310514	0.316614	0.40002	0.433033	
650	0.796223	0.723277	0.574662	0.31434	0.319212	0.402249	0.436382	
660	0.79658	0.724852	0.581315	0.317912	0.321645	0.403895	0.439168	
670	0.794933	0.725337	0.587303	0.321476	0.323984	0.405193	0.4411	
680	0.799496	0.729305	0.594255	0.325488	0.326643	0.407782	0.445422	
690	0.804927	0.733809	0.601076	0.329566	0.329343	0.410407	0.449903	
700	0.809283	0.73812	0.607982	0.334007	0.332506	0.413186	0.454458	

**Table 25: K/S values and wavelengths of laser treated glass samples:**

Wavelength [nm]	Energy Density [mJ/cm <sup>2</sup> ]							K/S Value
	0	2.62	5.16	10.24	12.75	16.97	20.35	
400	0.1139654	0.1772669	0.6365285	1.3943883	1.1799248	0.7365982	0.7850503	
410	0.0860338	0.1488078	0.5863795	1.3409356	1.1307686	0.68344	0.6970493	
420	0.0689328	0.1312654	0.5448285	1.2960313	1.0905809	0.6485531	0.6409155	
430	0.0602209	0.1206857	0.5109422	1.2651162	1.068449	0.631148	0.6130884	
440	0.0550435	0.1131786	0.4819929	1.2362813	1.0510218	0.6184647	0.5925027	
450	0.0505684	0.1061431	0.4527377	1.2030543	1.0283606	0.6054592	0.5737676	
460	0.0463991	0.0998284	0.4257079	1.1745646	1.0079407	0.592695	0.5562183	
470	0.0424502	0.0936428	0.4013113	1.1450481	0.9866152	0.5794031	0.5389219	
480	0.0389185	0.0880011	0.3773538	1.1144149	0.9661151	0.5658316	0.5223465	
490	0.0360384	0.0834052	0.356238	1.0877317	0.9484442	0.5552097	0.5082727	
500	0.0333027	0.0786854	0.3355591	1.0592906	0.9288946	0.5429595	0.493694	
510	0.031342	0.0750059	0.3169926	1.0340228	0.9115102	0.5331094	0.4810645	
520	0.0296449	0.0715809	0.2996043	1.0094138	0.8950171	0.5237052	0.4690115	
530	0.0281724	0.0683718	0.2829827	0.9845271	0.8784889	0.514055	0.4568959	
540	0.0271144	0.0658365	0.2679042	0.9616303	0.8634193	0.5060282	0.4460657	
550	0.0263534	0.0635458	0.2536377	0.938955	0.8484283	0.4977414	0.4359583	
560	0.0257834	0.0616443	0.2404566	0.9179527	0.8339412	0.4911169	0.4265016	
570	0.0254041	0.0600475	0.2284295	0.8967466	0.8205775	0.4843525	0.4174687	
580	0.0253161	0.0586682	0.2172923	0.8762157	0.8079927	0.478621	0.4096803	
590	0.0255192	0.0577457	0.2069573	0.8570614	0.7956496	0.4734037	0.4027613	
600	0.0258074	0.0570088	0.1974255	0.8381957	0.7833653	0.4680977	0.3960374	
610	0.0261113	0.0562571	0.1882823	0.8191325	0.7712136	0.4636201	0.3896949	
620	0.0263502	0.0556378	0.1799881	0.8014535	0.7605785	0.4594391	0.383722	
630	0.026502	0.0549635	0.1722343	0.7838576	0.7494274	0.4548732	0.3778651	
640	0.0264676	0.0540923	0.1646724	0.7654898	0.737518	0.4499473	0.3711636	
650	0.0260763	0.0529365	0.1574075	0.747806	0.7259625	0.4441369	0.3639768	
660	0.0259733	0.0522218	0.1507759	0.7317189	0.7153319	0.4398942	0.3581004	

<b>670</b>	0.0264504	0.0520032	0.1450009	0.7160659	0.7052785	0.4365769	0.3540803	
<b>680</b>	0.025142	0.0502366	0.1385173	0.6988979	0.6940454	0.430036	0.3452425	
<b>690</b>	0.0236379	0.0482807	0.1323796	0.6819293	0.6828475	0.4235051	0.336302	
<b>700</b>	0.0224723	0.0464566	0.1263834	0.6639772	0.6699842	0.416702	0.3274405	

