DISSERTATION REPORT

Mechanical and Microstructural Characterization of Hybrid Composite Developed By Compression Molding

By

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
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Approved by,

(Dr. Faiz Ahmad)

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TRONOH, PERAK
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CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

MOHAMMAD ARIFF BIN SUKUR

ABSTRACT

Hybrid composites are developed using compression molding machine. The developed hybrid composite consists of a matrix material with a combination of 2 fiber reinforcements. There are 3 types of fiber reinforcements used in this study which are the woven glass, carbon and Kevlar fibers. The matrix materials used are either epoxy or polyester. The developed hybrid composite consists of fiber contents ranging from 15% to 45%. For polyester based composite, it is cured at room temperature while for epoxy based composite, it was cured at a temperature of 80°C. Both of the composite types were tested for its mechanical properties which are the tensile test and impact test. Then, the microstructural structure of the developed hybrid composite is analyzed.

Results showed that the tensile strength increases with the fiber volume concentration. Hybrid composite reinforced with Kevlar and glass possesses high impact properties compared to the hybrid composite reinforced with carbon and glass fiber.

The Microstructural analysis showed that impact resulted in brittle fracture in the case of carbon and glass fibers. While the Kevlar fibers show a ductile type of fracture.

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Alhamdulillah, thank God for giving me the chance on completing this project which is proven beneficial to me in my degree studies.

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ABBREVIATION AND NOMENCLATURES

Abbreviation	Description
MEKP	Methyl Ethyl Ketone Peroxide – Hardener for polyester matrix material
SEM	Scanning Electron Microscopy
EGC	Epoxy + Glass Fiber + Carbon Fiber Hybrid Composite
EGK	Epoxy + Glass Fiber + Kevlar Fiber Hybrid Composite
ECK	Epoxy + Carbon Fiber + Kevlar Fiber Hybrid Composite
PGC	Polyester + Glass Fiber + Carbon Fiber Hybrid Composite
PGK	Polyester + Glass Fiber + Kevlar Fiber Hybrid Composite
PCK	Polyester + Carbon Fiber + Kevlar Fiber Hybrid Composite
FVF	Fiber Volume Fraction – the fraction or percentage of fiber in a particular composite

CHAPTER 1
INTRODUCTION

1.1 PROJECT BACKGROUND

A composite consists of polymer matrix and fiber. When two or more type of fiber is used in the composite, it is called a hybrid composite. In this project the author will develop multiple hybrid composites using compression molding. Epoxy and Polyester are selected to be the matrix while Glass, Kevlar49 and Carbon fibers are selected to be the reinforcing constituent in the composite formed. The developed hybrid composite will later be tested for its mechanical properties. Calculation based on composites theory will be done beforehand and both experimental and theoretical result will be compared. Compression molding technique is expected to improve the matrix fiber cross linking and results in better properties of composite.

1.2 PROBLEM STATEMENT

Various hybrid composites will be developed using compression molding. The author wants to study the effect of compression molding technique to the developed composite mechanical properties and using the help of equipments like Scanning Electron Microscope, the author could look into the microstructure of developed hybrid composites

The traditional method in producing a composite is by the hand layup technique. This technique requires skills of the operator himself to produce a good quality composite. Using a machine, perhaps the gap of the skill can be decreased. The compression molding machine also possesses the ability to heat up the mold and use compressive force. With compressive force, it is believe that the composite developed would have better bonding between the matrix material and fiber reinforcement.

With the compression molding machine itself, automation of process could be done for mass production of the product

1.3 OBJECTIVE AND SCOPE OF STUDY

The objectives of this project are:

1. To learn and determine the volume fraction of fiber and matrix that will produce maximum properties improvement.
2. To fabricate the hybrid composite using the compression molding technique.
3. To study the mechanical properties of the produced hybrid composite by running a series of mechanical test.
4. To compare the experimental values of the developed hybrid composite properties using both the conventional hand layup technique and compression moulding.

CHAPTER 2
LITERATURE REVIEW

2.1 MATRIX

Matrix in a composite performs 2 major roles. First it transfers load to the reinforcing fibers. Secondly, it protects the fiber reinforcement from environment. Matrix materials are generally polymers, ceramics or metals. 2 types of matrix that will be used in this study are the polyester resins and epoxy resins.

2.1.1 Polyester

Polyester resins dominate the market and commercial fiber glass reinforced composites. A polyester resin is an unsaturated polyester solid dissolved in polymerizable monomer. Polyester is the simplest of the thermosets and is generally made by reacting diabetic acids with dihydric alcohol. Polyesters generally are the lowest cost matrices for composites which given rise to their wide usage. The limitations of polyester are the low temperature capability, low weathering resistance and low physical properties when compared to other available resins.

2.1.2 Epoxy

Epoxy resins on the other hand becomes the most common matrix for advanced composites due to its excellent adhesion, strength, low shrinkage, corrosion protection, processing versatility and other properties. It is also much more expensive than polyester resins due to the high cost of the precursor chemicals.

The good mechanical properties and resistance to environmental degradation makes them almost exclusive material used in aircraft components. Its resistance to water degradation makes epoxy the suitable material for application like boat building. Like polyester, epoxy can be cured at room temperature but it is quite often to add heat to accelerate and improve curing process. Epoxy can be quickly cured at any temperature ranged from 5°C to 150°C

2.2 FIBER REINFORCEMENT

Fibers are the most common reinforcement in composites compared to particles and whiskers due to its greatest influence in properties. The fibers will have significantly more strength in its length direction than in the other directions. 3 types of fibers that will be used in this study are the Glass, Kevlar49 and Carbon fibers

2.2.1 Glass Fiber

Glass fiber is an amorphous material consists of a silica backbone with various oxide components to give specific compositions and properties. It has good mechanical properties and environmental resistance. Its relatively low price is the primary reason on its competitiveness to other type of reinforcement fibers. It is widely used in commercial and industrial products.

2.2.2 Carbon Fiber

Carbon fibers are the predominant high strength; high modulus reinforcement used in the fabrications of high performance resin matrix composites. Carbon fibers are built by long carbon-carbon molecular chain yielding very stiff fibers. The current technology to produce carbon fibers is by thermal decomposition of various organic precursors. 3 most commonly used precursors would be polyacrylonitrile, rayon and pitch. The down side of carbon fiber is the highest fiber cost and poor impact or damage tolerance

2.2.3 Kevlar (Aramid 49) Fiber

Kevlar has highest tensile strength and modulus when compared to all of the 3 fibers. Aramid fiber is a generic name for a class of synthetic organic fibers called aromatic polyamide fibers. Other than high tensile strength and modulus, Aramid fibers also possess excellent impact and damage tolerance, but poor compression and shear strength.

2.3 LAY-UP PROCESS

Hand lay-up technique is the oldest yet simplest method to manufacture reinforced products. The process could be divided into 4 major operations which are the mold preparations, gel coating, hand lay-up and spray-up.

The most important function in this process is the mold preparation. The molding will look good and separation from mold will be easy if the mold preparation is done well. After the desired finish from buffing and polishing process is attained, several coats of wax are applied for the mold release purpose.

When good surface appearance is desired, the first step in open mold process would be the application of specially formulated resin layer called the gel coat. Normally polyester, it is applied first and becomes the outer surface of the laminate when completed. This will produce a glossy finish that requires no subsequent finishing.

In the hand lay-up operation, the fiber is applied in form of chopped strand mat or woven roving. Premeasured resin and catalyst are thoroughly mixed together. The resin mixture can be applied to the glass either outside of or on the mold. Serrated rollers are used to compact the material against the mold to prevent trapped air. In the spray-up operation, the chopped fibers and resin are simultaneously deposited on an open mold. The resin mix precoats the fiber strands. The advantage of this technique includes the ability to produce large yet complex items, and the tooling cost is relatively low.

2.4 COMPRESSION MOULDING

Figure 1: Compression Molding Control Panel

In a compression molding, the mixture of liquid resin and filler material is placed directly into a heated mold cavity that typically is around 200°C or higher. Forming is done under pressure from upper half of the die making the process somewhat similar to die-forging of metals.

Pressure of the process would range from 10 to 15MPa. Compression molding technique is mainly used with thermosetting plastic. Cross linking is completed in the heated die. Curing times range from 0.5 to 5 minutes depending on the material and part thickness.

2.5 LONGITUDINAL STRENGTH AND STIFFNESS

Properties of a composite material depend on the constituent properties and its distribution, physical and chemical interactions. These properties can be determined through series of experiment. But the experiments might become time and cost consuming. Thus mathematical model can be used to predict the properties.

By assuming the fibers to be uniform in properties and diameter, continuous and parallel throughout the composite, a unidirectional composite can be modeled. It is also convenient to assume that a perfect bonding exist between fibers and matrix which leads to no slip occurring at the interface and the strains experienced by fiber, matrix and composite are equal.

$$\epsilon_{f1} = \epsilon_{f2} = \epsilon_m = \epsilon_c$$

Thus for this model the load carried by composite is shared between matrix and fibers,

$$P_c = P_m + P_{f1} + P_{f2}$$

$$P_c = \sigma_c A_c = \sigma_m A_m + \sigma_{f1} A_{f1} + \sigma_{f2} A_{f2}$$

$$\sigma_c = \sigma_m \frac{A_m}{A_c} + \sigma_{f1} \frac{A_{f1}}{A_c} + \sigma_{f2} \frac{A_{f2}}{A_c}$$

But for parallel fibers composite, the volume fraction is equal to the area fraction,

$$\sigma_c = \sigma_m V_m + \sigma_{f1} V_{f1} + \sigma_{f2} V_{f2}$$

The equation is differentiated with respect to strain,

$$\frac{d\sigma_c}{d\epsilon} = \frac{\sigma_m}{d\epsilon}V_m + \frac{\sigma_{f1}}{d\epsilon}V_{f1} + \frac{\sigma_{f2}}{d\epsilon}V_{f2}$$

Where $d\sigma/d\epsilon$ represents the slope of the stress strain diagram at given strain. If the curves are linear, it is a constant and can be replaced with elastic modulus,

$$E_c = E_m V_m + E_{f1}V_{f1} + E_{f2}V_{f2}$$

It is clearly indicated that the contributions of the fiber and matrix to the average composite properties are proportional to their volume fractions. This relationship is called the rules of mixtures.

2.6 TRANSVERSE STIFFNESS AND STRENGTH

Simple mathematical model can be constructed to study the transverse properties of composites. Fibers are assumed to be uniform in properties and diameter, continuous and parallel throughout the composite. The composite is the stressed in the transverse direction, which would make every layer to carry same load and experience equal stress.

$$\sigma_{f1} = \sigma_{f2} = \sigma_m = \sigma_c$$

Each layer is assumed to have uniform thickness so that the cumulative thickness of fiber layers and matrix layers will be proportional to their respective volume fractions. Thus the composite elongation is equal to the fiber and matrix elongation.

$$\delta_c = \delta_m + \delta_{f1} + \delta_{f2}$$

The elongation in material can then be written as product of strain and thickness.

$$\epsilon_c t_c = \epsilon_m t_m + \epsilon_{f1} t_{f1} + \epsilon_{f2} t_{f2}$$

But thickness is proportional to the volume fractions

$$\epsilon_c = \epsilon_m \frac{t_m}{t_c} + \epsilon_{f1} \frac{t_{f1}}{t_c} + \epsilon_{f2} \frac{t_{f2}}{t_c} = \epsilon_m V_m + \epsilon_{f1} V_{f1} + \epsilon_{f2} V_{f2}$$

Assuming the fiber and matrix to deform elastically,

$$\frac{\sigma_c}{E_c} = \frac{\sigma_m}{E_m} V_m + \frac{\sigma_{f1}}{E_{f1}} V_{f1} + \frac{\sigma_{f2}}{E_{f2}} V_{f2}$$

Thus the transverse modulus for composite would be

$$\frac{1}{E_c} = \frac{V_m}{E_m} + \frac{V_{f1}}{E_{f1}} + \frac{V_{f2}}{E_{f2}}$$

2.7 MECHANICAL TESTING OF HYBRID COMPOSITE

Utilization of materials are always supported by testing activities which have developed over centuries from simple test of fit-to-utilize test to a modern science based procedure that covers all aspects of science and technology of the material and their utilization. A test laboratory for composite is often referred to a torture chamber since it tests the material to the maximum point or till fracture. But it is in a controlled and measured way to identify its mechanical properties and failure modes.

Forces like bending, pulling, pushing and hitting are some of the familiar test discipline. For this project, since we are dealing with hybrid composite, having a dual-phase entity, it poses a particular test challenge. Different forms of strength depend on which material phase is dominant. Tensile strength is fiber dominant while compressive strength depends more on the resin.

The purpose of testing the composite and hybrid composite is to predict its performance to a more relevant service conditions and can be applied with confidence to a variety of configurations. The mechanical property data is important in the design process if the composite materials are to perform with high reliability in its service life.

There are standards both national and international that prescribes the techniques that should be used when testing materials to obtain its mechanical data. Typical standard test methods are published by various standards organization such as ISO (International Standard Organization), ASTM (American Society for Testing and Materials), BSI (British Standards Institute) and CRAG (Composite Research Advisory Institute).

2.7.1 Tensile Testing

The purpose of tensile testing is to determine the ultimate tensile stress and tensile modulus of the fabricated hybrid composite. This test is to assess the hybrid composite when subjected to a uniaxial tensile stress. The advantage of tensile test is that ductile material can also be tested to complete break point. The elasticity modulus serves as a parameter of comparison between different materials and to measure its stiffness. Tensile stress strain characteristic are derived by monitoring both the force required to pull the material apart and the displacement that the material undergoes as a result of the applied force at constant deformation rate.

Tensile tests measure the force needed to break the specimen and the extent to which the specimen stretches or elongates to the breaking point. Load is transferred to the test coupon via grips. Tensile test produce stress strain diagram which will later be used to determine the tensile modulus. This data will be used to specify material, designing part to withstand certain force and also serves as quality control check for the material. The standard test that will be carried out in this project is ASTM D3039 which is the Standard Test Method for the Tensile Properties of Polymer Matrix Composite Materials. The required test coupon specifications are width of 25.4mm and gage length of 100mm.

2.7.2 Impact Testing

This test is to stimulate the impact conditions that a material or structure is expected to withstand in real life. The purpose of the test is to find the impact resistance of the composite materials. The impact resistance is the ability of the material to withstand a given blow without any damage.

The standard test that will be carried out in this project is the Charpy Impact Test (ISO179/1eU) where

1 stands for flat test piece with measurement of 80mm length and 10mm width

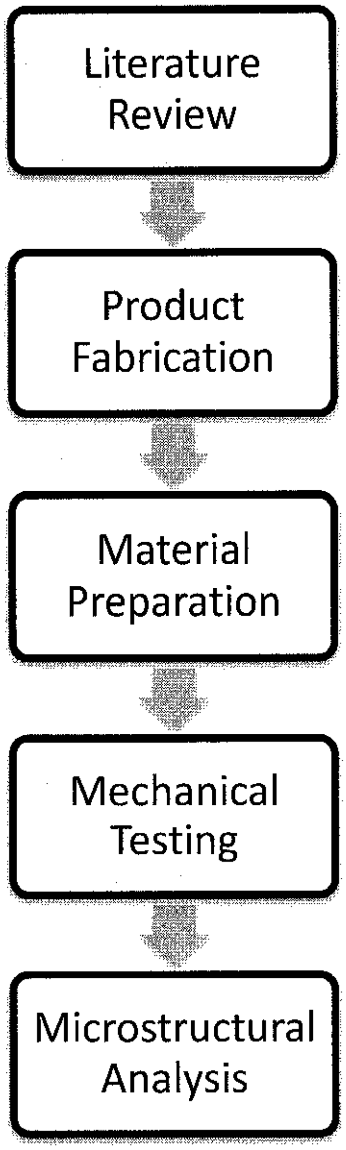
e stands for the direction of impact which is edgewise

U stands for unnotched specimen.

Charpy Impact is a single point test that measures a materials resistance to impact from a swinging pendulum. The pendulum will strike the specimen which is in the form of beam. The datum recorded from each test would be the energy absorbed by the hybrid composite specimen. This is measured by the angle through which the striker moves after it has impacted and fractures the specimen. The greater the swing of pendulum after impact, the smaller the amount of energy absorbed.

CHAPTER 3
METHODOLOGY

3.1 PROJECT FLOW CHART



3.2 HYBRID COMPOSITE PREPARATION

Below are the steps to prepare a hybrid composite with matrix A, and 2 type of reinforcement fiber B and C.

