

DURABILITY AND PERFORMANCE OF CARBON FIBRE REINFORCED
POLYMER-CONCRETE BONDING SYSTEM UNDER TROPICAL CLIMATES

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To my beloved parent,

HJ. MOHD HASHIM ISMAIL

and

HJH. CHE NAH BINTI HJ. MOHD YATIM

My beloved wife,

ROBIHA BINTI MD SABIRIN

And our children,

MOHD NAZHIF MOHD HISBANY

MOHD NAUFAL MOHD HISBANY

MOHD NUDZRAN MOHD HISBANY

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ABSTRACT

The existing reinforced concrete structures may require rehabilitation and strengthening to overcome defect and environmental deterioration. Fibre Reinforced Polymer (FRP)-concrete bonding systems can provide solution for the deficiencies, but the durability of the bonded joint needs to be investigated for structural reliability. This research studies the flexural performance of reinforced concrete beams strengthened with Carbon FRP and the interfacial bonding behaviour of CFRP-concrete system under tropical climate exposure. A 300 mm concrete prisms were bonded with CFRP plate and exposed for 3, 6, and 9 months to continuous natural weather, laboratory environment, and wet-dry exposure in 3.5% saltwater solution at room and 40 °C temperature. The prisms were subjected to tension and compression load under bonding test to determine the strain, stress distribution and shear stress transfer behaviour. The flexural performance was studied on 2400 mm length reinforced concrete beams strengthened with CFRP plate and fabric and exposed for six months to similar conditions as the concrete prisms without the higher temperature. The results of the bonding test showed that load transfer was fairly linear and uniform at lower load level and changed to non-linear and non-uniform at higher load level. The force transfers affected and shifted the shear stress distribution along the bonded length. The flexural capacity of the reinforced concrete beams increased between 32% and 37% and for CFRP plate and between 10% and 12% for CFRP fabrics. High interfacial stress developed near the cut-off point and decreased towards the centre of the beam. Plate-end debonding dominated the failure pattern of the beam. The combination of climate effects may have provided better curing of the bonded joints, but longer duration of exposure may be required to weaken the bond strength. Nevertheless, the tropical climate and salt solution did not yield significant bad effect on the CFRP-concrete bonding system.

ABSTRAK

Struktur konkrit sedia ada berkemungkinan memerlukan pemulihan dan pengukuhan bagi mengatasi kecacatan dan kemerosotan disebabkan persekitaran. Sistem ikatan Konkrit-Polimer Bertetulang Gentian boleh memberikan penyelesaian kepada kekurangan tersebut, tetapi ketahanan ikatannya perlu diselidiki untuk keutuhan struktur. Penyelidikan ini mengkaji prestasi lenturan bagi rasuk bertetulang konkrit yang diperkuat dengan Polimer Bertetulang Gentian Karbon dan kelakuan permukaan ikatan Konkrit-Polimer Bertetulang Gentian Karbon dalam iklim tropika. Prisma konkrit berukuran 300 mm diikat dengan plat dan didedahkan sepanjang masa di dalam cuaca semulajadi, persekitaran makmal, dan kitaran basah-kering di dalam 3.5% larutan garam di dalam suhu bilik dan 40 °C selama 3, 6, dan 9 bulan. Prisma tersebut dikenakan daya tegangan dan mampatan untuk ujian ikatan bagi mendapatkan terikan, pembahagian tegasan, dan kelakuan pemindahan tegasan ricih. Ujian prestasi lenturan dijalankan ke atas rasuk bertetulang konkrit sepanjang 2400 mm yang diperkuat dengan plat dan fabrik karbon dan didedahkan selama enam bulan sama seperti keadaan prisma tanpa suhu yang dinaikkan. Keputusan ujian ikatan menunjukkan bahawa pemindahan daya adalah bersifat hampir lurus dan seragam pada peringkat beban rendah dan bertukar kepada tidak lurus dan tidak seragam pada peringkat beban tinggi. Pemindahan daya telah mempengaruhi dan mengalihkan agihan tegasan ricih di sepanjang ikatan. Rasuk yang diperkuat telah mengalami pertambahan kapasiti lenturan diantara 32% sehingga 37% untuk plat dan 10% sehingga 12% untuk fabrik. Tegasan permukaan yang tinggi telah terbentuk berhampiran hujung ikatan dan berkurangan ke bahagian tengah rasuk. Ikatan yang tertanggal di hujung rasuk menguasai corak kegagalan rasuk. Kombinasi kesan iklim mungkin telah menghasilkan pembaikan pengawetan ikatan, tetapi tempoh dedahan yang lebih panjang mungkin diperlukan untuk melemahkan kekuatan ikatan. Namun, iklim tropika dan larutan garam tidak memberikan kesan buruk ketara kepada sistem ikatan Konkrit-Polimer Bertetulang Gentian Karbon.

TABLE OF CONTENTS

CHAPTER	TITLE	PAGE
	TITLE PAGE	i
	DECLARATION	ii
	DEDICATION	iii
	ACKNOWLEDGEMENT	vi
	ABSTRACT	v
	ABSTRAK	vi
	TABLE OF CONTENTS	vii
	LIST OF TABLES	xiii
	LIST OF FIGURES	xvi
	LIST OF SYMBOLS	xxix
	LIST OF APPENDICES	xxx
1	INTRODUCTION	1
	1.1 Background	1
	1.2 Problem Statement	2
	1.3 Objective of Research	3
	1.4 Scope of Research	4
	1.5 Significant of Research	5
2	LITERATURE REVIEW	7
	2.1 Introduction	7
	2.2 Tropical Climate of Malaysia	8
	2.2.1 Rainfall distribution	9
	2.2.2 Temperature Distribution	10
	2.2.3 Relative Humidity	11