**Table 26: remission values and wavelngths of laser treated kevlar samples:**

Wave length [nm]	Energy Density [mJ/cm <sup>2</sup> ]										Remission values
	0	2.62	5.16	10.24	12.75	16.97	20.35	25.39	33.85	101.37	
400	0.07303	0.05434	0.072151	0.07074	0.07237	0.07005	0.06858	0.07596	0.06083	0.0626	R e m i s s i o n  v a l u e s
410	0.07944	0.06668	0.07760	0.07684	0.07708	0.07473	0.07290	0.07923	0.06470	0.06379	
420	0.09464	0.09512	0.09210	0.09128	0.09130	0.08825	0.08570	0.09121	0.0750687	0.070743	
430	0.12414	0.14757	0.12022	0.11993	0.11935	0.11586	0.11169	0.11653	0.096585	0.0875734	
440	0.1798	0.21970	0.1731977	0.17324	0.17254	0.16845	0.16167	0.16652	0.1376953	0.1188705	
450	0.25930	0.2959	0.24764	0.24821	0.247	0.24262	0.23189	0.23701	0.1924236	0.1578689	
460	0.34656	0.36534	0.3273169	0.32883	0.33011	0.32322	0.30747	0.3133	0.247823	0.1943082	
470	0.42582	0.42092	0.3971449	0.40056	0.40476	0.39610	0.37533	0.38182	0.2948819	0.2237475	
480	0.49522	0.46747	0.4551284	0.46212	0.46991	0.45948	0.43387	0.44126	0.3343247	0.2480612	
490	0.54882	0.50340	0.4970883	0.50836	0.51975	0.50793	0.47890	0.48679	0.3640608	0.2669064	
500	0.59043	0.53298	0.529614	0.54437	0.55793	0.54499	0.51315	0.52143	0.3875974	0.2825788	
510	0.62433	0.55822	0.5598267	0.57402	0.58823	0.57363	0.53970	0.54752	0.4063191	0.2957466	
520	0.65331	0.58040	0.5901071	0.6003	0.6133	0.59619	0.56153	0.56797	0.4221287	0.3074406	
530	0.67848	0.59991	0.6183606	0.62299	0.63420	0.61465	0.57926	0.58430	0.4360293	0.318179	
540	0.69848	0.61669	0.6418202	0.64149	0.65096	0.62919	0.59327	0.59733	0.4476582	0.3279381	
550	0.71550	0.63187	0.661165	0.65715	0.66501	0.64158	0.60544	0.60873	0.458325	0.337080	
560	0.72931	0.64552	0.67639	0.66994	0.67656	0.65208	0.6155	0.61809	0.467888	0.345565	
570	0.74116	0.65787	0.688842	0.68073	0.68624	0.66113	0.62449	0.62623	0.476395	0.353572	
580	0.75144	0.66962	0.699328	0.69038	0.69498	0.66914	0.63247	0.63373	0.484580	0.361425	
590	0.76065	0.68091	0.708849	0.69907	0.70309	0.67667	0.63967	0.64087	0.492372	0.369286	
600	0.76978	0.69256	0.71802	0.70794	0.71082	0.68417	0.64708	0.64775	0.500121	0.377316	
610	0.77840	0.70369	0.726623	0.71612	0.71837	0.69121	0.65408	0.65444	0.507480	0.385201	
620	0.78645	0.71428	0.73428	0.72374	0.72493	0.6974	0.66023	0.66023	0.51431	0.39230	
630	0.79391	0.72473	0.7420	0.73097	0.73116	0.70343	0.66626	0.66596	0.52086	0.39924	
640	0.80110	0.73489	0.74887	0.73796	0.73729	0.70921	0.67174	0.67143	0.52729	0.40599	
650	0.8076	0.74439	0.755494	0.74410	0.74277	0.71435	0.67684	0.67615	0.5331	0.41227	
660	0.81336	0.75305	0.7611	0.7497	0.74754	0.71886	0.68125	0.68015	0.53859	0.41822	
670	0.81758	0.76049	0.76652	0.75459	0.7514	0.72212	0.68527	0.68423	0.5437	0.42399	
680	0.82386	0.76840	0.77104	0.75932	0.75563	0.7265	0.68882	0.68723	0.54849	0.42933	
690	0.82942	0.77533	0.77521	0.76330	0.75903	0.72953	0.69160	0.69008	0.55266	0.43432	
700	0.83555	0.78319	0.78008	0.76785	0.76305	0.73303	0.69509	0.69356	0.55749	0.43998	

