

CHARACTERIZATION OF CONTINUOUS KENAF-GLASS FIBER HYBRID
COMPOSITES FOR STRUCTURAL APPLICATION

REZA MAHJOUR

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy (Civil Engineering)

Faculty of Civil Engineering
Universiti Teknologi Malaysia

DECEMBER 2013

Dedicated to:

My beloved parents

My lovely wife and daughter

My dear sisters

Thank you for your prayers and understanding

ACKNOWLEDGEMENT

I would like to thank my supervisors Associated Prof. Dr. Jamaludin Mohamad Yatim and Dr. Abdul Rahman Mohd. Sam for their commitment, valuable guidance, and comments in assisting me to complete this thesis. Without their guidance this study would not have been possible.

ABSTRACT

Kenaf fibers generally has some advantages such as eco-friendly, biodegradability, renewable nature and lighter than synthetic fibers. However, their mechanical properties are lower than synthetic fibers. Hybridization of bio-fiber with a synthetic fiber could improve the mechanical properties of composites. The aims of the study are to characterize and evaluate the properties of kenaf fiber composites and its hybridizations with glass fiber and also to investigate the performance of bio-composite as the strengthening plate for structural applications. The study was conducted in three stages. Firstly, the raw materials and composites were developed by conducting laboratory tests on physical and mechanical properties. The properties and the effects of different conditions of alkaline treatment on the properties of kenaf fibers were studied due to the various alkaline treatment conditions. Besides, the scanning electron microscopy was employed to observe the specimens appearance, fracture area and fiber diameter. The tensile properties of glass fiber composites, kenaf fiber composites and hybrid kenaf/glass fiber composites were determined with various fiber volume contents. The second stage was the application of composite materials as strengthening plate in reinforced concrete beams and subjected to flexural test under the four points loading system until failure. Fifteen beam specimens were prepared and tested for the study. The third stage was analytical investigations and theoretical development of the properties of composites and performance of strengthened reinforced concrete (RC) beams. According to the results of this study, the average diameter, the density and tensile strength of kenaf fiber were $67.6 \mu\text{m}$, 1.2 g/cm^3 and 780 MPa , respectively. Meanwhile, the tensile strength of hybrid kenaf/glass bio-composites exhibited almost equivalence to the glass fiber composites and also the highest strain energy density among the composites in the same value of fiber content. It was observed that increasing the glass fiber fraction more than 10% in hybrid composite caused the reduction in the ultimate tensile strain. For the hybrid bio-composites, debonding between the kenaf and glass layers caused the failure of composites. The flexural tests of RC beams showed the equivalent performance of the hybrid kenaf/glass bio-composite and the glass fiber composite strengthening plates. An analytical investigation has validated that the rule of mixture (ROM) could predict reasonably the elastic modulus of composites. The analytical model of this study based on the nonlinear stress-strain curve of concrete predicted well the moment capacity of RC beams as compared to the ACI 440.2R guideline. Therefore, this model was proposed in order to establish the analytical formulations for RC beams strengthened with the composites plates.

ABSTRAK

Kebaikan gentian kenaf adalah kerana sifat-sifat yang mesra alam, kebolehan biodegradasi, boleh diperbaharui secara penanaman semula dan ringan berbanding dengan gentian sintetik. Walaubagaimanapun sifat-sifat mekanikal gentian kenaf adalah lebih rendah berbanding dengan gentian sintetik. Keadaan ini boleh dipertingkatkan dengan melaksanakan penghibridan gentian asli dengan gentian sintetik. Oleh itu, tujuan kajian ini adalah untuk mencirikan dan menilai sifat-sifat komposit gentian Kenaf dan penghibridannya dengan gentian kaca, dan juga untuk mengkaji prestasi bio-komposit sebagai plat pengukuh untuk aplikasi struktur. Kajian ini telah dijalankan dalam tiga peringkat. Di peringkat pertama, bahan-bahan mentah dan komposit telah dikaji dan dibangunkan melalui pengujian makmal ke atas sifat-sifat fizikal dan mekanikal. Ciri-ciri dan kesan rawatan alkali yang berbeza atas sifat-sifat gentian Kenaf juga telah dikaji. Selain itu, mikroskop elektron pengimbas telah digunakan untuk memerhatikan penampilan spesimen, kawasan patah, diameter gentian, dan ciri-ciri lain yang boleh diperhatikan. Sifat tegangan komposit gentian kaca, komposit gentian Kenaf, dan hibrid komposit gentian Kenaf/kaca telah ditentukan mengikut kandungan jumlah gentian yang berbeza. Peringkat kedua adalah untuk mengkaji penggunaan bahan komposit sebagai plat pengukuh dalam rasuk konkrit bertetulang melalui ujian lenturan berasaskan sistem pembebanan empat titik sehingga mencapai tahap gagal. Sebanyak 15 spesimen rasuk telah disediakan dan diuji untuk kajian ini. Peringkat ketiga melibatkan proses analisis dan pembangunan teori sifat-sifat komposit dan prestasi kekukuhan rasuk konkrit tetulang. Keputusan menunjukkan bahawa diameter purata gentian Kenaf adalah $67.6 \mu\text{m}$, ketumpatan ialah 1.2 g/cm^3 , dan kekuatan tegangan adalah 780 MPa . Kekuatan tegangan hibrid Kenaf/kaca bio-komposit telah didapati setara dengan komposit gentian kaca dan juga didapati bahawa ia mempunyai ketumpatan tenaga terikan tertinggi di kalangan komposit dengan kandungan gentian yang sama. Malahan, penambahan kuantiti gentian kaca melebihi 10% dalam gentian hibrid juga didapati telah mengurangkan terikan tegangan muktamad. Bagi bio-komposit hibrid, rekahan antara lapisan Kenaf dan lapisan kaca dalam komposit adalah ciri kegagalan yang paling ketara di bawah beban muktamad. Hasil ujian lenturan untuk kedua-dua bio-komposit hibrid kenaf/kaca dan plat pengukuh gentian kaca adalah didapati setara. Kajian analisis secara teori telah mengesahkan bahawa model "rule of mixture" berkebolehan meramalkan nilai modulus keanjalan komposit dengan munasabah. Berdasarkan lengkung tegasan-terikan tak linear, model analisis kajian ini juga boleh meramalkan keupayaan momen bagi rasuk konkrit dengan lebih baik berbanding dengan garis panduan ACI 440.2R. Oleh itu model ini adalah sesuai disyorkan sebagai model teori untuk membangunkan rumusan analisis rasuk konkrit yang diperkukuhkan dengan plat komposit.

TABLE OF CONTENTS

CHAPTER	TITLE	PAGE
	DECLARATION	ii
	DEDICATION	iii
	ACKNOWLEDGEMENTS	iv
	ABSTRACT	v
	ABSTRAK	vi
	TABLE OF CONTENTS	vii
	LIST OF TABLES	xii
	LIST OF FIGURES	xv
	LIST OF ABBREVIATIONS	xxv
	LIST OF SYMBOLS	xxvi
	LIST OF APPENDICES	xxvii
1	INTRODUCTION	1
	1.1 1.1 Introduction	1
	1.2 Background of the study	2
	1.3 Problem statement	3
	1.4 Aim and objectives of the study	4
	1.5 Scope of the study	5
	1.6 Significance of research	6
2	LITERATURE REVIEW	7
	2.1 Introduction	7
	2.2 Polymer	8
	2.3 Fibers	12
	2.3.1 Glass fiber	13
	2.3.2 Natural fiber	13
	2.4 Kenaf fiber	17

2.5	Chemical surface treatment	20
2.5.1	Alkaline treatment	20
2.5.2	Silane treatment	23
2.5.3	Acetylation treatment	23
2.5.4	Isocyanate treatment	23
2.5.5	Other chemical treatments	24
2.6	Natural fiber reinforced composite	24
2.6.1	Processing of making composite (fabricating methods)	27
2.7	Kenaf fiber reinforced polymer composites	28
2.8	Kenaf fiber hybrid reinforced polymer composite	38
2.9	Analytical methods	42
2.10	Reinforced concrete beam strengthened by FRP plate	47
2.11	Conclusion	51
3	RESEARCH METHODOLOGY	53
3.1	Introduction	53
3.2	Outline of the tests program	53
3.3	Materials used in the study	54
3.3.1	Kenaf fiber	54
3.3.1.1	Alkaline treatment of kenaf fibers	56
3.3.1.2	Tensile test on kenaf fiber	57
3.3.1.3	Physical test of kenaf fibers	60
3.3.2	Glass fiber properties	61
3.3.3	Polymer properties	61
3.3.4	Kenaf/glass fiber polymer composites	62
3.3.4.1	Mold preparation	63
3.3.4.2	Preparation fibers and resin	63
3.3.4.3	Fabricating of composite series	65
3.3.4.4	Tensile tests of composites	67
3.4	Strengthening of reinforced concrete beams	68
3.4.1	Fabricating of strengthening plate	69
3.4.2	Reinforced concrete beam	71
3.4.3	Strengthened the beam specimens with composite plates	72
3.4.4	Beam specimens details	73

