INVESTIGATION OF ENVIRONMENTAL DURABILITY OF CARBON FIBER/EPOXY COMPOSITES

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ABSTRACT

INVESTIGATION OF ENVIRONMENTAL DURABILITY OF CARBON FIBER/EPOXY COMPOSITES

Fiber reinforced polymer composites, that have increasing demand in many applications such as aircraft and automotive industry, are usually exposed to different environmental conditions which may be harmful to them. The investigation of their environmental durability is critical for those applications.

The objective of this study was to investigate the effects of temperature and moisture on durability of carbon fiber reinforced epoxy composites. For this purpose, 0/90° woven, plain unidirectional and non-crimp biaxial ±45 fabrics were used as reinforcement. The specimens were manufactured using vacuum resin infusion process to obtain relatively high fibre volume fraction ratios. The composites manufactured were exposed to cyclic aging conditions to simulate aircraft flight environment. Hygrothermal, high temperature and freezing conditions were used as in one cycle which was 12 hours long. Moisture absorption was determined by weighing the specimens at regular intervals as a function of aging cycles. Tensile and flexural tests were performed prior to aging and after 500, 1000 and 1500 hours aging. After the completion of aging cycles, the moisture content did not increase significantly due to presence of subzero and high temperatures in aging cycles. The mechanical test results revealed differences based on the fabric types used. It was found that the tensile strength and modulus values of woven composites increased after aging cycles as compared to those of unidirectional and biaxial composites. On the other hand, flexural properties decreased at the end of the aging cycles for the composites aged as test coupons.

ÖZET

KARBON FİBER EPOKSİ KOMPOZİTLERİN ÇEVRESEL ETKİLERE KARŞI DAYANIMININ İNCELENMESİ

Havacılık ve otomotiv sanayi gibi bir çok uygulamada kullanımı artan elyaf takviyeli kompozit malzemeler kendileri için zararlı olabilecek farklı çevresel etkilere maruz kalırlar ve bu etkilere karşı dayanımlarının araştırılması önemlidir.

Bu çalışmanın amacı; sıcaklık ve nemin karbon elyaf takviyeli epoksi kompozitlerin dayanımı üzerindeki etkisini araştırmakdır. Bu amaçla takviye malzemesi olarak 0/90° örgülü, tekyönlü ve iki eksenli ±45 elyaflar kullanılmıştır. Numuneler yüksek elyaf hacim oranı elde etmek için göreceli olarak etkili bir üretim tekniği olan vakum reçine infüzyonu ile üretilmiştir. Üretilen karbon elyaf / epoksi kompozitler uçak uçuş koşullarını simule etmek için çevrimsel yaşlandırma koşullarına maruz bırakılmıştır. 12 saat süren bir çevrim olarak içinde nem ve ısının bir arada olduğu, yüksek sıcaklık ve donma koşulları kullanılmıştır. Nem soğurma özelliklerinin incelenmesi için numunelerin ağırlıkları belirli aralıklarla ölçülmüştür. Çekme ve eğme testleri yaşlandırmadan önce ve 500, 1000, 1500 saat yaşlandırmadan sonra yapılmıştır. Kullanılan yaşlandırma çevriminde bulunan sıfırın altında ve yüksek sıcaklık koşullarının varlığı yaşlandırma sonunda malzemede nem miktarının belirgin bir şekilde artış göstermemesine neden olduğu gözlenmiştir. Mekanik test sonuçları ise kullanılan elyaf çeşidine göre farklılıkların olduğunu göstermiştir. Tek yönlü ve çift eksenli kompozitlerin çekme mukavemeti ile elastik modül değerleri azalırken dokuma kompozitlerin çekme mukavemeti ve elastik modül değerleri artış göstermiştir. Diğer bir tarafdan, eğme özellikleri yaşlandırma çevrimi sonunda test numunesi olarak yaşlandırılan kompozitlerde azalma göstermiştir.

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CHAPTER 1

INTRODUCTION

Fiber reinforced polymer matrix composites are increasingly being used in aerospace industry due to their high specific (property/density) strength, stiffness and corrosion resistance over conventional materials (Baker et al. 2004). Beside their superior mechanical properties, the main reason to use composite materials for aircrafts is to reduce the weight and so fuel consumption, and increase their performance.

Parts manufactured from titanium, steel, aluminum and nickel based materials are considerably heavy compared to polymeric composites. In 1970s, when carbon fibers were introduced, carbon fiber epoxy matrix composites have become the primary material in many wing, fuselage, and empennage components. For example, the airframe of AV-8B™, a vertical and short take-off and landing (VSTOL) aircraft introduced in 1982, contains nearly 25% by weight of carbon fiber reinforced epoxy. Also, Airbus™ used many composites in their A310 in 1987, components such as lower access panels and top panles of the wing leading edge, outer deflector doors, nose wheel doors, main wheel leg fairing doors, engine cowling panels, elevators and fin box weighed about 10% of the aircraft's weight (Mallick 2007). As an example, Boeing™ 777 which was introduced in 1995, has 11% of composites by weight and Boeing™ 787 has 50% of composites by weight (Wang, Zheng and Y.Zheng 2011, Tenney, D.R. et al. 2009). The use of carbon fiber reinforced and other composites offer weight savings up to 20 percent when compared to conventional metallic designs. Most recently, the aircraft called " Dreamliner " of Boeing™ used whole body as composites as shown in Figure 1.1.

Despite the advantages and increasing use of composites in aircrafts, the durability of polymer composites is affected by temperature, moisture, ultraviolet radiation, exposure to jet fuel and hydraulic fluid in service conditions. These environmental factors may cause degradation in the mechanical and physical properties of a fiber reinforced polymer composite. For this reason, it is important to predict maximum lifetime of polymeric composites under aircraft service environment (Chung, Seferis and Nam 2000).

Many studies have focused on the effects of temperature and moisture in service conditions, which may cause an irreversible damage for material. Usually, hygrothermal cycles can cause degradation of fiber reinforced polymer matrix composites. During flight and service conditions, temperatures can be -55°C and 80°C and these temperatures can effect the lifetime of composites used in aircrafts (Reynolds 1998).

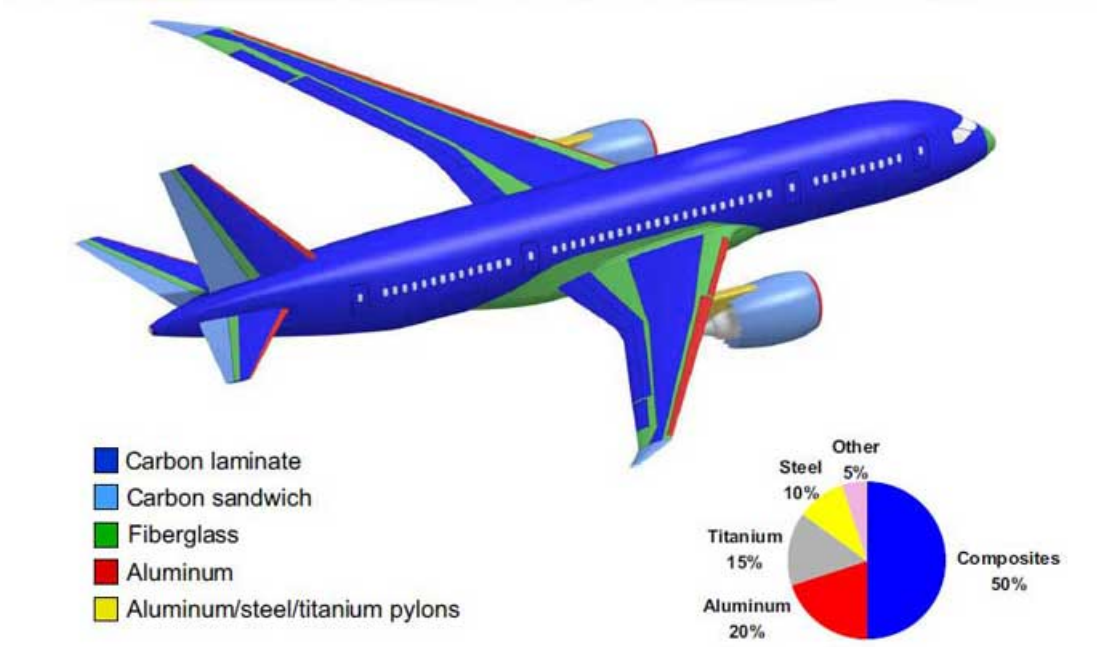


Figure 1.1. Materials used in the construction of the Boeing™ 787 Dreamliner (Source: Freissinet 2011)

Several studies showed that polymer matrix composites absorb moisture when they are exposed to humid environment. Moisture diffusion into the epoxy matrix leads to plasticization and hydrolysis of matrix, which cause both reversible and irreversible changes in polymer composites. (Kumar Singh and Nakamura 2002).

Accelerated cyclic tests were carried out to simulate the service conditions. Jedidi et al. investigated the effects of hygrothermal fatigue associated with the accelerated cycles for different stacking sequence specimens. Tensile test results showed that elastic modulus values for quasi-isotropic and biaxial ±45 laminates were decreased (Jedidi, Jacquemin and Vautrin 2006).

In this thesis study, carbon fiber reinforced epoxy composites were manufactured and they were cyclically aged to simulate aircraft service conditions. The aim of this study was to investigate the effects of temperature and moisture on the

durability of carbon fiber reinforced epoxy composites. To investigate these effects on durability, mechanical, physical and thermal tests were conducted prior to and after aging cycles.

CHAPTER 2

ENVIRONMENTAL DURABILITY OF FIBER REINFORCED POLYMER MATRIX COMPOSITES

The increasing use of polymer matrix composites for various applications requires the response to different environmental exposure. Temperature, humidity and chemical attacks are main environmental degradation factors which affect the durability. The mechanical, thermal and chemical properties of fiber reinforced polymer matrix composites change during environmental exposure (Springer 1988). Especially, the combined effects of elevated temperature and high moisture content reduce the stiffness and strength of many polymer matrix composites. Significant research was made to study these hygrothermal effects (Adams 2012).

Since the materials for aircraft structures are exposed to high and low temperatures, moisture and a spectrum of mechanical stresses over the entire design lifetime of 20,000 flight cycles (Reynolds 1998). Therefore, the effects of environmental factors should be carefully investigated.

2.1. Environmental Factors

2.1.1. Temperature

Fiber reinforced polymer matrix composites used for aircraft structures are exposed to different temperatures in flight and ground conditions. These temperatures may be low as -55°C and high as 130°C during service (Jedidi, Jacquemin and Vautrin 2005). Exposures to low and/or elevated temperatures can decrease the mechanical properties of composites, such as compression strength, ultimate tensile strength, and ±45 tensile strength (Mei Li 2000).

The behavior of composite materials is usually sensitive to changes in temperature. There are two main reasons of this behavior. Firstly, the response of the matrix to an applied load is temperature dependent, and secondly changes in temperature can cause internal stresses due to differential thermal contraction and

expansion of two constituents (Hull and Clyne 1996). As an example, the large difference between the coefficient of thermal expansion (CTE), carbon fibers (typically around -0.6 x 10^{-6}°C^{-1} in the longitudinal direction) and the polymer matrix (typically ranging from 81 x 10^{-6} to 117 x 10^{-6}°C^{-1} for epoxy) results in change in the amount of these internal stresses. The thermal stress is much significant when the fibers in different directions in laminae. This can cause thermal fatigue if a large number of temperature cylces have been encountered. And the damage usually occurs at the fiber matrix interface (Wang and Chung 2000).

Extensive studies have been conducted to investigate the effects of temperature on the behavior of polymer matrix composites. Lafarie-Frenot et al. investigated the effects of isothermal aging and thermal cycling at temperatures between -50 and 180°C on carbon/epoxy laminates. Hodgkin et al. revealed the effects of long term thermal aging of epoxy composites at temperatures of 70°, 120°, 170° and 200°C (in air). The results showed that the effects of isothermal aging is significant with increasing temperature. Many types of damages, such as retention in mechanical properties, matrix cracking and shrinkage, weight loss were observed as a result of temperature aging in theses studies (Lafarie-Frenot et al. 2006, Hodgkin et al. 2006). Furthermore, elevated temperatures can initiate the chemical degradation process. The rate of kinetic reaction increases with respect to increasing temperature. A higher temperature causes a higher reaction rate. For example, increasing the temperature from 60 to 70°C will cause an increase in chemical reaction rate more than those from 30 to 40°C (Jelle 2012). This can be explained by the Arrhenius equation which is given in Equation 2.1 (Dixon 1980).

$$\frac{dR}{dt} = A\exp\left(-E/kT\right) \tag{2.1}$$

In this equation, *dR/dt* is the reduction in property with respect to time, A is the constant, k is the gas constant or, depending on the units, the Boltzmann constant, T is absolute temperature, and E is the activation energy of the reaction.

The subzero temperatures and freeze thaw exposure may effect the fiber reinforced polymer matrix composites which results in changes in thermomechanical response. Matrix hardening and stiffening, formation of cryogenic microcracks parallel

to fibers and at the fiber matrix interphase may be the results of the effect of these low temperatures (Ray 2005).

Temperature has more detrimental effect when combined with moisture. Hygrothermal effects may significantly weaken the material's constituents. It is more significant in the case of glass fiber reinforced composites due to moisture sensitive properties of glass fibers (Chateauminois 1998). Miller et al. studied the hygrothermal aging characteristics of an epoxy resin which included temperature and moisture cycles. It has been reported that hygrothermal aging affects the properties of epoxy resin resulting color change, increase in brittleness, reduction in ductility and embrittlement (Miller et al. 2012).

2.1.2. Moisture

Moisture has an adverse effect on long term structural durability. It has been observed in many studies that polymeric matrix materials used in fiber reinforced composites absorb moisture from high humidity environments. Especially fiber/matrix interface may be damaged resulting reduction of the mechanical and physical behavior of composite such as swelling, degradation of mechanical properties, and lowering of glass transition temperature (T_g) (Hu and Sun 2003, Meziere et al. 2005). The effect of moisture on composites can be within the matrix, on the fiber or at the fiber matrix interface (Jungkuist 2000). Figure 2.1 shows the effects of moisture on composites.

Considering carbon fiber reinforced epoxy composites; the epoxy matrix absorbs greater amount of moisture than those of the fibers. Moisture absorption can act as a plasticizer and results hydrolysis of the epoxy matrix which changes the mechanical properties and chemical composition of the matrix (Chhibber 2006). Although epoxy matrix is very sensitive to moisture, carbon fibers do not absorb moisture, and they remain unaffected. However, the deterioration of the matrix is quite enough to cause a decrease in performance and durability (Dongxing Zhang et al. 2012).

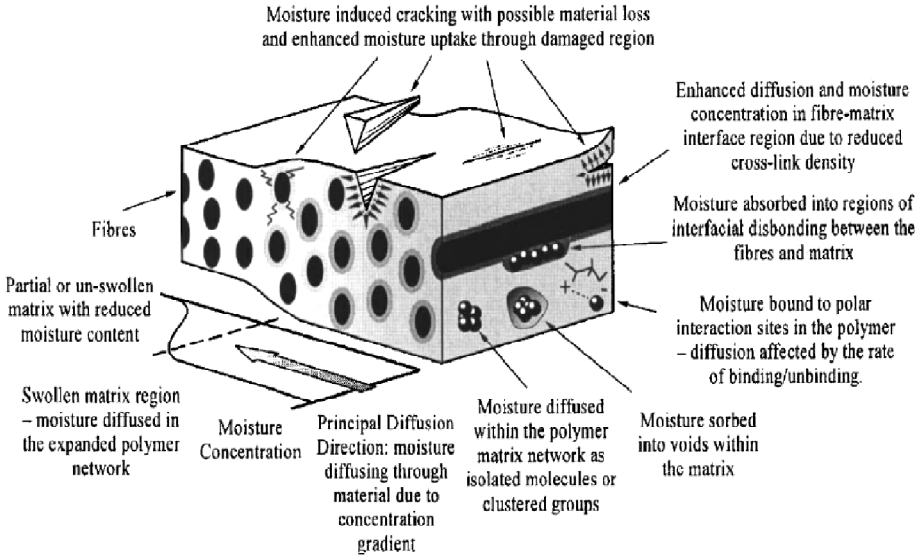


Figure 2.1. The different effects of moisture on polymer matrix composites (Source: Bond and Smith 2006)

2.1.2.1. Moisture Diffusion

Fick's law is generally assumed as the physical mechanism for moisture gain in composite materials. The driving force for moisture absorption is the gradient of moisture concentration (Naceri 2009). Moisture diffusion in polymer matrix composites follows Fick's second law (Adams 2012).

To estimate the moisture concentration in a polymer matrix, Equations 2.2 to 2.5 can be used (Mallick 2007). The moisture concentration M of a composite laminate at any time during its exposure to humid environment at a given temperature can be calculated from following equation:

$$M = M_i + G\left(M_m - M_i\right) \tag{2.2}$$

In this equation, M_i is the initial moisture concentration. Equilibrium moisture concentration in the saturated condition is given by M_m and G is expressed with time dependent dimensionless parameter related to the diffusion coefficient of the material. For the humid environment M_m is given as in Equation 2.3 where RH is the relative

humidity (%) of the surrounding air. A and B are constants that depend on the type of polymer.

$$M_m = A(RH)^B \tag{2.3}$$

Assuming a Fickian diffusion through the laminate thickness, the time dependent parameter *G* can be approximated as in Equation 2.4.

$$G \approx 1 - \frac{8}{\pi^2} \exp\left(-\frac{\pi^2 D_z t}{c^2}\right) \tag{2.4}$$

D_z is expressed as diffusion coefficient (mm^2/s) of the material in the direction normal to the surface. Laminate thickness h if both sides of the laminates are exposed to humid environment is shown by *c*. Time (s) is shown by *t*.

The diffusion coefficient D_z is related to the matrix diffusion coefficient D_m by the Equation 2.5 where ϕ is fiber angle with z direction and v_f is volume fraction.

$$D_z = D_{11}\cos^2\phi + D_{22}\sin^2\phi \tag{2.5}$$
$$D_{11} = D_m(1 - v_f)$$
$$D_{12} = D_m\left(1 - 2\sqrt{\frac{v_f}{\pi}}\right)$$

In addition; void content, fiber type, resin type, temperature, stress level, microcracks, thermal spikes and reverse thermal effect may cause deviations from the calculated moisture concentrations (Mallick 2007).

2.1.2.2. Moisture Absorption

When a body absorbs water, as it is the case for resins in polymeric matrix composites, it expands. The change in dimensions of the body are measured by the coefficient of moisture expansion defined as the change in the linear dimension of a body per unit length per unit change in weight of moisture content per unit weight of the

body. There are two coefficients of moisture expansion: one in the longitudinal direction 1 and the other in the transverse direction 2. In most polymeric matrix composites, fibers do not absorb or desorb moisture. The following are the expressions for the two coefficients of moisture expansion.

$$\beta_1 = \frac{E_m}{E_1}\frac{\rho_c}{\rho_m}\beta_m \tag{2.6}$$

$$\beta_2 = (1+v_m)\frac{\rho_c}{\rho_m}\beta_m - \beta_1 v_{12} \tag{2.7}$$

$\beta_1 = linear\ coefficient\ of\ moisture\ expansion\ in\ direction\ 1,\ m/m/kg/kg$

$\beta_2 = linear\ coefficient\ of\ moisture\ expansion\ in\ direction\ 2,\ m/m/kg/kg$

Further simplifications for composites such as graphite/epoxy with high fiber to matrix moduli ratio (E_f/E_m) and no moisture absorption by fibers lead to Equations 2.8 and 2.9 (Autar K. Kaw 2006).

$$\beta_1 = 0, \text{ and} \tag{2.8}$$

$$\beta_2 = (1+v_m)\frac{\rho_c}{\rho_m}\beta_m \tag{2.9}$$

2.2. Polymer Matrix Composites

The use of polymer matrix composites in various engineering applications has become very important in recent years. Most of commercially produced composites use polymer matrix material. Polyester, vinyl ester, epoxy, phenolic, polyimide, polyamide, polypropylene, poylether ether ketone (PEEK) are known as the most common matrix materials. (T.Sabu et al. 2012).

Polymer matrix composite materials consist of organic polymers as matrix and fibers as reinforcement. Strength and modulus of fiber are much higher than the matrix material. Table 2.1 shows the mechanical properties of reinforcement fibers. For this reason, fibers bear the load of the composite. But, also the matrix materials should have

good adhesion properties to bond fibers together. The performance of fiber, matrix and interface between them determines the performance of composites materials (Wang, Zheng and Y. Zheng 2011).

Table 2.1. Mechanical Properties of reinforcement fibers
(Source: Campbell 2003)

Fiber	*Density* lb/in^3	*Tensile Strength (ksi)*	*Elastic Modulus (msi)*	*Strain to Failure (%)*	*Diameter (Mils)*	*Thermal Expansion Coefficient 10-6 in/in/ F*
E-glass	0.090	500	11.0	4.8	0.36	2.8
S-glass	0.092	650	12.6	5.6	0.36	1.3
Quartz	0.079	490	10.0	5.0	0.35	1.0
Aramid (Kelvar 49)	0.052	550	19.0	2.8	0.47	–1.1
Spectra 1000	0.035	450	25.0	0.7	1.00	–1.0
Carbon (AS4)	0.065	530	33.0	1.5	0.32	–0.2
Carbon (IM-7)	0.064	730	41.0	1.8	0.20	–0.2
Graphite (P-100)	0.078	350	107	0.3	0.43	–0.3
Boron	0.093	520	58.0	0.9	4.00	2.5

The matrix transfers load into and out from fibers, separates the fibers to prevent failure of adjacent fibers one fails, protects the fibers from environmental damage and supports the fibers in the shape of the component (Baker, Dutton and Kelly 2004).

There are two main type resin systems to manufacture advanced polymer composites; thermoplastic and thermosetting. Thermoset resins usually consist of a resin and curing agent. They are mixed together and form a hard rigid solid by chemical cross-linking. And this leads to the formation of tightly bound three dimensional network. The most commonly used thermoset resins are epoxy, unsaturated polyester and vinly ester (Hull and Clyne 1996).

The curing reaction of thermoset resins are given in Figure 2.2. Thermoplastic resins start as fully reacted and they do not crosslink on heating. So, they can be reprocessed many times.

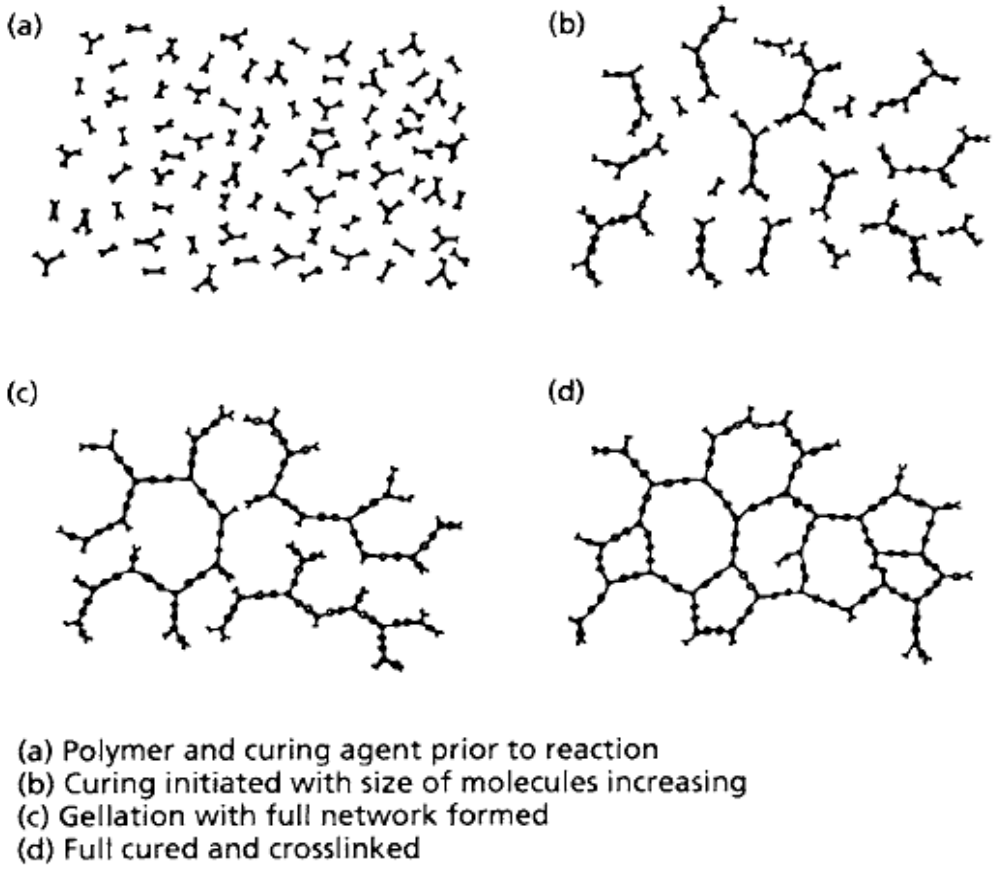


Figure 2.2. Crosslinking reaction of a thermoset resin
(Source: Baker, Dutton and Kelly 2004)

The service temperature in various applications for the parts should be considered in selecting a resin system. Glass transition temperature (T_g) at which a polymer changes from a rigid glassy solid into a softer and semi flexible material is also an important parameter for selecting resin system. The resin also have an environmental performance such as resistant to chemicals, temperature and humidity (Baker, Dutton and Kelly 2004).

Another constituents of composites are fibers which usually dominate the mechanical properties of the composites. Glass, carbon, boron and aramid fibers are mainly used in fiber reinforced polymer matrix composites. Glass fibers are most commonly used due to their good strength to low cost ratio (Campbell 2003). However, carbon fibers are mainly used for the applications require high strength and high modulus such as in aerospace industry. Aramid fibers are the first organic fibers and their major advantage is their ability to absorb large amount of energy during fracture (Baker, Dutton and Kelly 2004). They have high tensile strength and modulus, good

thermal resistance, good anti radiation and low specific density (Wang, Chen and Q.Wang 2013).

2.2.1. Epoxy Resins

Epoxy resins are polyether resins and they contain more than one epoxy group which can be converted into thermoset form. They are formed by the reaction of active hydrogen containing compounds with epichlorohydrin followed by dehydro halogenation (Bhatnagar 1996).

Epoxy resin has strong bonding properties with the fibers, high mechanical strength, low shrinkage, excellent dielectric properties and good chemical corrosion resistance. They are very tolerant of alkalinity and can be used at elevated temperatures. The glass transition temperature (T_g) of epoxy resins increases with increasing temperature of cure which allows higher service temperature. However glass transition temperature is reduced by absorbed moisture (Baker, Dutton and Kelly 2004). Typical properties of cast epoxy resin at 23°C are given in Table 2.2.

Table 2.2. Typical Properties of cast epoxy resin at 23°C
(Source: Mallick 2007)

Density (g/cm^3)	1.2 – 1.3
Tensile strength, MPa (psi)	55 – 130 (8,000 – 19,000)
Tensile Modulus, GPa (10^6 psi)	2.75 – 4.10 (0.40 – 0.595)
Poisson's ratio	0.2 – 0.33
Coefficient of thermal expansion, 10^{-6} m/m per °C (10^{-6} in./in. per °F)	50 – 80 (28 – 44)
Cure shrinkage, %	1 - 5

In recent years; epoxy resins and curing agents are greatly developed, and it attracted many composite applications especially in the carbon fiber and boron fiber composite materials (W.Zheng and Y.Zheng 2011). Furthermore, epoxy resins are commonly used as matrix materials for the aerospace industry. General structure of epoxy resin systems used in aerospace industry are shown in Figure 2.3.

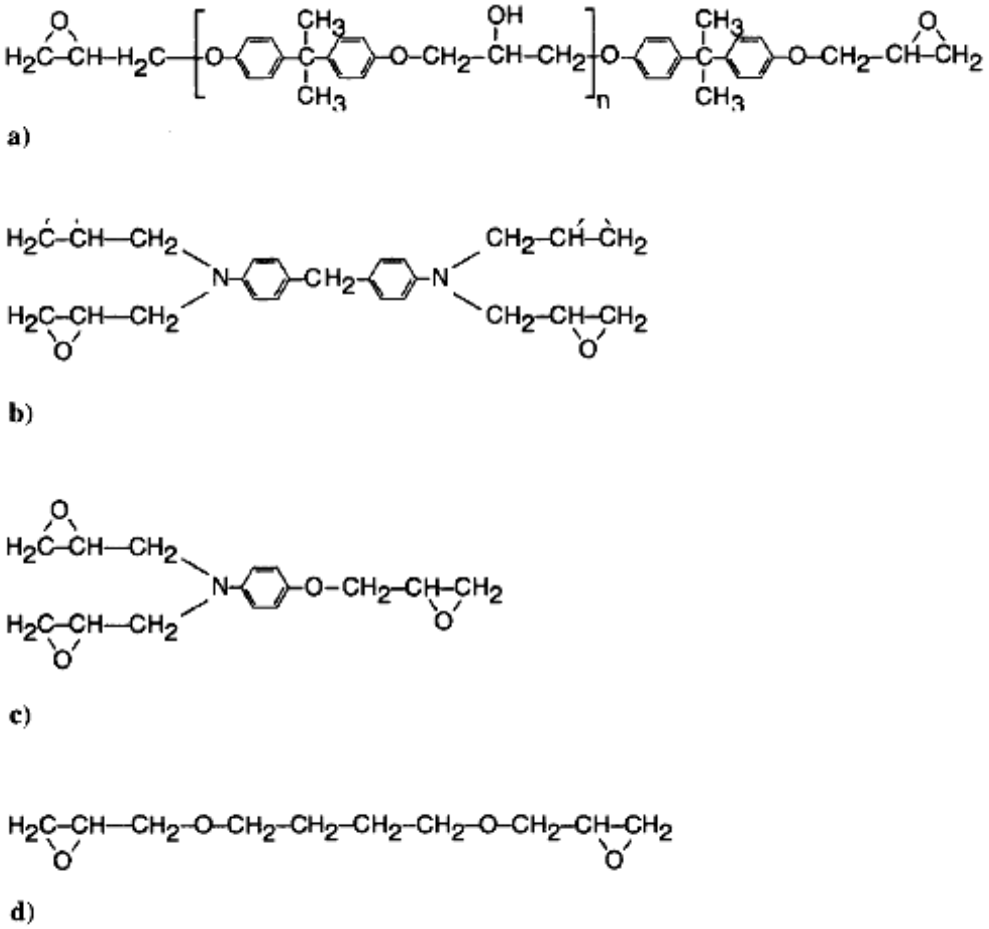


Figure 2.3. General epoxy resins used in aerospace composite matrixes. a) bisphenol A-epichorohydrin (DGEBA) resins; b) tetraglycidyl derivative of diamino diphenyl methane (TGGM); c) triglycidyl derivative of p-aminophenol (TGAP); d) reactive diluents epoxy resin such as the bis epoxy from butane diol (Source: Baker, Dutton and Kelly 2004)

2.2.2. Carbon Fibers

Carbon fibers are utilized in many application areas due to their excellent properties in composite manufacturing industry. Mainly, they are used for the production of secondary aircraft structures, high pressure gas storage, automotive parts, sports goods and so on. Carbon fibers have strength between 3-7 GPa, modulus 200-500 GPa, compressive strength 1-3 GPa, shear modulus 10-15 GPa, and low density 1.75-2.00 g/cm^3 (Kumar and Minus 2005). Carbon fibers have the best combination of properties, however they are more expensive than glass and aramid fibers.

Structurally, carbon fibers contain a blend of amorphous carbon and graphitic carbon. Their high tensile modulus results from graphitic form, in which carbon atoms are arranged in a crystallographic structure of parallel planes or layes. Figure 2.4 shows the arrangement of carbon atoms in a graphite crystal. Strong covalent bonds exist between the carbon atoms in each plane, but the bond between the planes is due to van der Waals type forces, which is much weaker. This results in highly anisotropic physical and mechanical properties for the carbon fiber (Mallick 2007).