2.2.4	Sunshine, Solar radiation and Evaporation	11
2.2.5	Effect of Ultraviolet Radiation	12
2.2.6	Air Quality – Rain Acidity	13
2.3	Concrete Characteristic	14
2.3.1	High Strength and High Performance Concrete	15
2.3.2	High range water reducing admixture (Superplasticizers)	15
2.3.3	Other binder material for high strength concrete	17
2.3.4	Mix Proportions	18
2.3.5	Mixing and Casting	19
2.4	Type of Fibre Reinforced Materials	20
2.4.1	Carbon Fibre	22
2.4.2	Glass Fibre	22
2.4.3	Aramid Fibre	23
2.5	Polymer Matrix Resin	23
2.5.1	Polyester Resin	24
2.5.2	Epoxy Resins	25
2.5.3	Vinylester	26
2.6	Interfacial bond	26
2.6.1	Experimental Programme and Testing method	28
2.6.2	Failure Modes	30
2.6.3	Strain distribution of FRP	31
2.6.4	Force Transfer Length	34
2.6.5	Shear stress distribution	36
2.6.6	Effective bond length	38
2.6.7	Local Bond Stress-slip Relationship	39
2.6.8	Surface Preparation	41
2.6.9	Selecting the right adhesive	43
2.6.10	Adhesive bond durability	43
2.7	FRP for Flexural Strengthening	45
2.7.1	Durability of FRP as strengthening materials	48
2.7.2	Durability of FRP under Tropical climate	57
2.7.3	FRP as internal strengthening materials	61
2.7.4	Failure modes of FRP strengthened beams (Flexural)	64
2.7.5	Interfacial stress in FRP bonded reinforced concrete beam	68
2.7.5.1	Concrete Cover Separation and Plate-end Interfacial Debonding Failure	69
2.7.5.2	Intermediate Crack-induced Interfacial Debonding	70

2.7.5.3	Debonding strength models	70
2.8	Conclusion	73
3	EXPERIMENTAL PROGRAMME	74
3.1	Introduction	74
3.2	Overview of Experimental Program	75
3.3	Equipment and materials requirement	77
3.4	Raw Material	77
3.4.1	Cement	78
3.4.2	Coarse Aggregates	78
3.4.3	Fine Aggregates	79
3.4.4	Water	79
3.4.5	Steel reinforcement	80
3.4.6	Fibre Reinforced Polymer	80
3.4.7	Epoxy	80
3.4.8	Admixtures	82
3.5	Trial Mix for concrete	82
3.6	Mixing Process	83
3.7	Aggregates Physical Properties	84
3.7.1	Sieve Analysis	84
3.7.2	Moisture Content	85
3.8	Steel reinforcement physical properties	85
3.9	Adhesive (Epoxy) physical properties	85
3.9.1	Specimen Geometry	86
3.9.2	Casting of Specimens	86
3.9.3	Exposure Conditions	88
3.9.4	Tensile Testing	90
3.10	Carbon Fibre reinforced polymer physical properties	90
3.10.1	Tensile Strength for CFRP Plate	90
3.11	CFRP Plate Bonding	92
3.11.1	Casting of Concrete Prism	92
3.11.2	Grinding of Concrete Prism Surface	94
3.11.3	Bonding Mild Steel End Tab to Carbon Plate	95
3.11.4	CFRP plate bonding to concrete	98
3.11.5	Conditioning of FRP-concrete bonded prism	101
3.11.6	Instrumentation and test set-up	103

3.12	Determination of bond stress in bonding test	105
3.13	Bonding Test	107
3.14	Flexural Strengthening	109
3.14.1	Casting of Beams	109
3.14.2	Grinding and Bonding FRP to Reinforced Concrete Beam	110
3.14.3	Conditioning of FRP-concrete bonded RC beams	113
3.14.4	Instrumentation and Test set-up	115
3.14.5	Beam Testing for flexural performance	117
3.14.6	Determination of bond Stress in FRP bonded beams	118
3.15	Preparation of Salt Water (NaCl)	119
3.16	Compressive Strength of Exposed Concrete	120
3.17	Concluding Remarks	120
4	PROPERTIES OF ADHESIVE AND CFRP PLATE BEHAVIOUR UNDER TROPICAL CLIMATE	121
4.1	Introduction	121
4.2	Aggregates Properties	121
4.2.1	Sieve Analysis	122
4.2.2	Moisture Content	123
4.3	Cubes Compressive strength	124
4.4	Trial Mix	124
4.5	Concrete for prism and reinforced concrete beams	126
4.6	Tensile Strength for Steel reinforcement	128
4.7	Results and Discussion for CFRP Properties	129
4.7.1	Tensile strength	130
4.7.2	Weight Observation	133
4.7.3	Failure Modes	142
4.8	Results and Discussion for Adhesive Properties	143
4.8.1	Tensile Strength	144
4.8.2	Density	147
4.8.3	Weight Observation	150
4.8.4	Failure Modes	160
4.9	Conclusion	162
4.9.1	Compressive strength of concretes	162
4.9.2	CFRP Plate Properties	162
4.9.2.1	Tensile strength of CFRP Plates	162

	4.9.2.2 Weight Observation	163
	4.9.2.3 Failure Modes	163
	4.9.3 Adhesive Properties	163
	4.9.3.1 Tensile Strength	163
	4.9.3.2 Density	165
	4.9.3.3 Weight Observation	165
	4.9.3.4 Failure Modes	166
5	BONDING PERFORMANCE OF CFRP-ADHESIVE-CONCRETE SYSTEM	167
5.1	Introduction	167
5.2	Experimental Results and Discussion	168
	5.2.1 Tensile Failure Load	170
	5.2.2 Plate Strain along Bonded Joint	174
	5.2.3 Force Transfer between Plate and Concrete	183
	5.2.4 Bond Stress Distribution (shear)	192
	5.2.5 Failure Modes	215
5.3	Climate Observation during Experimental Works	221
5.4	Strain in concrete prism and CFRP plate	223
5.5	Conclusion	226
6	FLEXURAL PERFORMANCE OF CFRP-BONDED REINFORCED CONCRETE BEAM	228
6.1	Introduction	228
6.1	Results and Discussion for Control and Conditioned Beams under Flexural Test	228
	6.1.1 Load Carrying Capacity	229
	6.1.2 Load – strain at Mid-span	232
	6.1.3 Load-deflection characteristics	239
	6.1.4 Modes of Failure and Cracking Behaviour	249
	6.1.5 Structural Ductility	254
	6.1.6 Position of Neutral Axis	258
	6.1.7 Measuring Interfacial Shear Stress Concentration	263
	6.1.8 Comparison between test results and existing model predictions	274
6.2	Conclusion	279