I. Cut 2 layers of B fibers to a 12cm x 12cm dimensions.
II. Cut 2 layers of C fibers to a 12cm x 12cm dimensions.
III. Apply mould release wax coat onto the 12cm x 12cm mold.
IV. Spray silicone gel thoroughly to the mold to enhance the effect of the mould release wax coat.
V. Prepare the matrix material, the matrix A by referring to calculation made using the rules of mixture. The ratio of matrix material and hardener can be referred on the literature review. Mix thoroughly for a minute.
VI. Place a layer of B fiber which has been cut earlier onto the mold.
VII. Pour the mixture of matrix material and hardener on top of the aforementioned B fiber.
VIII. Compact the material against the mold by using serrated rollers to remove entrapped air.
IX. Place a layer of C fiber on the top of the matrix and hardener layer.
X. Pour again the mixture of matrix material and hardener on top of the aforementioned C fiber.
XI. Compact the material against the mold by using serrated rollers to remove entrapped air.
XII. Repeat step V to XI for 1 more times. This is to create a sandwich structure of all three matrix and reinforcements.
XIII. Prepare the compression molding machine by turning on the plate heater if the matrix used need presence of heat to be cured
XIV. Place the prepared material onto the heat plate of the compression molding machine.
XV. Shut down the safety glass and switch on the hydraulic option.
XVI. Press the close clamp button using both left and right hand at the same time.

Control the applied pressure using the adjustable knob which is situated on the far right below of the compression molding machine

Figure 1: Layers of fiber glass cut in 12cm x 12cm dimensions, Mold release wax used on the mold, Silicone spray to enhance mold release effect, Sandwiched matrix and reinforcement.

Figure 2 : Tensile Testing and Impact Testing Machine

3.3 IMPACT TESTING GENERAL PROCEDURE

I. Set up the machine using settings in accordance with the standards specified earlier

II. Measure and record the test coupon's thickness

III. Press the TEST button for new test

IV. Open the window to insert test coupon

V. Press the O button for safety purpose. This will lock the pendulum

VI. Place the test coupon

VII. Close back the window
VIII. Press POWER button to power up the machine back
IX. Press TEST button again to reset the reading
X. Press START button to release the pendulum to hit the test coupon
XI. Collect the test coupon on the bottom left part of the machine.
XII. Record readings
XIII. Repeat from step II for another test coupon

3.4 TENSILE TESTING GENERAL PROCEDURE

I. Set the testing operation parameters according to the standards specified
II. Measure and record the test coupon using micrometer
III. Identify and mark the center line of the test coupon
IV. Clamp the test coupon firmly with the center line situated at the center between both upper and lower clamp.
V. Secure the clamp to make sure that the test coupon is gripped firmly
VI. Click the start button to run the test.
VII. Collect the broken test coupon
VIII. Plot and record the graph of stress versus strain
IX. Repeat from step I for another test coupon

3.5 CALCULATION

The calculation purpose is to get the weight of matrix (Epoxy and Polyester resins) needed to fabricate hybrid composite with predefined fiber volume fraction. The first step is to gather information of the composites constituents.

The second step is to obtain the weight of fiber constituent for given dimension. For this project the dimension that will be used is 20cm x 20cm. The information that the author have on his hand is the areal density of the fibers. Using these equations,

$$weight, W = \rho_{areal} \times A$$

Constituent Properties	$Density,$ ρ (kg/m^3)	$Tensile\ Modulus,$ E (GPa)	$Tensile\ Strength,$ σ (MPa)	$Poisson's\ Ratio,$ v
Polyester	1100	2.09	41.8	0.33
Epoxy	1200	3.83	83.6	0.33
Glass	2500	73	2400	0.22
Carbon	1800	251	4500	0.2
Kevlar49	1450	125	3600	3.5

Table 1: Physical properties of matrix material and fiber reinforcement

FIBER	AREAL DENSITY	WEIGHT OF 12 X 12 CM	
		1 PLY	2PLY
GLASS	385	5.544	11.088
CARBON	200	2.88	5.76
KEVLAR 49	300	4.32	8.64

Table 2: Areal density of fiber reinforcement used

Calculation of needed matrix weight for given Volume Fiber Fraction

Ex: Polyester + 15% FVF (Glass + Kevlar49)

For 2 ply of glass fiber and Kevlar fiber used, the weight is,

$$w_{glass} = 11.088g \qquad w_{kevlar49} = 8.64g$$

$$Total\ fiber\ weight, w_f = w_{glass} + w_{kevlar49} = 11.088 + 8.64 = 19.73g$$

$$Total\ fiber\ volume, v_f = \frac{w_{glass}}{\rho_{glass}} + \frac{w_{kevlar}}{\rho_{kevlar}} = \frac{11.088g}{2.5\ g/cm^3} + \frac{8.64g}{1.45\ g/cm^3}$$

$$= 10.39cm^3$$

$$Since\ \ fiber\ volume\ fraction, V_f = 15\% = 0.15$$

$$Thus\ composite\ volume, v_c = \frac{v_f}{V_f} = \frac{10.3938}{0.15} = 69.292cm^3$$

$$volume\ of\ matrix, v_m = v_c - v_f = 69.292 - 10.3938 = 58.90cm^3$$

$$volume\ calculated\ can\ be\ transformed\ to\ get\ the\ weight\ of\ matrix\ needed,$$

$$w_m = \rho_m v_m = 1.1\ g/cm^3 \times 58.8982cm^3 = 64.79g$$

$$ratio\ of\ polyester\ and\ MEKP\ are\ 50{:}\,1$$

$$\therefore w_{polyester} = 63.5176g\ and\ w_{MEKP} = 1.27g$$

CHAPTER 4

RESULTS

4.1 WEIGHT OF MATRIX NEEDED

COMPOSITE	FIBER VOLUME FRACTION	COMPOSITE VOLUME	MATRIX VOLUME	MATRIX WEIGHT
Polyester + Glass + Kevlar	15%	$69.292cm^3$	$58.898cm^3$	$64.788g$
	30%	$34.646cm^3$	$24.252cm^3$	$26.677g$
	45%	$23.097cm^3$	$12.703cm^3$	$13.974g$
	60%	$17.323cm^3$	$6.93cm^3$	$7.623g$
Polyester + Glass + Carbon	15%	$50.9013cm^3$	$43.266cm^3$	$47.5926g$
	30%	$25.451cm^3$	$17.8158cm^3$	$19.5974g$
	45%	$16.967cm^3$	$9.3318cm^3$	$10.265g$
	60%	$12.725cm^3$	$5.0898cm^3$	$5.5988g$
Polyester + Carbon + Kevlar	15%	$61.0573cm^3$	$51.8987cm^3$	$57.0886g$
	30%	$30.5286cm^3$	$21.37cm^3$	$23.507g$
	45%	$20.3524cm^3$	$11.1938cm^3$	$12.313g$
	60%	$15.264cm^3$	$6.1054cm^3$	$6.716g$
Epoxy + Glass + Kevlar	15%	$69.292cm^3$	$58.898cm^3$	$70.678g$
	30%	$34.646cm^3$	$24.252cm^3$	$29.102g$
	45%	$23.097cm^3$	$12.703cm^3$	$15.244g$
	60%	$17.323cm^3$	$6.93cm^3$	$8.316g$
Epoxy + Glass + Carbon	15%	$50.9013cm^3$	$43.266cm^3$	$51.919g$
	30%	$25.451cm^3$	$17.8158cm^3$	$21.379g$
	45%	$16.967cm^3$	$9.3318cm^3$	$11.198g$
	60%	$12.725cm^3$	$5.0898cm^3$	$6.108g$
Epoxy + Carbon + Kevlar	15%	$61.0573cm^3$	$51.8987cm^3$	$62.278g$
	30%	$30.5286cm^3$	$21.37cm^3$	$25.644g$
	45%	$20.3524cm^3$	$11.1938cm^3$	$13.433g$
	60%	$15.264cm^3$	$6.1054cm^3$	$7.326g$

Table 3: Required Matrix Weight

4.2 IMPACT TEST RESULT

FIBER REINFORCEMENT	FVF	Test No	Thickness (mm)	Length (mm)	Area (mm^2)	Absorbed Energy (J)	Normalised Absorbed Energy (kJ/m^2)	Average Normalised Absorbed Energy (kJ/m^2)
GLASS + CARBON	15%	1	3.00	80.00	240.00	2.049	8.537	8.563
		2	2.70	80.00	216.00	2.049	9.486	
		3	3.00	80.00	240.00	1.840	7.666	
	30%	1	2.40	80.00	192.00	2.049	10.671	10.463
		2	2.40	80.00	192.00	1.840	9.583	
		3	2.30	80.00	184.00	2.049	11.135	
	45%	1	2.20	80.00	176.00	2.469	14.028	14.604
		2	2.00	80.00	160.00	2.469	15.431	
		3	2.15	80.00	172.00	2.469	14.354	
GLASS + KEVLAR	15%	1	3.4	80.00	272.00	3.967	14.584	14.605
		2	3.4	80.00	272.00	3.967	14.584	
		3	3.2	80.00	256.00	3.75	14.648	
	30%	1	3.8	80.00	304.00	4.167	13.707	15.125
		2	3.2	80.00	256.00	4.403	17.199	
		3	3.6	80.00	288.00	4.167	14.468	
	45%	1	2.6	80.00	208.00	4.622	22.221	22.286
		2	2.7	80.00	216.00	4.842	22.416	
		3	2.6	80.00	208.00	4.622	22.221	

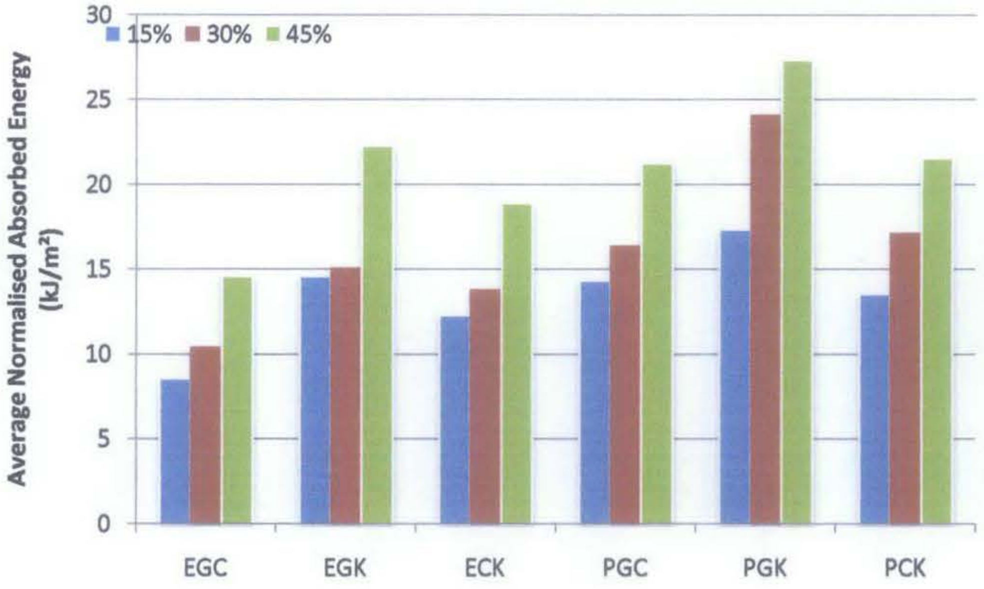
CARBON + KEVLAR	15%	1	3.2	80.00	256.00	3.32	12.968	12.318
		2	3	80.00	240.00	3.106	12.941	
		3	4	80.00	320.00	3.535	11.046	
	30%	1	3	80.00	240.00	3.106	12.941	13.865
		2	2.8	80.00	224.00	3.32	14.821	
		3	3	80.00	240.00	3.32	13.833	
	45%	1	2	80.00	160.00	2.893	18.081	18.902
		2	2.2	80.00	176.00	3.32	18.863	
		3	2.1	80.00	168.00	3.32	19.761	

Table 1 : Epoxy Matrix Material

FIBER REINFORCEMENT	FVF	Test No	Thickness (mm)	Length (mm)	Area (mm^2)	Absorbed Energy (J)	Normalised Absorbed Energy (kJ/m^2)	Average Normalised Absorbed Energy (kJ/m^2)
GLASS + CARBON	15%	1	2.4	80.00	192.00	2.893	15.067	14.331
		2	2.4	80.00	192.00	2.469	12.859	
		3	2.4	80.00	192.00	2.893	15.067	
	30%	1	1.4	80.00	112.00	1.632	14.571	16.421
		2	1.3	80.00	104.00	1.84	17.692	
		3	1.2	80.00	96.00	1.632	17.000	
	45%	1	1	80.00	80.00	1.632	20.400	21.267
		2	1	80.00	80.00	1.84	23.000	
		3	1	80.00	80.00	1.632	20.400	

GLASS + KEVLAR	15%	1	3.8	80.00	304.00	5.507	18.115	17.372
		2	4	80.00	320.00	4.842	15.131	
		3	3.5	80.00	280.00	5.284	18.871	
	30%	1	2.6	80.00	208.00	5.284	25.403	24.140
		2	3	80.00	240.00	5.507	22.945	
		3	2.4	80.00	192.00	4.622	24.072	
	45%	1	3	80.00	240.00	5.954	24.808	27.372
		2	2.4	80.00	192.00	5.507	28.682	
		3	2.6	80.00	208.00	5.954	28.625	
CARBON + KEVLAR	15%	1	3.3	80.00	264.00	3.967	15.026	13.564
		2	3.2	80.00	256.00	3.535	13.808	
		3	3.5	80.00	280.00	3.32	11.857	
	30%	1	2	80.00	160.00	2.893	18.081	17.194
		2	2	80.00	160.00	2.68	16.750	
		3	2	80.00	160.00	2.68	16.750	
	45%	1	2	80.00	160.00	3.967	24.793	21.546
		2	2.2	80.00	176.00	3.535	20.085	
		3	2.1	80.00	168.00	3.32	19.761	

Table 4 : Polyester Matrix Material



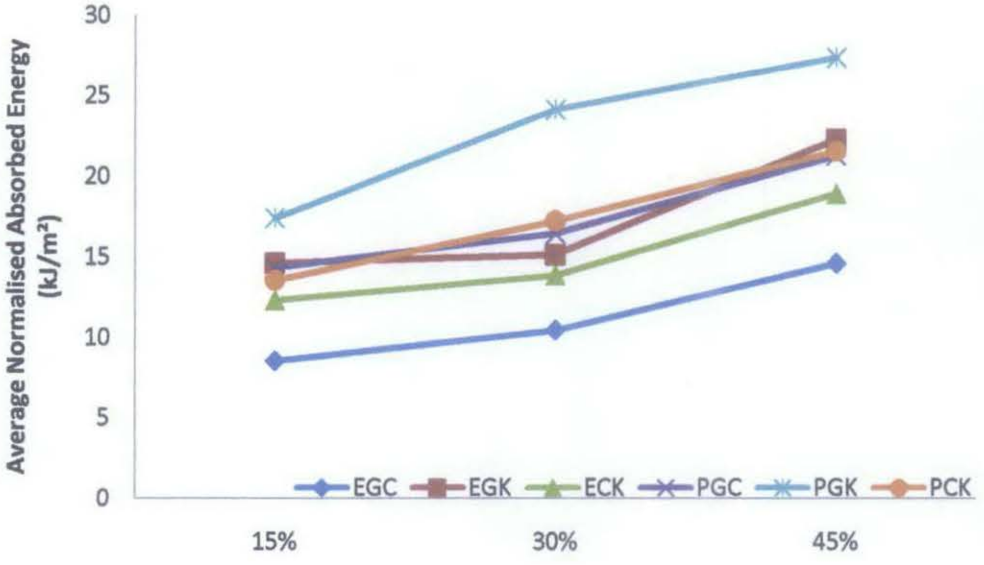


Figure 1 : Impact Testing Diagrams

Both of the diagrams above are the visual representative of the result gathered from the impact testing process. It is clearly shown that the FVF is directly proportional to the absorbed energy of the sample itself. This can also be proven by calculation. Taking the Polyester + Carbon + Kevlar for instance, changing from 15% FVF to 30%FVF increase the value of impact properties up to 26.762% while changing from 30% FVF to 45%FVF increase the value of impact properties to 25.31%