**Table 27: K/S values and wavelengths of laser treated Kevlar samples:**

Wavelength [nm]	Energy Density [mJ/cm <sup>2</sup> ]										K / S values
	0	2.62	5.16	10.24	12.75	16.97	20.35	25.39	33.85	101.37	
400	5.87991	8.22437	5.965958	6.103385	5.944714	6.173053	6.325278	5.620588	7.249894	7.0181417	K / S values
410	5.333590	6.53177	5.482028	5.545523	5.525043	5.727781	5.895195	5.350131	6.7602955	6.8700444	
420	4.330272	4.30403	4.475121	4.523071	4.522195	4.709692	4.877308	4.527460	5.6980973	6.1032136	
430	3.089867	2.46195	3.219194	3.229252	3.249094	3.373345	3.532417	3.348890	4.2250798	4.7532843	
440	1.871590	1.3856	1.973473	1.972838	1.984108	2.052479	2.173625	2.085897	2.7000534	3.2656933	
450	1.05788	0.83755	1.142831	1.138514	1.142681	1.182159	1.272153	1.228121	1.6946452	2.246119	
460	0.616029	0.55124	0.691229	0.684920	0.679662	0.708506	0.779863	0.752500	1.1414806	1.6703858	
470	0.387113	0.39832	0.457558	0.448528	0.437661	0.460338	0.519818	0.500410	0.843035	1.346536	
480	0.257257	0.30330	0.326155	0.313026	0.298986	0.317926	0.369354	0.353738	0.6627146	1.1396619	
490	0.185450	0.2449	0.254401	0.237724	0.221875	0.238351	0.283502	0.270530	0.5554275	1.0067694	
500	0.142046	0.20460	0.208890	0.190675	0.175125	0.189936	0.230943	0.219610	0.4837971	0.9107072	
510	0.113018	0.17481	0.173046	0.158059	0.144114	0.158450	0.196282	0.186959	0.4337196	0.83851	
520	0.091985	0.15166	0.142357	0.133037	0.121835	0.136748	0.171188	0.164313	0.3955372	0.7800505	
530	0.076176	0.13341	0.117769	0.114073	0.105492	0.120788	0.152794	0.147869	0.3647267	0.7305318	
540	0.065079	0.11911	0.099944	0.100174	0.093571	0.109265	0.139413	0.135719	0.3407527	0.6886472	
550	0.056561	0.10723	0.086823	0.089431	0.084371	0.100114	0.128565	0.125743	0.3200898	0.6518641	
560	0.050234	0.09732	0.077412	0.081300	0.077308	0.092812	0.120020	0.117988	0.302575	0.6196864	
570	0.045195	0.08895	0.070276	0.074870	0.071725	0.086842	0.112891	0.111543	0.2877463	0.5909245	
580	0.041108	0.08149	0.064635	0.069423	0.066935	0.081792	0.106785	0.105838	0.2741102	0.5641237	
590	0.037657	0.07475	0.059793	0.064770	0.062688	0.077244	0.101482	0.100620	0.2616778	0.5386045	
600	0.034425	0.06823	0.055369	0.060240	0.058821	0.072895	0.096239	0.095772	0.2498184	0.5138055	
610	0.031542	0.06238	0.051425	0.056266	0.055201	0.068970	0.09147	0.091225	0.2389999	0.4906217	
620	0.028992	0.05714	0.048078	0.052724	0.052183	0.065596	0.087422	0.087422	0.2293301	0.470664	
630	0.026747	0.05227	0.044850	0.049506	0.049421	0.062517	0.083585	0.083773	0.2203769	0.4519879	
640	0.024689	0.04781	0.042105	0.046522	0.046802	0.059614	0.080200	0.080391	0.2118841	0.4345275	
650	0.022892	0.04388	0.039565	0.044000	0.044537	0.057109	0.077146	0.077553	0.2044465	0.4189188	
660	0.021412	0.04049	0.037480	0.041749	0.042629	0.054972	0.074566	0.075203	0.1976433	0.4046393	
670	0.020267	0.03756	0.035548	0.039760	0.040957	0.053098	0.072329	0.072953	0.1914057	0.3913323	
680	0.018826	0.03490	0.033394	0.038142	0.039513	0.051473	0.070283	0.071173	0.1858301	0.3792643	
690	0.017540	0.03255	0.032588	0.036700	0.038249	0.050137	0.068759	0.069591	0.1810442	0.3683668	
700	0.016183	0.03000	0.030998	0.035090	0.036788	0.048613	0.066871	0.067694	0.175619	0.3563957	