	3.4.5 Flexural test of RC beams	74
	3.5 Complimentary tests	75
	3.6 Instrumentation	76
	3.7 Conclusions	77
4	PROPERTIES OF FIBERS AND COMPOSITES	78
	4.1 Introduction	78
	4.2 Kenaf fiber properties	78
	4.2.1 Density	79
	4.2.2 Kenaf fiber surface appearance	79
	4.2.3 Kenaf fiber diameter	83
	4.2.4 Tensile properties of kenaf fiber	86
	4.3 Tensile properties of pure epoxy matrix	99
	4.4 Characterization of kenaf fiber reinforced polymer bio composites	100
	4.4.1 Tensile properties of kenaf fiber reinforced epoxy composite (KFRP)	100
	4.5 Tensile properties of glass fiber reinforced epoxy composite (GFRP)	103
	4.6 Tensile properties of hybrid kenaf/glass fiber reinforced epoxy composite (HKGFRP)	108
	4.6.1 Tensile properties of 10% fiber volume content of hybrid kenaf/glass fiber reinforced epoxy composite (HKGFRP-10)	108
	4.6.2 Tensile properties of 30% fiber volume content of hybrid kenaf/glass fiber reinforced epoxy composite (HKGFRP-30)	111
	4.6.3 Tensile properties of 40% fiber volume content of hybrid kenaf/glass fiber reinforced epoxy composite (HKGFRP-40)	115
	4.7 Morphology of composites	120
	4.7.1 Fiber orientation and arrangement	120
	4.7.2 Bonding between fibers and layers	121
	4.7.3 Failure forms	125
	4.8 Compilation of test results	127
	4.9 Conclusion	129

5	<p>FLEXURAL PERFORMANCE OF REINFORCED CONCRETE BEAMS STRENGTHENED BY COMPOSITE PLATES</p> <p>5.1 Introduction</p> <p>5.2 The results of Control RC beam specimens</p> <p>5.3 The results of RC beams strengthened with GFRP-PL50</p> <p>5.4 The results of RC beams strengthened with GFRP-PL100</p> <p>5.5 RC beams strengthened with KFRP-PL50</p> <p>5.6 RC beam strengthened with KFRP-PL100</p> <p>5.7 RC beam strengthened with HKGFRP-PL50</p> <p>5.8 RC beams strengthened with HKGFRP-PL100</p> <p>5.9 Overall results of flexural test of strengthened RC beams</p> <p style="padding-left: 20px;">5.9.1 Failure mode of flexural test</p> <p style="padding-left: 20px;">5.9.2 Flexural capacity of beams</p> <p style="padding-left: 20px;">5.9.3 Bending stiffness of RC beams</p> <p>5.10 Conclusion</p>	<p>131</p> <p>131</p> <p>131</p> <p>134</p> <p>137</p> <p>140</p> <p>144</p> <p>147</p> <p>150</p> <p>154</p> <p>156</p> <p>158</p> <p>160</p> <p>161</p>
6	<p>THEORITICAL ANALYSIS AND DISCUSSION</p> <p>6.1 Introduction</p> <p>6.2 The properties of fiber reinforced composites</p> <p style="padding-left: 20px;">6.2.1 Density of composites</p> <p style="padding-left: 20px;">6.2.2 Tensile modulus of composites</p> <p style="padding-left: 20px;">6.2.3 KFRP properties</p> <p style="padding-left: 20px;">6.2.4 GFRP properties</p> <p style="padding-left: 20px;">6.2.5 HKGFRP properties</p> <p style="padding-left: 20px;">6.2.6 HKGFRP-10 properties</p> <p style="padding-left: 20px;">6.2.7 HKGFRP-30 properties</p> <p style="padding-left: 20px;">6.2.8 HKGFRP-40 properties</p> <p>6.3 Flexural behavior of strengthened reinforced concrete (RC) beams</p> <p style="padding-left: 20px;">6.3.1 Analytical method</p> <p style="padding-left: 20px;">6.3.2 Analytical results</p> <p style="padding-left: 20px;">6.3.3 ACI 440.2R proposed model</p> <p style="padding-left: 20px;">6.3.4 Comparison between models</p>	<p>162</p> <p>162</p> <p>162</p> <p>162</p> <p>164</p> <p>165</p> <p>167</p> <p>169</p> <p>169</p> <p>171</p> <p>173</p> <p>175</p> <p>176</p> <p>180</p> <p>181</p> <p>182</p>

6.4	Ductility	184
6.5	Conclusion	185
7	CONCLUSION AND RECOMMENDATION	186
7.1	Introduction	186
7.2	Characterization of kenaf fiber bio-composites	186
7.3	Mechanical properties of kenaf/glass hybrid bio-composites	187
7.4	Performance of kenaf/glass hybrid composite strengthening plates	187
7.5	Analytical investigations	188
7.6	Recommendations for further research	188
	REFERENCES	190
	Appendices A - E	203 - 212

LIST OF TABLES

TABLE NO.	TITLE	PAGE
2.1	Qualitative comparison between thermoset and thermoplastic polymers	10
2.2	Mechanical properties of some polymers	11
2.3	List of some natural fibers	16
2.4	Mechanical properties of some natural fiber	16
2.5	Kenaf fiber mechanical properties	18
2.6	Physical and chemical properties of treated and untreated agave fiber	21
2.7	Mechanical properties of polymers	25
2.8	Tensile strength of OPEFB composites	26
2.9	Tensile modulus of OPEFB composites	26
2.10	Flexural properties of various fiber polymer composites	37
3.1	Notation of fiber series for testing	59
3.2	The physical and mechanical properties of glass fiber	61
3.3	Physical and mechanical properties of Epicot 2175 (Epoxy) polymer (reported by manufacturer)	61
3.4	Properties of Sikadur-30 (Manufacturer data sheet)	62
3.5	Strengthening plate specifications	71
3.6	RC beam specimens notification and details	74

3.7	Data acquisition equipment	76
4.1	Determination of kenaf fiber density	79
4.2	Statistical parameter of fiber diameter determination	86
4.3	Tensile properties of untreated kenaf fiber from group A by using of System Compliance method	88
4.4	The averaging of data method for tensile properties of untreated kenaf fiber from group A	89
4.5	Tensile properties of 3hours-5% alkaline treatment of kenaf fiber from group A by using of System Compliance method	90
4.6	The averaging of data method for tensile properties of 3hours-5% alkaline treatment of kenaf fiber from group A	91
4.7	Tensile properties of pure epoxy resin	99
4.8	Mechanical properties of KFRP for different fiber volume content	102
4.9	Mechanical properties of GFRP for different fiber volume content	106
4.10	Mechanical properties of HKGFRP-10 for different glass fiber volume fraction	110
4.11	Mechanical properties of GFRP-30 for different glass fiber volume fraction	115
4.12	Mechanical properties of HKGFRP-40 for different glass fiber volume fraction	119
4.13	Tensile properties of materials	128
5.1	Average values of the important parameters of control beams	133
5.2	The average value of BG50 beams test results	137
5.3	The average value of BG100 beams test results	140
5.4	The average value of BK50 specimens test results	144

5.5	The average value of BK100 beams test results	147
5.6	The average value of BH50 beams test results	150
5.7	The average value of BH100 beams test results	154
5.8	Summary of tests results of flexural test of beams	155
5.9	Failure modes of beam specimens	157
6.1	Density of composites and void contents	163
6.2	Mechanical properties of strengthening plates	176
6.3	Experimental and theoretical results of moment capacity of strengthened RC beam groups	181
6.4	Experimental and ACI 440.2R model results of moment capacity of strengthened RC beam groups	181
6.5	Deflection ductility index of beam groups	184

LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
2.1	The use of FRP in civil engineering	8
2.2	Biodegradable polymers	9
2.3	Construction of (a) Thermoplastic polymer (b) Thermoset polymer	9
2.4	Comparison between several common matrix in composites	11
2.5	A variety of orientation of fibers for using in composites	12
2.6	Natural fiber classification	14
2.7	Structure of natural fiber	14
2.8	Cellulose structure	15
2.9	Lignin structure	15
2.10	Tensile strength and elastic modulus of kenaf fiber	19
2.11	Effect of distance from ground on the tensile property of kenaf fiber	19
2.12	Effects of treatment on the tensile property of sisal/ glass polyester composite. (A) Control; (B) Alkali treatment 5%; (C) Alkali treatment 10%; (D) Cyanoethylation; (E) Acetylation	21
2.13	SEM graph of (a) untreated kenaf fiber, (b) 3% alkaline treated	22
2.14	Hand lay-up process	27

2.15	Effects of kenaf fiber content of kenaf/PLLA on the mechanical properties of composite	29
2.16	Mechanical properties of kenaf sheet, PLLA film and kenaf/PLLA composite	30
2.17	Comparison of tensile strength of some bio-fiber/PP composites	30
2.18	Comparison of flexural strength of some bio-fiber/PP composites	31
2.19	Tensile strength Vs. fiber weight fraction in fiber/PP composite	31
2.20	Tensile modulus Vs. fiber weight fraction in fiber /PP composite	32
2.21	Tensile strength for different fiber volume content, AD: air dried kenaf fibre; H: The temperature of the mold (heated)	33
2.22	Tensile modulus for different fiber volume content, AD: air dried kenaf fibre); H: the temperature of the mold (heated)	33
2.23	Flexural strength for different fiber volume content, AD: air dried kenaf fibre; H: the temperature of the mould (heated)	34
2.24	Flexural modulus for different fiber volume content, AD: air dried kenaf fibre; H: the temperature of the mould (heated)	34
2.25	Specific tensile strength for different fiber volume content, AD: air dried kenaf fibre or GE (undried glass fibre), H: the temperature of the mould (heated) and NH: not heated	35
2.26	Flexural properties of kenaf fiber epoxy composite	36
2.27	Flexural modulus of kenaf fiber epoxy composite	36
2.28	Stress-strain diagram Carbon/Glass hybrid composite	39
2.29	The effect of glass fiber loading on the tensile strength of hybrid sisal/glass composite	40

2.30	Hybrid glass/kenaf epoxy composite properties: a) Tensile modulus b) Tensile strength	41
2.31	Hybrid glass/kenaf epoxy composite properties: a) Flexural modulus b) flexural strength	41
2.32	Simple explanation of stress directions in fiber reinforced composite	43
2.33	Tensile modulus of short glass fiber polymer composites	45
2.34	Tensile modulus of short hemp fiber reinforced composite	45
2.35	Tensile modulus of randomly oriented long kenaf fiber polymer composite	46
2.36	Tensile modulus of banana/sisal hybrid composite	46
2.37	Load-Deflection diagram of FRP wrapped beams	48
2.38	Debonding failure modes	49
2.39	Distribution of interfacial shear and normal stresses	50
2.40	Debonding because of vertical cracks	50
2.41	Debonding because of diagonal shear crack	50
2.42	Failure modes of RC beam strengthened with soffit plate	51
3.1	Different long kenaf fiber bundles	55
3.2	Process of extracting kenaf fibers	56
3.3	Immersion of fiber in NaOH solution	57
3.4	Printed pattern	58
3.5	Single fiber specimen for tensile test	58
3.6	Tensile testing machine	59
3.7	SEM equipment	60
3.8	Fiber specimens for SEM visualization	60
3.9	Steel molds for fabricating composites	63

3.10	Kenaf fiber after cutting	64
3.11	Kenaf fiber air dried	64
3.12	Fiber reinforced polymer composite fabrication	66
3.13	Composite specimens	67
3.14	Strain gages on the composite specimens	68
3.15	Testing equipment	68
3.16	Procedure of making strengthening plate	70
3.17	Casting of RC beams	72
3.18	RC beams strengthening	73
3.19	Testing setup	73
3.20	Geometry of RC beam specimens	75
3.21	The connection of LVDT and strain gauges to data logger	77
4.1	The physical appearance of kenaf fiber after treatment	80
4.2	SEM images of the effects of the alkaline treatment on the kenaf fiber groups	81
4.3	SEM images of the effect of the alkaline treatment on kenaf fiber of group A	82
4.4	Evaluation of diameter by using of SEM	83
4.5	Histogram of untreated kenaf fiber from group A	84
4.6	Histogram of untreated kenaf fiber from group B	84
4.7	Histogram of 3 hours immersion of 5% alkaline treatment of kenaf fiber group A	85
4.8	A typical diagram of tensile test of kenaf fiber	87
4.9	System Compliance method for untreated kenaf fiber from group A	88
4.10	Regression of a line between the strain-stress point of	89

	untreated kenaf fiber specimens from group A	
4.11	System compliance method for 3 hours-5% alkaline kenaf fiber from group A	90
4.12	Regression of a line between the strain-stress point of 3 hours-5% alkaline treatment of kenaf fiber specimens	91
4.13	Tensile strength of different treatment conditions of group A	92
4.14	Maximum strain of different treatment conditions of group Av	92
4.15	Tensile modulus of different treatment conditions of group A	93
4.16	Tensile strength of different treatment conditions of group B	93
4.17	Maximum strain of different treatment conditions of group B	94
4.18	Tensile modulus of different treatment conditions of group B	94
4.19	Tensile strength of untreated kenaf fiber from different groups	95
4.20	Elongation at break of untreated kenaf fiber from different groups	95
4.21	Tensile modulus of untreated kenaf fiber from different groups	96
4.22	Tensile strength of 5% alkaline treatment in 3 hours for different kenaf fiber groups	96
4.23	Elongation at break of 5% alkaline treatment in 3 hours for different kenaf fiber groups	97
4.24	Tensile modulus of 5% alkaline treatment in 3 hours for different kenaf fiber groups	97
4.25	A typical force-stroke diagram of testing machine	99

4.26	Stress-strain diagram of different fiber volume content of KFRP	101
4.27	The effect of kenaf fiber volume content on the tensile strength and maximum strain of KFRP	101
4.28	The effect of kenaf fiber volume content on the tensile strength and tensile modulus of KFRP	102
4.29	Rupture section of KFRP	103
4.30	SEM image of rupture area of KFRP	103
4.31	Stress-strain diagram of different fiber volume content of GFRP and KFRP	105
4.32	The effect of glass fiber volume content on the tensile strength and maximum strain of GFRP	105
4.33	The effect of glass fiber volume content on the tensile strength and tensile modulus of GFRP	106
4.34	SEM image of fracture section of GFRP	107
4.35	The strain energy density of GFRPs and KFRPs	107
4.36	Stress-strain diagram of HKGFRP-10	109
4.37	The effect of glass fiber volume fraction on the tensile strength and elongation at break in HKGFRP-10	109
4.38	The effect of glass fiber volume fraction on the tensile strength and tensile modulus in HKGFRP-10	110
4.39	The stress-strain curve of HKGFRP-30	112
4.40	The effect of glass fiber volume fraction on the tensile strength and strain of HKGFRP-30	112
4.41	The effect of glass fiber volume fraction on the tensile strength and tensile modulus of HKGFRP-30	113
4.42	Mode of failure in the tensile test of HKGFRP-30	113
4.43	Fracture section of HKGFRP-30	114
4.44	The strain energy density of HKGFRP-30	114

4.45	Stress-strain curve of HKGFRP-40 (40% fiber volume content)	116
4.46	The effect of glass fiber volume fraction on the tensile strength and strain of HKGFRP-40	117
4.47	The effect of glass fiber volume fraction on the tensile strength and tensile modulus of HKGFRP-40	117
4.48	SEM image of fracture section of HKGFRP-40 with 35% glass fiber fraction	118
4.49	Fracture section of HKGFRP-40 with 35% glass fiber fraction	118
4.50	The strain energy density of HKGFRP-40	119
4.51	Glass fibers orientation in composite	120
4.52	Kenaf fibers orientation in composite	121
4.53	Bonding between glass fiber and matrix	122
4.54	Deficient of bonding strength between glass fiber and epoxy matrix	123
4.55	Close view of the contact surface of glass fiber and polymer matrix	123
4.56	The fracture section of KFRP	124
4.57	The strong bonding of kenaf fiber and polymer matrix	124
4.58	SEM image of the section of fracture point from HKGFRP-30 ($V'_G= 50\%$)	125
4.59	SEM image of fracture section of hybrid composite from HKGFRP-30 ($V'_G= 10\%$)	126
4.60	Fracture section of hybrid composite	126
4.61	Comparison between some known bio fibers	127
4.62	Stress-strain curve of some significant composite series	128
4.63	The strain energy density of some significant composite series	129