4.3 TENSILE TEST RESULT

COMPOSITE	FVF	TEST NO	THICKNESS (mm)	WIDTH (mm)	TENSILE STRENGTH (MPa)	AVERAGE TENSILE STRENGTH (MPa)	STRAIN (%)	TENSILE MODULUS (MPa)	AVERAGE TENSILE MODULUS (MPa)	FAILURE LOCATION
EPOXY + GLASS + CARBON	15%	1	3.00	25.50	76.00	75.56	11.29	6.73	6.05	CENTER
		2	3.00	25.60	86.25		13.50	6.39		CENTER
		3	3.10	25.40	64.44		12.83	5.02		CENTER
	30%	1	3.00	25.50	48.75	82.08	8.08	6.03	7.03	BELOW AT GRIP
		2	3.00	25.50	88.75		11.50	7.72		BELOW AT GRIP
		3	3.00	24.00	108.75		14.83	7.33		BELOW AT GRIP
	45%	1	2.00	26.00	110.00	125.00	12.00	9.17	12.66	ABOVE AT GRIP
		2	2.00	25.50	128.75		8.16	15.78		BELOW AT GRIP
		3	2.00	25.00	136.25		10.46	13.03		BELOW AT GRIP
EPOXY + GLASS + KEVLAR	15%	1	2.40	25.00	137.50	149.80	14.92	9.22	10.60	ABOVE AT GRIP
		2	2.00	25.50	167.50		13.58	12.33		ABOVE AT GRIP
		3	2.30	25.00	144.40		14.10	10.24		ABOVE AT GRIP
	30%	1	3.24	25.80	150.00	147.50	13.58	11.05	12.07	BELOW AT GRIP
		2	3.10	25.50	166.25		13.50	12.31		BELOW AT GRIP
		3	3.20	25.50	126.25		9.83	12.84		ABOVE AT GRIP
	45%	1	3.50	25.50	157.50	139.79	12.08	13.04	12.26	BELOW AT GRIP
		2	4.00	26.00	116.25		11.17	10.41		BELOW AT GRIP
		3	3.60	25.00	145.63		10.92	13.34		ABOVE AT GRIP

COMPOSITE	FVF	TEST NO	THICKNESS (mm)	WIDTH (mm)	TENSILE STRENGTH (MPa)	AVERAGE TENSILE STRENGTH (MPa)	STRAIN (%)	TENSILE MODULUS (MPa)	AVERAGE TENSILE MODULUS (MPa)	FAILURE LOCATION
EPOXY + CARBON + KEVLAR	15%	1	2.90	24.90	80.00	98.33	11.33	7.06	7.35	ABOVE AT GRIP
		2	2.76	26.50	110.00		15.25	7.21		CENTER GAGE LENGTH
		3	2.81	25.00	105.00		13.50	7.78		CENTER GAGE LENGTH
	30%	1	3.00	25.30	110.00	120.00	10.33	10.65	9.33	CENTER GAGE LENGTH
		2	2.96	25.70	120.00		14.00	8.57		ABOVE AT GRIP
		3	2.76	25.50	130.00		14.83	8.77		ABOVE AT GRIP
	45%	1	3.30	25.10	133.75	140.42	10.46	12.79	13.93	ABOVE AT GRIP
		2	3.50	25.50	131.88		8.83	14.94		BELOW AT GRIP
		3	3.42	25.50	155.63		11.08	14.05		CENTER GAGE LENGTH
POLYESTER + GLASS + CARBON	15%	1	3.00	25.40	120.00	94.66	20.78	5.77	5.75	ABOVE AT GRIP
		2	3.30	26.00	61.88		10.63	5.82		CENTER GAGE LENGTH
		3	3.20	25.20	102.10		18.00	5.67		CENTER GAGE LENGTH
	30%	1	3.20	25.60	125.00	135.42	12.16	10.28	9.80	CENTER GAGE LENGTH
		2	2.50	26.20	151.25		15.00	10.08		ABOVE AT GRIP
		3	3.10	26.10	130.00		14.40	9.03		ABOVE AT GRIP
	45%	1	2.70	25.50	153.75	142.74	9.00	17.08	16.10	CENTER GAGE LENGTH
		2	2.20	26.00	109.78		8.55	12.84		CENTER GAGE LENGTH
		3	2.50	25.60	162.70		8.85	18.38		CENTER GAGE LENGTH

COMPOSITE	FVF	TEST NO	THICKNESS (mm)	WIDTH (mm)	TENSILE STRENGTH (MPa)	AVERAGE TENSILE STRENGTH (MPa)	STRAIN (%)	TENSILE MODULUS (MPa)	AVERAGE TENSILE MODULUS (MPa)	FAILURE LOCATION
POLYESTER + GLASS + KEVLAR	15%	1	3.90	24.70	96.25	94.31	12.92	7.45	7.16	BELOW AT GRIP
		2	4.00	25.80	94.50		13.10	7.21		CENTER GAGE LENGTH
		3	4.70	27.40	92.19		13.50	6.83		ABOVE AT GRIP
	30%	1	2.20	26.00	146.88	137.01	13.08	11.23	10.31	ABOVE AT GRIP
		2	2.70	26.00	133.75		13.33	10.03		ABOVE AT GRIP
		3	2.50	26.00	130.41		13.50	9.66		ABOVE AT GRIP
	45%	1	2.50	25.40	148.75	149.18	11.58	12.85	12.53	CENTER GAGE LENGTH
		2	2.70	26.30	154.30		12.80	12.05		CENTER GAGE LENGTH
		3	2.55	25.40	144.50		11.40	12.68		CENTER GAGE LENGTH
POLYESTER + CARBON + KEVLAR	15%	1	2.00	26.00	76.00	112.88	8.92	8.52	13.54	CENTER GAGE LENGTH
		2	2.11	25.80	138.13		8.13	16.99		CENTER GAGE LENGTH
		3	2.14	25.85	124.50		8.24	15.11		CENTER GAGE LENGTH
	30%	1	2.20	25.20	121.25	105.62	7.50	16.17	15.11	CENTER GAGE LENGTH
		2	3.00	24.60	95.60		6.70	14.27		CENTER GAGE LENGTH
		3	2.50	25.00	100.00		6.71	14.90		CENTER GAGE LENGTH
	45%	1	1.60	24.60	129.05	118.23	7.13	18.10	15.75	BELOW AT GRIP
		2	1.50	23.90	114.86		7.84	14.65		BELOW AT GRIP
		3	1.55	24.20	110.78		7.64	14.50		BELOW AT GRIP

Table 5 : Tensile Testing Results

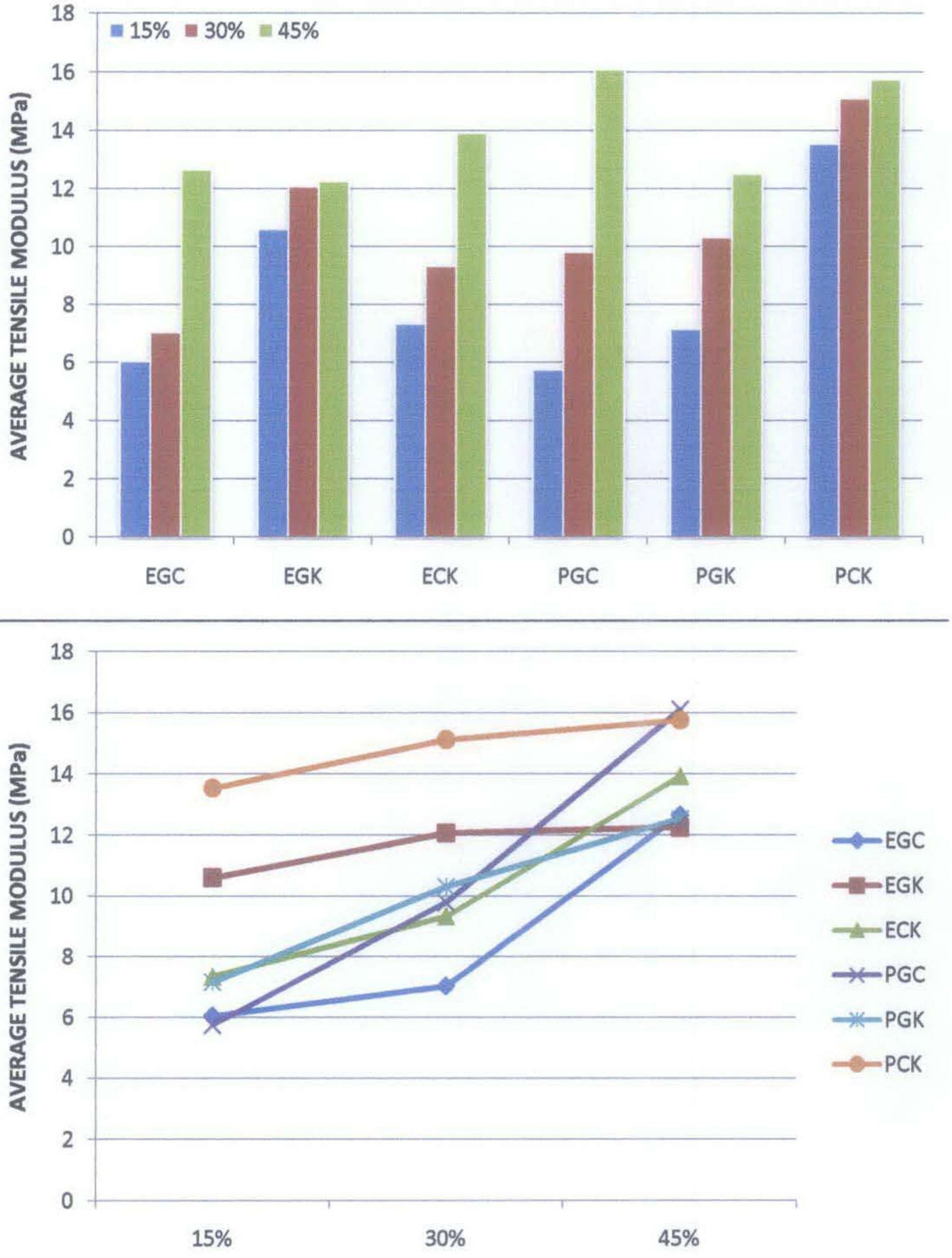


Figure 1 : Tensile Testing Diagrams

Both of the diagrams above are the visual representative of the results gathered from the tensile testing process. From the second graph, it is appropriate to conclude that the FVF is directly proportional to the tensile properties of a sample. Taking Polyester + Glass + Kevlar hybrid composite for instance, going to 30% FVF from 15%FVF increase the properties by 43.99% while changing from 30% FVF to 45%FVF increase the properties by 21.5325%

4.4 MICROSTRUCTURAL STUDIES

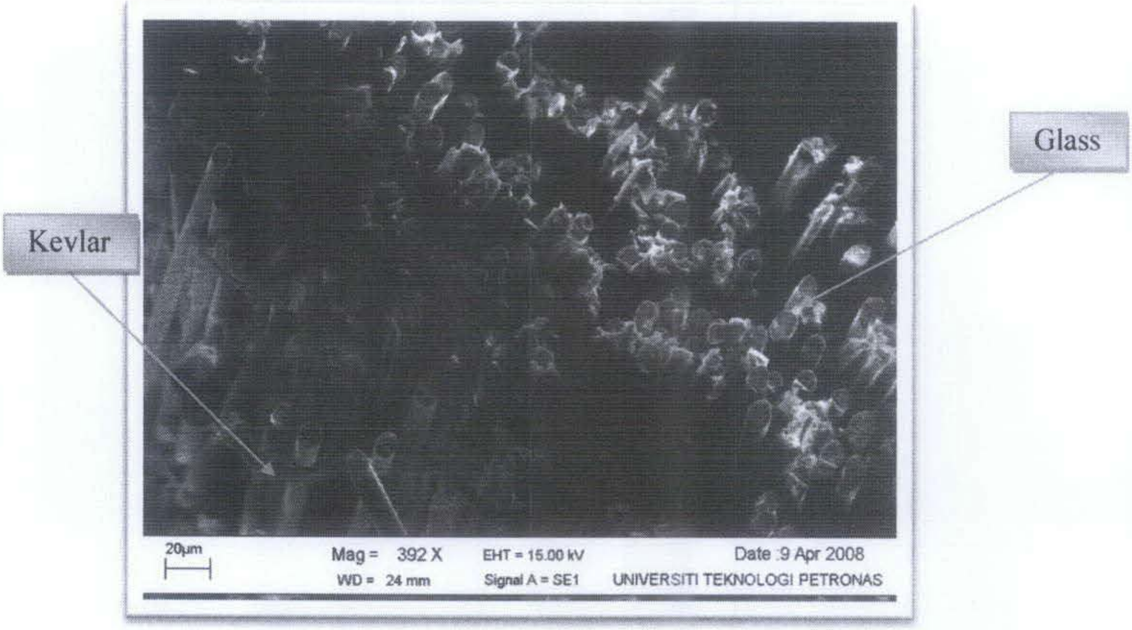


Figure 2 : SEM Photo of 30% PGK

Brittle fracture of glass fiber and ductile failure of Kevlar fibers

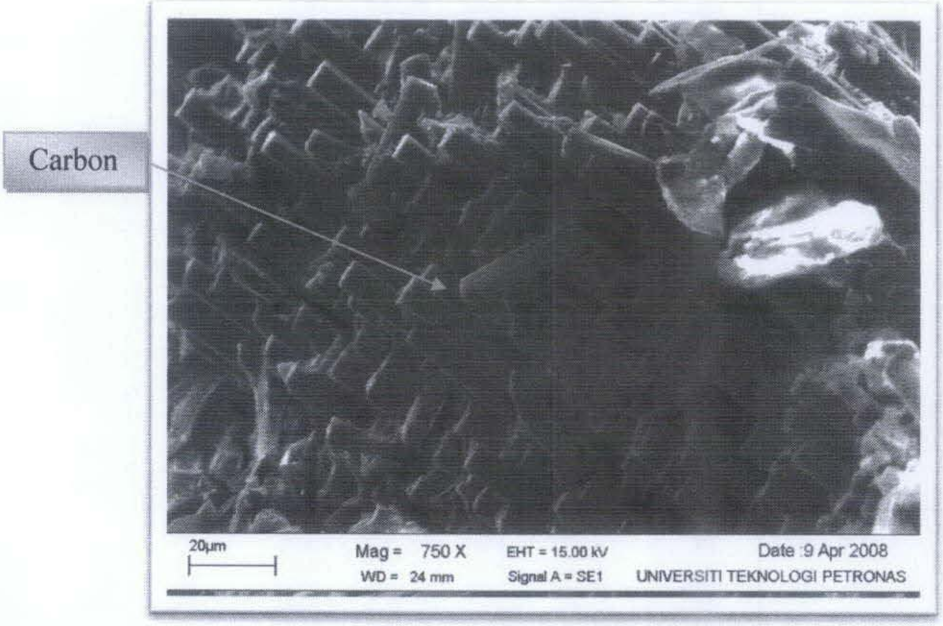


Figure 3 : SEM Photo of 45% PGC

Brittle failure of carbon fiber

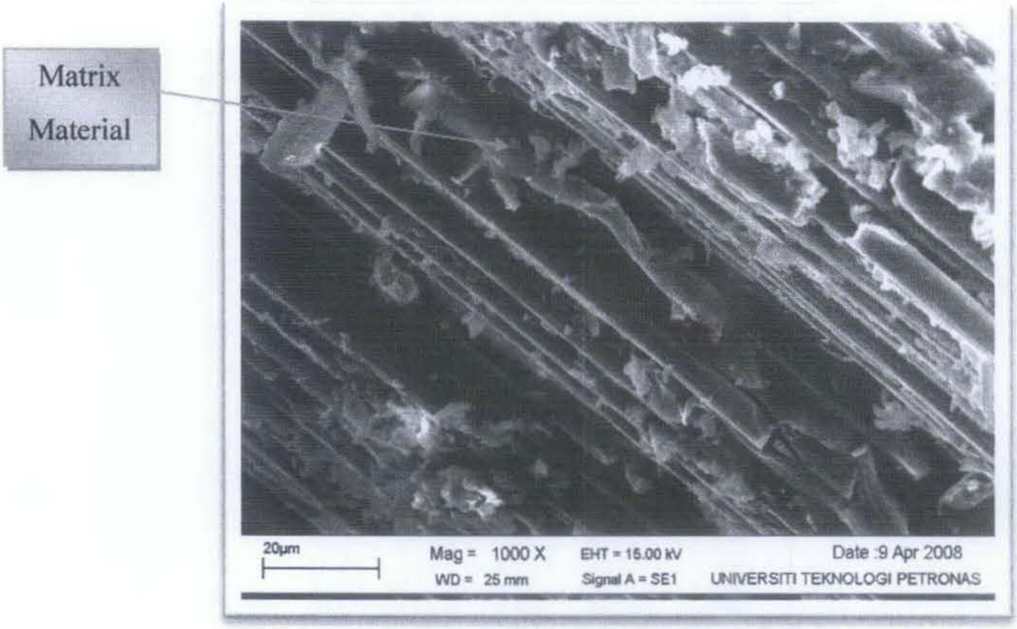


Figure 4 : SEM Photo of 45% PGC

Poor wetting of fiber by the matrix material. This lowers the material properties.

