ÇUKUROVA UNIVERSITY
INSTITUTE OF NATURAL AND APPLIED SCIENCES

PhD THESIS

Şafak YILDIZHAN

FABRICATION AND CHARACTERIZATION OF EXPANDED POLYSTYRENE/CHOPPED GLASS FIBER/EPOXY NOVEL COMPOSITE

DEPARTMENT OF AUTOMOTIVE ENGINEERING

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ABSTRACT

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This study investigates the fabrication and characterization of a novel composite material that consists of expanded polystyrene beads as filler, chopped glass fibers as reinforcement and epoxy resin as matrix. Material samples were fabricated with vacuum infusion technique. Experimental studies were carried out at two stages. At the first stage, a bulk material was fabricated and three different types of specimens were cut to determine the material behavior when material is tested in different directions. At the second stage of the study, specimens with different ingredient ratios were fabricated. 14 different specimen types with varying parameters were fabricated, characterized and compared with neat resin. Experimental studies of first stage revealed that, the novel composite possess quasi-isotropic properties although it has non-homogeneous nature. The novel composite has significantly low density and thus considerably high specific modulus value. The second stage revealed that, the optimum fiber/filler ratio for the novel composite is 20:1. At higher ratio than 20:1, the increased clustering regions deteriorated the properties of the composite and caused high variation in results. The cost analysis showed that the expanded polystyrene/glass/epoxy composite have significantly high cost-property efficiency which means the novel composite is a good candidate for many engineering applications.

Key Words: Composite material, filler, expanded polystyrene, glass fiber, hybrid, characterization, mechanical testing

ÖZ

DOKTORA TEZİ

GENLEŞMİŞ POLİSTİREN/KIRPILMIŞ CAM ELYAFI/EPOKSİ KOMPOZİTİN ÜRETİMİ VE KARAKTERİZASYONU

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Bu çalışma dolgu olarak genleşmiş polistiren boncukları, takviye olarak kırpılmış cam elyafları ve matris olarak epoksi reçineden oluşan yeni bir kompozit malzemenin üretimini ve karakterizasyonunu araştırmaktadır. Malzeme numuneleri vakum infüzyon tekniği ile imal edilmiştir. Deneysel çalışmalar iki aşamada gerçekleştirilmiştir. İlk aşamada, üretilen malzemeden, malzeme farklı yönlerde test edildiğinde davranışını belirlemek için üç farklı tipte numune kesilmiştir. Çalışmanın ikinci aşamasında, farklı bileşen oranlarına sahip örnekler üretilmiştir. Değişken parametrelere sahip 14 farklı örnek tipi imal edilmiş, karakterize edilmiş ve saf reçine ile karşılaştırılmıştır. İlk aşamadaki deneysel çalışmalar, yeni kompozitin homojen olmayan bir yapıya sahip olmasına rağmen yarı izotropik özelliklere sahip olduğunu ortaya koymuştur. Yeni kompozit, önemli ölçüde düşük yoğunluğa ve dolayısıyla oldukça yüksek spesifik modül değerine sahiptir. İkinci aşama, yeni kompozit için optimum elyaf/dolgu oranının 20:1 olduğunu ortaya koymuştur. 20:1'den daha yüksek bir oranda, artan kümelenme bölgeleri kompozitin özelliklerini bozmuş ve sonuçlarda yüksek değişkenliğe neden olmuştur. Maliyet analizi, genleşmiş polistiren/cam fiber/epoksi kompozitin önemli ölçüde yüksek maliyet-özellik verimliliğine sahip olduğunu göstermiş, bu da yeni kompozitin birçok mühendislik uygulaması için iyi bir aday olduğu anlamına gelmektedir.

Anahtar Kelimeler: Kompozit malzeme, dolgu, genleşmiş polistiren, cam fiber, hibrit, karakterizasyon, mekanik test

EXTENDED ABSTRACT

Engineering materials can be categorized basically in four categories as metals, ceramics, polymers and composites. Composite materials are the combination of the first three categories and include at least two discrete ingredients. In general sense, the macroscopic combination of at least two different materials with different properties is called as composite material and composite materials are used by mankind since ancient times.

Engineering materials are chosen by evaluating the design requirements for each particular application. Each system or product needs different materials with different properties. But all systems and products also have cost limitation. For instance, for a particular application, many different metals can provide the required properties but the selection of the material is also done by evaluating the cost analysis of the materials. Therefore a material has to be evaluated in many aspects. Since the ancient times, mankind have used a very wide variety of materials even that the known first ages in the history named by the dominant material used. For example, in timeline some ages are named as Bronze Age, Iron Age, and Stone Age etc. The usage intensity and thus the relative importance of the material types have changed over the years. For example straw-brick had been used intensely as building materials in the old ages. But, the relative importance decreased because of usage metals and polymers in early 20^{th} century. But with the significant development of technology, the relative importance of the composite materials enormously increased.

Composite materials are the combination of at least two discrete ingredients in macro scale. Composite materials generally consist of a matrix material and a reinforcement agent. Also fillers or additives can be added to composites in order to further improvement in properties. Composites can be categorized according to matrix material, reinforcement material or reinforcement type. The most common composite materials are polymer matrix composites which are utilized in various

industries. Composite materials have remarkable advantages such as low density, high specific strength and stiffness. However, they have also critical disadvantages such as high cost and difficulty of mass production.

Short fiber or particulate reinforced composites are a special type of composites which have advantageous properties such as easy processing, relatively low cost and quasi-isotropic nature. Especially laminated composites and sandwich structures are anisotropic which means material behaves differently when the load is applied in different directions.

In this study, a novel composite material was designed, fabricated and characterized. Composite material was designed to be a polymer matrix composite with filler and short fiber reinforcement. The novel material was fabricated using expanded polystyrene beads as filler, chopped glass fibers as reinforcement agent and epoxy resin as matrix material. Experimental studies were conducted at two different stages. At the first stage of the study, a bulk material sample was fabricated and specimens in three orthogonal directions [x(1)-y(2)-z(3)] were obtained for tensile and impact tests. The aim of the first stage was to fabricate the novel material and understand the mechanical properties of the material in different directions. Also thermogravimetric analyses were performed for neat resin and composite specimen to determine the thermal characteristic of the novel composite.

At the second stage of the study, 14 different specimen types were fabricated to determine the optimum parameters. Two different density of expanded polystyrene, two different lengths of chopped glass fibers and three different fiber/filler ratio were used to fabricate the specimens. Densities of the expanded polystyrene beads were 8 and 13 kg/m^3, the lengths of chopped glass fibers were 3 and 6 mm, the fiber/filler ratios were 10:1, 20:1, and 30:1. All specimens were fabricated via vacuum infusion technique and post curing was applied for complete curing of the matrix resin. Fabricated specimens were subjected to tensile, impact, hardness and water absorption tests. Also cost-property efficiency analyses for all specimens were performed.

The first stage of the studies revealed that specimens obtained from composite sample fabricated with 8 kg/m^3 EPS beads and 3 mm lengths of chopped glass fibers had ultimate tensile strengths of 11,83±0,86 MPa, 10,94±1,67 MPa and 10,19±0,45 MPa, strains of 2,83%, 3,29%, and 3,61% impact strengths of 25,27 kJ/m^2, 24,26 kJ/m^2 and 30,13 kJ/m^2 for x(1), y(2), and z(3) direction specimens, respectively. Results prove that novel composite possesses similar characteristics when load is applied on different directions. The material can be assumed to be quasi-isotropic even the non-homogeneous structure. Thermogravimetric analyses indicated that composite specimens started to mass loss at a lower temperature than neat resin due to low thermal resistance of EPS beads.

The second stage of the studies showed that fiber/filler ratio and EPS bead density are critical parameters for the mechanical characteristic of the material. Fabricating the material with higher density of EPS beads resulted in higher tensile strength. Adding chopped glass fibers to mixture significantly increased the strength of the materials in comparison with the specimens fabricated with only fillers. The optimum values were obtained at the fiber/filler ratio of 20:1. When the ratio is increased to 30:1, the variations in result were high due to the increased non-homogeneity and clustering regions in the material structure.

Hardness measurements were conducted for all specimens but when the load applied points coincided with EPS beads, the measurement were distorted since the traces on the specimens were not clear and measurements were not accurate. Thus, hardness measurements were conducted only on the completely resin covered regions. As a result of the measurements the hardness value of the specimens were found as 102,04±19,16 HV1.

Water absorption test results revealed that neat resin has a very low absorbance and thus it is a critical advantage for many engineering applications. All of the composite specimens had higher water absorbance than neat resin. When the specimens soaked into water, EPS beads and glass fibers tend to absorb water especially at the points of where EPS and glass fibers directly contact with water.

Since the specimens were obtained by cutting the bulk material, surfaces of the specimens were not completely covered with matrix material. For actual application of the material, if the product is molded there will not be that high water absorbance.

Cost-property analysis studies revealed that the novel composites fabricated in the study has remarkable specific modulus values. When the cost-property efficiencies are examined, it was seen that the novel composite is a low cost material. The reason for that is the extremely low density of the material. When the comparison was made according to unit volume, the novel composite had significant advantages especially over conventional plastics such as HDPE, PVC and PP. As a result of the cost analysis, the material could be defined as a cost effective alternative composite.

GENİŞLETİLMİŞ ÖZET

Mühendislik malzemeleri temel olarak metaller, seramikler, polimerler ve kompozitler olmak üzere dört kategoride sınıflandırılabilir. Kompozit malzemeler, ilk üç kategorinin kombinasyonudur ve en az iki ayrı bileşen içerir. Genel anlamda farklı özelliklere sahip en az iki farklı malzemenin makroskopik kombinasyonuna kompozit malzeme denilmekte ve kompozit malzemeler insanlık tarafından eski çağlardan beri kullanılmaktadır.

Mühendislik malzemeleri, her uygulama için tasarım gereksinimleri değerlendirilerek seçilir. Her sistem veya ürün, farklı özelliklere sahip farklı malzemelere ihtiyaç duyar. Ancak tüm sistem ve ürünlerin de maliyet sınırlaması vardır. Örneğin belirli bir uygulama için birçok farklı metal gerekli özellikleri sağlayabilir ancak malzeme seçimi malzemelerin maliyet analizleri de değerlendirilerek yapılır. Bu nedenle bir malzemenin birçok açıdan değerlendirilmesi gerekir. Antik çağlardan beri insanoğlu çok çeşitli malzemeler kullanmıştır ve hatta tarihte bilinen ilk çağlar dönemde kullanılan baskın malzeme ile adlandırılmıştır. Örneğin, zaman çizelgesinde bazı çağlar Bronz Çağı, Demir Çağı ve Taş Devri vb. olarak adlandırılır. Yıllar içinde malzeme türlerinin kullanım yoğunluğu ve dolayısıyla göreceli önemi değişmiştir. Kerpiç gibi kompozit malzemeler eski çağlarda yapı malzemesi olarak yoğun bir şekilde kullanılmıştır. Fakat, 20. yüzyılın başlarında metal ve polimer kullanımı nedeniyle göreceli önem azalmıştır. Ancak teknolojinin önemli ölçüde gelişmesiyle, kompozit malzemelerin göreceli önemi büyük ölçüde artmıştır.

Kompozit malzemeler, makro ölçekte en az iki ayrı bileşenin birleşimidir. Kompozit malzemeler genellikle bir matris malzemesi ve bir takviye maddesinden oluşur. Ayrıca özelliklerin daha da iyileştirilmesi için kompozitlere dolgu maddeleri veya katkı maddeleri eklenebilir. Kompozitler, matris malzemesi, takviye malzemesi veya takviye tipine göre kategorize edilebilir. En yaygın kompozit malzemeler, çeşitli endüstrilerde kullanılan polimer matrisli kompozitlerdir. Kompozit

malzemeler, düşük yoğunluk, yüksek özgül mukavemet ve rijitlik gibi önemli avantajlara sahiptir. Bununla birlikte, yüksek maliyet ve seri üretim zorluğu gibi kritik dezavantajları da vardır.

Kısa elyaf veya partikül takviyeli kompozitler, kolay işleme, nispeten düşük maliyet ve yarı izotropik yapı gibi avantajlı özelliklere sahip özel bir kompozit türüdür. Özellikle lamine kompozitler ve sandviç yapılar anizotropiktir, bu farklı yönlerde yük uygulandığında malzemenin farklı davranması anlamına gelir.

Bu çalışmada, yeni bir kompozit malzeme tasarlanmış, üretilmiş ve karakterize edilmiştir. Kompozit malzeme, dolgulu ve kısa elyaf takviyeli bir polimer matris kompozit olacak şekilde tasarlanmıştır. Yeni malzeme, dolgu maddesi olarak genleşmiş polistiren boncuklar, takviye maddesi olarak kırpılmış cam elyafları ve matris malzemesi olarak epoksi reçinesi kullanılarak üretilmiştir. Deneysel çalışmalar iki farklı aşamada yapılmıştır. Çalışmanın ilk aşamasında, bir dökme malzeme numunesi üretilmiş ve çekme ve darbe testleri için üç dikey yönde [x(1)-y(2)-z(3)] numuneler elde edilmiştir. İlk aşamanın amacı, yeni malzemeyi imal etmek ve malzemenin mekanik özelliklerini farklı yönlerde anlamaktır. Ayrıca yeni kompozitin termal karakteristiğini belirlemek için saf reçine ve kompozit numune için termogravimetrik analizler yapılmıştır.

Çalışmanın ikinci aşamasında, optimum parametreleri belirlemek için 14 farklı numune tipi üretilmiştir. Numuneleri imal etmek için iki farklı yoğunlukta genleşmiş polistiren, iki farklı uzunlukta kırpılmış cam elyaf ve üç farklı takviye/dolgu oranı kullanılmıştır. Genleşmiş polistiren boncukların yoğunlukları 8 ve 13 kg/m^3, kırpılmış cam elyafların uzunlukları 3 ve 6 mm, takviye/dolgu oranları ise 10:1, 20:1 ve 30:1 olarak seçilmiştir. Tüm numuneler vakum infüzyon tekniği ile imal edilmiş ve matris reçinesinin tam kürlenmesi için post kürleme uygulanmıştır. Üretilen numuneler çekme, darbe, sertlik ve su emilimi testlerine tabi tutulmuştur. Ayrıca tüm numuneler için maliyet-özellik verimi analizleri yapılmıştır.

Çalışmaların ilk aşaması, 8 kg/m^3 EPS boncuklar ve 3 mm uzunlukta kırpılmış cam elyafları ile üretilmiş kompozit malzemeden elde edilen numunelerin

x(1), y(2) ve z(3) yönlerinde sırasıyla; 11,83±0,86 MPa, 10,94±1,67 MPa ve 10,19±0,45 MPa gerilme mukavemetine, % 2,83,% 3,29 ve % 3,61 uzama değerlerine ve 25,27 kJ/m^2, 24,26 kJ/m^2 ve 30,13 kJ/m^2 darbe dayanımına sahip olduğunu ortaya koymuştur. Sonuçlar, yeni kompozitin, yük farklı yönlere uygulandığında benzer özelliklere sahip olduğunu kanıtlamıştır. Yeni malzemenin homojen olmayan yapısına rağmen yarı izotropik olduğu varsayılabilir. Termogravimetrik analizler, EPS boncuklarının düşük ısıl direnci nedeniyle kompozit numunelerin saf reçineden daha düşük bir sıcaklıkta kütle kaybına başladığını göstermiştir.

Çalışmaların ikinci aşaması, takviye/dolgu oranının ve EPS boncuk yoğunluğunun malzemenin mekanik özelliği için kritik parametreler olduğunu göstermiştir. Daha yüksek yoğunlukta EPS boncuklarla üretilen numunelerin daha yüksek çekme mukavemetine sahip olduğu gözlenmiştir. Karışıma kırpılmış cam elyaflarının eklenmesi, sadece dolgu maddeleri ile imal edilen numunelere kıyasla malzemelerin mukavemetini önemli ölçüde artırmıştır. Optimum değerler 20:1 takviye/dolgu oranında elde edilmiştir. Oran 30: 1'e yükseltildiğinde ise malzeme yapısındaki azalan homojenlik ve kümelenme bölgeleri nedeniyle sonuçtaki varyasyonlar yüksek olmuştur.

Tüm numuneler için sertlik ölçümleri yapılmıştır, ancak uygulanan yük noktaları EPS boncuklarla çakıştığında, numuneler üzerindeki izler net olmadığından dolayı doğru ölçümler alınamamıştır. Bu nedenle sertlik ölçümleri sadece tamamen reçine kaplı bölgelerde yapılmıştır. Yapılan ölçümler sonucunda numunelerin sertlik değeri 102,04 ± 19,16 HV1 olarak bulunmuştur.

Su emilimi testi sonuçları, saf reçinenin çok düşük bir emiciliğe sahip olduğunu ve bu nedenle birçok mühendislik uygulaması için kritik bir avantajı olduğunu ortaya koymuştur. Testler sonucunda tüm kompozit numunelerin saf reçineden daha yüksek su emiciliğine sahip olduğu bulunmuştur. Örnekler suya batırıldığında, EPS boncuklar ve cam elyaflar, özellikle EPS ve cam elyaflarının su ile doğrudan temas ettiği noktalarda suyu emme eğilimindedir. Numuneler dökme

malzeme kesilerek elde edildiğinden, numunelerin yüzeyleri tamamen matris malzeme ile kaplanmamıştır. Malzemenin gerçek uygulaması için, ürün kalıplanırsa, yüksek su emme olmayacaktır.

Maliyet-özellik verim analizi çalışmaları, çalışmada üretilen yeni kompozitlerin dikkat çekici spesifik modül değerlerine sahip olduğunu ortaya koymuştur. Maliyet-özellik verimlilikleri incelendiğinde yeni kompozit malzemenin düşük maliyetli bir malzeme olduğu tespit edilmiştir. Bunun nedeni, malzemenin son derece düşük yoğunluğudur. Birim hacme göre karşılaştırma yapıldığında, yeni kompozit özellikle HDPE, PVC ve PP gibi geleneksel plastiklere göre önemli avantajlara sahiptir. Maliyet analizinin bir sonucu olarak, malzeme uygun maliyetli bir alternatif kompozit olarak tanımlanabilir.

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SYMBOLS AND ABBREVIATIONS

$	:	Dollar
l_0	:	Gauge length
δ_i	:	Extensometer displacement
Al	:	Aluminium
Al_2O_3	:	Aluminium oxide
B	:	Boron
B_2O_3	:	Boron trioxide
c	:	Specific heat
C	:	Carbon
$CaCO_3$	:	Calcium carbonate
CaO	:	Calcium oxide
CGFC	:	Chopped glass fiber composites
cm	:	Centimetre
CMC	:	Ceramic matrix composite
CNSL	:	Cashew nut shell liquid
Cu	:	Copper
CV	:	Coefficient of variation
d	:	Diagonal length
E	:	Elastic (Young's) modulus
EPS	:	Expanded polystyrene
Fe_2O_3	:	Ferric oxide
g	:	Gram
G_{IC}	:	Toughness
GPa	:	Gigapascal
HDPE	:	High density polyethylene
HV	:	Vickers hardness
J	:	Joule
K_2O	:	Potassium oxide
kg	:	Kilogram
kgf	:	Kilogram-force
K_{IC}	:	Fracture toughness
kN	:	kilo-Newton
LDPE	:	Low density polyethylene
Li	:	Lithium
m	:	Meter
Mg	:	Magnesium
mg	:	Milligram
$Mg_2B_2O_5$	:	Magnesium borate
MgO	:	Magnesium oxide
mm	:	Millimetre

MMC	:	Metal matrix composite
MPa	:	Mega Pascal
mPas	:	Millipascal second
N	:	Newton
n	:	Number of experiments
Na_2O	:	Sodium oxide
n_{EPS}	:	Total EPS number
PEEK	:	Polyether ether ketone
PET	:	Polyethylene terephthalate
PMC	:	Polymer matrix composite
PP	:	Polypropylene
PVC	:	Poly vinyl chloride
r	:	Radius
Re	:	Rhenium
RTM	:	Resin transfer molding
S	:	Standard deviation
Si	:	Silicon
SiC	:	Silicon carbide
SiO_2	:	Silica
T	:	Temperature
TGA	:	Thermogravimetric analysis
TiO_2	:	Titanium dioxide
VARTM	:	Vacuum assisted resin transfer molding
v_c	:	Composite volume
v_{EPS}	:	EPS volume
v_f	:	Fiber volume
v_m	:	Matrix volume
v_{void}	:	Void volume
w_c	:	Composite weight
W_{EPS}	:	EPS weight fraction
w_{EPS}	:	EPS weight
W_f	:	Fiber weight fraction
w_f	:	Fiber weight
W_m	:	Matrix weight fraction
w_m	:	Matrix weight
wrt	:	With respect to
wt	:	Weight ratio
ZnO	:	Zinc oxide
α	:	Thermal expansion coefficient
ε	:	Rupture strength
ε_d	:	Dielectric constant
λ	:	Thermal conductivity
μ_k	:	Friction coefficient (Kinetic)

μ_s	:	Friction coefficient (Static)
ρ	:	Density
ρ_c	:	Composite density
ρ_e	:	Electrical resistivity
ρ_{EPS}	:	EPS density
ρ_{exp}	:	Experimental density
ρ_f	:	Fiber density
ρ_m	:	Matrix density
ρ_{theo}	:	Theoretical density
σ_c	:	Yield strength
σ_e	:	Flexural strength
σ_f	:	Compressive strength
σ_r	:	Tensile strength
σ_t	:	Tensile strength
σ_y	:	Yield strength

1. INTRODUCTION

Engineering materials can be categorized basically in four categories as metals, ceramics, polymers and composites. Composite materials are the combination of the first three categories and include at least two discrete ingredients. In general sense, the macroscopic combination of at least two different materials with different properties is called as composite material and composite materials are used by mankind since ancient times (Kaw, 2006).

In engineering, materials are generally specified according to the material properties which are evaluated in six basic aspects. In Table 1.1 different aspects of the materials are given. Engineering materials are chosen by evaluating the design requirements for each particular application. Each system or product needs different materials with different properties. But all systems and products also have cost limitation. For instance, for a particular application, many different metals can provide the required properties but the selection of the material is also done by evaluating the cost analysis of the materials. Therefore a material has to be evaluated in many aspects. Since the ancient times, mankind have used a very wide variety of materials even that the known first ages in the history named by the dominant material used. For example, in timeline some ages are named as Bronze Age, Iron Age, and Stone Age etc. (Callister and Rethwisch, 2014). The usage intensity and thus the relative importance of the material types have changed over the years. Composite materials for example straw-brick had been used intensely as building materials in the old ages. But, the relative importance decreased because of usage metals and polymers in early 20^{th} century (Kaw, 2006). But with the significant development of technology, the relative importance of the composite materials enormously increased (Ashby, 2005).

Table 1.1. General properties of engineering materials

Aspect	Property	Unit (SI)	Symbol
Mechanical	Density	kg/m^3	ρ
	Elastic Modulus	GPa	E
	Yield Strength	MPa	σ_y
	Tensile Strength	MPa	σ_t
	Compressive Strength	MPa	σ_c
	Rupture Strength	MPa	σ_r
	Flexural Strength	MPa	σ_f
	Flexural Modulus	GPa	
	Elongation	-	ε
	Fatigue Endurance Limit	MPa	σ_e
	Toughness	$MPa.m^{1/2}$	G_{IC}
	Fracture Toughness	kJ/m^2	K_{IC}
	Hardness	HV (Vickers)	HV
Thermal	Thermal Conductivity	W/m.K or W/m.^oC	λ
	Thermal Expansion Coefficient	K^{-1}	α
	Specific Heat	kJ/kg.K	c
	Maximum-Minimum Service Temperature	T_{max} - T_{min}	^oC or K
	Glass Transition Temperature	T_g	^oC or K
	Melting Temperature	T_m	^oC or K
Electrical	Electrical Resistivity	Ω.m	ρ_e
	Dielectric Constant	-	ε_d
Optical	Optical-Transparent-Translucent-Opaque	-	-
Abrasive	Friction Coefficient (Static)	-	μ_s
	Friction Coefficient (Kinetic)	-	μ_k
Corrosive	Oxidation	-	-
	Corrosion	-	-

The idea of the composite materials is not new. Composites are used for a very long time. But, the new developments in engineering technologies brought new requirements which can't be provided by monolithic materials alone. Composites are mostly man-made materials but in nature there are examples of composite materials. For instance, body of a tree or bones are good examples of composites in the nature.

The importance of the composite materials in engineering applications have increased in last few decades and thus the studies on the composite materials has

increased significantly in recent times. The main idea in fabrication of a composite material is the tailoring of the material properties according to design requirements of the products or systems. The great amount of development in engineering applications has brought the necessity of different material characteristics and these characteristics may not be possessed by conventional materials alone in most cases. When the ingredients of a composite material are used individually the material behaviour is significantly different from the composite material. For instance, the matrix of a composite material can't possess a high strength without the reinforcement as well as the reinforcement can't distribute the applied load over the entire structure.

Composite materials are generally fabricated by reinforcing a matrix material with an agent. Also, some additives with different functions, fillers or core materials can be added to composite materials (Yildizhan et al., 2018). The matrix is the major phase that forms the material shape and keeps the all structure together in a composite material. The reinforcement is the phase in a composite material that carries load. Figure 1.1. illustrates the general form of a composite material.

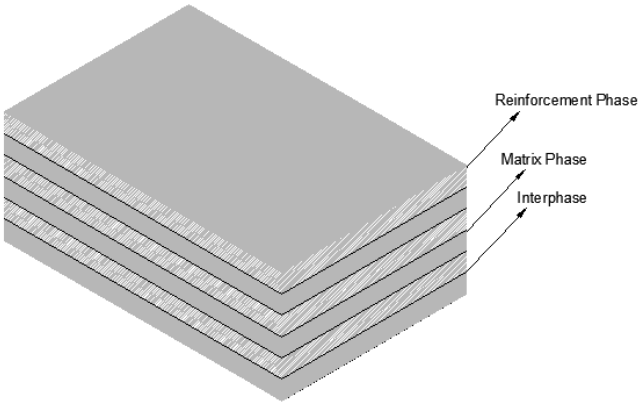


Figure 1.1. General form of a composite material

Composite materials have some advantages and disadvantages in comparison with conventional materials. The main advantage of the composite materials comes from the idea of the composite fabrication which is the combining the properties of different materials and by this way the tailoring the material properties according to design requirements. Composite materials can be fabricated as light, high strength, durable and resistant materials. Besides the advantages, composite materials also have some disadvantages such as high cost of raw materials and tooling, different fabrication techniques from the conventional methods, and anisotropic nature (Kaw, 2006). In Table 1.2. general advantages and disadvantages of composite materials are summarized.

Table 1.2. Advantages and disadvantages of composite materials

Advantages	**Disadvantages**
High specific modulus (modulus density ratio)	Anisotropic nature
High specific strength (strength density ratio)	Higher cost in most cases
High corrosion and fatigue resistance	Design difficulty
Lower weight in comparison with monolithic counterparts	Analysing difficulty
Tailorable properties	Different manufacturing methods from common methods
Possibility of reducing the part number for complex assemblies	Difficulty of repair
	Mass production difficulty

Usage of composite materials in civil, energy, aerospace and automotive sectors has drastically increased in last decades. According to Turkish Composites Manufacturers Association report, market share of composite materials has reached to 84 billion and 11.1 billion tonnes volume of production in the world market. For Turkey, the composite sector has reached 1,3 billion Euro and 242000 tonnes volume of production. More increment is expected for all manufacturing industries all over the world (Composites Turkey, 2019). The shares of the sectors in composite materials market are given in Table 1.3.

Table 1.3. Shares of composite material in different sectors (Composites Turkey, 2019)

Sector	World (%)	Europe (%)	Turkey (%)
Construction	19,7	14,7	23
Transportation and Automotive	28,5	46,7	29
Electric and Electronics	16	9,7	6
Consumer Goods	7,8	6,7	2
Wind Energy	5,4	7,1	10
Pipe and Tank	15	7,8	25
Defence and Aviation	0,4	0,4	-
Marine	2,4	2,9	2
Other	4,8	4	2

Composite materials have a broad range of application area from automotive industry to sporting goods. Especially, in the specific applications that require different material properties, composite materials are intensely used. Conventional materials are mostly not able to provide the necessary properties in specific application in the case of using the material alone. Thus the tailored materials with modified properties are crucial. Some examples of composite applications are given below;

Aerospace

In aerospace industry, major considerations for the applications are weight saving and safety. Thus, composite materials are widely utilized in aerospace industry.

- Structural components
- Wing skins
- Spars
- Fins
- Rudders
- Elevons
- Frames
- Rotor blades
- Fuselage (Mangalgiri, 1999).