7	CONCLUSION AND RECOMMENDATIONS FOR FUTURE RESEARCH	282
7.1	Conclusion	282
7.2	Recommendation for Future Research	287
	REFERENCES	289
	Appendices A – S	301-324

LIST OF TABLES

TABLE NO.	TITLE	PAGE
2.1	Typical Fibre Properties used in Strengthening Application	21
2.2	Qualitative comparison between common fibres	21
2.3	Comparison of common fibres properties to steel	22
2.4	Basic properties of thermoset resin	24
2.5	The effect of having good surface condition on the short and long term of adhesive bonds	42
2.6	Ultimate strength for each type of reinforcement and exposure condition	51
2.7	Effect of Moisture Content of structural system	55
2.8	Tensile properties of GFRP sheets after conditioning	61
2.9	Failure mechanism of flexural capacities of FRP strengthened beams	67
3.1	Test for materials properties	76
3.2	Test Program for interfacial bond behaviour (prism)	76
3.3	Test Program for strengthened RC beams	77
3.4	Chemical Composition of Cement used in the investigation	78
3.5	Properties of CFRP used in the investigation	80
3.6	Typical physical properties of Adhesive	81
3.7	Quantities of materials for concrete mix	83
3.8	The exposure and the duration of conditioning for tensile adhesive specimens	89

3.9	The exposure and the duration of conditioning for CFRP plate tensile specimens	92
3.10	The exposure and the duration of conditioning for CFRP-concrete bonded prisms	101
3.11	Test programme for CFRP bonded prisms, tensile adhesive and CFRP tensile plate	103
3.12	Beam dimension and Strengthening details	114
3.13	Test programme for CFRP-bonded reinforced concrete beams	115
3.14	Exposure conditions for concrete cubes	120
4.1	Particle Size distributions for the Fine and Coarse Aggregates	122
4.2	Results of Moisture for Fine and Coarse Aggregates	124
4.3	Results of selected trial mix	125
4.4	Compressive strength of cubes for prisms	127
4.5	Compressive strength of concrete used for reinforced concrete beams	127
4.6	Tensile stress of tension and hanger bar	129
4.7	Average tensile strength of control and conditioned CFRP plate	132
4.8	Tensile strength of epoxy adhesive at all exposure durations	145
4.9	The average densities of adhesive specimens	148
5.1	Tensile load at ultimate failure	171
5.2	Local strains at 45 kN for all bonded specimens at each exposure conditioned at 3, 6 and 9 months of exposure	175
5.3	Force transfer length at three months exposure	188
5.4	Force transfer length at six months exposure	188
5.5	Force transfer length at nine months exposure	188
5.6	The magnitude of local force along bonded length at applied load at 3, 6 and 9 months of exposure	189
5.7	The rate of local force transfer at 45 kN along bonded length at 3, 6, and 9 months of exposure	190

5.8	Normalized load for various exposure conditions at 3, 6 and 9 months of exposure duration	208
5.9	Location of maximum shear stress for 3, 6 and 9 months of exposure	208
5.10	Stress concentration ratio for samples subjected to 3, 6 and 9 months of exposure	211
6.1	Load performance of control and exposed beams	230
6.2	Deflection behaviour of all beams at ultimate load	244
6.3	Deflection behaviour of all beams at yield of steel reinforcement	246
6.4	Deflection behaviour of all beams at serviceability limit state	246
6.5	Deflection behaviour of all beams at a same load level of 66 kN	248
6.6	Cracks behaviour and failure modes pattern	253
6.7	Ductility indices and ratios	256
6.8	The effect of exposure condition on depth of neutral axis at same load level	263
6.9	Strain and shear stress distribution near ultimate failure for beams	265
6.10	Average bond stress at maximum strain	274
6.11	Geometrics and materials properties	275
6.12	Comparison of peak interfacial shear stress	279

LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
2.1	World Map of climate classification	9
2.2	Annual rainfall distribution of Johor and Peninsular Malaysia.	10
2.3	Temperature records for Malaysia for the last 50 years	11
2.4	Annual Average rainwater pH for Malaysia for (a) 2003, (b) 2004, and (c) 2005	14
2.5	Compressive strength of 10mm and 20 mm aggregates	19
2.6	Comparison between typical FRP and mild steel stress-strain behaviour	22
2.7	The bonding system of FRP to concrete surface	26
2.8	Bonding failure mechanism (a) flexural peeling (b) shear peeling (c) axial peeling	27
2.9	Specimen Size and Test Set –up for single shear test (a) specimen for single shear (b) Test rig set –up	29
2.10	Pull off test arrangement (a) The details of specimens size with location of reading instruments and (b) Special built rest rig for instrumentation and measurement	29
2.11	Observed failure modes in plate bonded joint (a) cohesive failure through adhesive (b) adhesive failure and (c) concrete shearing failure	31
2.12	Strain distribution along bonded joint of (a) 1-sheet GFRP-concrete for bonded length = 180 mm (b) 2-sheet GFRP-concrete for bonded length = 320 mm (c) 1-sheet CFRP-concrete for bonded length = 160 mm (d) 2-sheet GFRP-concrete for bonded length = 320 mm	32