5.1	Load versus mid-span deflection of control RC beams	132
5.2	Load versus steel and concrete strain for RC control beams	132
5.3	The crack propagation in the control beams	133
5.4	The load versus mid-span deflection of BG50 beams	135
5.5	Load versus strain of tensile steel, compression concrete and strengthening plate at the mid-span of BG50	135
5.6	The crack propagation of BG50-2	136
5.7	Debonding of strengthening plate from concrete substrate in BG50-1	136
5.8	Load versus mid-span deflection of BG100 beams	138
5.9	Load versus strain of tensile steel, compression concrete and strengthening plate at the mid-span for BG100	138
5.10	Crack pattern and debonding area of BG100-2	139
5.11	Debonding area and the placement of main crack of BG100-1	139
5.12	Load versus mid-span deflection in BK50 beams	141
5.13	Load versus strain of tensile steel, compression concrete and strengthening plate at the mid-span for BK50 specimens	141
5.14	Crack propagation in BK50-2	142
5.15	The crack which caused the failure in BK50-2	142
5.16	Debonding from the crack point followed by plate rupture in BK50-2	143
5.17	Close view of failure region of strengthening plate between two point loads in BK50-1	143
5.18	Load versus mid-span deflection in BK100	145
5.19	Load versus strain of tensile steel, compression concrete and strengthening plate at the mid-span for BK100	145

5.20	Crack pattern of BK100-1	146
5.21	Close view of the failure area of strengthening plate and crack width in BK100-1	146
5.22	Load versus mid-span deflection of BH50	148
5.23	Load versus strain of tensile steel, compression concrete and strengthening plate at the mid-span for BH50	148
5.24	The crack pattern for the BH50-1	149
5.25	The fracture area of BH50-1 at the mid-span	149
5.26	Debonding in BH50-2 at the mid-span	150
5.27	Load versus mid-span deflection of BH100	151
5.28	Load versus strain of tensile steel, compression concrete and strengthening plate at the mid-span for BH100	152
5.29	Crack propagation and failure mode of BH100-1	152
5.30	Close view of the concrete fracture area for BH100-1	153
5.31	Concrete fracture area of BH100-2	153
5.32	Failure modes of beams in this study	156
5.33	Moment capacity and mid-span deflection of beam samples	158
5.34	Load - deflection curves of all beam specimens	159
5.35	The stiffness of beams	160
6.1	The tensile modulus of KFRP due to ROM and experimental results	166
6.2	The stress – strain diagram of KFRPs from tests and theory	166
6.3	Stress-strain diagram of KFRPs from tests and adapted ROM method	167
6.4	Comparison between analytical method and experimental results of tensile modulus for GFRP	168

6.5	The stress –strain curve of GFRPs due to experimental results and ROM method	168
6.6	Comparison between analytical method and experimental results of tensile modulus for HKGFRP-10	170
6.7	The stress – strain diagram of HKGFRP-10 due to tests results and ROM	170
6.8	Comparison between analytical method and experimental results of tensile modulus for HKGFRP-30	172
6.9	The stress – strain diagrams of KHGFRP-30 for different glass fiber volume fraction due to tests results and ROM	172
6.10	The tensile modulus of HKGFRP-40 for different glass fiber volume fraction due to tests results and ROM	174
6.11	The stress – strain diagrams of HKGFRP-40 for different glass fiber volume fraction due to tests results and ROM	174
6.12	Stress - strain diagram of concrete under compression	177
6.13	Stress and strain distribution of RC beam section	177
6.14	Experimental and analytical results of moment capacity of RC beam section for different strengthened beam series	180
6.15	The moment capacity of RC beam groups due to tests results, analytical model and ACI 440.2R	182
6.16	The strain of tensile steel of RC beam groups due to tests results, analytical method of this study and ACI 440.2R	183
6.17	The maximum compressive concrete strain of strengthened beams due to experimental results, analytical model and ACI 440.2R model	183

LIST OF ABBREVIATION

KFRP	-	Kenaf fiber reinforced composite
GFRP	-	Glass fiber reinforced composite
HKGFRP	-	Hybrid kenaf/glass fiber composite
RC	-	Reinforced concrete
ROM	-	Rule of mixture

LIST OF SYMBOLS

A	-	Sectional area
C	-	Neutral axis placement
E	-	Modulus of elasticity
F	-	Force
h	-	Height of beam
L	-	Length of specimen
$\rho_{c(p)}$	-	Density of composite
ρ_m	-	Density of matrix
ρ_f	-	Density of kenaf fiber
ρ_G	-	Density of glass fiber
V_m	-	Volume content of matrix
V_f	-	Kenaf fiber volume content
E_k	-	Elasticity moduli of kenaf fiber
E_G	-	Elasticity moduli of glass fiber
V_G	-	Glass fiber volume content
V'_G	-	Glass fiber volume fraction
E_m	-	Elasticity moduli of polymer
V_m	-	Volume content of the polymer matrix
C	-	The distance of neutral axis of beam section from the top of beam
ε_c	-	The distribution of compressive strain of concrete
ε_1	-	The maximum compressive strain of concrete at the top of RC beam
x	-	The distance variable due to neutral axis

LIST OF APPENDICES

APPENDIX	TITLE	PAGE
A	Notification of composite samples	203
B	Concrete mixture	205
C	Tensile test of steel bar	207
D	Kenaf fiber properties by system compliance method	208
E	Calculation the density and modulus of elasticity of composites	210

CHAPTER 1

INTRODUCTION

1.1 Introduction

According to environmental concerns and financial problems, natural fibers have become interesting and fascinating nowadays to be used as an industrial material such as sport equipment, automotive application and construction material for structural and non-structural elements [1-4]. Bio-fibers offer several advantages including high specific strength and modulus, low density, renewable nature, biodegradability, absence of associated health hazards and so on. All natural fibers are cellulosic in texture and composed of cellulose, hemicellulose, lignin and pectin. The major ingredients of natural fibers are cellulose and lignin. Cellulose is a semi crystalline polysaccharide hydrophilic component consisting of a linear chain of anhydroglucose units, which contain alcoholic hydroxyl groups. So, all natural fibers are hydrophilic in nature [5-7]. Therefore, fiber-matrix interface adhesion is the most significant parameter in the properties of composites. One of the important issues of natural fiber is the hydrophilic property of cellulose which impacts the weak interface bonding with hydrophobic polymer as a matrix. Chemical surface modifications methods of natural fiber are well documented in literature include alkaline treatment, acidity treatment, coupling agents and, etc.

Using natural fibers in polymer composites has become interesting because of the advantages of renewable fiber source, biodegradability and sustainability. However, an important drawback of natural fibers is the low mechanical properties in comparison to man-made fibers that this issue prevents to use bio fiber as a qualified

material for using as load carrying materials and structural elements [8]. Therefore, for enhancing the mechanical properties of natural fiber composites, man-made fiber, e. g. glass fiber, is used as hybridize the composites [9]. This study is conducted to investigate the characteristics of kenaf-glass fiber hybrid composites and its potential use as the structural elements.

1.2 Background of the study

All vegetable fibers are cellulosic in nature and composed of cellulose, hemicellulose, lignin and pectin. So, all natural fibers are hydrophilic in nature [5-7]. Lignin is an untidy, cross-linked polymer which gives rigidity to fiber [10].

Generally, the mechanical properties of natural fibers like kenaf, hemp, flax and jute lower than that of E-glass fiber commonly used in composites but the density of E-glass is high, $\sim 2.5 \text{ g/cm}^3$, while that of natural fibers is much lower (~ 1.2 to 1.5 g/cm^3). So, The specific strength and specific moduli of some of these natural fibers are quite comparable to glass fibers [7, 11].