Automotive

- Dashboard
- Door panel
- Carpet lining
- Rear shelf
- Floor
- Headliner
- Tunnel
- Engine hood
- Head rest
- Storage bin – inner lid
- Integral seat, safety seat
- Undershield
- Hood
- B-pillar
- Roof Panel
- Front and Rear Bumper
- Triangle joint
- Bumper support
- Transverse support beam
- Wheel arch housing
- Engine compartment
- Noise insulator
- Subsystems
- Gasket lining
- Clutch lining
- Brake pads
- Spare tire cover
- Tires

(Pinette P.E.I., 2020; Kaw, 2006; Composites Turkey, 2019;).

Biomedical

- Bone plate

Construction

- Bridge decks
- Profiles
- Columns
- Prefabs (Bakis et al., 2002)

Defence and military

- Aircraft bodies
- Helmet
- Vest

Marine

- Boat
- Lifeboats

Rail

- Bogie
- Train interior parts

Energy

- Isolators
- Antennas
- Fuses
- Cables
- Carriers

Other

- Vessels
- Sport equipment

Composite materials can be classified according to matrix material, reinforcement material or reinforcement type.

According to matrix material;

Polymer Matrix Composites (PMC), Metal Matrix Composites (MMC), Ceramic Matrix Composites (CMC)

According to reinforcement type;

Particulate Reinforced, Discontinuous Reinforced (short fiber or whiskers), Continuous Reinforced. In Figure 1.2., a general classification of composite materials is illustrated.

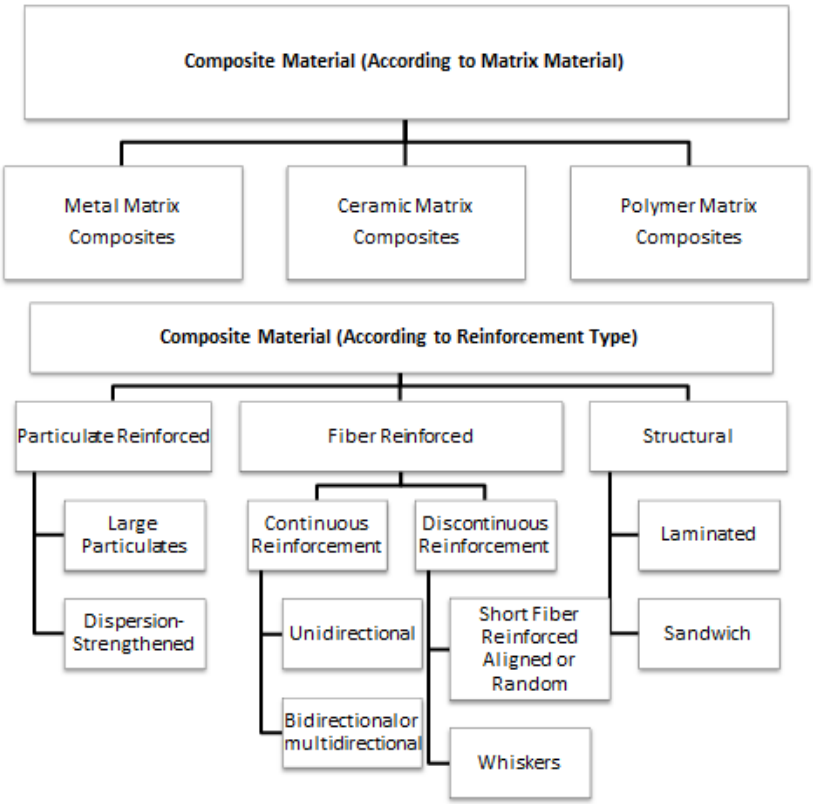


Figure **1**.2. General classification of composite materials

A matrix material can be any type of conventional materials like metal, ceramic or polymer. Composite materials are categorized according to the matrix materials as metal-matrix composites, ceramic-matrix composites and polymer-matrix composites. Also two or more different matrix systems can be used for hybrid

composite fabrication. Metal matrix composites are generally fabricated by reinforcing a low density metal ingredient such as aluminium or magnesium with a reinforcement agent. These materials are used in specific applications and the most important disadvantage of MMCs is the extremely high cost. MMCs are used in robots, internal combustion engines, high speed machinery and aerospace (Kumar et al., 2018). Ceramic matrix composites are the materials that are fabricated to utilize the high temperature properties of ceramics. The main problem with the ceramic materials is being extremely brittle. Thus, a ceramic matrix is reinforced with an agent and higher fracture toughness is obtained. CMCs are used in automotive, military, medical, and aerospace applications (Naslain, 2005). Polymer matrix composites are fabricated by using a polymer as matrix material. The polymer can be either natural or synthetic. The polymers are divided into two main categories as thermoplastic and thermoset. The main difference between thermoplastic and thermoset polymers is being recyclable. Thermoplastic polymers are recyclable and can be used again after a series of processes (Kaw, 2006).

Reinforcement agents are generally small diameter long length fibers or too small diameter and short length whiskers. The particles are also used as reinforcement agents in some applications. Composite materials are generally categorized according to reinforcement type as continuous or discontinuous composite materials. In Figure 1.3., a general form of composite material categorization according to reinforcement type is illustrated. The most common reinforcement agents are synthetic glass, carbon or aramid and natural fibers such as jute, flax, cotton, bamboo etc. The most versatile reinforcement agents are glass fibers due to the relatively lower cost and good mechanical properties. The reinforcement type is a very critical parameter for the composite materials. The reinforcement type directly alters the mechanical properties of the final product and thus the reinforcement type is chosen according the design requirements.

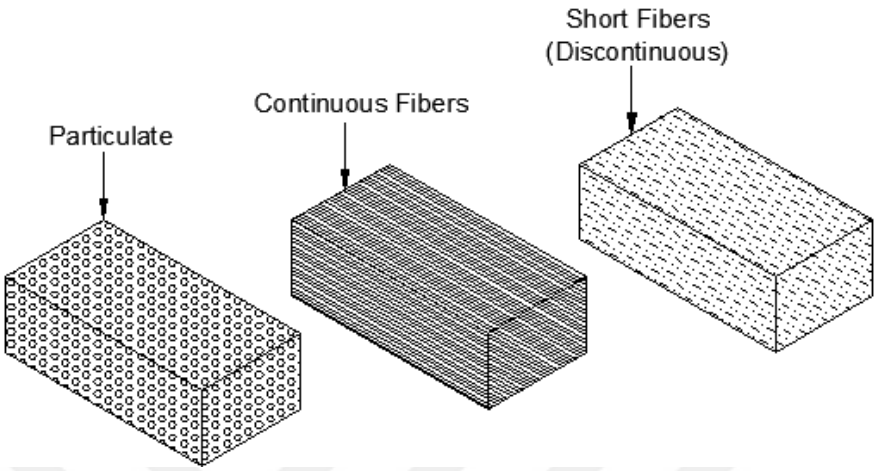


Figure 1.3. General composite forms according to reinforcement type

1.1. Objectives and Structure of the Study

Composite materials are getting increasingly more interest day by day. The diversity of composite materials brings the difficulty of analysing and designing products. Also, the relatively high cost of composite materials is a critical issue in most cases. The motivation of the study was to fabricate a novel type material that could be used as a counterpart to current expensive composites and plastics for various engineering applications.

In this study, a novel type of composite material was fabricated and characterized. The scope of the study can be listed as:

- Fabrication of a novel composite material,
- Using of expanded polystyrene beads as filler material,
- Using the chopped glass fibers as reinforcing agent,
- Determining the compatible matrix material,
- Determining the theoretical density an related properties,
- Achieving the quasi-homogenous structure

- Optimizing the fiber/filler ratio,
- Characterization of the novel composite,
- Determining the direction dependence of the novel composite,
- Cost analysis of the novel composite

For completing the objectives above, experimental studies were conducted at two stages. At the first stage, a chosen sample was fabricated and specimens in three orthogonal directions [x(1)-y(2)-z(3)] were obtained. The tensile and impact tests were conducted for the obtained specimens to determine the direction dependence of the material. Also micrographs of the specimens were examined to understand the mechanical behaviour of the specimens.

At the second stage of the study, samples with varying fiber lengths, expanded polystyrene densities and fiber/filler ratios were fabricated. The specimens obtained from those samples were characterized. To characterize the samples: tensile, impact, hardness and water absorption tests were conducted. The theoretical calculations and experimental results were compared. Also cost-property efficiency analyses were performed to determine the economic feasibility of the novel composite material.

2. PRELIMINARY WORK

The emerging technologies and the industrial requirements are leading researchers to investigate the composite materials which are the combinations of at least two different materials. Even though the composite materials are widely studied due to the variety of the raw materials (different reinforcements, matrices, fillers, additives, coupling agents, etc.), different fabrication methods, and also the production parameters (reinforcement type, weight fraction, etc.), there are many lacking points on the studies of composite materials.

Due to the flexible tailoring chance in composite materials, a wide variety of composite materials are fabricated with discrete properties. And also this leads the many lacking points in composite material researches.

2.1. Fiber Types

Composite materials are generally fabricated with reinforcement of a matrix material with a reinforcement agent. Generally the most known reinforcement agents are fiber materials. Besides fibers particulates and whiskers are also used for different composite applications.

Fibers are the reinforcing agents of the composite materials and main part of the composite system that carries structural loads. Composite materials are mostly produced with synthetic reinforcing agents. Generally, carbon, aramid and glass fibers are used for composite material production. Fibers can be divided into two main categories as natural and synthetic. Fibers can be utilized as woven, non-woven, short (chopped), uni-directional, bidirectional, multidirectional and etc. Composite materials are generally fabricated with carbon, glass and aramid synthetic fibers but recently there are also many attempts to use natural fiber to produce composite products. (Yildizhan et al., 2018). Glass fibers are preferred due to comparatively low cost and good mechanical characteristics. Carbon fibers have better mechanical characteristics than glass fibers but carbon fiber usage cost higher

than glass fibers. Aramid fibers (known as Kevlar commercially) also have high cost besides its superior mechanical characteristic. Thus aramid fibers are generally preferred in aerospace and defence applications (Yildizhan et al, 2018).

Natural fibers are obtained from plants or animals. Plant based fibers are composed of cellulose and animal fibers includes proteins (hair, silk, wool, etc.). Plant fibers consist of leaf, seed, bast, fruit, wood, grass, and stalk (Yildizhan et al., 2018). Using bio-fibers has some cons as well as pros. The main drawbacks of bio-fibers are the high moisture absorption, relatively lower structural strength and poor adhesion with matrix material. Thus, many researchers studied on morphological properties and the treatments for modifications of bio fibers (Li et al., 2007, Santucci et al., 2016, El Boustani et al., 2017, Liu and Cheng, 2017, Malenab et al., 2017, Yildizhan et al., 2018). Also many articles have been published that reviews the treatment methods and the effects of these treatments on mechanical, chemical and morphological properties of bio-fibers and bio-composites (Irina et al., 2004, Albinante et al., 2013, Chandrasekar et al., 2017, Verma and Jain, 2017, Yildizhan et al., 2018). The main goal for all treatment types (physical, chemical or physico-chemical) is to improve the adhesion characteristics of the fibers and by this way to improve the mechanical properties of the bio-composites. The most common physical methods are simple mechanical methods (stretching, calendaring, rolling), solvent extraction, electric discharge (corona, plasma, ionized air), thermal treatments. Alkaline, coupling (silane, acylation, graft copolymerization), bleaching (reduction, oxidation), enzyme, peroxide treatments are the chemical methods for modification of the fibers. Also there are some methods that combine the physical and chemical methods and called pyhsico-chemical methods such as hydrothermal and steam explosion (Li, Tabil and Panigrahi, 2007, Jawaid and Khalil, 2011, Fuqua et al., 2012, Yildizhan et al., 2018). In Table 2.1., some critical mechanical properties of natural and synthetic fiber types are given.

Table 2.1. Mechanical properties of some natural and synthetic fiber types (Yildizhan et al., 2018)

Type	Fiber	Density (g/cm^3)	Tensile Strength (MPa)	Elastic Modulus (GPa)	Elongation at Break (%)
GRASS	Bagasse	1,2-1,25	20-290	17-27,1	1,1
	Bamboo	0,6-11	140-230	11-17	-
WOOD	Hard Wood	0,3-0,88	51-210,7	5,2-15,6	-
	Soft Wood	0,3-1,5	45,5-1000	3,6-40,0	4,4
FRUIT	Coir	1,15-1,45	106-593	1,27-6,0	15,0-59,9
	Oil palm	0,7-1,55	100-400	1,0-9,0	8-25
BAST (STEM)	Jute	1,3-1,46	393-800	10-30	1,5-10,0
	Flax	1,4-1,5	345-1500	27,6-80	1,2-3,2
	Hemp	1,47-1,48	550-900	70	1,6-4,0
	Kenaf	1,2-1,45	295-930	53	1,6-6,9
	Kudzu	-	130-418		-
	Nettle	-	650	38	1,7
	Ramie	1,45-1,5	220-938	24,5-128	1,2-3,8
LEAF	Abaca	1,5	400-980	3-12	3-10
	Banana	1,35-	355-500	12-33,8	5,9-53
	Henequen	1,2-1,4	430-580	10,1-16,3	3,0-4,7
	Pineapple	0,8-1,6	170-1672	82	1,0-3,0
	Sisal	1,33-1,5	400-700	9,0-38,0	2,0-14
SEED	Cotton	1,5-1,6	287-597	5,5-12,6	3,0-10,0
	Kapok	0,38	93,3	-	-
SYNTHETIC	Carbon	1,4	4000	23-240	1,4-1,8
	E-glass	2,5	2000-3500	70,0	0,5-3,0
	S-glass	2,5	4570	86,0	2,8
	Aramide	1,4	3000-3150	63-70	2,5-3,7

2.2. Metal Matrix Composites

Metal matrix composites are used in particular applications which especially require too high strength and stiffness with low density. Also, in the case of some specific properties are required such as thermal expansion, thermal stability and tribological properties. Most common matrix materials for MMC fabrication are aluminium, magnesium, titanium, copper and super alloys. Metal matrices can be reinforced with fibers (continuous or discontinuous), whiskers or particles. Reinforcement materials are generally ceramics or polymer based fibers. MMCs are

generally used to produce turbine blades, produce piston walls, cylinder sleeves, callipers, brake pads, brake discs, bearings, missiles, etc.

The most common MMC material is aluminium based (aluminium or an aluminium alloy with Si, Mg, Cu, etc.) matrix composites which have relatively low density, enhanced strength and stiffness, improved high temperature properties and wear resistance (Kumar and Venkatesh, 2019). Reinforcing an aluminium based matrix can result with superior strength and stiffness. The most common reinforcement agents in aluminium based MMCs are non-metallic ceramics such as aluminium oxide (Al_2O_3), silicon carbide (SiC), boron (B), carbon (C) etc. Many researchers studied on the fabrication, characterization and applications of the aluminium based MMCs. Since the aluminium based MMC materials are the most common MMC type there are numerous studies and reviews on this particular subject.

Magnesium based MMC materials are also one of the most important type of MMC materials. Magnesium based MMC materials are fabricated by using magnesium or magnesium alloys (Mg-Li, Mg-Al, Mg-Ag-Re, etc) as matrix material and Magnesium has low density and good mechanical properties but in contrary magnesium based MMC materials has a very high cost relatively. Reinforcement agents such as SiC, magnesium borate ($Mg_2B_2O_5$), (Al_2O_3) and fly ash are mostly used for MMC material fabrication. Magnesium based MMC materials are intensely utilized in automotive industry (Satish and Satish, 2018).

Copper based MMC materials are used in the particular applications such as good wear and corrosion resistance and high thermal and electrical conductivity needed (Somani et al., 2019). Copper based MMC materials are mostly fabricated by using reinforcement agents such as alumina and graphite. Copper based MMC materials are frequently utilized in electronic devices and integrated circuits. Also titanium and some super alloys are used as matrix materials for MMC fabrication in the case of the high temperature resistance is required (Wilzer et al., 2015).

2.3. Ceramic Matrix Composites

Ceramic materials have a broad range of application area in engineering due to their appealing properties. Ceramic materials possess high strength, stiffness, and high thermal resistance characteristics. Beside these advantageous properties, also there are some disadvantages like low toughness. Monolithic ceramic materials are extremely brittle and mostly catastrophic failures occur in case of impact shocks. Thus, the main objective in fabrication of a CMC material is to enhance the toughness properties of the monolithic ceramics. Continuous or discontinuous reinforcement can be used in CMC materials. Ceramic matrices can be reinforced with particulates, whiskers or continuous fibers. The most common reinforcement agent in CMC fabrication is SiC. Also, different fibers and whiskers such as carbon and Al_2O_3 are used. CMC materials are mostly utilized in aeronautics and space applications for example, rocket engine nozzles which requires high service temperatures (Griffith and Halloran, 1996, Lu et al., 2019).

CMC materials have quite different mechanical properties than other type composites. In contrary to PMCs, the stronger phase in CMC material is the matrix phase and failure strain is larger than the matrix (Naslain, 2005). CMC materials can be fabricated with powder dispersion, liquid precursors or gaseous infiltration. Glass matrix composites and carbon glass composites are also CMC materials. Recently, especially there is an increased interest on carbon/carbon (C/C) composites. C/C composites are used in missiles and space shuttles due to superior temperature resistance. With increasing number of studies, it is expected to widen the usage area of C/C composites (Windhorst and Blount, 1997).

CMC materials are fabricated with methods such as;

- Gas phase route or chemical vapour infiltration
- Liquid phase route
- Polymer infiltration and pyrolysis

- Reactive melt infiltration
- Powder route
- Combined-hybrid routes (Naslain, 2005)

2.4. Polymer Matrix Composites

Polymer matrix composites are fabricated with reinforcement of a thermoset, thermoplastic or an elastomer resin with an agent. PMC materials are the most popular composite type commercially and have the highest percentage of usage among the all composite types. PMC materials have lower cost and simpler fabrication methods in comparison with MMC and PMC materials. Properties such as high specific strength and stiffness (strength/density, stiffness/density), high fracture toughness, good corrosion and abrasion resistance make PMC materials favourable for many different applications. Aerospace, automotive, marine, biomedical, structural, biomedical, and sporting goods are the primary fields that PMC materials are utilized in large quantities.

2.4.1. Fabrication and Properties

The final characteristics of all types of composite materials are determined from many different parameters. The major factors are matrix material, fiber material, matrix-fiber interface, reinforcement type and the fabrication method. PMC materials are generally fabricated with thermosetting or thermoplastic polymer resins. Thermoset resins are crosslinked polymers and do not soften upon heating (Saba and Jawaid, 2018). Because of the crosslinking, the thermoset resins have higher strength and lower sensitivity to temperature in comparison with thermoplastic resins. Some examples of thermoset resins are; epoxies, vinyl esters, unsaturated polyesters, phenol formaldehyde and urethane. Thermoset resins have chemical and creep resistance besides the good mechanical characteristic. But, these resins are brittle (low strain rate at fracture) and not recyclable with traditional

methods. Also shell-life of thermoset resins is limited before the curing (Kaw, 2006). Unlike thermoset resins, thermoplastic resins are linked or branched polymers and soften upon heating. Thermoplastic resins could be recycled and re-shaped after the curing (re-processable) (Kaw, 2006). In comparison with thermoset resins, thermoplastic resins have higher toughness but lower strength. Also, have low creep resistance and thermal stability. Polymers such as low density polyethylene (LDPE), high density polyethylene (HDPE), nylon, polypropylene (PP), polyvinyl chloride (PVC), polyethylene terephthalate (PET) are the some examples of the thermoplastic resins.

The characteristic of the fiber/matrix interphase determines the mechanical behaviour of the composite material. The better adhesion between fibers and matrix means better mechanical properties (Karger-Kocsis et al., 2015). The fiber/matrix interphase in termed as mesophase in some sources. In Figure 2.1., a schematic model of fiber/matrix interphase is illustrated.

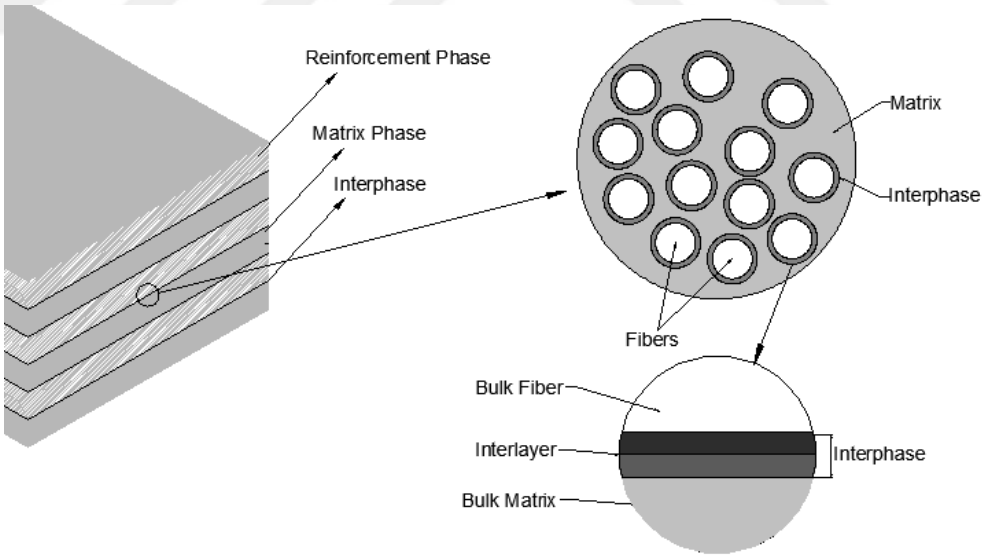


Figure **2**.1. Fiber-matrix interphase illustration

Composite materials are fabricated with different manufacturing techniques than the conventional methods and this is the one of the main disadvantages of composite material usage. The fabrication technique is determined by the composite types and product shape. The fabrication techniques can be classified as open mold and closed mold techniques (generally convenient for mass production) (Serin et al., 2019, Yildizhan et al., 2019). The mass production of a product by using a composite material can cause extra tooling cost. Therefore, many manufacturers are slogged on changing the current material to composite material even though the composite material usage brings extra advantages and higher quality products. MMC material are generally fabricated with methods such as casting (die, squeeze, stir, investment, etc.), diffusion bonding, deposition, powder processing, etc. For CMC material fabrication methods such as conventional ceramic processing, prepreg, porous preform infiltration techniques are some general examples. In this study, main focus is the PMC materials and thus a detailed literature survey on PMC material fabrication is summarized below.

2.4.1.1. Hand Lay-Up

Hand lay-up method is the simplest and oldest fabrication technique for PMC materials. This method is simply the stacking the fiber layers on an open mold by hand and impregnating the resin system via a roller (Figure 2.2.). Generally woven mats or chopped strand mats are used as reinforcing phase. The method doesn’t cause high tooling costs and also irregular complex shaped products can be manufactured by this method, and thus many manufacturers use this method. Also, this method is most preferred technique for composite product prototyping. In some applications, hand lay-up method is combined with autoclave process for controlling the curing process. Many researchers used this method for composite sample fabrication (Sureshkumar et al., 2014, Cui et al., 2016, Munawar et al., 2016, Nandaragi et al., 2018, Thippesh, 2018).

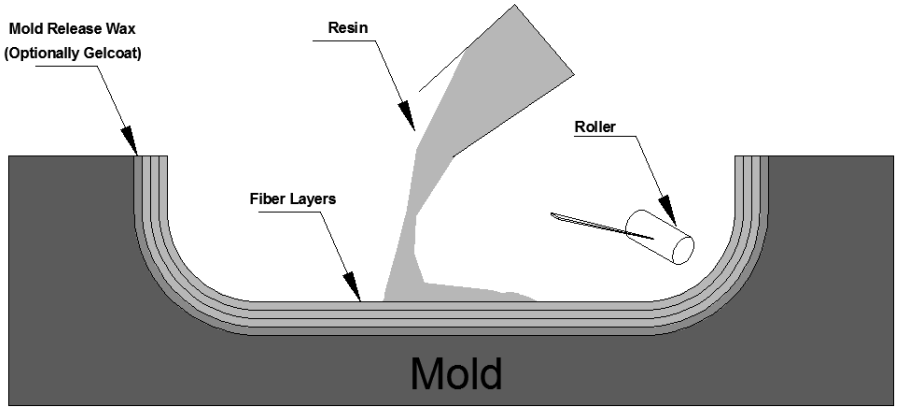


Figure 2.2. Hand lay-up technique schematic (Serin et al., 2019)

2.4.1.2. Spray Lay-Up

In this method, the mixture of reinforcement and resin is sprayed on the mold by a spray gun. Spray-up method is similar to hand lay-up method (Figure 2.3.). With this method, discontinuous reinforced composite are fabricated. The main advantage of the method is there is no limitation for the product size.

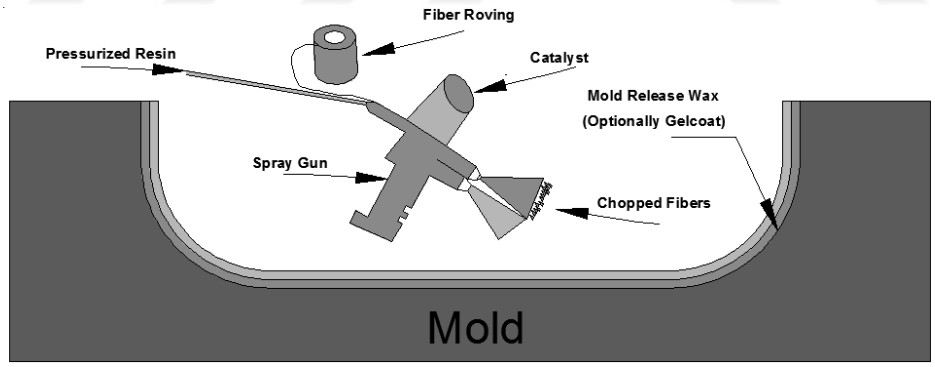


Figure 2.3. Spray lay-up technique schematic (Serin et al., 2019)

2.4.1.3. Vacuum Bagging

Vacuum bagging process is used with hand lay-up or spray lay-up method. After the lamination or spraying process the mold is covered with a flexible bag and vacuumed. The vacuum process provides the extraction of trapped air cavities. The

method provides better quality products due to better interfacial bonding between resin and reinforcement phases (Abdelal et al., 2018).

2.4.1.4. Vacuum Infusion

Vacuum infusion method (also called vacuum assisted resin infusion) is an advanced fabrication technique and adaptable to mass production. The application of the method is similar to vacuum bagging process but the major difference is resin is infused in to the reinforcement by vacuum force (Figure 2.4.). After the stacking the reinforcement phase, the mold is vacuumed. This provides the extraction of the air cavities like in vacuum bagging method. Afterwards, the resin introduced on the reinforcement by vacuum force due to pressure difference between the bagged mold and the vent. The low viscosity and slow curing resins are used for the process (Aktas et al., 2015). This provides the very high quality products. With this method, the minimum resin usage could be achieved. Many researchers utilized this technique for their studies (Belov et al., 2016, Xu et al., 2016, Zhang et al., 2016, Bulgakov et al., 2017, Subbiah et al., 2017, Wang et al., 2017).

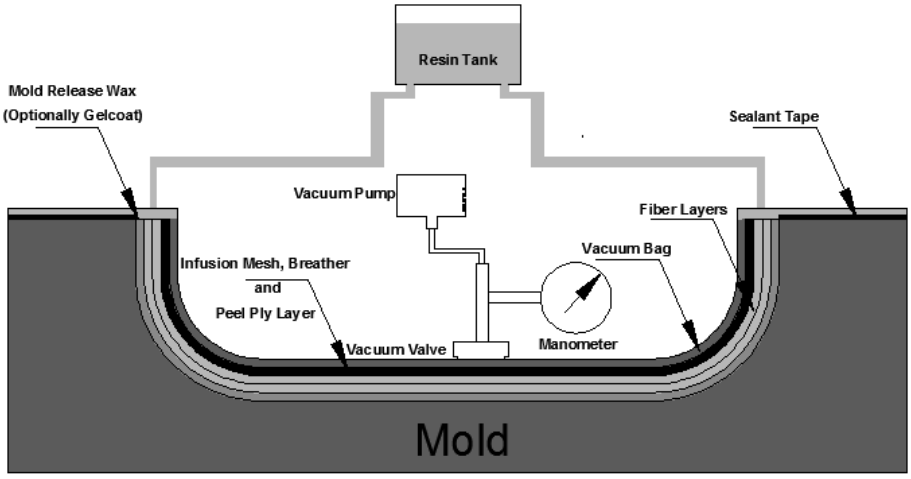


Figure 2.4. Vacuum infusion technique schematic (Serin et al., 2019)

2.4.1.5. Pultrusion

Pultrusion is an automated processing which is similar to metal extrusion process. While the material is pushed through the dies in extrusion method, in pultrusion method the material is pulled out (Figure 2.5.). The method is low cost and applicable for mass production of constant cross-sectional profiles (Sun and Chen, 2012). The main disadvantage of the method is incapability of manufacturing complex shaped products. There are numerous studies that utilize pultrusion methods (or its derivative methods) as fabrication technique for composite material researches (Methven et al., 2000, Peng et al., 2012, Epple and Bonten, 2014, Foller et al., 2014, Li et al., 2014).