2.13	Strain distribution along FRP strips for various length and load level (a) lower load level and $L_{FRP} = 75$ mm (b) higher load level and $L_{FRP} = 75$ mm (c) lower load level and $L_{FRP} = 190$ mm and (d) higher load level and $L_{FRP} = 190$ mm	33
2.14	Strain level as a function of load level and distance from the loaded end for (a) Steel bonded plate and (b) CFRP bonded plate	33
2.15	Strain distribution along the bonded sheet (a) at early age and (b) at post peak region of load response – point C.	34
2.16	Plate force distribution for lower strength concrete (a) control (b) wet-dry (c) freeze-thaw and (d) dual wet-dry, freeze-thaw	35
2.17	Plate force distribution	35
2.18	Shear stress distribution as function of relative load level of (a) 1-sheet GFRP-concrete (b) 2-sheet GFRP-concrete (c) 1-sheet CFRP-concrete (d) 2-sheet CFRP-concrete	37
2.19	(a) Strain distribution and (b) Shear stress distribution along the bonded joint for GFRP plate-100 mm	37
2.20	Shear stress distribution for lower strength concrete (a) control (b) wet-dry NaCl (c) freeze-thaw and (d) dual wet-dry, freeze-thaw	38
2.21	Effective bond length vs stiffness	39
2.22	Bond-stress model	40
2.23	Bond-slip behaviour in tropical climate	41
2.24	Experimental results on load-slip for FRP plate	41
2.25	Ultimate strength of FRP strengthened concrete bonded with epoxy adhesive cured in different water content	44
2.26	Strength reduction of epoxy after 3 months immersion in water (excess)	45
2.27	Various plate arrangement for RC strengthening	46
2.28	Ratio of maximum flexural load of bonded beam to unbonded for different FRP sheets (C= carbon, G= Glass)	50
2.29	Percentage reduction in strength due to wet-dry cycle exposure	50
2.30	Relationship between beam strength and number of cycle of exposure	52
2.31	Load deflection behaviour for CFRP in tropical climate	57

2.32	Effect of weathering on Long term deflection	59
2.33	Load deflection behaviour for beam with load 350 mm from support for the conditioned beams [89]	60
2.34	Typical failure modes of externally bonded RC beams (a) FRP rupture (b) compressive concrete crushing (c) shear failure (d) concrete cover separation (e) plate-end interfacial debonding and (f) interfacial cracked induced debonding (flexural)	66
3.1	Particles shape and surface texture of coarse aggregates used.	79
3.2	Samples of fine aggregates (sand) used in the research works	79
3.3	Adhesive used in this study (a) Two part, Mapei, Adesilex PG2 SP structural epoxy (A and B) and (b) Sika, Sikadur 330 saturating epoxy	81
3.4	(a) Trial mix in small amount in small container (b) Mixing ingredient in mechanical mixer (c) slump test and (d) trial mix specimen in mould	83
3.5	Dimension of dog-bone shape epoxy specimen for tensile test	86
3.6	Mould for casting the tensile test for epoxy (a) male components and (b) female parts	87
3.7	The process of mixing epoxy and hardener for tensile test for epoxy (a) separated components – epoxy (dark grey) and hardener (white) (b) mixing of the materials using low speed electrical mixer and (c) mixed materials	87
3.8	Casting Curing and demoulding process of dog bone specimens for tensile test (a) Laying and shaping the specimens for epoxy tensile test (b) curing- hardening (c) demoulding using rubber hammer and (d) demoulded specimens	88
3.9	Tensile specimen for adhesive in various exposure conditions (a) control and laboratory (b) tropical weather exposure (c) samples in heated saltwater	89
3.10	Testing adhesive tensile specimen being tested for tensile strength	90
3.11	The dimension and configuration of CFRP plate for tensile test	91
3.12	Preparation sequence of casting concrete prism (a) preparation of plywood formwork (b) mixing of ingredient using pan-type mixer (c) casting of mould (d) concrete cubes for compression and (e) curing of concrete prisms	93

3.13	Concrete prism after demoulding from the formworks.	93
3.14	The grinding process of concrete prism (a) measuring and taping the area needed to be ground (b) clamping the end of concrete prism and (c) the roughened surface of the concrete prism	94
3.15	Mild steel end tab used in the investigation (a) dimension and (b) actual appearance	95
3.16	Special built fixture for bonding end tab to concrete plate.	96
3.17	Removal of plate plastic cover (a) peeling off the plastic sheet on both sides and (c) measuring the length to be bonded	96
3.18	Process of bonding mild steel end tab to carbon plate (a) applying adhesive to mild steel end tab (b) placing the mild steel end tab on base plate (c) applying adhesive to both sides of CFRP plate (d) placing CFRP plate on plate (e) placing top plate on bonded FRP plate and (f) specimen after demoulding	97
3.19	Special rig used for bonding FRP plate to concrete surface	98
3.20	Bonding process of CFRP to concrete surface (a) cleaning exposed concrete surface (b) drying the concrete surface (c) applying adhesive to exposed concrete surface (d) applying thin adhesive on CFRP plate (e) applying plate to concrete surface (f) applying pressure to concrete surface (g) removing excess adhesive (h) completed bonding on one side (i) bonding complete on both sides of concrete and (j) Concrete prism completely bonded and ready for conditioning and testing.	100
3.21	Concrete prism in various exposure conditions (a) laboratory (b) immersion in saltwater for three days (c) immersion in at 40 °C saltwater for four days (d) outside tropical exposure and (e) drying in lab	102
3.22	Demec disc applied on concrete and CFRP plate of concrete prisms	104
3.23	Both sides of concrete prism instrumented with strain gauges (a) six numbers and (b) four numbers	105
3.24	Equilibrium of element of bonded joint	105
3.25	Specimen dimension and instrumentation location and Test Rig	108
3.26	Details of beams prepared (a) in longitudinal arrangement and (b) the cross section.	109