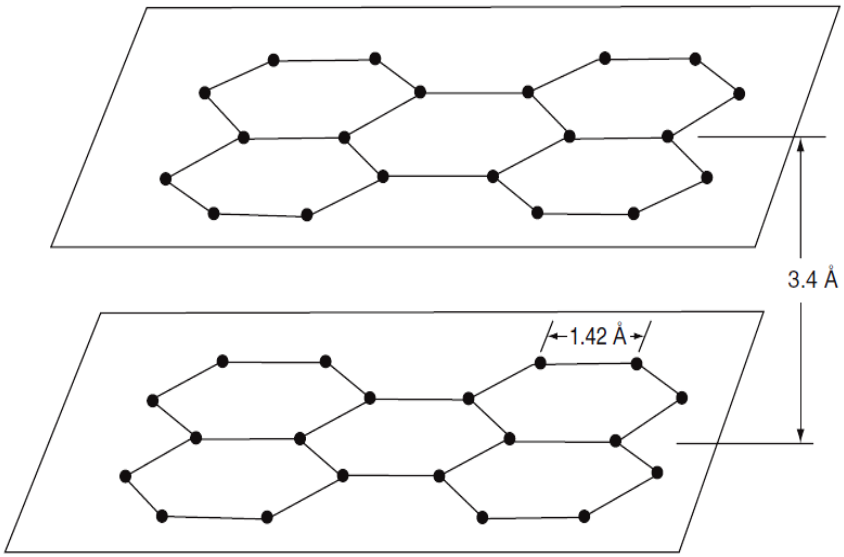


Figure 2.4. Arrangement of carbon atoms in a graphite crystal

Generally carbon fibers are classified into three categories acoording to type of precursors and production method. Carbon fibers are produced from rayon, PAN (polyacrylonitrile), or petroleum based pitch. Commonly, carbon fibers used in aerospace applications are made from polyacrylonitrile (PAN) fibers (Baker, Dutton and Kelly 2004).

2.3. Manufacturing Methods

Since the manufacturing techniques have an influence on composite properties, considerable efforts have been made to develop the methods used. Each day fabrication techniques are being developed. There are usually two methods in the preparation technology of polymer composites, one step method and two step method. One step

method is based on mixing and soaking of fiber and resin directly and at the same time cure and mold to get the composites. Two step method is to first mix and wet fiber and resin to form a middle product and then make the composite product from it. Compression molding process can be given as an example of one step method (Wang, Zheng and Ya-Ping Zheng 2011).

There are many commercial manufacturing methods available for polymer matrix composites. Schematic illustration of the fabrication of polymer matrix composites can be seen in Figure 2.5. Injection moulding, compression moulding, pultrusion, filament winding, resin transfer moulding, hand lay-up and vacuum resin infusion can be given as mostly used manufacturing techniques.

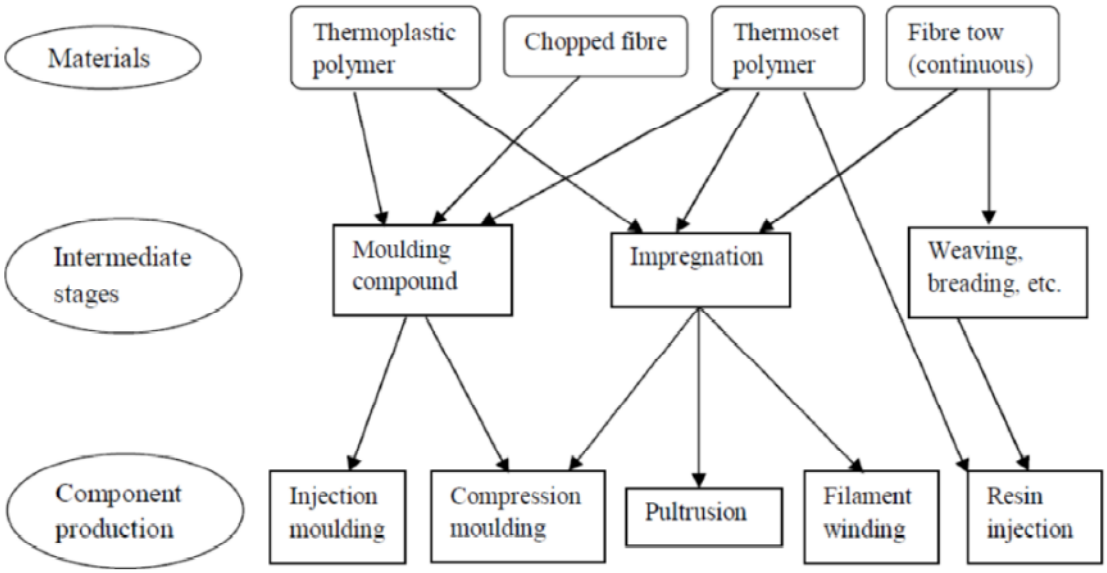


Figure 2.5. Schematic illustration of the fabrication of polymer matrix composites (Source:Hull and Clyne 1996)

2.4. Vacuum Resin Infusion

Vacuum resin infusion is low cost and one of the mostly used composite manufacturing technique. Compared to hand lay-up, it offers lower void content, higher volume fraction, emissions-free work environment etc. (Modi et al. 2008).

The term resin infusion is used to describe which resin is driven into the reinforcement using a vacuum system. There are different acronyms in literature for vacuum infusion. Vacuum Assisted Resin Transfer Moulding (VARTM), Vacuum Assisted Resin Infusion Moulding (VARIM), Seemann Composites Resin Infusion

Moulding Process (SCRIMP^{TM}), Vacuum Bag Resin Transfer Moulding (VBRTM) and Vacuum Assisted Resin Infusion process (VARI) are the most common terms to describe vacuum infusion process (A.Goren and C.Atas 2008). Following illustriations in Figures 2.6 and 2.7 show the typical vacuum resin infusion setup and stages.

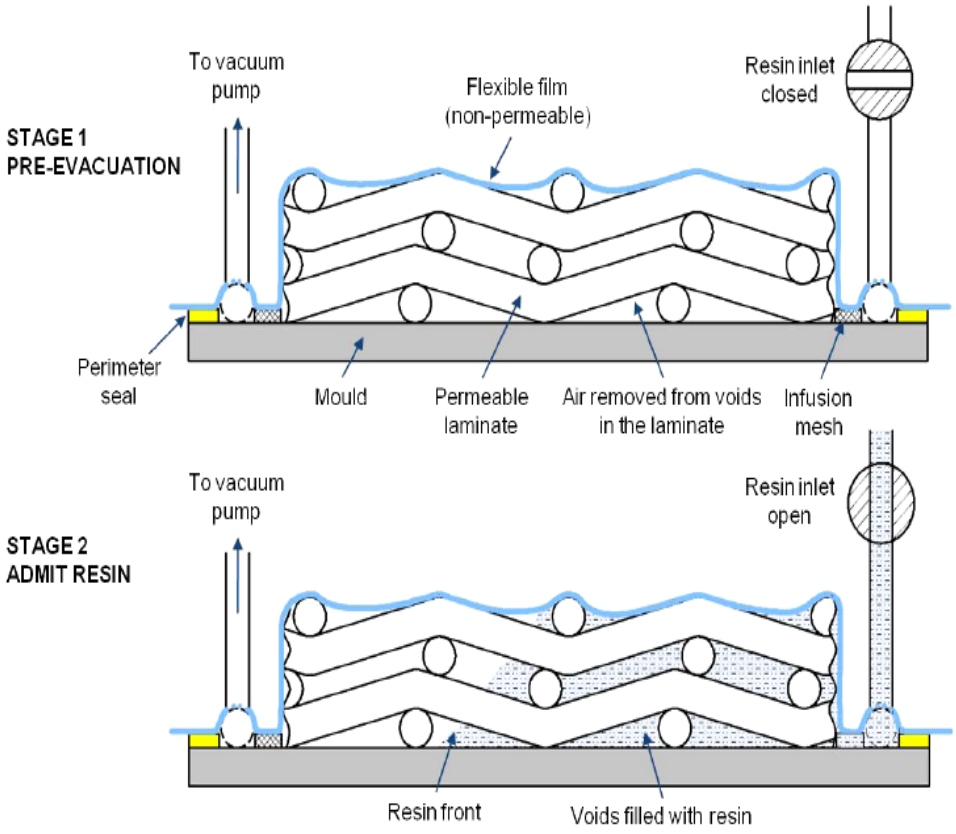


Figure 2.6. Vacuum Resin Infusion Process Stages - Pre-evacuation and Infusing of Resin (Source: Vacmobiles.com Limited)

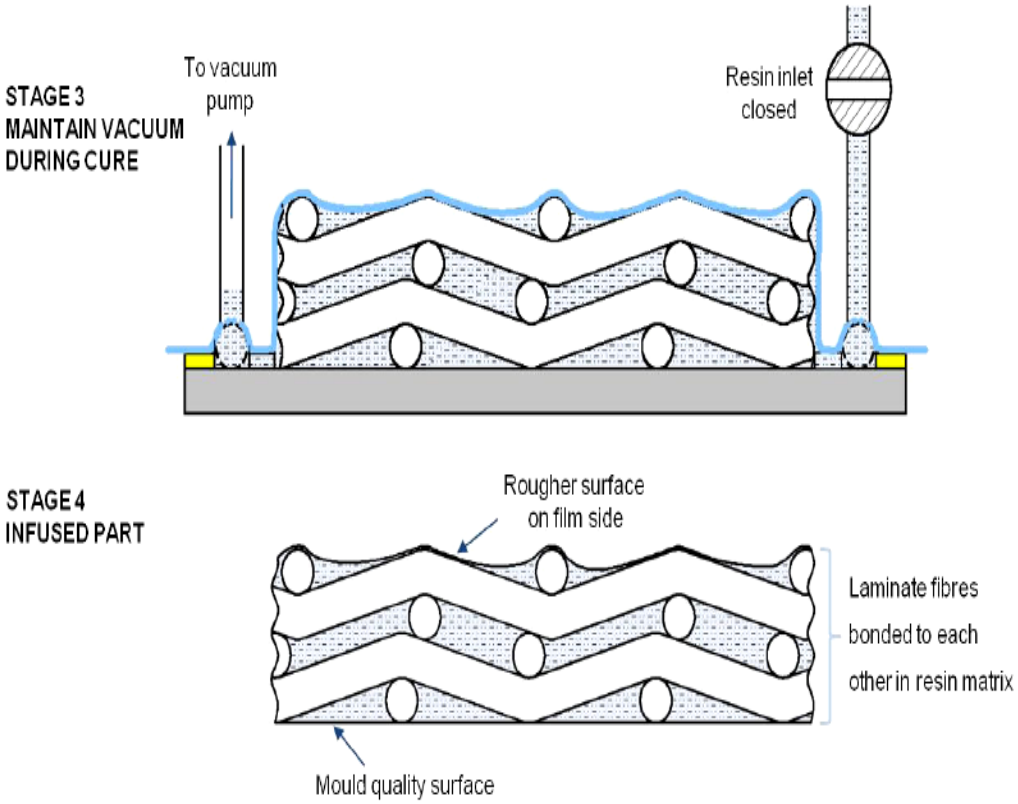


Figure 2.7. Vacuum Resin Infusion Stages - Cure and Finished Part
(Source: Vacmobiles.com Limited)

CHAPTER 3

EXPERIMENTAL

3.1. Materials

In this study, carbon fiber reinforced epoxy matrix polymeric composites were manufactured for cyclic environmental aging test.

As a matrix material, Momentive^{TM} MGS L160 laminating epoxy resin and mixture of hardeners Momentive^{TM} H160 and H260S were used. Hardener and resin mixture compositions were chosen according to technical data sheet of product to ensure desired processing time, glass transition temperature (T_g) and viscosity for vacuum resin infusion process.

Three types of carbon fabric materials were used as a reinforcement; 0/90° woven, plain unidirectional and non-crimp biaxial ±45. Plain unidirectional fabrics were purchased from Spinteks Tekstil. Non-crimp biaxial and woven fabrics were purchased from Metyx Composites.

3.2. Manufacturing of Carbon Fiber Polymeric Composites

All of the composite laminates were manufactured using vacuum resin infusion technique. Six layers of fabrics were used for manufacturing of each laminate. All fabrics were stacked at 0° direction. Fabrics were cut properly using a battery powered cutting machine. Hardener and epoxy resin mixture were prepared in accordance with technical data sheet of products. Before mixing the hardener and epoxy resin; hardeners (H160 and H260S) were mixed with 70:30 weight ratio to provide sufficient processing time.(approximately 2 – 2.5 hours). Epoxy matrix was prepared from mixture of epoxy resin and hardener with 100:27 weight ratio. Prior to vacuum infusion process, the epoxy resin was placed in a glass vacuum desiccator approximately fifteen minutes to ensure that most of the air dissolved in the resin has been removed. Vacuum infusion process steps are shown in Figures 3.1 to 3.3.

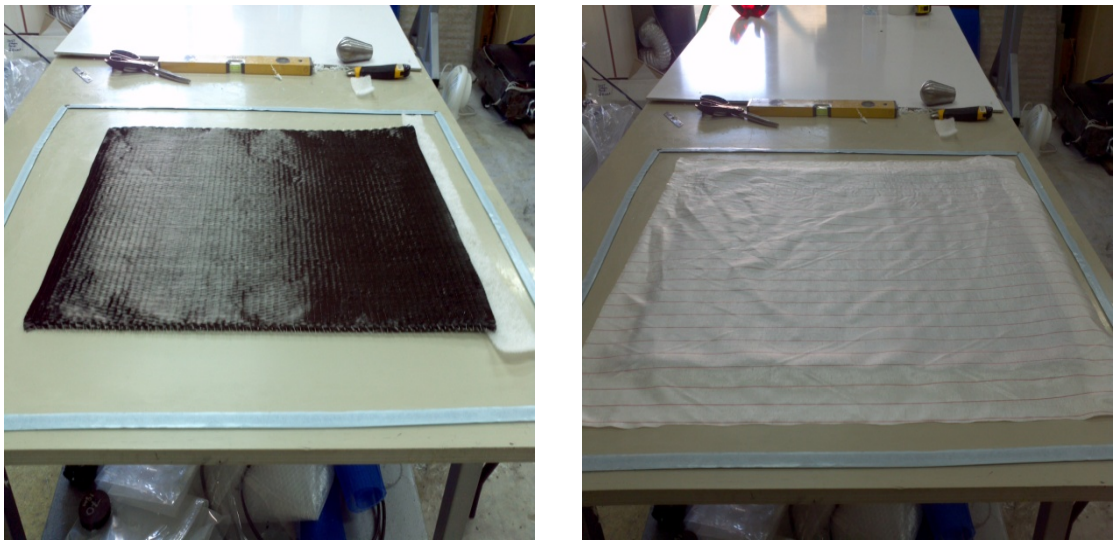


Figure 3.1. Laying out of fabrics on the infusion table and application of peel-ply material

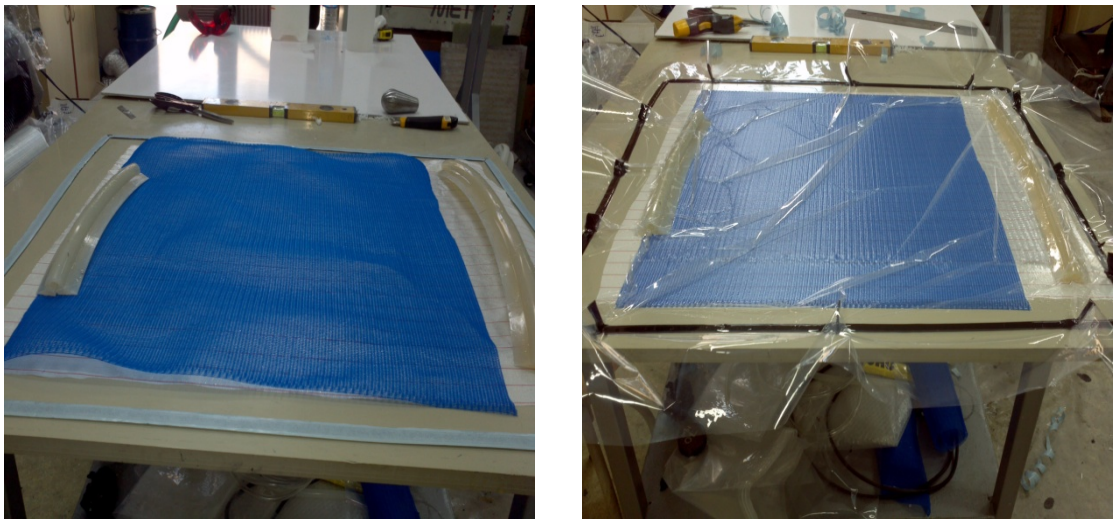


Figure 3.2. Positioning of infusion mesh and the finished bag

As can be seen from Figure 3.1, peel-ply was positioned to completely cover all areas of reinforcement to peel off the finished part easily after application. Infusion mesh was placed on the peel-ply covering approximately 75% of total area of fabrics to ensure that resin will flow from the resin feeder line easily through the laminate. Finally the part configuration was enclosed with vacuum bag by using a sealing tape. Air was evacuated from the fabrics using a vacuum pump. The parts were kept under vacuum for at least thirty minutes to ensure that there is no leakage from the bagging.

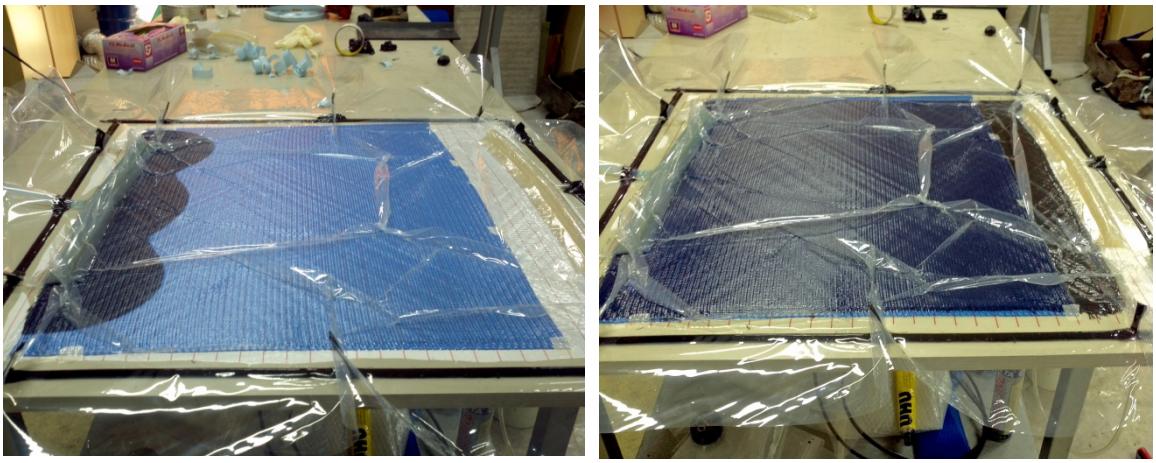


Figure 3.3. Resin flow during infusion process

The resin inlet was opened to allow resin flow into the fabrics. After the resin reached to vacuum line and resin trap, resin feed line and vacuum line were clamped. After the resin infusion, the finished part was left to fully cure at room temperature for 24 hours. After demolding, the parts were post-cured in an air circulating oven at 160°C for 5 hours. Figures 3.4, to 3.6 show the composite laminates manufactured within this study.

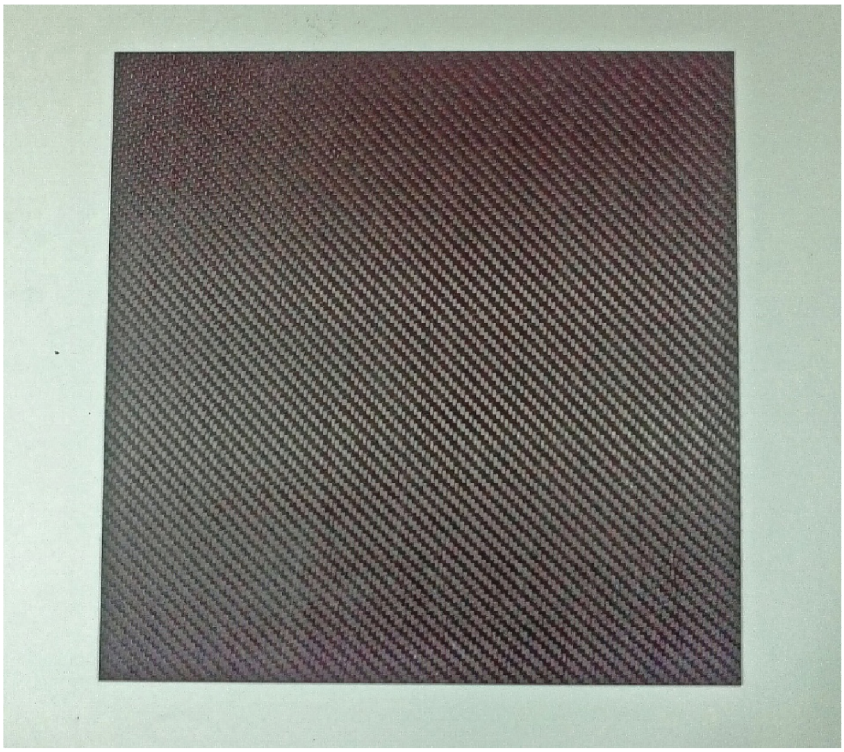


Figure 3.4. Photo of composite laminate fabricated with woven carbon fabrics for environmental durability study

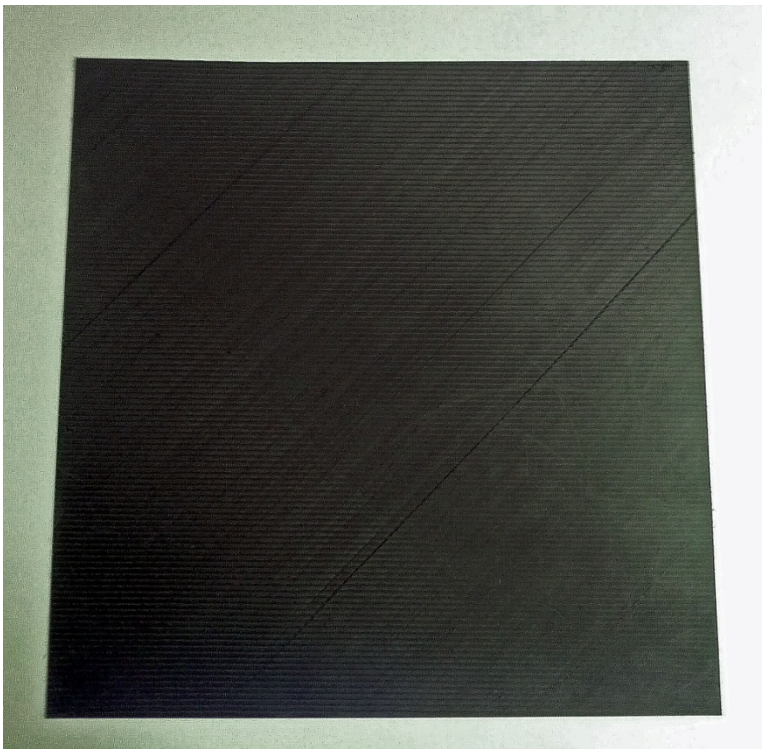


Figure 3.5. Photo of composite laminate fabricated with biaxial ±45 fabrics for environmental durability study

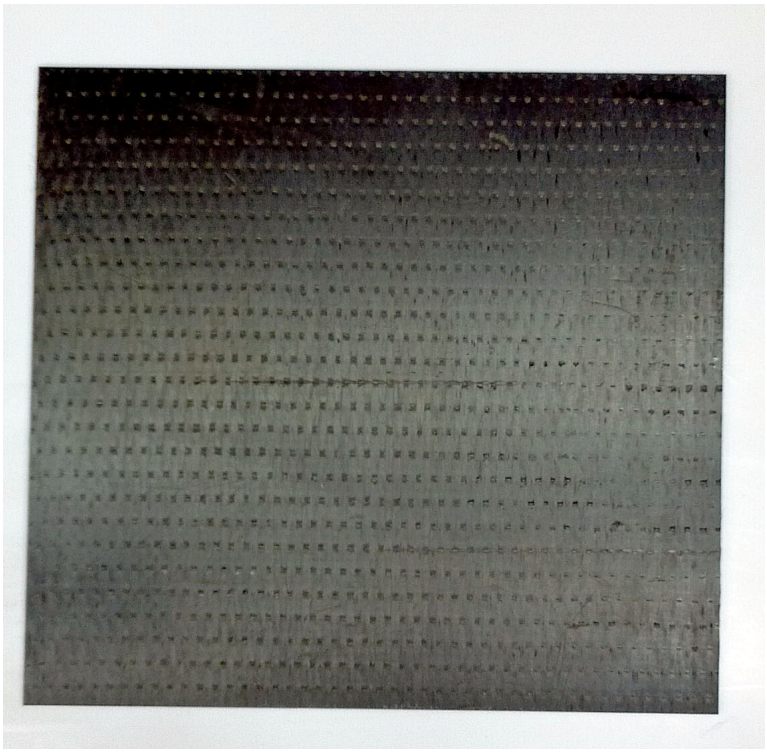


Figure 3.6. Photo of composite laminate fabricated with unidirectional fabrics for environmental durability study

3.3. Cyclic Aging

To investigate the effects of environmental aging, carbon fiber reinforced polymer composites were exposed to three environmental aging conditions in one cycle to simulate the temperature and humidity conditions in which aircrafts are subjected. Two different type of test specimens were exposed to aging cycles; the composites which were cut into test specimens prior to aging (as tensile, flexural, DMA test samples) and as manufactured plates. Angelantoni DY 340 C computer controlled environmental chamber shown in Figure 3.7 was used for aging cycles. Aging cycles were set according to flight conditions which aircrafts can be subjected during ground or operating conditions. To simulate the moisture uptake of aircraft on the ground or during maintenance operations, the specimens were exposed 30°C, 85% relative humidity for 5 hours. Then, temperature was decreased to -55°C to simulate freezing conditions during subsonic flight and specimens were kept in this condition for one hour. Finally, the specimens were exposed to 100°C for 1 hour, which corresponds to supersonic flight conditions. All specimens were exposed to these conditions for 500, 1000 and 1500 hours. Aging cycles are demonstrated in Figure 3.8.

Figure 3.7. Photo of environmental chamber used

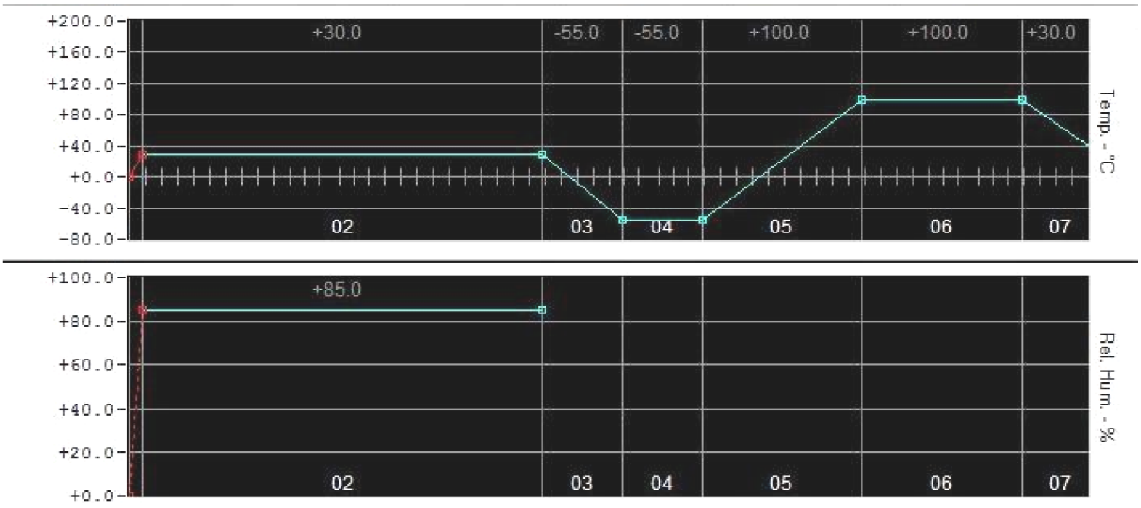


Figure 3.8. Environmental aging cycle

3.4. Characterization of Aged Composites

3.4.1. Microstructural Characterization

3.4.1.1. Fiber Volume Ratio

Archimedes' principle was used to calculate the fiber volume fractions of the composites manufactured. Five specimens were weighed in air and in distilled water for each composite plate using the setup as shown in Figure 3.9. The density values used for carbon fiber was 1.80 g/cm^3, and for the resin was 1.1 g/cm^3. The density of composites were calculated using Equation 3.1.

$$\rho_c = \frac{W_{air}}{\left(W_{air} - W_{dw}\right)} \rho_{dw} \tag{3.1}$$

In this equation, ρ_C is the density of composite, ρ_{dw} is the density of distilled water. W_{air} is the weight of sample in air and W_{dw} is the weight of sample in distilled water. After calculating the density of composite, the rule of mixture was used for the fiber volume fraction calculations which is given in following equation:

$$v = (\rho_c - \rho_{resin}) / (\rho_{fiber} - \rho_{resin}) \quad (3.2)$$

where v is the volume fraction, ρ_{fiber} is the density of fibers and ρ_{resin} is the density of the cured resin.

Figure 3.9. Test setup for density calculation

3.4.1.2. Scanning Electron Microscopy (SEM)

Tensile fracture surface of polymer composites were examined by scanning electron microscopy (SEM). All of the aged specimens were analyzed after tensile testing. All analysis was done by using Quanta 250FEG scanning electron microscope at IZTECH Materials Research Center.

3.4.2. Dynamic Mechanical Analysis

Dynamic mechanical analysis (DMA) experiments were carried out by using TA Instruments Q800 (Figure 3.10). Dual cantilever mode was used for analysis. All

specimens were tested prior to and after aging for studying the effects of aging on their thermomechanical behaviors. Storage modulus (E'), loss modulus (E'') and tangent delta (tanδ) values were evaluated and glass transition temperature (T_g) was determined from the maximum value of tanδ.

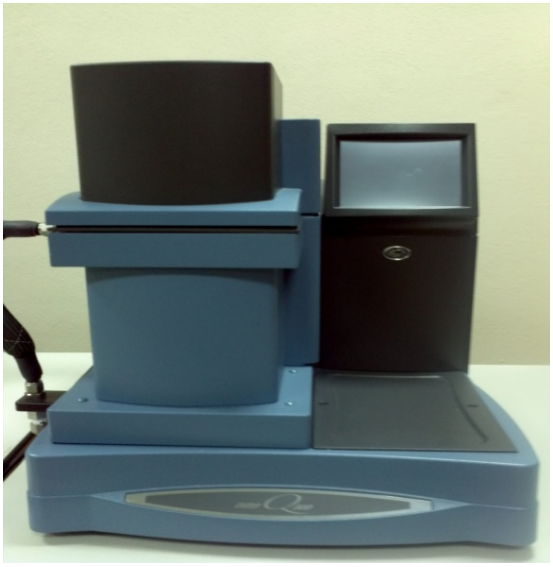


Figure 3.10. Photo of TA Instruments Q800 DMA equipment

3.4.3. Investigation of Mechanical Properties

Tensile and flexural properties of polymeric composites were measured to evaluate the effects of cyclic environmental aging on the mechanical behavior of the composites. All specimens were tested prior to and after cyclic environmental aging.

3.4.3.1. Tensile Test

The tensile tests were conducted using a Shimadzu AG-IC 100 KN universal mechanical testing machine at a cross head speed of 2 mm/min. Video extensiometer was used to measure strain values of test samples. Test samples were cut using a diamond saw with dimensions of 250 mm length and 25 mm width. For determination of tensile strength, tensile modulus and strain at failure of polymeric composites, ASTM

3039-00 standard test procedure was used. Tensile test and tensile test specimens are shown in Figure 3.11.

