

ACKNOWLEDGMENT

First and foremost, gratitude and praises goes to Allah, in whom I have put my faith and trust in. During the entire course of this study, my faith has been tested countless times and with help of the Almighty, I have been able to go pass the obstacle that stood in my way.

I also would like to take this opportunity to express profound gratitude to my research supervisors Assoc. Prof. Dr. Aziz Hassan and Prof. Dr. Rosiyah Yahya for the noble guidance and valuable advance throughout the period of study. Their patience, time, and understanding are highly appreciated. A word of thanks also goes to the staffs of Chemistry Department, Mr. Zulkifli Abu Hasan, Ms. Ho Wai Ling & Ms. Nisrin , Mr. Chan from Mecomb, Mr. Keong & Mr. Lau from Melchers as well as Mr. William & Mr. Chua from Research Instrument for providing assistance in many ways.

My fellow friends especially Nor Mas Mira, Noordini, Rafiq, Ruth, Rozana Othman and Chin Sek Peng should also be recognized for their support in their invaluable views.

Last but not least I would like to thank my family members whom I owe a debt of attitude for their prayers, encouragement and moral support throughout the whole duration of studies.

ABSTRACT

Polyamide 6 (PA6) with various loading of short glass fibres, SGF (2%, 5%, 8%, 10% & 16% V_f) were prepared by injection moulding. The mechanical properties of composites were studied through tensile and impact tests. Composites were subjected to a series of mechanical tests at various testing conditions. The aim of the investigations was to show in which way the SGF content and testing conditions influence the materials behaviour. For different conditions, SGF/PA6 composites were subjected to dry as moulded (DAM), 50% RH and wet conditions. Results showed that composites strength decreases as moisture is introduced and temperature is raised. The melting temperatures as well as thermal stability of composites were also studied by DSC and TGA techniques respectively. The composites were also subjected to DMA analysis to examine the viscoelastic behaviour of materials under periodic stress. TGA analyses revealed that the thermal stability increase with an increase in the SGF content. DSC results showed that as the glass fibre content increases, the degree of crystallinity also decrease. Mechanical test showed that the tensile modulus and tensile strength increase steadily while the elongation at break decrease with an increase in the SGF content and/or strain rate. The toughness of moulded materials was characterised using linear elastic fracture mechanics approach. The critical strain energy release rate, (G_c) increases as the glass fibre loading increases. The reduction in ductility and toughness are attributed to the constrained mobility of polymer chains in the presence of SGF.

ABSTRAK

Poliamida 6 dengan pelbagai komposisi gentian kaca pendek (2%, 5%, 10% & 16% V_f) disediakan dengan menggunakan mesin acuan suntikan. Ciri-ciri mekanikal komposit dikaji dengan menggunakan ujian regangan dan impak. Komposit didedahkan kepada siri-siri ujian mekanikal pada pelbagai keadaan pengujian. Tujuan kajian ini adalah untuk menunjukkan bagaimana komposisi gentian kaca dan keadaan persekitaran mempengaruhi bahan komposit. Bagi persekitaran yang berbeza, gentian kaca pendek dan poliamida telah didedahkan kepada keadaan kering, 50% kelembapan relatif dan basah. Keputusan ujian menunjukkan yang kekuatan komposit menurun apabila terdedah kepada kelembapan dan kenaikan suhu. Suhu cair penghabluran serta kestabilan terma diuji dengan menggunakan teknik DSC dan TGA. Komposit turut diuji dengan menggunakan kepada analisis DMA untuk menguji tahap kekenyalan pada tekanan berkala. TGA analisis menunjukkan bahawa kestabilan terma bertambah dengan peningkatan kandungan gentian kaca. Keputusan DSC pula menunjukkan, dengan peningkatan komposisi gentian kaca pendek, darjah penghabluran turut menurun. Ujian mekanikal menunjukkan bahawa modulus dan kekuatan regangan turut meningkat, dengan peningkatan komposisi gentian kaca pendek. Ketahanan bahan pula telah dicirikan menggunakan pendekatan mekanik kegagalan kenyal berterusan. Kadar lepas tenaga pemanjangan kritikal, (G_c) meningkat dengan pertambahan gentian kaca pendek. Penurunan dalam kemuluran dan ketahanan adalah disebabkan oleh pergerakan terhad rantai polimer dengan kehadiran gentian kaca pendek.