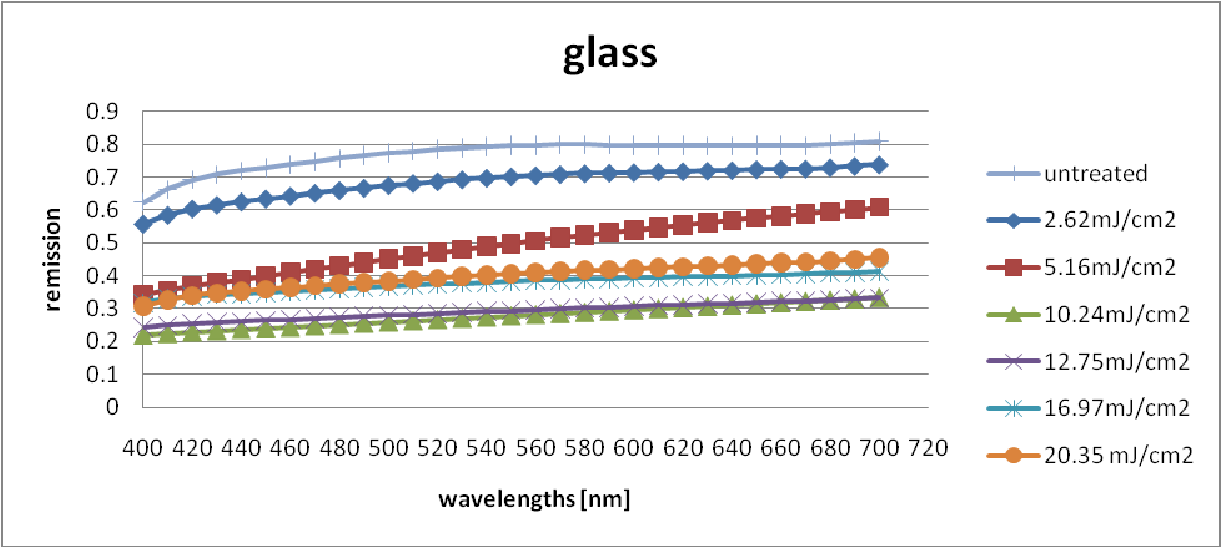


Figure 50: Graph of glass fabric, remission values vs. wavelength.

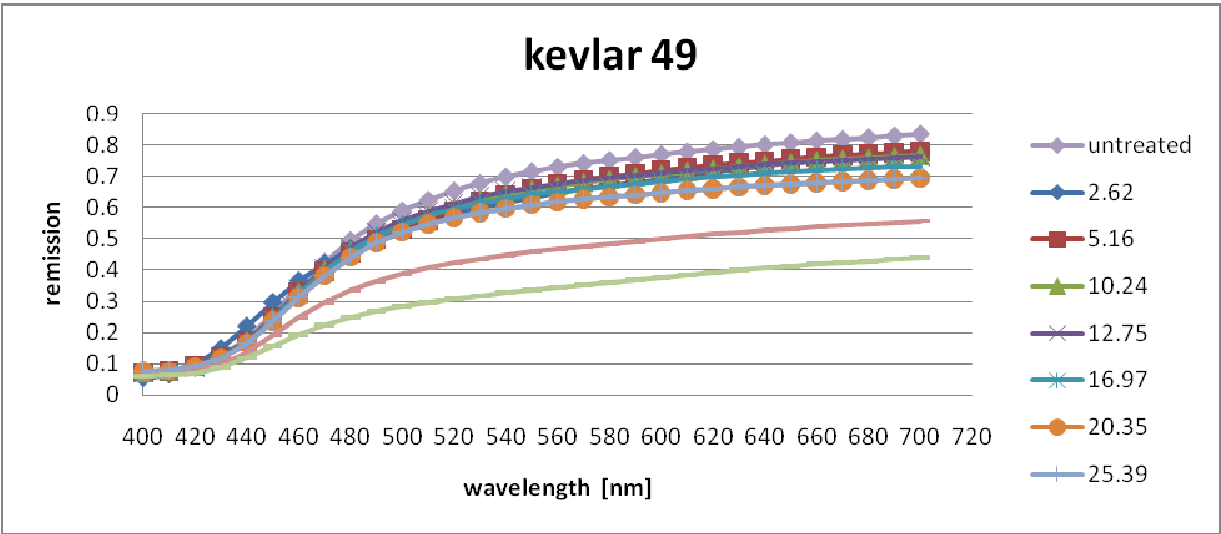


Figure 51: Graph of Kevlar 49, remission values vs. wavelength.

