CHAPTER 06: CONCLUSIONS AND RECOMMENDATIONS

This research is based on flexural behavior of CFRP strength concrete beams. The experimental work was carried out to study on RC beam elements flexural strengthen with externally bonded CFRP and the suitability of using cement grout as bonding agent was investigated. Two other modifications have been carried out for strengthen beams with CFRP bonded with cement grout adhesive. Those were;

1. Strengthening RF concrete (primed) beams with CFRP, and use of cement grout as bonding agent.
2. Strengthening RF concrete (primed) beams with CFRP, and use of cement grout as bonding agent while both ends were anchored with two 'U' wraps.

Two type of CFRP samples were used for the experiment works that was sample 1 (having properties Ultimate tensile strength 2650N/mm^2, Modulus of elasticity 640kN/mm^2) and sample 2 (having properties Ultimate tensile strength 4300N/mm^2, Modulus of elasticity 240kN/mm^2). The sample 1 CFRP was used with beams which were bonded with epoxy and the sample 2 CFRP was used with beams which were bonded with cement grout.

5.1 Conclusions and Recommendations

CFRP fabric properly bonded to the tension face of RC beams can enhance the flexural strength substantially. Within the indicated scope of this investigation, the particular conclusions emerging from this study are summarized as follows:

1. The experimental results show that beams which used CFRP (sample 1) and epoxy adhesive exhibited an increase in flexural strength about 39 %, relative to control beam, for single layer CFRP. According to the theoretical calculation, the predicted strength gain by using sample 1 CFRP was 52.6%.That shows there is a significant effect on enhancement of flexural performance with CFRP. It was observed that failure mode was de-bonding.

2. When observing the experimental results, beams which used CFRP (sample 2) and cement grout adhesive exhibited an increase of flexural strength about 179 %, relative to control beam, for single layer CFRP. According to experimental results, there is a significant effect on flexural performance enhancement with CFRP on ultimate load capacity. It was observed that failure mode was end delamination.

3. When primer coated on tension face of the beams which used cement grout as bonding agent, the ultimate strength was increased by 208%, relative to control beam. This is about 29% increment with respective to non-primed beam strength using cement grout. That clearly implies the primer has ability to increase bond capacity of the cement grout bond. It was observed that failure mode was de-bonding.

4. When primer coated on tension face of the beams which used cement grout as bonding agent and both ends of the beams were anchored using ‘U’ wrapped showed increase of flexural strength about 279%, relative to the control beam. This is about 71 % with respect to end anchored beam with the same substrate condition. Therefore, it can be concluded the ends ‘U’ wrapped can effectively increase the load carrying capacity of the beams. It was observed that failure mode was de-bonding.

5. In this investigation CFRP strengthened beams demonstrated appreciable ductility when compared to the control beam. CFRP specimens used with cement grout as bonding agent had higher tensile strength which demonstrated higher ductility.

Finally, the experimental results have shown that the strengthening with CFRP sheets bonded with cement grout material enhances the flexural stiffness of the beam. Therefore, it can be concluded that when mortar (2:1 cement water ratio) was used as bonding material, it can effectively contribute to increase load capacity and ductility of the structural members. Results show that considerable composite action can be achieved using cement grout as bonding agent. In addition to that, the primer has ability to increase excellent bond properties of the cement grout that will further improve loading capacity of the beams. The proposed ‘U’ wraps at both ends are more effective method to enhance the strength capacity of the beams. It prevented the end deboning failure of CFRP sheet.

5.2 Further studies

1. Better flexural performance was shown when cement grout was used as bonding agent from the current study. Performance was further improved when primer

coated on bonding surface and ends are anchoraged. It is suggested to study shear stress and compression capacity with similar bonding agents and methods.

2. In the current study ends were anchored 75 mm from edge of the beam to test flexural strength gain. It is proposed to study optimum anchoring distance from edge of beam to test flexural strength, shear stress and compression capacity.
3. Finite element modeling of the system should be done for better behavioral understanding and for better predictability of results.
4. It is suggested to compare results of end anchored beams while using bonding agents as epoxy and cement grout.