LIST OF TABLES

- Table 3.1: Temperature settings on automatic injection moulding machine model Boy® 50M.
- Table 3.2: Specimens code and description.
- Table 3.3: Impact test parameters for Instron Dynatup 9210.
- Table 4.1: Determination of fibre volume fraction.
- Table 4.2: The fibre characteristic of injection moulded SGF/PA6 composites.
- Table 4.3: TGA thermogravimetric data of injection moulded SGF/PA6 composites.
- Table 4.4: DSC melting and crystallization parameters of injection moulded SGF/PA6 composites at various environmental conditions.
- Table 4.5: DMA thermomechanical data of injection moulded glass fibre composites at various environmental conditions.

LIST OF FIGURES

- Figure 4.1: Fibre length distribution of injection moulded SGF/PA6 composites.
- Figure 4.2: Cumulative fibre frequency of injection moulded SGF/PA6 composites.
- Figure 4.3: Average residual fibre length against fibre volume fraction of injection moulded SGF/PA6 composites.
- Figure 4.4: TGA curves of injection moulded SGF/PA6 composites at DAM.
- Figure 4.5: TGA curves of injection moulded SGF/PA6 composites subjected to 50% RH.
- Figure 4.6: TGA curves of injection moulded SGF/PA6 composites subjected to wet condition.
- Figure 4.7: TGA curves of neat PA6 subjected to different environmental condition.
- Figure 4.8: TGA curves of injection moulded 2% V_f SGF/PA6 composites subjected to different environmental condition.
- Figure 4.9: TGA curves of injection moulded 5% V_f SGF/PA6 composites subjected to different environmental condition.
- Figure 4.10: TGA curves of injection moulded 10% V_f SGF/PA6 composites subjected to different environmental condition.
- Figure 4.11: TGA curves of injection moulded 16% V_f SGF/PA6 composites subjected to different environmental condition.
- Figure 4.12: DSC results of injection moulded SGF/PA6 composites at various V_f at DAM.
- Figure 4.13: DSC results of injection moulded SGF/PA6 composites at various V_f subjected to 50% RH.
- Figure 4.14: DSC results of injection moulded SGF/PA6 composites at various V_f subjected to wet condition.
- Figure 4.15: DSC results of neat PA6 subjected to different environmental condition.

- Figure 4.16: DSC results of injection moulded 2% V_f SGF/PA6 composites subjected to different environmental condition.
- Figure 4.17: DSC results of injection moulded 5% V_f SGF/PA6 composites subjected to different environmental condition.
- Figure 4.18: DSC results of injection moulded 10% V_f SGF/PA6 composites subjected to different environmental condition.
- Figure 4.19: DSC results of injection moulded 16% V_f SGF/PA6 composites subjected to different environmental condition.
- Figure 4.20: The tan delta-temperature behaviour of injection moulded SGF/PA6 composites at DAM.
- Figure 4.21: The tan delta-temperature behaviour of injection moulded SGF/PA6 composites subjected to 50% RH.
- Figure 4.22: The tan delta-temperature behaviour of injection moulded SGF/PA6 composites subjected to wet condition.
- Figure 4.23: The storage modulus-temperature behaviour of injection moulded SGF/PA6 composites at DAM.
- Figure 4.24: The storage modulus-temperature behaviour of injection moulded SGF/PA6 composites subjected to 50% RH.
- Figure 4.25: The storage modulus-temperature behaviour of injection moulded SGF/PA6 composites subjected to wet condition.
- Figure 4.26: The tan delta-temperature behaviour of injection moulded neat PA6 subjected to different conditions.
- Figure 4.27: The tan delta-temperature behaviour of injection moulded 2% V_f SGF/PA6 composites subjected to different conditions.