Several different initial retting methods were reported [7] that alkaline treatment (mercerization) is a well-known chemical treatment of surface modification of natural fiber for making natural fiber reinforced polymer. This treatment removes lignin, hemicellulose, wax and oils covering the surface of the fiber [12].

Due to particular character of kenaf fiber and its benefit to environment, using of kenaf fiber reinforced polymer composite is increased. The performance of materials is always presented in terms of their mechanical characteristics, such as tensile properties, flexural properties, compression properties, impact properties and wears behavior [13]. These features are significant to determine material ability, especially under extreme and critical situations. Recently, many studies have been completed on kenaf fiber reinforced polymer composites; with the purpose of totally characterize its mechanical behavior [14-17]. Generally, the tensile and flexural

properties of kenaf fiber reinforced polymer composites, differ depending on the variety of fiber, fiber aspect ratio, treatment method, its orientation (random or arrangement), fiber volume content and form (fiber or fabric), type of polymer used, curing method and also the quality of fabricating.

However, an important drawback of natural fibers is the low mechanical properties in comparison to man-made fibers that this issue prevents to use bio fiber as a qualified material for using as load carrying material and structural element [8]. So, for enhancing the mechanical properties of natural fiber composites, man-made fiber, e. g. glass fiber, is used as hybridize the composites [9]. There are a lot of reports done by scientists about making hybrid composite to prove the natural fiber composite properties such as oil palm fiber, jute, sisal, ramie and etc. [8, 9, 18, 19].

1.3 Problem statement

Fiber reinforced polymer composites (FRPs) are being used widely in all industrial aspects that each FRP contains two major parts include polymer matrix and reinforced fiber. Common thermoset polymers such as epoxy, polyester and vinyl ester and common fibers such as carbon, aramid and glass fiber are synthetic materials which are not sustainable to environment due to high energy consumption during process, long time remaining in environment, high smoke emission; on the other side, the green material especially bio-based materials which are made by plant not only does not have any impact to environment but also help to save the nature. Therefore, scientists are attempting to get green composite materials by using of bio-fiber (natural fiber) named bio-composites. Kenaf fiber is one of natural fibers which is cultivated a lot in Malaysia and could be the main nominee for bio-composite as reinforcing fiber. Indeed, characterization of this fiber is the most important subject.

Significantly, bio-fiber like kenaf fiber has two main drawbacks including the hydrophilic surface which is not compatible with epoxy resin (hydrophobic nature) resulting the insufficient interfacial stress between fiber and matrix. The hydroxyl (-OH) group of kenaf fiber causes the hydrophilic nature of kenaf fiber. Also, the

other issue is the lower strength of kenaf fiber as compared to synthetic fiber. The first issue can be improved by using of chemical surface modification method named alkaline treatment which will be done in different conditions in this study. The next issue can be improved by hybridization that in this method the kenaf fiber and synthetic fiber like glass fiber are put in the polymer matrix together as reinforcing material. The aspect ratio of fiber, stacking sequence of fiber layer and fabricating method in FRP can vary depend on the desired goal. For making structural element, it needs to have adequate mechanical properties to meet the design requirements.

Furthermore, due to the changing of design codes in terms of loading coefficients, safety factors and also because of some problems as a result of natural hazards or unexpected loading on structures, some of them need to be strengthened or rehabilitated. Using of strengthening plate to strengthen beams especially RC beams is a well-known method that can be done by using of bio-composite plate. The capability of this green composite should be investigated and clarified.

1.4 Aim and Objectives of the study

The aim of the study is to investigate the characteristics of kenaf-glass fiber hybrid composites and its performance as a strengthening element for reinforced concrete beams. The objectives of the study are,

- a) To characterize the properties of kenaf fiber polymer bio-composites
- b) To evaluate the mechanical properties of kenaf-glass fiber hybrid polymer composites
- c) To investigate the performance of kenaf-glass fiber hybrid polymer composite plates as strengthening element for reinforced concrete beams
- d) To propose a theoretical formulation for kenaf-glass fiber hybrid polymer composites and its application as strengthening element

1.5 Scope of the study

This study is conducted as experimental works in laboratory in two major parts. The first part is about the material development including bio fiber and bio composites and another part is about the application of hybrid bio-composite as structural element to strengthen the RC beam.

* **Material development:** The physical and mechanical properties of kenaf fiber which is supplied by the National Kenaf and Tobacco Board (Malaysia) as long fiber are determined due to the four different conditions of initial water retting process and also nine different settings of chemical surface modifications by NaOH solution. According to ASTM C1557-03 (approved 2008)[20], at least 15 specimens from 3 different gauge lengths are needed to test to get the proper result of the tensile properties of kenaf fiber.

Also, the tensile properties of unidirectional kenaf fiber epoxy bio-composite, unidirectional glass fiber epoxy composite and unidirectional kenaf/glass fiber epoxy composite are investigated in this part based on the well-known standard code named ASTM D3039M-08 [21]. The variable parameter of composites and bio-composite series is the fiber volume content while the variable parameters of hybrid composite are total fiber volume content and kenaf/glass fiber volume fraction. Accordingly, total number of composite series and specimens are 15 and at least 75, respectively, because 5 reasonable results are needed to determine the tensile properties of each series.

* **Application as strengthening plate:** The last part is conducted experimentally to investigate the performances of bio-composite plate and glass/kenaf hybrid composite as structural element to strengthen RC beam under pure flexural moment. Consequently, 3 control RC beams and also 12 RC beams strengthened by kenaf fiber bio-composite, glass fiber composite and hybrid kenaf/glass fiber composite in 2 different plate widths are considered to 4 point loading flexural test. Load, mid-span deflection, tensile steel strain at the middle and compressive concrete at the mid-span are reported as results of test for further

discussion and analysis. Analytical investigation including analysis the results and suggestion of mathematical model is the last section of this part.

1.6 Significance of research

According to the environmental concerns of the man-made materials such as synthetic fibers for fiber reinforced polymer composites, bio materials like bio fibers becomes the best replacing material for using as reinforced fiber in polymer composite field. To introduce the use of green materials for engineering applications is the main goal of this study that it can help to save the nature and to reduce the emission of carbon dioxide. Increasing the knowledge of hybrid composite properties by using of kenaf and glass fiber, can encourage others to follow this kind of research to gain a sustainable material. Furthermore, this study can define new application of natural fiber and also will benefit engineers and industries to use of renewable materials. Besides, this study introduces the continuous unidirectional natural fiber especially kenaf bio-composites structural application for future research. This study establishes design and construction procedure of kenaf bio-composite to assist designer, engineer and architect. Moreover, it may succor to increase the agronomic activities and improve economic sector in Malaysia due to the demanding of kenaf fiber production.

REFERENCES

1. Bernard, M., Khalina, A., Aidy, A., Janius, R., Faizal, M., Hasnah, K. S. and Sannuddin, A. B. The effect of processing parameters on the mechanical properties of Kenaf fiber plastic composite. *Materials and Design*. 2010. 32: 1039-1043.
2. Pervaiz, M. and Sain, M. M. Carbon storage potential in natural fiber composites. *Resources, Conservation and Recycling*. 2003. 39: 325-340.
3. Sreekala, M. S., Kumaran, M. G. and Thomas, S. Water sorption in oil palm fiber reinforced phenol formaldehyde composites. *Composites Part A: Applied Science and Manufacturing*. 2002. 33: 763–77.
4. Saheb, D. N. and Jog, J. P. Natural fiber polymer composites: a review. *Advanced Polymer Technology*. 1999. 18(4): 351–63.
5. Mohanty, A. K. and Misra, M. Kenaf natural fiber reinforced polypropylene composites: a discussion on manufacturing problems and solutions. *Composites: Part A*. 2007. 38(6): 1569-1580.
6. Clemons, C. M. Natural fibers. In: Xanthos, M. ed. *Functional fillers for plastics*. Weinheim: Wiley-VCH. 213-222; 2005.
7. Holbery, J. and Houston, D. Natural-fiber-reinforced polymer composites in automotive applications. *JOM*. 2006. 58(11): 80-86.
8. Cicala, G., Cristaldi, G., Recca, G., Ziegmann, G., El-Sabbagh, A. and Dickert, M. Properties and performances of various hybrid glass/natural fibre composites for curved pipes. *Materials and Design*. 2009. 30: 2538-2542.
9. Jarukumjorn, K. and Suppakarn, N. Effect of glass fiber hybridization on properties of sisal fiber–polypropylene composites. *Composites: Part B*. 2009. 40: 623-627.