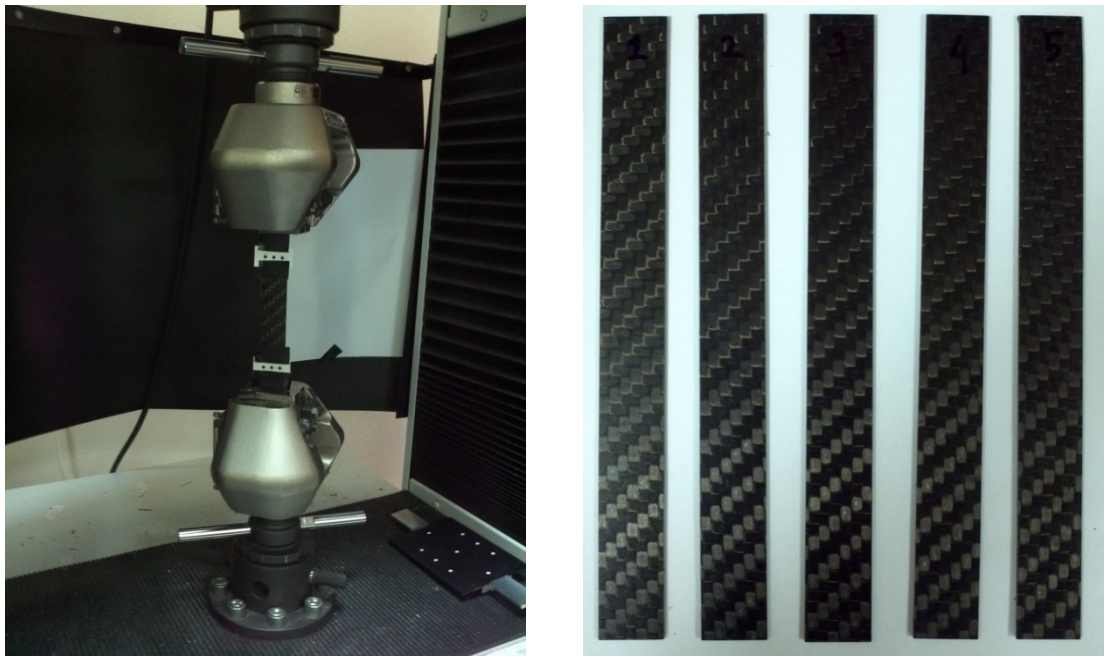


Figure 3.11. Tensile test fixture and tensile test specimens

3.4.3.2. Flexural Test

Flexural tests were made according ASTM D 790-03 standard at room temperature. At least 5 test specimens were used for each flexural test and all specimens were cut with 12.7 mm width. Specimens were tested in three point bending configuration using the universal testing machine. Figure 3.12 shows the experimental setup for three point flexural tests. Specimen length, span distance and test speed were selected according to specimen thickness.

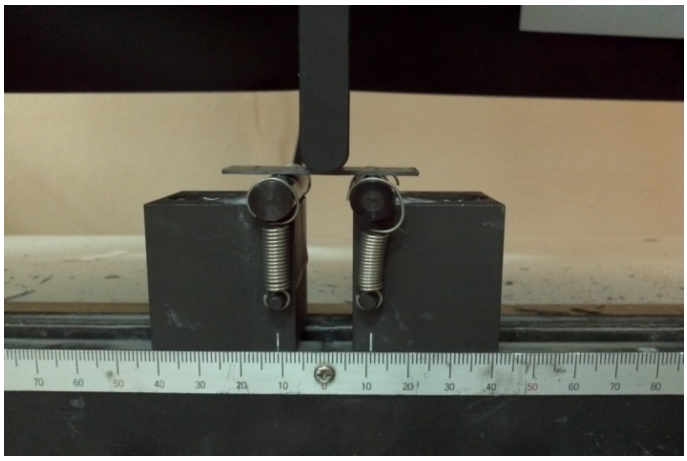


Figure 3.12. Photo of flexural mechanical test setup

3.4.4. Moisture Absorption Test

Moisture uptake records were taken during cyclic aging to investigate the moisture absorption rates during aging cycles. Test specimens were periodically weighed and recorded. Measurements were taken at the end of cycles to prevent undesired thermal shocks that can occur, such as while specimens are in freezing condition. All of the composite specimens were weighed after every fifteen cycles.

CHAPTER 4

RESULTS AND DISCUSSIONS

This chapter covers the results of the effects of environmental aging on durability of carbon fiber reinforced epoxy matrix composites. Moisture absorption test, mechanical and thermomechanical property changes after aging, and microstructural analysis results are given within the following sections.

4.1. Moisture Absorption

Figures 4.1 and 4.2 show the weight change in the samples during aging cycles. In Figure 4.1, the results are given for the composites which were cut into test specimens prior to aging. Figure 4.2 illustrates the results of weight change during aging cycles for the composites aged as manufactured plates.

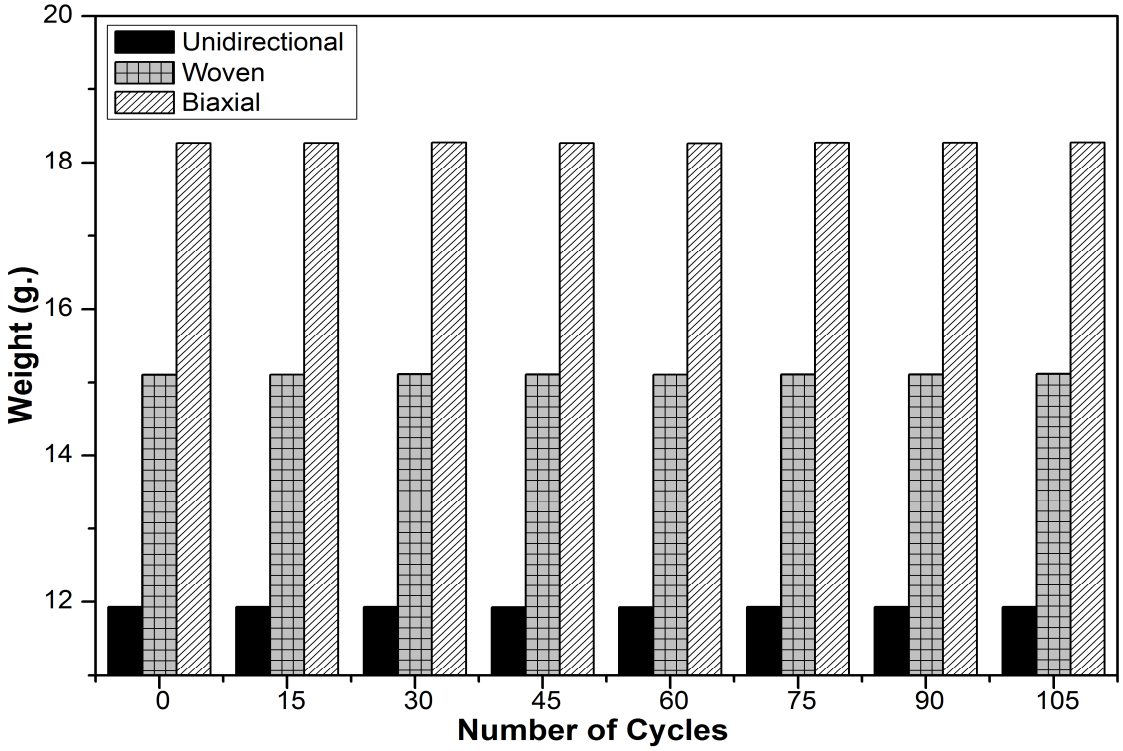


Figure 4.1. Sample weight change as a function of aging cycles for the composites which were cut into test specimens prior to aging

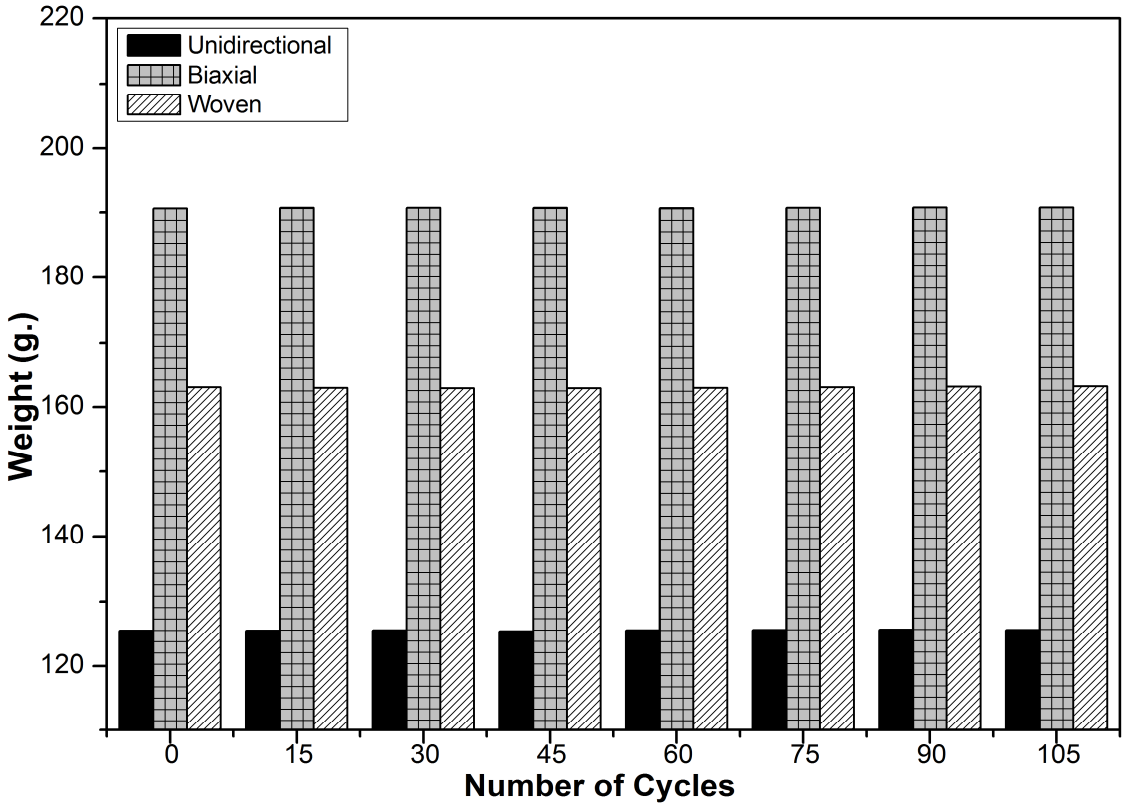


Figure 4.2. Sample weight change as a function of aging cycles for the composites aged as manufactured

As seen from Figures 4.1 and 4.2 with the increasing number of aging cycles, no significant changes were observed in weight of samples as a function of moisture for both specimen types. The moisture content of unidirectional composite plate sample increased only 0.12 grams at the end of aging cycles which corresponds to 0.09% mass gain due to moisture uptake. For the specimens which were cut into test specimens prior to aging, moisture gain was about 0.02%. In each part of aging cycle, composite specimens were subjected to hygrothermal, high temperature and freezing conditions. It can be concluded that the moisture absorbed in hygrothermal part of aging cycle was eliminated in the subsequent thermal aging part at 100°C. Long term exposure to moisture especially at elevated temperatures cause both reversible and irreversible degradation effects. In this study, materials were exposed to moisture at low temperatures. As a result, thermal and freezing conditions in aging cycles effected the moisture uptake of the composite. Hence, it requires for longer exposure time and higher temperatures combined with moisture to reach moisture saturation.

4.2. Thermal Properties

The change in glass transition temperature (T_g) was observed by Dynamic Mechanical Analysis (DMA) and the effect of aging on glass transition temperature was investigated. Figures 4.3 to 4.6 show the DMA analysis results and glass transiton temperature of unidirectional carbon / epoxy composite specimens which were cut into test specimens before aging cycles. Tables 4.1 to 4.4 show the results of T_g analysis for all specimens which were cut into test specimens prior to aging. The results for the specimens aged as manufactured plates are given in Tables 4.5 to 4.8.

It was observed that the glass transition temperatures were significantly decreased after 500 hours aging. However, the glass transition temperatures started to increase slightly after 1000 hours aging. Usually, an increase in T_g suggests chain extension or network crosslinking due to thermo oxidative aging (Gates and Gravson 1999). The change in glass transition temperatures for both specimen types (as manufactured plates and test specimens) did not differ from each other. They showed similar results after aging cycles.

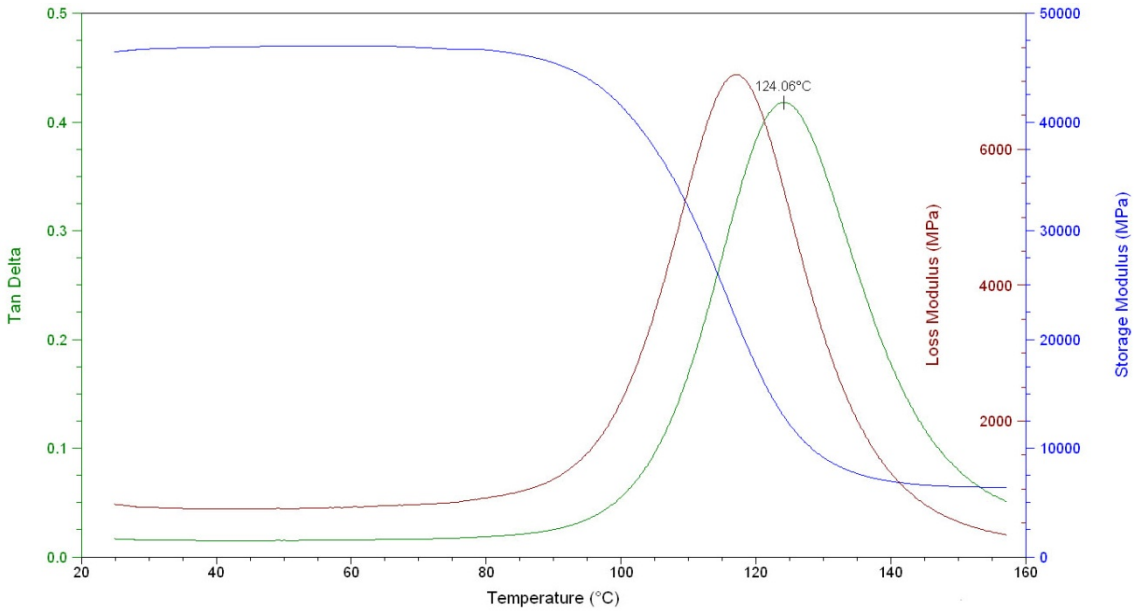


Figure 4.3. DMA analysis result and T_g of unidirectional carbon / epoxy composite prior to aging

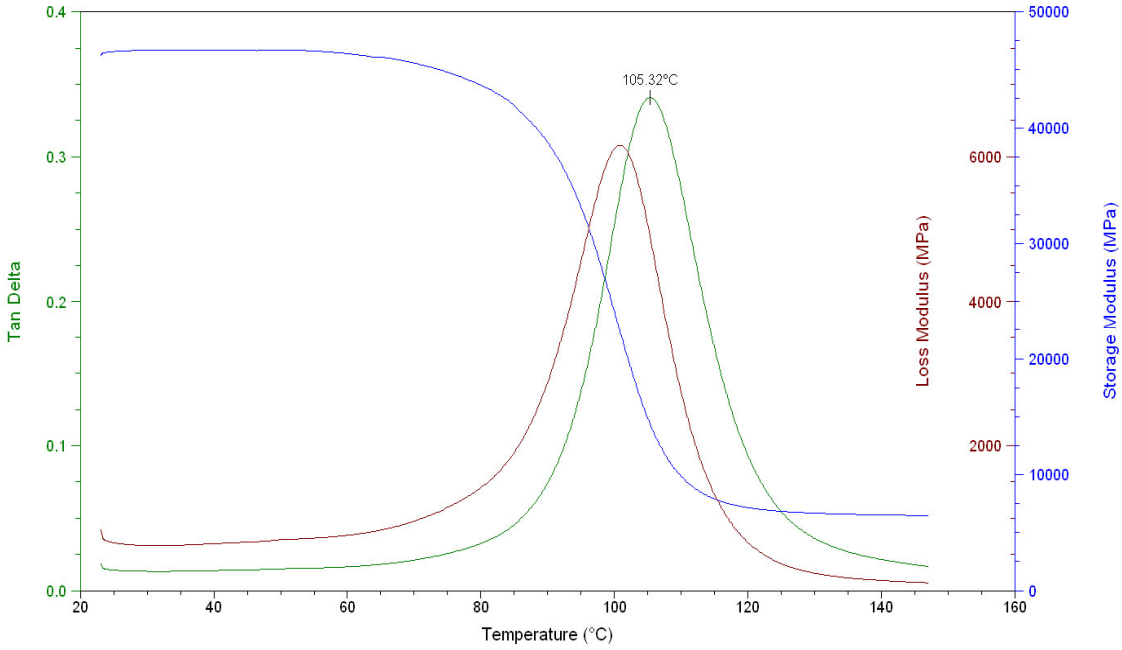


Figure 4.4. DMA analysis result and T_g of 500 hours aged unidirectional carbon/epoxy composite

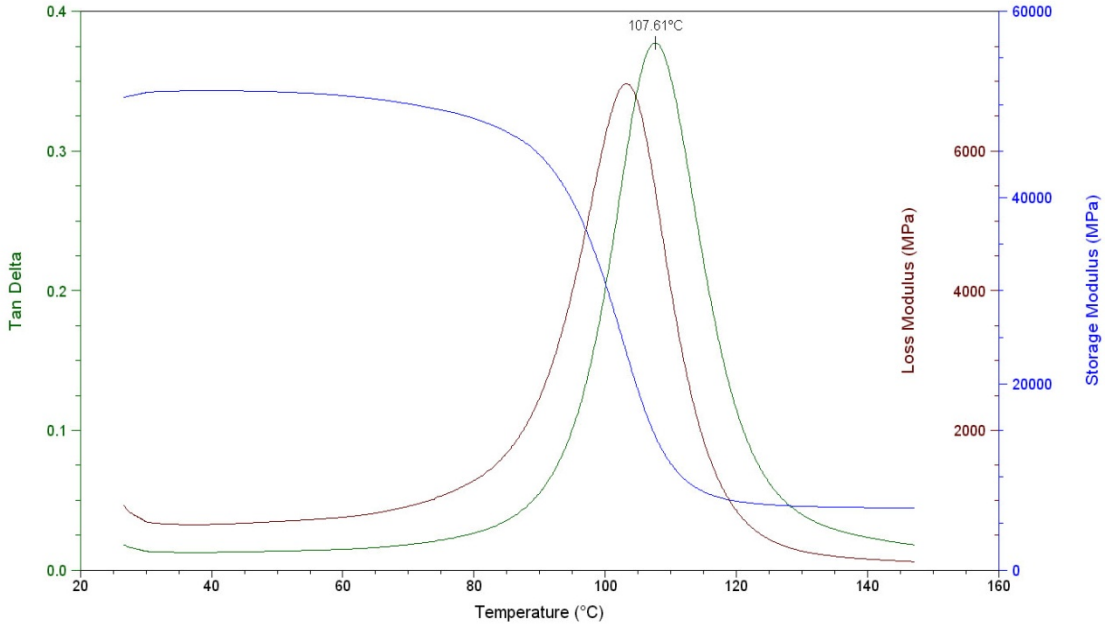


Figure 4.5. DMA analysis result and T_g of 1000 hours aged unidirectional carbon/epoxy composite

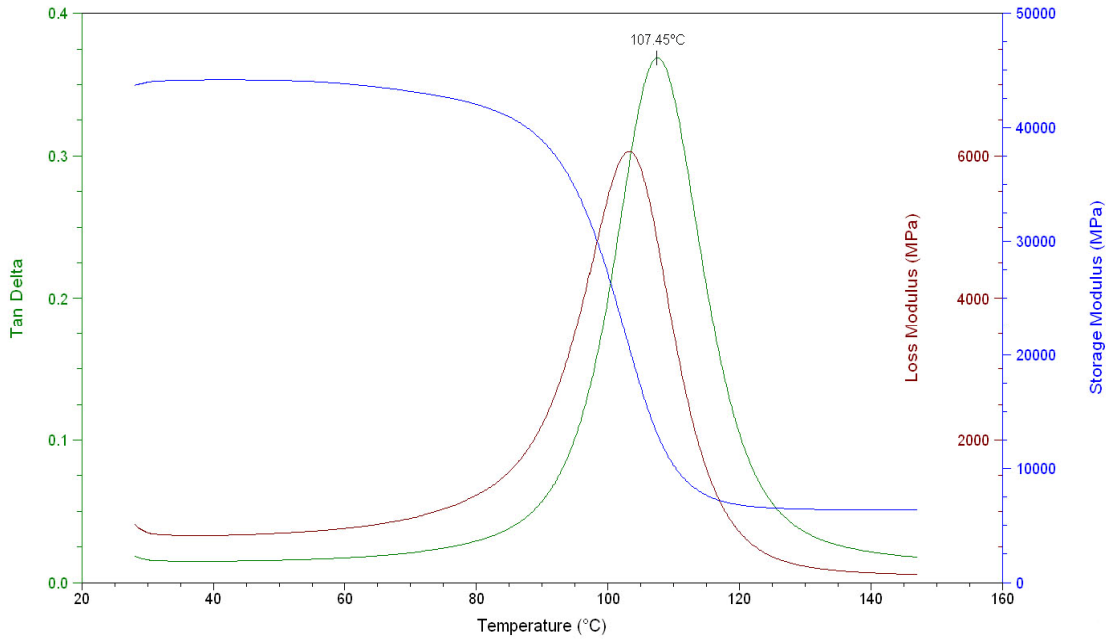


Figure 4.6. DMA analysis result and T_g of 1500 hours aged unidirectional carbon/epoxy composite

Table 4.1. T_g of carbon / epoxy composites prior to aging (the composites were cut into test specimens prior to aging)

Sample #	**Unidirectional**	**Woven**	**Biaxial**
1	124.45	124.83	124.90
2	124.06	125.31	124.23
Average	**124.25**	**125.07**	**124.56**

Table 4.2. T_g of carbon / epoxy composites after 500 hours aging (the composites were cut into test specimens prior to aging)

Sample #	**Unidirectional**	**Woven**	**Biaxial**
1	105.32	104.81	106.84
2	104.07	103.64	106.20
Average	**104.69**	**104.22**	**106.52**

Table 4.3. T_g of carbon / epoxy composites after 1000 hours aging (the composites were cut into test specimens prior to aging)

Sample #	**Unidirectional**	**Woven**	**Biaxial**
1	107.61	105.02	106.78
2	106.22	105.55	105.99
Average	**106.91**	**105.28**	**106.38**

Table 4.4. T_g of carbon / epoxy composites after 1500 hours aging (the composites were cut into test specimens prior to aging)

Sample #	**Unidirectional**	**Woven**	**Biaxial**
1	107.87	110.60	107.98
2	107.45	111.76	107.82
Average	**107.66**	**111.18**	**107.90**

Table 4.5. T_g of carbon / epoxy composites prior to aging (the composites were aged as manufacured plates)

Sample #	**Unidirectional**	**Woven**	**Biaxial**
1	122.07	126.39	125.29
2	121.16	124.89	124.32
Average	**121.61**	**125.64**	**124.80**

Table 4.6. T_g of carbon / epoxy composites after 500 hours aging (the composites were aged as manufacured plates)

Sample #	**Unidirectional**	**Woven**	**Biaxial**
1	102.78	104.33	104.77
2	99.66	101.01	102.82
Average	**101.22**	**102.67**	**103.79**

Table 4.7. T_g of carbon / epoxy composites after 1000 hours aging (the composites were aged as manufacured plates)

Sample #	**Unidirectional**	**Woven**	**Biaxial**
1	103.96	105.50	107.51
2	103.11	104.47	106.32
Average	**103.53**	**104.98**	**106.91**

Table 4.8. T_g of carbon / epoxy composites after 1500 hours aging (the composites were aged as manufacured plates)

Sample #	**Unidirectional**	**Woven**	**Biaxial**
1	104.05	104.48	105.40
2	103.89	104.98	106.18
Average	**103.97**	**104.73**	**105.79**

4.3. Mechanical Properties

Tension and bending tests were conducted to investigate the effects of environmental aging on the mechanical properties of composites manufactured in this study. All of the tests were performed prior to and after 500, 1000 and 1500 hours aging cycles and the stress-strain graphs were produced. At least five specimens were tested for each specimen type. Strength, modulus and strain at break values are reported in tables below. Stress – strain graphs are plotted and the comparison of tensile strength, bending strength, tensile and flexural modulus values prior to and after aging are made.

4.3.1. Tensile Tests

Tensile test results of all specimens are given in Tables 4.9 to 4.20. The stress-strain graphs are also shown in Figures 4.7 to 4.18. Finally, the comparison of tensile strength and elastic modulus values prior to and after aging are summarized in Figures 4.19 to 4.22.

Results obtained from tensile tests show that the tensile strength of unidirectional composites after 500, 1000 and 1500 hours aging decreased by about 3.28%, 6.41% and 6.39%, respectively. Prior to aging, tensile modulus of unidirectional composite samples were 121.1 GPa. After 1500 hours aging cycle, the tensile modulus of these samples decreased to 115.75 GPa. The results revealed a slow degradation of mechanical strength and modulus. For the composites aged as manufactured plates, it was found that tensile strength decreased by about 7.78% and modulus values by about 5.31% after 1500 hours aging.

For the unidirectional composites, no significant difference was observed between the specimens as manufactured plates and the aged test specimens. On the other hand, for the biaxial composites, tensile strength and modulus values decreased more significantly after aging cycles. The degradation in tensile modulus values were more significant as compared to change in tensile strength. Tensile modulus values of biaxial composites were 12.75 GPa prior to aging. At the end of aging cycles tensile modulus values decreased to 9.46 GPa. For the composites which were cut into test specimens, tensile modulus decreased by about 25.80%. It is noted that the tensile modulus values of the composites aged as manufactured plates decreased by about

20.72% after 1500 hours aging. Since the specimens did not absorb significant amount of moisture after aging, the reason for the decrease in mechanical properties may associate with the development of microcracks due to the effect of temperature. It can be said that the change in temperature, such that from cold condition to normal ambient or high temperature condition, thermal expansions and contractions results in internal stresses and produces micro damages.

In contrast to decrease in the mechanical properties of biaxial and unidirectional composites due to aging, mechanical properties of woven composites was found to be increased after aging. Prior to aging, tensile strength of woven composite samples was 696.20 MPa. After 1500 hours aging, tensile strength of woven composite samples increased to 849.39 MPa. Tensile modulus values of woven composites increased from 57.72 GPa to 62.80 GPa after 1500 hours aging. For woven composites, after 500, 1000 and 1500 hours aging, the tensile strength increased by about 7.88%, 10.21% and 22%, respectively. The tensile modulus increased by about8.80% after 1500 hours aging. The increase in strength values are less significant for the composites aged as manufactured plates. The tensile strength increased by about 7.66% after 1500 hours aging.

Table 4.9. Tensile properties of unidirectional carbon/epoxy composites prior to aging and after 500 hours aging

Aging Time	**Prior to Aging**			**After 500 Hours Aging**		
Sample #	**Tensile Strength (MPa)**	**Tensile Modulus (GPa)**	**Strain at Break (%)**	**Tensile Strength (MPa)**	**Tensile Modulus (GPa)**	**Strain at Break (%)**
1	1196.3	121.3	1.02	1158.13	119.59	1.05
2	1182.6	122	1.01	1126.51	119.12	1.01
3	1197.5	120.03	1.04	1170.05	124.98	1.01
4	1174.5	123.1	1.02	1187.38	126.74	0.99
5	1209.5	119.2	1.07	1121.93	123.65	0.98
Average	**1192**	**121.1**	**1.03**	**1152.80**	**122.82**	**1.01**
Std. Dev. (±)	**13.68**	**1.53**	**0.02**	**28.13**	**3.34**	**0.02**

Table 4.10. Tensile properties of unidirectional carbon/epoxy composites after 1000 hours and 1500 hours aging

Aging Time	**After 1000 Hours Aging**			**After 1500 Hours Aging**		
Sample #	**Tensile Strength (MPa)**	**Tensile Modulus (GPa)**	**Strain at Break (%)**	**Tensile Strength (MPa)**	**Tensile Modulus (GPa)**	**Strain at Break (%)**
1	1160.78	115.24	1.03	1049.31	112.67	0.98
2	1167.36	116.98	1.06	1087.80	117.58	0.96
3	1044.41	114.02	0.96	1080.60	112.98	0.98
4	1141.41	117.54	1.03	1137.93	120.91	0.97
5	1064.02	114.61	0.99	1101.71	114.58	1.01
Average	**1115.59**	**115.67**	**1.01**	**1091.47**	**115.75**	**0.98**
Std. Dev. (±)	**57.26**	**1.52**	**0.03**	**32.30**	**3.83**	**0.02**

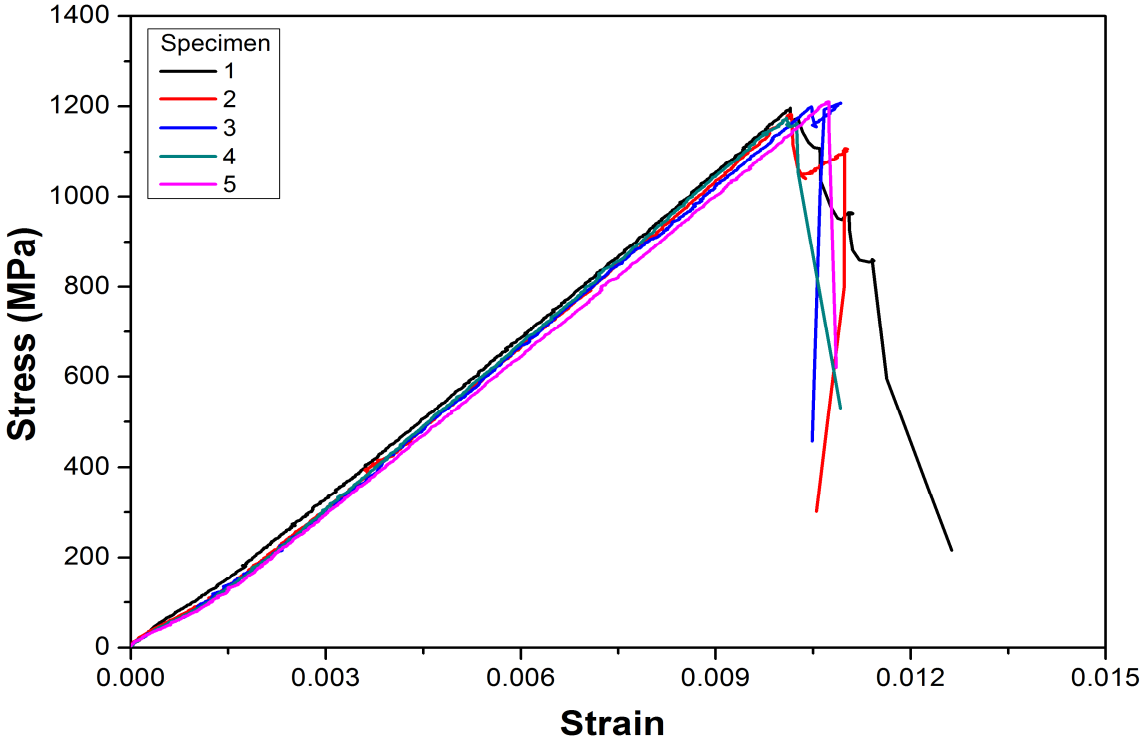


Figure 4.7. Tensile stress - strain graphs of unidirectional carbon/epoxy composites prior to aging