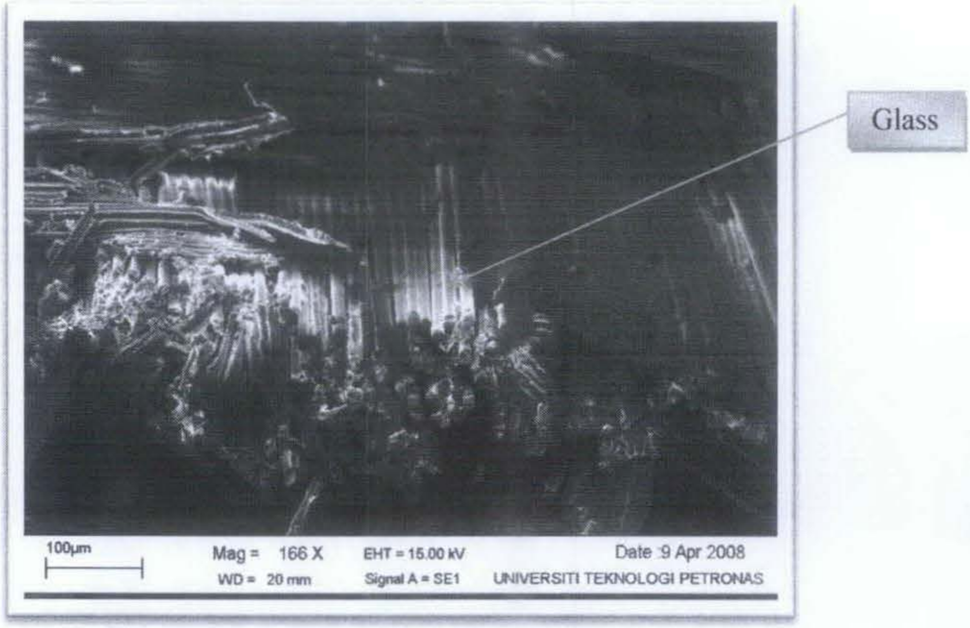


Figure 5 : SEM Photo of 30% PCK

Brittle fracture of glass fiber.

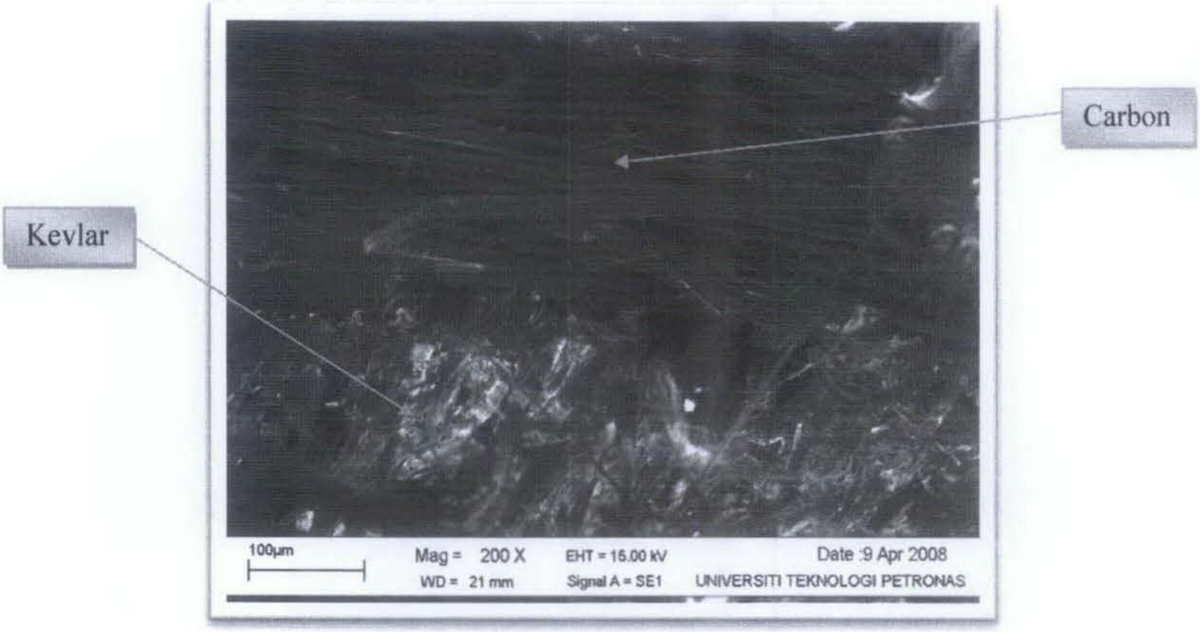


Figure 6 : SEM Photo of 30% PCK

Brittle failure of carbon fibers and ductile fracture of Kevlar fibers

Figure 7 : SEM Photo of 30% EGC

This photo shows the matrix material, epoxy and the glass fibers bonding on the top most of the lay-up process. It is obvious that the upmost level have the highest matrix material distribution. Segregation occurs.

4.5 DISCUSSION

a. Comparison Of Results

In this study a comparison is done between different hybrid composite with the same fiber volume fraction (FVF). It is questioned that what is the proportion of the fiber itself in the hybrid composite since the one that is set are the total fiber fraction. Below are the calculated fraction of each fibers in various combination of fiber reinforced composite.

Fiber Reinforcement	Total Fiber Volume Fraction	Fiber 1 Volume Fraction	Fiber 2 Volume Fraction
Glass + Kevlar	15%	6.4%	8.6%
	30%	12.8%	17.2%
	45%	19.2%	25.8%
Glass + Carbon	15%	8.71%	6.29%
	30%	17.43%	12.57%
	45%	26.14%	18.86%
Carbon + Kevlar	15%	5.24%	9.76%
	30%	10.48%	19.52%
	45%	15.72%	29.27%

Table 5 : Fiber Volume Fraction

According to the table above it is clearly shown that the volume fraction of each fiber reinforcement in hybrid composite is not balanced. For instance a 15%FVF Epoxy reinforced with Carbon and Glass fibers would not have 7.5% Carbon fiber and the other 7.5% Glass fiber. Instead Glass fiber will dominate more with 8.71% fraction in the particular hybrid composite

b. Impact Test

Referring to *Figure 4*, both of the diagrams succeeded in showing the impact of the Fiber Volume Fraction (FVF) to the impact properties of a sample. With increasing value of FVF, the sample impact properties improve. Through calculation, a change from 15% FVF Polyester + Carbon + Kevlar composite to

30% FVF yields an increase value of 26.762% while a change from 30% to 45% FVF yields and increase value of 25.311%.

From the first diagram of *Figure 4* also it can be seen that the combination of Glass and Kevlar fibers possess the highest impact properties. It can be concluded that Carbon possesses the lowest impact property when compared among these 3 fiber reinforcement used. It is proven by calculation, taking 45% FVF of Epoxy hybrid composite into consideration, a change from Glass + Carbon reinforcement combination to Glass + Kevlar combination yields to an increase of impact properties to 28.706%. Changing from Carbon + Kevlar combination to Glass + Kevlar meanwhile results in an increase of impact properties to 27.0398%. In this example both of the Kevlar fractions are near in values with 25.8% FVF in the Glass combination and 29.27% FVF in the Carbon combination.

Kevlar on the other hand possess the highest impact properties. This can be clearly seen by calculation where a comparison is made between 45% FVF Epoxy + Glass + Carbon and Epoxy + Carbon + Kevlar. The presence of Kevlar increases the impact properties to 29.43%. This comparison is feasible as for the Carbon reinforced hybrid composite, both Kevlar and Glass have the majority of volume fraction.

c. Tensile Test

Referring to *Figure 5*, both of the diagrams shown are the visual representative of the results gathered from the tensile testing process. From the second diagram, it is shown that the FVF is directly proportional to the tensile properties of a sample. An increase of the Fiber Volume Fraction will increase the value of the tensile properties of a sample. Taking Polyester + Glass + Kevlar hybrid composite for instance, going to 30% FVF from 15%FVF increase the properties by 43.99% while changing from 30% FVF to 45%FVF increase the properties by 21.53%

From the first diagram of *Figure 5*, glass fibers are identified to possess the lowest quality of tensile property. This statement can be derived since the combination of Carbon and Kevlar reinforcement possesses the greatest tensile properties. Taking the 30% FVF Polyester hybrid composite for instance, changing from Glass + Kevlar combination to Carbon + Kevlar yields an increase of tensile properties to 46.5567% while changing from Glass + Carbon combination to Carbon + Kevlar results in an increase of tensile properties by 54.1836%.

Carbon fibers on the other hand possess the highest tensile properties compared to the other 3. For a 30% FVF Polyester hybrid composite, changing from Glass + Kevlar combination to Glass + Carbon combination results in an increase of 5.204%

d. Microstructural Analysis

Figure 6 to 11 shows the fabricated hybrid composite using scanning electron microscope. From the images itself the type of failure for each component can be easily distinguished.

Brittle type of fracture occurs on both the glass fibers and carbon fibers. At the point where the energy concentration point is high, both types of fibers snapped completely leaving a clean fracture point. Figure 6, 7 and 9 shows the mentioned clean fracture point of both materials.

Kevlar fibers meanwhile have ductile type of fracture. Strands of Kevlar fibers are left after impact and tensile test have been done. Some of the Kevlar reinforced fibers didn't even break after testing.

In figure 8, the poor wetting of fibers results in an uneven distribution of matrix material to the fibers. One of the matrix material functions is to protect the reinforcement fibers from environment and with insufficient wetting; the exposed part would definitely make the properties of the sample lower.

In figure 11, the topmost part is noticeably dominated by the matrix material. Segregation occurs during the hand layup technique part where the matrix material cannot went through the fibers and since the matrix itself is less dense than the fiber reinforcements, fibers are brought downwards and concentrated at the lowest part of the hybrid composite.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 CONCLUSION

From the impact testing program, results gathered showed that the impact property of hybrid composite is directly proportional to the fiber volume fraction. An increase in the fiber volume fraction will results in increasing impact properties of hybrid composites. From this study, the presence of Kevlar fiber reinforced hybrid composite will results in higher impact properties compared to the Glass and Carbon fiber reinforcement combination.

From the tensile testing program, results gathered showed that the tensile strength and tensile modulus of composites is dependent on the fiber volume fraction (FVF). Increasing the fiber volume fractions showed a significant increase in the tensile properties. From this study, it is found that Carbon fiber reinforced hybrid composite possess higher tensile properties.

Glass fibers can be considered to have good tensile and impact characteristic. Carbon fibers meanwhile possess excellent tensile properties but poor impact properties. Kevlar fibers or Aramid49 on the other hand have good tensile properties and excellent impact properties.

Combination of the fiber reinforcement is related to the hybrid composite characteristic. For Glass and Carbon fiber reinforcement combination, the carbon can produce a high tensile strength and stiffness. It also reduces the composite's density and the Glass fibers works as a cost reducer.

Glass and Kevlar fiber reinforcement combination yields a good high impact resistance and tensile strength with Kevlar fibers while the Glass fibers contributes the good compressive and tensile strength characteristic aside from its low cost.

The Carbon and Kevlar fiber reinforcement combination produces composite with high impact resistance and tensile strength of Kevlar fibers. Carbon fibers contribute the high compressive and tensile strength. Although both of the fibers are relatively low in density, the cost itself is relatively high.

The limitation faced during this study is to fabricate hybrid composite with FVF more than 45%. The matrix material is insufficient to cover the reinforcement material. This will lead to deformation characteristic of the fibers itself rather than as a hybrid composite. With increasing fiber volume fraction, more pressure is needed to ensure proper wetting of resin into fibers.

Through series of experiment on production of glass composite, the operating temperature of 80°C produces the best surface finish.

5.2 RECOMMENDATION

It is appropriate to have more samples for each hybrid composite developed with compression molding to obtain a more accurate data. This can be done by having a much larger mould or by having more materials so that repetitive production can be done.

When dealing with reinforcement fibers, they are proven to be hazardous to one's health. Thus proper personal protective equipment such as rubber gloves and face mask are important to personnel handling the material. MEKP, the polyester hardener is highly flammable thus proper and extreme care is required when handling this material.

Since the epoxy matrix material is not properly stored by previous users, there are some cases of contamination which the author believes affects the properties of the developed hybrid composite. Thus it is important for students to store back the matrix material property for future usage.

Entrapped airs are one of the factors contributing in voids and porosity of the developed hybrid composite. Bubbles are observed by author to form during the mixing process of matrix material and its hardener. It is not recommended to mix both of the materials in a quick manner as more bubbles could form with increasing speed.

As for the testing part, both of the tensile and impact machine would require additional training program as students cannot often rely on the technicians. There are also various types of testing method other than the impact and tensile testing such as the flexural testing, 3 point bending etc. Through this various type of testing, a more complete mechanical properties data can be obtained.

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APPENDIX

GRAFIL INC.

GRAFIL 34-600

Grafil 34-600 carbon fiber is a continuous, high strength, PAN based fiber. It is available in 48K filament count tows and can be supplied in either round tow or flat tow formats. The flat tow (designated by 'WD') is the ideal fiber to use in applications where spreading is required, e.g., tape production. The round tow is used in applications where spreading is not necessarily required, e.g., braiding and weaving.

Typical Fiber Properties

Tow Tensile	Strength	650 4500	ksi MPa	SRM 16
	Modulus	34 234	msi GPa	
Typical Density		0.065 1.80	lb/in^3 g/cm^3	SRM 15
Typical Yield	48K	155 3200	yds/lb mg/m	SRM 13

Typical Mechanical Properties

Tensile Properties	0°	Strength	308	ksi	ASTM D3039 / 0°10ply
		Modulus	19.89	msi	ASTM D3039 / 0°10ply
	90°	Strength	10.00	ksi	ASTM D3039 / 0°16ply
		Modulus	1.35	msi	ASTM D3039 / 0°16ply
Compressive Properties	0°	Strength	163	ksi	ASTM D3410 / 0°10ply
		Modulus	18.29	msi	ASTM D3410 / 0°10ply
	90°	Strength	168	ksi	ASTM D3410 / 0°20ply
		Modulus	17.51	msi	ASTM D3410 / 0°20ply
Flexural Properties	0°	Strength	272	ksi	ASTM D790 / 0°10ply, L/D=32, Vf=61%
		Modulus	18.30	msi	ASTM D790 / 0°10ply, L/D=32, Vf=61%
	90°	Strength	16.93	ksi	ASTM D790 / 0°10ply, L/D=16, Vf=61%
		Modulus	1.25	msi	ASTM D790 / 0°10ply, L/D=16, Vf=61%
ILSS		Strength	13.15	ksi	ASTM D2344 / 0°10ply, L/D=4, Vf=59%

- 250F Epoxy Prepregs
- Resin: Newport 301 resin system
- Tensile and compressive properties are normalized to 60% fiber volume

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A Comparison of Mechanical Properties of Natural Fiber Filled Biodegradable and Polyolefin Polymers

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ABSTRACT: A great value is nowadays being given to light-weight structures and durable light-weight materials and composites. In this respect, fiber reinforced plastics (FRP) are given more importance and are becoming one of the most distinguishing material categories next to metals. This research provides some results of mechanical properties of natural fiber reinforced polyolefins (PP, PE) in comparison to some biodegradable polymers, combined without any bonding enhancements, such as bonding agents or surface modifications. It is for this reason that the composites in this study do not show significant improvement in the mechanical properties of polymers; however they can be used as reference values for the mere natural fiber reinforcement. A comparison of polyolefins and biodegradable polymers shows that some biodegradable polymers eventually provide higher mechanical properties, mainly depending on the initial properties of the neat material.

KEY WORDS: natural fibers, flax, hemp, biodegradable polymers, biocomposites.

INTRODUCTION

NATURAL FIBER REINFORCED composites (NFRC) are finding much interest as a substitute for glass or carbon reinforced polymer composites. Several advantages are in favor of natural fibers if compared with other synthetic fibers, glass, or carbon fibers. Natural fibers sequester CO_2 from the atmosphere, hence providing an advantageous contribution to the global carbon budget. The easy disposal of natural fiber composites is also important, since they can be easily combusted or composted at the end of their product life cycle. Next to the cost benefits compared to glass fibers, natural fibers offer comparably high security if used for automotive applications as an example [1].

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Figures 3–10 appear in color online: http://jcm.sagepub.com

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The alteration of the reinforcement fiber next to the matrix system provides an extremely wide scope for the creation of tailored composite materials, according to the desired material requirements [1,2]. In this study, the most commonly used thermoplastic polymer materials have been used as an embedding floor for different natural fibers, such as hemp and flax, hence providing a base for a natural fiber composite database. It must be noted that the fiber matrix bonding in this study is based on the inherited properties of the polymer and fiber and that there has been no treatment of any kind for the improvement of the fiber–matrix interface.