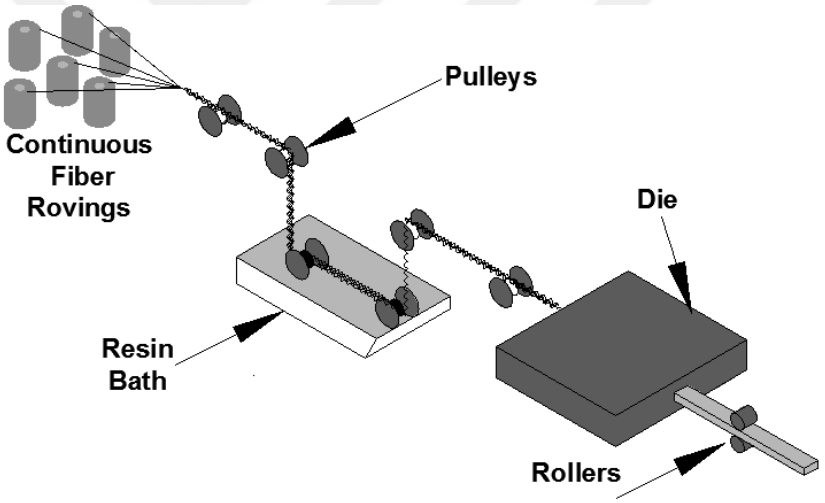


Figure 2.5. Pultrusion technique schematic (Yildizhan et al., 2019)

2.4.1.6. Filament Winding

Filament winding is one of the most preferred automated manufacturing methods and it is mostly used to manufacture products such as pressure vessels, tubes, storage tanks, sporting goods, etc. Continuous fiber strands or filament are wound on a mandrel or product shaped support (Figure 2.6.) (Shen, 1995). Filament

winding method was used and investigated by many researchers to fabricate composite specimens or products (Zu et al., 2011, Jiang and Qi, 2012, Almeida et al., 2016, Almeida et al., 2017, Gemi et al., 2018, Toh et al., 2018).

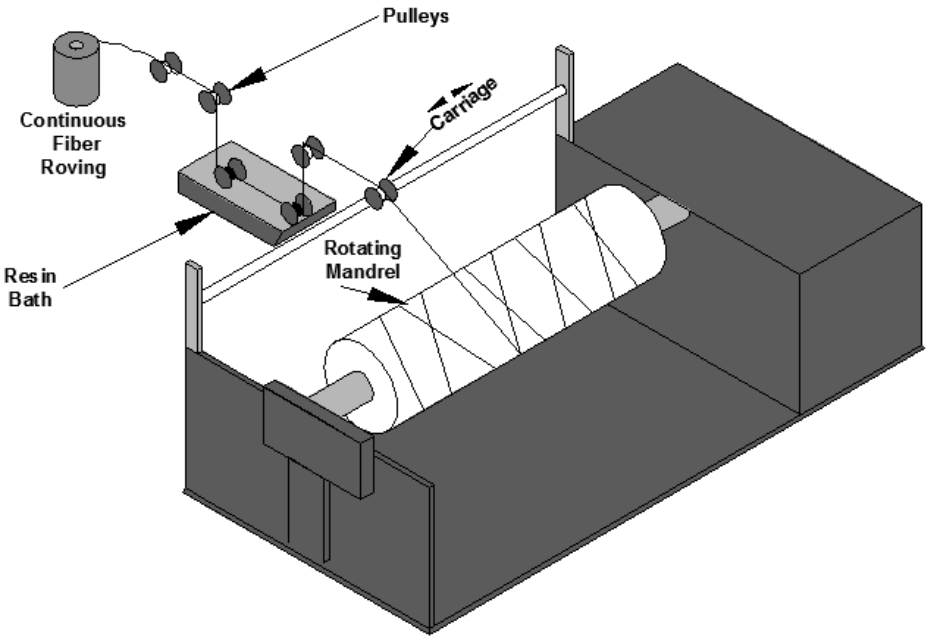


Figure 2.6. Filament winding technique schematic (Yildizhan et al., 2019)

2.4.1.7. Prepreg Molding

Prepregs are tapes or sheets that include fibers impregnated with partially cured thermoplastic or thermoset resins. Prepregs are stored at room temperature or in refrigerator depending on the resin type. The tapes or sheets are cured at room temperature or high temperatures (may also be combined with autoclave, pressure molding or vacuum assisted processes) (Kaw, 2006). Prepregs are widely used to manufacture high performance products. In many researches, the prepreg composites were used (Shi et al., 2014, Hong et al., 2016, Ma et al., 2018).

2.4.1.8. Resin Transfer Molding (RTM)

Resin transfer molding (also referred as vacuum assisted resin transfer molding (VARTM) if the vacuum is utilized) is similar to vacuum infusion technique and used for mass production. A closed mold is used and reinforcement phase is laid in the mold cavity (Figure 2.7.). A low viscosity resin is introduced into the mold and curing is done. The major disadvantage of the method is the necessity of two molds which causes extra cost (Kaw, 2006). RTM method is intensely used for composite production by manufacturers and researchers (Menta et al., 2013, Ashworth et al., 2016, Li et al., 2017, Swan et al., 2017, Zailinda et al., 2017, Asadi et al., 2018, Schillfahrt et al., 2018).

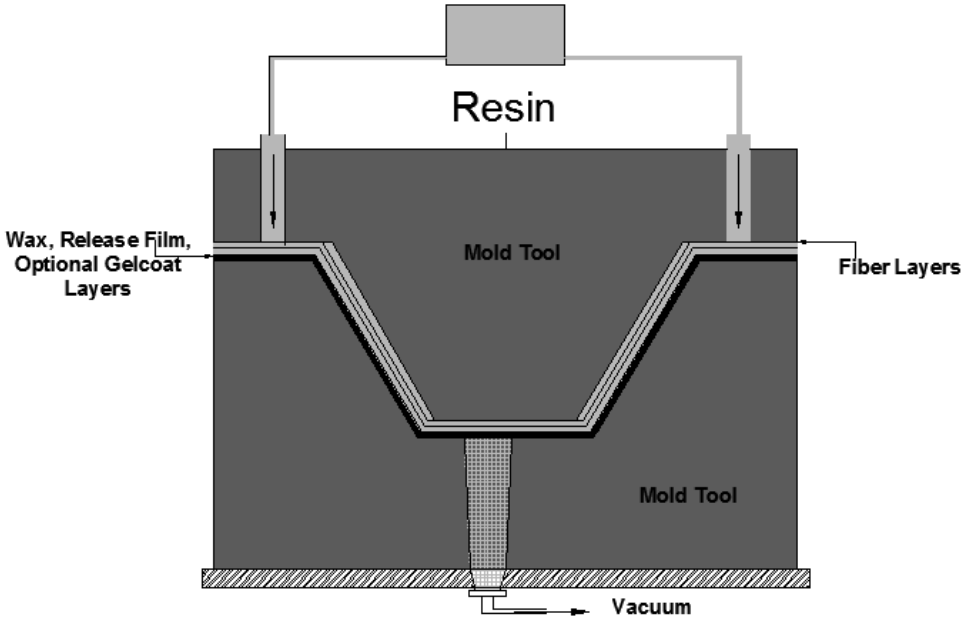


Figure 2.7. Resin transfer molding technique schematic (Yildizhan et al., 2019)

2.4.1.9. Injection Molding

Injection molding is closed molding type manufacturing method for plastic materials. And this method also could be utilized for PMC products (Karaaslan et al., 2009, Rausch et al., 2010, Takenaka and Ichigo, 2014, Sporleder et al., 2017).

Both thermoplastics and thermoset polymer composites with short fibers can be used. The reinforcement phase (short glass, carbon, etc.) and the matrix phase (thermoset; polyester, epoxy, vinyl ester, polyurethane etc, or thermoplastic; polypropylene, nylon, polyvinyl chloride, polyethylene, etc.) is mixed outside the mold and with a screw the mixture is blended in a heated barrel. Then, via a high pressure, the mixture is injected into the mold cavity through a nozzle. Also, a method called reaction injection molding which is illustrated in Figure 2.8. (reinforced reaction injection molding) is similar to injection molding. The main difference between these methods is in reaction injection method; that curing of the matrix phase (polymer) is situated in the mold. And thus, a hardener component is added. Both methods are widely used for PMC products.

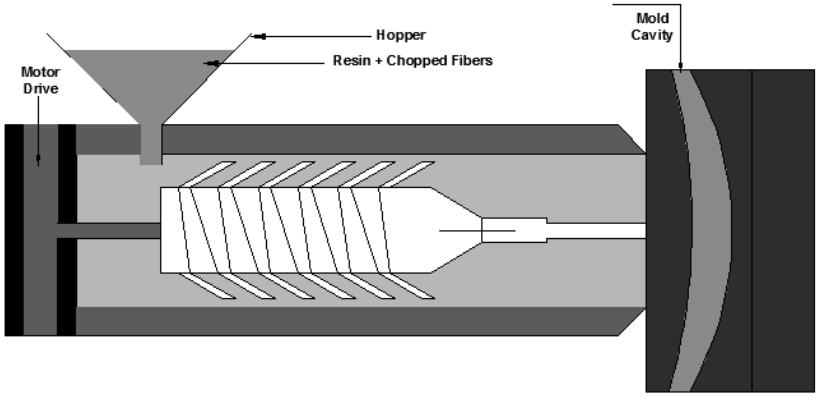


Figure 2.8. Reaction injection molding technique schematic (Yildizhan et al., 2019)

Many parameters that affect the composite material properties result in a huge number of diversity in composite materials. Also, composite materials are applicable for many different industrial products and thus composite materials are getting more and more attention by manufacturers and researchers progressively.

Hsu et al., (2018) investigated the mechanical properties of carbon fiber/epoxy composites by considering the environmental effects. The composite specimens were fabricated with vacuum assisted resin transfer injection molding

method with different numbers of layers. The authors tested the tensile and bending characteristics of the specimens. The study showed that increment of layer number improved the impregnation, maximum stress and Young's modulus of the specimens. The tensile and bending tests after the exposing humidity showed a slight improvement up to a point, but with the increment of moisture absorption a significant decrement in tensile and flexural strength was observed. Average maximum stress and the flexural stress of the 10 layer specimen was reported as 657,71 MPa with 24,58 MPa standard deviation and 571,94 MPa with 52,80 standard deviation without moisture absorption, respectively. After the specimens exposed to 85% relative humidity at 40 ^{o}C temperature for 58 days, those values decreased to 540,45 MPa with 32,78 MPa standard deviation and 414,18 MPa with 55,07 MPa standard deviation for maximum stress and bending stress, respectively (Hsu et al., 2018).

Li et al., (2018) studied the poly-ether-ether-ketone (PEEK)/short carbon fiber composites. In the study, tribological, thermal and mechanical properties of specimens fabricated via injection molding method were investigated. The authors observed that the tensile strength, flexural strength and strain of the specimens decreased with the usage of higher viscosity resin. The tensile strength, flexural strength and thermal stability of the composite specimens were improved with higher fiber/resin ratio. The authors also observed that PEEK/short carbon fiber composites had relatively lower friction coefficient in comparison with PEEK (Li et al., 2018).

Wonderly et al., (2005) compared different vinyl ester composites reinforced with carbon and glass fibers that are fabricated with vacuum infusion method. The authors observed that in the tensile testing, while failure of the carbon fiber reinforced specimens occurred laterally near the tab, failure of glass fiber reinforced composites were around gage area. The average tensile strength of the carbon and glass fiber reinforced specimens were 958,0±109,3 MPa and 544,4±10,6 MPa, respectively. The authors also tested the compression, transverse, indentation and ballistic properties of the specimens. Compression tests revealed that glass fiber

reinforced specimens had higher compression strength which was 396.2±20.3 MPa than carbon fiber reinforced specimens. The authors also observed that carbon fiber reinforced specimens had better indentation performance even the thinner laminates were used (Wonderly et al., 2005).

Currently, numerous fiber types are used for composite material production. Glass and carbon fibers are the most common fiber types for polymer matrix composites and used in many different applications. Different type fibers are also used as reinforcement agent for PMC material production. Kevlar, basalt, flax, jute or hybrid fibers (at least two different reinforcement combinations) are some examples of different fiber types. In Table 2.2., a brief summary of different PMC types obtained from literature survey is given.

Table 2.2. Properties of different PMC types (Yildizhan et al., 2018)

Fiber Type	Matrix	Fiber Fraction (% wt)	Tensile Stenght (MPa)	Young's Modulus (GPa)	Elongation (%)	Flexural Strenght (MPa)	Ref.
E-glass (Woven)	Polyester	60	287	7,9	-	183	(Kumar et al., 2018)
		65	304	7,55		197	
		70	306	5,38		209	
Glass (Filament)	Epoxy	69,2±0,3	1056,8±106,9	49,9±3,1	0.26±0,04	1653,7±63,6	(Deng et al., 1999)
Glass (Woven Mat)	Epoxy	45	186,12	1029	-	184	(Nandaragi, Reddy and Narayana, 2018)
Basalt	Epoxy	0,6% (volume)	18,54	13,638	0,257	-	(He et al., 2018)
		0,9% (volume)	23,56	14,741	0,273		
		1,2% (volume)	30,37	16,568	0,323		

Table 2.2. Continued

Fiber Type	Matrix	Fiber Fraction (% wt)	Tensile Strength (MPa)	Young's Modulus (GPa)	Elongation (%)	Flexural Strength (MPa)	Reference
Carbon (Laminate)	Epoxy	40	871,9±22,9	28±5	2,2±0,3	-	(Rallini et al., 2013)
Kevlar 49	Epoxy	40	550	30	2,5	345	(Meredith et al., 2013, Audibert et al., 2018)
Flax	Epoxy	37	76,7	11,2	-	57	(Audibert, Andreani, Laine and Grandidier, 2018)
Kevlar-Flax Hybrid	Epoxy	40	172	16	1,6	200	

2.5. Short Fiber/Particulate Reinforced Composites

Short fibers (or whiskers) and particulates could be used as reinforcement phase in order to fabricate composite materials. Those types of composites are generally fabricated to assess more toughness. Short fibers could be aligned or randomly distributed in the matrix phase. The most common short fiber composites are fabricated via chopped fibers (mostly glass fibers) or chopped strand mats. Chopped glass reinforced composite (chopped strand mat – CGFC) materials are getting interest due to its low cost and the ease of manufacturing. Using randomly dispersed chopped fibers could decrease the final product weight, makes the material behaviour more isotropic. Besides the enhancing the mechanical characteristics of the material also the tribological properties could be enhanced by randomly dispersed fibers. A composite material fabricated with lamination of the fiber layers could possess high strength and good stiffness parallel to fiber orientation but this behaviour is not same in perpendicular direction if the material is uni-directional. This means the material is anisotropic and can't possess the same characteristics in all directions. This is the main difference between the most engineering materials and composites. CGFC could decrease the degree of the anisotropy and the material could behave more similar in all directions due to the randomness of the fibers.

Nayak et al., (2018) investigated the mechanical properties of chopped E-glass (chopped strand mat) reinforced cashew nut shell liquid (CNSL) – epoxy composites which are fabricated with different reinforcement weight fractions by using hand lay-up technique. The experimental studies revealed that, increment of fibre content (weight fraction) improves tensile, flexural and hardness properties of the specimens. The authors reported that the increment in the tensile, flexural strength and the hardness values are due to the increment of withstanding capability of fibers with higher fractions (Nayak et al., 2018).

Ozsoy et al., (2017) studied on the mechanical and tribological behaviour of epoxy composite materials which are reinforced with chopped E-glass fibers. The researchers fabricated specimens with different fiber fraction ratios. In the study,

tensile, hardness, bending, impact and wearing tests were conducted. The authors reported that the coefficient of friction of the specimens were high due the weak bonding of reinforcement and matrix material. The authors claimed that; reinforcing the material with chopped glass fibers is not an effective way for increasing the tensile flexural strength according to tensile and bending test results. The tensile test experiments showed that when fiber fraction is over 30% the tensile strength and flexural strength is starting to decrease with more reinforcing material. But in contrary, increment of fiber fraction significantly increased the impact energy of the specimens (Ozsoy et al., 2017).

Lee et al., (2017) studied to improve the mechanical properties of glass fiber (fabric)/polyvinylchloride (PVC) composites by filling the regions which are devoid of fiber with chopped fiber which are treated with silane coupling. The study revealed that filling the undulated regions of the composite specimen with chopped glass fibers is an effective way to increase the tensile strength of the material especially with short fibers. According to experimental results, increasing the fiber length decreased the effect of improvement which occurs with filling. The results also revealed that silane treatment is also improved the mechanical properties due the effect of increased interface adhesion (Lee et al., 2017). A similar study also conducted by Park et al., (2017). In that study authors reported that the critical aspect ratio is different for different mechanical properties (Bin Park et al., 2017).

Stanciu et al., (2016) compared the viscoelastic characteristics and breaking modes of the polyester composites reinforced with chopped strand mat glass fabric. The authors observed that fabric reinforced composites stored more deformation energy than chopped fiber reinforced composites. The tensile strength of the specimens was higher when the composite reinforced with fabric instead of chopped fiber reinforcement. Authors also reported that chopped fiber reinforced materials showed visco-elastic behaviour at bending loading. According to study, while reinforcing the specimens with fabric results with good mechanical properties,

chopped fiber reinforcement decrease the degree of anisotropy and makes the material quasi-isotropic (Stanciu et al., 2016).

Thiagarajan et al., (2015) investigated the impact test responses of chopped glass fiber-epoxy nano-composites with additive of nano-clay. In the study, the samples were prepared by hand lay-up method and then subjected to the falling weight impact test. To determine the impact properties the absorbed energy was measured. The study revealed that addition of nano-clay to matrix of the material improved the energy absorption capability and load carrying capacity of the chopped glass reinforced composite samples (Thiagarajan et al., 2015).

Many authors studied on CGFC materials and reported many studies. Table 2.3. shows the production methods and some critical results of these studies.

Table 2.3. Fabrication methods and some critical properties of CGFC materials (Yildizhan et al., 2018)

Fiber	Matrix	Fiber Content (%)	Fabrication Method	Tensile Strength (MPa) / Modulus (GPa)	Flexural Strength (MPa) / Modulus (GPa)	Impact Energy	Ref.
E-Glass Chopped	Polyester	35,0±0,2	Hand lay-up	79,5 / 4,910	127,1 / 2,280	136,5 kJ/mm^2	(Varga et al., 2011)*
	Vinyl ester	33,4±1,0		83,1 / 4,690	142.2 / 2,380	137,6 kJ/mm^2	
E-Glass Chopped	Epoxy	15	Hand lay-up + compression molding	25,2 / 0,8	16,1 / 1,3	8,1 kJ/mm^2	(Siddhartha and Gupta, 2012)*
		20		29,6 / 0,56	76,6 / 2,2	7,7 kJ/mm^2	
		25		42,1 / 1,15	111,2 / 3,1	10,2 kJ/m^2	
		30		52,7 / 1,71	124,1 / 5,7	1,4 kJ/m^2	
E-Glass bi-directional		35		54,6 / 1,82	132,4 / 2,11	12,1 kJ/m^2	
		15		7,1 / 0,54	10,9 / 0,3	0,6 kJ/m^2	
		20		6,1 / 1,09	17,4 / 0,4	0,7 kJ/m^2	
		25		6,2 / 0,76	20,8 / 0,3	0,9 kJ/m^2	

Table 2.3. Continued

Fiber	Matrix	Fiber Content (%)	Fabrication Method	Tensile Strength (MPa) / Modulus (GPa)	Elongation at Break (%)	Flexural Strength (MPa) / Modulus (GPa)	Ref.
E-Glass Chopped + Wood sawdust	PVC	10	Screw extrusion	17,1 / 0,78	7,6	27,7 / 1,5	(Tungjitpornkull et al., 2007)*
		20		18,2 / 1,0	7,2	31,1 / 2,1	
		30		18,9 / 1,2	7,1	32,1 / 2,6	
E-Glass Chopped Strand Mat	CNSL + epoxy		Molding	116	-	93	(Nayak, Hecka dka, Thomas and Baby, 2018)
				160		136	
				178		166	
*The values are approximate readings on the graphs of the cited references							

One of the important aspects in materials is the thermal properties. Polymer matrix composites have a limited range of usage temperature due to the low decomposition and melting temperatures of the polymers. There are various types of polymer resins that are used to fabricate composite materials that have high thermal durability but, most polymers have low thermal durability in comparison with metals and ceramics. The increment of the application areas of the PMCs recently, leaded to further research on composites and composite properties. There are numerous studies on the thermal properties of the PMCs (Chung, 2000, Bertoncelj et al., 2015, Yu et al., 2016, Alva et al., 2018, Kopal et al., 2019). Many parameters such as crystallization, melting point (Cebe and Chung, 1990), glass transition temperature (Greenberg, 1987, Bussu and Lazzeri, 2006, Kim et al., 2009, Harmon et al., 2011, Siddiqui and Arif, 2018), thermal conductivity (Takenaka and Ichigo, 2014), thermal expansion coefficient (Takenaka and Ichigo, 2014), mass loss (Bertoncelj, Vojisavljevic, Vrabelj and Malic, 2015) etc., and the parameters that effect the properties have been reported.

2.6. Usage of Fillers in Composites

Composite materials may also be fabricated via fillers. The function of fillers is generally to improve mechanical properties of the matrix material and decrease the overall cost of the composite materials. Filler materials are generally inorganic compounds such as fly ash, quartz, silicon carbide (SiC), aluminium oxide (Al_2O_3), zinc oxide (ZnO), calcium carbonate ($CaCO_3$) (Kiran et al., 2018, Rao, 2020). Fillers may be used alone in matrix and also combined with a fiber reinforcement which results in a hybrid composite.

Nilugal and Kumar (2015) studied effect of silicon carbide and calcium sulphate fillers on mechanical, thermal and fire resistance of E-glass/epoxy composites. The authors reported that combination of calcium sulphate (7,5 % in volume) and silicon carbide as filler (7,5 % in volume) shows the highest ultimate tensile strength and hardness while that combination showed lower impact resistance

compared to composite material with no filler. The authors also concluded that calcium sulphate and silicon carbide combination filled composite exhibited lower thermal expansion coefficient in comparison with neat, calcium sulphate and silicon carbide filled composite (Nilugal and Kumar, 2015).

Vaisakh et al., (2016) investigated the effects of nano-modified SiO_2/Al_2O_3 fillers on mechanical, thermal and tribological properties of epoxy. The researchers fabricated 17 different types of composites at varying filler ratios and combinations. The authors concluded the followings after the experimental studies;

SiO_2/Al_2O_3 fillers showed a uniform distribution throughout the matrix.

The glass transition temperature of the epoxy did not show a significant change with fillers addition.

The thermal conductivity of the neat epoxy was enhanced.

In comparison with neat epoxy, filler usage improved the modulus and bulk hardness (Vaisakh et al., 2016).

Erklig et al., (2016) investigated the effects of various micro particle fillers (sewage sludge, fly ash and silicon carbide) at varying ratios in polyester resin. The authors reported that tensile and flexural strengths of the samples increased at the ratio of 5% wt. and decreased at higher ratios (Erklig et al., 2016).

EPS usage in composite material fabrication is not common. EPS is used as filler in cement composites. Since EPS is a relatively low cost and extremely low weight material, it is preferred as filler material in cement composites.

Wang et al., (2020) fabricated cement composites by using silica coated EPS and epoxy (as binder). Authors reported that; with the increment of the EPS amount in the composite, mechanical strength of the cement composite decreased, thermal conductivity of the composite decreased up to a point and increased after a point. The study also revealed that surface coated EPS particles have better compatibility with the cement system and has good fire resistance (Wang et al., 2020).

de Oliveira et al., (2019) researched the sound absorption characteristics of recycled gypsum matrix composites. The researchers fabricated acoustic insulation

panels with industrial gypsum, EPS and cellulose solid wastes. The authors reported that EPS containing composite can be used for sound absorbing purposes (de Oliveira et al., 2019).

3. MATERIAL AND METHOD

3.1. Materials

3.1.1. Expanded Polystyrene

Expanded polystyrene (EPS) is a thermoplastic material which is expanded from expandable polystyrene via steam. EPS is generally used as foam block. In Figure 3.1. raw beads and expanded beads are shown. As a thermoplastic polymer, polystyrene is in a solid (glassy) state at room temperature. EPS beads are closed cellular containing almost 98% trapped air (Sulong et al., 2019). Thus EPS beads have very low density and EPS is characterized with its density and especially mechanical properties are determined by the density (Solomon and Hemalatha, 2020). The main application areas of EPS are the construction, packaging industries. EPS is preferred in construction due to its good thermal insulation characteristic (Solomon and Hemalatha, 2020). Due to the low cost and low density of EPS, it is also a good candidate for many engineering applications.



Figure 3.1. Raw and expanded polystyrene beads

3.1.2. Chopped Glass Fibers

Glass fibers are the most widely used reinforcing agent in composite materials. Glass fibers are strong, durable and mostly chemically resistant materials, besides their lower cost in comparison with other synthetic fibers like carbon and aramid. Glass fibers are produced by conversion of many different raw materials. Glass fibers consist substances as silica (SiO_2), aluminium oxide (Al_2O_3), titanium dioxide (TiO_2), boron trioxide (B_2O_3), calcium oxide (CaO), magnesium oxide

(MgO), sodium oxide (Na_2O), potassium monoxide (K_2O), and ferric oxide (Fe_2O_3) at varying ratios. The type and characteristic of the glass fiber is determined by the chemical composition. Glass fibers are classified as A-glass, AR-glass, C-glass, D-glass, E-glass, S-glass, R-glass (Sathishkumar et al., 2014, Demina, 2016, Yildizhan et al., 2018). These types are utilized with different purposes. Glass fibers can be used as roving, strand mat, yarn, fabric, and chopped types (Yildizhan et al., 2018).

3.1.3. Epoxy Resin and Hardener

Epoxies are a large family of polymers and characterized by the presence of more than one epoxy group per molecule (Unnikrishnan and Thachil, 2006, Ernault et al., 2017). In the chemical structure besides the epoxy group, there may be aliphatic, cyclo-aliphatic or aromatic hydrocarbon molecules as non-epoxy group (Unnikrishnan and Thachil, 2006). Epoxies are generally available in market as two-component system (resin and hardener). Epoxies have relatively high strength and stiffness, high adhesiveness, good heat and chemical resistance (Jin et al., 2015). Nevertheless, epoxies have relatively very high cost. Epoxies are used in wide range of applications such as automotive, aviation, electronics, coating etc (Saba et al., 2016).

Epoxies are solidified with a curing agent. In market there are many different curing agents available. Curing agents used for epoxies can be classified as amine type, alkali type, anhydride, and catalytic type agents. Curing systems can be as room temperature curing, heat curing or photo curing (electron beam irradiation, ultraviolet or infrared) (Jin, Li and Park, 2015).

In the study, two different types of EPS (8 kg/m^3 and 13 kg/m^3), two different lengths of chopped glass fibers (3 mm and 6 mm) and epoxy resin were used to fabricate the composite samples. Photographs of EPS beads and chopped glass fibers are given in Figures 3.2.-3.5. Epoxy resin and chopped glass fibers were purchased from Dost Kimya and EPS were purchased from a local supplier. In Table 3.1.,

technical properties of the materials used to fabricate the composite samples are given.