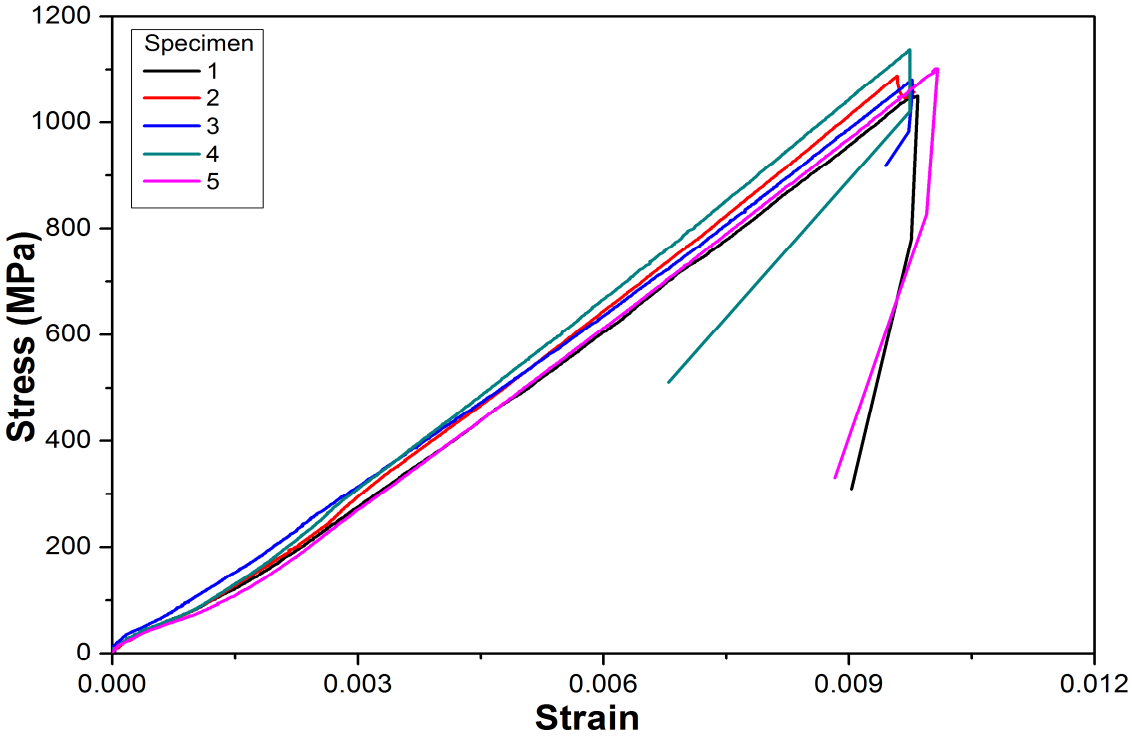


Figure 4.8. Tensile stress - strain graphs of unidirectional carbon/epoxy composites after 1500 hours aging

Table 4.11. Tensile properties of woven carbon/epoxy composites prior to aging and after 500 hours aging

Aging Time	**Prior to Aging**			**After 500 Hours Aging**		
Sample #	**Tensile Strength (MPa)**	**Tensile Modulus (GPa)**	**Strain at Break (%)**	**Tensile Strength (MPa)**	**Tensile Modulus (GPa)**	**Strain at Break (%)**
1	737.03	59.82	1.22	702.16	58.19	1.25
2	638.43	58.14	1.10	680.90	56.17	1.24
3	775.45	56.83	1.37	754.97	58.69	1.30
4	656.93	57.66	1.13	796.99	54.90	1.48
5	673.18	56.16	1.22	820.63	57.40	1.49
Average	**696.20**	**57.72**	**1.21**	**751.13**	**57.07**	**1.35**
Std. Dev. (±)	**57.79**	**1.40**	**0.11**	**59.75**	**1.54**	**0.12**

Table 4.12. Tensile properties of woven carbon/epoxy composites after 1000 and 1500 hours aging

Aging Time	**After 1000 Hours Aging**			**After 1500 Hours Aging**		
Sample #	**Tensile Strength (MPa)**	**Tensile Modulus (GPa)**	**Strain at Break (%)**	**Tensile Strength (MPa)**	**Tensile Modulus (GPa)**	**Strain at Break (%)**
1	759.63	54.09	1.47	855.22	63.00	1.37
2	777.34	57.66	1.40	865.27	64.30	1.41
3	670	55.87	1.27	853.13	65.20	1.37
4	814.30	57.59	1.49	819.53	61.26	1.37
5	815.26	59.64	1.45	853.79	60.22	1.41
Average	**767.31**	**56.97**	**1.42**	**849.39**	**62.80**	**1.39**
Std. Dev. (±)	**59.45**	**2.08**	**0.09**	**17.40**	**2.06**	**0.02**

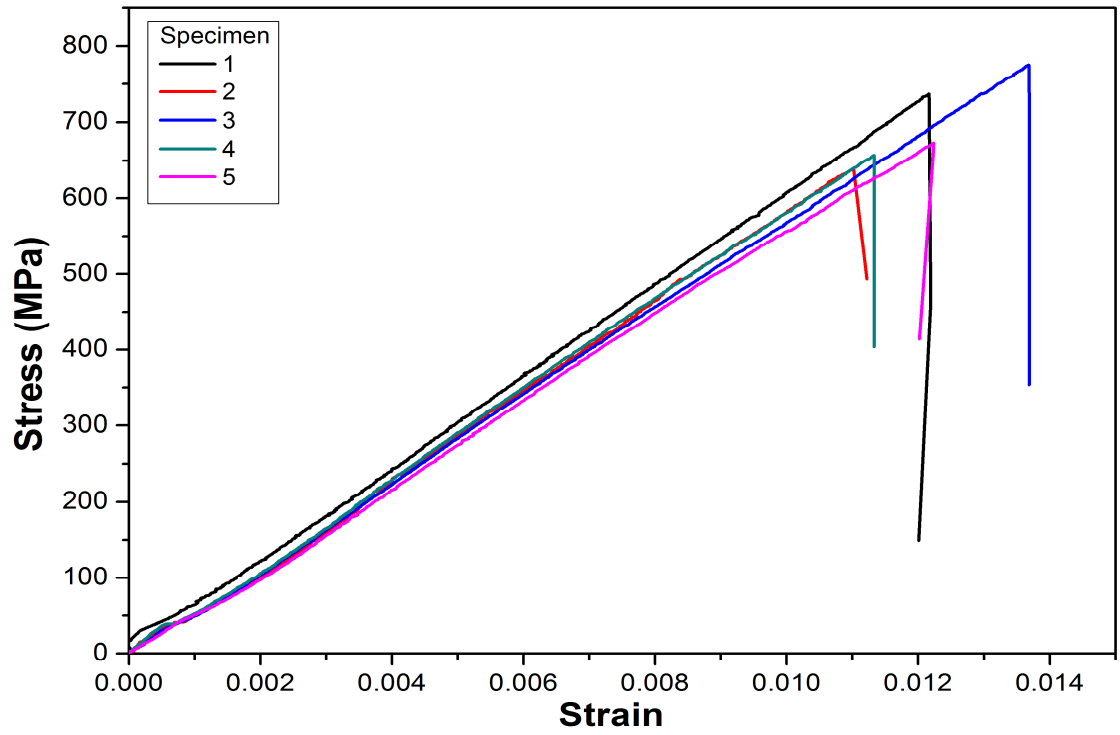


Figure 4.9. Tensile stress – strain graphs of woven carbon/epoxy composites prior to aging

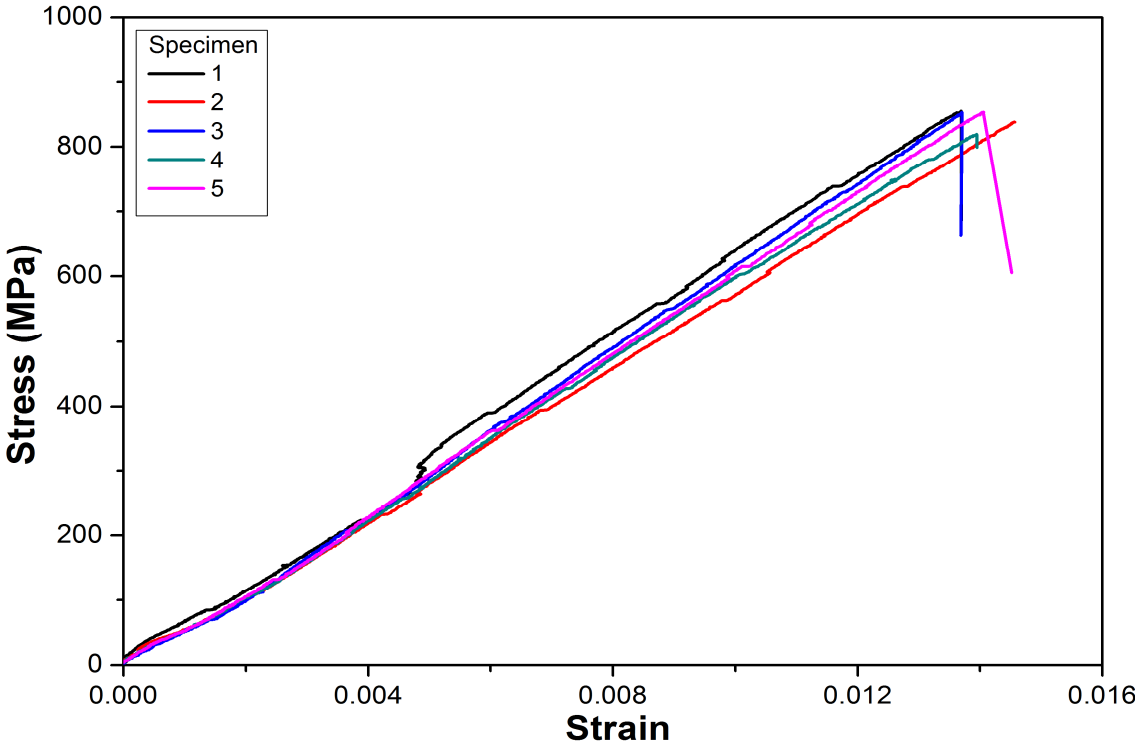


Figure 4.10. Tensile stress – strain graphs of woven carbon/epoxy composites after 1500 hours aging

Table 4.13. Tensile properties of biaxial carbon/epoxy composites prior to aging and after 500 hours aging

Aging Time	**Prior to Aging**			**After 500 Hours Aging**		
Sample #	**Tensile Strength (MPa)**	**Tensile Modulus (GPa)**	**Strain at Break (%)**	**Tensile Strength (MPa)**	**Tensile Modulus (GPa)**	**Strain at Break (%)**
1	158.86	13.62	9.12	149.37	10.93	8.38
2	156.08	11.95	9.37	154.01	10.49	9.18
3	157.25	13.83	8.45	142.55	10.09	8.63
4	159.36	12.97	9.85	159.20	10.74	10.47
5	153.32	11.38	9.60	151.96	10.78	9.62
Average	**156.97**	**12.75**	**9.28**	**151.42**	**10.61**	**9.26**
Std. Dev. (±)	**2.42**	**1.05**	**0.54**	**6.13**	**0.32**	**0.83**

Table 4.14. Tensile properties of biaxial carbon/epoxy composites after 1000 and 1500 hours aging

Aging Time	**After 1000 Hours Aging**			**After 1500 Hours Aging**		
Sample #	**Tensile Strength (MPa)**	**Tensile Modulus (GPa)**	**Strain at Break (%)**	**Tensile Strength (MPa)**	**Tensile Modulus (GPa)**	**Strain at Break (%)**
1	146.85	9.26	9.36	153.08	9.98	8.97
2	163.35	11.49	8.47	151.13	8.71	9.98
3	152.04	11.22	9.64	143.13	9.40	8.63
4	156.33	10.59	8.93	142.76	9.24	8.81
5	146.30	9.90	9.05	147.94	9.99	9.82
Average	**152.97**	**10.49**	**9.09**	**147.61**	**9.46**	**9.24**
Std. Dev. (±)	**7.10**	**0.92**	**0.44**	**4.64**	**0.54**	**0.62**

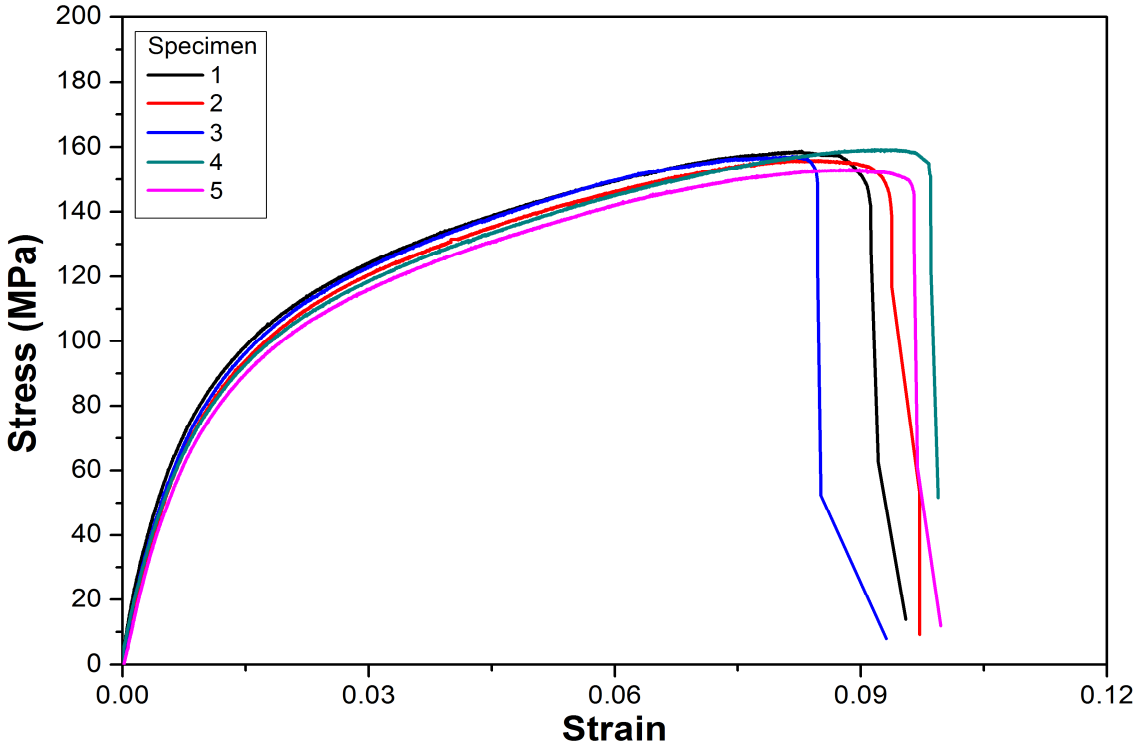


Figure 4.11. Tensile stress – strain graphs of biaxial carbon/epoxy composites prior to aging

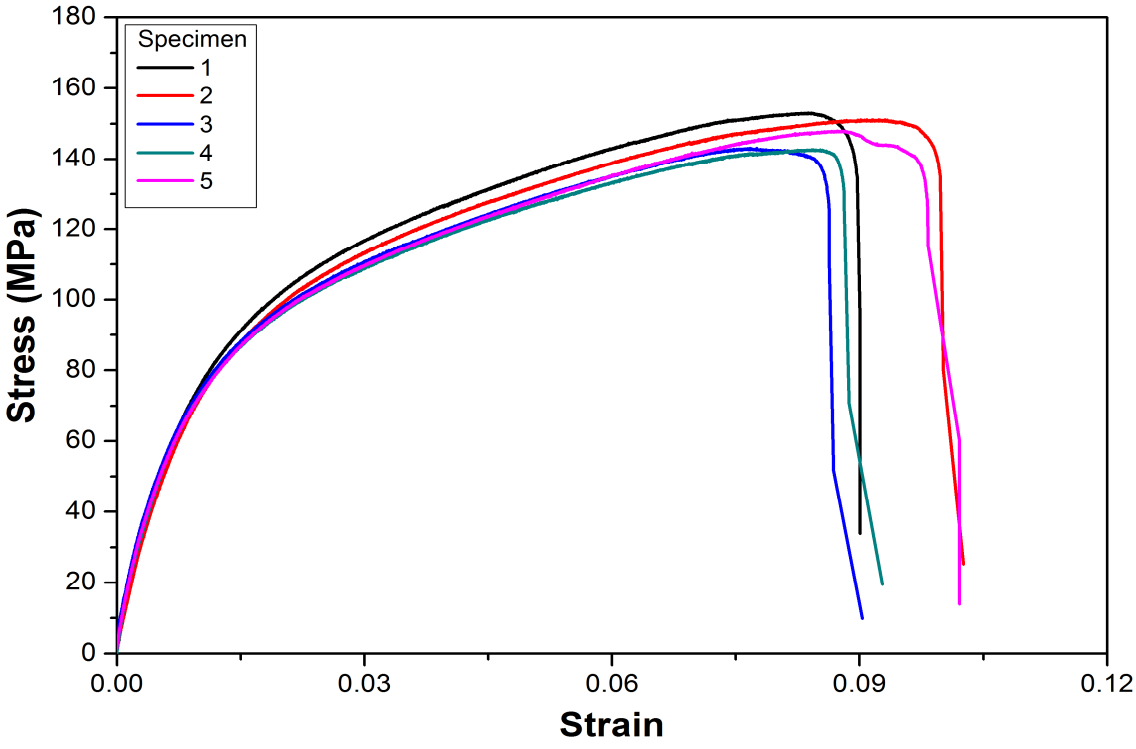


Figure 4.12. Tensile stress – strain graphs of biaxial carbon/epoxy composites after 1500 hours aging

Table 4.15. Tensile properties of unidirectional carbon/epoxy composites prior to aging and after 500 hours aging (the composites were aged as manufactured plates)

Aging Time	**Prior to Aging**			**After 500 Hours Aging**		
Sample #	**Tensile Strength (MPa)**	**Tensile Modulus (GPa)**	**Strain at Break (%)**	**Tensile Strength (MPa)**	**Tensile Modulus (GPa)**	**Strain at Break (%)**
1	1161.40	125.62	0.97	1095.40	121.28	0.93
2	1124	121.35	0.96	1070.72	113.04	0.95
3	1146.80	123.91	1.02	1115.35	116.78	0.98
4	1123.92	117.40	1.03	992.44	113.39	0.89
5	1146.18	118.88	1.01	1083.51	115.58	0.94
Average	**1140.46**	**121.43**	**1.00**	**1071.48**	**116.01**	**0.94**
Std. Dev. (±)	**16.25**	**3.40**	**0.03**	**47.14**	**3.32**	**0.03**

Table 4.16. Tensile properties of unidirectional carbon/epoxy composites after 1000 hours and 1500 hours aging (the composites were aged as manufactured plates)

Aging Time	**After 1000 Hours Aging**			**After 1500 Hours Aging**		
Sample #	**Tensile Strength (MPa)**	**Tensile Modulus (GPa)**	**Strain at Break (%)**	**Tensile Strength (MPa)**	**Tensile Modulus (GPa)**	**Strain at Break (%)**
1	1170.23	123.29	0.96	1079.91	118.03	0.94
2	1220.10	122.08	1.07	1043.01	115.71	0.95
3	1051.14	112.45	0.97	960.27	121.35	0.80
4	1143.53	121.66	0.94	1031.41	111.25	0.92
5	1142.22	121.25	0.97	1052.34	114.92	0.94
Average	**1145.44**	**120.15**	**0.98**	**1033.39**	**116.25**	**0.91**
Std. Dev. (±)	**61.43**	**4.36**	**0.05**	**44.63**	**3.74**	**0.06**

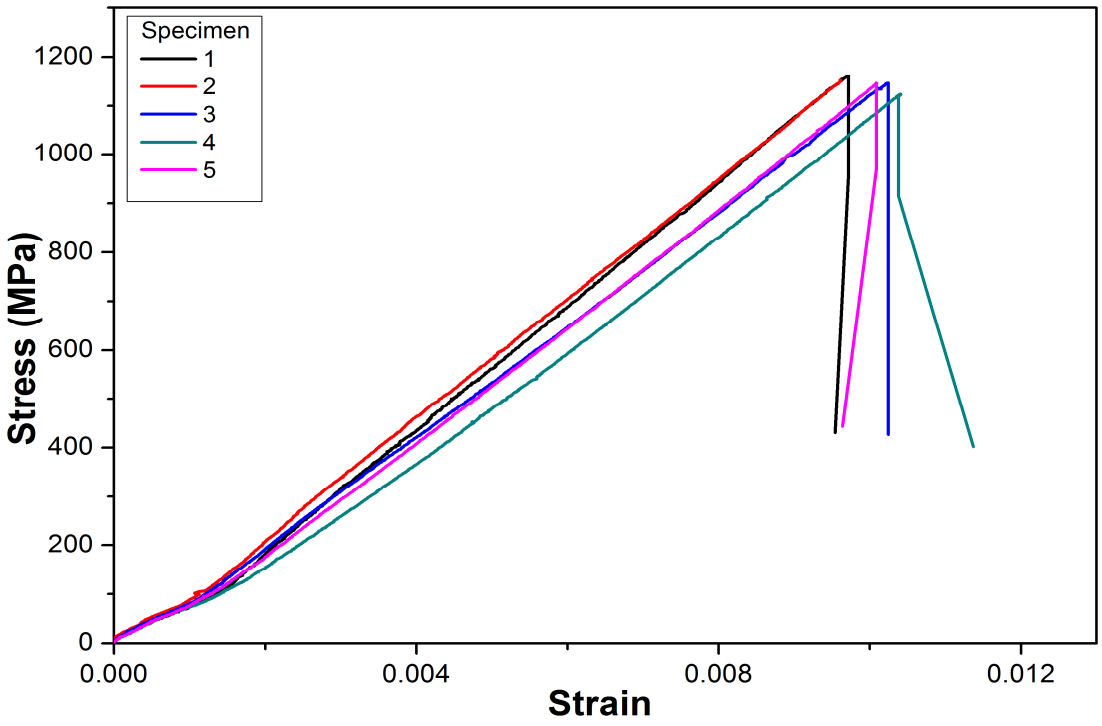


Figure 4.13. Tensile stress – strain graphs of unidirectional carbon/epoxy composites prior to aging (the composites were aged as manufactured plates)

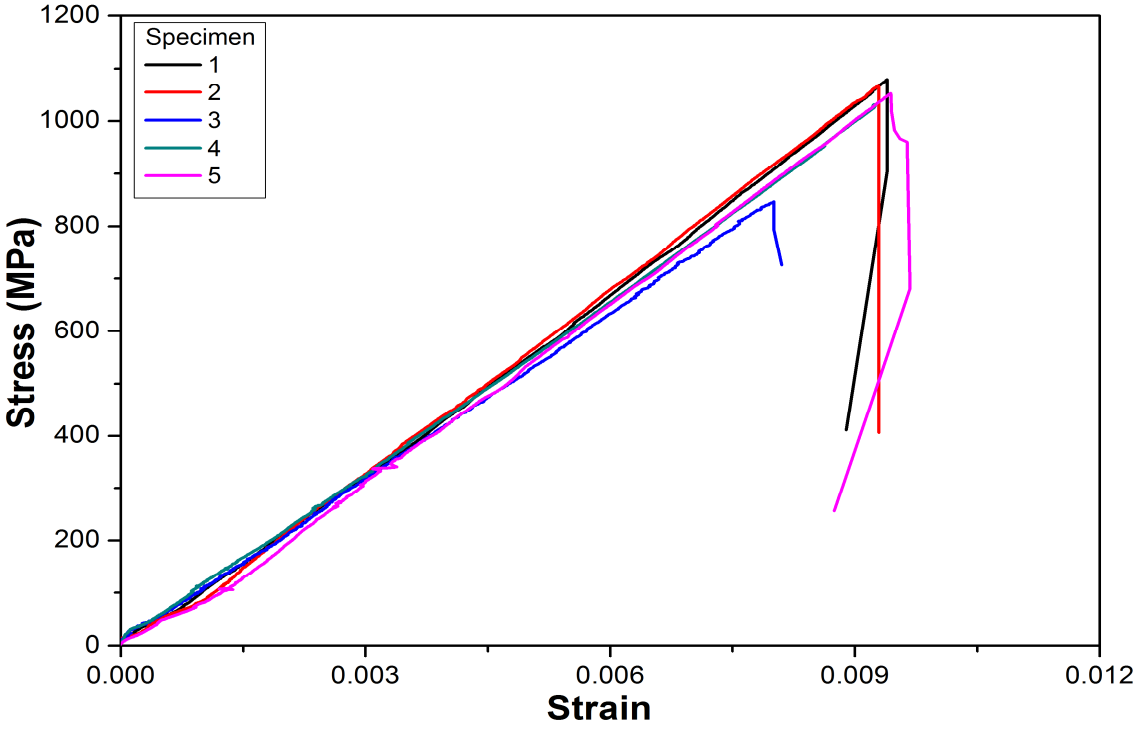


Figure 4.14. Tensile stress – strain graphs of unidirectional carbon/epoxy composites after 1500 hours aging (the composites were aged as manufactured plates)

Table 4.17. Tensile properties of woven carbon/epoxy composites prior to aging and after 500 hours aging (the composites were aged as manufactured plates)

Aging Time	**Prior to Aging**			**After 500 Hours Aging**		
Sample #	**Tensile Strength (MPa)**	**Tensile Modulus (GPa)**	**Strain at Break (%)**	**Tensile Strength (MPa)**	**Tensile Modulus (GPa)**	**Strain at Break (%)**
1	812.19	62.42	1.33	939.82	61.34	1.48
2	807.10	61.70	1.36	999.46	62.05	1.57
3	893.88	64.03	1.42	889.56	66.14	1.35
4	809.76	61.70	1.35	680.93	62.84	1.10
5	805.84	62.92	1.30	867.47	65.30	1.36
Average	**825.75**	**62.55**	**1.35**	**859.36**	**63.53**	**1.35**
Std. Dev. (±)	**38.16**	**0.97**	**0.04**	**132.22**	**2.08**	**0.19**

Table 4.18. Tensile properties of woven carbon/epoxy composites after 1000 hours and 1500 hours aging (the composites were aged as manufactured plates)

Aging Time	**After 1000 Hours Aging**			**After 1500 Hours Aging**		
Sample #	**Tensile Strength (MPa)**	**Tensile Modulus (GPa)**	**Strain at Break (%)**	**Tensile Strength (MPa)**	**Tensile Modulus (GPa)**	**Strain at Break (%)**
1	943.89	62.93	1.55	903.36	65.21	1.45
2	879.33	61.65	1.47	907.64	65.54	1.43
3	862.33	61.16	1.43	940.28	63.03	1.54
4	873.44	59.67	1.46	875.46	64.95	1.38
5	810.41	62.17	1.34	818.49	62.48	1.34
Average	**873.88**	**61.52**	**1.45**	**889.05**	**64.24**	**1.43**
Std. Dev. (±)	**47.68**	**1.22**	**0.08**	**45.66**	**1.38**	**0.08**

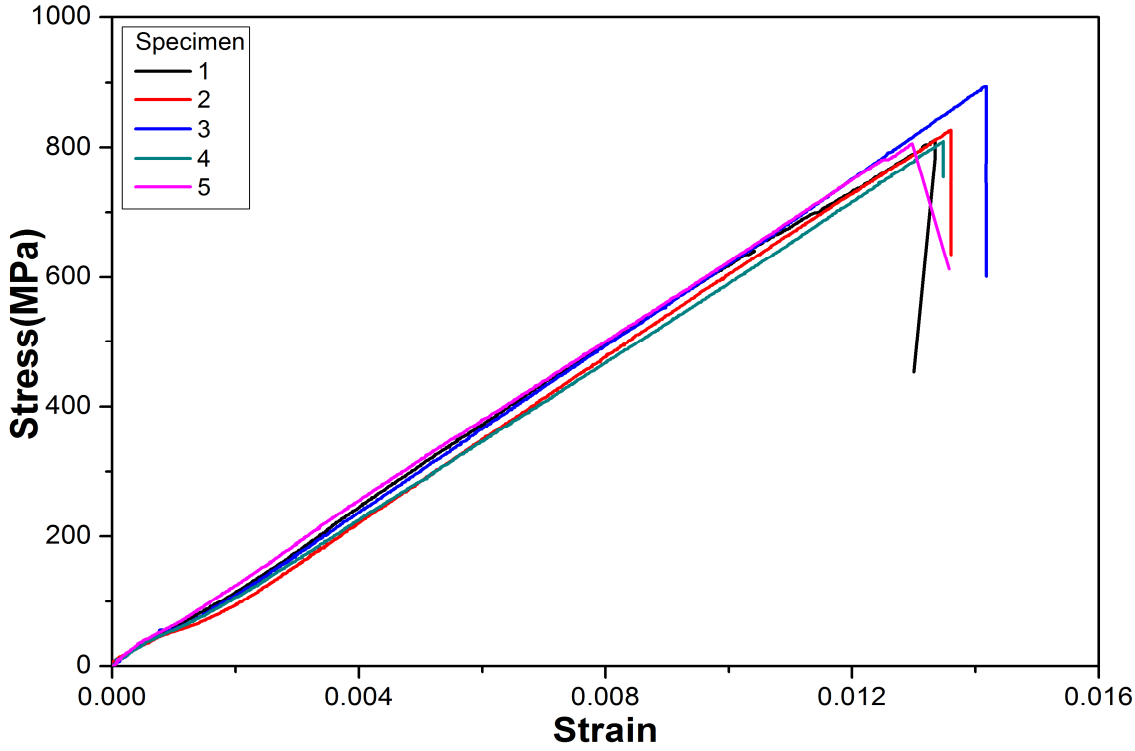


Figure 4.15. Tensile stress – strain graphs of woven carbon / epoxy composites prior to aging (the composites were aged as manufactured plates)

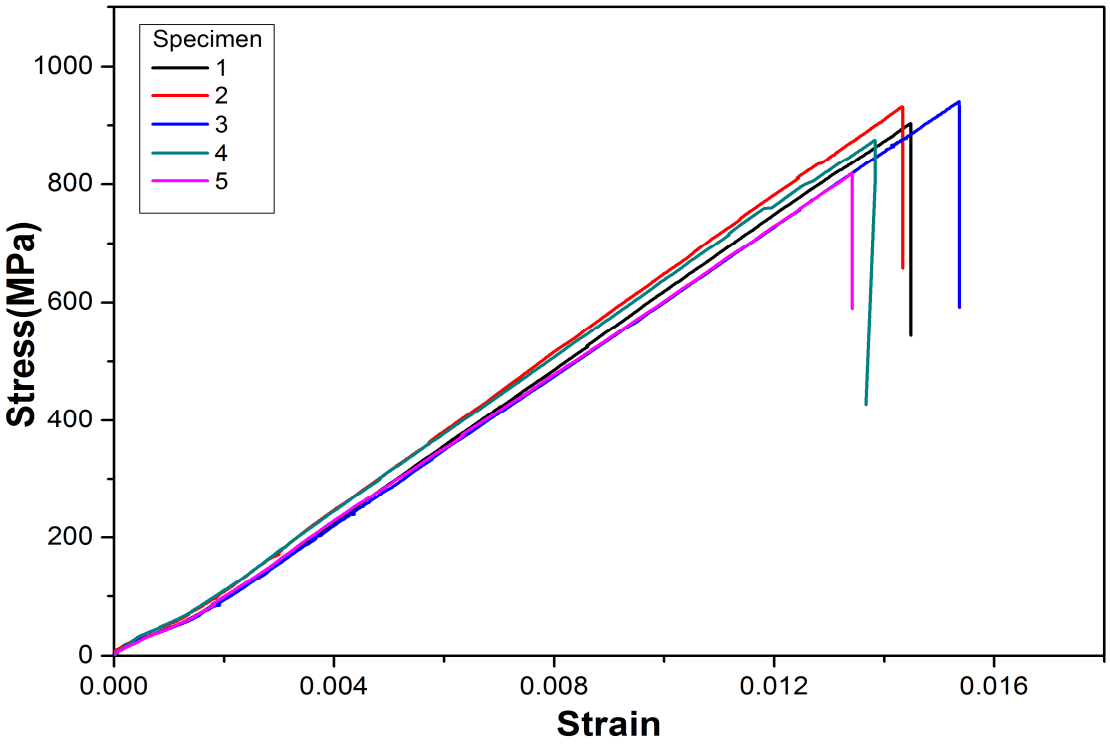


Figure 4.16. Tensile stress – strain graphs of woven carbon / epoxy composites after 1500 hours aging (the composites were aged as manufactured plates)

Table 4.19. Tensile properties of biaxial carbon / epoxy composites prior to aging and after 500 hours aging (the composites were aged as manufactured plates)