Next to the flame retardant PP (Polyflam RPP 500D – Schulmann) and PE (PE-LD R700 – Dow Plastics), three different biopolymers have been used as a polymeric matrix for the natural fibers. Such polymers are defined as a group of polymeric materials that is able to degrade – under certain humidity and temperature conditions and under the attack of microorganisms as bacteria, fungi, or algae – into natural components such as H_2O, CO_2, or biological mass [3]. Here, it is important to differentiate between 'biopolymers' and 'biodegradable polymers.' On the one hand, biopolymers are of natural origin, such as from plants or animals, whereas the term 'biodegradable' does not imply that the material is developed on a natural basis, but only describe the fact that they degrade upon biological activities that lead to a change in the chemical structure of the polymer and the creation of metabolites. In this study, biodegradable polymers have been used on a natural basis: Bioceta® (on the basis of cellulose acetate), Biomer® PHB 226 (on the basis of thermoplastic polyester built of 3-hydroxy butyric acid) and Biomer® L9000 (based on thermoplastic polyester of 2-hydroxy lactate known as lactic acid) [4,5].

The tensile, flexural, and impact properties of the various fiber reinforced polymers were determined in a range of fiber contents. Although, throughout this article, reference is made to hemp and flax as fibers, it should be noted that these were fiber bundles rather than ultimates.

EXPERIMENTAL

Fiber Preparation

In the present study, flax and hemp have been applied for the reinforcement of the polymer matrix. The applied hemp fibers in this work were derived from German cultivation, which is slightly retted and further roughly decomposed by mechanical means. The applied flax fibers were left to rot on the field for about 4 weeks. The continuous alternation between wet and dry environmental conditions activates a biological decomposition process that attacks the bond between fiber and plant residues. This allows for a clean decomposition of the fibrous material, which is then processed through a rocker resulting in a separation of fibers of different lengths, which are then again combed into cards. Figures 1 and 2 illustrate the SEM (scanning electron microscopy) micrograph of the mechanically prepared flax and hemp fibers. A close look at the flax fibers allows us to see that the fiber surface is very smooth with only very few bonded deposits on top. Similarly, a micrograph onto the hemp fiber topography in Figure 2 allows the view of denser residue deposits on a relatively rough surface area of the fibers.

Fiber dimensions applied in this study are given in Table 1.

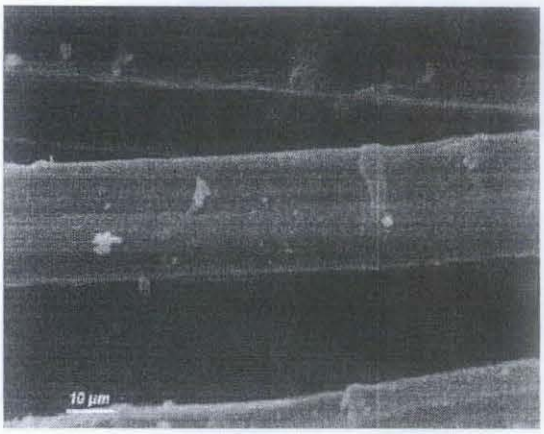

Figure 1. *SEM micrograph of mechanically prepared flax fibers.*

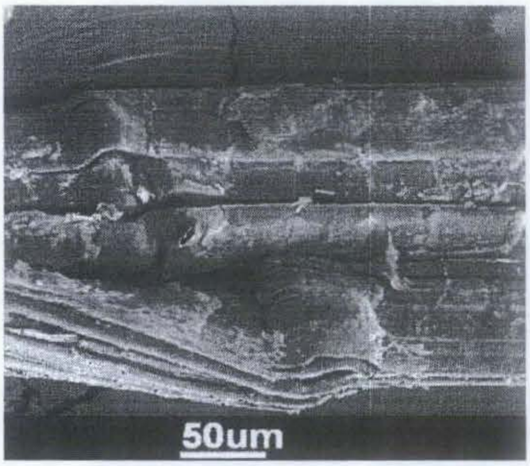

Figure 2. *SEM micrograph of mechanically prepared hemp fibers.*

Table 1. Dimensions of flax and hemp fibers as applied in this study.

	Fineness (ktex)	Average length (mm)	Average diameter (µm)	
			Longitudinal direction	Cross direction
Flax	25	79	35.44	21.23
Hemp	31	130	69.49	40.36

Composite Manufacture

As mentioned above, the raw materials within the scope of this study were processed without any additional bonding materials or coupling agents. The composite materials were first compounded by means of a twin extruder (Berstorff ZE 25Ax40D-UTS-UG) resulting in a homogenized composite. In accordance to Lampke [6], the gravimetric metering of the fibrous bands was well applicable. The fibers (≈20, 40, and 60%)

were introduced into the extruder in parallel with the polymer granules (polymer feeding 10 kg/h). Further, fiber feeding was attained independently through a screw rotation of 200 rpm. Composite strands were extruded at temperatures of about 190–230°C and were then immersed into a water basin for cooling. After oven drying at temperatures of about 80°C for 24 h, the strands were shredded and further processed via injection molding. Here, general parameters for the processing of common polymer materials were applied under consideration of the maximum endurance temperature of natural fibers (230°C); injection pressures used lie within the range of 800 bar and dwell pressures of about 500 bar. Table 2 provides an overview of the applied manufacturing conditions.

The manufactured samples were tested for tensile, flexural, and impact properties.

Mechanical Testing

Tensile tests of the composites were performed on a universal testing machine of the model Zwick Z100/TL3A according to the DIN EN ISO 527-1, 69-04, and 97-07. The tests were performed using a load cell of 100 kN with a gauge length of 60 mm and a crosshead speed of 2 mm/min. For each test batch, seven dumbbell-shaped specimens were injection molded under the above described parameters. The tensile strength (σ), tensile modulus (E), and strain to failure (ε) were determined.

The flexural properties were determined according to the DIN EN ISO 178, 97-02. Samples of $80 \times 10 \times 4\,\text{mm}^3$ (length × width × thickness) dimensions were cut from the injected parts. The sample edges were filed to remove small cracks. The support span for the bending tests was $(16 \pm 1)h$ mm, where h is the sample thickness, and the diameter of the loading nose was 5 mm. Tests were conducted using a crosshead speed of 10 mm/min. A low load cell of 2 kN was used to ensure accuracy. The load deflection curve was recorded until failure and the means of seven samples was used for calculating the bending strength and bending modulus.

Impact tests were performed according to EN ISO 179. Test specimens (10 replicates, $80 \times 10 \times 4\,\text{mm}^3$) were tested on a WOLPERT machine impact pendulum tester at a velocity of impact 3.8 m/s and 160° swing angle using a 15-J hammer. The charpy impact strength was calculated according to

$$\sigma_{\text{impact}} = \left(\frac{A}{bt}\right) \times 10^3 \qquad (1)$$

where A is the impact energy (J), b is the specimen width (mm), and t is the specimen thickness (mm).

Table 2. Composite manufacturing conditions.

Extruder polymer feeding	10 kg/h
Extruder screw rotational speed	200 rpm
Extruding temperatures	190–230°C
Injection pressure	800 bar
Injection dwell pressure	500 bar
Injection temperatures	230°C

Scanning Electron Microscopy (SEM)

The samples were mounted onto holders using double-sided electrically conducting carbon adhesive tabs. The specimens were coated with gold using a Cressington sputter coater at a voltage of 20 mA for 100 s and the samples were observed with a SC44 Camscan SEM.

RESULTS AND DISCUSSION

The following results and discussion are based on the nomenclature shown in Table 3.

Tensile Properties

The effect of fiber reinforcement on the tensile properties of composites was determined for a range of fiber contents from 0 to 40 and 60% (by volume) for biopolymers and polyolefins, respectively. The results illustrated in Figure 3 present the results obtained for the flax and hemp reinforced PP compared to Bioceta. The results show that an increase in fiber volume fraction does increase the tensile strength, though this improvement is only marginal. Furthermore, it can be noted that a maximum improvement could be attained at a fiber content of approximately 25 vol%, where after the tensile strength starts to decrease again. This behavior was often reported for randomly oriented natural fiber composites. However, with unidirectional FRC, a linear relationship between the fiber content and the matrix content could be observed, although there is a tendency to decrease at very high fiber loadings [7]. This decrease is mainly associated to the likelihood of fiber–fiber contact at high percentages, leading to a poor load transmission between the fibers. Moreover, high fiber contents also imply resin starved areas which lead to a generally insufficient fiber–matrix adhesion for stress transfer.

The adhesion between fiber and polymeric matrix primarily depends on the compatibility of the fibers with the hydrophobic polymer. Better contact between the fiber and the polymeric matrix is basically enhanced through a hydrophobic fiber surface, a property which is not provided by the untreated fibers used in this study. Furthermore, the insufficient wettability of the polar natural fiber through the unpolar polyolefin

Table 3. Nomenclature of the composites under investigation.

Notation	Description
HPP	Hemp fibers + PP
FPP	Flax fibers + PP
HPE	Hemp fibers + PE
FPE	Flax fibers + PE
HBioceta	Hemp fibers + Bioceta
FBioceta	Flax fibers + Bioceta
H-L9000	Hemp fibers + Biomer L9000
F-L9000	Flax fibers + Biomer L9000
H-P226	Hemp fibers + Biomer P226
F-P226	Flax fibers + Biomer P226

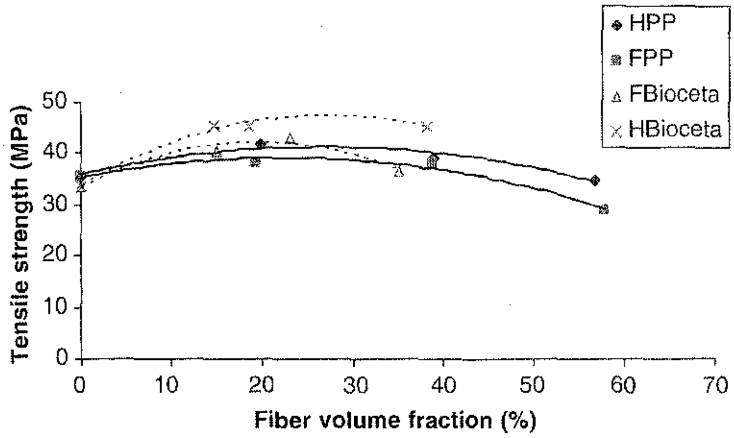

Figure 3. The variation of the tensile strength with the fiber content for polypropylene and Bioceta matrix composites reinforced with flax and hemp. H, hemp; F, flax.

Table 4. Comparison of the effect different fiber–matrix combinations on the tensile properties at a fiber volume fraction of 20%.

	Flax			Hemp		
	E (MPa)	σ (MPa)	ε (%)	*E* (MPa)	σ (MPa)	ε (%)
PP	3630	38.2	3.58	2862	41.9	5.98
PE	1639	15.3	3.72	2094	21.2	3.03
Bioceta (CA)	4230	43.1	5.37	4452	45.4	5.29
Biomer P226 (PHB)	3621	22.9	4.63	2421	21.4	4.20
Biomer L9000 (PLA)	6197	64.4	6.21	6750	71	5.81

is a very problematic matter concerning the proper adhesion between the two [6]. This effect becomes obvious through the results indicated in Figure 3; the natural fiber reinforcement of the relatively polar biopolymeric materials resulted in higher tensile strength compared to the identical reinforcement of the unpolar PP.

The tensile properties of the flax and hemp fiber reinforced polyolefins and biopolymers are further presented in Table 4. The properties of the unreinforced polymer thermoplastics are listed for comparison in Table 5. It is apparent that the highest tensile properties are achieved in the case of using the PLA matrix, however, it should be noted that the unreinforced polymer initially provides such high values. In this case, the effect of reinforcement is minor if compared to its effect upon the other polymer matrices or originally low tensile properties. Generally, properties of Bioceta and flax were reported by George et al. [8]. Peijs et al. [9] found that adhesion of flax fibers to a PHB matrix offers the possibility of obtaining cheap products together for improved toughness.

In some cases, especially in case of biopolymeric matrices, the relationship between tensile strength and fiber content is slightly different from the above described behavior. Figure 4 illustrates such behavior for flax reinforced Biomer® L9000, where a reduction of strength at the beginning of the fiber loading occurs. A surpass of the unreinforced matrix does not take place up to the investigated fiber content of 40vol%. This behavior was reported previously for randomly oriented natural fiber reinforced composites [9–11].

Table 5. Properties of the unreinforced polymer matrices.

	Tensile properties			Flexural properties		Impact properties (kJ/m^2)
	σ (MPa)	*E* (MPa)	ε (%)	σ (MPa)	*E* (MPa)	
PP	35.6	1747	28.17	43.6	1320	2.45
PE	8.1	116.7	181.52	6.8	101.2	2.11
Bioceta (CA)	33.5	2044	18.17	60.1	2059	5.3
Biomer P226 (PHB)	22.7	1331	19.67	39.8	1359	5.6
Biomer L9000 (PLA)	67.3	3710	6.62	126.7	3960	2.6

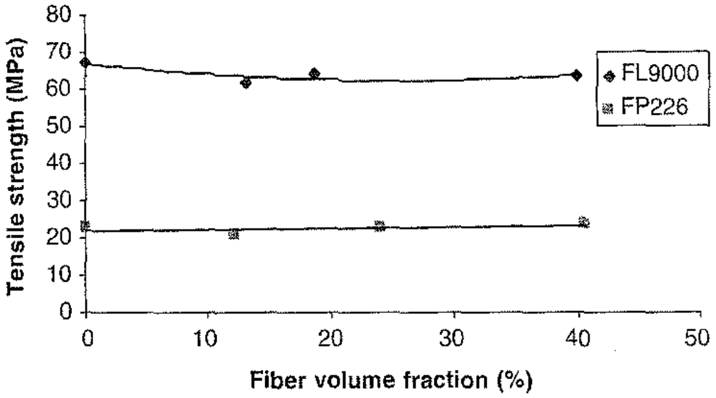

Figure 4. The variation of the tensile strength with the fiber content for flax fiber reinforced PLA (Biomer® L9000) and P226 (Biomer).

At the lowest fiber contents, it is possible that the presence of voids at the fiber–matrix interface may be responsible for this reduction in tensile strength, which may be induced by a poor polymer melt flow around the fiber intersections. This in turn is primarily dependent on the fiber surface properties, which provides better contact to the matrix the more hydrophobic the surface is [7]. This behavior can be seen in Table 4 in case of FL9000.

The effect of fiber reinforcement on the tensile modulus of flax and hemp reinforced Bioceta and PP are presented in Figure 5. Also here the superior behavior of the fiber reinforced Bioceta becomes apparent. Compared with tensile strength, the tensile modulus does not show a reduction at higher fiber loads, an observation that may lead to the conclusion that this property does not depend on the fiber–matrix interface properties, but more likely on the absolute fiber content, as the elastic modulus is determined as a secant-modulus ($\Delta\varepsilon = \varepsilon_{0.25} - \varepsilon_{0.05}$) at low strength/strain loading conditions.

The relationship between the elongation at break and the fiber content is illustrated in Figure 6. The elongation at break of the composites decreases with increasing fiber content. In this case, the elongation witnesses a rapid fall up to an asymptote at around 20% fiber volume fraction. This behavior was observed for all fiber–matrix combinations, although the rate in reduction of the elongation at break varied from case to case, depending on the polymeric matrix. According to Figure 6, the decrease in the elongation at break for Bioceta matrix is not as dramatic as in case of a PP matrix due to the basic difference in polymer deformation behavior. A tentative conjecture for this behavior might be the fact that when fibers are introduced to a matrix, defects are likely to

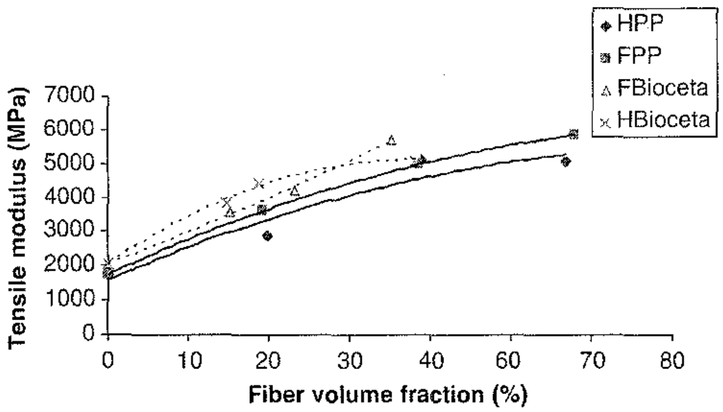

Figure 5. The variation of the tensile modulus with the fiber content for polypropylene and Bioceta matrix composites reinforced with flax and hemp.