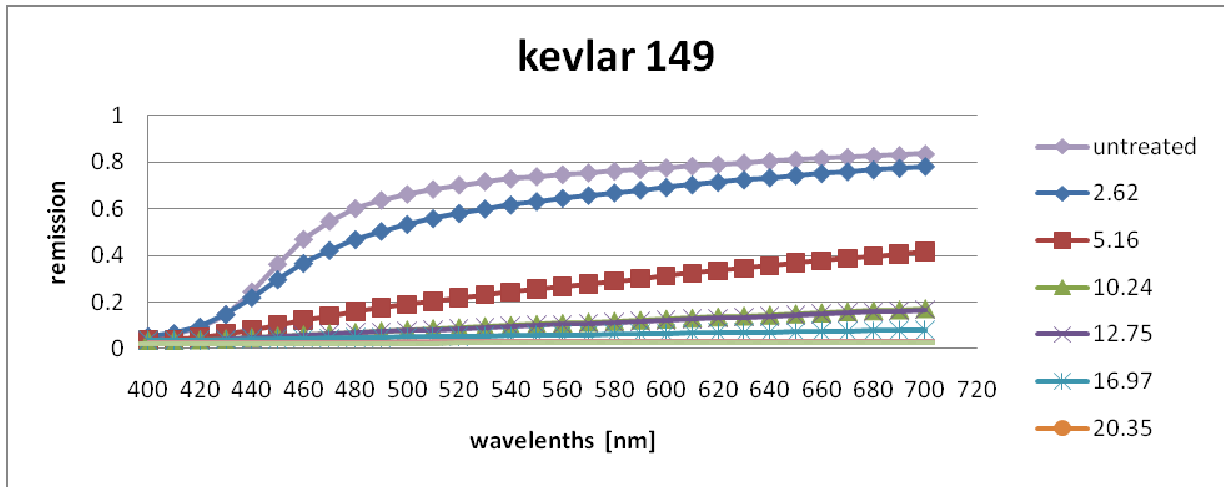


Figure 52: graph of Kevlar 149, remission values vs. wavelength.

#### 8.4 Appendix D: Test for mechanical properties:

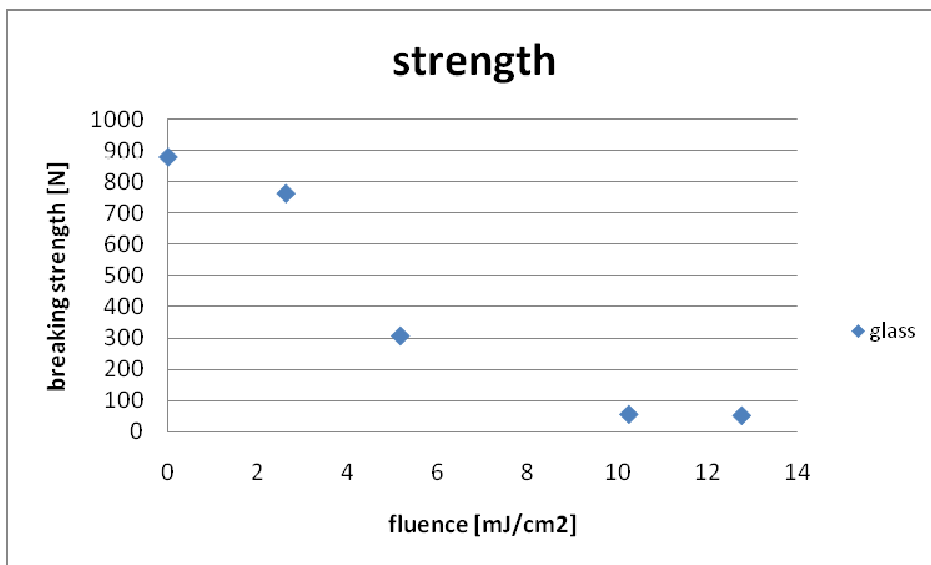


Figure 53: Strength of glass vs. Fluence (energy density).