Aging Time	**Prior to Aging**			**After 500 Hours Aging**		
Sample #	**Tensile Strength (MPa)**	**Tensile Modulus (GPa)**	**Strain at Break (%)**	**Tensile Strength (MPa)**	**Tensile Modulus (GPa)**	**Strain at Break (%)**
1	175.31	12.12	9.69	176.87	10.27	9.89
2	173.76	12.35	9.09	173.89	11.69	9.61
3	172.28	14.67	9.30	183.46	11.40	10.50
4	168.43	12.52	8.96	184.22	10.79	9.62
5	172.54	11.80	9.24	182.69	10.30	9.76
Average	**172.46**	**12.69**	**9.26**	**180.23**	**10.89**	**9.88**
Std. Dev. (±)	**2.55**	**1.13**	**0.28**	**4.58**	**0.63**	**0.37**

Table 4.20. Tensile properties of biaxial carbon/epoxy composites after 1000 hours and 1500 hours aging (the composites were aged as manufactured plates)

Aging Time	**After 1000 Hours Aging**			**After 1500 Hours Aging**		
Sample #	**Tensile Strength (MPa)**	**Tensile Modulus (GPa)**	**Strain at Break (%)**	**Tensile Strength (MPa)**	**Tensile Modulus (GPa)**	**Strain at Break (%)**
1	185.65	10.31	10.38	164.84	10.08	8.71
2	186.56	11.50	9.69	166.43	10.99	9.92
3	179.28	10.52	8.17	158.53	9.30	9.24
4	161.98	10.34	7.91	171.11	10	10.30
5	170.27	10.75	7.91	169.63	9.93	9.70
Average	**176.25**	**10.68**	**8.81**	**166.11**	**10.06**	**9.57**
Std. Dev. (±)	**10.51**	**0.49**	**1.15**	**4.91**	**0.60**	**0.62**

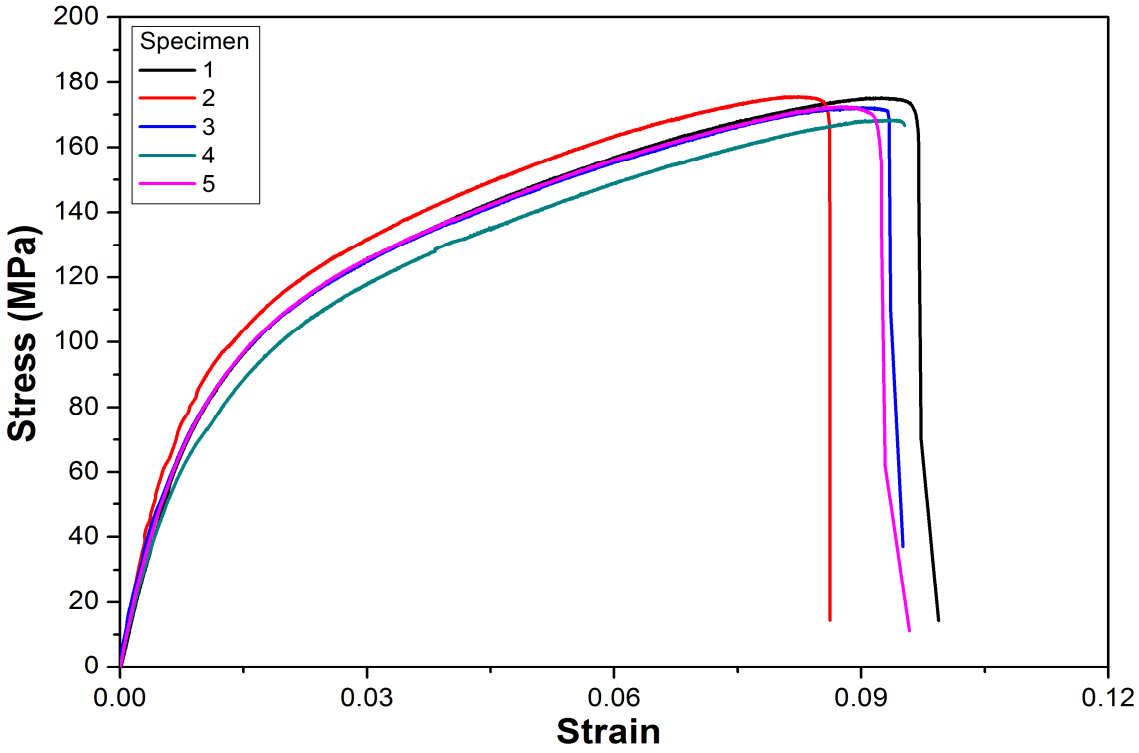


Figure 4.17. Tensile stress – strain graphs of biaxial carbon / epoxy composites prior to aging (the composites were aged as manufactured plates)

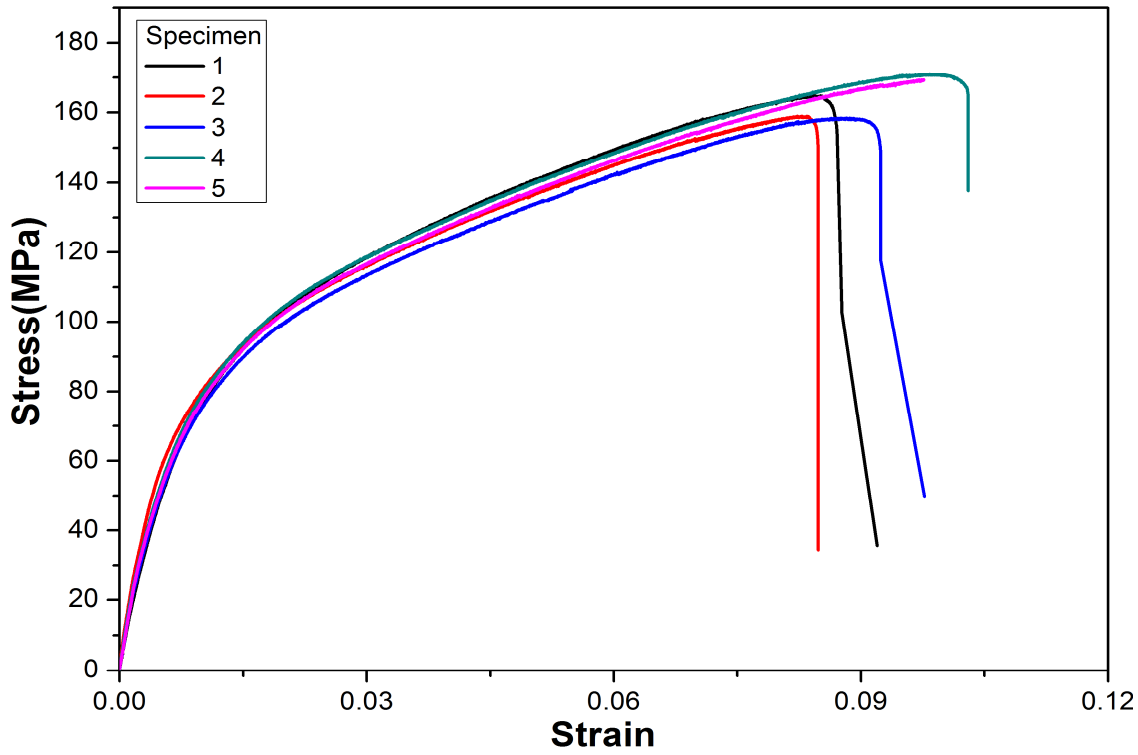


Figure 4.18. Tensile stress – strain graphs of biaxial carbon / epoxy composites after 1500 hours aging (the composites were aged as manufactured plates)

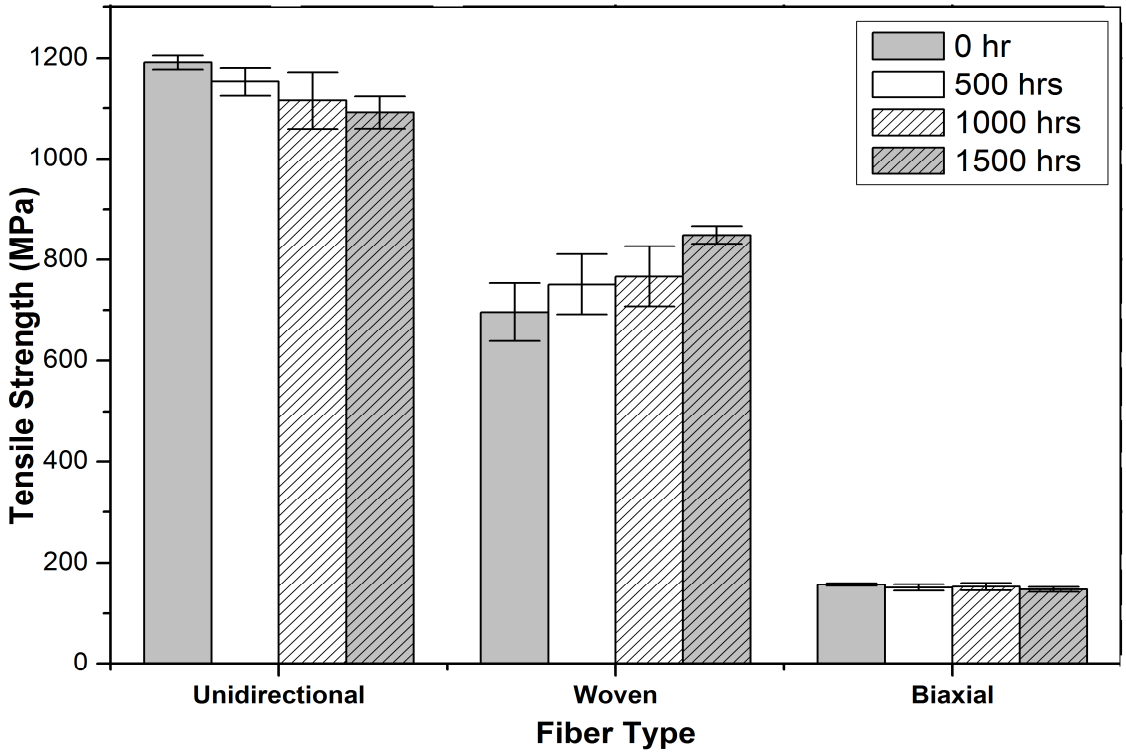


Figure 4.19. Change in tensile strength as a function of aging cycles for all composites which were cut into test specimens prior to aging

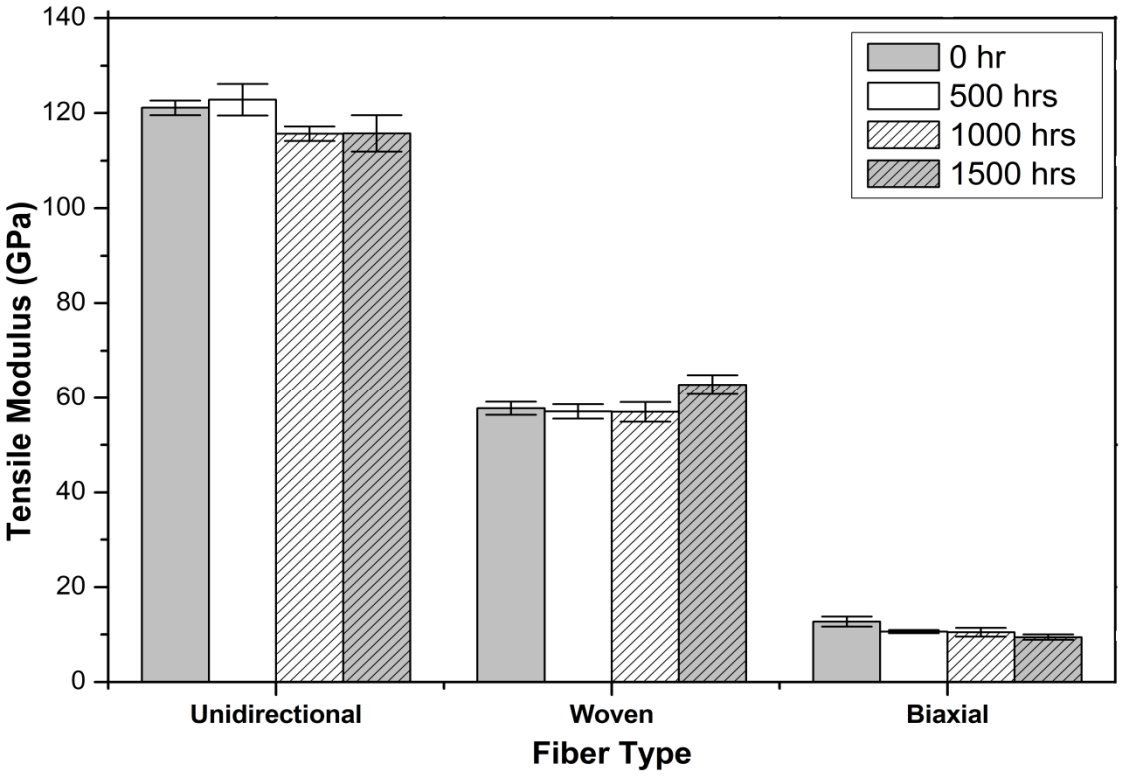


Figure 4.20. Change in tensile modulus as a function of aging cycles for all composites which were cut into test specimens prior to aging

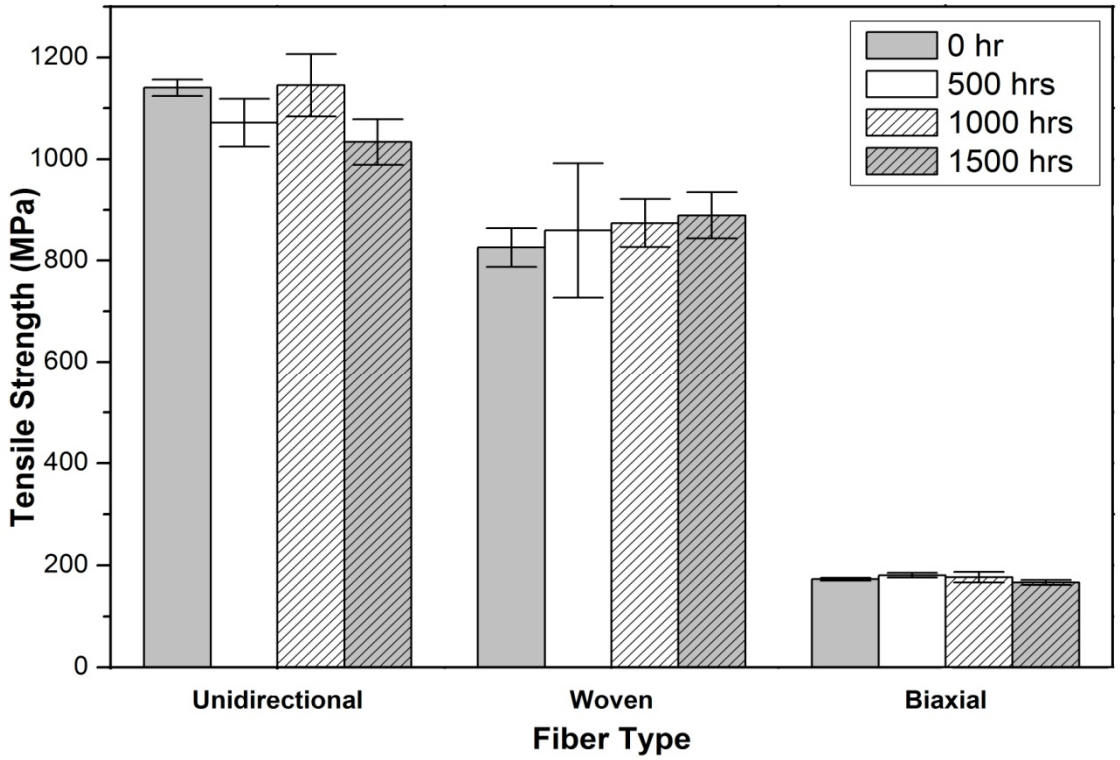


Figure 4.21. Change in tensile strength as a function of aging cycles for all composites which were aged as plates

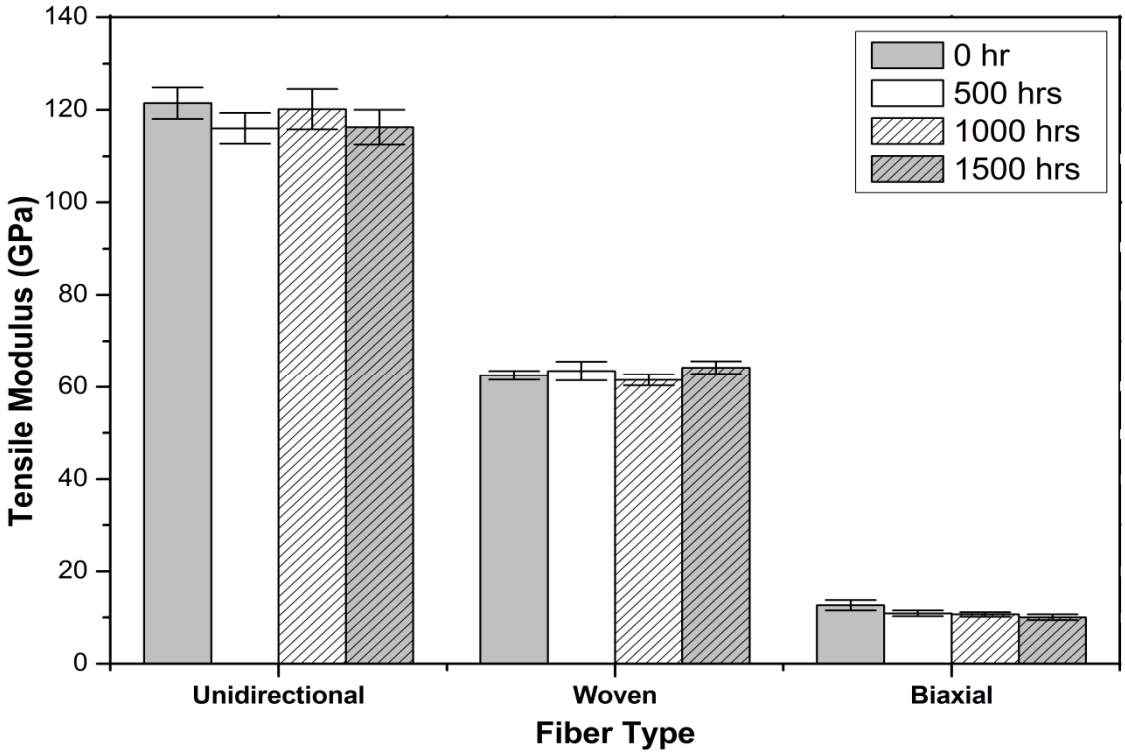


Figure 4.22. Change in tensile modulus as a function of aging cycles for all composites which were aged as plates

4.3.2. Flexural Tests

The results of the 3-point bending tests are given in Tables 4.21 to 4.32 and stress-strain graphs are shown in Figures 4.23 to 4.28 and 4.31 to 4.36 (the composites were aged as manufactured plates). Finally, the comparison of bending strength and flexural modulus values prior to and after aging are summarized in Figures 4.29 to 4.30 and 4.37 to 4.38.

The bending strength of the unidirectional composites decreased from 1208.50 to 1095.70 MPa which is equal to about 9.33% reduction in strength after 1500 hours aging. The flexural modulus of these composites decreased after 500 and 1000 hours aging, and showed slight increase after 1500 hours aging. For the woven composites, the bending strength decreased by about 12% and flexural modulus decreased by 5.67% after 1500 hours aging. Finally, the results for the biaxial composite showed reduction in bending strength and flexural modulus after 1500 hours aging. The reduction in bending strength was 16.32% and 9.54% in flexural modulus after 1500 hours aging.

However, the results are different for the as manufactured plates. The bending strength values increased by about 10% after 1500 hours for the unidirectional and woven composites. For the biaxial composite, the increase in bending strength was about 1.23%.

It can be concluded that the flexural properties of the composites aged as test specimens decreased due to aging cycles. On the other hand, the flexural properties of the composites that were aged as manufactured plates increased slightly after 1500 hours aging. The increase in flexural properties of the composites that were aged as manufactured plates can be interpreted as a result of high standard deviation values.

Table 4.21. Flexural properties of unidirectional carbon/epoxy composites prior to aging and after 500 hours aging

Aging Time	**Prior to Aging**			**After 500 Hours Aging**		
Sample #	**Bending Strength (MPa)**	**Flexural Modulus (GPa)**	**Flexural Strain at Break (%)**	**Bending Strength (MPa)**	**Flexural Modulus (GPa)**	**Flexural Strain at Break (%)**
1	1107.54	79.56	0.97	1056.97	78.43	0.94
2	1225.25	72.25	1.03	1035.03	64.98	0.97
3	1141.50	81.35	0.95	1128.52	67.94	1.13
4	1360.30	75.82	1.11	1073	63.89	0.87
5	1207.87	77.56	0.95	1162.90	71.90	1.04
Average	**1208.49**	**77.31**	**1.00**	**1091.28**	**69.43**	**0.99**
Std. Dev. (±)	**97.47**	**3.51**	**0.06**	**52.89**	**5.91**	**0.09**

Table 4.22. Flexural properties of unidirectional carbon / epoxy composites after 1000 hours and 1500 hours aging

Aging Time	**After 1000 Hours Aging**			**After 1500 Hours Aging**		
Sample #	**Bending Strength (MPa)**	**Flexural Modulus (GPa)**	**Flexural Strain at Break (%)**	**Bending Strength (MPa)**	**Flexural Modulus (GPa)**	**Flexural Strain at Break (%)**
1	1086.90	72.66	0.90	1124.61	86.63	1.05
2	989.24	75.74	0.77	1042.89	76.60	0.84
3	1175.74	78.31	0.93	937.22	69.90	0.90
4	956.85	66.70	0.78	1207.86	80	0.94
5	1113.87	73.94	0.94	1165.81	75.11	0.90
Average	**1064.52**	**73.47**	**0.88**	**1095.67**	**77.65**	**0.92**
Std. Dev. (±)	**90.22**	**4.33**	**0.06**	**107.51**	**6.2**	**0.07**

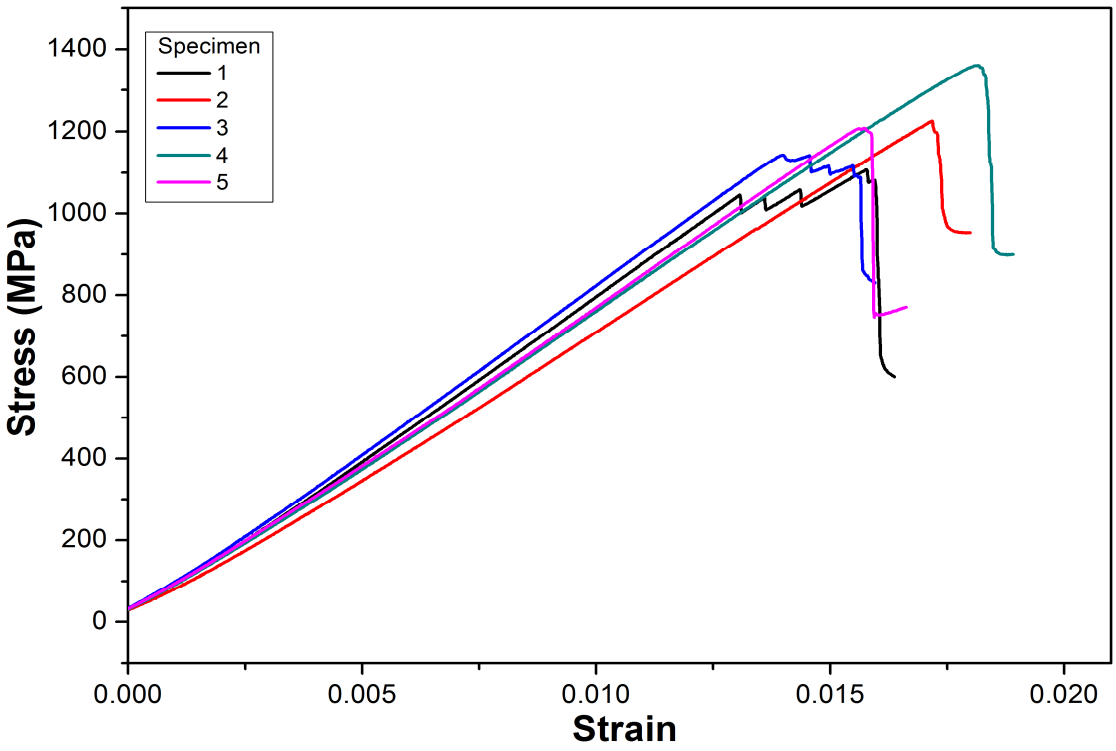


Figure 4.23. Flexural stress – strain graphs of unidirectional carbon / epoxy composites prior to aging

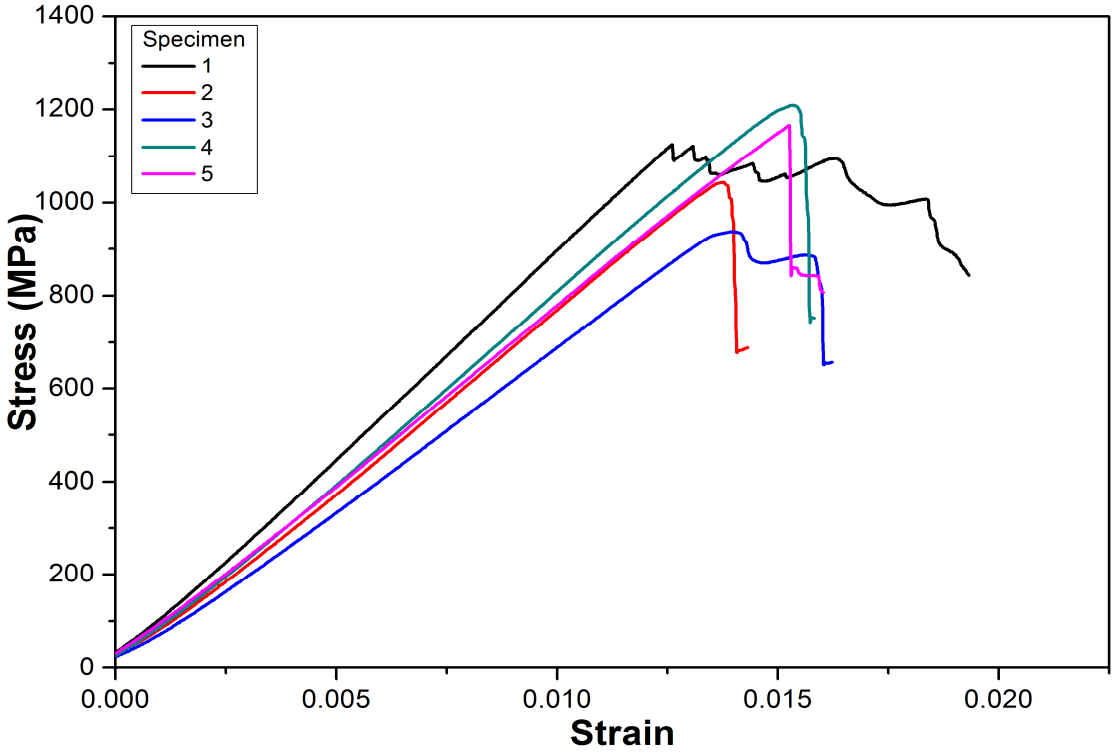


Figure 4.24. Flexural stress – strain graphs of unidirectional carbon / epoxy composites after 1500 hours aging

Table 4.23. Flexural properties of woven carbon/epoxy composites prior to aging and after 500 hours aging

Aging Time	Prior to Aging			After 500 Hours Aging		
Sample #	Bending Strength (MPa)	Flexural Modulus (GPa)	Flexural Strain at Break (%)	Bending Strength (MPa)	Flexural Modulus (GPa)	Flexural Strain at Break (%)
1	839.70	46.62	1.63	665.51	38.35	1.74
2	849.37	42.62	1.65	657.76	37.58	1.85
3	754.97	42.60	1.37	673.40	40.41	1.52
4	859.76	46.87	1.39	713.08	41.03	1.41
5	751.68	43.18	1.38	668.14	40.15	1.48
Average	**811.10**	**44.38**	**1.48**	**675.58**	**39.50**	**1.60**
Std. Dev. (±)	**53.22**	**2.17**	**0.14**	**21.70**	**1.46**	**0.18**

Table 4.24. Flexural properties of woven carbon / epoxy composites after 1000 hours and 1500 hours aging

Aging Time	After 1000 Hours Aging			After 1500 Hours Aging		
Sample #	Bending Strength (MPa)	Flexural Modulus (GPa)	Flexural Strain at Break (%)	Bending Strength (MPa)	Flexural Modulus (GPa)	Flexural Strain at Break (%)
1	747.77	40.76	1.39	733.09	44.01	1.38
2	753.42	41.68	1.37	697.14	40.48	1.58
3	774.03	41.93	1.39	696.84	41.22	1.25
4	772.39	41.97	1.40	703.59	42.17	1.16
5	715.01	40.72	1.46	738.31	41.41	1.41
Average	**752.52**	**41.41**	**1.40**	**713.79**	**41.86**	**1.35**
Std. Dev. (±)	**23.91**	**6.22**	**0.03**	**20.26**	**1.34**	**0.16**

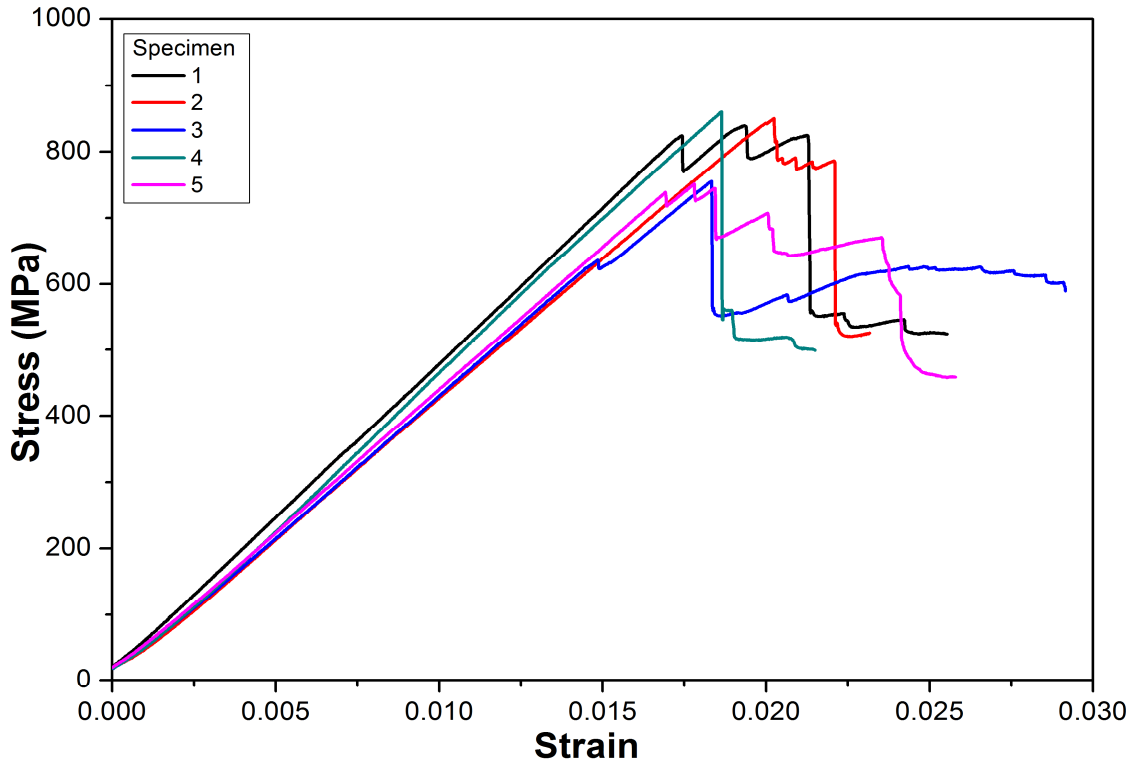


Figure 4.25. Flexural stress – strain graphs of woven carbon / epoxy composites prior to aging