10. Fuqua, M. A., Huo, S. and Ulven, C.A. Natural Fiber Reinforced Composites. *Polymer Reviews*. 2012. 52: 259-320.
11. Mohanty, A. K., Misra, M. and Drzal, L. T. Natural fibers, biopolymers, and bio composites . Boca Raton: CRC Press, Taylor & Francis Group. 2005.
12. Li, X., Tabil, L. G. and Panigrahi, S. Chemical Treatments of Natural Fiber for Use in Natural Fiber-Reinforced Composites: A Review. *J Polym Environ*. 2007. 15: 25-33.
13. Akil, H. M., Omar, M. F., Mazuki, A. A. M., Safiee, S., Ishak, Z. A. M. and Abu Bakar, A. Kenaf fiber reinforced composites: A review. *Materials and Design*. 2011. 32: 4107-4121.
14. Omar, M. F., Akil, H., Ahmad, Z. A., Mazuki, A. A. M. and Yokoyama, T. Dynamic properties of pultruded natural fiber reinforced composites using Split Hopkinson Pressure Bar technique. *Material Design*. 2010. 31: 4209–4218.
15. Ochi, S. Mechanical properties of Kenaf fibers and Kenaf/PLA composites. *Mechanics of Materials*. 2008. 40(4-5): 446-452.
16. Sanadi, A. R., Caulfield, D. F., Jacobson, R. E. and Rowell, R. M. Renewable agricultural fibers as reinforcing fillers in plastics: mechanical properties of kenaf fiber– polypropylene composites. *Industrial Engineering Chemical Resource*. 1995. 34: 1889–1896.
17. Chow, C. P. L., Xing, X. S. and Li, R. K. Y. Moisture absorption studies of sisal fibre reinforced polypropylene composites. *Composites Science and Technology*. 2007. 67: 306–313.
18. Junior, C. Z. P., Carvalho, L. H., Fonseca, V. M., Monteiro, S. N., and Almeida, J. R. M. Analysis of the tensile strength of polyester/ hybrid ramie–cotton fabric composites. *Polymer Testing*. 2004. 23: 131–135.
19. Jawaid, M.; Abdul Khalil, H. P. S. and Abu Bakar A. Mechanical performance of oil palm empty fruit bunches/jute fibres reinforced epoxy hybrid composites. *Materials Science and Engineering A*. 2010. 527: 7944-7949.
20. American society for testing and material. *Standard Test Method for Tensile Strength and Young's Modulus of Fibers*. Pennsylvania, ASTM C1557-03. 2008.

21. American society for testing and material. *Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials*. Pennsylvania, ASTM D3039/D3039M. 2008.
22. Hollaway, L. C. A review of the present and future utilisation of frp composites in the civil infrastructure with reference to their important in-service properties. *Construction and Building Materials*. 2010. 24: 2419-2445.
23. American society for testing and material. *Standard Terminology Relating to Plastics* (2011). Pennsylvania, ASTM D883. 2011.
24. GangaRao, H. V. S., Taly, N. and Vijay, P. V. *Reinforced Concrete Design with FRP Composites*. United State of America: Taylor & Francis Group. 2006.
25. Averous, L. and Boquillon, N. Biocomposites based on plasticized starch: Thermal and mechanical behaviours. *Carbohydrate Polymers*. 2004. 56: 111–122.
26. Sheikh-Ahmad, J. Y. *Machining of Polymer Composites*. New York: springer. 2009.
27. Kaw, A. K. *Mechanics of composite materials*. 2nd. ed. Boca Raton: CRC, Taylor & Francis. 2006.
28. Cheremisinoff, N. P. and Cheremisinoff P. N. *Fibreglass-reinforced plastics desk book*. Ann Arbor: Ann Arbor Science. 1979.
29. Harper, C. A. *Handbook of plastics and elastomers*. New York: McGraw-Hill. 1975.
30. Richardson, T. L. and Lokensgard E. *Industrial plastics: theory and applications*. New York: Delmar. 1997.
31. Rassmann, S., Paskaramoorthy, R., Reid, R. G. Effect of resin system on the mechanical properties and water absorption of kenaf fibre reinforced laminates. *Materials and Design*. 2010. 32: 1399-1406.
32. Pecce, M., Ceroni, F., Prota, A. and Manfredi, G. Response Prediction of RC Beams Externally Bonded with Steel-Reinforced Polymers. *Journal of composites for construction*. 2006. 10(3): 195-203.
33. Yu-Fei, W., Jun-Hui, Y. and Ying-Wu Zhou, Y. Ultimate Strength of Reinforced Concrete Beams Retrofitted with Hybrid Bonded Fiber-Reinforced Polymer. *ACI Structural Journal*. 2010. 107(4): 451-460.

34. Jianchun, L., Bakoss, L. S., Samali, B. and Ye, L. Reinforcement of concrete beam±column connections with hybrid FRP sheet. *Composite Structures*. 1999. 47; 805-812.
35. De Farias, M. A., Farina, M. Z., Pezzin, A.P.T. and Silva, D. A. K. Unsaturated polyester composites reinforced with fiber and powder of peach palm: Mechanical characterization and water absorption profile. *Materials Science and Engineering C*. 2003. 29: 510-513.
36. Jawaid, M. and Abdul Khalil, H. P. S. Cellulosic/synthetic fibre reinforced polymer hybrid composites: A review. *Carbohydrate Polymers*. 2011. 86: 1-18.
37. John, M. J. and Thomas, S. Biofibres and biocomposites. *Carbohydrate Polymers*. 2008. 71: 343-364.
38. Cheung, H. Y., Ho, M. P., Lau, K. T., Cardona, F., and Hui, D. Natural fibre-reinforced composites for bioengineering and environmental engineering applications. *Composites: Part B*. 2009. 40: 655-663.
39. Summerscales, J. A review of bast fibres and their composites. Part 1 – Fibres as reinforcements. *Composites: Part A*. 2010. 41: 1329-1335.
40. Pearsall, J. *Concise Oxford English dictionary*. 10th. New York: Oxford University Press. 2002.
41. Mazuki, A. A. M., Akil, H. M., Safiee, S., Ishak, Z. A. M., and Bakr, A. A. Degradation of dynamic mechanical properties of pultruded kenaf fiber reinforced composites after immersion in various solutions. *Composites: Part B*. 2011. 42(1): 71-76.
42. Davoodi, M. M., Sapuan, S. M., Ahmad, D., Ali, A., Khalina, A., & Jonoobi, M. Mechanical properties of hybrid Kenaf/glass reinforced epoxy composite for passenger car bumper beam. *Materials and Design*. 2010. 31: 4927-4932.
43. Aziz, S. H., Ansell, M. P., Clarke, S. J. and Panteny, S. R. Modified polyester resins for natural fiber composites. *Composite Science Technology*. 2005. 65:525–35.
44. Virk, A.S., Hall, W., Summerscales, J. Failure strain as the key design criterion for fracture of natural fibre composites. *Composites Science and Technology*. 2010. 70: 995-999.

45. Parikh, D. V., Calamari, T. A., Sawhney, A. P. S., Blanchard, E. J., Screen, F. J., Warnock, M., Muller, D. H. and Stryjewski, D. D. Improved chemical retting of kenaf fibers. *Textile Resource Journal*. 2002. 72(7): 618-624.
46. Ribot, N. M. H., Ahmad, Z. and Mustaffa, N. K. Mechanical properties of kenaf fiber composite using co-cured in-line fiber joint. *International Journal of Engineering Science and Technology*. 2011. 3(4): 3526-3534.
47. Yousif, B. f., shalwan, A., Chin, C. W. and Ming, K. C. Flexural properties of treated and untreated kenaf/epoxy composites. *Materials and Design*. 2012. 40: 378–385.
48. Malkapuram, R. and Kumar, V. Recent development in natural fiber reinforced polypropylene composites. *Journal of Reinforced Plastics and Composites*. 2008. 28; 1169–1189.
49. Graupner, N., Herrmann, A. S. and Mussig, J. Natural and man-made cellulose fibre-reinforced poly(lactic acid) (PLA) composites: An overview about mechanical characteristics and application areas, *Composites Part A: Applied Science and Manufacturing*. 2009. 40: 810–821.
50. Shibata, S., Cao, Y. and Fukumoto, I. Press forming of short natural fiber-reinforced biodegradable resin: Effects of fiber volume and length on flexural properties. *Polymer Testing*. 2005. 24: 1005–1011.
51. Zampaloni, M., Pourboghraat, F., Yankovich, S. A., Rodgers, B. N., Moore, J., Drzal, L. T., Mohanty, A. K. and Misra, M. Kenaf natural fiber reinforced polypropylene composites: a discussion on manufacturing problems and solutions. *Composites: Part A*. 2007. 38(6): 1569-1580.
52. Michell, A. Composites containing wood pulp fibres. *Appita Journal*. 1986. 39(3): 223-229.
53. Joshi, S.V., Drzal, L.T., Mohanty, A.K. and Arora, S. Are natural fiber composites environmentally superior to glass fiber reinforced composites? *Composites: Part A*. 2004. 35(3): 371-376.