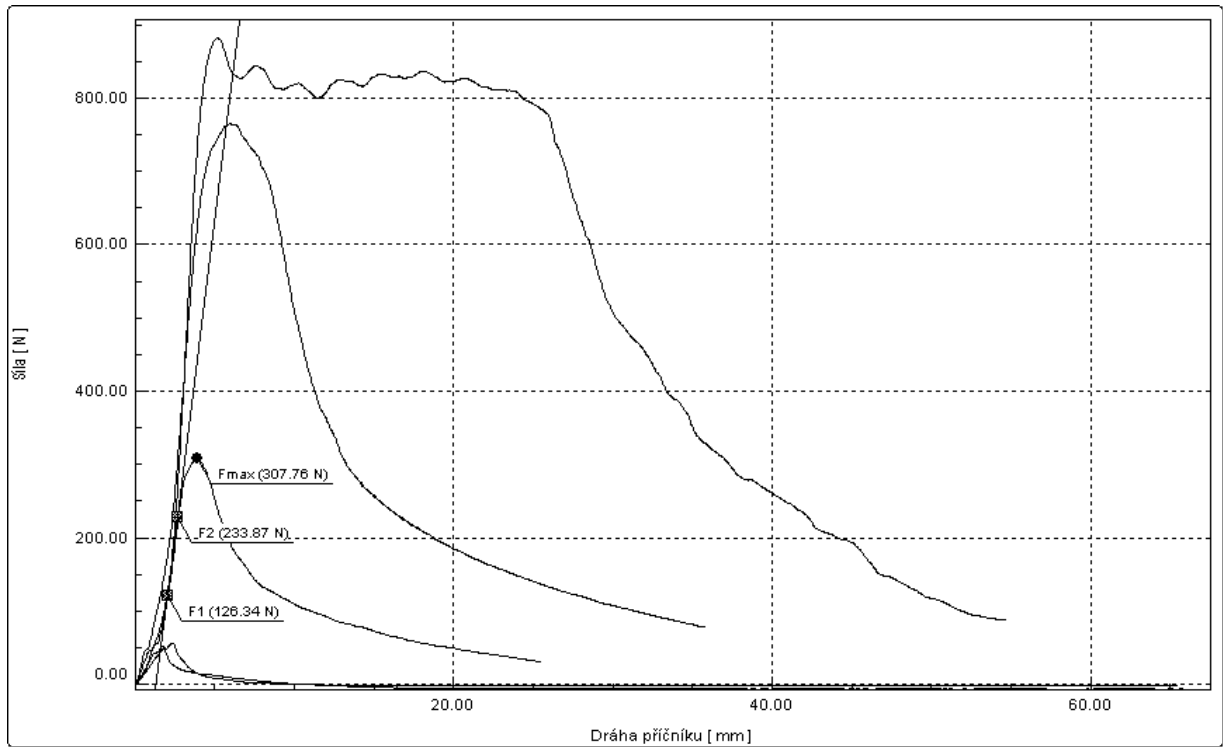


Figure 54: mechanical properties of irradiated glass fabrics.

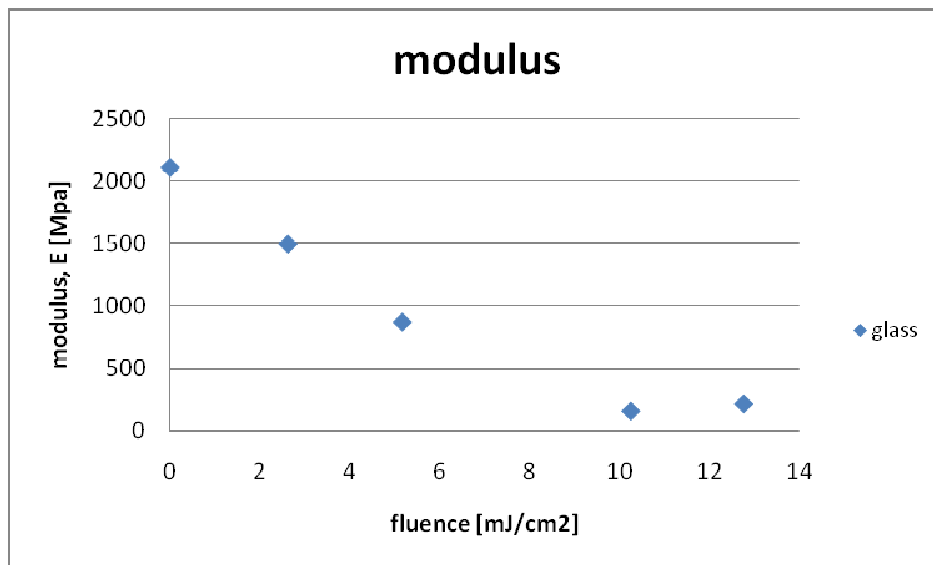


Figure 55: Glass irradiated samples modulus vs. Fluence.

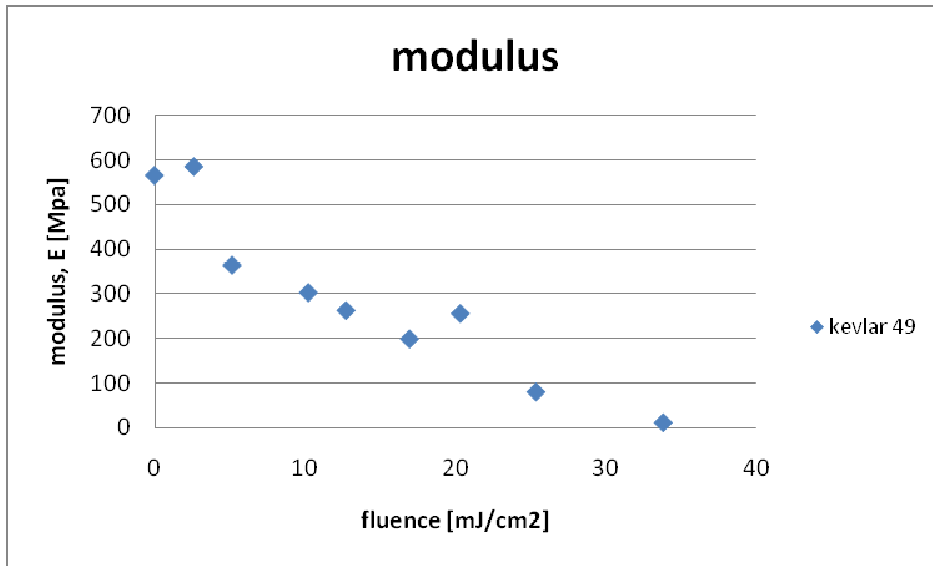


Figure 56: Graph of modulus of Kevlar 49 vs. fluence.