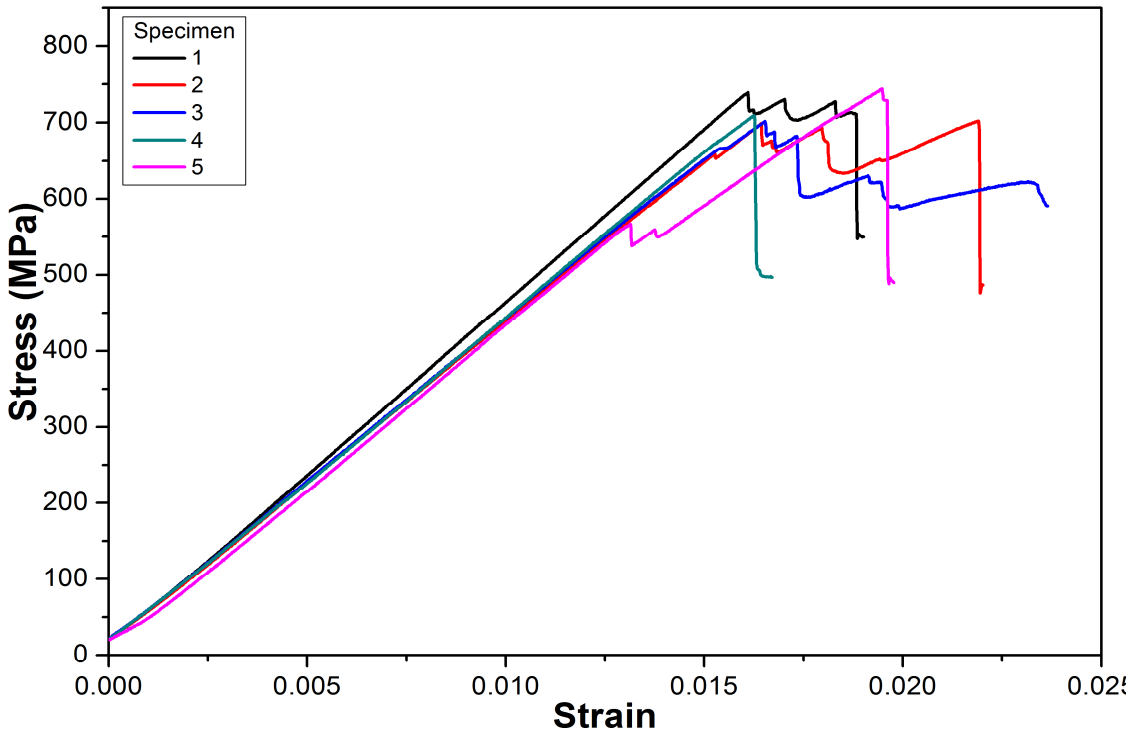


Figure 4.26. Flexural stress – strain graphs of woven carbon / epoxy composites after 1500 hours aging

Table 4.25. Flexural properties of biaxial carbon/epoxy composites prior to aging and after 500 hours aging

Aging Time	**Prior to Aging**			**After 500 Hours Aging**		
Sample #	**Bending Strength (MPa)**	**Flexural Modulus (GPa)**	**Flexural Strain at Break (%)**	**Bending Strength (MPa)**	**Flexural Modulus (GPa)**	**Flexural Strain at Break (%)**
1	357.06	10.09	5.10	296.31	9.43	6.86
2	335.01	9.34	5.74	283.25	8.27	8.02
3	341.18	9.63	6.32	268.60	7.70	7.26
4	373.49	11.08	5.23	313.71	9.53	7.16
5	342.53	10.63	5.78	304.11	8.96	7.80
Average	**349.85**	**10.16**	**5.63**	**293.19**	**8.78**	**7.42**
Std. Dev. (±)	**15.49**	**0.71**	**0.48**	**17.70**	**0.78**	**0.47**

Table 4.26. Flexural properties of biaxial carbon / epoxy composites after 1000 hours and 1500 hours aging

Aging Time	**After 1000 Hours Aging**			**After 1500 Hours Aging**		
Sample #	**Bending Strength (MPa)**	**Flexural Modulus (GPa)**	**Flexural Strain at Break (%)**	**Bending Strength (MPa)**	**Flexural Modulus (GPa)**	**Flexural Strain at Break (%)**
1	324.98	10.23	6.76	282.31	8.41	5.46
2	325.99	9.68	6.94	268.31	8.45	6.07
3	347.35	11.52	5.65	294.32	9.65	6.89
4	344.13	10.10	7.38	319.95	9.98	5.02
5	343.71	11.04	5.34	298.88	9.44	5.97
Average	**337.23**	**10.52**	**6.41**	**292.75**	**9.19**	**5.88**
Std. Dev. (±)	**10.82**	**0.74**	**0.87**	**19.27**	**0.71**	**0.70**

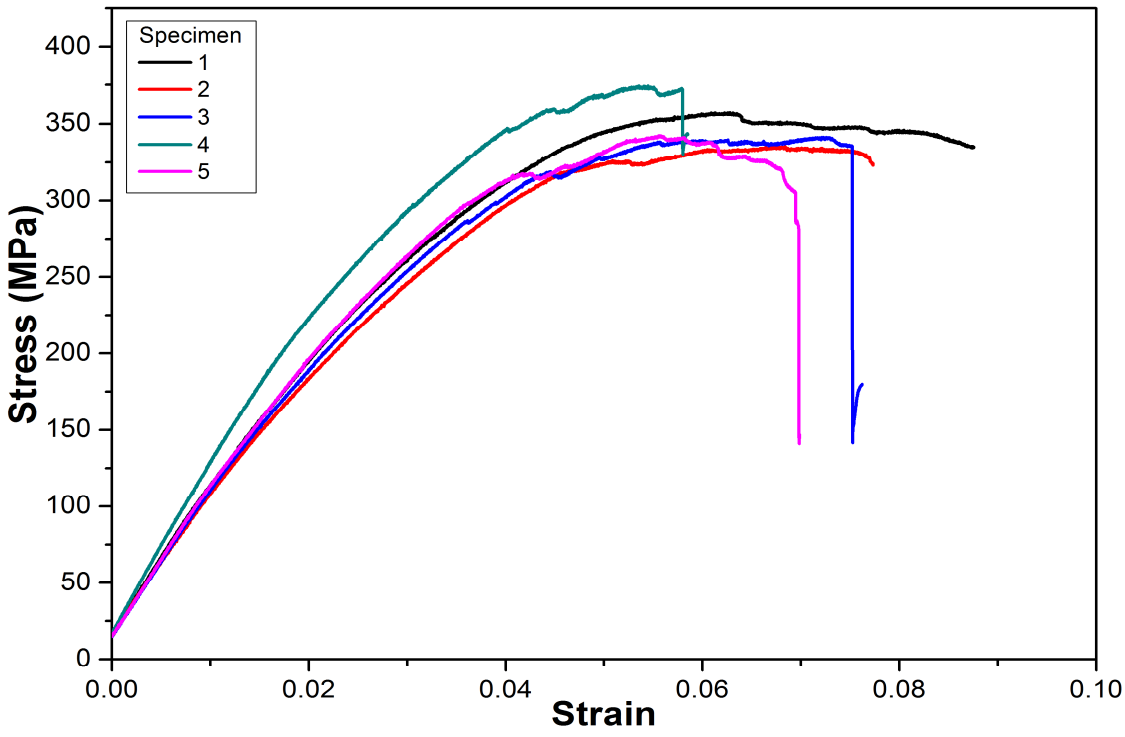


Figure 4.27. Flexural stress – strain graphs of biaxial carbon / epoxy composites prior to aging

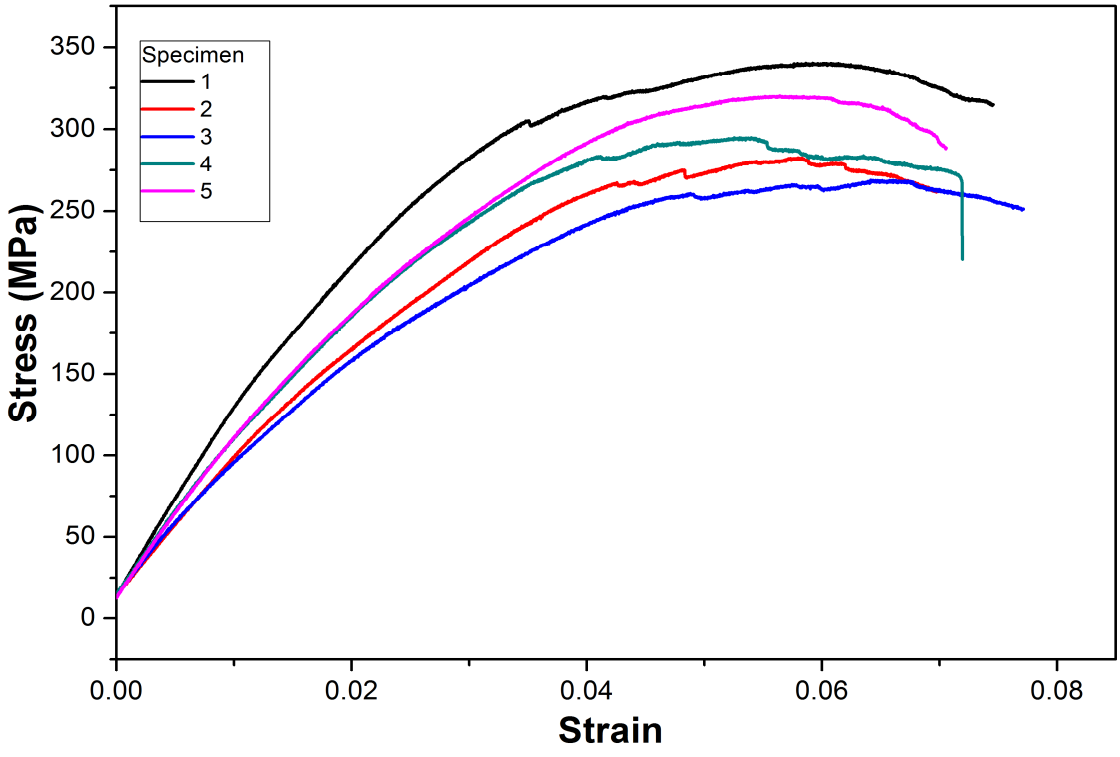


Figure 4.28. Flexural stress – strain graphs of biaxial carbon / epoxy composites after 1500 hours aging

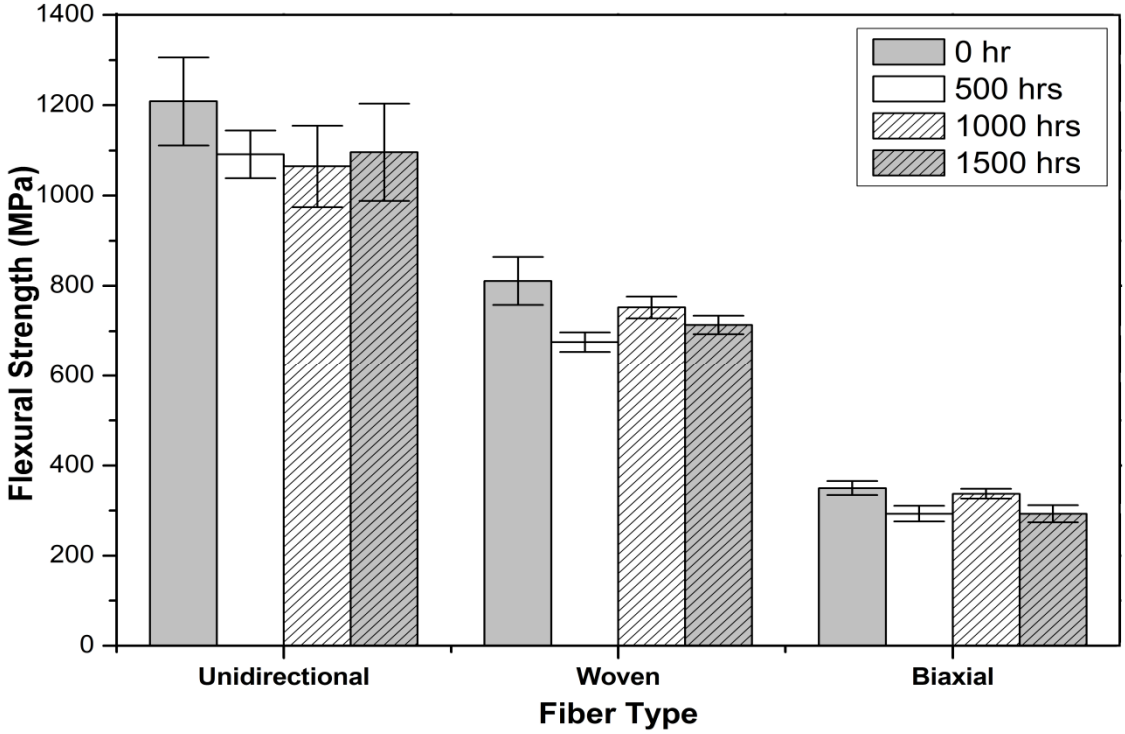


Figure 4.29. Change in flexural strength as a function of aging cycles for all composites which were cut into test specimens prior to aging

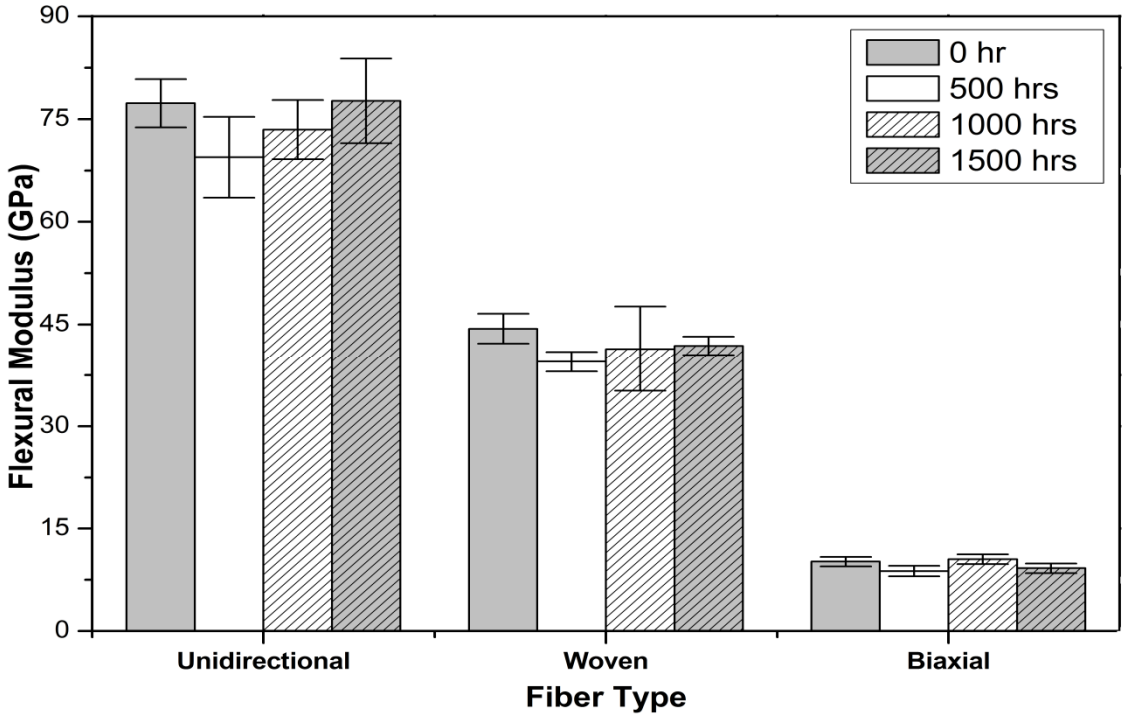


Figure 4.30. Change in flexural modulus as a function of aging cycles for all composites which were cut into test specimens prior to aging

Table 4.27. Flexural properties of unidirectional carbon/epoxy composites prior to aging and after 500 hours aging (the composites were aged as manufactured plates)

Aging Time	Prior to Aging			After 500 Hours Aging		
Sample #	Bending Strength (MPa)	Flexural Modulus (GPa)	Flexural Strain at Break (%)	Bending Strength (MPa)	Flexural Modulus (GPa)	Flexural Strain at Break (%)
1	986.32	63.13	1.07	1134.49	79.59	0.98
2	891.58	68.57	1.08	1057.87	77.40	0.83
3	987	72.56	0.92	1213.70	77.40	1.00
4	1137.57	71.61	1.01	1179.95	83.04	0.86
5	954.85	66.98	0.91	1055.64	75.04	0.90
Average	**991.46**	**68.57**	**0.99**	**1128.33**	**78.49**	**0.91**
Std. Dev. (±)	**90.42**	**3.78**	**0.08**	**71.13**	**3.00**	**0.07**

Table 4.28. Flexural properties of unidirectional carbon/epoxy composites after 1000 hours and 1500 hours aging (the composites were aged as manufactured plates)

Aging Time	After 1000 Hours Aging			After 1500 Hours Aging		
Sample #	Bending Strength (MPa)	Flexural Modulus (GPa)	Flexural Strain at Break (%)	Bending Strength (MPa)	Flexural Modulus (GPa)	Flexural Strain at Break (%)
1	1016.24	70.26	0.89	1001.68	76.03	0.77
2	1185.22	75.94	0.95	1066.35	78.37	0.78
3	1000.49	73.65	0.81	1065.58	77.05	0.82
4	1039.31	75.64	0.89	1186.42	75.87	1.01
5	947.53	75.61	0.76	1134.61	73.50	0.90
Average	**1037.74**	**74.22**	**0.86**	**1090.92**	**76.16**	**0.85**
Std. Dev. (±)	**89.07**	**2.39**	**0.07**	**71.13**	**1.79**	**0.10**

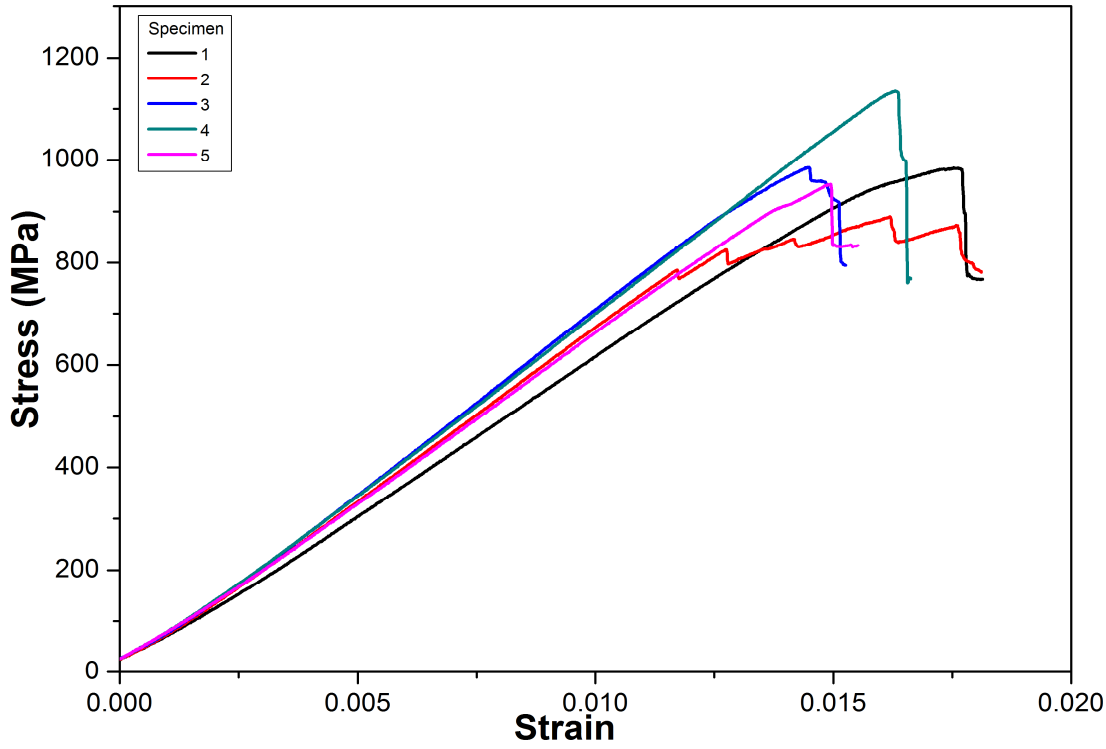


Figure 4.31. Flexural stress – strain graphs of unidirectional carbon / epoxy composites prior to aging (the composites were aged as manufactured plates)

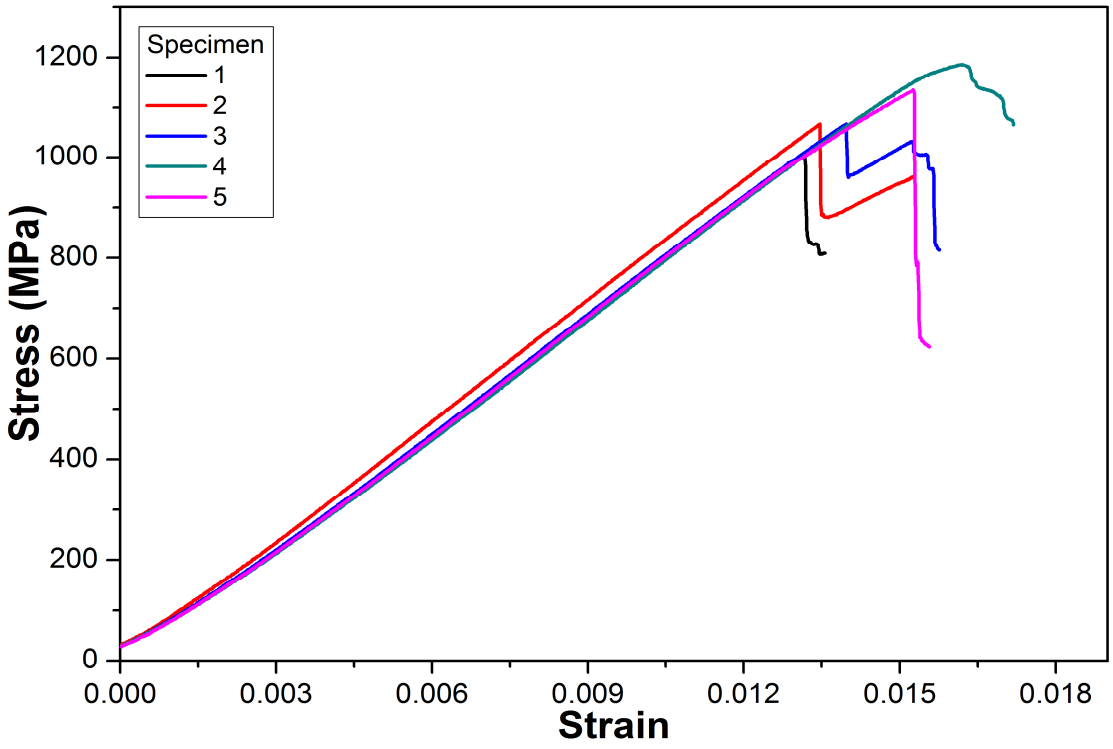


Figure 4.32. Flexural stress – strain graphs of unidirectional carbon / epoxy composites after 1500 hours aging (the composites were aged as manufactured plates)

Table 4.29. Flexural properties of woven carbon/epoxy composites prior to aging and after 500 hours aging (the composites were aged as manufactured plates)

Aging Time	**Prior to Aging**			**After 500 Hours Aging**		
Sample #	**Bending Strength (MPa)**	**Flexural Modulus (GPa)**	**Flexural Strain at Break (%)**	**Bending Strength (MPa)**	**Flexural Modulus (GPa)**	**Flexural Strain at Break (%)**
1	892.3	47.05	1.41	898.03	53.13	1.21
2	763.81	45.64	1.57	911.86	52.47	1.37
3	762.06	45.67	1.20	812.04	53.02	1.10
4	850.84	44.75	1.36	1063.14	55.13	1.34
5	866.56	49.33	1.32	846.43	53.94	1.08
Average	**827.11**	**46.49**	**1.37**	**906.31**	**53.54**	**1.22**
Std. Dev. (±)	**60.43**	**1.79**	**0.13**	**96.39**	**1.03**	**0.13**

Table 4.30. Flexural properties of woven carbon/epoxy composites after 1000 hours and 1500 hours aging (the composites were aged as manufactured plates)

Aging Time	**After 1000 Hours Aging**			**After 1500 Hours Aging**		
Sample #	**Bending Strength (MPa)**	**Flexural Modulus (GPa)**	**Flexural Strain at Break (%)**	**Bending Strength (MPa)**	**Flexural Modulus (GPa)**	**Flexural Strain at Break (%)**
1	736.56	47.06	1.10	929.50	51.27	1.26
2	872.46	51.98	1.18	945.02	53.76	1.37
3	750.41	47.87	1.12	887.70	51.80	1.24
4	661.32	43.08	1.06	962.86	51.20	1.31
5	640.45	47.91	1.16	828.14	49.88	1.15
Average	**732.24**	**47.58**	**1.12**	**910.65**	**51.58**	**1.26**
Std. Dev. (±)	**91.47**	**3.16**	**0.04**	**53.84**	**1.40**	**0.08**

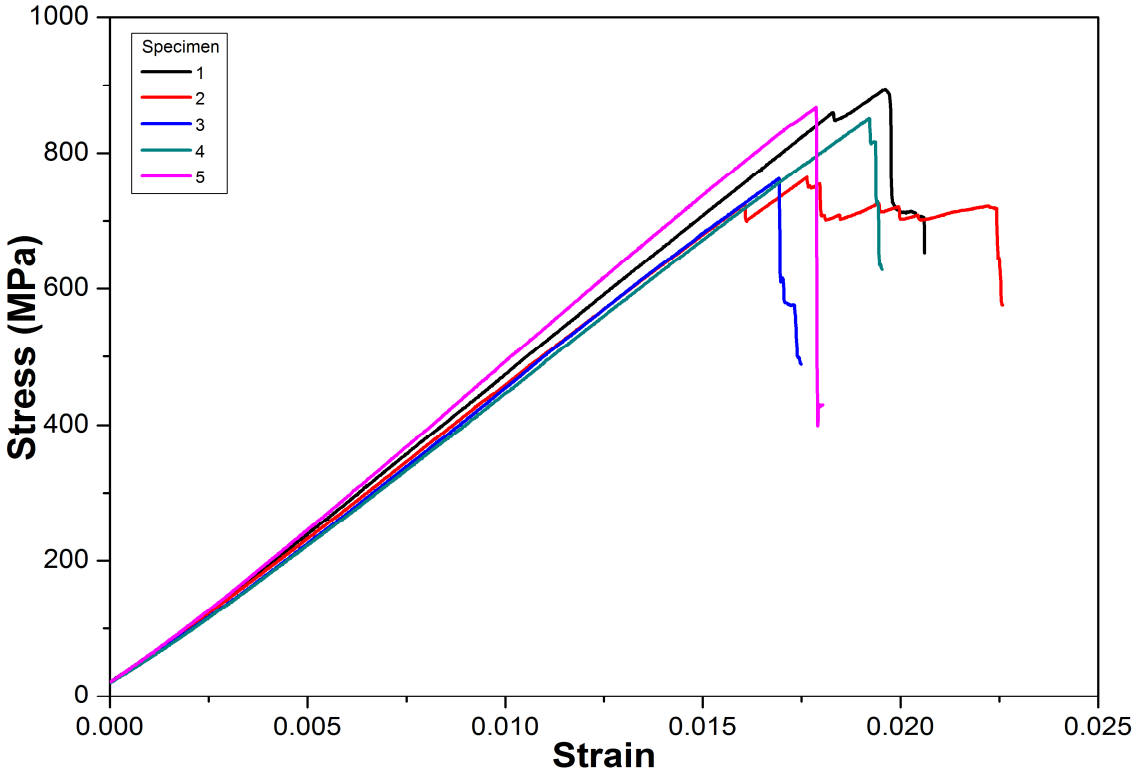


Figure 4.33. Flexural stress – strain graphs of woven carbon / epoxy composites prior to aging (the composites were aged as manufactured plates)

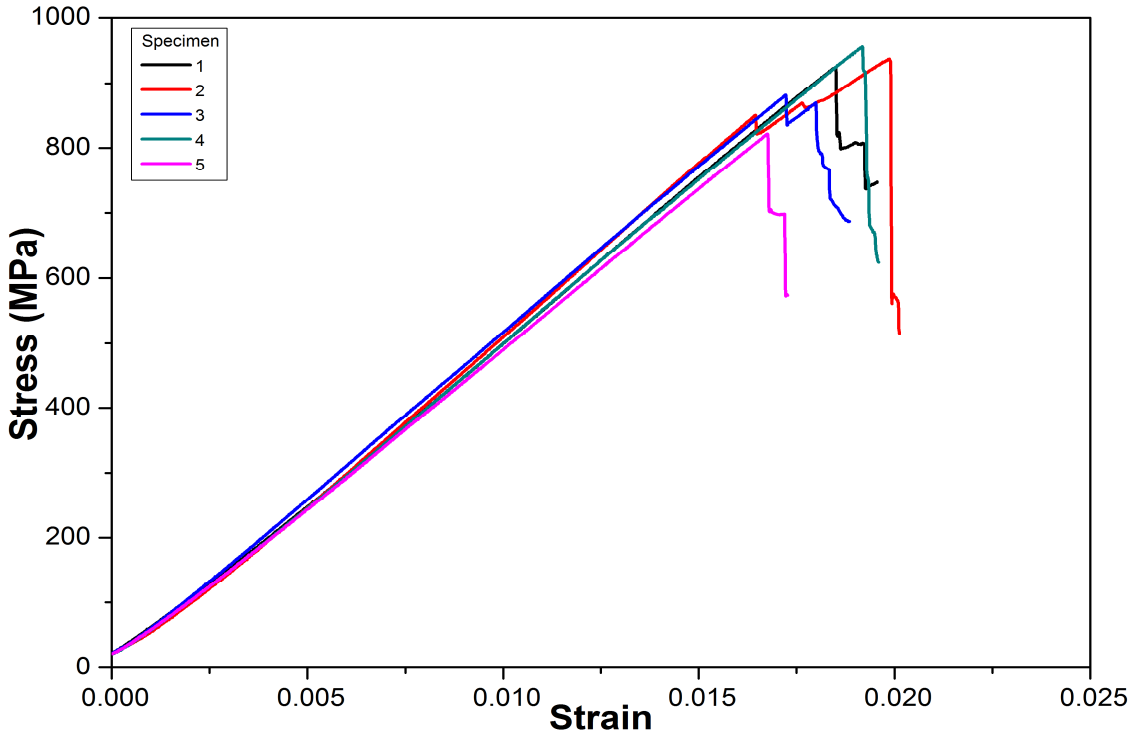


Figure 4.34. Flexural stress – strain graphs of woven carbon / epoxy composites after 1500 hours aging (the composites were aged as manufactured plates)

Table 4.31. Flexural properties of biaxial carbon/epoxy composites prior to aging and after 500 hours aging (the composites were aged as manufactured plates)

Aging Time	**Prior to Aging**			**After 500 Hours Aging**		
Sample #	**Bending Strength (MPa)**	**Flexural Modulus (GPa)**	**Flexural Strain at Break (%)**	**Bending Strength (MPa)**	**Flexural Modulus (GPa)**	**Flexural Strain at Break (%)**
1	315.59	9.58	5.88	418.03	13.06	7.01
2	340.99	9.46	6.10	420.73	14.53	7.15
3	370.92	12.18	5.33	444.74	14.81	5.04
4	286.34	8.54	6.26	396.49	12.99	6.26
5	370.36	11.98	5.45	369.02	12.45	7.67
Average	**336.84**	**10.35**	**5.8**	**409.80**	**13.57**	**6.62**
Std. Dev. (±)	**36.41**	**1.63**	**0.40**	**28.49**	**1.03**	**1.01**

Table 4.32. Flexural properties of biaxial carbon/epoxy composites after 1000 hours and 1500 hours aging (the composites were aged as manufactured plates)