- Figure 4.28: The tan delta-temperature behaviour of injection moulded 5% V_f SGF/PA6 composites subjected to different conditions.
- Figure 4.29: The tan delta-temperature behaviour of injection moulded 10% V_f SGF/PA6 composites subjected to different conditions.
- Figure 4.30: The tan delta-temperature behaviour of injection moulded 16% V_f SGF/PA6 composites subjected to different conditions.
- Figure 4.31: The storage modulus-temperature behaviour of injection moulded neat PA6 subjected to different condition.
- Figure 4.32: The storage modulus-temperature behaviour of injection moulded 2% V_f SGF/PA6 composites subjected to different condition.
- Figure 4.33: The storage modulus-temperature behaviour of injection moulded 5% V_f SGF/PA6 composites subjected to different condition.
- Figure 4.34: The storage modulus-temperature behaviour of injection moulded 10% V_f SGF/PA6 composites subjected to different condition.
- Figure 4.35: The storage modulus-temperature behaviour of injection moulded 16% V_f SGF/PA6 composites subjected to different condition.
- Figure 4.36: Tensile strength of neat PA6 at different environmental condition.
- Figure 4.37: Tensile modulus of neat PA6 at different environmental condition.
- Figure 4.38: Fracture strain of neat PA6 at different environmental condition.
- Figure 4.39: Tensile strength of injection moulded SGF/PA6 composites at DAM.
- Figure 4.40: Tensile strength of injection moulded SGF/PA6 composites subjected to 50% RH.
- Figure 4.41: Tensile strength of injection moulded SGF/PA6 composites subjected to wet condition.
- Figure 4.42: Tensile modulus of injection moulded SGF/PA6 composites at DAM.

- Figure 4.43: Tensile modulus of injection moulded SGF/PA6 composites subjected to 50% RH.
- Figure 4.44: Tensile modulus of injection moulded SGF/PA6 composites subjected to wet condition.
- Figure 4.45: Fracture strain of injection moulded SGF/PA6 composites at DAM.
- Figure 4.46: Fracture strain of injection moulded SGF/PA6 composites subjected to 50% RH.
- Figure 4.47: Fracture strain of injection moulded SGF/PA6 composites subjected to wet condition.
- Figure 4.48: Tensile specimen fracture surface of injection moulded 2% V_f SGF/PA6 composites at strain rate of $6.67 \times 10^{-3} \text{ s}^{-1}$ (20mm/min) subjected to DAM.
- Figure 4.49: Tensile specimen fracture surface of injection moulded 2% V_f SGF/PA6 composites at strain rate of $6.67 \times 10^{-3} \text{ s}^{-1}$ (20mm/min) subjected to wet condition.
- Figure 4.50: Tensile specimen fracture surface of injection moulded 2% V_f SGF/PA6 composites at strain rate of $0.33 \times 10^{-3} \text{ s}^{-1}$ (1 mm/min).
- Figure 4.51: Tensile specimen fracture surface of injection moulded 2% V_f SGF/PA6 composites at strain rate of $6.67 \times 10^{-3} \text{ s}^{-1}$ (20 mm/min).
- Figure 4.52: Fracture energy, W values of injection moulded SGF/PA6 composites subjected to different support span.
- Figure 4.53: Peak load values of injection moulded SGF/PA6 composites subjected to different support span.
- Figure 4.54: Fracture energy against $BD\Phi$ of neat PA6 subjected to different support span.

- Figure 4.55: Fracture energy against $BD\Phi$ of injection moulded 2% V_f SGF/PA6 composites subjected to different support span.
- Figure 4.56: Fracture energy against $BD\Phi$ of injection moulded 5% V_f SGF/PA6 composites subjected to different support span.
- Figure 4.57: Fracture energy against $BD\Phi$ of injection moulded 10% V_f SGF/PA6 composites subjected to different support span.
- Figure 4.58: Fracture energy against $BD\Phi$ of injection moulded 16% V_f of SGF/PA6 composites subjected to different support span.
- Figure 4.59: Variation of σY against $1/\sqrt{a}$ of neat PA6 subjected to different support span.
- Figure 4.60: Variation of σY against $1/\sqrt{a}$ of injection moulded 2% V_f SGF/PA6 composites subjected to different support span.
- Figure 4.61: Variation of σY against $1/\sqrt{a}$ of injection moulded 5% V_f SGF/PA6 composites subjected to different support span.
- Figure 4.62: Variation of σY against $1/\sqrt{a}$ of injection moulded 10% V_f SGF/PA6 composites subjected to different support span.
- Figure 4.63: Variation of σY against $1/\sqrt{a}$ of injection moulded 16% V_f SGF/PA6 composites subjected to different support span.
- Figure 4.64: Critical strain energy release rate, G_c values of injection moulded SGF/PA6 composites subjected to different support span.
- Figure 4.65: Critical stress intensity factor, K_{Ic} values of injection moulded SGF/PA6 composites subjected to different support span.
- Figure 4.66: Variation of fracture energy, W of injection moulded of injection moulded SGF/PA6 composites subjected to different test velocities.
- Figure 4.67: Variation of G_c values of injection moulded SGF/PA6 composites subjected to different test velocities.