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Appendix A: Details of flexural capacity enhancement of beams

No	Research and Author	Description of sample	Material Properties	Strength gain in flexure	Observed failure mode
1.	Srisangeerthanan, S. (2013) "Investigation on alternatives to prevent debonding of reinforced concrete members"	Beam size 150 mmX 200 mmX750	Thickness= 0.19 mm, Tensile strength =2,600 N/mm^2 , weight of fabric= 200 g/m^2'uni directional , E = 6.44 $X10^5$ N/mm^2" G 30 concrete, f_y = 460 N/mm^2	29%	Flexure. debonding
2.	Anthony J. L., Lawrence, C, B. and David, W. S. (2004), "Flexural Strengthening of Reinforced Concrete Beams by Mechanically Attaching Fiber-Reinforced Polymer Strips" Journal of composites for construction volume 8(3), P 203-210	Beam size 304.8mm X304.8mm X 3658.6 mm,	Thickness= 1 mm, Tensile strength =3,600 N/mm^2 , uni directional , E = 1.52 $X10^5$ N/mm2,, G 30 concrete,	19%	Flexure debonding

No	Research and Author	Description of sample	Material Properties	Strength gain in flexure	Observed failure mode
3.	Imam,M., A. Tahwia,A., Elagamy,A, and Yousef,M.(2013) "Behavior of Reinforced Concrete Beams Strengthened With Carbon Fiber Strips"	Beam size 120 mm X200 mm X 2300 mm,	Thickness= 0.13 mm, Tensile strength =3,500 N/mm^2 , weight of fabric= 220 g/m^2,uni directional , E = 6.44 X105 N/mm^2,, G 30 concrete, f_y = 400 N/mm^2	20%	Flexture. fiber separation
4.	Balamuralikrishnan, R. and Antony, C, J. (2009) "Flexural Behavior of RC Beams Strengthened with Carbon Fiber Reinforced Polymer (CFRP) Fabrics" The Open Civil Engineering Journal. Volume 3 (6). P 102-109	Beam size 150 mm X250 mm X 3000 mm,	Thickness= 0.30 mm, Tensile strength =3500 N/mm^2 , weight of fabric= 200 g/m^2 uni directional, E = $1.55X10^5$ N/mm^2, G 20 concrete, f_y = 512 N/mm^2	20%	Flexure

No	Research and Author	Description of sample	Material Properties	Strength gain in flexure	Observed failure mode
5.	Davood, M., Seyed , M, S., Ardalan, H. (2012). "Experimental Study on the effectiveness of EBROG method for flexural strengthening of RC beams" Proceedings of the International Conference on FRP Composites in Civil Engineering	Beam size 120 mmX140 mmX1000 mm,	Thickness= 0.12 mm, Tensile strength =4100 N/mm^2 , uni directional E = $2.3X10^5$ $N/mm^{2,}$ G 30 concrete, f_y = 530 N/mm^2	52%	CFRP debonding
6	Alaa, M. and Tony, E M. (2012). "Bonding techniques for flexural strengthening of R.C. beams using CFRP" Journal of Ain Shams Engineering Volume 30 (9) P 30-36	Beam size 150 mmX300 mmX2400 mm	Thickness= 0.12 mm, Tensile strength =2600 N/mm^2 , uni directional E = $1.65X10^5$ N/mm^2 G 20 concrete, f_y = 360 N/mm^2	12%	FRP debonding with concrete cover separation
7	Siddiqui, N, A. (2009). "Experimental investigation of RC beams strengthened with externally bonded FRP composites" Lathin American journal of solids and structures. Volume 6(10) P 343-362	Beam size 120 mmX140 mmX1000 mm,	Thickness= 1.0 mm, Tensile strength =846 N/mm^2 , uni directional E = $7.7X10^5$ N/mm^2) G 35 concrete,f_y = 420 N/mm^2	23%	Debonding

No	Research and Author	Description of sample	Material Properties	Strength gain in flexure	Observed failure mode
8	Riyadh Al-Amery.and Riadh Al-Mahaidi (2006) "Coupled flexural–shear retrofitting of RC beams using CFRP straps" International journal of composite structure, volume 75 (3), P 457–464	Beam size 260 mmX340 mm X2700 mm,	Thickness=1.40 mm, 76 mm wide Tensile strength =1,710 N/mm^2 , uni directional E = 2.15X10^5 N/mm^2) G 30 concrete, f_y = 504 N/mm^2	62%	Debonding,crushing of concrete
9	Dolawatte, N, N, W. (2013) "Study on use of Carbon fiber reinforced polymer (CFRP) for strengthening of reinforced concrete beams (RC)" A Thesis submitted in partial fulfillment of the requirements of IESL Engineering course part III: IESL Sri Lanka	Beam size 200 mmX150 mm X2000 mm,	Thickness= 1 mm, Tensile strength =834 N/mm^2 , uni directional, E = 8.2X10^5 N/mm^2, G 30 concrete, f_y = 490 N/mm^2	78%	Separation of concrete cover
10	Piyong, Y., Silva, P, F. and Antonio, N. (2008) "Flexural Performance of RC beams strengthened with prestressed CFRP sheets"	Beam size 768 mmX305 mmX6096 mm,	Thickness= 1 mm, Tensile strength =760 N/mm^2 , uni directional, E = 2.28X10^5 N/mm^{2,} G 20, concrete ,f_y = 414 N/mm^2	65%	Flexure.