Aging Time	**After 1000 Hours Aging**			**After 1500 Hours Aging**		
Sample #	**Bending Strength (MPa)**	**Flexural Modulus (GPa)**	**Flexural Strain at Break (%)**	**Bending Strength (MPa)**	**Flexural Modulus (GPa)**	**Flexural Strain at Break (%)**
1	373.43	10.87	4.94	369.42	11.98	5.03
2	391.62	11.85	5.13	356.31	11.13	6.05
3	369.62	10.24	5.91	328.81	10.57	6.09
4	461.34	12.58	4.92	348.95	9.93	5.27
5	429.92	14.34	4.85	301.51	9.07	5.04
Average	**405.19**	**11.98**	**5.15**	**341**	**10.53**	**5.49**
Std. Dev. (±)	**39.43**	**1.59**	**0.43**	**26.52**	**1.11**	**0.53**

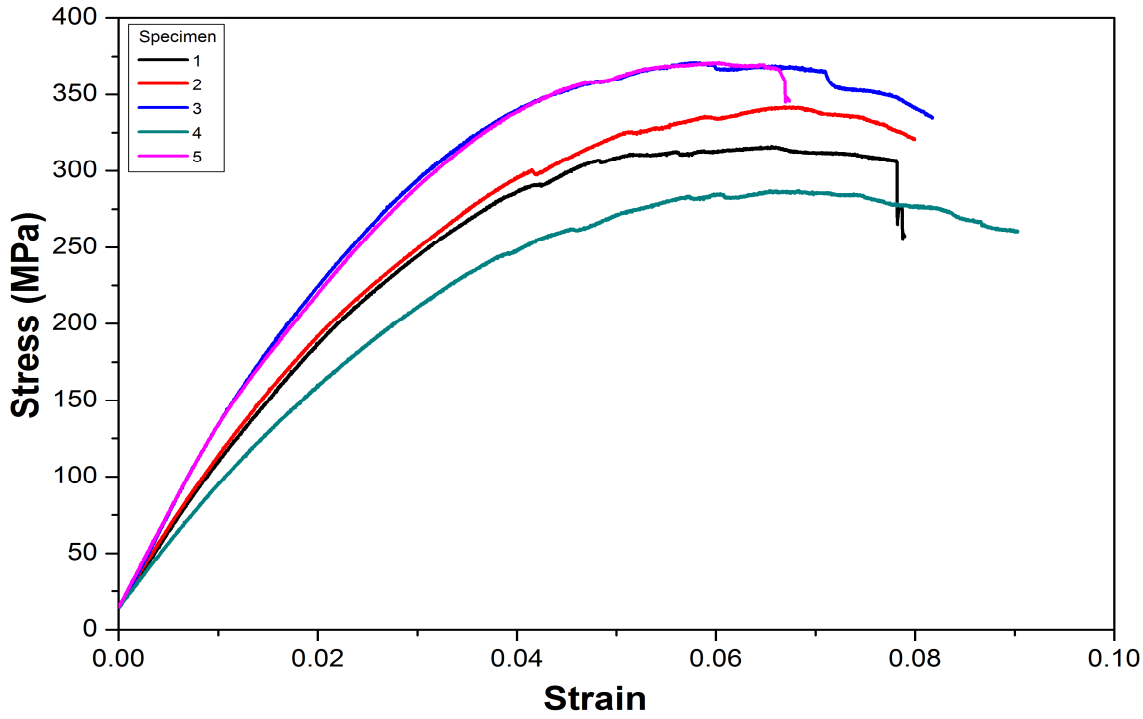


Figure 4.35. Flexural stress – strain graphs of biaxial carbon / epoxy composites prior to aging (the composites were aged as manufactured plates)

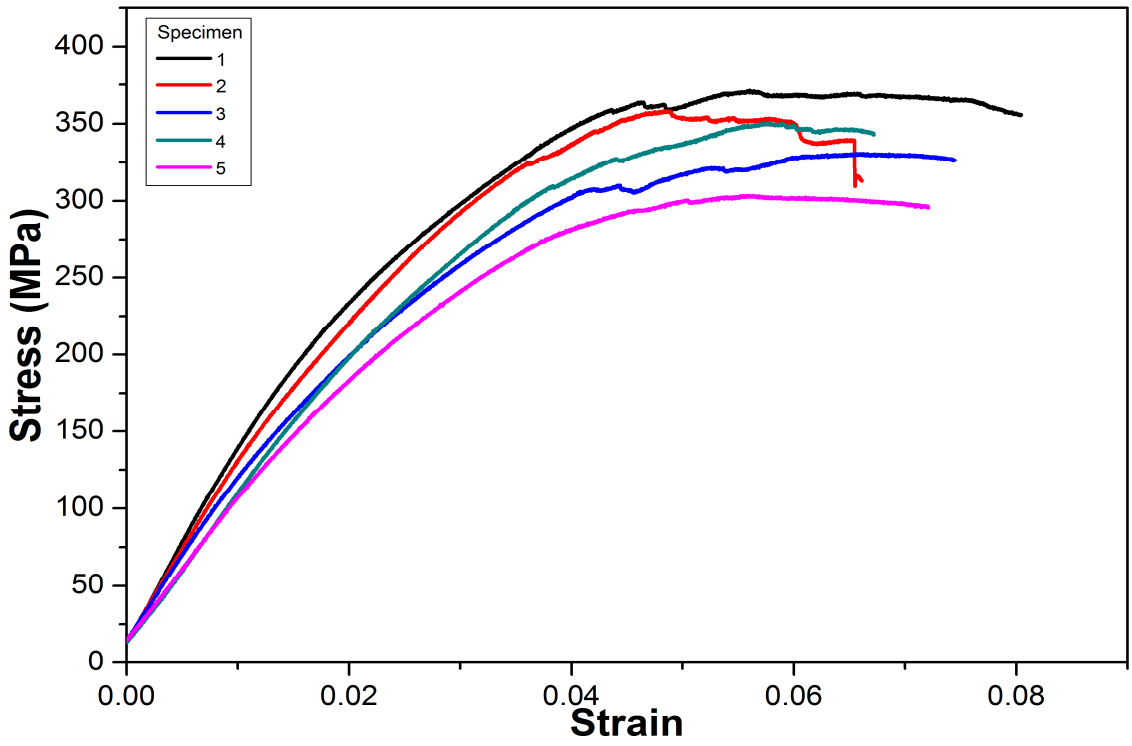


Figure 4.36. Flexural stress – strain graphs of biaxial carbon / epoxy composites after 1500 hours aging (the composites were aged as manufactured plates)

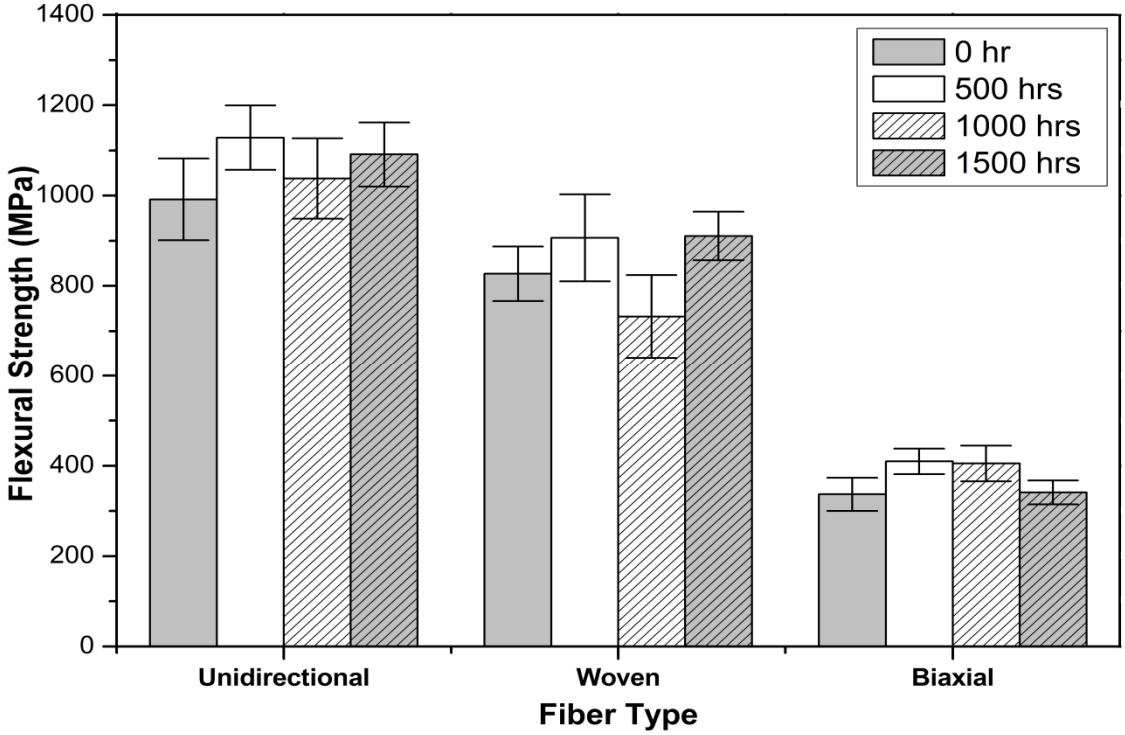


Figure 4.37. Change in flexural strength as a function of aging cycles for all composites which were aged as manufactured plates

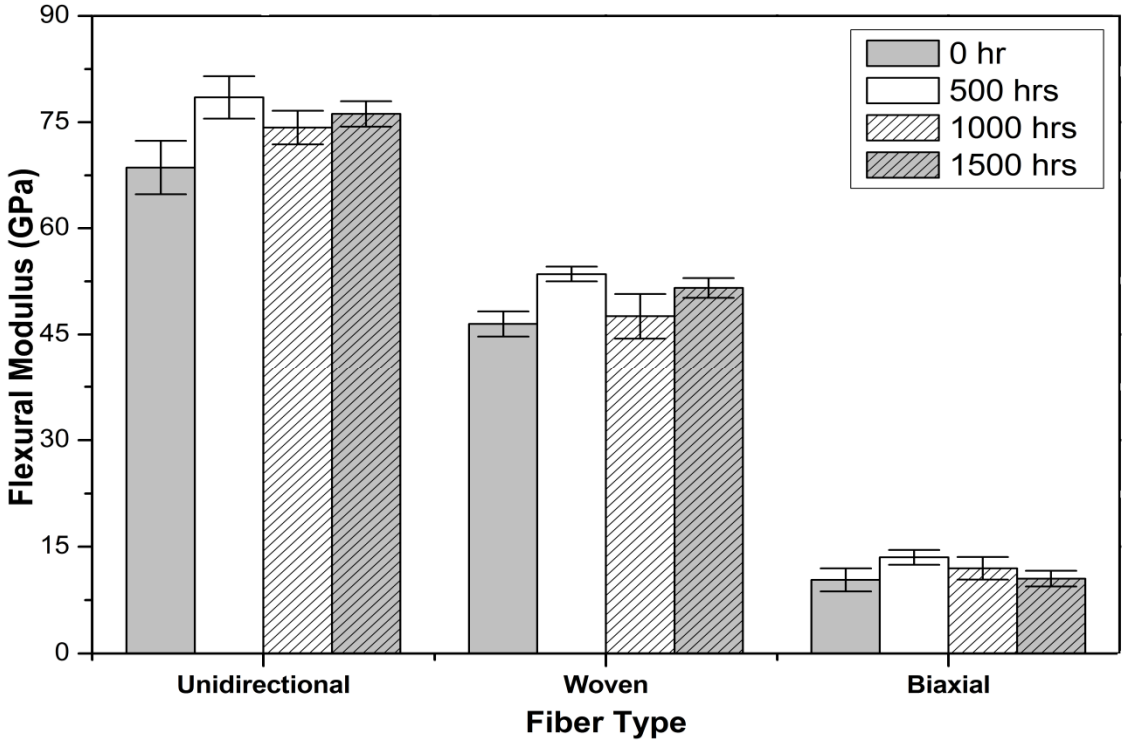


Figure 4.38. Change in flexural modulus as a function of aging cycles for all composites which were aged as manufactured plates

4.4. Microstructural Properties

4.4.1. Fiber Volume Fraction

Microstructural features (arrangement and orientation of fibers and etc.) are very important for designing a composite with expected properties. Since the fibers are the main constituents of composites which bear the loads, the volume fraction of the fibers are critical to determine. The fiber volume fractions for each sample are given in Tables 4.33 and 4.34.

Table 4.33. Fiber volume fractions for the composites that were cut into specimens prior to aging

Sample #	Unidirectional	Woven	Biaxial
1	54.7	54.8	50.6
2	53	55.4	50.2
3	56.7	56.4	50.5
4	53.8	55.1	50.7
5	56	56.6	46.5
Average	**54.8**	**55.6**	**49.7**
Std. Dev. (±)	**1.52**	**0.79**	**1.79**

Table 4.34. Fiber volume fractions for the composites that were aged as manufactured plates

Sample #	Unidirectional	Woven	Biaxial
1	54.4	55.8	49
2	53.5	55.8	49.2
3	51.9	55.6	49.7
4	51.7	55.1	49
5	51.7	55.1	48.6
Average	**52.6**	**55.4**	**49.1**
Std. Dev. (±)	**1.24**	**0.35**	**0.4**

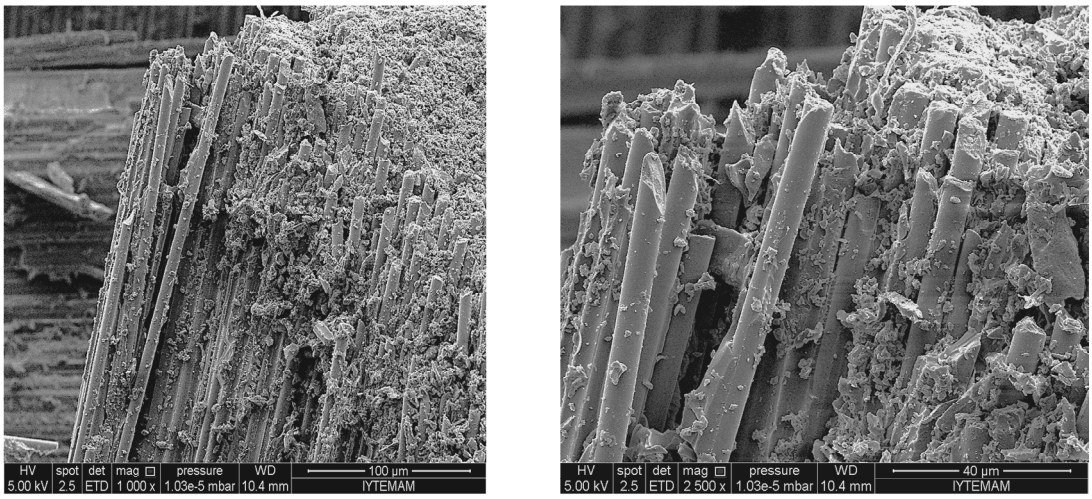
4.4.2. Scanning Electron Microscopy (SEM) Analysis of Tensile Fracture Surfaces

Tensile fracture surfaces of all composites were investigated after each tensile test. SEM images of tensile fracture surfaces for all specimens prior to and after 500, 1000 and 1500 hours aging were depicted in figures below. Figures 4.39 to 4.42 show the SEM micrographs for the woven composite samples which were cut into specimens prior to aging. Figures 4.43 to 4.46 are given for the unidirectional composite samples which were cut into specimens prior to aging. Finally, Figures 4.47 to 4.50 show the scanning electron micrographs for the biaxial ±45 composite samples which were cut into specimens prior to aging. In addition, the specimens aged as manufactured plates were analysed and SEM images are given in Figures from 4.51 to 4.62.

It can be seen from SEM micrographs in Figures 4.39 to 4.42, several regions containing the epoxy matrix are recovering the fiber surface and indicating better adhesion compared to unaged specimens. However, in some regions fiber matrix debonding can be clearly observed. In addition, after 500 hours aging matrix hackles began to form adjacent to the fibers. In Figures 4.55 to 4.58, SEM images exhibit typical tensile fracture surface. After 1500 hours aging, in addition to fiber matrix debonding, little amount of fibers are seen to be degraded.

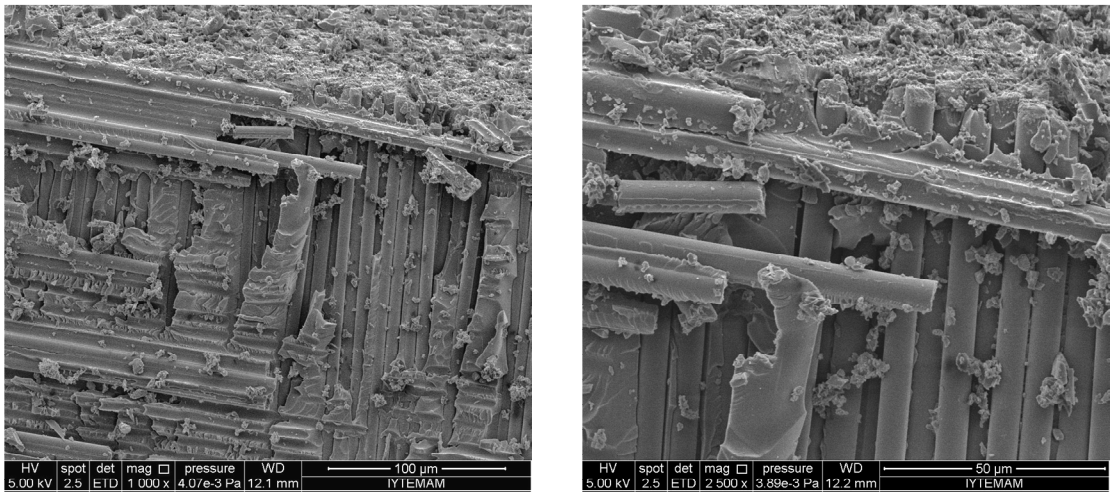
Compared to unaged specimens, no significant difference is observed from the SEM images of tensile fracture surfaces of unidirectional composites after aging. Fiber matrix debonding can be seen from all of the images. With increasing aging time, degradation of adhesion between the fibers and matrix is more clear in some regions of unidirectional composites. Micrographs of fractured specimens of unidirectional composites also showed fiber pull-out and fiber breakage in some regions for both specimen types.

For the biaxial composites, typically less matrix is adhering to fibers and fiber – matrix debonding can be observed in Figures 4.47 to 4.50. Also, for the composites aged as manufactured plates, SEM observations show more significant fiber matrix debonding and fiber pull-out with increasing aging cycles.



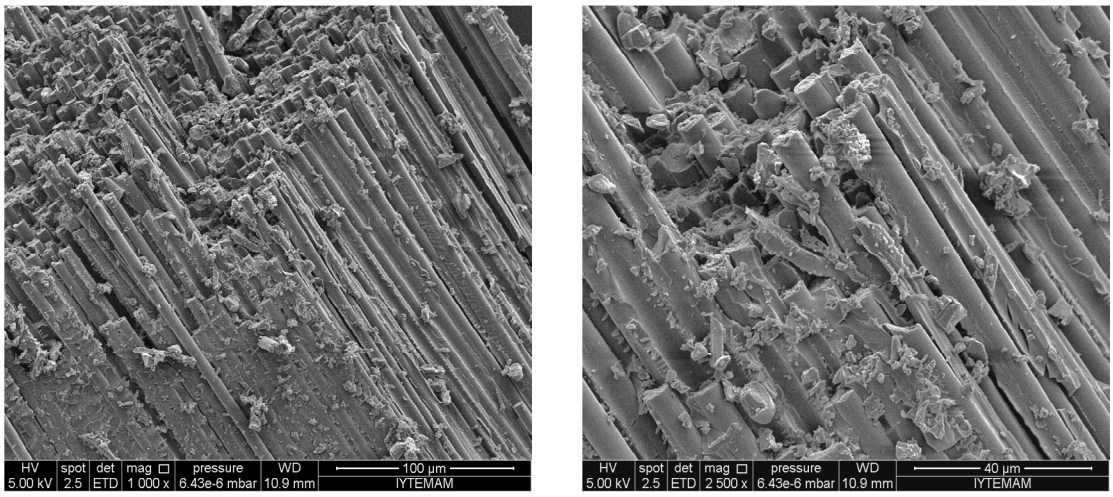
(a) (b)

Figure 4.39. Scanning electron micrograph of tensile fracture surface of woven carbon fiber / epoxy composite prior to aging (the composites were cut into specimens before aging) (a) 1000X (b)2500X



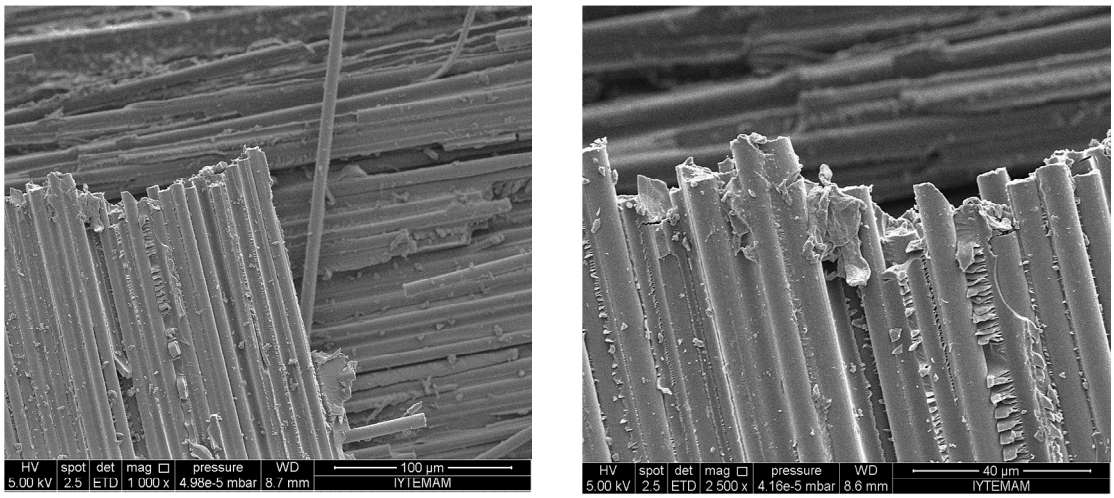
(a) (b)

Figure 4.40. Scanning electron micrograph of tensile fracture surface of woven carbon fiber / epoxy composite after 500 hours aging (the composites were cut into specimens before aging) (a) 1000X (b)2500X



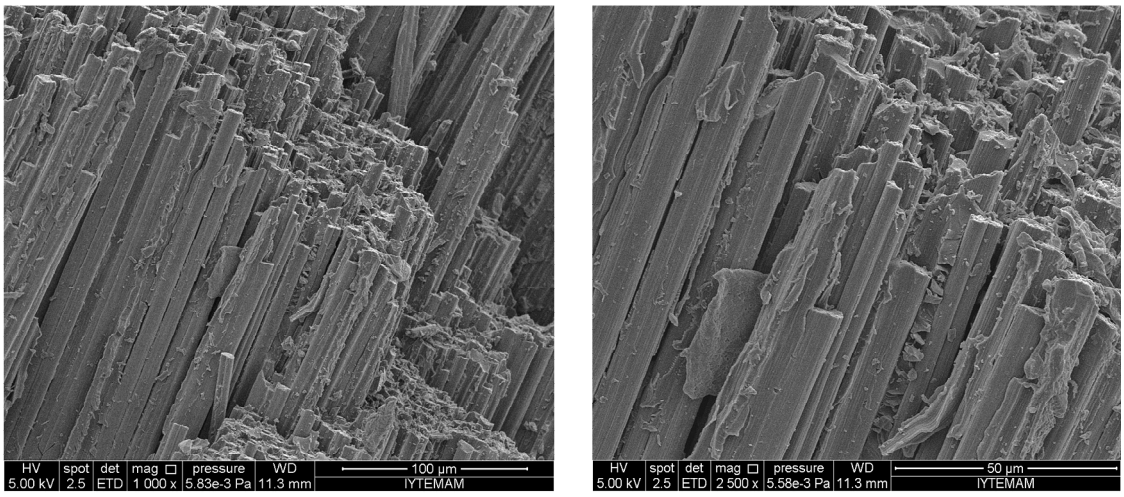
(a) (b)

Figure 4.41. Scanning electron micrograph of tensile fracture surface of woven carbon fiber / epoxy composite after 1000 hours aging (the composites were cut into specimens before aging) (a) 1000X (b)2500X



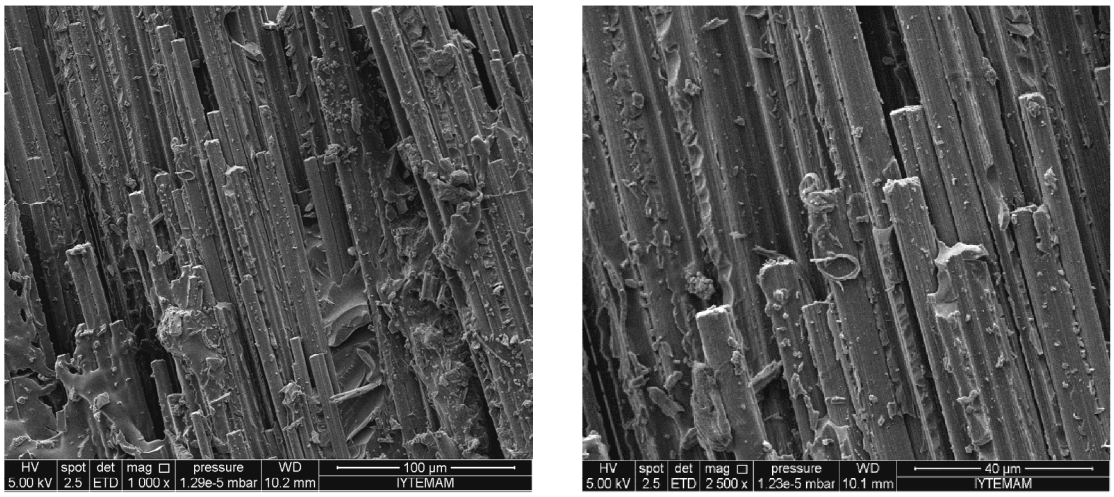
(a) (b)

Figure 4.42. Scanning electron micrograph of tensile fracture surface of woven carbon fiber / epoxy composite after 1500 hours aging (the composites were cut into specimens before aging) (a) 1000X (b)2500X



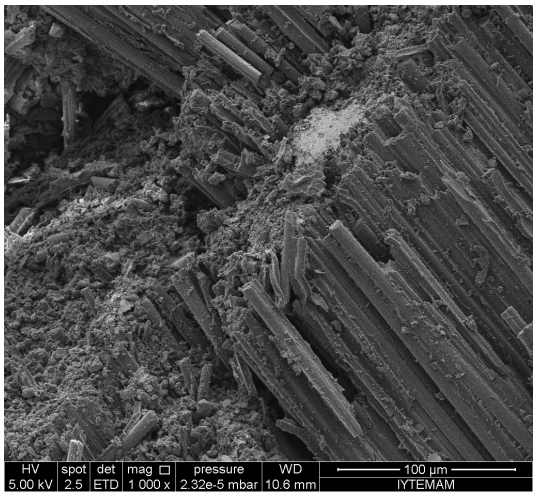
(a) (b)

Figure 4.43. Scanning electron micrograph of tensile fracture surface of unidirectional carbon fiber / epoxy composite prior to aging (the composites were cut into specimens before aging) (a) 1000X (b)2500X

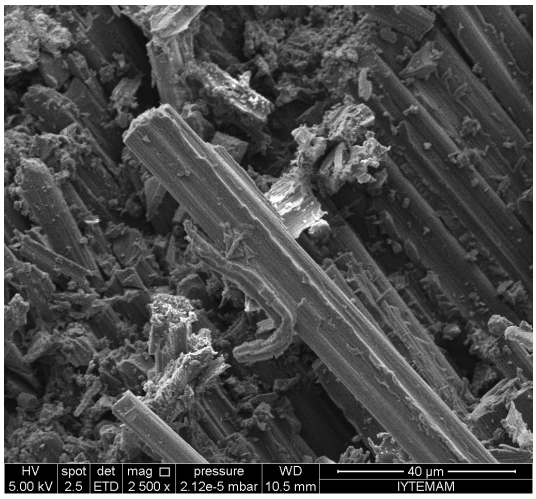


(a) (b)

Figure 4.44. Scanning electron micrograph of tensile fracture surface of unidirectional carbon fiber / epoxy composite after 500 hours aging (the composites were cut into specimens before aging) (a) 1000X (b)2500X

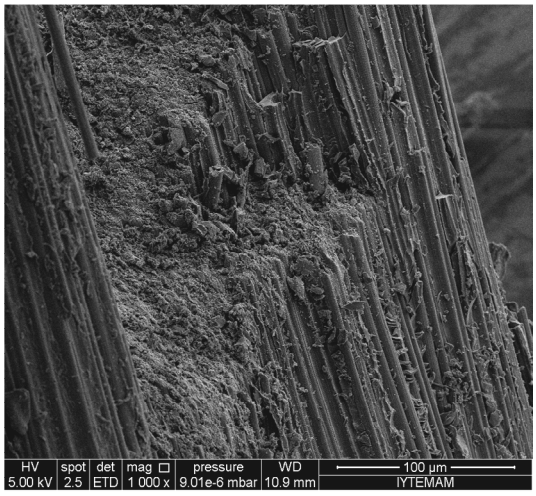


(a)

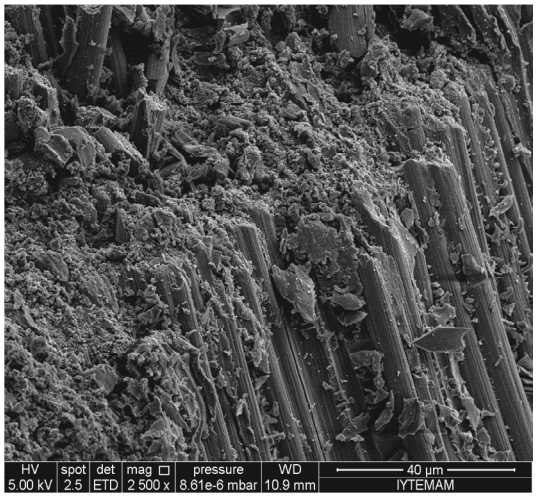


(b)

Figure 4.45. Scanning electron micrograph of tensile fracture surface of unidirectional carbon fiber / epoxy composite after 1000 hours aging (the composites were cut into specimens before aging) (a) 1000X (b)2500X

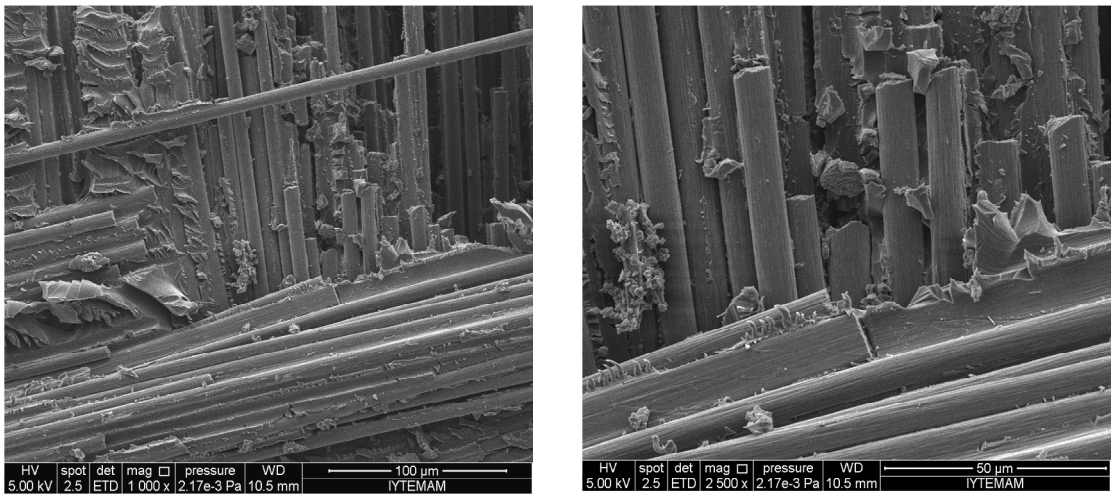


(a)