Figure 3.2. Photograph of 8 kg/m^3 EPS beads



Figure 3.3. Photograph of 13 kg/m^3 EPS beads



Figure 3.4. Photograph of 3 mm chopped glass fibers

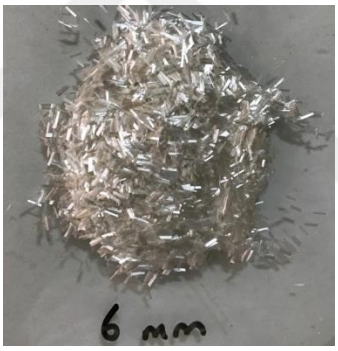


Figure 3.5. Photograph of 6 mm chopped glass fibers

Table 3.1. Properties of materials used to fabricate composite materials

Material	Property	Value	
L160 epoxy resin (2006)	Brand	HEXION	
	Density (g/cm^3)	1,13-1,17	
	Viscosity (mPas)	700-900	
	Epoxy equivalent (g/equivalent)	166-182	
	Epoxy value (equivalent/100 g)	0,55-0,60	
H260 hardener (2006)	Brand	HEXION	
	Density (g/cm^3)	0,93-0,97	
	Viscosity (mPas)	80-100	
	Amine value (mg KOH/g)	450-500	
	wt% in resin	35	
Cured Neat Resin (Curing: 24 h at 23 °C + 15 h at 60 °C) (2006)	Density (g/cm^3)	1,18 – 1,20	
	Modulus of elasticity (kN/mm²)	3,2 – 3,5	
	Tensile strength (N/mm²)	70 - 80	
	Elongation at break (%)	5,0 – 6,5	
	Impact strength (kJ/m²)	40 - 50	
EPS beads	Average diameter (mm)	6	2.8
	Density (g/cm^3)	0,008	0,013
Chopped glass fibers (supplier data)	Length (mm)	3	6
	Fiber diameter (µm)	13-15	
	Density (g/cm^3)	2,60	
	Tensile strength (N/mm²)	3400	
	Modulus of elasticity (kN/mm²)	77	

3.2. Method

3.2.1. Material Design

Considering a cube shaped mold and filling that mold via EPS beads (assuming beads are perfect spheres and no force exerts on the balls);

$v_c = a^3$, $v_{EPS} = \frac{4}{3}\pi r^3$ (for one EPS ball)

$n_{EPS} = \frac{a^3}{8r^3}$ (total EPS number)

$$v_{EPS(total)} = v_{EPS} n_{EPS} = \frac{4}{3}\pi r^3 \frac{a^3}{8r^3}$$

$$v_{EPS(total)} = \frac{\pi a^3}{6}$$

$$v_{void} = a^3 - \frac{\pi a^3}{6} \quad (3.1)$$

Equation 3.1 shows that, the void volume in the composite material is independent of sphere radius (EPS bead size) theoretically. The equation allows determining the void volume in the matrix for introducing the chopped glass fibers. Theoretical void volume for introducing the resin is 47,6%.

The main objective in the material design is to create a novel material with a high strength and stiffness, durability, impact strength, corrosion resistance and especially low cost material. The idea of the novel composite was to cover the EPS beads via chopped glass fibers to utilize the high strength and stiffness of the glass fibers and impact absorbent properties of the EPS beads. Besides, EPS has extremely low density and relatively low cost. Filling an epoxy matrix with such a low density and low cost material creates a very feasible material for various engineering applications.

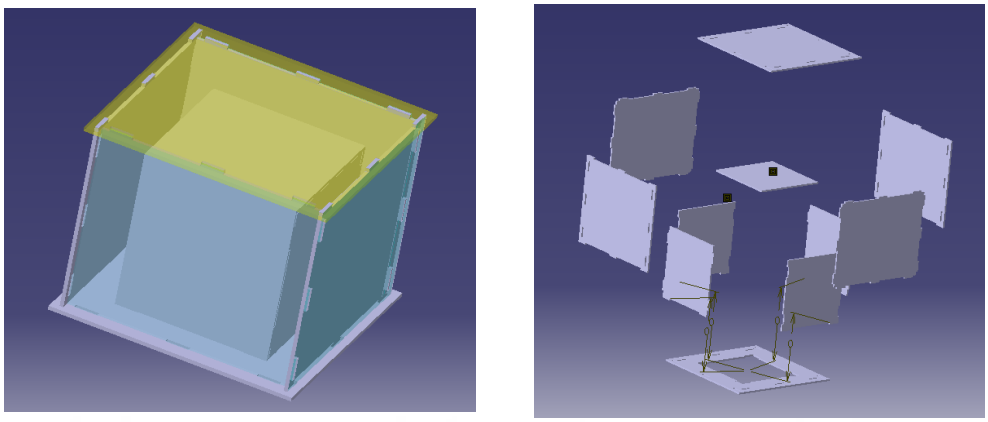
In the study, two different molds were used to fabricate the novel material. The aim of the first mold was to obtain test specimens in three orthogonal directions (specimens from the same bulk material). Those specimens were used to understand the direction dependence of the properties which is generally a critical issue in composites. To check the direction dependence of the material, tensile and impact test were conducted for those specimens in three main orthogonal directions. The second mold was used to fabricate the samples with varying ratios of ingredients. The main objective here was to determine the optimum ratios of filler and reinforcement.

3.2.2. Fabrication of Specimens

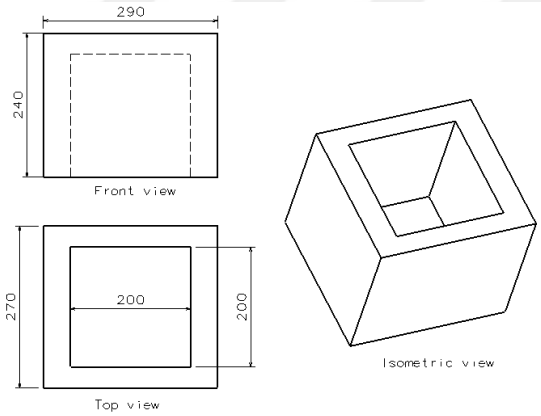
Composite specimens were fabricated in Material Laboratory of Automotive Engineering Department, Çukurova University. Specimens were fabricated via vacuum infusion technique. Before the fabrication of the actual specimens, pre-fabrications were tried to determine the possible fiber/filler ratios. In the pre-fabrication studies the main challenge was to cover the EPS beads via chopped glass fibers. For that purpose, a temporary adhesive (polybutene, hexane and butyl rubber – used as trap adhesive- diluted with hexane) was used as binder material. For actual specimens two different steel molds were designed and manufactured. The molds were manufactured from steel sheet (thickness: 5 mm) with laser cutting method. The molds were designed as to be completely disassembled. The mold cavity was chosen as rectangular for convenience of the material specimens.

The first mold (Figure 3.6.) was used to fabricate the material sample to obtain test specimens in three orthogonal directions. In the first mold only one type of sample was fabricated with 8 kg/m^3 EPS and 3 mm chopped glass fibers. The ingredient ratios for the first mold are;

Weigth ratio of EPS beads=0,0108
Weigth ratio of chopped glass fibers=0,2166
Weigth ratio of matrix (resin) =0,774
Weight ratio of fiber to EPS beads=20:1



(a) (b)



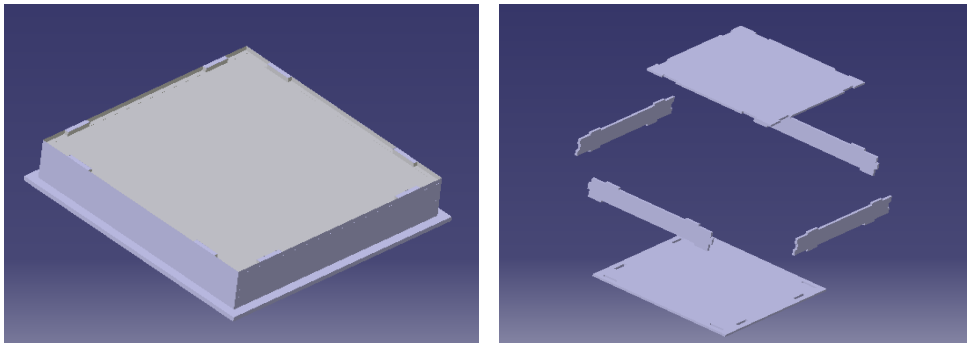
(c)

Figure 3.6. Mold for specimen fabrication (first stage), (a) 3D model, (b) exploded view, (c) technical drawing- dimensions in mm

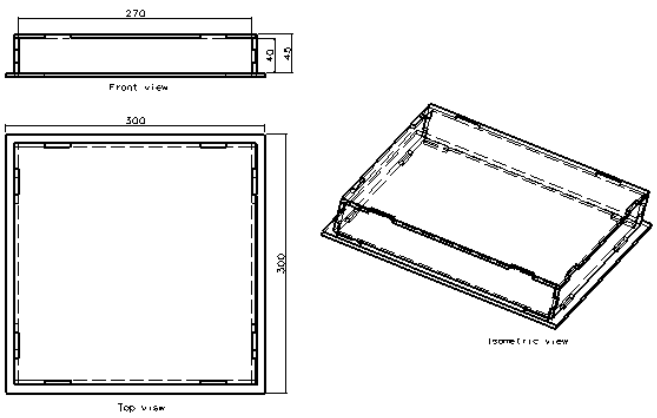
Fabrication parameters of the specimens fabricated in second stage of the study are given in Table 3.2. and mold used to fabricate specimens in second stage is illustrated in Figure 3.7.

Table 3.2. Fabrication parameters of the specimens for stage 2

Specimen Code	Filler Size (EPS coded with density)	Fiber Length (mm)	Reinforcement/ Filler (w/w)	Filler Weight (kg)	Fiber Weight (kg)
A1	8	-	-	0.0233	-
A2	13	-	-	0.0379	-
B1	8	3	10:1	0,0233	0,233
B2	8	3	20:1		0,466
B3	8	3	30:1		0,699
C1	8	6	10:1		0,233
C2	8	6	20:1		0,466
C3	8	6	30:1		0,699
D1	13	3	10:1	0,0379	0,379
D2	13	3	20:1		0,758
D3	13	3	30:1		1,137
E1	13	6	10:1		0,379
E2	13	6	20:1		0,758
E3	13	6	30:1		1,137



(a) (b)



(c)

Figure 3.7. Mold for specimen fabrication (second stage), (a) 3D model, (b) exploded view, (c) technical drawing- dimensions in mm

Fabrication Steps;

The same procedure was followed for the both molds.

1. Mixing the chopped glass fibers and EPS beads (Figure 3.8.),

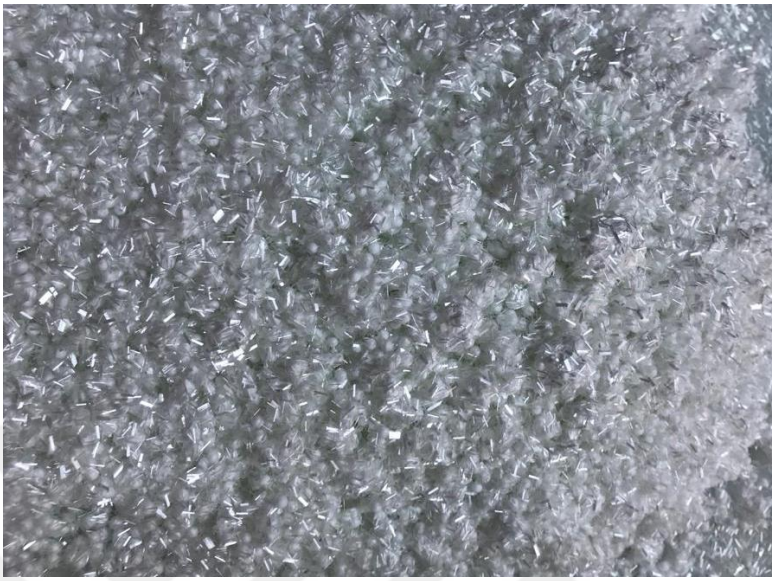


Figure 3.8. Mixture of chopped glass fibers and EPS beads

2. Assembling the mold,
3. Covering the mold surface via releasing wax for easy removal,
4. Filling the mold cavity with material (Figure 3.9.),



Figure 3.9. Mold with filled material

5. Closing the mold,

6. Vacuuming the mold (until the absolute vacuum- gage pressure: -101,25 kPa≈-760 mmHg) and checking the vacuum pressure for possible leakage (Figure 3.10.),



Figure 3.10. Mold under absolute vacuum

7. Preparing the matrix system (resin+hardener with recommended ratios from supplier),
8. Introducing the matrix system into the mold via vacuum force (Figure 3.11),



Figure 3.11. Infusion process

9. After infusion completion, waiting for 24 hours at room temperature for complete curing of the matrix,
10. Post curing at 50 ºC for 24 hours in a temperature controlled oven.
11. Disassembling the mold and removal of the material sample (Figure 3.12.).

The fabrication technique is also illustrated in Figure 3.13. and 3.14. schematically.



Figure 3.12. Removal of the material sample

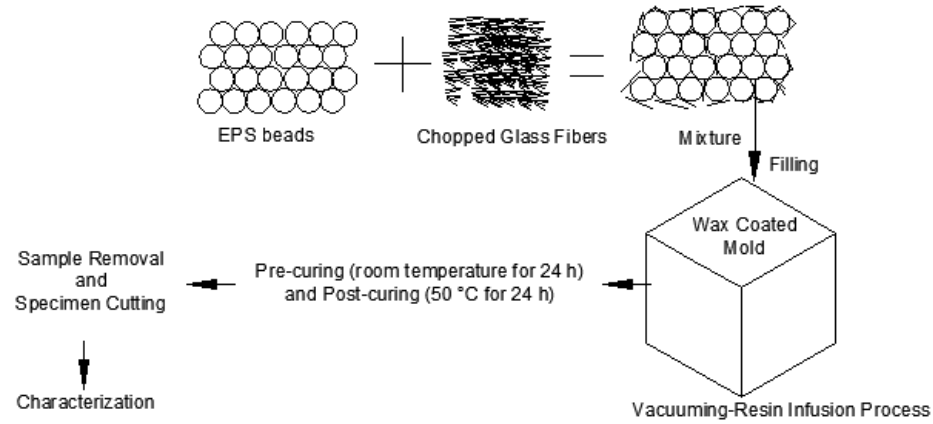


Figure 3.13. Fabrication processes of the samples

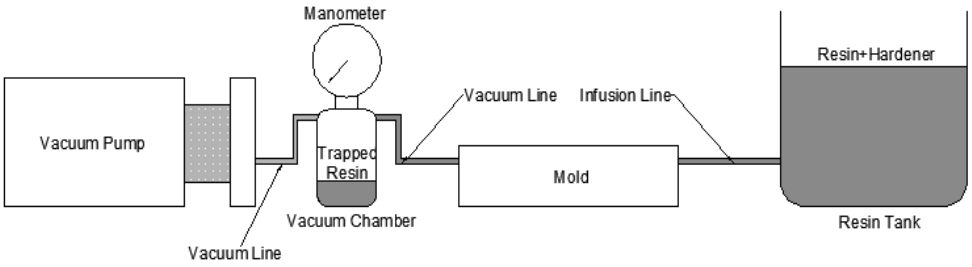


Figure 3.14. Vacuum infusion process schematic

3.2.3. Specimen Cutting

Fabricated specimens were cut to obtain tensile and impact test specimens. In Figure 3.14. and 3.15. specimen cutting schemes for the first and second stages studies are illustrated, respectively. For the first stage study, the cube shaped bulk material was cut in three orthogonal directions as shown in Figure 3.15.

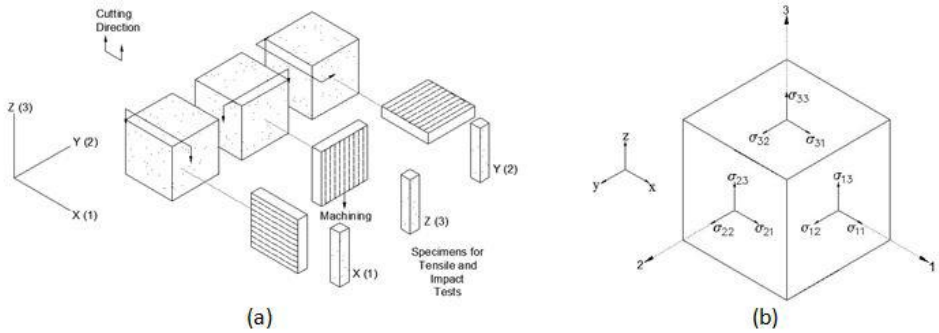


Figure 3.15. Specimen cutting scheme of the samples (first stage) to be tested in three orthogonal directions (a) and stress tensors (b)

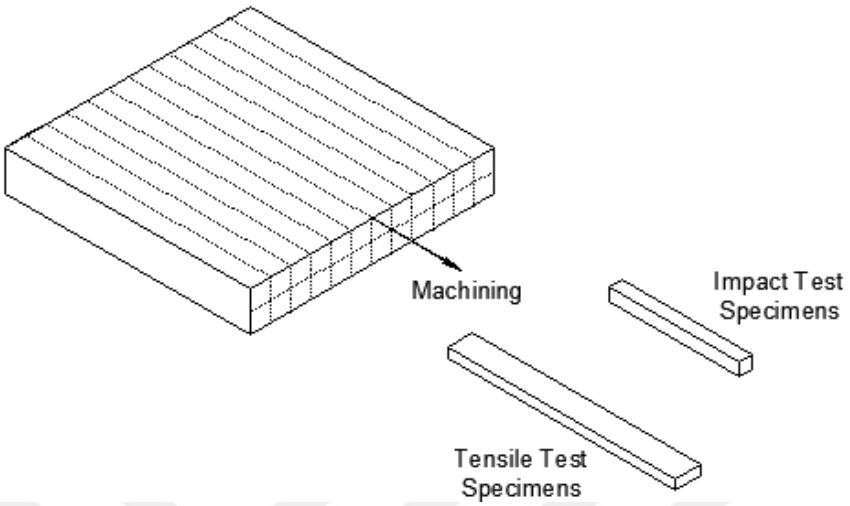


Figure 3.16. Specimen cutting scheme of specimens (second stage)

In Figures 3.17. and 3.18., the sample photographs of the fabricated material specimens are showed.

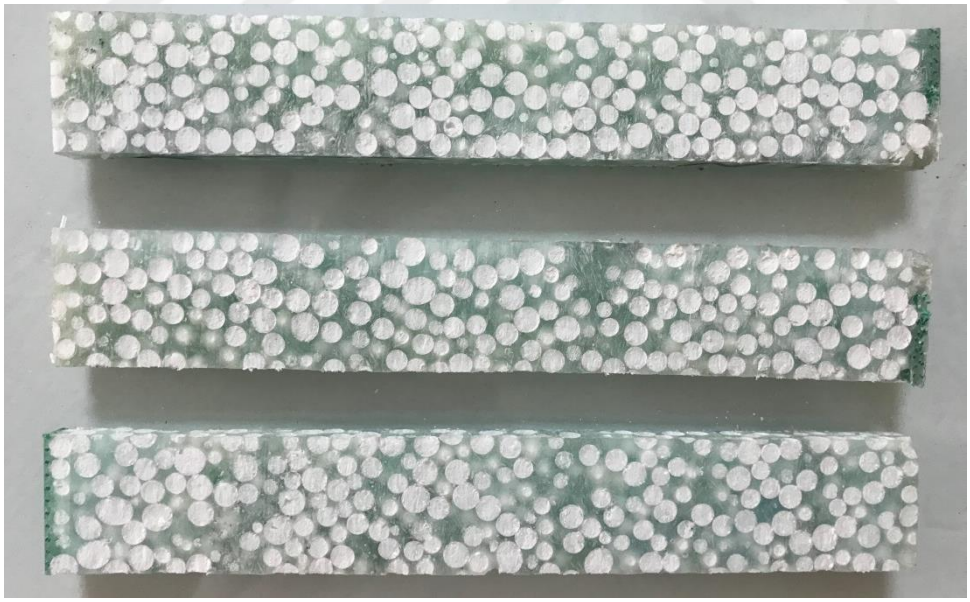


Figure 3.17. Sample photographs of tensile test specimens



Figure 3.18. Sample photographs of impact test specimens

3.2.4. Volume and Weight Fractions

Volume

$$V_f = \frac{v_f}{v_c} \tag{3.2}$$

$$V_m = \frac{v_m}{v_c} \tag{3.3}$$

$$V_f + V_m = 1 \tag{3.4}$$

$$v_f + v_m = v_c \tag{3.5}$$

Weight

$$W_f = \frac{w_f}{w_c} \tag{3.6}$$

$$V_m = \frac{w_m}{w_c} \tag{3.7}$$

$$W_f + W_m = 1 \tag{3.8}$$

$$w_f + w_m = w_c \tag{3.9}$$

$$w_f = \rho_f v_f \tag{3.10}$$

$$w_m = \rho_m v_m \tag{3.11}$$

$$w_c = w_f + w_m \tag{3.12}$$

$$w_c = \rho_c v_c \tag{3.13}$$

Density

$$\rho_c v_c = \rho_f v_f + \rho_m v_m \tag{3.14}$$

$$\rho_c = \rho_f \frac{v_f}{v_c} + \rho_m \frac{v_m}{v_c} \tag{3.15}$$

$$\rho_c v_c = \rho_f V_f + \rho_m V_m \tag{3.16}$$

$$v_c = v_f + v_m \tag{3.17}$$

$$\frac{1}{\rho_c} = \frac{W_f}{\rho_f} + \frac{W_m}{\rho_m} \tag{3.18}$$

Void

$$V_v = \frac{v_v}{v_c} \tag{3.19}$$

Total volume of the composite with void;

$$v_f + v_m + v_v = v_c \tag{3.20}$$

Experimental density of the composite ρ_{exp}

$$v_c = \frac{w_c}{p_{exp}} \tag{3.21}$$

Theoretical density of the composite ρ_{theo}

$$v_f + v_m = \frac{w_c}{\rho_{theo}} \tag{3.22}$$

$$\frac{w_c}{\rho_{exp}} = \frac{w_c}{\rho_{theo}} + v_v \tag{3.23}$$

$$v_v = \frac{w_c}{\rho_{exp}}\left[\frac{\rho_{theo}-\rho_{exp}}{\rho_{theo}}\right] \tag{3.24}$$

The equations 3.2-3.20 are adapted from Mechanics of Composite Materials (Second Edition) book written by Autar K. Kaw (Kaw, 2006).

Modifying the equations 3.2-3.24 for the EPS/Glass/Epoxy composite;

Volume

$$V_f = \frac{v_f}{v_c} \tag{3.25}$$

$$V_{EPS} = \frac{v_{EPS}}{v_c} \tag{3.26}$$

$$V_m = \frac{v_m}{v_c} \tag{3.27}$$

$$V_f + V_{EPS} + V_m = 1 \tag{3.28}$$

$$v_f + v_{EPS} + v_m = v_c \tag{3.29}$$

Weight

$$W_f = \frac{w_f}{w_c} \tag{3.30}$$

$$W_{EPS} = \frac{w_{EPS}}{w_c} \tag{3.31}$$

$$W_m = \frac{w_m}{w_c} \tag{3.32}$$

$$W_f + W_{EPS} + W_m = 1 \tag{3.33}$$

$$w_f + w_{EPS} + w_m = w_c \tag{3.34}$$

Density (theoretical)

$$w_c = w_f + w_{EPS} + w_m \tag{3.35}$$

$$\rho_c v_c = \rho_f v_f + \rho_{EPS} v_{EPS} + \rho_m v_m \tag{3.36}$$

$$\rho_c = \rho_f \frac{v_f}{v_c} + \rho_{EPS} \frac{v_{EPS}}{v_{EPS}} + \rho_m \frac{v_m}{v_c} \tag{3.37}$$

$$\rho_c = \rho_f V_f + \rho_{EPS} V_{EPS} + \rho_m V_m \tag{3.38}$$

$$v_c = v_f + v_{EPS} + v_m \tag{3.39}$$

$$\frac{1}{\rho_c} = \frac{W_f}{\rho_f} + \frac{W_{EPS}}{\rho_{EPS}} + \frac{W_m}{\rho_m} \tag{3.40}$$

Void

$$V_v = \frac{v_v}{v_c} \tag{3.41}$$

Total volume of the composite with void;

$$v_f + v_{EPS} + v_m + v_v = v_c \tag{3.42}$$

Experimental density of the composite ρ_{exp}

$$v_c = \frac{w_c}{p_{exp}} \tag{3.43}$$

Theoretical density of the composite ρ_{theo}

$$v_f + v_{EPS} + v_m = \frac{w_c}{\rho_{theo}} \tag{3.44}$$

$$\frac{w_c}{\rho_{exp}} = \frac{w_c}{\rho_{theo}} + v_v \tag{3.45}$$

$$v_v = \frac{w_c}{\rho_{exp}}\left[\frac{\rho_{theo}-\rho_{exp}}{\rho_{theo}}\right] \tag{3.46}$$

Where;

v_f, v_{EPS}, v_m, v_c , are volumes of fiber, EPS, matrix, and composite, respectively,
w_f, w_{EPS}, w_m, w_c are weights of fiber, EPS, matrix, and composite, respectively,
V_f, V_{EPS}, V_m are volume fractions of fiber, EPS and matrix, respectively,
W_f, W_{EPS}, W_m are weight fractions of fiber, EPS and matrix, respectively.

3.2.5. Tensile Tests and Micrographs

Tensile test is a mechanical test used for determining tensile properties of the materials (ASTM, 2017). Tensile test has a great importance to characterize a material mechanically. Outputs of a tensile test are yield strength, tensile strength, rupture strength, elastic modulus (Young's Modulus) and Poisson's ratio. The test is conducted by pulling the specimen and measuring the elongations and the force exerted by the device. Tensile tests were conducted according to ASTM D3039 standards via ALŞA universal testing device (computer controlled, hydraulic, 60 tons of load capacity) (Figure 3.19. and 3.20.). Standard specimens (technical drawing is given in Figure 3.21.) were prepared according to requirements of ASTM

D3039. The recommended dimensions for random-discontinuous composites are given as 250 mm, 25 mm, and 2,5 mm for length, width, and thickness, respectively (ASTM, 2017). But the sample was produced with average diameter of 2,8 mm and 6 mm EPS beads and thus, in order to assess the complete representation of sample structure, the specimens were prepared with the modified dimensions of 220mm x 25mm x 10mm. Emery cloth was used for the tabs as recommended in ASTM D3039.The head speed was set as 2 mm/min during the tests.



Figure 3.19. Tensile testing device (Koluman Otomotiv Endüstri A.Ş.)

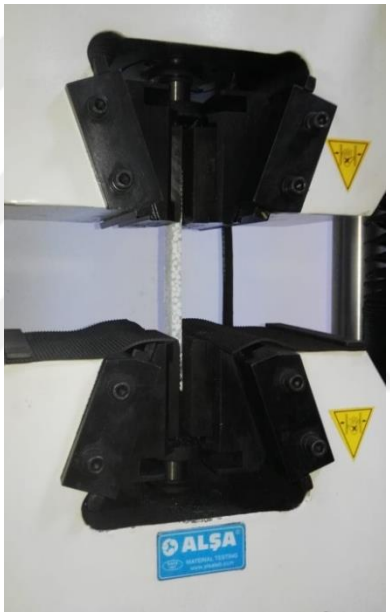


Figure 3.20. Composite material on tensile testing

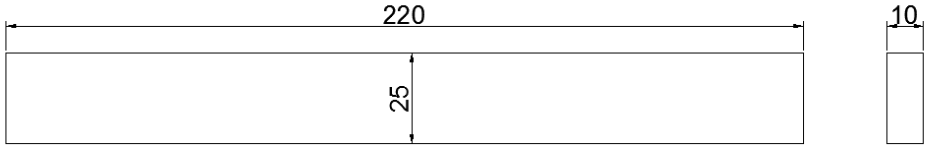


Figure 3.21. Tensile test specimen with modified dimension (dimensions in mm)

Calculation

Tensile strength

$$\sigma_t = \frac{P_{max}}{A} \quad (3.47)$$

Strain

$$\varepsilon_t = \frac{\delta_i}{l_0} \quad (3.48)$$

ε_t = tensile strain

δ_i = extensometer displacement

l_0 = gauge lenght

Tensile modulus E_t

$$E_t = \frac{\Delta\sigma}{\Delta\varepsilon} \quad (3.49)$$

$$Specific\ strength = {}^{\sigma_t}/_{\rho}\ (\text{MPa.m}^3/\text{kg}) \quad (3.50)$$

$$Specific\ modulus = {}^{E}/_{\rho}\ (\text{GPa.m}^3/\text{kg}) \quad (3.51)$$

After tensile tests of the first stage, micrographs of the samples were taken with a 5 MP microscope camera (Figure 3.22.).



Figure 3.22. AOB stereo microscope and camera

3.2.6. Impact Test

Impact test is conducted to determine the fracture properties of the materials under the dynamic loads (ASTM, 2004). The test is conducted by applying an impact with a weighted pendulum hammer (Figure 3.23.) to a standard specimen (generally notched-Figure 3.24.). The test results give the energy absorbed by the specimen during fracture and toughness of the material. There are two standardized impact tests; Charpy and Izod tests. The main difference of these tests is the position of the specimen during the impact. In this study, Charpy impact test was applied according to ASTM D 6110 (ASTM, 2004).



Figure 3.23. Charpy impact test device

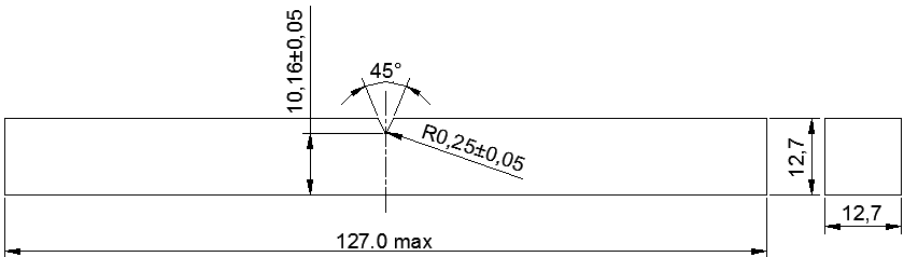


Figure 3.24. Notched impact test specimen

3.2.7. Hardness Test

Hardness is defined as the resistance of a material to localized plastic deformation. In this study, micro-Vickers hardness tests (load≤1 kgf) were conducted to determine the hardness of the material specimens. Technical

specifications of the test device (Figure 3.25.) are given in Table 3.3. In Figure 3.26. diagonal measurement of the intender trace is illustrated.