3.27	Preparation of reinforced concrete beams (a) steel mould and reinforcement (b) mixer used in the investigation (c) casted concrete (d) preparing specimens for compressive strength for beams (e) curing of beams and (f) beams demoulded from the steel mould.	110
3.28	Concrete surface exposure and bonding of CFRP plate and onto the concrete (a) grinding concrete surface using air tools hammer (b) removing dust from the concrete surface (c) applying structural epoxy (d) applying epoxy in the CFRP plate (e) applying force on the plate and (f) applying fabric onto the wet saturating epoxy.	112
3.29	Beams bonded with CFRP fabric and plate	113
3.30	Exposure conditions of strengthened beams (a) open tropical weather (b) we-dry with salt solution in laboratory environment (c) full immersion in saltwater for dual saltwater and tropical exposure (d) wet-dry in saltwater (with cover) and (e) 1 week tropical exposure for F-SDT specimens	116
3.31	Instrumentation set-up for flexural test on beam shown on half side	117
3.32	Stress distribution in an arbitrary element of FRP	118
3.33	Preparing sodium chloride solution with salt (a) weighted salt (b) diluting the salt with water in 40L container (c) a tank filled up with salt water and (d) hydrometer for measuring specific density and pH test kid	119
4.1	Size distribution for fine aggregates	123
4.2	Size distribution for coarse aggregates	123
4.3	A samples of concrete cubes physical appearance after compression test	125
4.4	Development of concrete strength for prism	127
4.5	Development of compressive strength for concrete used in reinforced concrete beams	128
4.6	Compressive strength of exposed concrete at 9 months exposure	128
4.7	Typical failure modes of tension bar	129
4.8	Conditioned CFRP plate (a) immediately after exposure and (b) specimens ready for testing	130

4.9	Average tensile strength of CFRP plate at various exposures duration	131
4.10	The percentage change in weight of CFRP specimens exposed under various environments at completed cycle for three months exposure group	134
4.11	The percentage change in weight of CFRP specimens exposed under various environments at completed cycle for six months exposure group	135
4.12	The percentage change in weight of CFRP specimens exposed under various environments at completed cycle for nine months exposure group	135
4.13	Development of physical appearance of dual exposure specimen (TP-S40DT)	135
4.14	Salts crystal formed on the surface of CFRP plate after nine months	136
4.15	The percentage change in weight of specimen conditioned under salt solution in the laboratory at each measured day for three months exposure samples	137
4.16	The percentage change in weight of specimen conditioned under salt solution in the dual environment at each measured day for three months exposure samples	138
4.17	The percentage change in weight of specimen conditioned under salt solution in the laboratory at each measured day for six months exposure samples	138
4.18	The percentage change in weight of specimen conditioned under salt solution in the dual environment at each measured day for six months exposure samples	139
4.19	The percentage change in weight of specimen conditioned under salt solution in the laboratory at each measured day for nine months exposure	140
4.20	The percentage change in weight of specimen conditioned under salt solution in the dual environment at each measured day for nine months exposure	141
4.21	Typical failure modes of CFRP plate tested at three months exposure duration	142
4.22	Typical failure modes of CFRP plate tested at six months exposure duration	143
4.23	Tensile strength of adhesive at all exposure duration months	144

4.24	Mass density of adhesive under various environmental exposures	148
4.25	Samples of cross section of failure adhesive for control and at nine months exposure	149
4.26	The percentage change in weight of adhesive specimens exposed under various environments for three months (cycles) of exposure	151
4.27	The percentage change in weight of adhesive specimens exposed under various environments for six months (cycles) of exposure	152
4.28	The percentage change in weight of adhesive specimens exposed under various environments for nine months (cycles) of exposure	153
4.29	Weight development of adhesive specimens for a duration of three months from exposure day for laboratory conditioning	155
4.30	Weight development of adhesive specimens for three months from exposure day for dual conditioning	156
4.31	Weight development of adhesive specimens for a duration of six months from exposure day for laboratory conditioning.	156
4.32	Weight development of adhesive specimens for six months from exposure day for dual conditioning	157
4.33	Weight development of adhesive specimens for a duration of nine months from exposure day for laboratory conditioning	158
4.34	Weight development of adhesive specimens for nine months from exposure day for dual conditioning	159
4.35	Failure patters of each conditioned adhesives specimens and comparison in physical appearance (colour) for three, six (centre) and nine months of exposure	161
5.1	Physical appearance of specimens after being conditioned for nine months	169
5.2	Testing process of bonded concrete prism (a) placing and securing the bottom holder of test rig on tensile machine (b) placing the specimen inside the test rig (c) inserting the top plate of test rig (d) securing the test rig top holder and specimen into the machine and (e) specimen ready for testing	170
5.3	Tensile strength of CFRP plate for prisms at various exposures duration	173

5.4	Strain distribution at load level 20kN along bonded joint under various exposures condition (a) 3 months (b) 6 months and 9 months	176
5.5	Strain distribution at 45 kN along bonded joint under various exposures condition (a) 3 months (b) 6 months and 9 months	177
5.6	Strain distribution along bonded joint under various environmental conditions at three months of exposure	179
5.7	Strain distribution along bonded joint under various environmental conditions at six months of exposure	180
5.8	Strain distribution along bonded joint under various environmental conditions at nine months of exposure	181
5.9	Intersection of strain distribution for selected specimens at each load level	182
5.10	Plate force distribution along bonded length for under various environmental conditions at three months of exposure	185
5.11	Plate force distribution along bonded length for under various environmental conditions at six months of exposure	186
5.12	Plate force distribution along bonded length for under various environmental conditions at nine months of exposure	187
5.13	Local force distribution at applied load of 20kN along bonded joint under various exposures condition (a) 3 months (b) 6 months and (c) 9 months	191
5.14	Local force distribution at applied load of 45 kN along bonded joint under various exposures condition (a) 3 months (b) 6 months and (c) 9 months	192
5.15	Shear stress distribution for BCL specimen after three months of exposure	195
5.16	Shear stress distribution for BCT specimen after three months of exposure	196
5.17	Shear stress distribution for SDL specimen after three months of exposure	196
5.18	Shear stress distribution for SDT specimen after three months of exposure	196
5.19	Shear stress distribution for S40DL specimen after three months of exposure	197