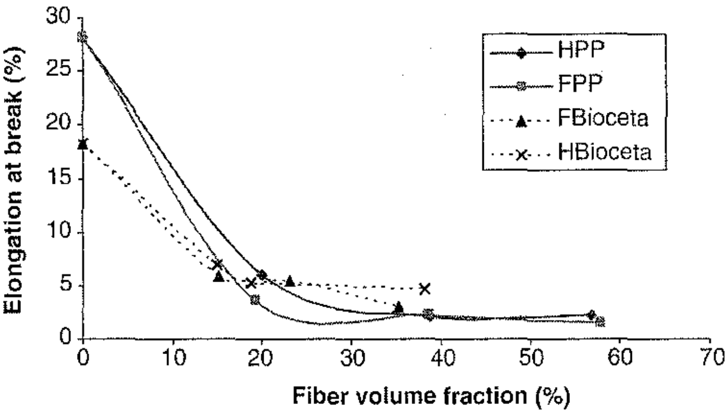

Figure 6. The variation of the elongation at break with the fiber content for polypropylene and Bioceta matrix composites reinforced with flax and hemp.

occur at the fiber–matrix interface, resulting in stress-concentrated areas and hence accelerated failure of composites. This explanation is supported by the more dramatic decrease in FPP and HPP composites, since the compatibility between these fibers and the PP matrix is even worse than in the case of Bioceta.

Bending Properties

The relationship between the bending strength and the fiber content is shown in Figure 7. Similar to the tensile strength, the bending strength also witnesses a slight increase at higher volume fractions up to a certain limit such that at the highest fiber loading a small decrease in the bending strength occurs.

In some cases, such as in case of the flax fiber reinforced Biomer® L9000 a decrease in bending strength is observed when fibers are present in the matrix, as can be seen in Figure 8. This relation is particularly severe at the low fiber contents. In this case, there is no fiber content at which the bending strength exceeds that of the unreinforced resin.

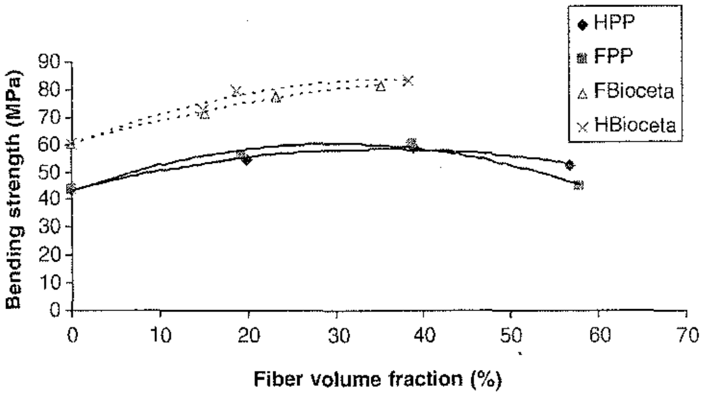

Figure 7. The variation of the bending strength with the fiber content for polypropylene and Bioceta matrix composites reinforced with flax and hemp.

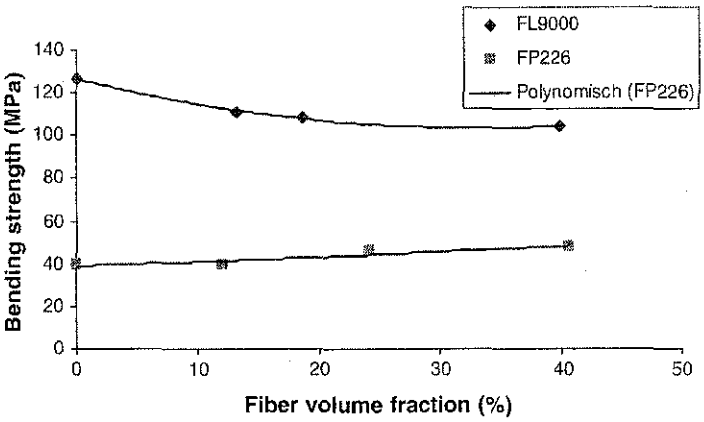

Figure 8. The variation of the bending strength with the fiber content for flax fiber reinforced PLA (Biomer® L9000) and P226 (Biomer).

In this case, the randomly distributed fibers are acting more or less as separators within the matrix, such that there is little effective load transfer between the separated regions of the polymer. Such behavior has been reported by a number of studies [7,10,11].

The relationship between the flexural modulus (Figure 9) and fiber content is very similar to that of the tensile modulus. Similar to the bending strength, the flexural modulus values obtained for the natural fiber reinforced Bioceta exceed those obtained for PP. This is enhanced by the improved mechanical properties of the neat Bioceta compared to PP. However, in both cases the relation is nearly linear, such that an increase of fiber content is always associated with an increase in the flexural modulus, which also alludes to the conjecture that fiber reinforcement does not affect this property.

The application of other polyolefins and biopolymers in conjunction with flax and hemp leads to the results indicated in Table 6.

Impact Properties

The relationship between fiber content and impact strength is very different in a comparison between Bioceta® and PP, as illustrated in Figure 10. It becomes

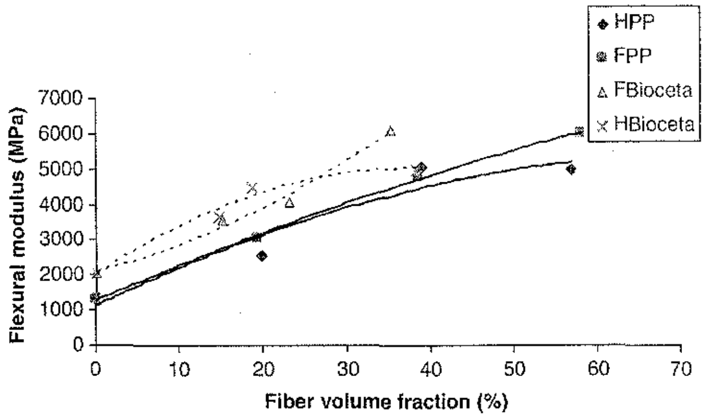

Figure 9. The variation of the flexural modulus with the fiber content for polypropylene and Bioceta matrix composites reinforced with flax and hemp.

Table 6. Comparison of the effect of different fiber–matrix combinations on the bending properties at a fiber volume fraction of 20%.

	Flax		Hemp	
	σ_f (MPa)	E_f (MPa)	σ_f (MPa)	E_f (MPa)
PP	56.53	3070	54.7	2577
PE	21.4	1248	25.2	1431
Bioceta (CA)	77.3	4078	80	4465
Biomer P226 (PHB)	46.1	3988	45.8	3665
Biomer L9000 (PLA)	108.9	5968	125.5	6389

Table 7. Comparison of the effect of different fiber–matrix combinations on the impact properties at a fiber volume fraction of 20%.

	Impact strength (kJ/m^2)	
	Flax	Hemp
PP	6.14	6.49
PE	12.25	16.2
Bioceta (CA)	5.1	4.6
Biomer P226 (PHB)	9	7.2
Biomer L9000 (PLA)	3.6	3.9

very apparent that while a fiber reinforcement of PP causes a clear increase in impact strength, the identical reinforcement brings the impact properties to a fall in case of the biopolymeric CA, although this behavior could not be observed with the other biopolymeric matrices as presented in Table 7 (compare with unreinforced polymer properties in Table 5).

The impact strength of a composite in a random oriented short fiber structure composite depends on several factors such as the toughness of the matrix and reinforcement, the nature of the interface, and the frictional work involved in pulling out the fibers from

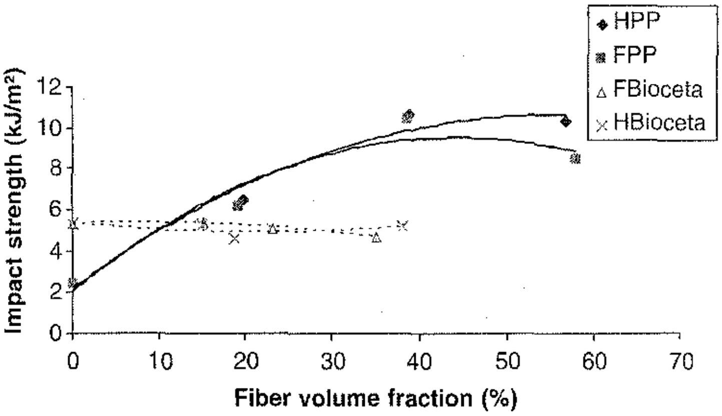

Figure 10. The variation of the impact strength with the fiber content for polypropylene and Bioceta matrix composites reinforced with flax and hemp.

the matrix [7]. Hence, only a general trend can be seen from Table 7: biopolymers seem to have lower impact properties compared to the polyolefins PP and PP, but on comparison with flax and hemp, no statement can be made concerning better fiber influence on impact behavior. According to the Cook–Gordon theory, the presence of a weak fiber–matrix interface is able to account for a tough composite. The opening up of a new surface at the interface results in the absorption of energy, diversion of cracks, etc. [7]. This implies that a strong interfacial bond allows for efficient stress transfer but produces a composite of poor toughness. Bearing the tensile properties of fiber reinforced PP and Bioceta® (Figure 3), one can see that the high tensile properties of Bioceta® composites are connected with poor impact properties compared to PP composites.

The SEM micrographs of the fracture surface of these composites at a 20% fiber volume fraction enforce this thesis.

The relatively poor fiber–matrix bonding between flax fibers and PP can be interpreted from Figure 11 through the long fiber ends penetrating out of the matrix, which indicates a fiber pull-out, in turn implying a weak bonding. It is in fact this pull out work which absorbs a large amount of energy during impact loading, leading to an increased toughness of the composite. In Figure 12, the stronger bond between flax and Bioceta® is indicated by the short fibers protruding from the matrix. Moreover, the intensity of the bond interface can be seen in terms of the gaps between fiber and surrounding matrix in the SEM micrographs. Hence, the gaps between flax and PP seems to be wider in Figure 11 when compared with the flax/Bioceta® gap in Figure 12.

A further observation is the fact that the flax fibers in case of the Bioceta® matrix seem to be wetted by the polymer compared to the relatively smooth surface of the unwetted fibers in case of the PP matrix. This emphasizes the statement that better fiber wetting was achieved through the more hydrophilic biopolymer.

Furthermore, it becomes obvious from the SEM micrographs that the fiber is brittle in nature and that there is no evidence of the defibrillation of the fiber bundles.

CONCLUSIONS

The reinforcement of thermoplastic polymers (both polyolefins and biodegradable biopolymers) with natural fibers generally results in slight improvements in their

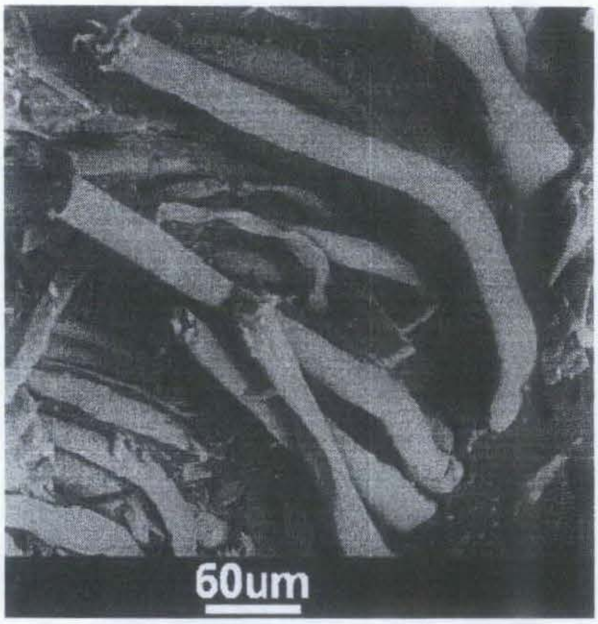

Figure 11. SEM micrograph of the fracture surface of impact testing of flax reinforced PP at a fiber content of 20 vol%.

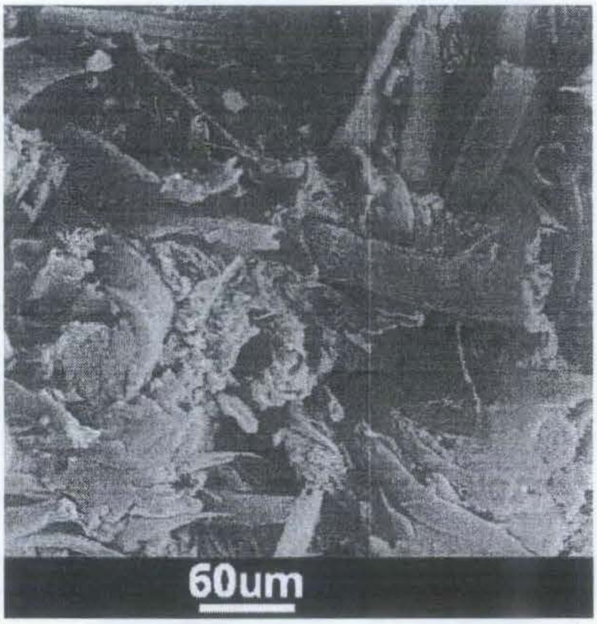

Figure 12. SEM micrograph of the fracture surface of impact testing of flax reinforced Bioceta® at a fiber content of 20 vol%.

mechanical properties. Tensile and flexural properties could be increased by the mere compounding of the natural untreated fiber bundles into the polymeric matrix. It was found that tensile and flexural strength could be increased proportionally to the fiber content up to a certain limit lying at approximately 25% fiber volume fraction, where after the strength starts falling again due to improper fiber–matrix interface as a result of high fiber-to-fiber contact due to high fiber content. On the other hand, the tensile and flexural moduli are continuously increasing with higher fiber loading, which implies that this property is not mainly dependent on the fiber–matrix interface. For certain fiber–biopolymer combinations, the tensile and flexural properties first witness a reduction up to a certain fiber content percentage, after which they start increasing again, hardly reaching the initial values of the unreinforced matrix at 40 vol% fiber content. Furthermore, it was observed that composites of high tensile and bending properties usually performed relatively poor impact behavior. A poor fiber–matrix interface negatively affecting strength properties is on the other hand able to account for a tough composite, since loose fibers in the matrix absorb more impact energy.

Generally, a reinforcement of polymer materials of high elongation at break is highly affected by the low fiber elongations at break resulting in overall low elongation behavior.

A comparison between polyolefins and biopolymers as presented in this study shows the competitiveness of biodegradable materials with the generally used PP and PE, since they provide comparable (Bioceta even higher) tensile strengths. It is due to the relatively more hydrophilic nature of the biopolymers that they result in a better bonding with the hydrophilic natural fibers, leading to improved tensile and bending properties. As discussed above, the higher tensile and bending properties are associated with poor impact properties, due to the stronger fiber–matrix interface.

Finally, it must be noted that the results of this study are those of natural unmodified and highly hydrophilic fibers. Fiber–matrix bonding could be enhanced by several chemical fiber modifications on the one hand, or by the application of coupling agents such as silanes or titanates.

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ntraply and interply hybrid composites based on E-glass and poly(vinyl alcohol) woven fabrics: tensile and impact properties

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Abstract: E-glass and poly(vinyl alcohol) (PVA) fibres were used to produce both homogeneous and hybrid composites with an orthophthalic unsatured polyester resin. Results are presented regarding the tensile and impact behaviour of both intraply and interply hybrid composites, with particular regard to the effects of the plies stacking sequence and the loading direction. With a proper choice of composition and stacking sequence, E-glass/PVA hybrid composites were proved to achieve a property profile superior to those of homogeneous E-glass laminates in terms of specific properties. In particular, hybridization with PVA fibres resulted in improving the specific impact energy of E-glass laminates. Resistance to impact crack propagation was higher for intraply with respect to interply hybrid composites, as evidenced by their ductility index values.

Keywords: mechanical properties; hybrid; glass fibres; poly(vinyl alcohol) fibres

NTRODUCTION

Composites containing two or more different reinforcing materials bound in the same matrix are commonly known as hybrid composites. Hybridization allow designers to tailor the composite properties to the exact needs of the structure under consideration.[1–5] In most cases, the purpose of hybridization is to obtain a new material retaining the advantages of its constituents, and hopefully overcoming some of their disadvantages. Another desired achievement is related to the cost, with one of the two components being generally cheaper than the other one. There are several types of hybrid composites,[4,5] depending on the way the constituent materials are mixed, ie: (i) interply hybrids where layers of the two (or more) homogeneous reinforcements are stacked; (ii) intraply hybrids in which rows of the two (or more) constituent types of fibres are mixed in the same layer; (iii) intimately mixed (intermingled) hybrids where the constituent fibres are mixed as randomly as possible so that no concentrations of either type are present in the material; (iv) selective placement in which reinforcements are placed where additional strength is needed, over the base reinforcing laminate layer; (v) superhybrid composites which are composed of metal foils or metal composite plies stacked in a specified orientation and sequence.