54. Joseph, K., Thomas, S. and Pavithran, C. Effects of chemical treatment on the tensile properties of short sisal fibre-reinforced polyethylene composites. *Polymer*. 1996. 37: 5139–5149.
55. Alawar, A., Hamed, A. M. and Al-Kaabi, K. Characterization of treated date palm tree fiber as composite reinforcement. *Composites: Part B*. 2009. 40: 601-606.
56. Mysamy, K. and Rajendran, I. Investigation on Physio-chemical and Mechanical properties of raw and alkali-treated Agave Americana fibre. *Journal of Reinforced Plastics and Composites*. 2010. 29(19): 2925-2935.
57. Mishra, S., Mohanty, A. K., Drzal, L. T., Misra, M., Parija, S., Nayak, S. K. and Tripathy, S. S. Studies on mechanical performance of biofibre/glass reinforced polyester hybrid composites. *Composites Science and Technology*. 2003. 63: 1377–1385.
58. Ray, D., Sarkar, B. K., Rana, A. K. and Bose, N. R. Effect of alkali treated jute fibres on composite properties. *Bulletin of Materials Science*. 2001. 24(2): 129-135.
59. Morrison, W. H., Archibald, D.D., Sharma, H. S. S., and Akin, D. E. Chemical and Physical Characterization of Water- and Dew-retted Flax Fibers. *Industrial Crops Production*. 2000. 12: 39-46.
60. Edeerozey, A. M. M., Akil, H. M., Azhar, A. B. and Ariffin, M. I. Z. Chemical modification of kenaf fibers. *Materials Letters*. 2007. 61(10): 2023-2025.
61. Valadez-Gonzalez, A., Cervantes-Uc, J. M., Olayo, R. and Herrera-Franco, P. J. Chemical modification of henequén fibers with an organosilane coupling agent. *Composites Part B: Engineering*. 1999. 30(3): 321–331.
62. Agrawal, R., Saxena, N. S., Sharma, K. B., Thomas, S. and Sreekala, M. S. Activation energy and crystallization kinetics of untreated and treated oil palm fibre reinforced phenol formaldehyde composites. *Materials Science and Engineering A*. 2000. 277(1/2): 77-82.
63. Sreekala, M. S. and Thomas, S. Effect of fibre surface modification on water absorption characteristics of oil palm fibres. *Composite Science Technology*. 2003. 63: 861–869.

64. Nair, M. K. C., Thomas, S., and Groeninckx, G. Thermal and dynamic mechanical analysis of polystyrene composites reinforced with short sisal fibres. *Composites Science and Technology*. 2001. 61: 2519–2529.
65. Paul, A., Joseph, K. and Thomas, S. Effect of surface treatments on the electrical properties of low-density polyethylene composites reinforced with short sisal fibers. *Composites Science and Technology*. 1997. 57(1): 67-79.
66. Thomas, S., and Pothan, L. A. *Natural fiber reinforced polymer composites: From macro to nanoscale*. Philadelphia: Old city publishing, Inc. 2008.
67. Bledzki, A. K., Gassan, J. Composites reinforced with cellulose based fibres. *Progress in Polymer Science*. 1999. 24: 221–274.
68. Sreekala, M. S., Kumaran, M. G., Joseph, S., Jacob, M. and Thomas, S. Oil palm fibre reinforced phenol formaldehyde composites: influence of fibre surface modifications on the mechanical performance. *Applied Composite Materials*. 2000. 6: 295-329.
69. Herrera-Franco, P. J. and Valadez-Gonzalez, A. Mechanical properties of continuous natural fibre-reinforced polymer composites. *Composites Part A: Applied Science and Manufacturing*. 2004. 35: 339–45.
70. Herrera-Franco, P. J. and Valadez-Gonzalez, A. A. Study of the mechanical properties of short natural-fiber reinforced composites. *Composites Part A: Applied Science and Manufacturing*. 2005. 36: 597–608.
71. Yang, H. S., Kim, H. J., Son, J., Park, H. J., Lee, B. J. and Hwang, T. S. Rice-husk flour filled polypropylene composites; mechanical and morphological study. *Composite Structures*. 2004. 63; 305–12.
72. Bachtiar, D., Sapuan, S. M. and Hamdan, M. M. The effect of alkaline treatment on tensile properties of sugar palm fibre reinforced epoxy composites. *Materials and Design*. 2008. 29: 1285–1290.
73. Gu, H. Tensile behaviour of the coir fibre and related composites after NaOH treatment. *Materials and Design*. 2009. 30: 3931–3934.

74. Pasquini, D., de Morais Teixeira, E., da Silva Curvelo, A. A., Belgacem, M. N. and Dufresne, A. Surface esterification of cellulose fibres: processing and characterisation of low-density polyethylene/cellulose fibres composites. *Composites Science and Technology*. 2008. 68: 193–201.
75. Seki, Y. Innovative multifunctional siloxane treatment of jute fiber surface and its effect on the mechanical properties of jute/thermoset composites. *Materials Science and Engineering A*. 2009. 508: 247–252.
76. Xue, Y., Du, Y., Elder, S., Wang, K. and Zhang, J. Temperature and loading rate effects on tensile properties of kenaf bast fiber bundles and composites. *Composites Part A: Applied Science and Manufacturing*. 2009. 40:189–96.
77. Sapuan, S. M., Leenie, A., Harimi, M. and Beng, Y. K. Mechanical properties of woven banana fibre reinforced epoxy composites. *Materials and Design*. 2006. 27, 689–93.
78. Chen, H., Miao, M. and Ding, X. Influence of moisture absorption on the interfacial strength of bamboo/vinylester composites. *Composites Part A: Applied Science and Manufacturing*. 2009. 40: 2013–2019.
79. Liew Shan Chin. *Characterization of natural fiber polymer composites for structural application*. Master Thesis. Universiti Teknologi Malaysia, Johor Bahru, Malaysia, 2008.
80. Zuhri, M., Yusoff, M., Salit, M. S., Ismail, N. and Wirawan, R. Mechanical Properties of Short Random Oil Palm Fibre Reinforced Epoxy Composites. *Sains Malaysiana*. 2010. 39(1): 87-92.
81. Rozman, H. D., Tay, G. S., Kumar, R. N., Abusamah, A., Ismail, H. and Ishak, Z. A. M. Polypropylene–oil palm empty fruit bunch–glass fibre hybrid composites: a preliminary study on the flexural and tensile properties. *European Polymer Journal*. 2001. 37(6): 1283-1291.
82. Kalam, A., Sahari, B. B., Khalid, Y. A., Wong, S. V. Fatigue behaviour of oil palm fruit bunch fibre/epoxy and carbon fibre/epoxy composites. *Composite Structures*. 2005. 71: 34-44.