5.20	Shear stress distribution for S40DT specimen after three months of exposure	197
5.21	Shear stress distribution for BCL specimen after six months of exposure	198
5.22	Shear stress distribution for BCT specimen after six months of exposure	198
5.23	Shear stress distribution for BSDL specimen after six months of exposure	198
5.24	Shear stress distribution for BSDT specimen after six months of exposure	199
5.25	Shear stress distribution for BS40DL specimen after six months of exposure	199
5.26	Shear stress distribution for BS40DT specimen after six months of exposure	199
5.27	Shear stress distribution for BCL specimen after nine months of exposure	200
5.28	Shear stress distribution for BCT specimen after nine months of exposure	200
5.29	Shear stress distribution for BSDL specimen after nine months of exposure	200
5.30	Shear stress distribution for BSDT specimen after nine months of exposure	201
5.31	Shear stress distribution for BS40DL specimen after nine months of exposure	201
5.32	Shear stress distribution for BS40DT specimen after nine months of exposure	201
5.33	Shear stress distribution for various exposure conditions along the bonded length at 20 kN applied load after (a) 3 (b) 6 and, (c) 9 months of exposure	202
5.34	Shear stress distribution for various exposure conditions along the bonded length at 45 kN applied load after (a) 3 (b) 6 and, (c) 9 months of exposure	203
5.35	Shear stress distribution at normalized load at three months exposure at various exposure conditions	204

5.36	Shear stress distribution at normalized load at six months exposure at various exposure conditions	205
5.37	Shear stress distribution at normalized load at nine months exposure at various exposure conditions	206
5.38	Shear stress distribution at normalized load at various exposure conditions and duration (a) 3 months (b) 6 months and, (c) 9 months	207
5.39	Stress concentration after three months of exposure for various environmental conditions	212
5.40	Stress concentration after six months of exposure for various environmental conditions	213
5.41	Stress concentration after nine months of exposure for various environmental conditions	214
5.42	The typical failure position of the bonded prisms immediately after ultimate load (a) BCT (b) BSDL (c) BCL (d) BSDT and (e) BS40DT	215
5.43	Failure modes of tested prism at (a) 3 (b) 6 and, (c) 9 months of exposure	217
5.44	Failure modes of CFRP bonded plate under various exposure conditions after (a) 3 (b) 6 and (c) 9 months of exposure	218
5.45	A small section of concrete rip off from the top part of the prism	219
5.46	The close up view of concrete debonded from prism for three months group	219
5.47	The close up view of concrete debonded from prism for six months group	220
5.48	The close up view of concrete debonded from prism for nine months group	221
5.49	Monthly Rainfall intensity for study area	222
5.50	Monthly mean temperature for study area	223
5.51	Monthly mean relative humidity for study area	223
5.52	Recorded strain of concrete and CFRP plate at various stages of exposure	224
5.53	Recorded strain of concrete at various stages of exposure	226

6.1	Development of strains for concrete, CFRP plate and fabrics for control beam	233
6.2	Development of strains for concrete, and CFRP plate strains at mid span for CFRP strengthened beam	234
6.3	Development of strains for concrete and CFRP fabrics at mid span for CFRP strengthened beam	235
6.4	The close up view of the early stages of strain development (a) control beams (b) beam strengthened with CFRP plates and (c) beam strengthened with CFRP fabrics	236
6.5	Load deflection characteristics of all beams	240
6.6	Load deflection behaviour of concrete beams strengthened with CFRP Plates	241
6.7	Load deflection behaviour for concrete beams strengthened with CFRP fabrics	242
6.8	The elastic section stage at uncracked and cracked section	243
6.9	Flexural cracks for control beams	250
6.10	Cracks pattern for all beams strengthened and exposed beams	250
6.11	Plate debonded with thin layer concrete	251
6.12	Typical debonded pattern of beam at failure	252
6.13	FRP rupture for beam bonded with CFRP fabrics for laboratory salt immersion (FF-SDL-C1)	252
6.14	Depth of neutral axis for control beam without strengthening	259
6.15	Depth of neutral axis for control beam strengthened with CFRP plate	259
6.16	Depth of neutral axis for pre-cracked beam strengthened with CFRP plate and exposed to natural weather	259
6.17	Depth of neutral axis for un-cracked beam strengthened with CFRP plate and exposed to wet-dry salt solution at room temperature in laboratory	260
6.18	Depth of neutral axis for pre-cracked beam strengthened with CFRP plate and exposed to wet-dry salt cycle of solution at room temperature in laboratory	260

6.19	Depth of neutral axis for pre-cracked beam strengthened with CFRP plate and exposed to dual exposure of wet-dry cycle of salt solution and natural weather	260
6.20	Depth of neutral axis for control beam strengthened with CFRP fabrics	261
6.21	Depth of neutral axis for pre-cracked beam strengthened with CFRP fabrics and exposed to natural weather	261
6.22	Depth of neutral axis for pre-cracked beam strengthened with CFRP fabrics and exposed wet-dry cycle of salt solution at room temperature	261
6.23	Depth of neutral axis for pre-cracked beam strengthened with CFRP fabrics and exposed dual exposure of wet-dry cycle of salt solution and natural weather	262
6.24	Strain gauge location viewed from the bottom of the reinforced concrete beams	264
6.25	Strain development during loading for control strengthened specimen	265
6.26	Shear stress distribution along bonded length (a) constant between strain gauges and (b) assuming linear line between two consecutive strain gauges	266
6.27	Samples of strain distribution subjected to curve fitting	267
6.28	Shear stress distribution along bonded length for FP-C-N	268
6.29	Shear stress distribution along bonded length for FP-CT-C1	268
6.30	Shear stress distribution along bonded length for FP-CT-N	268
6.31	Shear stress distribution along bonded length for FP-SDL-C1	269
6.32	Shear stress distribution along bonded length for FP-SDL-N	269
6.33	Shear stress distribution along bonded length for FP-SDT-C1	269
6.34	Shear stress distribution along bonded length for all specimens at 12 kN	270
6.35	Shear stress distribution along bonded length for all specimens at 20 kN	271
6.36	Shear stress distribution along bonded length for all specimens at 40 kN	271