- Figure 4.68: Variation of peak load values of injection moulded SGF/PA6 composites subjected to different test velocities.
- Figure 4.69: Variation of K_c values of injection moulded SGF/PA6 composites subjected to different test velocities.
- Figure 4.70: Fracture energy, W against $BD\Phi$ values of neat PA6 subjected to different test velocities.
- Figure 4.71: Fracture energy, W against $BD\Phi$ values of injection moulded 8% V_f SGF/PA6 composites subjected to different test velocities.
- Figure 4.72: Fracture energy, W against $BD\Phi$ values of injection moulded 16% V_f SGF/PA6 composites subjected to different test velocities.
- Figure 4.73: Variation of σY against $1/\sqrt{a}$ of neat PA6 subjected to different test velocities.
- Figure 4.74: Variation of σY against $1/\sqrt{a}$ of injection moulded 8% V_f SGF/PA6 composites subjected to different test velocities.
- Figure 4.75: Variation of σY against $1/\sqrt{a}$ of injection moulded 16% V_f SGF/PA6 composites subjected to different test velocities.
- Figure 4.76: Variation of fracture energy, W of injection moulded of SGF/PA6 composites subjected to different test load.
- Figure 4.77: Variation of peak load of injection moulded SGF/PA6 composites subjected to different test load.
- Figure 4.78: Critical strain energy release rate, G_c values of injection moulded SGF/PA6 composites subjected to different test load.
- Figure 4.79: Critical stress intensity factor, K_c values of injection moulded SGF/PA6 composites subjected to different test load.
- Figure 4.80: Variation of fracture energy against $BD\Phi$ of neat PA6 subjected to different test load.

- Figure 4.81: Variation of fracture energy against $BD\Phi$ of injection moulded 8% V_f SGF/PA6 composites subjected to different test load.
- Figure 4.82: Variation of fracture energy against $BD\Phi$ of injection moulded 16% V_f SGF/PA6 composites subjected to different test load.
- Figure 4.83: Variation of σY against $1/\sqrt{a}$ of neat PA6 subjected to different test load.
- Figure 4.84: Variation of σY against $1/\sqrt{a}$ of injection moulded 8% V_f SGF/PA6 composites subjected to different test load.
- Figure 4.85: Variation of σY against $1/\sqrt{a}$ of injection moulded 16% V_f SGF/PA6 composites subjected to different test load.
- Figure 4.86: Impact specimen fracture surface of injection moulded 16% V_f SGF/PA6 composites at 50°C.
- Figure 4.87: Impact specimen fracture surface of injection moulded 16% V_f of SGF/PA6 composites at 60°C.
- Figure 4.88: Impact specimen fracture surface of injection moulded 16% V_f SGF/PA6 composites at 70°C.
- Figure 4.89: Fracture energy, W values of injection moulded 16% V_f SGF/PA6 composites subjected to different temperature.
- Figure 4.90: Peak load values of injection moulded 16% V_f SGF/PA6 composites subjected to different temperature.
- Figure 4.91: Critical strain energy release rate, G_c and critical stress intensity factor, K_{Ic} values of injection moulded 16% V_f SGF/PA6 composites.
- Figure 4.92: Variation of fracture energy against $BD\Phi$ of injection moulded 16% V_f SGF/PA6 composites.
- Figure 4.93: Variation of σY against $1/\sqrt{a}$ of injection moulded 16% V_f SGF/PA6 composites.