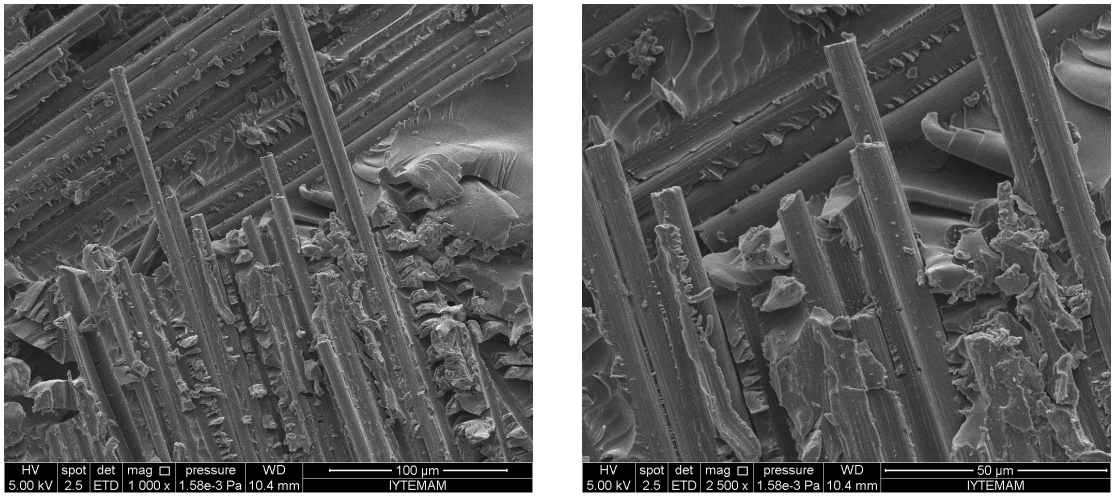
(b)

Figure 4.46. Scanning electron micrograph of tensile fracture surface of unidirectional carbon fiber / epoxy composite after 1500 hours aging (the composites were cut into specimens before aging) (a) 1000X (b)2500X



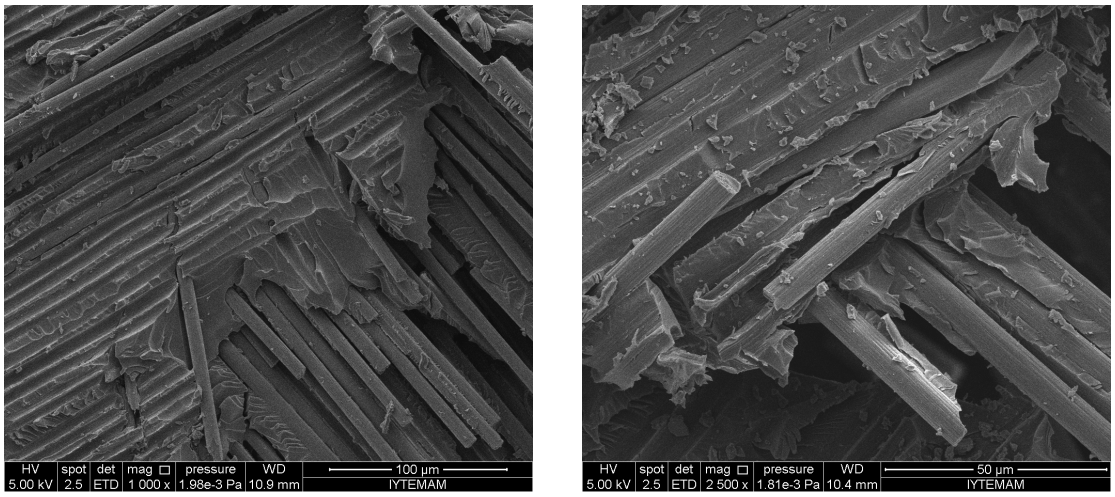
(a) (b)

Figure 4.47. Scanning electron micrograph of tensile fracture surface of biaxial carbon fiber / epoxy composite prior to aging (the composites were cut into specimens before aging) (a) 1000X (b)2500X



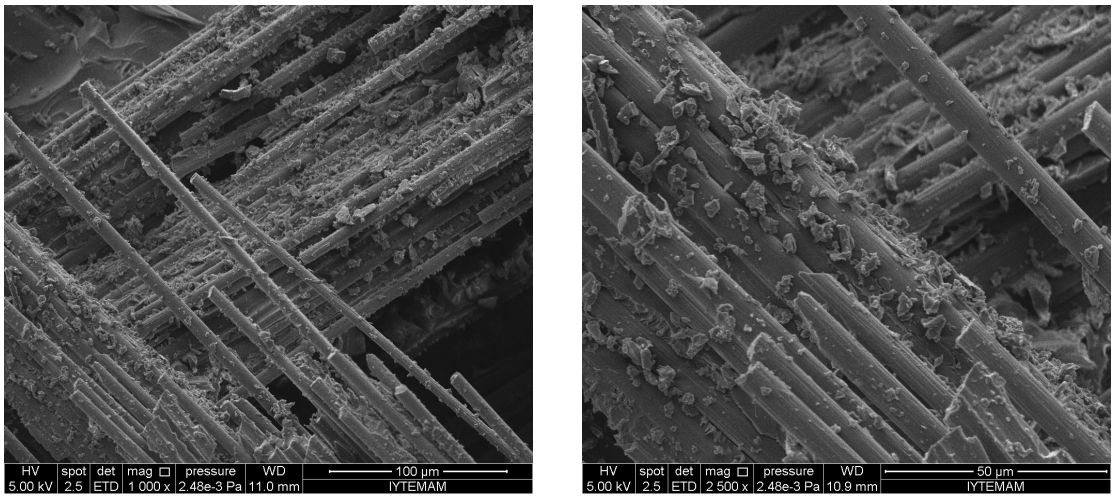
(a) (b)

Figure 4.48. Scanning electron micrograph of tensile fracture surface of biaxial carbon fiber / epoxy composite after 500 hours aging (the composites were cut into specimens before aging) (a) 1000X (b)2500X



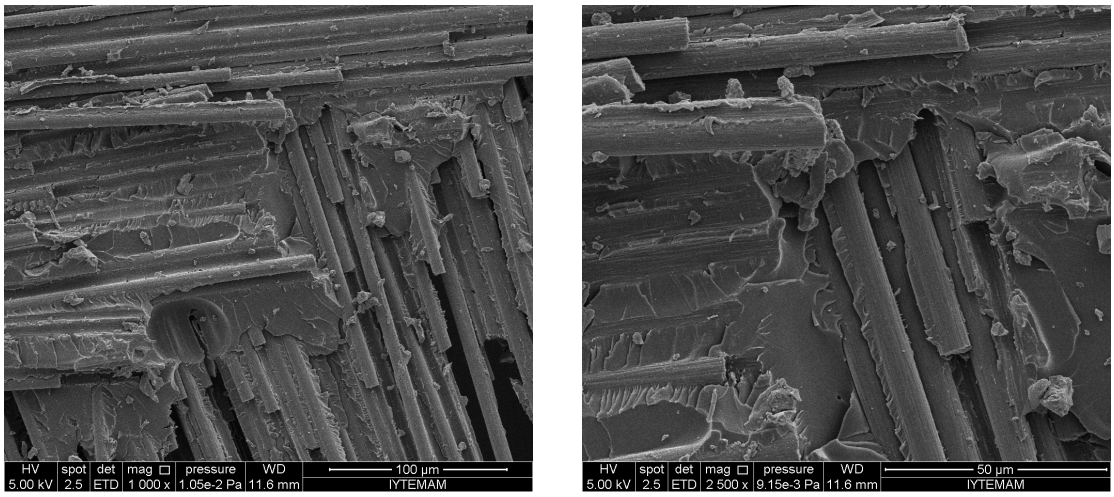
(a) (b)

Figure 4.49. Scanning electron micrograph of tensile fracture surface of biaxial carbon fiber / epoxy composite after 1000 hours aging (the composites were cut into specimens before aging) (a) 1000X (b)2500X



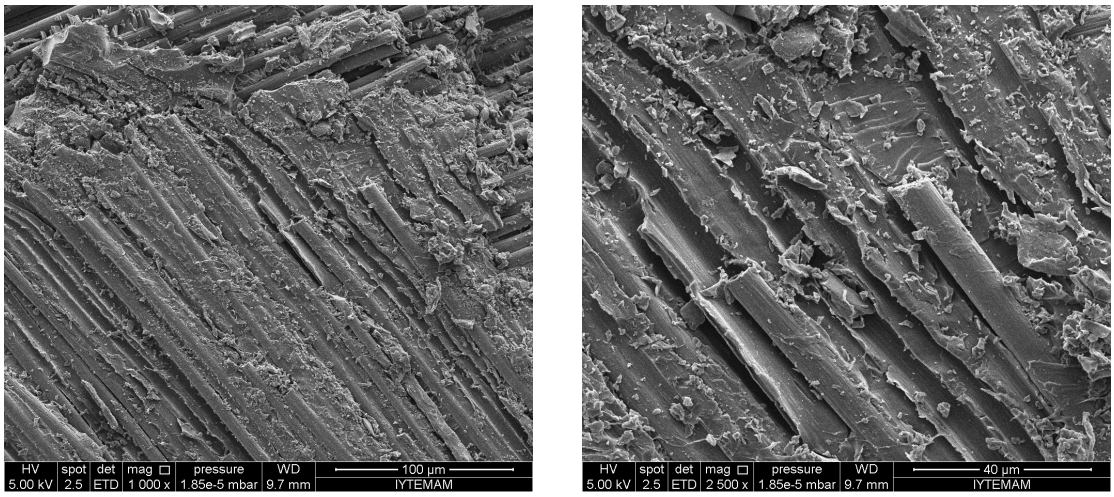
(a) (b)

Figure 4.50. Scanning electron micrograph of tensile fracture surface of biaxial carbon fiber / epoxy composite after 1500 hours aging (the composites were cut into specimens before aging) (a) 1000X (b)2500X



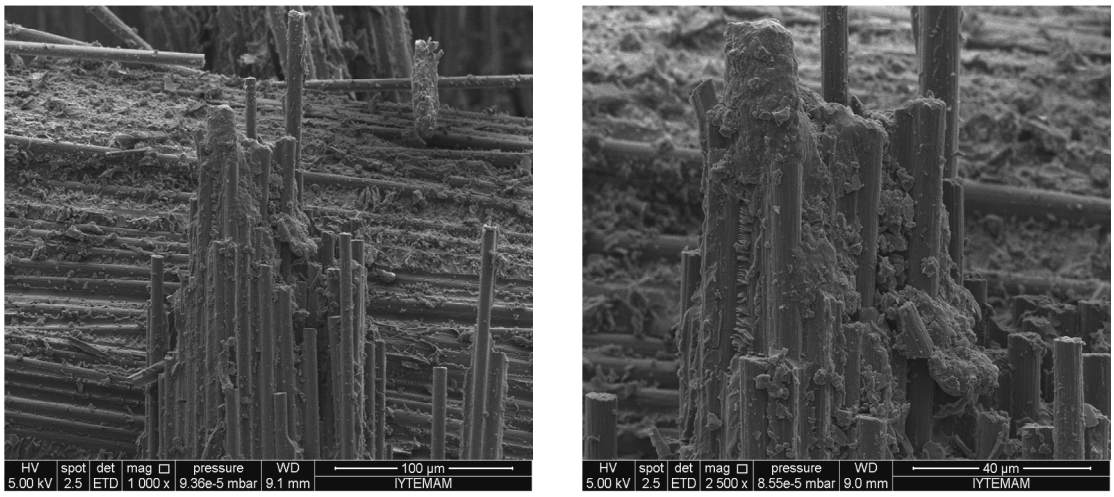
(a) (b)

Figure 4.51. Scanning electron micrograph of tensile fracture surface of biaxial carbon fiber / epoxy composite prior to aging (the composites were aged as manufactured plates) (a) 1000X (b)2500X



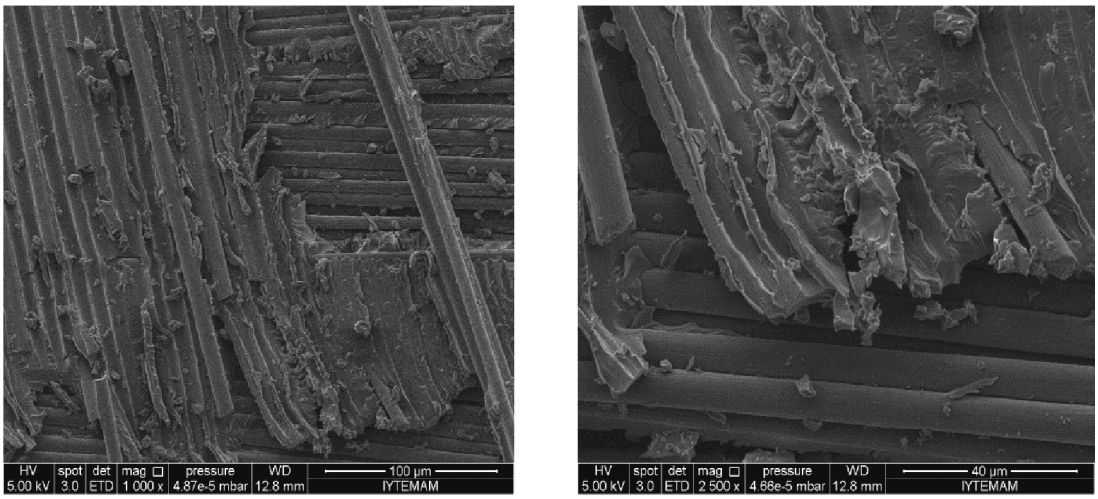
(a) (b)

Figure 4.52. Scanning electron micrograph of tensile fracture surface of biaxial carbon fiber / epoxy composite after 500 hours aging (the composites were aged as manufactured plates) (a) 1000X (b)2500X



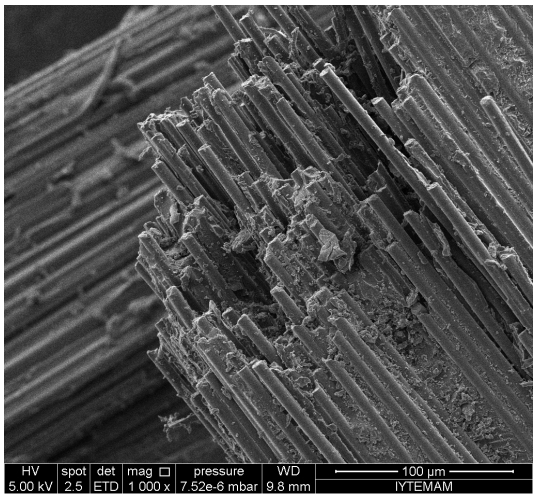
(a) (b)

Figure 4.53. Scanning electron micrograph of tensile fracture surface of biaxial carbon fiber / epoxy composite after 1000 hours aging (the composites were aged as manufactured plates) (a) 1000X (b)2500X

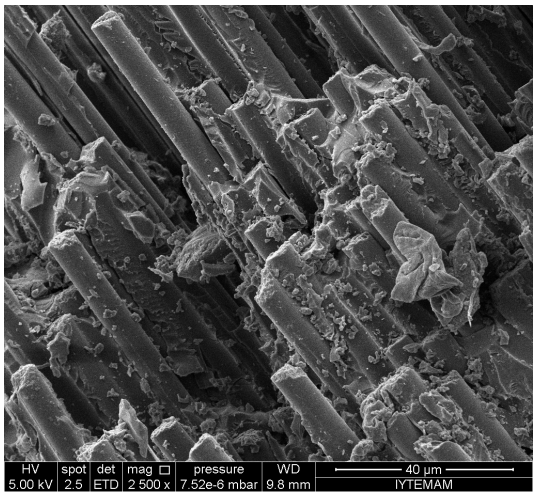


(a) (b)

Figure 4.54. Scanning electron micrograph of tensile fracture surface of biaxial carbon fiber / epoxy composite after 1500 hours aging (the composites were aged as manufactured plates) (a) 1000X (b)2500X

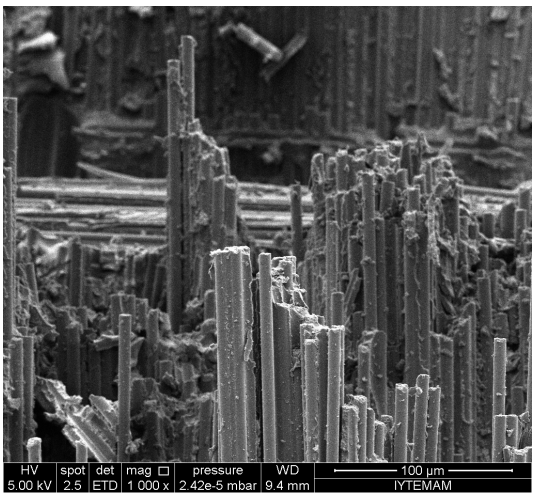


(a)

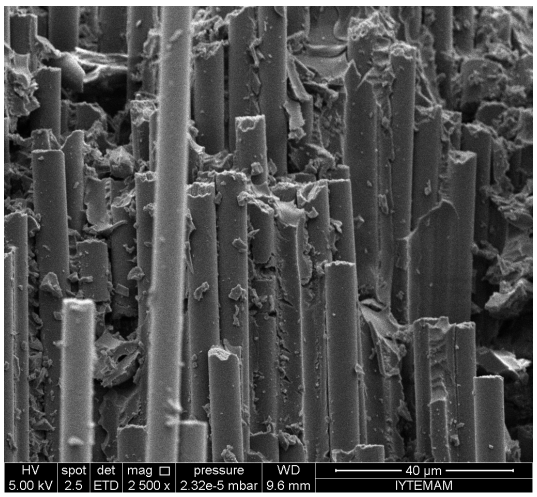


(b)

Figure 4.55. Scanning electron micrograph of tensile fracture surface of woven carbon fiber / epoxy composite prior to aging (the composites were aged as manufactured plates) (a) 1000X (b)2500X

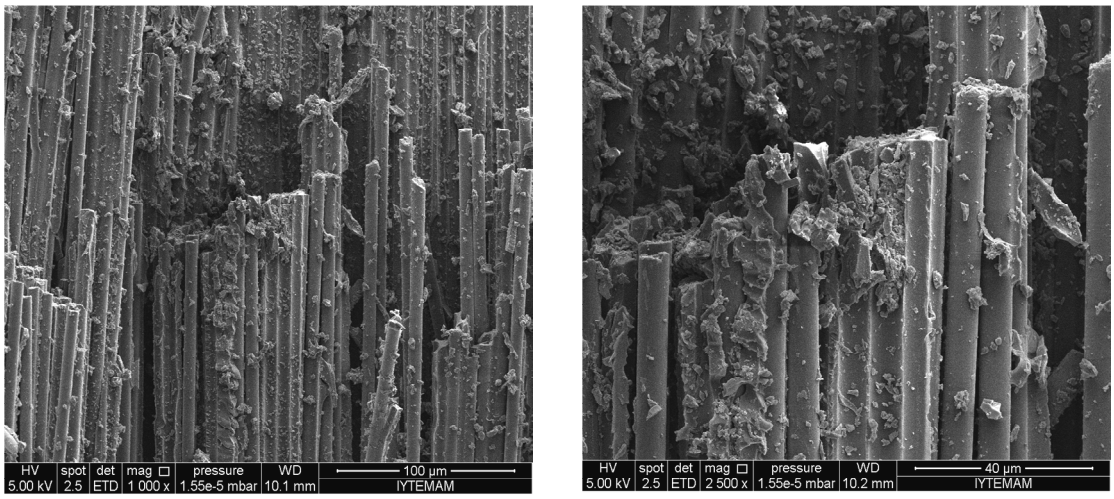


(a)



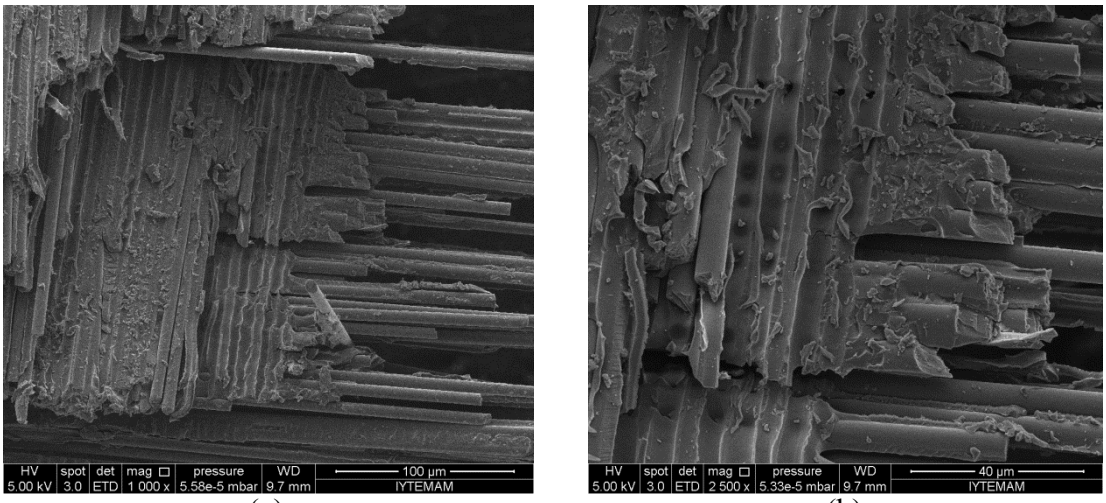
(b)

Figure 4.56. Scanning electron micrograph of tensile fracture surface of woven carbon fiber / epoxy composite after 500 hours aging (the composites were aged as manufactured plates) (a) 1000X (b)2500X



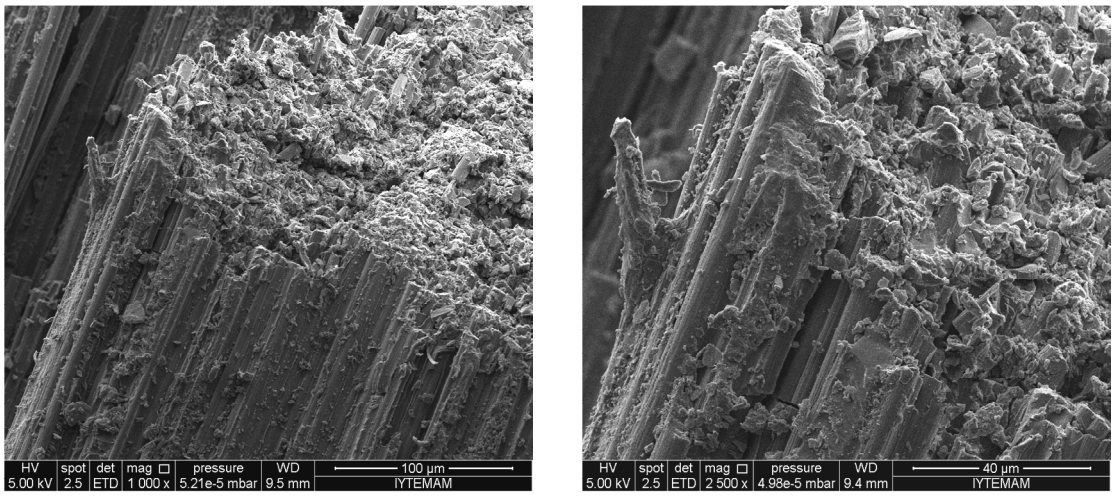
(a) (b)

Figure 4.57. Scanning electron micrograph of tensile fracture surface of woven carbon fiber / epoxy composite after 1000 hours aging (the composites were aged as manufactured plates) (a) 1000X (b)2500X



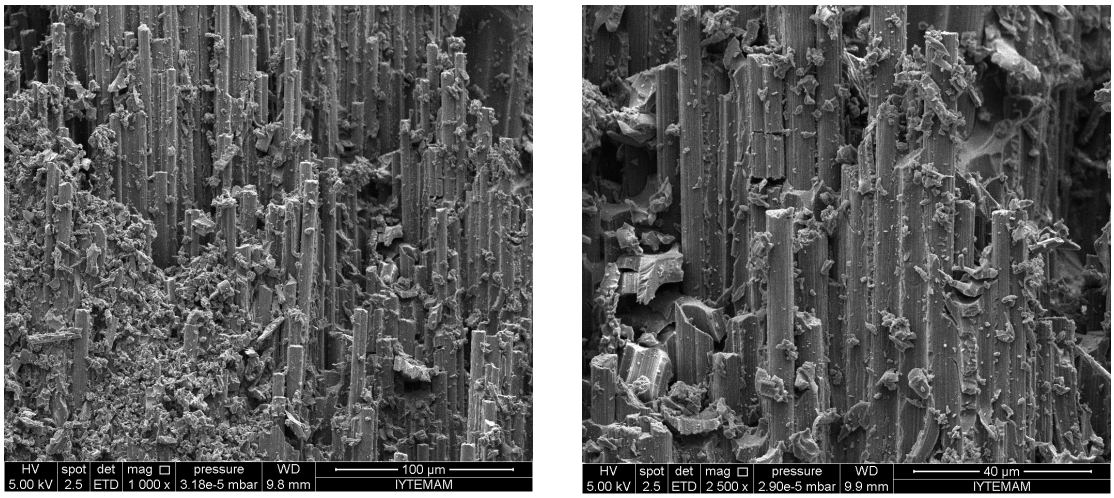
(a) (b)

Figure 4.58. Scanning electron micrograph of tensile fracture surface of woven carbon fiber / epoxy composite after 1500 hours aging (the composites were aged as manufactured plates) (a) 1000X (b)2500X



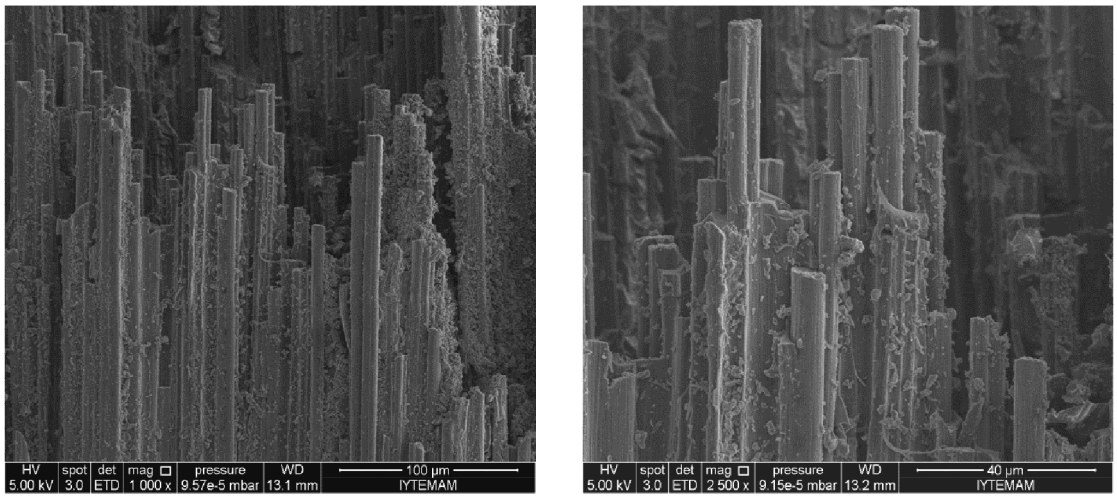
(a) (b)

Figure 4.59. Scanning electron micrograph of tensile fracture surface of unidirectional carbon fiber / epoxy composite prior to aging (the composites were aged as manufactured plates) (a) 1000X (b)2500X



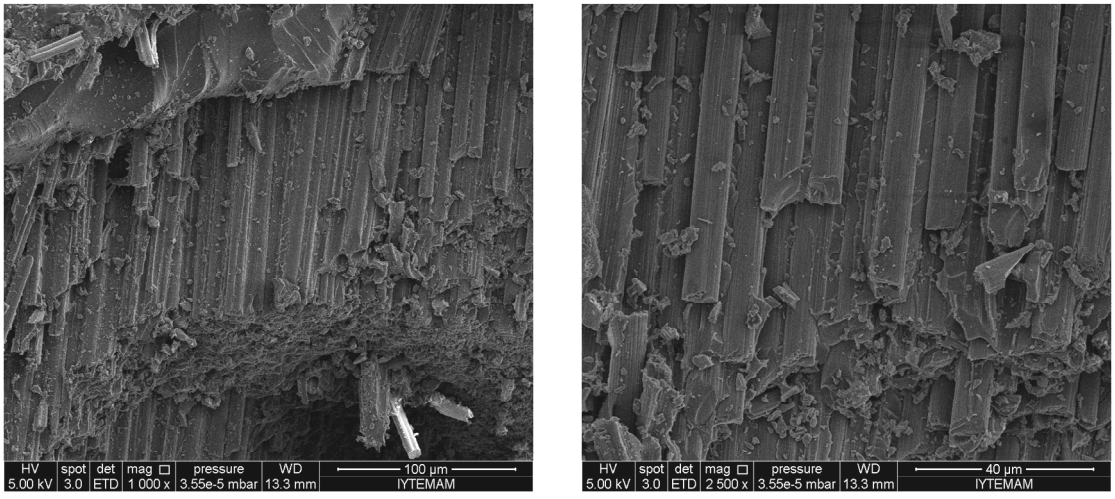
(a) (b)

Figure 4.60. Scanning electron micrograph of tensile fracture surface of unidirectional carbon fiber / epoxy composite after 500 hours aging (the composites were aged as manufactured plates) (a) 1000X (b)2500X



(a) (b)

Figure 4.61. Scanning electron micrograph of tensile fracture surface of unidirectional carbon fiber / epoxy composite after 1000 hours aging (the composites were aged as manufactured plates) (a) 1000X (b)2500X



(a) (b)

Figure 4.62. Scanning electron micrograph of tensile fracture surface of unidirectional carbon fiber / epoxy composite after 1500 hours aging (the composites were aged as manufactured plates) (a) 1000X (b)2500X

CHAPTER 5

CONCLUSIONS

In this study, the effects of environmental aging on durability of carbon fiber reinforced epoxy matrix composites were investigated. Three different types of composites were manufactured by vacuum infusion technique. Plain unidirectional, 0/90° woven and biaxial ±45 carbon fabrics were used for manufacturing of the composites used. To simulate the aircraft flight conditions, the composites were aged up to 1500 hours in a computer controlled environmental chamber. Five hours hygrothermal, one hour subzero and one hour high temperature conditions were considered as one aging cycle. The manufactured composites were placed in the chamber to investigate the different effects of aging based on their specimen types. For this purpose, composites were prepared as manufactured plates and test coupons for the aging cycles. Moisture content of the composites were measured at regular intervals. Mechanical and thermomechanical property changes were characterized prior to aging and after 500, 1000 and 1500 hours aging of the composites. Microstructural evaluation of tensile fracture surfaces were analysed by SEM.

It was found that no significant change was observed in moisture content during aging cycles. Moisture uptake of the composites seem to be non-uniform . Similar results were obtained for the as manufactured plates and test coupons. The glass transition temperature values were significantly influenced due to aging cycles. Fiber matrix debonding, hackle formation, matrix degradation and fiber breakage were observed by SEM analysis after aging cycles.

Tensile properties can be interpreted based on fabric type. For the unidirectional and biaxial composites, the results show reduction in mechanical properties at the end of the aging cycles. Fiber dominated properties showed little degradation after aging cycles. Reduction in modulus and strength was slight for the unidirectional composites. Matrix dominated properties were reduced more drastically and showed sensitivity to aging cycles for the biaxial composites. However, the mechanical properties exhibited increasing trend for the woven composites during aging cycles.

Bending test results revealed that flexural strength show decrease after aging cycles for the composites which were cut into test specimens prior to aging. For the composites aged as manufactured plates, the results show variations from each other and did not provide consistent results.

In future studies, further tests need to be conducted including more effective moisture simulations, longer low and high temperature cyles in order to obtain more accurate results. Morever, fatigue behavior of polymer composites under different environmental conditions can be investigated.

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