6.37	Shear stress distribution along bonded length for all specimens at 60 kN	271
6.38	Shear stress distribution along bonded length for all specimens at 68 kN	272
6.39	Shear stress distribution along bonded length for all specimens near ultimate failure	272
6.40	Comparison of shear stress distribution for specimen FP-C-N in the CFRP plate near ultimate failure	276
6.41	Comparison of shear stress distribution for specimen FP-CT-N in the CFRP plate near ultimate failure	276
6.42	Comparison of shear stress distribution for specimen FP-CT-C1 in the CFRP plate near ultimate failure	277
6.43	Comparison of shear stress distribution for specimen FP-SDL-N in the CFRP plate near ultimate failure	277
6.44	Comparison of shear stress distribution for specimen FP-SDL-C1 in the CFRP plate near ultimate failure	278
6.45	Comparison of shear stress distribution for specimen FP-SDT-C1 in the CFRP plate near ultimate failure	278

LIST OF SYMBOLS

A_{plate}	-	area of bonded CFRP plate
b	-	width of a CFRP plate
E_c	-	concrete modulus of elasticity
E_p	-	Modulus of Elasticity of CFRP plate
E_u	-	total area under load deflection curve
E_y	-	total area under load deflection curve until reinforcement yielding
g_i	-	strain measurement of CFRP plate
I_g	-	gross transformed section of moment of inertia including
L_{plate}	-	length of bonded CFRP plate
w_{plate}	-	width of bonded CFRP plate
t_p	-	CFRP plate thickness
$\varepsilon_{\text{ftrp}}$	-	rate of change of strain
ε_{max}	-	maximum strain
ΔF	-	longitudinal force in two consecutive points
Δl_i	-	distance between any two consecutive strain gauges
Δx	-	distance between any two consecutive strain gauges
Δ_u	-	ultimate deflection at mid-span of a beam
Δ_y	-	deflection of steel at yielding of steel reinforcement
$\mu\Delta$	-	deflection ductility factor
φ_u	-	ultimate curvature at mid span of a beam
φ_y	-	curvature of steel at yielding of steel reinforcement
$\mu\varphi$	-	curvature ductility factor
μ_E	-	energy ductility factor
μ_E	-	energy ductility factor
δ	-	mid-span deflection of a beam
τ	-	shear stress

LIST OF APPENDICES

APPENDIX	TITLE	PAGE
A-1:	Annual rainfall distribution for Peninsular Malaysia States	301
B-1:	Equation for Parameters for Equation 2.2 and Equation 2.3	302
C-1:	The coefficient and schematic diagram of beams for solving interfacial and normal stress	303
D-1:	Stress strain diagram of one sample of high yield strength reinforcement	304
E-1:	Percentage change of weight for CFRP Plate after three months exposure	305
F-1:	Percentage change of weight for CFRP Plate after six months exposure	306
G-1:	Percentage change of weight for CFRP Plate after nine months exposure	307
H-1:	Percentage change in weight for adhesive specimens for three months exposure	309
I-1:	Percentage change in weight for adhesive specimens for six months of exposure	310
J-1:	Percentage change in weight for adhesive specimens for nine months of exposure	312
K-1:	Different of percentage change of weight between SDL and S40DL	314
L-1:	Different of percentage change of weight between SDT and S40DT	316
M-1:	Strain distribution under various environmental conditions at three months of exposure at each load level	317

N-1:	Strain distribution under various environmental conditions at six months of exposure at each load level	318
O-1:	Strain distribution under various environmental conditions at nine months of exposure at each load level	319
P-1:	The rate of local force transfer along bonded length at three months exposure	320
Q-1:	The rate of local force transfer along bonded length at six months exposure	321
R-1:	The rate of local force transfer along bonded length at nine months exposure	322
S-1:	Strain development during loading for a pre-cracked specimen continuously exposed to natural weather	323
S-2:	Strain development during loading for a specimen continuously exposed to natural weather - no pre-cracked	323
S-3:	Strain development during loading for a non pre-cracked specimen subjected to wet-dry cycle of saltwater in laboratory	323
S-4:	Strain development during loading for a pre-cracked specimen subjected to wet-dry cycle of saltwater in laboratory	324
S-5:	Strain development during loading for a pre-cracked specimen subjected to dual exposure of wet-dry cycle of saltwater and tropical weather	324

CHAPTER 1

INTRODUCTION

1.1 Background

A large numbers of bridges, building, and other structures require rehabilitation and strengthening due to continuous deterioration during its service life. Reinforced concrete made by an ideal combination of concrete and reinforcing bars has been used as the main structural material in the construction of these structures. Some of these structures may be subjected to increases in service loads, changes in the use of the structure, design or construction errors, degradation problem, changes in design codes regulation and seismic retrofits that can possibly lead to the need for rehabilitation of the existing structure.

An appreciable worldwide interest has been given to the use of Fibre Reinforced Polymer (FRP) in the rehabilitation of concrete structures to extend their service life. Fibre Reinforced Polymer system comprises of continuous fibres of high tensile strength within a polymer matrix. The matrix has two functions in which it enable the loads to be transferred among the fibres and the matrix also acts to protect the fibres against environmental attacks and mechanical damage during handling. These fibres have beneficial properties such as high stiffness to weight ratio, high strength to weight ratio, superior environmental durability, resistance to corrosion, high durability, ease of application and low maintenance [1, 2]. The properties have made them a competing alternative to the conventional strengthening and repair materials. External pre-stressing and bonding of steel plates to the tension face of the concrete beams are some of the methods applied in strengthening and

repairing deteriorated concrete structures in order to improve the stiffness and strength.