LIST OF ABBREVIATIONS AND SYMBOLS

a	crack length
a/D	notch to depth ratio
B	specimen thickness
C	compliance
D	depth of specimen
DAM	Dry as moulded
E	Young's modulus
E'	Storage modulus
FRPC	Fibre reinforced polymer composites
G _c	critical strain energy release rate
h _{tup}	specimen height from tup until touch the specimen
K _c	critical stress intensity factor or fracture toughness
l	fibre length
l _c	critical fibre length
L _n	number average fibre length
L _w	weight average fibre length
M _f	weight of fibre
M _m	weight of matrix
P	peak load
S48	support span at 48 mm
S60	support span at 60 mm
S/D	support span to depth ratio
T _c	crystallisation temperature
T _g	glass transition temperature
T _m	melting temperature

$\tan \delta$	Damping factor
V_f	volume fraction of fibre
V_m	volume fraction of matrix
χ_c	degree of crystallinity
W	fracture energy
w	specimen width
Y	geometry factor
ΔH_m	heat of fusion
$-\Delta H_c$	crystalline enthalpy

TITLE	i
ACKNOWLEDGEMENTS	ii
ABSTRACT	iii
ABSTRAK	iv
LIST OF TABLES	v
LIST OF FIGURES	vi
LIST OF ABBREVIATIONS AND SYMBOLS	xiii
TABLE OF CONTENTS	xv

CHAPTER 1: INTRODUCTION

1.1	Current Perspectives and Future Prospects of Composites Material: An Overview.....	1
1.2	Applications of Fibre Reinforced Polymer Composites.....	2
1.3	Research Background.....	3
1.4	Objectives.....	5
1.5	Scopes.....	5

CHAPTER 2: LITERATURE REVIEW

2.1	Polyamide 6	
	2.1.1 Introduction.....	6
	2.1.2 Function of Matrix (Polyamide) Phase.....	7
2.2	Fillers	
	2.2.1 An Overview.....	8
	2.2.2 Types of Reinforcing Fibres	
	2.2.2.1 Aramid Fibres.....	8
	2.2.2.2 Carbon or Graphite Fibres.....	9
	2.2.2.3 Glass Fibres.....	10
2.3	Fibre Reinforced Polymer Composites	

2.3.1	Introduction.....	12
2.3.2	Interfacial Adhesion and Compatibility Between Particles and Matrix.....	13
2.4	Mechanical Properties	
2.4.1	Tensile Test.....	15
2.4.2	Impact Test.....	17
2.4.3	Fracture Toughness.....	19
2.5	Testing Condition Effect on Composite Properties	
2.5.1	Tensile Properties.....	22
2.5.2	Impact Properties.....	24
 CHAPTER 3: EXPERIMENTAL		
3.1	Materials.....	26
3.2	Preparations of Specimens.....	26
3.3	Determination of Fibre Volume Fraction (V_f).....	28
3.4	Determination of Fibre Length Distribution (FLD).....	28
3.5	Conditioning of Specimens.....	28
3.6	Thermal Characterisation	
3.6.1	Thermogravimetric Analysis (TGA).....	29
3.6.2	Differential Scanning Calorimetry (DSC).....	29
3.7	Dynamic Mechanical Analysis (DMA).....	30
3.8	Mechanical Properties	
3.8.1	Tensile Testing.....	30
3.8.2	Impact Testing.....	31
3.9	Fracture Surface Morphology.....	32

CHAPTER 4: RESULTS AND DISCUSSION

4.1	Fibre Volume Fraction, V_f	33
4.2	Fibre Length Distribution (FLD).....	35
4.3	Thermal Properties	
4.3.1	Thermogravimetric Analysis (TGA)	
4.3.1.1	The Effect of Fibre Volume Fraction, V_f	41
4.3.1.2	The Effect of Moisture.....	43
4.3.2	Differential Scanning Calorimetry (DSC)	
4.3.2.1	The Effect of Fibre Volume Fraction, V_f	49
4.3.2.2	The Effect of Moisture.....	57
4.4	Dynamic Mechanical Analysis (DMA)	
4.4.1	The Effect of Fibre Volume Fraction, V_f	58
4.4.2	The Effect of Moisture.....	66
4.5	Tensile Properties	
4.5.1	Neat Polyamide 6.....	73
4.5.2	The Effect of Fibre Volume Fraction (V_f).....	76
4.5.3	The Effect of Moisture.....	84
4.5.4	The Effect of Strain Rate.....	87
4.5.5	The Effect of Types of Extensometer.....	91
4.6	Impact Properties	
4.6.1	The Effect of Support Span.....	100
4.6.2	The Effect of Test Velocity.....	111
4.6.3	The Effect of Test Load.....	119
4.6.4	The Effect of Testing Temperature.....	126

CHAPTER 5: CONCLUSIONS AND SUGGESTION FOR FUTURE WORK

5.1	Conclusions.....	134
5.2	Suggestion for Future Work.....	135
	References.....	136