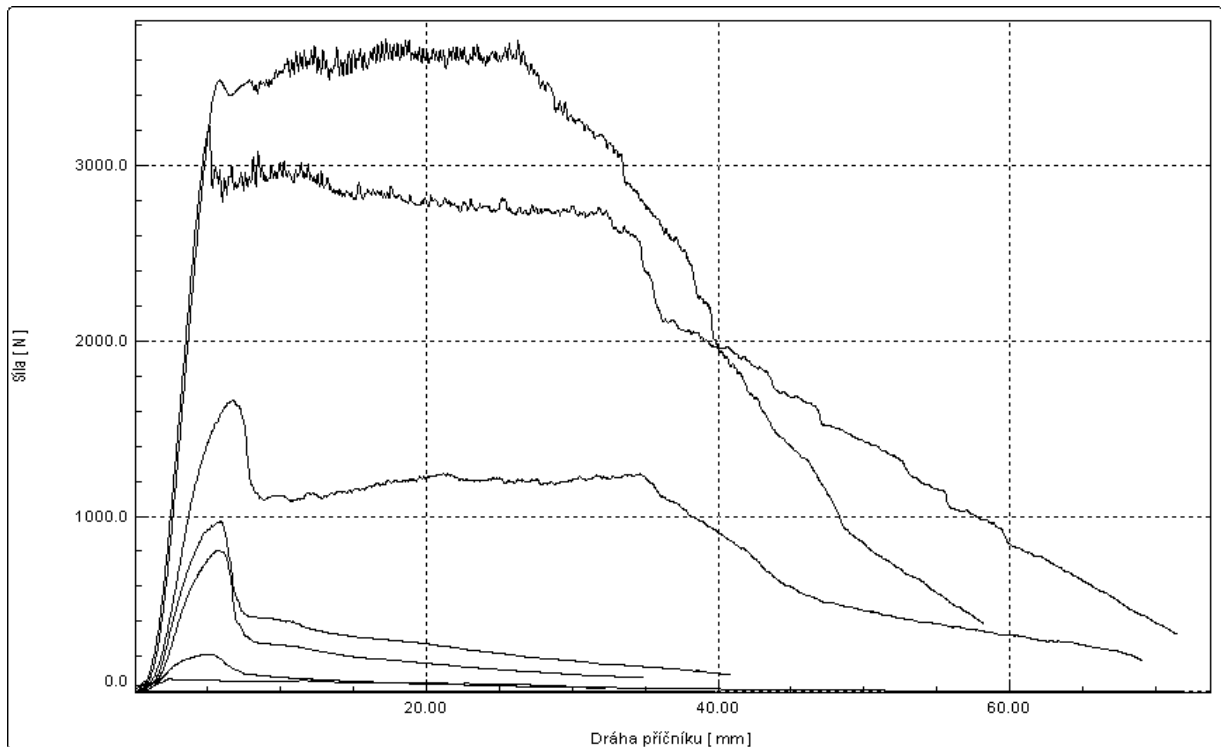


Figure 57: Graph of kevlar 49 mechanical properties after laser irradiation.

### 8.5 Appendix E: Absorbency test:

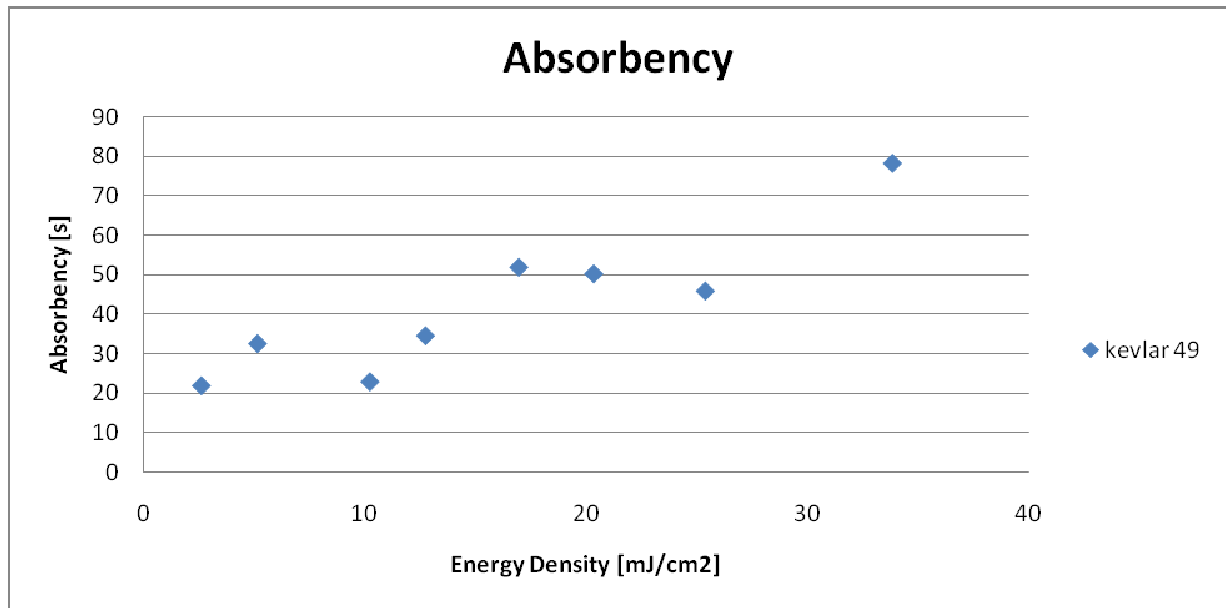


Figure 58: absorbency of un-cleaned Kevlar 49 vs. energy density.