83. GangaRao, H.V.S.; Taly, N. and Vijay, P. V. *Reinforced Concrete Design with FRP Composites*. United State of America: Taylor & Francis Group. 2006.
84. Nishino, T., Hirao, K., Kotera, M., Nakamae, K. and Inagaki, H. Kenaf reinforced biodegradable composite. *Composites Science and Technology*. 2003. 63: 1281–1286.
85. Brahim, S. B. and Cheikh, R. B. Influence of fibre orientation and volume fraction on the tensile properties of unidirectional Alfa-polyester composite. *Composite Science Technology*. 2007. 67(1): 140–147.
86. Ku, H., Wang, H., Pattarachaiyakoop, N. and Trada, M. A review on the tensile properties of natural fiber reinforced polymer composites. *Composites: Part B*. 2011. 42: 456-873.
87. Jacob, M., Thomas, S. and Varughese, K. T. Mechanical properties of sisal/oil palm hybrid fiber reinforced natural rubber composites. *Compos Sci Technol*. 2004. 64(7–8); 955–65.
88. Lee, B. H., Kim, H. J. and Yu, W. R. Fabrication of long and discontinuous natural fibre reinforced polypropylene biocomposites and their mechanical properties. *Fiber Polymer*. 2009. 10: 83–90.
89. American society for testing and material. *Standard Terminology for Composite Materials*. Pennsylvania, ASTM D3878. 2007.
90. American concrete institute. Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures. USA, ACI 440.2R. 2002.
91. Nanni, A. Flexural Behavior and Design of Reinforced Concrete Using FRP Rods,” *ASCE Journal of Structural Engineering*. 1993. 119(11): 3344-3359.
92. Hai, N. D., Mutsuyoshi, H., Asamoto, S. and Matsui, T. Structural behavior of hybrid FRP composite I-beam. *Construction and Building Materials*. 2010. 24(6): 956-969.
93. Moussavi-Torshizi, S. E., Dariushi, S., Sadighi, M. and Safarpour, P. A study on tensile properties of a novel fiber/metal laminates. *Materials Science and Engineering: A*. 2010. 527(18–19): 4920–4925.

94. American concrete institute. Report on Fiber-Reinforced Polymer (FRP) Reinforcement for Concrete Structures. USA, ACI 440.XR. 2009.
95. Ahmed S. K. and Vijayarangan, S. Tensile, flexural and interlaminar shear properties of woven jute and jute-glass fabric reinforced polyester composites. *Journal of Material Process Technology*. 2008. 207: 330–335.
96. Priya, S. P. and Rai, S. K. Mechanical Performance of Biofiber/Glass reinforced Epoxy Hybrid Composites. *Journal of Industrial Textiles January*. 2006. 35(3): 217-226.
97. Wan Busu, W. N., Anuar, H., Ahmad, S. H., Rasid, R. and Jamal, N. A. The Mechanical and Physical Properties of Thermoplastic Natural Rubber Hybrid Composites Reinforced with Hibiscus cannabinus, long and Short Glass Fiber. *Polymer-Plastics Technology and Engineering*. 2010. 49(13); 1315-1322.
98. Halpin, J. C. and Kardos, J. L. The Halpin–Tsai equations: a review. *Polymer Engineering Science*. 1976. 16(5): 344–52.
99. Agarwal, B. D. and Broutman, L. J. *Analysis and performance of fiber composites*. New York: John Wiley & Sons Inc. 1980.
100. Cox, H. L. The elasticity and strength of paper and other fibrous materials. *British J Appl Phys*. 1952. 3: 72–79.
101. Facca, A. G., Kortschot, M. T. and Yan, N. Predicting the elastic modulus of natural fibre reinforced thermoplastics. *Composites Part A: Applied Science and Manufacturing*. 2006. 37; 1660– 1671.
102. Piggott, M. R. *Load bearing fibre composites*. Ontario: Pergamon Press. 1980.
103. Thomason, J. L., Vlug, M. A. Influence of fibre length and concentration on the properties of glass fibre reinforced polypropylene: 1.Tensile and Flexural Modulus. *Comp Part A*. 1996. 27(A): 477–84.
104. Hsueh, C. Young’s modulus of unidirectional discontinuous-fibre composites. *Composite Science Technology*. 2000. 60: 2671–80.
105. Nayfeh, A. H. Thermodynamically induced interfacial stresses in fibrous composites. *Fibre Science Technology*. 1977. 10: 195–209.

106. Venkateshwaran, N., Elayaperumal, A. and Sathiya, G. K. Prediction of tensile properties of hybrid-natural fiber composites. *Composites: Part B*. 2012. 43: 793–796.
107. Obaidat, Y. T., Heyden, S., Dahlblom, O., Abu-Farsakh, G. and Abdel-Jawad, Y. Retrofitting of reinforced concrete beams using composite laminates. *Construction and Building Materials*. 2011. 25: 591-597.
108. Toutanji, H., Zhao, L. and Zhang, Y. Flexural behaviour of reinforced concrete beams externally strengthened with CFRP sheets bonded with an inorganic matrix. *Engineering Structure*. 2006. 28: 557–66.
109. Kachlakev, D. and McCurry, D. D. Behavior of full-scale reinforced concrete beams retrofitted for shear and flexural with FRP laminates. *Composites*. 2000. 31: 445–52.
110. Edalati, M. and Irani, F. Interfacial Stresses in RC Beams Strengthened by Externally Bonded FRP/Steel Plates with Effects of Shear Deformations. *Journal of composites for construction*. 2012. 16(1): 60-73.
111. Maalej, M. and Leong, K. S. Effect of beam size and FRP thickness on interfacial shear stress concentration and failure mode of FRP-strengthened beams. *Composites Science and Technology*. 2005. 65: 1148–1158.
112. Chajes, M. J., Thomson, T. A., Januszka, T. F. and Finch, W. W. Flexural strengthening of concrete beams using externally bonded composite materials. *Construction and Building Materials*. 1994. 8(3): 191-201.
113. Benrahou, K. H., Adda bedia, E. A., Benyoucef, S., Tounsi, A. and Benguediab, M. Interfacial stresses in damaged RC beams strengthened with externally bonded CFRP plate. *Materials Science and Engineering A*. 2006. 432: 12–19.
114. Malek, A. M., Saadatmanesh, H. and Ehsani, M. R. Prediction of failure load R/C beam strengthened with FRP plate due to stress concentration at the plate end. *ACI Structural journal*. 1998. 95(1).

115. Oehlers, D. J. and Moran, J. P. Premature failure of externally plated reinforced concrete beams. *Journal of structural engineering*. 1990. 116: 978-995.
116. Saadatmanesh, H. and Ehsani, M. R. RC beams strengthened with GFRP plates. I: experimental study. *Journal of structural engineering*. 1991. 117(11): 3417-3433.
117. Oehlers, D. J. Reinforced concrete beams with plates glued to their soffits. *Journal of structural engineering*. 1992. 118(8): 2023-2038.
118. Yang, J.; Ye, J. and Niu, Z. Simplified solutions for the stress transfer in concrete beams bonded with FRP plates. *Engineering Structures* 2008. 30: 533–545.
119. Vilnay, O. The analysis of reinforced concrete beam strengthened by epoxy bonded steel plate. *The international journal of cement composites and lightweight concrete*. 1988. 10(2): 73-78.
120. Aprile, A., and Limkatanyu, S. Role of bond in RC beams strengthened with steel and FRP plates. *Journal of structural engineering*. 2001. 127(12): 1445-1452.
121. Smith, S. T. and Teng, J. G. Interfacial stresses in plated beams. *Engineering Structures*. 2001. 23: 857–871.
122. Smith, S. T. and Teng, J. G. FRP-strengthened RC beams. I: review of debonding strength models. *Engineering Structures*. 2002. 24: 385-395.
123. National research council. *Guide for the design and construction of externally bonded FRP systems for strengthening existing structures*. Rome, CNR-DT 200. 2004.
124. Poornima, J. and Sivaraja, M. Performance Enhancement of Concrete Structures using Natural Fibre Composites. *European Journal of Scientific Research*. 2012. 80(3): 397-405.
125. Sen, T. and Reddy, H. N. J. A Numerical Study of Strengthening of RCC Beam Using Natural Bamboo Fibre. *International Journal of Computer Theory and Engineering*. 2011. 3(5): 707-713.
126. American society for testing and material. *Standard Test Method for Poisson's Ratio at Room Temperature*. Pennsylvania: ASTM E132-04. 2010.

127. American society for testing and material (2008). *Standard test methods for void content of reinforced plastics*. Pennsylvania: ASTM D2734-09.2009.
128. American concrete institute. Building code requirements for structural concrete and commentary. USA: ACI 318. 2008.
129. Hognestad, E. A study of combined bending and axial load in reinforced concrete members. *Bull. Series No. 399*, University of Illinois Engineering Experimental Station, Urbana, Ill. 1951.
130. Tucker, C. L., Liang, E. Stiffness predictions for unidirectional short fibre composites: review and evaluation. *Composite Science Technology*. 1999. 59: 655–71.
131. Ramadevi, P., Sampathkumar, D., Srinivasa, C. V. and Bennehalli, B. Effect of alkali on water absorption of single cellulose abaca fiber. *Bio resources*. 2012. 7(3): 3515-3524.