The diversity of the properties and the possible material combinations are too numerous to detail here. As far as polymer matrix composites are concerned, most of the available literature data refer to carbon/glass,[6–12] carbon/Kevlar[12–17] and carbon/ultra-high-modulus-polyethylene (UHMPE) [17–25] fibre-reinforced hybrids, with the main purpose being to improve the energy-absorbing capability of carbon fibres. Other hybrid systems recently investigated are based on carbon/nylon,[17] aramid/UHMPE[17,26,27] and UHMPE/glass[28] biofibre (pineapple leaf, sisal, bamboo fibres)/glass.[29–32] Sometimes, a 'hybrid effect', briefly defined as a positive deviation of a certain property from the 'rule of mixtures', have been reported.[33,34] With respect to the tensile behaviour, the hybrid effect is generally defined as an enhancement of the first failure strain of the low-elongation fibre-reinforced component. In many cases, an improvement in the specific ultimate properties of polymer composites with inorganic brittle reinforcements such as carbon or glass fibres was attempted[14,18–25] by the incorporation of more ductile organic fibres, such as aramid or UHMPE.

Recent developments in the field of high-performance organic fibres have been mainly directed toward the achievement of elevated strength and modulus values via molecular orientation and chain extension of semi-rigid[35] or flexible macromolecules.[36]

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t the same time, however, the transversal properties re reduced, being controlled by the secondary bonds etween the oriented polymer chains, such as hydroen bonding for aramid fibres, or van der Waals onding in the case of UHMPE fibres. In order to vercome this limitation, the techniques of solution gel)-spinning were applied to other, more polar, flexble polymers, such as polyamides, polyacrylonitrile, olyesters, and poly(vinyl alcohol) (PVA), even if the esulting modulus and strength values were rather ow.[37–41] Some interesting results were obtained for VA fibres, with a tensile modulus of up to 70 GPa nd a stress at break of up to 2.3 GPa.[37–40] Although he maximum tensile modulus and strength values are ower than in the case of UHMPE fibres, some advanages with respect to 'off-axis' and the long-term proprties of PVA-based composites were confirmed,[37,38] s expected from the specific intermolecular interacions (ie hydrogen bonds).

The objective of this present study is to evaluate commercially available high-strength PVA fibre s a reinforcing material for applications in hybrid omposites. Results are presented regarding the tensile nd impact mechanical properties of E-glass/PVA ibres intraply and interply hybrid composites, with articular regard to the effects of the plies stacking equence in different loading directions.

XPERIMENTAL

aterials

he fabrics used for composite manufacturing were ealized with the following fibres:

E-glass, type 111AX8 from Owens Corning Fiberlass, USA ($\rho = 2540\,\mathrm{kg\,m^{-3}}$, $E_L = 73.0\,\mathrm{GPa}$, $E_T = 73.0\,\mathrm{GPa}$, $\sigma_b = 2000\,\mathrm{MPa}$, $\varepsilon_b = 4.0\,\%$); poly(vinyl lcohol) (PVA), Vinylon HM1 from Unitika Kasei td, Japan ($\rho = 1270\,\mathrm{kg\,m^{-3}}$, $E_L = 29.0\,\mathrm{GPa}$, $E_T = 5.0\,\mathrm{GPa}$, $\sigma_b = 1400\,\mathrm{MPa}$, $\varepsilon_b = 6.0\,\%$). (In the above, ρ is the density, E_L the longitudinal modulus, E_T he transverse modulus, σ_b the longitudinal tenile strength, and ε_b the longitudinal strain at reak.)

All fabrics were fabricated and provided by Fibre Tessuti Speciali Srl, Turin, Italy (FTS) in the orm of both homogeneous and hybrid plain type abrics. In particular, three different types of fabric were used, namely, a homogeneous E-glass fabric, a omogeneous PVA fabric and a hybrid E-glass/PVA abric. More details about the composition of each fabric are reported in Table 1. An orthophthalic unsatured polyester (UP) resin, Sirester® FS 0995, provided by SIR Industriale Spa (Milan, Italy), was used as a matrix. The initial styrene content was about 39 wt%, methyl ethyl ketone peroxide (about 1.5 wt%) was added as the catalyst, the accelerator was cobalt octoate (about 0.2 wt%), and hydroquinone (about 0.15 wt%) was chosen as the inhibitor. The cured resin showed the following properties: $\rho = 1230\,\mathrm{kg\,m^{-3}}$, $E_L = E_T = 3.5\,\mathrm{GPa}$, $\sigma_b = 65\,\mathrm{MPa}$ and $\varepsilon_b = 2.2\,\%$.

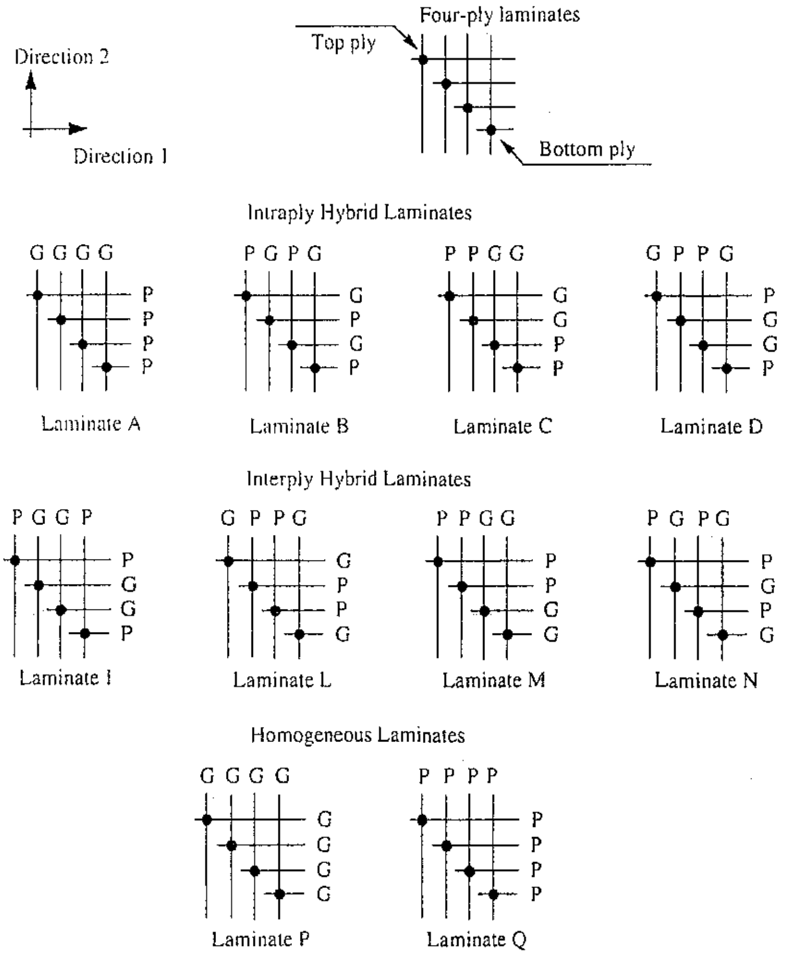
Sample preparation

All composites consisted of four-ply laminates prepared by impregnating each fabric with the mixed UP resin by means of a hand roller. Composites were laminated in order to achieve various stacking sequences, as depicted in Figure 1. In particular, three types of laminates were obtained: (i) intraply hybrids (laminates A, B, C, D) in which both E-glass and PVA fibres are combined in the same layer; (ii) interply hybrids (laminates I, L, M, N) where single layers consist entirely either of E-glass or PVA fibres; (iii) homogeneous (laminates P, Q). With reference to Figure 1, samples are identified with a letter, indicating the laminate type, and a number, indicating the test direction. For example, sample A1 is obtained from laminate type A, with the longitudinal axis directed along direction 1.

The four-ply composites were then degassed for 30 s in a vacuum oven and placed in a stainless-steel mould whose surfaces were previously treated with a release agent. The minimum distance between the upper and lower mould plates was fixed at 2 mm. The mould was then placed between the plates of a hot press and all laminates were cured for 2 h at 50 °C, followed by 2 h at 100 °C under a constant pressure of 0.6 MPa. After shutting off the hot-press heaters, the mould was allowed to slowly cool down to room temperature under pressure before removing the laminate. These curing conditions provided fully cured laminates as confirmed from differential scanning calorimetry analysis. The resulting laminates were in the form of square plates ($200 \times 200\,\mathrm{mm^2}$) whose average thickness was in the range 1.44–1.97 mm depending on the composition (see Table 2). Rectangular specimens were machined from the laminates by using an air-cooled diamond disc saw.

able 1. Composition of the various plain weave fabrics used for composite manufacturing

abric	Mass per unit area (kg m^{-2})	Density (kg m^{-3})	Fibre type		Fibre distribution (vol%)		Fibre yarn linear weight (dTex)		Fibre yarn count (yarn cm^{-1})	
			Warp	Weft	Warp	Weft	Warp	Weft	Warp	Weft
-glass, homogeneous	0.374	2540	E-glass	E-glass	50	50	3200	3200	6	6
VA, homogeneous	0.211	1270	PVA	PVA	68.4	31.6	3600	1800	4	3.7
E-glass/PVA hybrid	0.379	1660	PVA	E-glass	66.1	33.9	3600	3200	5.2	6



igure 1. Schematics of the selected stacking sequences, where each fabric is identified by two perpendicular lines crossing and a point videnced by a black circle. Letters G and P stand for glass and PVA fibres, respectively, while directions 1 and 2 represent the loading directions or the tensile tests.

Table 2. Average thickness, fibre volume fraction, density and void content data for the laminates

		Partial fibre volume fraction along direction 1 (vol%)		Partial fibre volume fraction along direction 2 (vol%)				
Laminate	Thickness (mm)	E-glass	PVA	E-glass	PVA	ρ_{th} (kg m^{-3})	ρ_{exp} (kg m^{-3})	Void content (%)
A	1.87 ± 0.05	0.0	34.5	17.5	0.0	1480	1470	0.68
B	1.88 ± 0.01	8.5	16.5	8.5	16.5	1460	1450	0.68
C	1.97 ± 0.03	8.5	15.5	8.5	15.5	1460	1450	0.34
D	1.83 ± 0.06	8.5	16.5	8.5	16.5	1470	1460	0.68
	1.60 ± 0.07	9.5	14.5	9.5	6.5	1490	1480	0.34
L	1.44 ± 0.11	10.0	15.0	10.0	7.0	1500	1490	0.67
M	1.67 ± 0.03	9.0	14.0	9.0	6.0	1480	1470	0.68
N	1.58 ± 0.08	9.5	15.0	9.5	7.0	1500	1480	1.00
P	1.60 ± 0.03	20.0	0.0	20.0	0.0	1750	1730	1.14
Q	1.58 ± 0.06	0.0	30.0	0.0	14.0	1250	1250	0.00

Fibre fraction and void content measurements

The fibre content data reported in Table 2 were obtained in the following ways: (i) the fibre weight fraction (W_f) of the composites was estimated by multiplying the mass per unit area of each inserted fabric by the measured external area of the specimen and rating the obtained value to the overall weight of the specimens; (ii) the fibre volume fraction (V_f) was then obtained by considering the fibre and matrix densities reported above.

The void content of the composites was calculated according to the following equation (ASTM Standard D2734):

$$V = 100\frac{(\rho_{th} - \rho_{exp})}{\rho_{th}} \qquad (1)$$

where V is the void content (vol%), ρ_{th} the theoretical density of the composite, and ρ_{exp} the experimental value of the density measured for the composite. The eoretical densities of the composites was estimated y using the following expression:[12]

$$\rho_{\mathrm{th}} = \frac{1}{\dfrac{(1 - W_f)}{\rho_m} + \dfrac{W_f}{\rho_f}} \tag{2}$$

here ρ_m and ρ_f are the densities of the matrix d fibre, respectively. The experimental densities the pure matrix and the composite specimens ere measured in water at 20 °C by the displacement ethod, following ASTM Standard D 792.

echanical tests

onotonic uniaxial tensile tests were performed y following the specifications of ASTM Standard 3039 on rectangular specimens with an overall ngth of 100 mm and a width of 10 mm, along the ading directions 1 and 2 shown in Figure 1. The istance between the grips was fixed at 60 mm and all mples were tested by using an Instron 4502 tensile ster equipped with a 10 kN load cell. All tensile easurements were performed at room temperature, a cross-head speed of 5 mm min^{-1} on at least ve specimens. In any case, the load–displacement w data were corrected by taking into account the achine compliance, separately evaluated under the me testing configuration and conditions.

The impact behaviour was evaluated by a Charpy strumented pendulum (CEAST model 6549) on ctangular specimens (10 mm wide and 100 mm ng), with the span length fixed at 43 mm. Specimens ere supported via a horizontal simple beam to the achine anvils and broken by a single swing of the endulum, with the impact line midway between the upports. The striking nose of the pendulum was haracterized by an included angle of 45° and the p was rounded to a radius of 3.17 mm. All impact ests were performed under the following experimental onditions: hammer weight, 2.5 kg; striking speed, .513 m s^{-1}; data acquisition time, 64 ms; sampling ime, 32 µs. At least six specimens were utilized or each experimental condition, and non-symmetric minates were tested on both sides.

ESULTS AND DISCUSSION

easurements of density were carried out in order o estimate the void content in the composites; the xperimental data (ρ_{th}) were then compared with he theoretical values of density (ρ_{exp}), calculated s described in the above experimental section. As videnced in Table 2, from comparison of ρ_{exp} and ρ_{th}, t clearly appears that the hand lay-up manufacturing rocess leads to a satisfactory impregnation level of he fabrics and consequently results in being effective n producing composites with a low void content in most cases, lower than 1 %). The void content f a composite may significantly affect some of its echanical properties: in fact, a good composite should have less than 1 % voids, whereas a poorly made composite can have up to 5 % void content.[12]

Tensile behaviour

Typical stress–strain curves, obtained for homogeneous composites and the pure matrix, reported in Figure 2, are characterized by a monotonic load increase up to rupture. The PVA fabric homogeneous samples (Q1 and Q2) show a pronounced 'knee', located between 0.5 and 1.0 % strain, which is associated with the peculiar yielding behaviour of the PVA fibres used for composite manufacture, as confirmed by tensile tests performed on single PVA fibres.[41] The stress–strain slope change displayed by the E-glass homogeneous sample (P1), at a strain level of about 2.0 % (which is also detectable in the Q1 sample), could be probably related to the occurrence of matrix damage, as can be hypothesized on the basis of the pure matrix stress–strain curve also reported in Figure 2. The characteristic stress–strain curves of hybrid intraply composites are reported in Figures 3a and 3b, where it can be seen how the stress–strain behaviour is strongly affected by the stacking sequence. As schematically illustrated in Figure 1, laminate type A contains only PVA fibres oriented along direction 1 and E-glass fibres along direction 2. As a consequence, the stress–strain behaviours of samples A1 and A2 (see Figure 3a) reflect those of the corresponding homogeneous composites, thus providing evidence that the presence of fibres of a different nature in the transversal direction does not substantially affects the tensile behaviour, besides the fact that a slightly higher elongation at break is observed for the hybrid composites. Intraply hybrid composites, in which both E-glass and PVA fibres are simultaneously present along the loading direction (ie laminates B, C, and D), show a more complex tensile behaviour, as characterized by a progressive failure of the various plies. In particular, for sample B2 (see Figure 3a), where PVA and E-glass fibres are alternatively stacked along the same loading direction, four following load drops can be detected: the first load drop is associated