## 8.6 Appendix F: Infrared spectrum

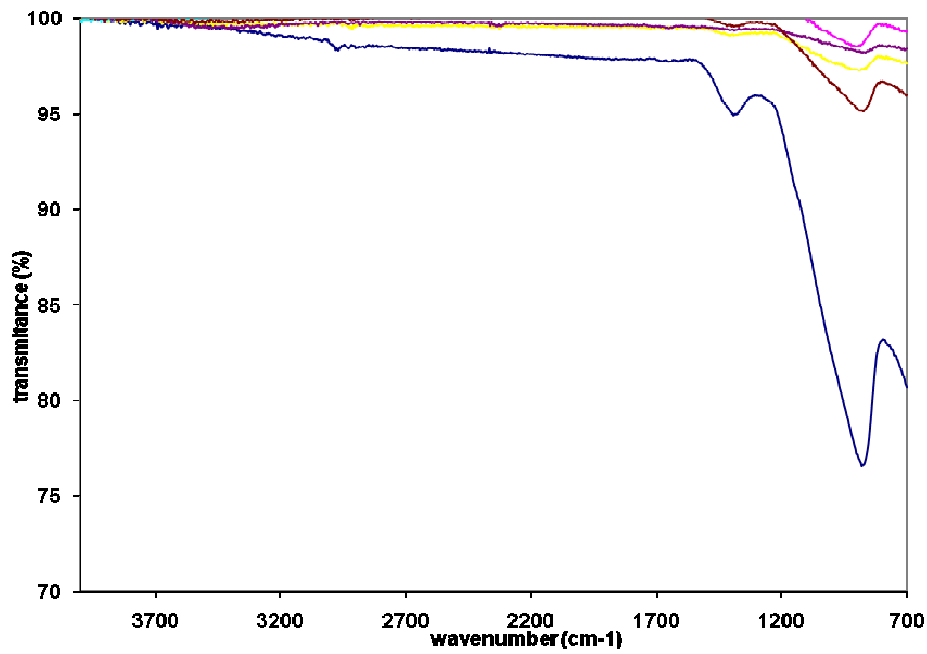


Figure 59: Infrared spectrum of glass fibre.

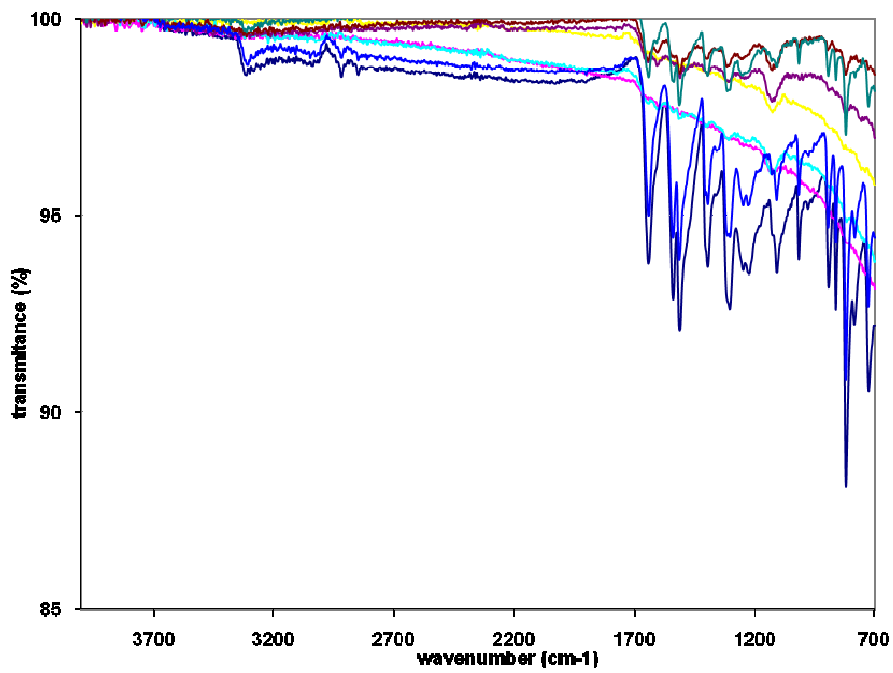


Figure 60: Infrared spectrum of Kevlar 149.