Figure 3.25. THV-1 MD Digital Vickers hardness tester

Table 3.3. Technical specifications of THV-1 MD

Specification	**Property**
Brand-model	Jiashan- THV-1 MD
Test forces	0,01 kgf, 0,025 kgf, 0,05 kgf, 0,1 kgf, 0,2 kgf, 0,3 kgf, 0,5 kgf, 1 kgf
Hardness range	8HV-2900HV
Microscope	100X for observation 400X for measurement
Dwell time	0-60 s

Calculation

$$HV = 1{,}854\frac{P}{d^2} \tag{3.52}$$

$$d = \frac{d_1+d_2}{2} \tag{3.53}$$

P; applied load

d: diagonal length

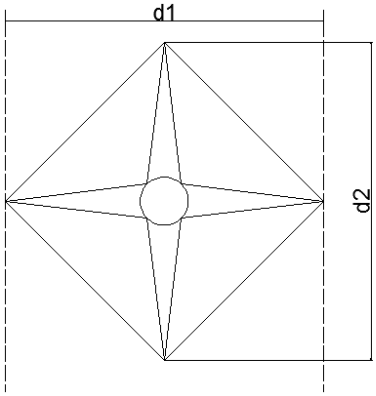


Figure 3.26. Diagonal measurement of test intender trace

3.2.8. Thermogravimetric Analysis (TGA)

TGA is a thermal analysis method that is used to determine the qualitative and quantitative characteristics of the samples. In the study analyses of two different samples (composite sample fabricated at first stage and neat resin) were conducted in Mettler Toledo TGA 3+ model (Figure 3.27.) (properties: 25-1600 ºC test range, 0,02-150 K/min heating ratio, 0,1 µg weight measuring resolution) from 25 ºC to 600 ºC with 10 ºC/min heating ratio.



Figure 3.27. Mettler Toledo TGA 3+

3.2.9. Water Absorption Tests

To determine the water absorption characteristic of the specimens, water absorption tests were conducted experimentally. Specimens were soaked and kept in tap water (without any physical or chemical treatment) (Figure 3.28) at room temperature. Before soaking the dry weights of the specimens were measured via precision balance. After one hour of soaking the specimens were taken out from the water. The specimens were wiped and dried. The weight measurement was conducted again and the results were noted. The same procedure was followed for 6 times with one hour period. Afterwards the same procedure was applied with period of 24 hours for 9 days. The precision balance used in the study to measure weight throughout the study is showed in Figure 3.29. and technical details of the device are given in Table 3.4.



Figure 3.28. Water absorption tests



Figure 3.29. Precision balance

Table 3.4. Technical specification of the precision balance

Specification	Property
Brand	Radwag AS 220 R.2
Maximum capacity	220 g
Readability	0,1 mg
Repeatability	0,1 mg
Linearity	0,2 mg

3.2.10. Experimental Error Analysis

For each experimental study error analysis was applied to obtained results. Average value, standard deviation and coefficient of variation values were calculated.

Average;

$$\bar{x} = \frac{1}{n}(\sum_{i=1}^{n} X_i) \quad (3.52)$$

n: number of experiments

$X_i = value\ of\ measured\ property$

Standard deviation;

$$S_{n-1} = \sqrt{\frac{(\sum_{i=1}^{n} {x_i}^2 - n\bar{x}^2)}{n-1}} \quad (3.53)$$

Coefficient of variation (%);

$$CV = 100\frac{S_{n-1}}{\bar{x}} \quad (3.54)$$

4. RESULTS AND DISCUSSIONS

4.1. Results of Sample Material Tested in Three Orthogonal Directions

Ingredient ratios of the composite sample fabricated in the first stage of the study are given below;

Volume fractions using equations 3.25-3.29;

$v_f = 576{,}92\ cm^3, v_{EPS} = \ 9375\ cm^3, v_m = 4507\ cm^3, v_c = 14458{,}92\ \ cm^3$

$V_f = 0{,}0399$, $V_{EPS} = 0{,}6483$, $V_m = 0{,}3117$, $V_f + V_{EPS} + V_m \approx 1$,

Actual (act) volume of the composite $v_{c,actual} = 10592\ cm^3$ and assuming the 25% shrinkage of EPS beads (pre-determined bulk density);

$V_{f,act} = 0{,}0543$, $V_{EPS,act} = 0{,}6638$, $V_{m,act} = 0{,}2819$

Weight fractions using equations 3.30-3.34;

$w_f = 1500\ gr, w_{EPS} = 75\ gr, w_m = 5364\ gr, w_c = \ \ 6939\ gr,$

$W_f = 0{,}2161$, $W_{EPS} = 0.0108$, $W_m = 0.7730$, $W_f + W_{EPS} + W_m \approx 1$,

Assuming there is no excess resin in the system and no volume change of EPS beads due to vacuum or cure shrinkage the expected theoretical density (ρ_c) of the material is:

$$\rho_c = 6939gr/14458.92cm^3,\ \rho_c = 0{,}4799\ gr/cm^3$$

Assuming the material volume is equal to the mold cavity and no vacuum and void, the expected theoretical density of the material is:

$$\rho_{c,act} = 6939gr/10592cm^3,\ \rho_{c,act} = 0{,}6551\ gr/cm^3$$

The experimental measurement on fabricated sample revealed that the experimental density of the sample;

$$\rho_{exp} = 0{,}5175 \pm 0{,}01\ gr/cm^3$$

The difference between the theoretical and experimental density is caused by shrinkage of EPS beads during the vacuum, removal of the voids in the sample and the excess resin from the sample via vacuum, the clustered liquid resin in the infusion pipes and absorbed resin in the infusion mesh.

4.1.1. Tensile Test Results and Micrographs

5 specimens for each orthogonal direction [x(1)-y(2)-z(3)] were tested and tensile strength, per cent (%) elongation and elastic (Young's) modulus of the specimens were determined. In Figures 4.1. - 4.3. sample graphs (test device output) for each direction are given. The average of each test is given Figure 4.4.

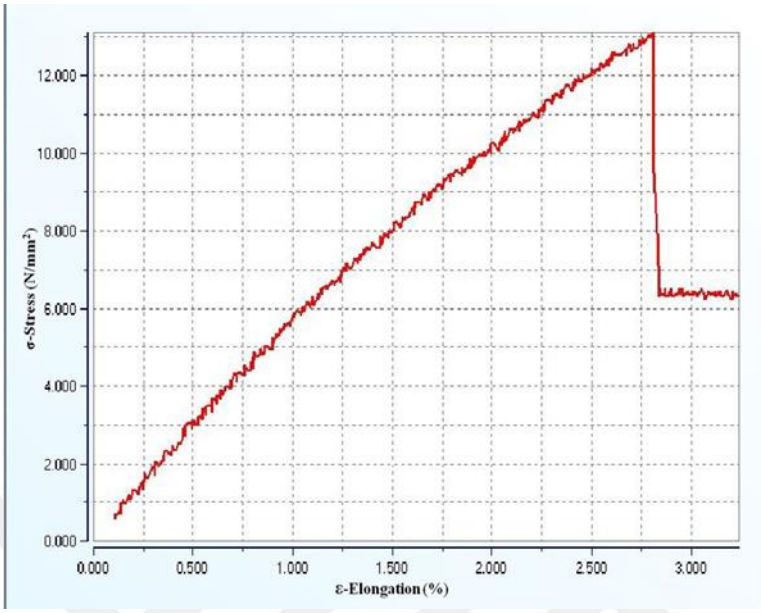


Figure 4.1. Tensile test graph sample of x(1) direction

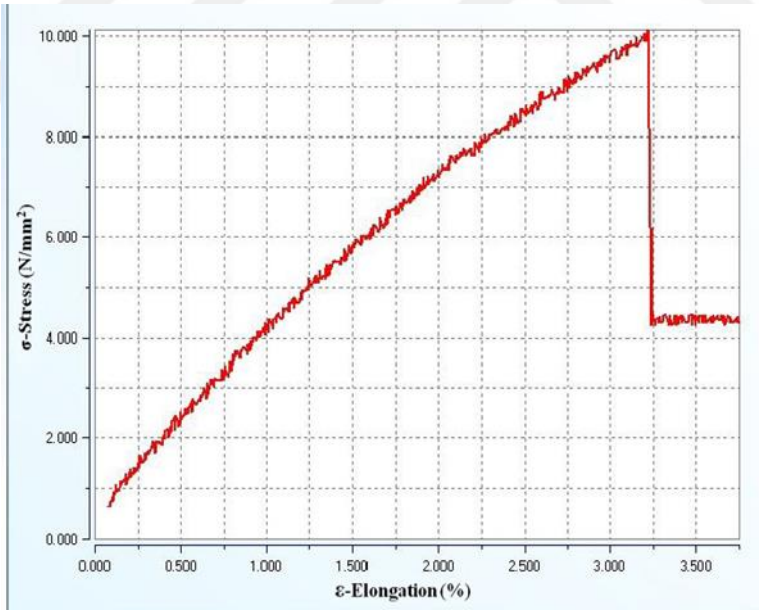


Figure 4.2. Tensile test graph sample of y(2) direction

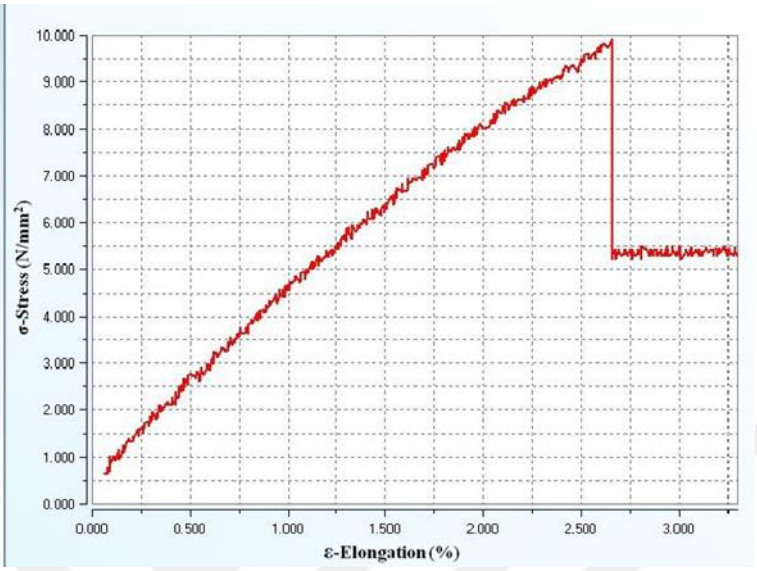


Figure 4.3. Tensile test graph sample of z(3) direction

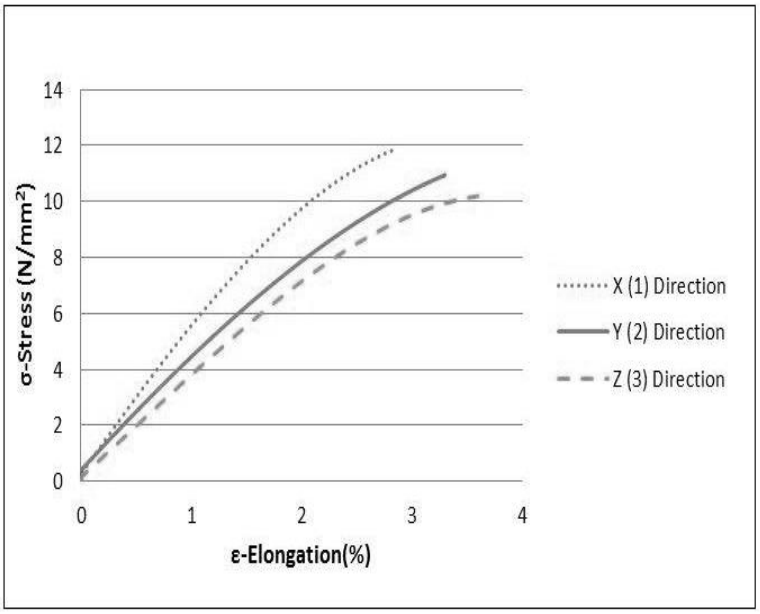


Figure 4.4. Tensile test averages for 3 directions [x(1)-y(2)-z(3)]

The ultimate tensile strengths (σ_T) of the specimens were found as 11,83±0,86 MPa, 10,94±1,67 MPa and 10,19±0,45 MPa for x, y, and z direction

specimens, respectively. The elongations at the break (ε-%) were found as 2,83%, 3,29%, and 3,61% for x(1), y(2), and z(3) direction specimens, respectively. Elastic modulus (Young's Modulus) values were found as 4,86±0,17 GPa, 3.778±0,9 GPa, and 3,60±0,79 GPa for x, y, and z direction specimens, respectively. EPS beads have very low tensile strength and the volume fraction of the EPS beads was 0,6638 and thus the tensile strength of the material was considerably low. But the specific modulus (elastic modulus/density) of the material is competitive for many applications.

The results revealed that the tensile behaviour of the EPS/Glass/Epoxy composite is slightly depends on the material direction. Generally the tensile properties of orthotropic laminates strictly depend on material direction. For instance, the mechanical properties of glass/epoxy composite (fiber volume fraction: 0,45) referred as (Tsai and Hahn, 1980, Kaw, 2006);

Longitudinal elastic modulus (E_1): 38,6 GPa,
Transverse elastic modulus (E_2): 8,27 GPa,
Ultimate longitudinal tensile strength ($(\sigma_1^T)_{ult}$: 1062 MPa,
Ultimate transverse tensile strength$(\sigma_2^T)_{ult}$: 31 MPa

Another example of composite properties for glass fiber reinforced composites are given as (Misra and Datta, 2008);

Longitudinal elastic modulus (E_1): 8,91 GPa, 13,7 GPa, 17,5 GPa, 21,6 GPa,
Transverse elastic modulus (E_2): 3,27 GPa, 3,88 GPa, 4,13 GPa, 4,37 GPa
(for 8,8, 17,6, 25,4, and 35,3 % fiber fraction in volume, respectively).

It is clear that there is a great behaviour difference between longitudinal and transverse directions for the laminated composites. Tensile tests of the EPS/Glass/Epoxy composites revealed that material shows a similar behaviour in

longitudinal, transverse and through thickness directions. The similarities between the trends of stress-strain of the samples were due to the random distribution of the EPS beads and chopped glass fibers in the matrix structure. The occurrence of small differences was an expected result due to the partial alignment of the chopped fibers by the resin sweeping during the vacuum and non-homogeneous structure. The main goal of the sample project was to possess quasi-homogenous structure which is partially accomplished. Because of the random distribution of EPS beads and chopped fiber glasses and the sweeping effect of the resin during the infusion process, it is not possible to fabricate a completely homogenous material as monolithic materials. But still the material is quasi-homogeneous and possesses quasi-isotropic tensile behaviour. Also the compatibility between the theoretical prediction and the experimental results supports that claim. The quasi-isotropic behaviour also brings the advantage of modelling the material with just 2 independent elastic constants (Elastic modulus-E and Poisson's ratio-ν) while modelling an orthotropic lamina requires 9 independent elastic constants (Vasiliev and Morozov, 2001, Kaw, 2006).

The maximum specific strengths and modulus values for specimens were calculated as 0,023 $MPa.m^3/kg$ and 0,009 $GPa.m^3/kg$, respectively. The typical values for specific strength and modulus are referred as (Kaw, 2006);

Steel: 0,083 $MPa.m^3/kg$ and 0,026 $GPa.m^3/kg$,
Aluminium: 0,106 $MPa.m^3/kg$ and 0,026 $GPa.m^3/kg$,
Unidirectional glass/epoxy: 0,590 $MPa.m^3/kg$ and 0,021 $GPa.m^3/kg$,
Quasi-isotropic glass/epoxy: 0,040 $MPa.m^3/kg$ and 0,010 $GPa.m^3/kg$

The comparison of the values shows that even the EPS/Glass/Epoxy composite has a very low strength and elastic modulus, due to its comparatively very low density; the material still could be utilized for many different applications.

In Figures 4.5. - 4.7., the graphs for toughness calculations are illustrated. Even the impact tests are conducted to determine the toughness of a material, also the area under the stress-strain curve indicates the total energy before fracture. To calculate the area under the stress-strain curve, third degree polynomial equations were fitted on the graphs and these equations were integrated in the definite limits of elongations.

$$Toughness\ (J.m^{-3}) = \int_0^{\varepsilon} y dx \qquad (4.1)$$

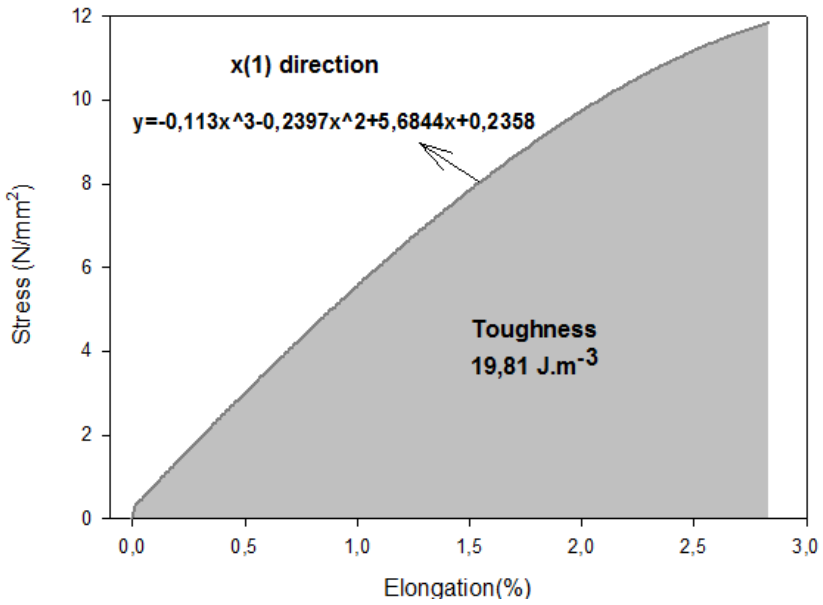


Figure 4.5. Toughness calculation of x(1) direction specimen

Equation curve for x(1) direction;

$$y = -0{,}113x^3 - 0{,}2397x^2 + 5{,}6844x + 0{,}2358$$

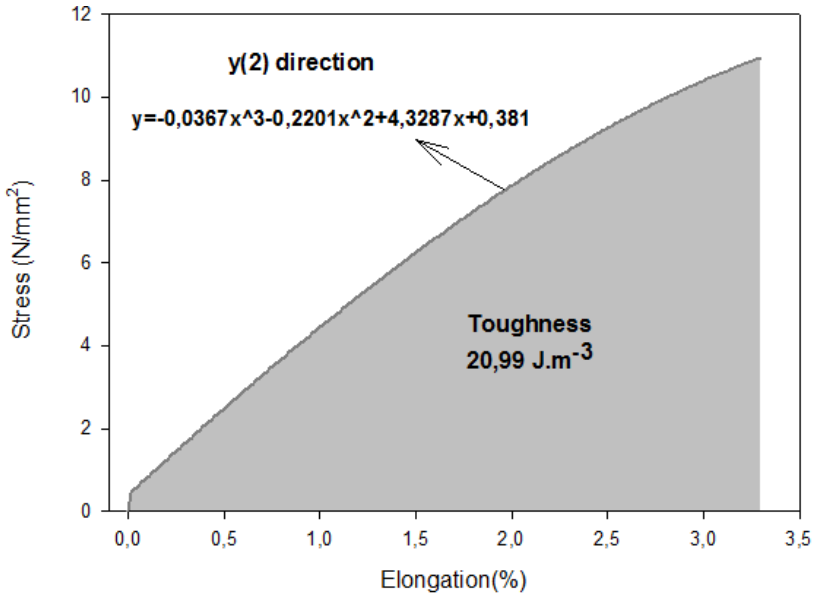


Figure 4.6. Toughness calculation of y(2) direction specimen

Equation curve for y(2) direction;

$$y = -0{,}0367x^3 - 0{,}2201x^2 + 4{,}3287x + 0{,}381$$

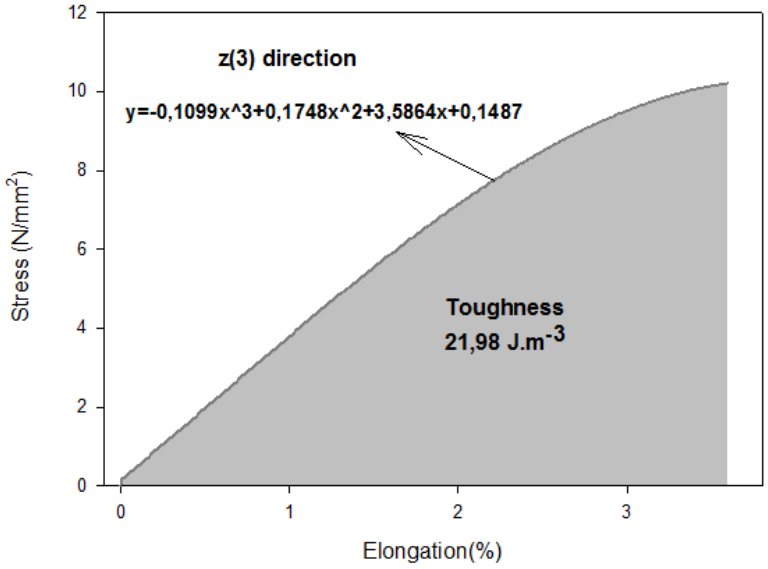


Figure 4.7. Toughness calculation of z(3) direction specimen

Equation curve for z(3) direction;

$$y = -0{,}1099x^3 + 0{,}1748x^2 + 3{,}5864x + 0{,}1487$$

Toughness values calculated according to stress-strain curves indicates that the specimens in different directions have similar behaviour in different directions and response the load in similar manner when the material is subjected to force from different points.

Figure 4.8. shows the microstructure of the sample specimen cross-section. Also, the micrographs of the samples after the tensile tests for three samples [x(1)-y(2)-z(3)] are given in Figures 4.9. - 4.11., respectively.

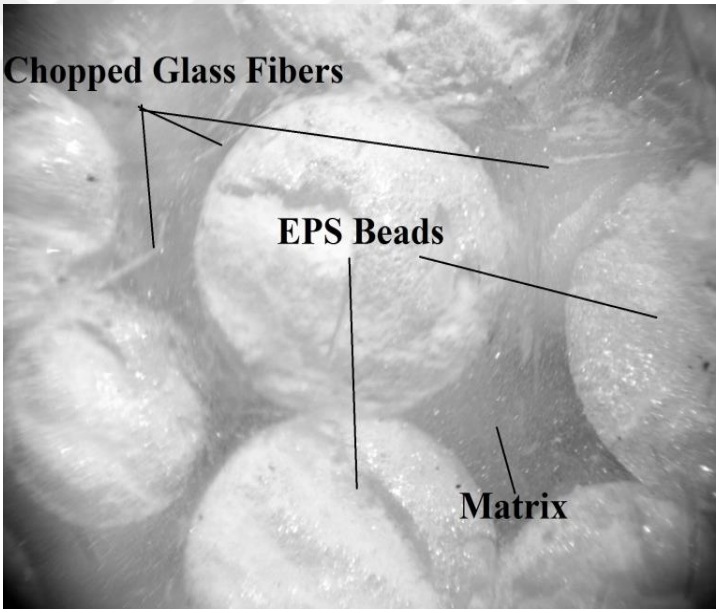


Figure 4.8. Micrograph of the sample cross section

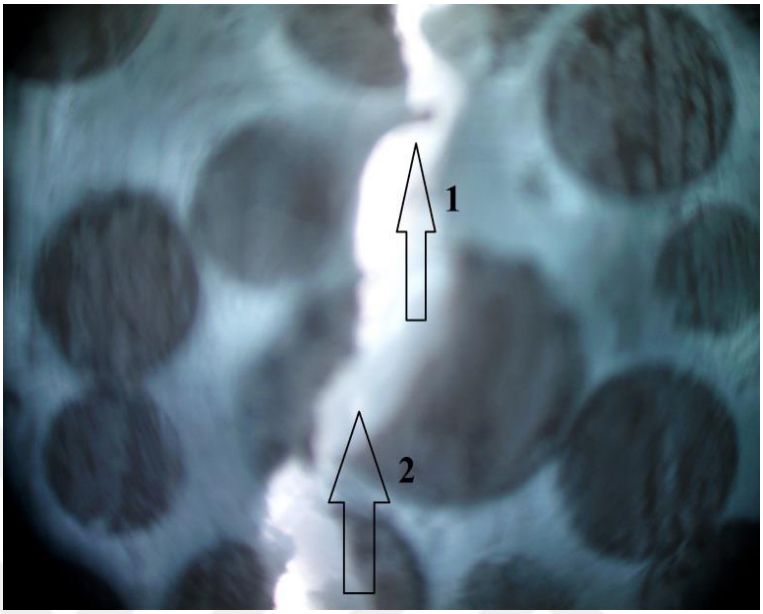


Figure 4.9. Micrograph of the x(1) direction specimen after the tensile test (1-matrix fracture, 2-EPS bead breakage)

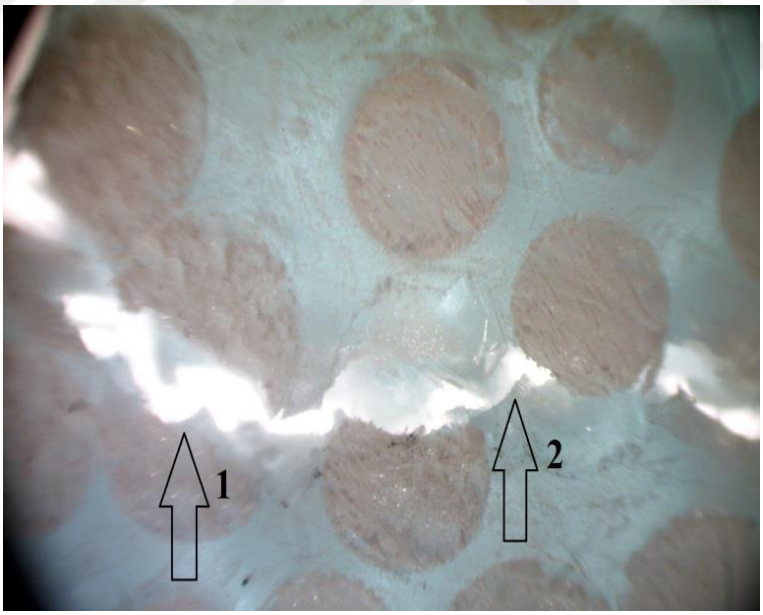


Figure 4.10. Micrograph of the y(2) specimen after the tensile test (1- EPS bead breakage, 2-matrix fracture)

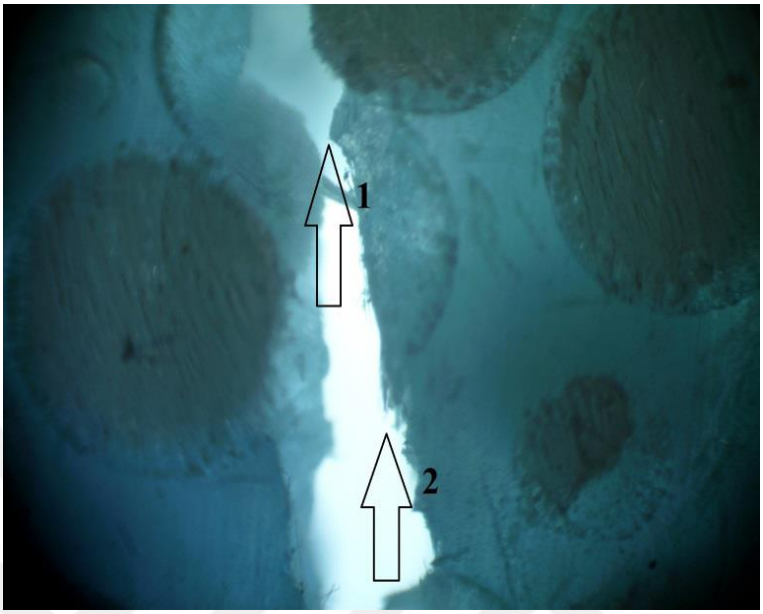


Figure 4.11. Micrograph of the z(3) specimen after the tensile test (1- EPS bead breakage, 2-matrix fracture)

The micrograph of the sample cross section shows that the material is not completely homogeneous. The distribution of the EPS beads and chopped glass fibers are not uniform and this is caused by the fabrication method (the mixture, resin infusion process and vacuum) and nature of the composite itself which is random discontinuous. On the other hand, a significant void occurrence which has negative effects on the composite materials was not observed in the sample structure. That is the one of the advantages of the vacuum infusion method. Micrographs of the samples after tensile tests show that the sample tends to break on the regions of EPS beads which are the weakest regions of the sample. The load transfer between the matrix and EPS beads-fibers caused to breakage in EPS itself. That also shows that matrix-EPS interphase is strongly established.