1.2 Problem Statement

Strengthening of existing reinforced concrete structures may be necessary in order to overcome the increase in loading capacity and also due to the effect of environmental degradation. Over the years, reinforced concrete structures are subjected to deterioration due to, among others, alkali-aggregates reaction, chloride induced corrosion, and carbonation. The damaged structures need to be addressed with rehabilitation.

Since 1980s, the use of fibre reinforced polymers for the strengthening of reinforced concrete members has taken momentum and a significant number of studies on flexural and shear strengthening of beams, axial strengthening of columns and more recently, strengthening of joints have been conducted. FRP has been used and studied in different configurations, techniques and environment to utilize the material effectively and to prolong the service life of selected structural system [3-10].

This present research focuses on the effect of tropical climate exposure as well as salt solution on the flexural performance and bond durability of externally bonded Carbon Fibre Reinforced Polymer (CFRP) plate and fabric on reinforced concrete beams and concrete prisms. Durability and ductility are essential to the long-term sustainable service life of FRP material and concrete structural members with FRP reinforcement [11]. Structural reliability and durability imply good performance of material that is able to resist degradation and capable to avoid structural damage. The strengthening of concrete structures through the use of externally bonded FRP composite system raises a two-prong concern on the durability of the system. The first one is the durability of the FRP material itself and the other is the durability of bonding between the FRP material and concrete

substrate. The latter concerns with the durability of the interface bond in the FRP-concrete bonding system [12-14].

There is an enormous concern with regards to the reduction in the performance of externally bonded FRP systems over long period of time. Tropical climate countries which experience high average annual temperature, humidity, rainfall and relatively constant ultra violet ray (UV) may have detrimental effect on the usage of FRP composite either externally or internally retrofitted. The amount of information on the durability of FRP subjected to environmental condition especially in the tropical climate environment is still very limited. The outcomes of the past researches show inconsistencies in the results on the degradation effect. Therefore, it is crucial to study the tropical climate effect on FRP and its matrix material in structural element in order to gain acceptance in a country which is experiencing tremendous wet and dry cycle through rain, moisture and dry season. This is essential because many of the applications of FRP as strengthening or repair materials are for outdoor exposure. However, there is another concern on the use of FRP as external strengthening material which is the interfacial fracture along the bonded joints that can limit the strengthening performance of FRP materials. A reinforced concrete beam strengthened with an external FRP plate or fabrics and subjected to flexural loading causes a development of a high tensile and bond shear stress in the concrete or near the adhesive layer. This high stress can possibly lead to the debonding of FRP plate from concrete. It is important for the long term behaviour of the structural bonded joints in civil engineering structures be guaranteed between 50 to 100 years for the acceptance of this bonded system in the construction industry [15].

1.3 Aim and Objectives of Research

The aim of the investigation is to study the flexural behaviour of reinforced concrete member strengthened with Carbon Fibre Reinforced Polymer (CFRP) plate and fabric and also the interfacial bonding of the CFRP-concrete system exposed to

tropical climate. The shortcomings of the published literature in this field were the rationale behind the investigation.

Related objectives of the research investigation are as follows:

- i) To examine the basic mechanical properties of concrete, CFRP plate, and adhesive in normal laboratory condition and climatic exposure as well as seawater solution.
- ii) To determine the effect of tropical climate exposure and saltwater solution (at normal laboratory and higher temperature) on the bonding performance (interfacial bonding) of the concrete prism strengthened with CFRP plate.
- iii) To investigate the short term flexural behaviour of reinforced concrete beam strengthened with externally bonded CFRP plate and fabric.
- iv) To determine the effect of tropical climate exposure as well as saltwater solution on the flexural behaviour of RC beam strengthened externally with CFRP fabrics and plate.
- v) To determine the effect of tropical climate exposure as well as saltwater solution on the interfacial bond of CFRP-reinforced-concrete bonding system using epoxy as adhesive for externally strengthened RC beams.

1.4 Scope of Research

The scope of research for this particular experimental study included:

- i) Tests on basic properties of materials used for laboratory and exposure condition (tensile strength, modulus and strain for CFRP plate, adhesive, steel reinforcement; sieve analysis and moisture content for aggregates; compression for concrete).

- ii) CFRP plate and fabrics were used as the external reinforcement for RC beam for flexural strengthening and only CFRP plate for bond load test with epoxy as adhesive.
- iii) The environmental response parameters studied both for concrete prism and RC beams were exposure to tropical weather, saltwater solution and dual exposure of tropical weather and saltwater solution and subjected to continuous and cyclic exposure.
- iv) Selected RC beam was pre-cracked before bonding the CFRP plate and fabrics to simulate in-service damage condition before being subjected to environmental exposure.
- v) All beams were subjected to four point load test for flexural studies to determine the load carrying capacity, load deflection behaviour, strain, failure modes, cracking behaviour (inclusive micro-cracking) and interfacial stress behaviour.

1.5 Significant of Research

The results obtained from this research are expected to make contribution in understanding the behaviour and performance of concrete structures strengthened with FRP composite that is very much needed in tropical climate environment. As such, the significant of the current research may include the following outcomes:

- i) The availability of new information in FRP strengthening system of reinforced concrete structures in the aspect of flexural can contribute to better understanding of the design and industrial application.
- ii) Added information on the characteristics of FRP strengthened structures due to tropical environmental exposure will contribute significantly to the acceptance of this material in the relevant locality.

- iii) Enhancing the understanding on interfacial stress behaviour between FRP and concrete using epoxy as adhesive due to tropical climate exposure and aggressive environment.

- iv) As steel is susceptible to corrosion and higher weight, the introduction of better used and sustainable building material such as FRP is anticipated to help in improving the effect of environmental degradation as well as managing, handling and costing problem of steel as repair and strengthening materials.

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