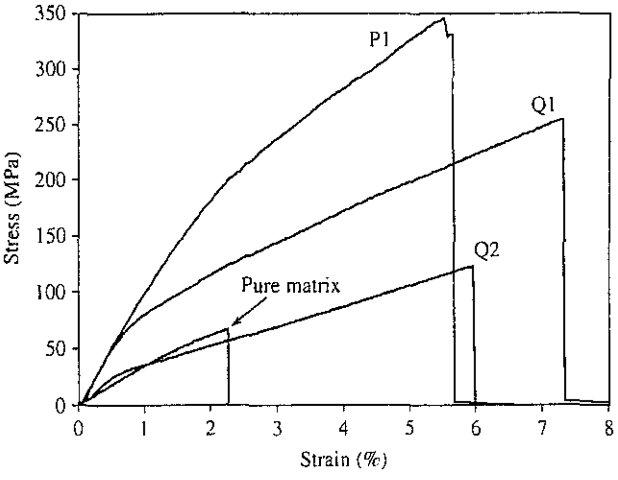
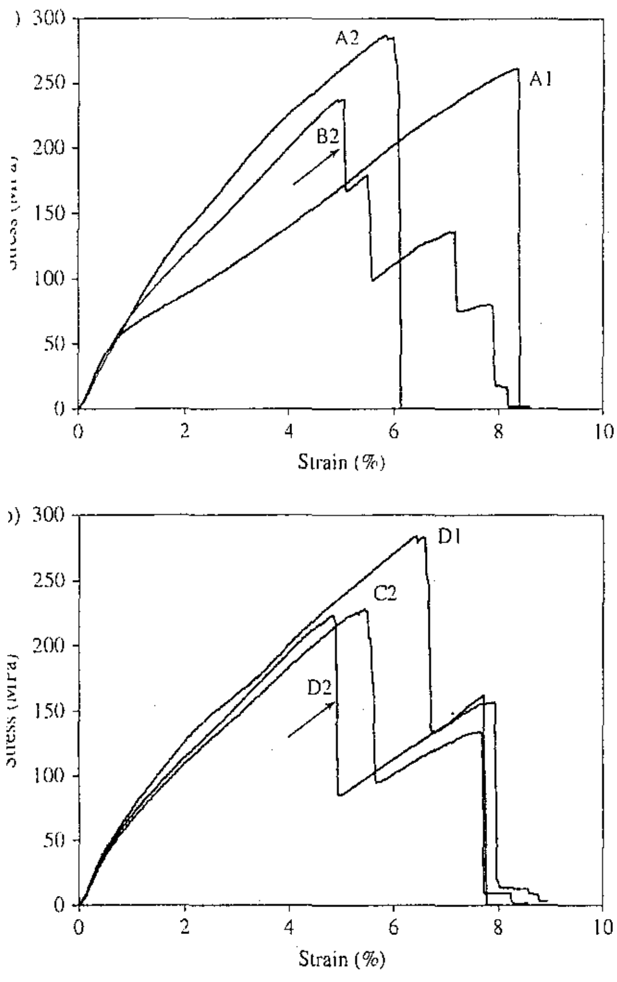


Figure 2. Stress–strain curves obtained for the homogeneous laminates (samples P1, Q1 and Q2) and the pure matrix.



igure 3. Stress–strain curves obtained for the intraply hybrid minates: (a) samples A1, A2 and B2; (b) samples C2, D1 and D2.

o the failure of the external E-glass layer, the second ne corresponds to the failure of the internal E-glass ayer, the third one indicates failure of the external VA layer, and the last load drop corresponds to the ailure of the internal PVA layer. The lower strain at reak of the external layers with respect to the internal nes is probably due to the higher probability of critcal defects on the external surfaces, due to handling nd sample machining, and to a more complex state f thermal stresses related to the presence of a free urface. Due to the different stacking sequence, for amples C2, D1 and D2, only two load drops can e observed, with the first one being related to the E-glass layers and the second one due to the PVA layers failure. For laminate D, it is interesting to observe hat along direction 1 the first load drop occurs at igh strain levels with respect to direction 2. This ehaviour could probably be explained by considering that along direction 1 both of the E-glass layers are internal and consequently fail at high strain levels, with respect to direction 2, where both E-glass layers are located externally. In general, a somewhat better behaviour is evidenced by the symmetric laminates (A and D) with respect to the non-symmetric laminates (B and C), probably due to residual thermal stresses.

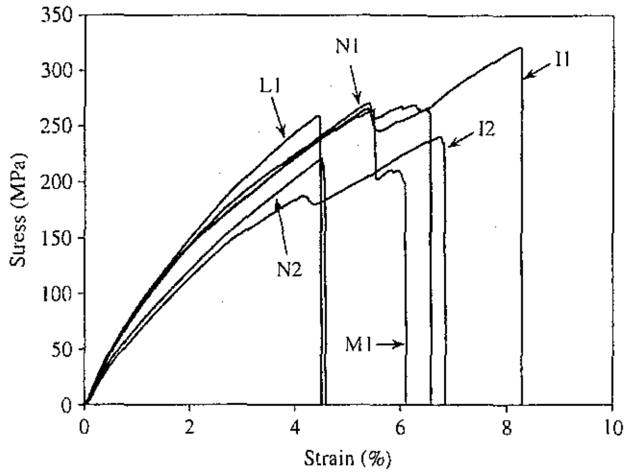


Figure 4. Stress–strain curves obtained for the interply hybrid laminates (samples I1, I2, L1, N1, N2, M1).

Typical stress-strain curves of the hybrid interply composites are reported in Figure 4. The Load drops are now not as pronounced as in the case of intraply hybrids composites. It is interesting to observe that, due to the higher PVA fibre content, sample I1 fails at a strain value higher than sample I2. A direct comparison between samples I1 and L1, characterized by an almost equal fibre volume fraction, clearly confirms that the presence of glass fibres in the external layers can be associated with the lower strain at break values. The tensile behaviour of samples M and N is quite similar. The higher strain at break of sample N1, in comparison to sample N2, can be related to the higher PVA fibre volume fraction along direction 1.

The tensile experimental data obtained for various composites and loading directions are summarized in Table 3, while Table 4 reports the specific tensile data, ie values normalized to the material density. It is important to observe that, with a proper choice of composition and stacking sequence, the E-glass/PVA hybrid composites can achieve tensile properties comparable with those of the homogeneous E-glass laminate (P1). In particular, the interply hybrid sample I1 is characterized by modulus and strength values which are essentially equal to those of the P1 sample while its elongation at break is much higher, which accounts for an improved tensile energy to break. By looking at the specific properties (Table 4), it is worth noting that most hybrid composites have specific tensile modulus and energy to break values which are comparable to, or higher than those of the homogeneous E-glass composites.

Impact performance

A typical load–displacement curve as obtained from the instrumented impact tests, is reported in Figure 5. For each specimen, the total impact absorbed energy (E_t) could be evaluated by measuring the total area under the curve and than normalizing this to the specimen cross-sectional area. As evidenced in Figure 5, E_t is the sum of the crack initiation energy (E_i) and the crack propagation energy (E_p). Beaumont able 3. Experimental data obtained from the uniaxial tensile tests on the various composites

ample	Elastic modulus (MPa)	Maximum stress (MPa)	Strain at maximum stress (%)	Strain at break (%)	Tensile energy to break ($J m^{-3}$)
1	9800 ± 300	264 ± 5	8.4 ± 0.2	8.4 ± 0.2	1250 ± 40
2	7800 ± 100	274 ± 8	5.7 ± 0.4	6.0 ± 0.6	1000 ± 100
1 (≈B2)	9300 ± 90	237 ± 8	5.1 ± 0.3	7.9 ± 0.2	1050 ± 40
1 (≈C2)	8600 ± 300	230 ± 10	5.4 ± 0.3	7.6 ± 0.2	970 ± 40
1	9600 ± 200	280 ± 10	6.7 ± 0.4	7.8 ± 0.1	1290 ± 60
2	9300 ± 100	240 ± 10	5.2 ± 0.3	8.0 ± 0.3	1100 ± 100
1	11300 ± 200	320 ± 10	8.0 ± 0.7	8.10 ± 0.5	1630 ± 140
2	8600 ± 100	240 ± 10	6.9 ± 0.3	6.9 ± 0.3	1000 ± 100
1	11200 ± 700	259 ± 6	4.6 ± 0.6	4.6 ± 0.6	690 ± 60
1	10700 ± 100	260 ± 10	5.4 ± 0.6	6.2 ± 0.2	1030 ± 80
1	11100 ± 400	270 ± 20	5.6 ± 0.4	6.0 ± 0.7	1050 ± 150
2	9100 ± 200	211 ± 7	4.5 ± 0.1	4.5 ± 0.1	540 ± 20
1 (= P2)	11800 ± 200	340 ± 30	5.7 ± 0.5	5.7 ± 0.5	1200 ± 200
1	10700 ± 50	250 ± 10	7.5 ± 0.5	7.5 ± 0.5	1100 ± 100
2	5900 ± 200	125 ± 6	6.3 ± 0.4	6.3 ± 0.4	440 ± 40
ure matrix	3500 ± 60	65 ± 9	2.2 ± 0.4	2.2 ± 0.4	80 ± 30

able 4. Specific tensile data obtained for the various composites

ample	Specific elastic modulus ($MPa m^3 kg^{-1}$)	Specific maximum stress ($MPa m^3 kg^{-1}$)	Specific energy to break ($J kg^{-1}$)
1	6.67 ± 0.18	0.180 ± 0.003	0.85 ± 0.03
2	5.31 ± 0.07	0.186 ± 0.005	0.68 ± 0.07
1 (≈B2)	6.41 ± 0.06	0.163 ± 0.006	0.72 ± 0.03
1 (≈C2)	5.93 ± 0.21	0.159 ± 0.007	0.67 ± 0.03
1	6.58 ± 0.14	0.192 ± 0.007	0.88 ± 0.04
2	6.41 ± 0.070	0.166 ± 0.007	0.76 ± 0.07
1	7.64 ± 0.14	0.216 ± 0.007	1.10 ± 0.09
2	5.81 ± 0.07	0.162 ± 0.007	0.68 ± 0.07
1	7.52 ± 0.47	0.174 ± 0.004	0.46 ± 0.04
1	7.33 ± 0.07	0.178 ± 0.007	0.71 ± 0.05
1	7.50 ± 0.27	0.182 ± 0.014	0.71 ± 0.10
2	6.15 ± 0.14	0.143 ± 0.005	0.36 ± 0.01
1 (= P2)	6.82 ± 0.12	0.197 ± 0.017	0.69 ± 0.12
1	8.56 ± 0.04	0.200 ± 0.008	0.88 ± 0.08
2	4.72 ± 0.16	0.100 ± 0.005	0.35 ± 0.03
ure matrix	2.85 ± 0.05	0.053 ± 0.007	0.07 ± 0.02

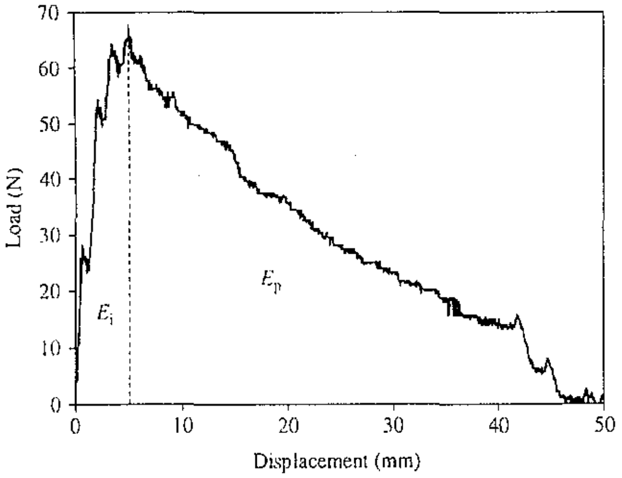


Figure 5. A typical load–displacement curve (for sample A1) from the instrumented impact test, displaying the energy partition between crack initiation (E_i) and crack propagation (E_p) contributions.

et al[13] defined a dimensionless parameter, known as the ductility index (*DI*), which has been found useful for ranking the impact performance of different materials under similar testing conditions. The *DI* is defined as the ratio between the propagation energy and the initiation energy, as follows:

$$DI = \frac{E_p}{E_i} \quad (3)$$

High values of DI would mean that most of the total energy is expended in crack propagation. The total impact energy, specific total impact energy and ductility index data for the various composites, impacted on the top and bottom surfaces, are summarized in Table 5. The homogeneous E-glass laminate shows a specific total impact energy of $64 J m kg^{-1}$, while for the homogeneous PVA laminate specific impact energies of 72 and $46 J m kg^{-1}$ were able 5. Impact data obtained for the various composites

ample	Impacted side	Total impact energy (kJ m^{-2})	Specific total impact energy (J m kg^{-1})	Ductility index
1	Top ply	90 ± 6	61 ± 4	5.15 ± 0.50
2	Top ply	79 ± 2	54 ± 1	7.38 ± 0.68
1	Top ply	89 ± 5	61 ± 3	7.37 ± 0.75
2	Top ply	96 ± 3	66 ± 2	4.89 ± 0.63
1	Top ply	92 ± 8	63 ± 6	4.47 ± 1.04
2	Top ply	103 ± 3	71 ± 2	5.10 ± 0.32
1	Top ply	91 ± 4	62 ± 3	4.05 ± 0.59
2	Top ply	85 ± 5	58 ± 3	5.50 ± 0.81
	Top ply	89 ± 7	60 ± 5	1.36 ± 0.27
	Top ply	66 ± 4	45 ± 3	1.73 ± 0.16
1	Top ply	99 ± 10	66 ± 7	4.45 ± 0.79
2	Top ply	96 ± 7	64 ± 5	3.48 ± 0.26
1	Top ply	108 ± 8	73 ± 5	2.01 ± 0.19
1	Bottom ply	67 ± 3	46 ± 2	1.82 ± 0.16
12	Top ply	89 ± 2	61 ± 1	2.95 ± 0.26
12	Bottom ply	45 ± 5	31 ± 3	0.66 ± 0.11
1	Top ply	111 ± 11	75 ± 7	1.34 ± 0.32
1	Bottom ply	84 ± 4	57 ± 3	3.52 ± 0.58
2	Top ply	93 ± 5	63 ± 3	1.71 ± 0.20
2	Bottom ply	68 ± 6	46 ± 4	3.43 ± 0.45
1 (= P2)	Top ply	111 ± 8	64 ± 5	3.90 ± 0.54
1	Top ply	90 ± 10	72 ± 8	2.19 ± 0.47
2	Top ply	58 ± 6	46 ± 5	3.26 ± 1.04
ure matrix	—	6 ± 2	5 ± 2	0

ıeasured for directions 1 and 2, respectively. The pecific total impact energy for the intraply composites anges from 54 to 71 J m kg^{-1}, depending on the tacking sequence and testing direction. The interply omposites, impacted on the top ply, show specific otal impact energy values in the range 45 to 5 J m kg^{-1}, while lower values, from 31 to 57 J m kg^{-1}, vere measured for non-symmetric interply composites mpacted on the bottom ply. In fact, the impact erformances of non-symmetric laminates are strictly elated to the stacking sequence with respect to he impact side:[28] in general, higher total impact nergy values were measured for interply laminates vhere the outer layers are of E-glass type. Similar omments can be extended to the specific total mpact energy values; for a few samples (C2, M1 op ply and N1 top ply), the specific total energy s significantly higher than that of the homogeneous -glass laminate.

In Figure 6, the ductility indices are reported n ascending order for both intraply and interply omposites. It is interesting to observe that hybrid ntraply composites show higher ductility index alues than those of the interply hybrid composites. his behaviour is indicating an higher efficiency in indering the crack propagation when E-glass and VA fibres are intimately mixed in the same layer vith respect to the case in which they are located in eparated plies. Moreover, as evidenced in Table 5, ll hybrid intraply composites are characterized y ductility index values superior to those of omogeneous laminates (P1, Q1 and Q2).

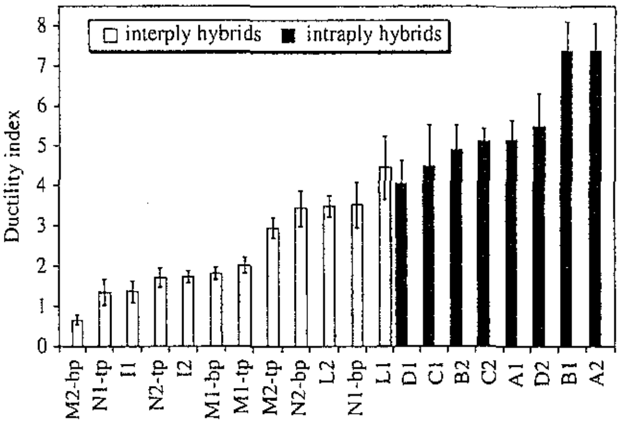


Figure 6. Ductility index values for interply and intraply hybrid composites, reported in ascending order.

CONCLUSIONS

The tensile and impact mechanical properties of intraply and interply hybrid composites, based on E-glass and poly(vinyl alcohol) fabrics, have been investigated. The stress–strain curves appear to be markedly affected by the plies stacking sequences and the loading directions. It is interesting to note that, through an appropriate laminate design, the E-glass/PVA hybrids could achieve specific tensile properties comparable to or higher than those of the homogeneous E-glass laminate, with an improved elongation at break. In particular, better tensile performances were achieved from symmetric interply hybrids with internal E-glass layers.

Impact data clearly show that hybrid intraply composites reached higher ductility index values hen compared to those of interply hybrids and omogeneous composites, probably due to the higher ficiency in hindering crack propagation in the case of -glass and PVA fibres intimately mixed in the same yer.

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