4.1.2. Impact Test Results

Fracture of composite materials is a complex phenomenon in comparison with monolithic materials due to delamination (fiber-matrix separation), matrix crack, and fiber breakage (Uzay et al., 2016). In Table 4.1., Charpy impact test results of the specimens are given. The impact test results showed that there is a slight dependence on the material direction as in tensile tests. Epoxy resins are generally brittle materials. But, the EPS beads in the matrix caused a ductile fracture relatively.

Table 4.1. Impact test results for three orthogonal directions

Specimen	Absorbed Energy (J)	Charpy Impact Strength (kJ/m^2) (Average)
x(1) Direction	4,077±0,28	25,27
y(2) Direction	3,914±0,86	24,26
z(3) Direction	4,86±0,36	30,13

Impact test results showed that impact strength in z(3) direction is 19,23% and 24,19% higher than impact strengths in x(1) and y(2) directions, respectively. The difference in different directions occurred due to the partial alignment and non-homogenous distribution of the chopped fibers throughout complete material structure.

4.1.3. TGA Results

The TGA analysis results of the neat resin and composite sample are given in Figure 4.12. and Figure 4.13., respectively.

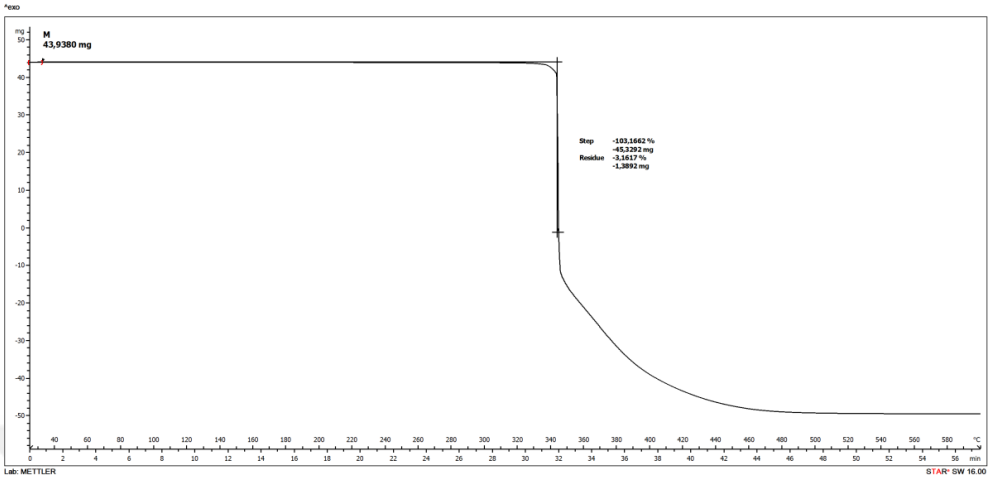


Figure 4.12. TGA graph of neat resin

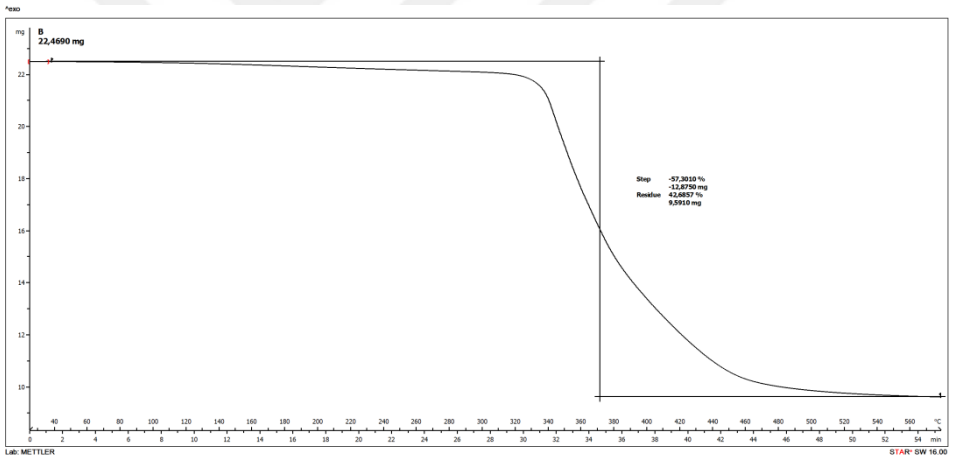


Figure 4.13. TGA graph of composite sample

The analyses of neat resin and composite sample revealed that composite sample had lower thermal stability. The main reason for that decrement is the EPS beads which have relatively low thermal resistance. It can be seen from the graphs mass loss started around 120 ^{o}C for the composite resin while it started around 345 ^{o}C for the neat resin. Composite specimen showed a decelerating model-like characteristic (Yildizhan and Serin, 2020).

4.2. Results of Sample Materials Fabricated with Varying Fiber/Filler Ratios

4.2.1. Theoretical Calculations

The density of the cured resin is expected to be between values of 1,18 and 1,20 gr/cm^3. Thus, the matrix density is assumed to be 1,19 gr/cm^3 and matrix volume is equals the void volume calculated from equation 3.1. Fractions of filler, fiber and matrix are given in Table 4.2.

Table 4.2. Fractions of ingredients

Specimen Code	Fiber Weight Fraction (W_f)	Filler Weight Fraction (W_{EPS})	Matrix Weight Fraction (W_m)	Fiber Volume Fraction (V_f)	Filler Volume Fraction (V_{EPS})	Matrix Volume Fraction (V_m)
A1	-	0,014	0,986	-	0,527	0,473
A2	-	0,023	0,977	-	0,527	0,473
B1	0,130	0,013	0,857	0,031	0,527	0,442
B2	0,243	0,012	0,745	0,062	0,527	0,411
B3	0,342	0,011	0,647	0,092	0,527	0,381
C1	0,130	0,013	0,857	0,031	0,527	0,442
C2	0,243	0,012	0,745	0,062	0,527	0,411
C3	0,342	0,011	0,647	0,092	0,527	0,381
D1	0,201	0,020	0,779	0,050	0,527	0,423
D2	0,363	0,018	0,619	0,100	0,527	0,373
D3	0,495	0,017	0,488	0,150	0,527	0,323
E1	0,201	0,020	0,779	0,050	0,527	0,423
E2	0,3627	0,018	0,619	0,100	0,527	0,373
E3	0,495	0,017	0,488	0,150	0,527	0,323

Table 4.3. Densities of the specimens

Specimen Code	Total Weight kg	Theoretical Density (Rule of Mixtures) kg/m^3	Theoretical Density* (total weight/volume) kg/m^3	Experimental Density kg/m^3
A1	1,665	567,086	762,061	425,8
A2	1,679	569,721	768,745	486,3
B1	1,790	610,309	819,762	667,1
B2	1,917	653,641	877,608	866,7
B3	2,043	696,974	935,454	1035,3
C1	1,790	610,309	819,762	737,6
C2	1,917	653,641	877,608	775,2
C3	2,043	696,974	935,454	1053,6
D1	1,884	640,096	862,692	785,2
D2	2,089	710,581	956,785	867,1
D3	2,295	781,066	1050,879	1048,3
E1	1,884	640,096	862,692	806,7
E2	2,089	710,581	956,785	877,4
E3	2,295	781,066	1050,879	1156,2

*Theoretical density (total weight/volume) of the specimens was calculated by assuming the 25% shrinkage of EPS beads (pre-determined bulk density) due to vacuum.

Densities of the specimens (Table 4.3.) were determined by measuring the specimen volume and weight experimentally. Results indicate that densities of the specimens are relatively low which and the low density for a material is a critical advantage for many engineering applications.

The density of the cured neat resin has been measured as 1060,1 kg/m^3. One of the main reasons of the difference between calculated and measured densities is the assumed resin density and experimental cured resin density.

Elastic Modulus by "Rule of Mixtures" for hybrid composites using equation 4.2 (Abrate, 1986),

$$E_c = E_m v_m + E_f v_f + E_{EPS} v_{EPS} \quad (4.2)$$

The equation 4.2 (modified from (Abrate, 1986)) gives the opportunity to predict the elastic modulus of the composite sample. To perform the prediction, the elastic modulus of the EPS beads is ignored since EPS beads have very low strength compared to resin and glass fibers. Besides the ignorance of effect of the EPS beads, the following assumptions have been made to perform the calculations;

- There is perfect adhesion and load transfer between the EPS beads, glass fibers and epoxy resin,
- The material is homogeneous,
- The partial alignment of the chopped glass fibers does not affect the mechanical behaviour.

With this aspect, the elastic modulus of the material fabricated in the first stage of the study has been predicted to be between 5,08-5,17 GPa. In Table 4.4. predicted elastic modulus values of the specimens fabricated in the second stage of the study are given.

Table 4.4. Predicted elastic modulus values of the specimens

Specimen Code	**Elastic Modulus (Rule of Mixtures) GPa**
A1	1,51-1,66
A2	1,51-1,66
B1	3,78-3,91
B2	6,05-6,17
B3	8,312-8,43
C1	3,78-3,91
C2	6,05-6,17
C3	8,32-8,43
D1	5,20-5,33
D2	8,89-9,00
D3	12,59-12,68
E1	5,20-5,33
E2	8,89-9,00
E3	12,58-12,67

4.2.2. Tensile Test Results

At least 5 specimens for each specimen type were tested and tensile strength, per cent (%) elongation and elastic (Young's) modulus of the specimens were determined. In Table 4.5. results of the tensile test for specimens are given.

Table 4.5. Tensile test results of second stage

Specimen Code	Ultimate Tensile Strength (MPa)	Elongation at Break (%)	Elastic Modulus (GPa)
Neat Resin	52,5±8,65	4,8	4,33±1,29
A1	1,9±0,2	0,68	2,33±0,34
A2	2,5±0,3	0,85	2,5±0,21
B1	8,74±055	2,96	2,43±0,45
B2	10,9±0,51	3,25	2,76±0,35
B3	13,7±3,09	3,36	3,36±0,9
C1	4,1±0,44	1,03	3,33±0,32
C2	9,56±0,35	1,36	5,79±0,69
C3	10,5±3,76	1,25	5,92±1,16
D1	12,28±0,38	2,06	4,88±0,45
D2	17,64±1,05	1,8	8,04±0,98
D3	25,65±7,36	2,96	6,41±1,94
E1	13,28±0,76	1,95	5,58±0,24
E2	16,43±0,96	1,55	9,33±0,88
E3	22,1±6,78	2,5	6,45±2,01

Specimens A1 an A2 do not contain fibers and thus the tensile strengths are significantly low as it is expected since EPS has a very low strength and modulus. Tensile behaviour of a material is directly related with the bounds in the atomic structure. For a composite material, the interphase can be seen as bounds. The stronger interphase means higher tensile strength. To establish a strong interphase there should be good compatibility between the joined ingredients. The examination of the specimens after the tensile tests revealed that fractures mostly occurred as EPS breakage. It shows that a strong interphase was established. But the main reason for

the low strength is the low strength of EPS beads. EPS beads were used as filler to decrease the matrix fraction. In such a structure, EPS behaves like voids between the molecules of the matrix material and decreases the tensile strength. Tensile test results are also illustrated in Figures 4.14. and 4.15.

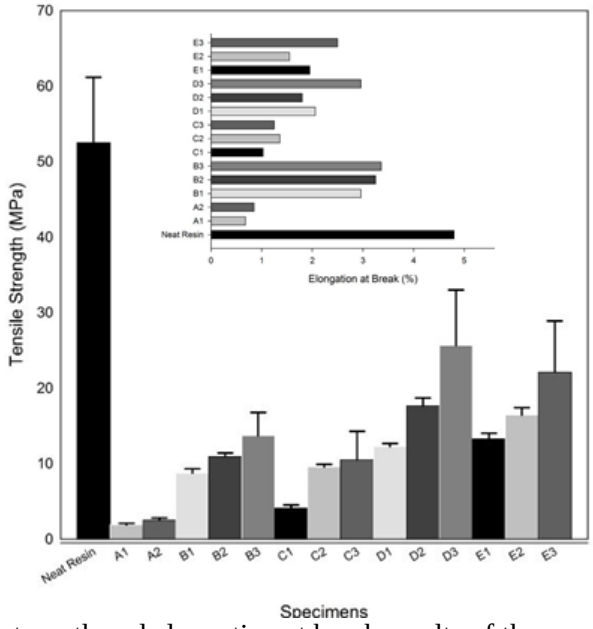


Figure 4.14. Tensile strength and elongation at break results of the specimens

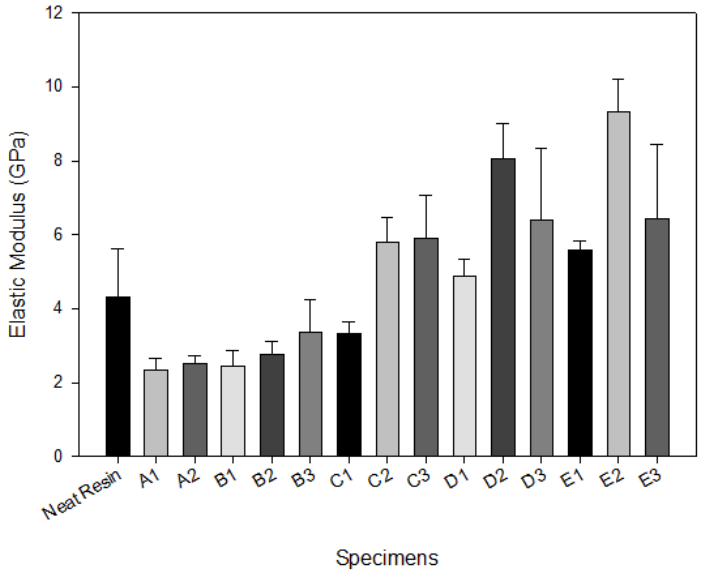


Figure 4.15. Elastic modulus values of the specimens

Density of EPS used to fabricate also affected the properties of the samples. Specimen B and C types were fabricated with 8 kg/m^3 EPS and D and E types were fabricated with 13 kg/m^3 EPS. D and E type specimens had higher tensile strength than B and C type specimens. The reason is 13 kg/m^3 EPS beads have lower diameter which means lower volume. Since EPS beads contain a high amount of air, the lower volume means lower air trapped in the bead.

Addition of fibers to composite structure significantly increased the tensile strength and modulus values. Comparing the A1 and B3 specimens, both tensile strength and elastic modulus ratios were higher. Adding fibers to structure increased tensile strength higher than 6 times. Fiber addition increased the tensile strength values at is expected. Chopped fibers around the EPS beads prevented the early fracture of weak EPS beads and provided a stronger structure. While fiber addition improved the tensile strength the critical point is the fiber filler ratio. Effects of fiber/filler ratio on tensile strength and modulus of the specimens and changes of values compared with neat resin are given in Table 4.6.

Two different length of glass fibers were used to fabricate specimens. The shorter fibers (3 mm) resulted in higher strength for B and C type specimens. For D and E type specimens, tensile strengths are not significantly different for 10:1 and 20:1 fiber filler ratios. Nevertheless, using 6 mm fibers decreased the tensile strength for fiber filler ratio of 30:1 in D and E type specimens.

Elastic modulus is the indicator of material stiffness. Modulus values were lower than the neat resin for A1, A2, B1, B2, B3, and C1 specimens. Since A1 and A2 specimens do not contain fibers, the specimens have relatively very low modulus. The main reason for lower modulus than the neat resin for B type specimens is EPS (8 kg/m^3). The lower modulus value of the C1 specimens than the neat resin may be due to effects of both EPS used and low fiber/filler ratio. Since C2 and C3 specimens have higher fiber/filler ratio than C1 specimens the modulus ratios were higher.

Table 4.6. Changes in values of tensile strength and elastic modulus

Specimen Code		Change of average tensile strength values in per cent (%)	Change of average elastic modulus values in per cent (%)	Change of average tensile strength values in per cent (%) (compared with neat resin)	Change of average elastic modulus values in per cent (%) (compared with neat resin)
A1				- 96,38	-46,18
A2				- 95,23	-42,26
B1				-83,35	-43,87
B2	Compared to B1 specimen	+24,71	+13,58	- 79,23	-36,25
B3		+56,75	+38,27	- 73,90	-22,40
C1				- 92,19	-23,09
C2	Compared to C1 specimen	+133,17	+73,87	- 81,79	+33,71
C3		+156,09	+77,77	- 80	+36,72
D1				- 76,60	+12,70
D2	Compared to D1 specimen	+43,64	+64,75	- 66,40	+85,68
D3		+108,87	+31,35	- 51,14	+48,03
E1				-74,70	+28,86
E2	Compared to E1 specimen	+23,71	+67,20	- 68,70	+115,47
E3		+66,41	+15,59	- 57,90	+48,96

As it can be seen in Table 4.6., increasing the fiber amount resulted in higher strength. But the variations of the tensile results especially for the specimens contain high fractions of chopped fibers (B3, C3, D3, and E3) are relatively too high in comparison with other specimens. The main reason for that is the non-homogeneous distribution of the fibers in the sample structure. The examination of the specimens showed that, with the increment of the fiber amount the homogeneity of the material decreases. During the mixing process, chopped fibers tend to cluster and create pellet structures. While the fiber clustered regions are stronger, the regions that have lower fibers are weaker. That deteriorates the homogeneous distribution of ingredients and stress in the material. Thus, variations of the results are high.

In Figures 4.16. and 4.17. specific strength and specific modulus values of the specimens are illustrated, respectively. The neat resin had significantly higher specific strength but, specific modulus values were higher for all specimens except B type from neat resin.

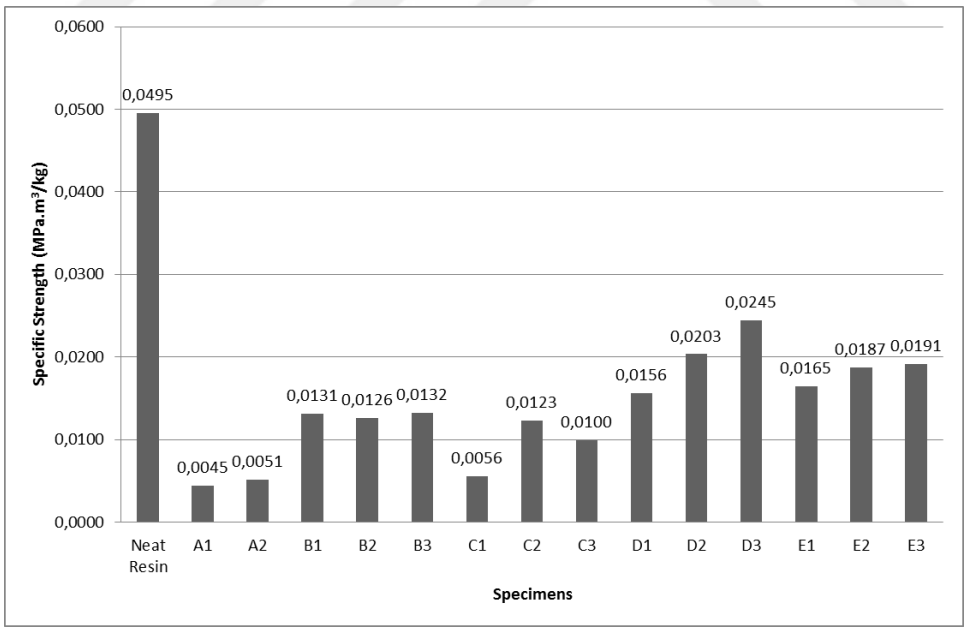


Figure 4.16. Specific strength values

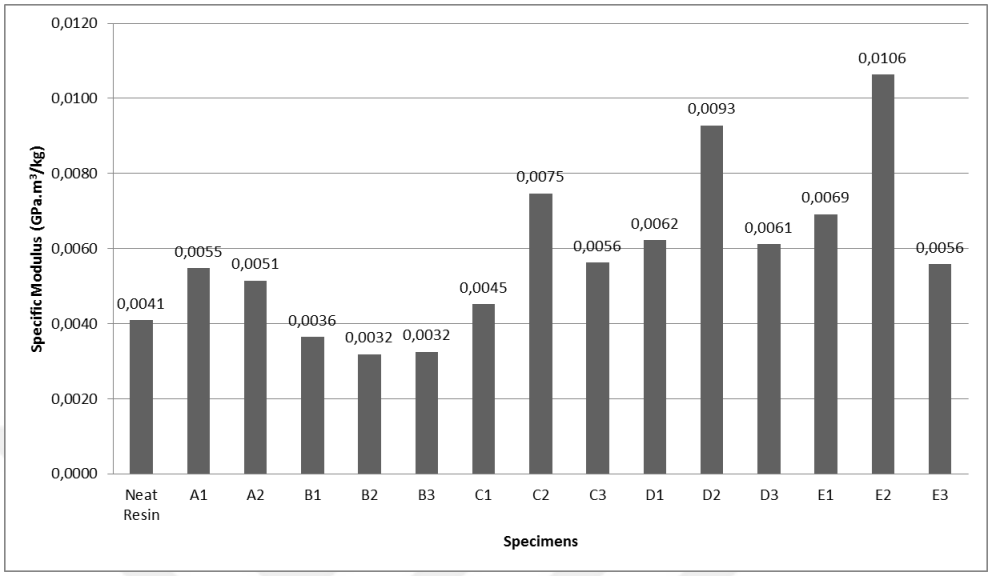


Figure 4.17. Specific modulus values

The tensile tests revealed that, the optimum fiber filler ratio throughout the specimens studied was 20:1. Even there is a trend of increment in strength with the increment of the fiber/filler ratio, for these particular composites, the ratio of 20:1 could be advised. The main reason of lower values and also higher variation in results is the fabrication process. Without any adhesive it is not possible to cover the beads with glass fibers. Thus, in fabrication process the EPS beads were covered with a temporary adhesive and afterwards the chopped glass fibers were mixed. In low ratio of fiber/filler ratios, the glass fibers cover the EPS beads in a more homogeneous way with very slightly low clustering regions. When the ratio is increased, the possibility of the glass fibers contacting each other increases and since they are wet, fibers tend to adhere and cluster. That deteriorates the homogeneity of sample. For mentioned reasons, the fiber/filler ratio of 20:1 is optimum ratio throughout the specimens studied.

4.2.3. Impact Test Results

Impact test results are given in Table 4.7. Impact test is the indicator of the toughness of a material which means the ability of a material's energy absorbance during fracture under dynamic loads. The same info can be obtained from the stress-strain curve but the critical point in the impact tests is the dynamic load. Testing with such loading gives information about the material behaviour in case of impacts under service conditions.

Table **4**.7. Impact test results of the specimens

Specimen Code	Absorbed Energy (J)	Charpy Impact Strength (kJ/m^2) (Average)
Neat Resin	5,78±0,97	35,47
A1	1,46±0,32	8,95
A2	1,73±0,29	10,60
B1	3,95±0,30	24,21
B2	4,63±0,43	28,45
B3	4,87±1,76	29,85
C1	2,57±0,25	15,75
C2	3,15±0,61	19,31
C3	4,05±1,86	24,64
D1	4,24±0,51	25,99
D2	5,06±0,43	31,02
D3	5,48±1,88	33,59
E1	4,35±0,74	26,67
E2	4,98±0,89	30,53
E3	5,13±2,06	31,45

Impact tests showed that specimens fabricated with higher density EPS beads had higher impact strength. But unlike tensile tests, with the increment of the fiber/filler ratio impact strength values were also increased. In Table 4.8., changes in impact strengths are given. The tests also showed that while neat resin fractures in brittle manner, composite specimens fractured in ductile manner.

Table 4.8. Changes in values of impact strength

Specimen Code		Change of average impact strength values in per cent (%)	Change of average impact strength values in per cent (%) (compared with neat resin)
A1			-74,76
A2			-70,11
B1			-31,74
B2	Compared to B1 specimen	+17,51	-19,79
B3		+23,29	-15,84
C1			-55,59
C2	Compared to C1 specimen	+22,56	-45,55
C3		+57,58	-30,53
D1			-26,72
D2	Compared to D1 specimen	+19,33	-12,54
D3		+29,24	-5,30
E1			-24,80
E2	Compared to E1 specimen	+14,48	-13,92
E3		+17,93	-11,33

4.2.4. Hardness Test Results

Hardness measurements of the specimens were conducted under 1 kgf load and 20 seconds dwell time. In the measurements, the points where the intender of the device is inserted were critical. When the load applied points coincided with EPS beads, the measurement were distorted since the traces on the specimens were not clear and measurements were not accurate. Thus, hardness measurements were conducted only on the completely resin covered regions. As a result of the measurements the hardness value of the specimens were found as 102,04±19,16 HV1.

4.2.5. Water Absorption Test Results

To determine the water absorption properties of the specimens, specimens were soaked in water and weight changes were measured. The measurements were taken hourly for the first 6 hours, and afterwards weight measurements were taken at every 24 hour for 9 days. In Table 4.9., maximum water absorption values of the specimens are given. In Figures 4.18., 4.19. and 4.20., water absorption test results are illustrated for neat resin, E1 (lowest water absorbed specimen) and B3 (highest water absorbed specimen) specimens, respectively.

Table 4.9. Maximum water absorption values of the specimens

Specimen	Maximum Water Absorption (%)
Neat Resin	0,35
A1	1,13
A2	1,11
B1	1,15
B2	1,17
B3	1,22
C1	1,1
C2	1,13
C3	1,16
D1	0,87
D2	0,92
D3	0,98
E1	0,78
E2	0,88
E3	0,95

Water absorption test results revealed that neat resin has a very low absorbance and thus it is a critical advantage for many engineering applications. All of the composite specimens had higher water absorbance than neat resin. When the specimens soaked into water, EPS beads and glass fibers tend to absorb water especially at the points of where EPS and glass fibers directly contact with water. Since the specimens were obtained by cutting the bulk material, surfaces of the

specimens were not completely covered with matrix material. For actual application of the material, if the product is molded there will not be that high water absorbance.

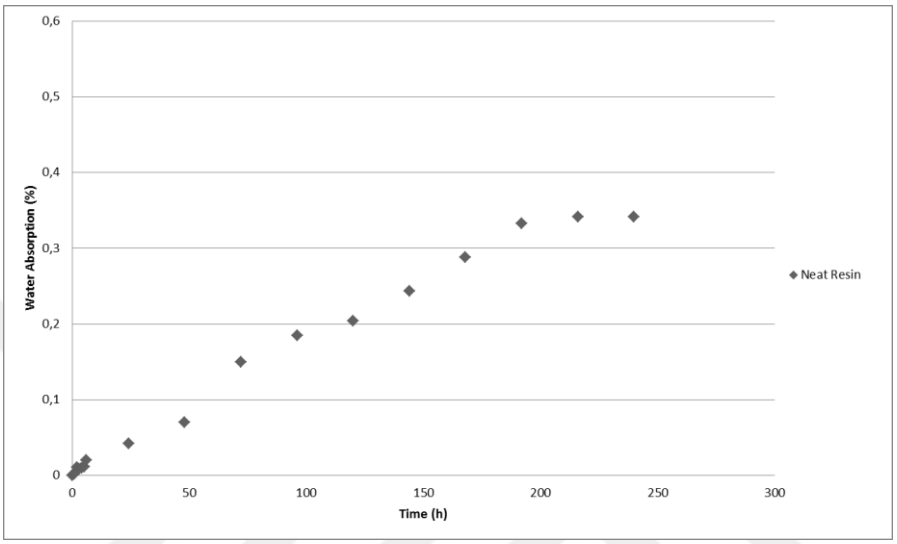


Figure 4.18. Water absorption test results of neat resin

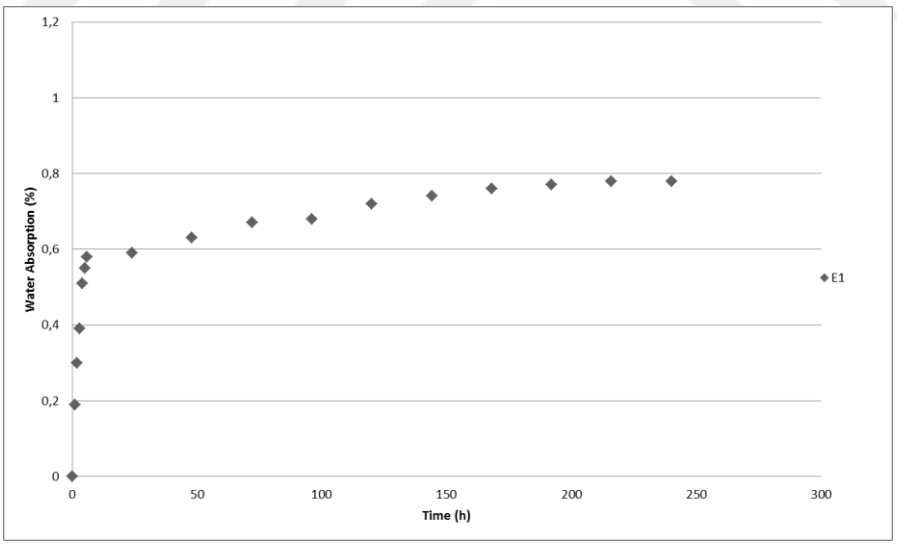


Figure 4.19. Water absorption test results of E1 specimen

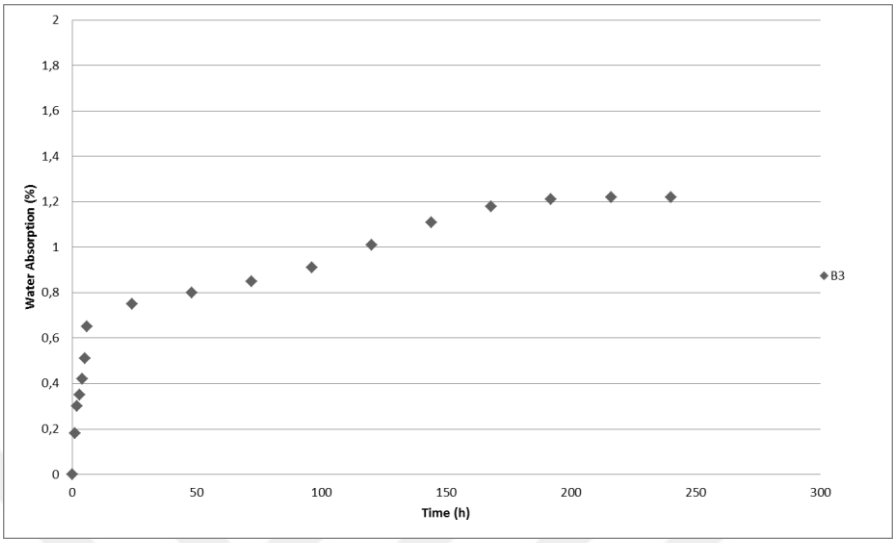


Figure 4.20. Water absorption test results of B3 specimen

In Figures 4.18.-4.20., general characteristics of the neat resin and specimens are illustrated. The given figures are chosen for the maximum and minimum absorbent specimens. The rest of the specimens also showed similar characteristics. As it can be seen from the graphs, specimens almost reach the maximum absorbance values around 120 hours.

4.2.6. Cost Analysis Results

The cost analysis of the fabricated specimens were evaluated and given in Table 4.10. and 4.11. For analysis, the unit costs of resin system (resin+hardener), EPS beads and chopped glass fibers were taken $25, $3,63 and $4,35, respectively. The values are local market prices of the materials from the local suppliers. In cost analysis, labor and tool costs are not included.

Table 4.10. Cost analysis results for unit weight

Specimen Code	Cost of EPS ($)	Cost of Fibers ($)	Cost of Matrix ($)	Total Cost ($)	Unit Cost ($/kg)
Neat Resin	-	-	86,75	86,75	25
A1	0,085	-	41,033	41,118	24,701
A2	0,138	-	41,033	41,171	24,518
B1	0,085	1,014	38,359	39,458	22,035
B2	0,085	2,0271	35,693	37,8051	19,721
B3	0,085	3,041	33,027	36,153	17,692
C1	0,085	1,014	38,359	39,458	22,035
C2	0,085	2,027	35,693	37,805	19,721
C3	0,085	3,041	33,028	36,154	17,692
D1	0,138	1,649	36,689	38,476	20,417
D2	0,138	3,297	32,352	35,787	17,123
D3	0,138	4,946	28,015	33,099	14,419
E1	0,138	1,649	36,689	38,476	20,417
E2	0,138	3,297	32,352	35,787	17,123
E3	0,138	4,946	28,015	33,099	14,419

Table 4.11. Cost analysis results for unit volume

Specimen Code	Cost of EPS ($)	Cost of Fibers ($)	Cost of Matrix ($)	Total Cost ($)	Unit Cost ($/m^3)
Neat Resin	-	-	86,75	86,75	29749,657
A1	0,085	-	41,033	41,118	14100,823
A2	0,138	-	41,033	41,171	14118,999
B1	0,085	1,014	38,359	39,458	13531,550
B2	0,085	2,0271	35,693	37,8051	12964,712
B3	0,085	3,041	33,027	36,153	12398,148
C1	0,085	1,014	38,359	39,458	13531,550
C2	0,085	2,027	35,693	37,805	12964,677
C3	0,085	3,041	33,028	36,154	12398,491
D1	0,138	1,649	36,689	38,476	13194,787
D2	0,138	3,297	32,352	35,787	12272,633
D3	0,138	4,946	28,015	33,099	11350,823
E1	0,138	1,649	36,689	38,476	13194,787
E2	0,138	3,297	32,352	35,787	12272,634
E3	0,138	4,946	28,015	33,099	11350,823

It is clear that with the increment of fiber/filler ratio, the unit cost of the material decreases since the increment of glass fiber amount in the sample decreases

the amount of the matrix material. Even the samples with 30:1 fiber/filler ratio had the lowest cost, considering the specific modulus ratios, samples with 20:1 fiber/filler ratio has the optimum cost-property efficiency. To determine the cost-property efficiency, the specific modulus and specific strength values were divided to unit cost and results are given in Table 4.12. and 4.13. The results of the cost-property analyses are also illustrated in Figures 4.21.-4.24. graphically.

Table 4.12. Cost-property efficiency analysis results (wrt unit weight cost)

Specimen Code	Cost-Property Efficiency (Specific Strength/Unit Cost) ($MPa.m^3/\$$)	Cost-Property Efficiency (Specific Modulus/Unit Cost) ($GPa.m^3/\$$)
Neat Resin	0,001980945	0,000163381
A1	0,000180648	0,000221532
A2	0,000209677	0,000209677
B1	0,000594576	0,000165311
B2	0,000637718	0,000161477
B3	0,000747958	0,000183441
C1	0,000252261	0,000204885
C2	0,000625339	0,000378735
C3	0,000563296	0,000317592
D1	0,000765995	0,000304402
D2	0,001188091	0,000541511
D3	0,001696941	0,00042407
E1	0,000806295	0,00033879
E2	0,001093604	0,000621018
E3	0,001325636	0,000386894

Table 4.13. Cost-property efficiency analysis results (wrt unit volume cost)

Specimen Code	Cost-Property Efficiency (Specific Strength/Unit Cost) ($MPa.m^6/kg.\$$)	Cost-Property Efficiency (Specific Modulus/Unit Cost) ($GPa.m^6/kg.\$$)
Neat Resin	1,66468E-06	1,37296E-07
A1	3,16449E-07	3,88066E-07
A2	3,64109E-07	3,64109E-07
B1	9,68218E-07	2,69195E-07
B2	9,70052E-07	2,45628E-07
B3	1,06733E-06	2,61768E-07
C1	4,10786E-07	3,33638E-07
C2	9,51223E-07	5,76107E-07
C3	8,03794E-07	4,53187E-07
D1	1,18527E-06	4,71018E-07
D2	1,65765E-06	7,55525E-07
D3	2,15563E-06	5,38698E-07
E1	1,24762E-06	5,24227E-07
E2	1,52582E-06	8,66455E-07
E3	1,68396E-06	4,91473E-07

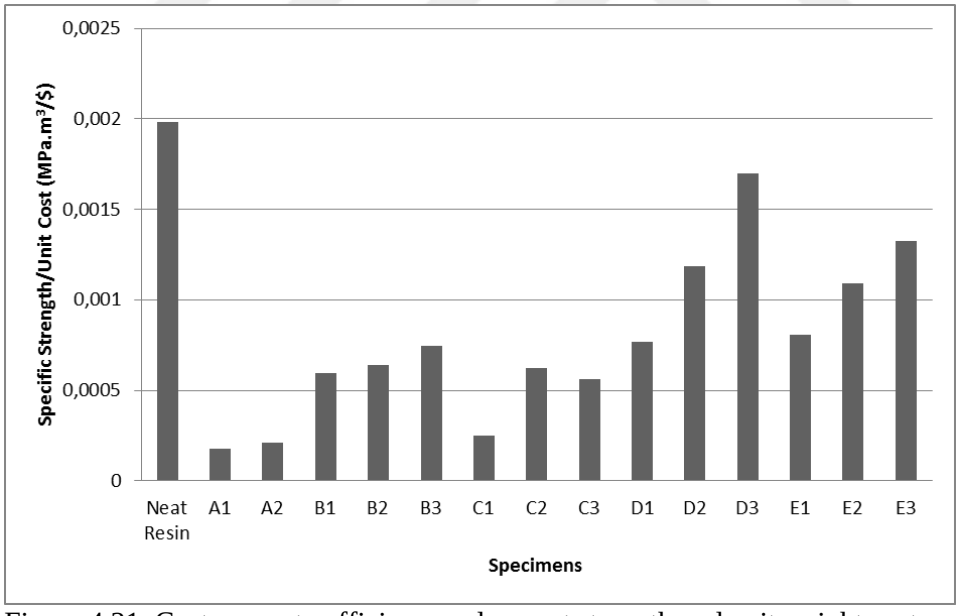


Figure 4.21. Cost-property efficiency values wrt strength and unit weight cost

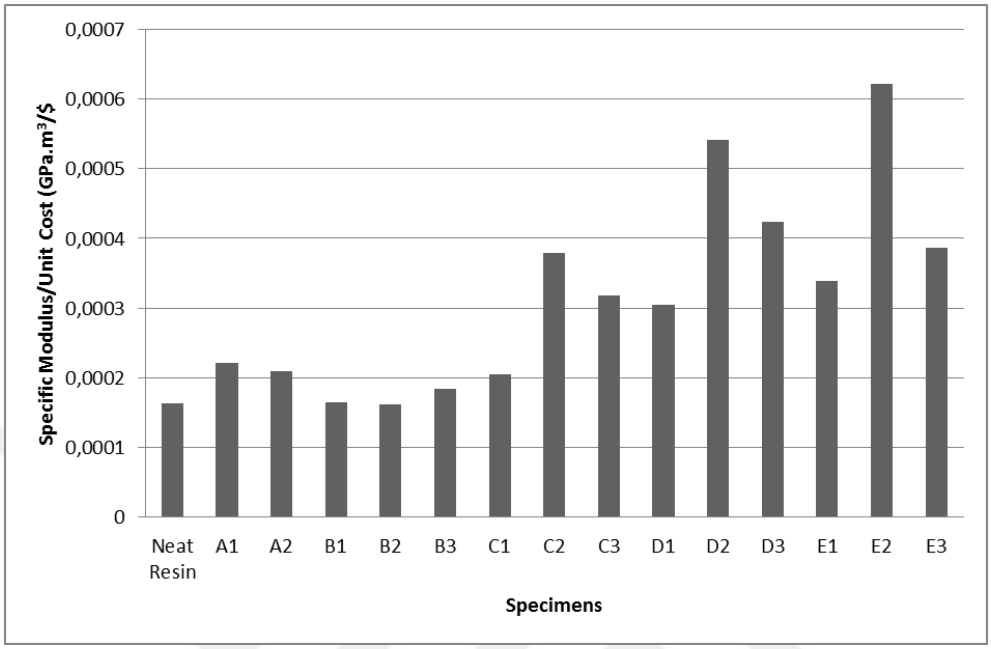


Figure 4.22. Cost-property efficiency values wrt stiffness and unit weight cost

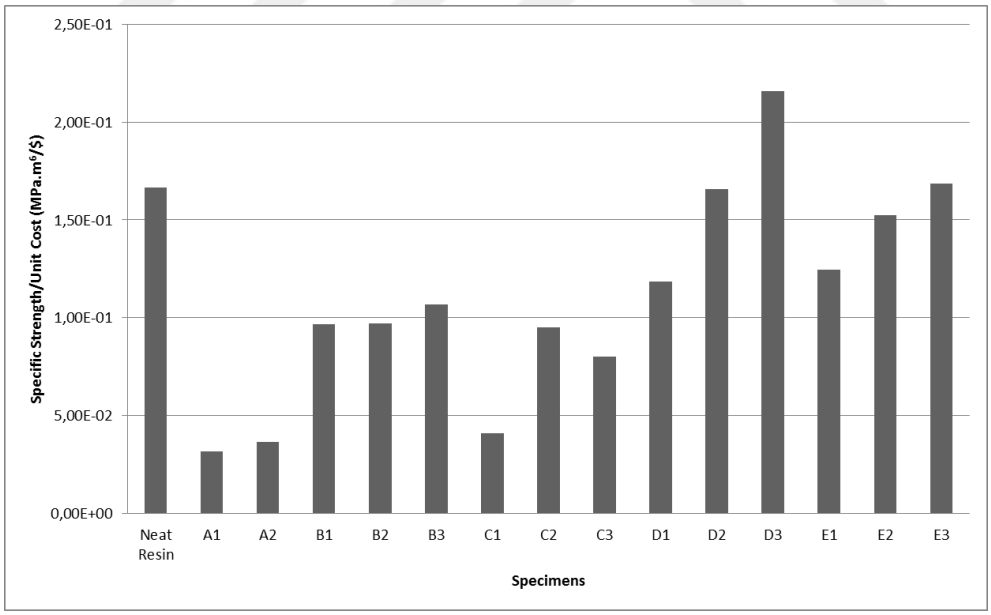


Figure 4.23. Cost-property efficiency values wrt strength and unit volume cost

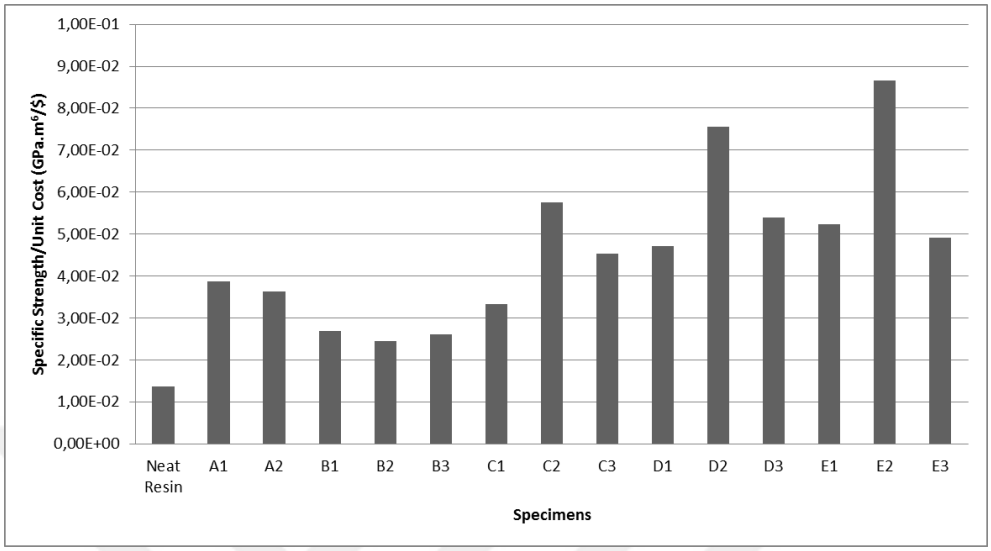


Figure 4.24. Cost-property efficiency values wrt stiffness and unit volume cost

To compare the cost-property efficiency of the studied composites with common engineering materials, the same values were calculated (given in Table 4.14 and comparison illustrated in Figure 4.25.) using the mechanical data obtained from references and prices of market research. The unit costs are the local market prices thus they may vary significantly. The values are the average values of market research.

Table 4.14. Cost-property efficiency analysis of various materials

Material	Density (kg/m^3)	Elastic Modulus (GPa)	Specific Modulus ($GPa.m^3/kg$)	Unit Cost ($/kg)	Cost-Property Efficiency (Specific Modulus/Unit Cost) ($Gpa.m^3/\$$)	Cost-Property Efficiency (Specific Modulus/Unit Cost) ($Gpa.m^6/kg.\$$)
Aluminium (Liu et al., 2013)	2650	72	0,0272	6	0,00453	1,70943E-06
Steel (Liu, Villavicencio and Soares, 2013)	7850	206	0,0262	5	0,00524	6,67515E-07
CFRP (glass/epoxy) (Kaw, 2006)	1800	18,96	0,0105	95	0,00011	6,14035E-08
HDPE (Plastem, 2020)	950	1	0,0011	4	0,00027	2,89473E-07
Nylon 6 (Plastem, 2020)	1140	3	0,0026	8	0,00032	2,85087E-07
Polypropylene (Plastem, 2020)	930	1,3	0,0014	7	0,00020	2,15053E-07
PVC (Plastem, 2020)	1380	3	0,0022	6	0,00066	2,6570E-07

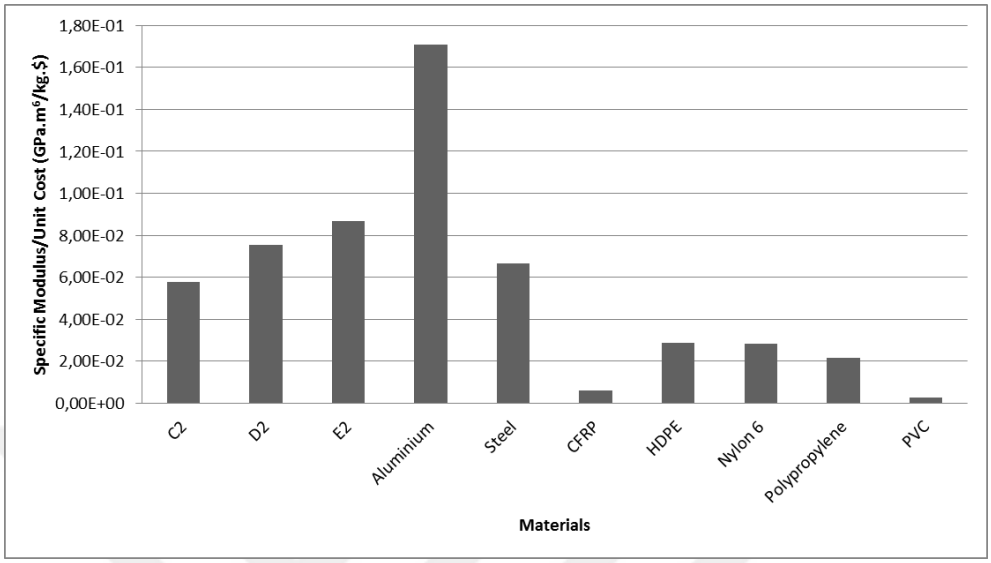


Figure 4.25. Comparison of cost-property efficiency values of various materials

As it can be seen from the graphs illustrated in Figures 4.21. - 4.25., the novel composite fabricated in the study has remarkable specific modulus values. When the cost-property efficiencies are compared, the material has lower value according unit cost with respect to weight. The reason for that is the extremely low density of the material. When the comparison is made according to unit volume, the novel composite has significant advantages especially over conventional plastics such as HDPE, PVC and polypropylene. As a result of the cost analysis, the material could be defined as a cost effective alternative composite.

5. CONCLUSIONS

In this study, fabrication and characterization of a novel composite material has been studied. The novel composite consists of expanded polystyrene beads as filler, chopped glass fibers as reinforcement agent and epoxy resin as matrix material. Studies were conducted at two stages. In the first stage of the study, the directional dependence of the novel material was investigated by fabricating a bulk material and obtaining specimens in three orthogonal directions [x(1)-y(2)-z(3)]. Tensile and impact tests were conducted and results were compared with each other. Also thermogravimetric analysis for the bulk material was evaluated for the neat resin and specimen from the bulk material. At the second stage of the study, to determine the optimum material ingredient ratios, 14 different composite specimens were fabricated with varying parameters. Two different types of expanded polystyrene (8 and 13 kg/m^3) and two different length of chopped glass fibers (3 and 6 mm) were used to fabricate specimens. To determine the optimum ratio of fiber/filler ratio, the specimens were fabricated with ratios of 10:1, 20:1, and 30:1. Tensile, impact and water absorption tests were conducted for the specimens and result were evaluated. Also, a cost analysis was executed for the fabricated specimens. As a result of the study, the followings are concluded;

- With the developing technology and increasing product variety, the need for the specialized materials has increased especially in last decades. Conventional engineering materials do not always fulfil the all required properties for all applications. Thus, the interest on engineering composites has increased drastically. The tailorable properties of the composites bring great advantages for many engineering applications. Besides, relatively high specific strength and modulus values also significant reasons of preference of using composites even with their relatively high cost.

- Expanded polystyrene is a thermoplastic material widely used in packaging and insulation applications. Expanded polystyrene is mostly used as foam blocks. The extremely low density and relatively very low cost makes expanded polystyrene a significant candidate to develop new cost effective engineering composites.
- Chopped glass fibers are the most versatile reinforcement materials in the industry. The low cost of glass fibers in comparison with other synthetic fibers such as carbon, graphite and aramid besides its good mechanical and chemical properties, is the main reason for wide usage area.
- Epoxy resins have good mechanical properties and mostly used synthetic matrix materials with polyester and vinyl ester resins. Epoxy resins are compatible with most of the reinforcement materials but the most important drawback of the epoxies is the relatively high cost. In this study, polyester and vinyl ester resins were tried besides the epoxy resin as matrix materials in pre-studies, but, expanded polystyrene was not compatible with polyester and vinyl ester resins.
- First stage of the study revealed that, the novel composite is quasi-isotropic which means the material possess the similar mechanical properties in different directions. Generally, composite materials are not isotropic and behave different than monolithic materials. The tensile and impact tests showed that the specimens had slightly different tensile and impact strength. The elongations at the break (ε-%) were found as 2,83%, 3,29%, and 3,61% for x(1), y(2), and z(3) direction specimens, respectively. Elastic modulus (Young's Modulus) values were found as 4,86±0,17 GPa, 3,778±0,9 GPa, and 3,60±0,79 GPa for x, y, and z direction specimens, respectively. Considering a laminated composite material, the difference is significantly low for different directions.

- Thermogravimetric analysis showed that composite sample started to mass loss around 120 ºC while neat resin starts around 345 ºC. The results indicated that the novel composite can be used in application where all plastic and composite materials are used.
- At the second stage of the study, specimens with varying parameters were fabricated. Composite specimens have low density which is critical parameter for many applications. Specimens without glass fiber had very low strength and modulus values as it is expected since EPS beads have very low strength and behaves like void in the material.
- Using higher density EPS beads resulted with higher strength and modulus values. The main reason is the lower volume of the beads which means lower amount of air in the beads.
- Addition of fiber glass increased the strength and modulus values for all specimens. Increment of fiber/filler ratios improved the tensile strength and modulus values while it results with high variation of the results. Error analysis revealed that, using fiber/filler ratio of 30:1 resulted with very high variation of results. The reason is the decrement of the homogeneity of the composite since the glass fibers tend to cluster and create pellet structures in the structure.
- The micrographs taken after tensile tests showed that the specimens were not completely homogenous. The random distribution of the EPS beads and glass fiber is the main cause for the non-homogeneous structure. The breaks were occurred mostly on EPS beads which means a strong interphase between matrix and filler was established. There was no significant void occurrence in the structure and thus the fabrication method is compatible with the novel composite and it is advisable.

- Specific strength values of all composite specimens were lower than neat resin while specific modulus values of most of the specimens were higher. Maximum specific modulus value was obtained from the E2 coded specimen which consists of 13 kg/m^3 EPS, 6 mm chopped glass fibers with the fiber/filler ratio of 20:1.
- Impact tests showed that, neat resin had higher impact strength than composite specimens. But, neat resin fractured in brittle manner while composite specimens fractured in ductile manner.
- The trend of high variation of result when the fiber/filler ratio is increased observed also for impact strength tests. Both impact and strength results conclude that fiber/filler ratio over 20:1 is not advisable.
- Cost analysis studies showed that the novel composite can be suitable candidate for many engineering applications where especially laminated glass composites or conventional plastics are preferred.
- The cost-property efficiency values of the specimens indicates that specimens C2, D2, and E2 specimens have very high cost-property efficiency (specific modulus/unit cost wrt volume-GPa.m^6/kg.$) especially in comparison with laminated glass composites and plastics such as HDPE, nylon, polypropylene, and PVC. This property is a significant advantage in material selection process. The relatively low density of the novel composite makes it a considerable for engineering products except load bearing applications.
- Water absorption tests revealed that all of the composite specimens had higher water absorbance than neat resin. When the specimens soaked into water, EPS beads and glass fibers tend to absorb water especially at the points of where EPS and glass fibers directly contact with water.
- The E2 specimen had the most preferable properties among the studied specimens.

Evaluating the all results of the study, the novel composite is successfully fabricated and characterized. Due to the need for new materials which are low weight and cost, the novel composite is a considerable candidate especially in automotive industry. To develop the material further the following studies can be conducted;

- Developing a new fabrication method for more uniform distribution of the EPS beads and glass fibers in the structure,
- Developing a new mixing method to prevent clustering regions and using higher fiber/filler ratios,
- Covering the surface of the EPS beads with a chemical to be able to fabricate the composite with a lower cost matrix material,
- Trying different foam types and fiber types to fabricate a similar composite for load bearing applications.

REFERENCES

Abdelal, N. R., Al-Saleh, M. H. and Irshidat, M. R., 2018. Utilizing Vacuum Bagging Process to Prepare Carbon Fiber/CNT-Modified-epoxy Composites with Improved Mechanical Properties. Polymer-Plastics Technology and Engineering, 57(3): 175-184.

Abrate, S., 1986. The Mechanics of Short-Fiber-Reinforced Composites - a Review. Rubber Chemistry and Technology, 59(3): 384-404.

Aktas, A., Krishnan, L., Kandola, B., Boyd, S. W., and Shenoi, R. A., 2015. A cure modelling study of an unsaturated polyester resin system for the simulation of curing of fibre-reinforced composites during the vacuum infusion process. Journal of Composite Materials, 49(20): 2529-2540.

Albinante, S. Pacheco, R., E. B. A. V., and Visconte, L. L. Y., 2013. A Review on Chemical Treatment of Natural Fiber for Mixing with Polyolefins. Quimica Nova, 36(1): 114-122.

Almeida, J. H. S., M. L. Ribeiro, V. Tita and S. C. Amico, 2017. Damage modeling for carbon fiber/epoxy filament wound composite tubes under radial compression. Composite Structures, 160: 204-210.

Almeida, J. H. S., Souza, S. D. B., Botelho, E. C., and Amico, S. C., 2016. Carbon fiber-reinforced epoxy filament-wound composite laminates exposed to hygrothermal conditioning. Journal of Materials Science, 51(9): 4697-4708.

Alva, G., Lin, Y. X., and Fang, G. Y., 2018. Thermal and electrical characterization of polymer/ceramic composites with polyvinyl butyral matrix. Materials Chemistry and Physics, 205: 401-415.

Asadi, A., Abusrea, M. R., Arakawa, K., Colton, J., and Kalaitzidou, K., 2018. A comparison of CFRP composite laminated joints fabricated with vacuum assisted resin transfer molding. Express Polymer Letters, 12(9): 781-789.

Ashby, M. F., 2005. Materials Selection in Mechanical Design. Elsevier s.

Ashworth, S., Rongong, J., Wilson, P., and Meredith, J., 2016. Mechanical and damping properties of resin transfer moulded jute-carbon hybrid composites. Composites Part B-Engineering, 105: 60-66.

Association, T. C. M. (2019). Composites Turkey. Composites Turkey, Turkish Composites Manufacturers Association. **24**.

ASTM (2004). ASTM D 6110, Standard Test Method for Determining the Charpy Impact Resistance of Notched Specimens of Plastics.

ASTM (2017). ASTM D3039 / D3039M-17, Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials, ASTM International.

Audibert, C., Andreani, Laine, E., and Grandidier, J. C., 2018. Mechanical characterization and damage mechanism of a new flax-Kevlar hybrid/epoxy composite. Composite Structures, 195: 126-135.

Bakis, C. E., Bank, L. C., Brown, V. L., Cosenza, E., Davalos, J. F., Lesko, J .J., Machida, A., Rizkalla, S.H., and Triantafillou, T.C., 2002. Fiber-reinforced polymer composites for construction-state-of-the-art review. Journal of Composites for Construction, 6(2): 73-87.

Belov, D. A., Makarenko, I. V., Dunaev, A. V., Babkin, A. V., Solopchenko, A. V., Yablokova, M. Y., Kepman, A. V., Tretyakov, A. V., Ulyanov, A. V., and Gromashev, A. G., 2016. Curing processes simulation of complex shape carbon fiber reinforced composite components produced by vacuum infusion. Polymer Composites, 37(7): 2252-2259.

Bertoncelj, B., Vojisavljevic, K., Vrabelj, M., and Malic, B., 2015. Thermal properties of polymer-matrix composites reinforced with E-glass fibers. Informacije Midem-Journal of Microelectronics Electronic Components and Materials, 45(3): 216-221.

Bin Park, S., J. Lee, J. S., and Kim, J. W., 2017. Effects of short glass fibers on the mechanical properties of glass fiber fabric/PVC composites. Materials Research Express, 4(3).

Bulgakov, B. A., Sulimov, A. V., Babkin, A. V., Timoshkin, I. A., Solopchenko, A. V., Kepman, A. V., and Avdeev, V. V., 2017. Phthalonitrile-carbon fiber composites produced by vacuum infusion process. Journal of Composite Materials, 51(30): 4157-4164.

Bussu, G. and Lazzeri, A., 2006. On the use of dynamic mechanical thermal analysis (DMTA) for measuring glass transition temperature of polymer matrix fibre reinforced composites. Journal of Materials Science, 41(18): 6072-6076.

Callister, W. D. and Rethwisch, D. G., 2014. Materials Science And Engineering An Introduction. Wiley s.

Cebe, P. and Chung, S. S., 1990. Melting Behavior of High-Performance Composite Matrix Polymers - Poly(Phenylene Sulfide). Polymer Composites, 11(5): 265-273.

Chandrasekar, M., Ishak, M. R., Sapuan, S. M., Leman, Z., and Jawaid, M., 2017. A review on the characterisation of natural fibres and their composites after alkali treatment and water absorption. Plastics Rubber and Composites, 46(3): 119-136.

Chung, D. D. L., 2000. Thermal analysis of carbon fiber polymer-matrix composites by electrical resistance measurement. Thermochimica Acta, 364(1-2): 121-132.

Cui, Y., Chang, J. M., and Wang, W. L., 2016. Fabrication of Glass Fiber Reinforced Composites Based on Bio-Oil Phenol Formaldehyde Resin. Materials, 9(11).

de Oliveira, K. A., Barbosa, J. C., Christoforo, A. L., Molina, J. C., Oliveira, C. A. B., Bertolini, M. S., Gava, M., and Ventorim, G., 2019. Sound Absorption of Recycled Gypsum Matrix Composites with Residual Cellulosic Pulp and Expanded Polystyrene. Bioresources, 14(2): 4806-4813.

Demina, N. M., 2016. Current Compositions for Processing High-Strength High-Modulus Continuous Glass Fiber (Review). Fibre Chemistry, 48(2): 118-124.

Deng, S. Q., L. Ye, L., and Mai, Y. W., 1999. Influence of fibre cross-sectional aspect ratio on mechanical properties of glass fibre epoxy composites I.

Tensile and flexure behaviour. Composites Science and Technology, 59(9): 1331-1339.

El Boustani, M., Lebrun, G., Brouillette, F., and Belfkira, A., 2017. Effect of a solvent-free acetylation treatment on reinforcements permeability and tensile behaviour of flax/epoxy and flax/wood fibre/epoxy composites. Canadian Journal of Chemical Engineering, 95(6): 1082-1092.

Epple, S., and Bonten, C., 2014. Production of Continuous Fiber Thermoplastic Composites by in-situ Pultrusion. Proceedings of Pps-29: The 29th International Conference of the Polymer - Conference Papers, 1593: 454-457.

Erklig, A., Alsaadi, M., and Bulut, M., 2016. A comparative study on industrial waste fillers affecting mechanical properties of polymer-matrix composites. Materials Research Express, 3(10).

Ernault, E., Richaud, E., and Fayolle, B., 2017. Origin of epoxies embrittlement during oxidative ageing. Polymer Testing, 63: 448-454.

Foller, B., Holub, M., and Sestak, J., 2014. Acoustic composite laminates with unidirectional fiber reinforcement by novel pultrusion drawing. Journal of Thermal Analysis and Calorimetry, 116(2): 703-707.

Fuqua, M. A., Huo, S. S., and Ulven, C. A., 2012. Natural Fiber Reinforced Composites. Polymer Reviews, 52(3-4): 259-320.

Gemi, L., Kayrici, M., Uludag, M., Gemi, D. S., and Sahin, O. S., 2018. Experimental and statistical analysis of low velocity impact response of filament wound composite pipes. Composites Part B-Engineering, 149: 38-48.

Greenberg, A. R., 1987. Influence of Filler Chemistry on the Glass-Transition Behavior of a Polymer Matrix Composite-Material. Journal of Materials Science Letters, 6(1): 78-80.

Griffith, M. L. and Halloran, J. W., 1996. Freeform fabrication of ceramics via stereolithography. Journal of the American Ceramic Society, 79(10): 2601-2608.

Harmon, M. E., Nikiforov, M. P., Sahagian, K., Jesse, S., and Kalinin, S.B., 2011. Mapping of glass transition temperatures in carbon fiber polymer matrix composites. Abstracts of Papers of the American Chemical Society, 242.

He, J. J., Shi, J. P., Cao, X. S., and Hu, Y. F., 2018. Tensile Mechanical Properties and Failure Modes of a Basalt Fiber/Epoxy Resin Composite Material. Advances in Civil Engineering.

Hong, S., Song, M. H., Song, K., Baik, S. M., and Shin, S. J., 2016. Fabrication and Evaluation of Integrated Composite Part for Aircraft using OoA (Out-of-Autoclave) Prepreg. Composites Research, 29(5): 315-320.

Hsu, C. F., Tsai, H. Y., and Chen, T. H., 2018. The Effect of Manufacturing Parameters and Environmental Factors on Mechanical Properties of Carbon Fiber/Epoxy Composites. Journal of Mechanics, 34(6): 839-846.

Irina, K. C., Stanciu, G., and Gutaga, S., 2004. The treatment of natural fibers used in composite materials. Bulletin of the University of Agricultural Sciences and Veterinary Medicine, Vol 61, 61: 473-473.

Jawaid, M., and Khalil, H. P. S. A., 2011. Cellulosic/synthetic fibre reinforced polymer hybrid composites: A review. Carbohydrate Polymers, 86(1): 1-18.

Jiang, S. and Qi, X., 2012. Study on Winding Pattern and Undulation Degree of Filament-wound Composite Tube. Material and Manufacturing Technology Ii, Pts 1 and 2, 341-342: 281-285.

Jin, F. L., Li, X., and Park, S. J., 2015. Synthesis and application of epoxy resins: A review. Journal of Industrial and Engineering Chemistry, 29: 1-11.

Karaaslan, A., Sabanci, S., and Atapek, H., 2009. Production of a Glass Fiber Reinforced Polymer Matrix Composite by Injection Moulding and its Characterization. Materials Testing-Materials and Components Technology and Application, 51(4): 215-218.

Karger-Kocsis, J., Mahmood, H., and Pegoretti, A., 2015. Recent advances in fiber/matrix interphase engineering for polymer composites. Progress in Materials Science, 73: 1-43.

Kaw, A. K., 2006. Mechanics of Composite Materials. Taylor & Francis Group, LLC s.

Kim, W. J., Taya, M., and Nguyen, M. N., 2009. Electrical and thermal conductivities of a silver flake/thermosetting polymer matrix composite. Mechanics of Materials, 41(10): 1116-1124.

Kiran, M. D., Govindaraju, H.K., Jayaraju, T., and Kumar, N., 2018. Review-Effect of Fillers on Mechanical Properties of Polymer Matrix Composites. Materials Today-Proceedings, 5(10): 22421-22424.

Kopal, I., Vrskova, J., Ondrusova, D., Harnicarova, M., Valicek, J., and Kolenicova, Z., 2019. Modeling the thermal decomposition of friction composite systems based on yarn reinforced polymer matrices using artificial neural networks. Materialwissenschaft Und Werkstofftechnik, 50(5): 616-628.

Kumar, S. M., Ravikiran, K. R., and Govindaraju, H. K., 2018. Development of E-Glass Woven Fabric / Polyester Resin Polymer Matrix Composite and Study of Mechanical Properties. Materials Today-Proceedings, 5(5): 13367-13374.

Kumar, S. M., Srinivas, Ramachandra, M., and Mahendra, K. V., 2018. Characterization of Aluminium Metal Matrix Composite Produced By Squeeze Casting Technique. Materials Today-Proceedings, 5(10): 22718-22726.

Kumar, V. M. and Venkatesh, C. V., 2019. A comprehensive review on material selection, processing, characterization and applications of aluminium metal matrix composites. Materials Research Express, 6(7).

Lee, J. W., Park, S. B., Lee, J. S., and Kim, J. W., 2017. Improvement in mechanical properties of glass fiber fabric/PVC composites with chopped glass fibers and coupling agent. Materials Research Express, 4(7).

Li, F. F., Hu, Y., Hou, X. C., Hu, X. Y., and Jiang, D., 2018. Thermal, mechanical, and tribological properties of short carbon fibers/PEEK composites. High Performance Polymers, 30(6): 657-666.

Li, J., Ben, G. C., and Yang, J. H., 2014. Fabrication of hemp fiber-reinforced green composites with organoclay-filled poly(butylene succinate) matrix by pultrusion process. Science and Engineering of Composite Materials, 21(2): 289-294.

Li, W., Li, H. Y., Yang, X. G., Feng, W., and Huang, H. Y., 2017. Preparation and properties of novel sulfonic graphene oxide-epoxy resin nanocomposites by resin transfer molding process. Journal of Composite Materials, 51(9): 1197-1208.

Li, X., Tabil, L. G., and Panigrahi, S., 2007. Chemical treatments of natural fiber for use in natural fiber-reinforced composites: A review. Journal of Polymers and the Environment, 15(1): 25-33.

Liu, B., Villavicencio, R., and Soares, C. G., 2013. Failure characteristics of strength-equivalent aluminium and steel plates in impact conditions. Analysis and Design of Marine Structures, Marstruct 2013: 167-174.

Liu, X. and Cheng, L., 2017. Influence of plasma treatment on properties of ramie fiber and the reinforced composites. Journal of Adhesion Science and Technology, 31(15): 1723-1734.

Lu, Z. L., Cao, J. W., Song, Z. Q., Li, D. C., and B. H. Lu, B. H., 2019. Research progress of ceramic matrix composite parts based on additive manufacturing technology. Virtual and Physical Prototyping, 14(4): 333-348.

Ma, Y., Jin, S. S., Ueda, M., Yokozeki, T., Yang, Y. Q., Kobayashi, F., HKobayashi, H., Sugahara, T., and Hamada, H., 2018. Higher performance carbon fiber reinforced thermoplastic composites from thermoplastic prepreg technique: Heat and moisture effect. Composites Part B-Engineering, 154: 90-98.

Malenab, R. A. J., Ngo, J. P. S., and Promentilla, M. A. B., 2017. Chemical Treatment of Waste Abaca for Natural Fiber-Reinforced Geopolymer Composite. Materials, 10(6).

Mangalgiri, P. D., 1999. Composite materials for aerospace applications. Bulletin of Materials Science, 22(3): 657-664.

Manufacturing systems for automotive composite parts. Retrieved 09.06.2020, 2020, from https://pinetteemidecau.eu/en/solutions-by-industry/automotive-composites.

Menta, V., R. Vuppalapati, R., Chandrashekhara, K., Schuman, T., and. Sha, J. L., 2013. Elevated-temperature vacuum-assisted resin transfer molding process for high performance aerospace composites. Polymer International, 62(10): 1465-1476.

Meredith, J., Coles, S. R., Powe, R., Collings, E., Cozien-Cazuc, S., Weager, B., Mussig, J., and Kirwan, K., 2013. On the static and dynamic properties of flax and Cordenka epoxy composites. Composites Science and Technology, 80: 31-38.

Methven, J. M., Ghaffariyan, S. R., and Abidin, A. Z., 2000. Manufacture of fiber-reinforced composites by microwave assisted pultrusion. Polymer Composites, 21(4): 586-594.

Misra, R. K. and Datta, C., 2008. Mechanical behavior of unidirectional glass fibers reinforced Resol/VAC-EHA Composites at different volume fraction of fibers. Soft Materials, 6(3-4): 99-118.

Munawar, M. A., Khan, S. M., Gull, N., Shafiq, M., Islam, A., Zia, S., Sabir, A., Ghouri, A. S., Butt, M. T. Z., and Jamil, T., 2016. Fabrication and characterization of novel zirconia filled glass fiber reinforced polyester hybrid composites. Journal of Applied Polymer Science, 133(27).

Nandaragi, S. R., Reddy, B., and Narayana, K. B., 2018. Fabrication, testing and evaluation of mechanical properties of woven glass fibre composite material. Materials Today-Proceedings, 5(1): 2429-2434.

Naslain, R., 2005. Fiber-Reinforced Ceramic Matrix Composites: State Of The Art, Challenge And Perspective Kompozyty (Composites), 5(1).

Naslain, R., 2005. Recent advances in the field of ceramic fibers and ceramic matrix composites. Journal De Physique Iv, 123: 3-17.

Nayak, S. Y., Heckadka, S. S., Thomas, L. G., and Baby, A., 2018. Tensile and Flexural Properties of Chopped Strand E-glass Fibre Mat Reinforced CNSL-Epoxy Composites. International Conference on Research in Mechanical Engineering Sciences (Rimes 2017), 144.

Nilugal, R. P. and Kumar, A., 2015. Effect Of Silicon Carbide And Calcium Sulphate On E-Glass/Epoxy Composites. International Journal of Mechanical Engineering and Technology, 6(7): 8-15.

Ozsoy, N., Ozsoy, M., and Mimaroglu, A., 2017. Mechanical and Tribological Behaviour of Chopped E-Glass Fiber-Reinforced Epoxy Composite Materials. Acta Physica Polonica A, 132(3): 852-856.

Peng, X., Fan, M. Z., Hartley, J., and Al-Zubaidy, M., 2012. Properties of natural fiber composites made by pultrusion process. Journal of Composite Materials, 46(2): 237-246.

Plastics, P. E. "Technical Data." Retrieved 21.07.2020, 2020, from https://plastem.co.za/plastic-technical-data/.

Rallini, M., Natali, M., Kenny, J. M., and Torre, L., 2013. Effect of boron carbide nanoparticles on the fire reaction and fire resistance of carbon fiber/epoxy composites. Polymer, 54(19): 5154-5165.

Rao, P. V. C., 2020. Effects of matrix modification on mechanical and durability characteristics of polymer composites through variations in micro fillers, macro fillers and fibers. Construction and Building Materials, 235.

Rausch, J., Zhuang, R. C., and Mader, E., 2010. Surfactant Assisted Processing of Carbon Nanotube/Polypropylene Composites: Impact of Surfactants on the Matrix Polymer. Journal of Applied Polymer Science, 117(5): 2583-2590.

Saba, N. and Jawaid, M., 2018. A review on thermomechanical properties of polymers and fibers reinforced polymer composites. Journal of Industrial and Engineering Chemistry, 67: 1-11.

Saba, N., Jawaid, M., Alothman, O. Y., Paridah, M. T., and Hassan, A., 2016. Recent advances in epoxy resin, natural fiber-reinforced epoxy composites and their applications. Journal of Reinforced Plastics and Composites, 35(6): 447-470.

Santucci, B. S., Bras, J., Belgacem, M. N., Curvelo, A. A. D., and Pimenta, M. T. B., 2016. Evaluation of the effects of chemical composition and refining treatments on the properties of nanofibrillated cellulose films from sugarcane bagasse. Industrial Crops and Products, 91: 238-248.

Sathishkumar, T. P., Satheeshkumar, S., and Naveen, J., 2014. Glass fiber-reinforced polymer composites - a review. Journal of Reinforced Plastics and Composites, 33(13): 1258-1275.

Satish, J. and Satish, K. G., 2018. Preparation of magnesium metal matrix composites by powder metallurgy process. International Conference on Advances in Materials and Manufacturing Applications (Iconamma-2017), 310.

Schillfahrt, C., Fauster, E., and Schledjewski, R., 2018. Forming of Complex-Shaped Composite Tubes using Optimized Bladder-Assisted Resin Transfer Molding. Proceedings of 21st International Esaform Conference on Material Forming (Esaform 2018), 1960.

Serin, H., Derici, O. B., and Yildizhan, S., 2019. A Review on Open Mold Techniques for Polymer Matrix Composite Products. 4th International Mediterranean Science and Engineering Congress (IMSEC 2019), Turkey.

Shen, F. C., 1995. A Filament-Wound Structure Technology Overview. Materials Chemistry and Physics, 42(2): 96-100.

Shi, Y. Y., Yu, T., Zhang, Y. M., He, X. D., and Kang, C., 2014. Research on Hot-Press Splicing Technology for Composite Prepreg Tape. Proceedings of the

2014 International Conference on Innovative Design and Manufacturing (Icidm): 143-148.

Siddhartha and Gupta, K., 2012. Mechanical and abrasive wear characterization of bidirectional and chopped E-glass fiber reinforced composite materials. Materials & Design, 35: 467-479.

Siddiqui, M. U. aA. F. M. Arif, A. F. M., 2018. Estimation and optimisation of effective thermal conductivity for polymer matrix composites with hybrid inclusions. Journal of Composite Materials, 52(16): 2139-2148.

Solomon, A. A. and Hemalatha, G., 2020. Characteristics of expanded polystyrene (EPS) and its impact on mechanical and thermal performance of insulated concrete form (ICF) system. Structures, 23: 204-213.

Somani, N., Tyagi, Y. K., Kumar, P., Srivastava, V., and Bhowmick, H., 2019. Enhanced tribological properties of SiC reinforced copper metal matrix composites. Materials Research Express, 6(1).

Sporleder, F., Carella, J. M., Dorao, C. A., and Luduena, L. N., 2017. Novel Approach for Modeling the Dynamics of Fiber Breakage in Polymer Matrix Composites during Capillary Extrusion. Advances in Polymer Technology, 36(4): 507-516.

Stanciu, M. D., Harapu, A., Draghicescu, H. T., Curtu, I., and Savin, A., 2016. Comparison between viscous elastic plastic behaviour of the composites reinforced with plain glass fabric and chopped strand mat. 7th International Conference on Advanced Concepts in Mechanical Engineering, 147.

Subbiah, R., Tjong, J., Nayak, S. K., and Sain, M., 2017. Effect of Natural Fiber Network on Permeability and Tensile Strength of Composites through Vacuum Infusion Process. Journal of Natural Fibers, 14(2): 278-286.

Sulong, N. H. R., Mustapa, S. A. S., and Rashid, M. K. A., 2019. Application of expanded polystyrene (EPS) in buildings and constructions: A review. Journal of Applied Polymer Science, 136(20).

Sun, Y. Y. and Chen, C. H., 2012. Process feasibility and kinetic analysis of glass fiber-reinforced vinyl ester/nano-Al2O3 matrix composites for pultrusion. Journal of Applied Polymer Science, 125: E429-E434.

Sureshkumar, M., Tamilselvam, P., Kumaravelan, R., and Dharmalingam, R., 2014. Design, Fabrication, and Analysis of a Hybrid FIBER Composite Monoleaf Spring Using Carbon and E-Glass Fibers for Automotive Suspension Applications. Mechanics of Composite Materials, 50(1): 115-122.

Swan, S., Yuksel, T., Kim, D., and Gurocak, H., 2017. Automation of the Vacuum Assisted Resin Transfer Molding Process for Recreational Composite Yachts. Polymer Composites, 38(11): 2411-2424.

Takenaka, K. and Ichigo, M., 2014. Thermal expansion adjustable polymer matrix composites with giant negative thermal expansion filler. Composites Science and Technology, 104: 47-51.

Technical Information Epoxy and Phenolic Resins Division Epoxy Resins, Hexion Specialty Chemicals, 2020.

The markets: Automotive (2020). Retrieved 09.06.2020, 2020, from https://www.compositesworld.com/blog/post/the-markets-automotive.

Thiagarajan, A., Palaniradja, K., and Velmurugan, K., 2015. Effect of interfacial bonding on impact properties of chopped glass fiber polymer nanocomposites. Composite Interfaces, 22(4): 265-280.

Thippesh, L., 2018. Fabrication of Hybrid Composite Mono-Leaf Spring with Unidirectional Glass Fibers. Materials Today-Proceedings, 5(1): 2980-2984.

Toh, W., Tan, L. B., Tse, K. M., Giam, A., Raju, K., Lee, H. P., and Tan, V. B. C., 2018. Material characterization of filament-wound composite pipes. Composite Structures, 206: 474-483.

Tsai, S. W. and Hahn, H. T., 1980. Introduction to Composite Materials. Technomic USAs.

Tungjitpornkull, S., Chaochanchaikul, K., and Sombatsompop, N., 2007. Mechanical characterization of E-chopped strand glass fiber reinforced

Wood/PVC composites. Journal of Thermoplastic Composite Materials, 20(6): 535-550.

Unnikrishnan, K. P. and Thachil, E. T., 2006. Toughening of epoxy resins. Designed Monomers and Polymers, 9(2): 129-152.

Uzay, Ç., Boztepe, M. H., and Geren, N., 2016. Impact Energy Absorption Capacity Of Fiber Reinforced Polymer Matrix (FRP) Composites. Conference of the International Journal of Arts & Sciences (IJAS)-International Conference for Engineering and Technology, Paris, France.

Vaisakh, S. S., Mohammed, A. A. P., Hassanzadeh, M., Tortorici, J. F., Metz, R., and Ananthakumar, S., 2016. Effect of nano-modified SiO2/Al2O3 mixed-matrix micro-composite fillers on thermal, mechanical, and tribological properties of epoxy polymers. Polymers for Advanced Technologies, 27(7): 905-914.

Varga, C., Miskolczi, N., Szakacs, H., and Lipoczi, G., 2011. Effects of industrial scale production on the chemical composition of novel coupling agents and its relationship to the mechanical properties of chopped glass fibre mat reinforced thermoset composites. Materials & Design, 32(1): 12-20.

Vasiliev, V. V. and Morozov, E. V., 2001. Mechanics and Analysis of Composite Materials. Elsevier s.

Verma, D. and Jain, S., 2017. Effect of Natural Fibers Surface Treatment and their Reinforcement in Thermo-Plastic Polymer Composites: A Review. Current Organic Synthesis, 14(2): 186-199.

Wang, C. C., Wang, G., Cheng, H. T., Zhang, S. B., Smith, L. M., and Shi, S. Q., 2017. CaCO3 in situ treated bamboo pulp fiber reinforced composites obtained by vacuum-assisted resin infusion. Wood Science and Technology, 51(3): 571-584.

Wang, Z. Z., Huang, Z. Y., and Yang, T., 2020. Silica coated expanded polystyrene/cement composites with improved fire resistance, smoke suppression and mechanical strength. Materials Chemistry and Physics, 240.

Wilzer, J., Windmann, M., Weber, S., Hill, H., van Bennekom, A., and Theisen, W., 2015. Thermal conductivity of advanced TiC reinforced metal matrix composites for polymer processing applications. Journal of Composite Materials, 49(2): 243-250.

Windhorst, T. and Blount, G., 1997. Carbon-carbon composites: a summary of recent developments and applications. Materials & Design, 18(1): 11-15.

Wonderly, C., Grenestedt, J., Fernlund, G., and Cepus, E., 2005. Comparison of mechanical properties of glass fiber/vinyl ester and carbon fiber/vinyl ester composites. Composites Part B-Engineering, 36(5): 417-426.

Xu, C. Q., Gu, Y. Z., Yang, Z. J., Li, M., Li, Y. X., and Zhang, Z. G., 2016. Mechanical properties of surface-treated ramie fiber fabric/epoxy resin composite fabricated by vacuum-assisted resin infusion molding with hot compaction. Journal of Composite Materials, 50(9): 1189-1198.

Yildizhan, S. and Serin, H., 2020. Thermogravimetric Analysis of EPS/Glass Epoxy Composite. 6th International Conference On Knowledge And Innovation In Engineering, Science and Technology. Budapest, Hungary.

Yildizhan, S., Calik, A., Ozcanli, M, and Serin, H., 2018. Bio-composite materials: a short review of recent trends, mechanical and chemical properties, and applications. European Mechanical Science, 2(3): 83-91.

Yildizhan, S., Akar, M. A., Ozcanli, M., and Serin, H., 2019. Manufacturing Methods of Polymer Matrix Composites: A Brief Review of Techniques Convenient for Mass Production. 4th International Mediterranean Science and Engineering Congress (IMSEC 2019), Turkey.

Yildizhan, S., Ozcanli, M., and Serin, H., 2018. Characteristics of Chopped Glass Reinforced Composite Materials: A Brief Review. 3rd International Mediterranean Science and Engineering Congress (IMSEC 2018), Adana Turkey.

Yu, G. C., Wu, L. Z., Feng, L. J., and Yang, W., 2016. Thermal and mechanical properties of carbon fiber polymer-matrix composites with a 3D thermal conductive pathway. Composite Structures, 149: 213-219.

Zailinda, A., Rivai, A., Yuhazri, M. Y., and Rus, M. K. M., 2017. Comparison of two different composite process using hand lay-up and resin transfer moulding for tensile properties. Proceedings of Mechanical Engineering Research Day 2017 (Merd): 308-309.

Zhang, K. M., Gu, Y. Z., Zhang, J. L., Li, M., Wang, S. K., and Zhang, Z. G., 2016. Rapid curing vacuum-assisted resin infusion molding using silicone rubber sheet heater and the effect of cooling process on the properties of carbon fiber/epoxy composites. Journal of Composite Materials, 50(13): 1837-1850.

Zu, L., Koussios, S., and Beukers, A., 2011. Integral Design for Filament-Wound Composite Pressure Vessels. Polymers & Polymer Composites, 19(4-5): 413-420.

CURRICULUM VITAE

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APPENDICES

In the scope of this study 3 projects have been supported by Çukurova University Scientific Research Projects Unit. The information of the projects and papers published from the contents of the PhD study are given below;

Projects

FBA-2017-9122, Otomotiv Mühendisliği Uygulamalarında Biyo-Kompozit Kullanımı (22.08.2017- 15.09.2018).

Project Administrator: **Hasan SERİN**, Researcher: **Şafak YILDIZHAN**

FBA-2018-10946, Atık malzemelerden üretilmiş kompozit malzemelerin mekanik özelliklerinin araştırılması (14.11.2018-16.12.2019).

Project Administrator: **Hasan SERİN**, Researcher: **Şafak YILDIZHAN**

FBA-2020-12502, EPS Cam Elyafı Epoksi Kompozitlerin Mekanik Özelliklerinin Araştırılması (04.02.2020-continues).

Project Administrator: **Hasan SERİN**, Researcher: **Şafak YILDIZHAN**

Papers

SERİN H., **YILDIZHAN Ş.**, Tensile properties and cost-property efficiency analyses of expanded polystyrene/chopped glass fiber/epoxy novel composite, JOURNAL of MECHANICAL SCIENCE AND TECHNOLOGY. Vol.35 (1) Article in Press. (Research Article Accepted in SCI-E Journal)

YILDIZHAN Ş., ÇALIK A., ÖZCANLI M., **SERİN H.**, Bio-composite materials: a short review of recent trends, mechanical and chemical properties, and applications, EUROPEAN MECHANICAL SCIENCE, vol.2, no.3, pp.83-91, 2018. (Review Article)

YILDIZHAN Ş., and **SERİN H.**, Thermogravimetric Analysis of EPS/Glass Epoxy Composite, 6th International Conference on Knowledge & Innovation In

Engineering, Science & Technology, Budapest, Hungary, 06 – 08 March 2020. (Conference Paper)

SERİN H., Derici O. B. , **YILDIZHAN Ş.**, A Review on Open Mold Techniques for Polymer Matrix Composite Products, 4th International Mediterranean Science and Engineering Congress (IMSEC 2019), Antalya, Turkey, 25 - 27 April 2019, pp.400-404. (Conference Paper)

YILDIZHAN Ş., AKAR M. A. , ÖZCANLI M., **SERİN H.**, Manufacturing Methods of Polymer Matrix Composites: A Brief Review of Techniques Convenient for Mass Production, 4th International Mediterranean Science and Engineering Congress (IMSEC 2019), Antalya, Turkey, 25 - 27 April
2019, pp.395-399. (Conference Paper)

YILDIZHAN Ş., ÖZCANLI M., **SERİN H.**, Characteristics of Chopped Glass Reinforced Composite Materials: A Brief Review, 3rd International Mediterranean Science and Engineering Congress (IMSEC 2018), Adana, Turkey, 24 – 26 October 2018, pp.1413-1417. (Conference Paper)

YILDIZHAN Ş., Derici O. B. , **SERİN H.**, Fabrication of a novel material: EPS/Chopped E-Glass/Epoxy Hybrid Composite, Multidisciplinary Academic Conferences: Engineering, IT and Artificial Intelligence (MAC-EITAI), Prag, Czech Republic, 25 - 27 May 2018, pp.25. (Conference Paper)