Appendix B: Details of flexural capacity enhancement of beams using Epoxy and Cement based adhesive

No	Research and Author	Description of sample	Material Properties	Strength gain in flexure		Observed failure mode	
				Using Epoxy	Using cement based adhesive	Using Epoxy	Using cement based adhesive
1	S.L. Sveinsdottir, "Experimental research on strengthening of concrete beams by the use of epoxy adhesive and cement-based bonding material"	Beam size 150 mmX 250 mmX2500	Tensile strength =2,500 N/mm^2 , E = 84 Gpa, G 35 concrete, $f_y = 460$ N/mm^2	11%	8%	debonding	Flexural failure
2	"Investigation on allternative bonding agents for CFRP concrete composites",S.R. Adhikarinayake,K.D.J.A. Gayan,N.G.T.T.Thathsarani,J.C.P.H.Gamage,UOM, Sri Lanka	Beam size 100mm X150mm X 600 mm,	Tensile strength =3,800 N/mm^2 , E = 230 Gpa, G 30 concrete, $f_y = 460$ N/mm^2	26%	37%	debonding	Rupture of fibre
3	Hashemi S, Al-Mahaidi, "Cement based bonding material for FRP", 11th inorganic-bonded fiber	Beam size 120 mm X200 mm X 2300 mm,	Tensile strength =3,800 N/mm^2 , E = 230 Gpa, G 30 concrete, $f_y = 460$ N/mm^2	56%	57%	debonding	Flexural failure

No	Research and Author	Description of sample	Material Properties	Strength gain in flexure		Observed failure mode	
				Using Epoxy	Using cement based adhesive	Using Epoxy	Using cement based adhesive
	composites conference, November 5-7, 2008 Madrid – Spain.						
4	Siavash Hasmi,Riadh Al Mahandi,May 2011, "Flexural performacne pf CFRP textile-retrofitted RC beam using cement based adhesive at high temperature"	Beam size 120 mm X180 mm X 1300 mm, ,	Tensile strength =3,600 N/mm^2, E= 230 Gpa, G 57 concrete, f_y = 460 N/mm^2	40%	44%	debonding	Flexural failure

No	Research and Author	Description of sample	Material Properties	Strength gain in flexure		Observed failure mode	
				Using Epoxy	Using cement based adhesive	Using Epoxy	Using cement based adhesive
5	Siavash Hasmi,Riadh Al Mahandi,June 2011, "Experiment and finite element analysis of flexure behaviour of FRP-strengthened RC beams uisng cement based adhesive"	Beam size 120 mmX140 mmX1000 mm,	Tensile strength =3,600 N/mm^2 , E = 200 Gpa, G 38 concrete, f_y = 460 N/mm^2	33%	27%	debonding	debonding
6	Al-Abdwais, R. Al-Mahaidi, K. Abdouka, "Modified cement-based adhesive for near-surface mounted CFRP strengthening system", Fourth Asia-Pacific Conference on FRP in Structures, Melbourne, Australia, Melbourne, Australia, 2013	Beam size 75 mmX75 mmX200 mm	Tensile strength =1450 N/mm^2 , E = 135 Gpa, G 41 concrete, f_y = 460 N/mm^2	170%	250%	debonding	crushing of concrete

No	Research and Author	Description of sample	Material Properties	Strength gain in flexure		Observed failure mode	
				Using Epoxy	Using cement based adhesive	Using Epoxy	Using cement based adhesive
7	Heshamdiab,Apri 2015,"Efficiency of cement based bonding agent for FRP sheets vs epoxy"	Beam size 100 mmX100 mmX500 mm,	Tensile strength =3800 N/mm^2 , E = 200 Gpa, G 20 concrete, f_y = 460 N/mm^2	125%	75%	debonding	Flexural failure
8	Thomas Blanksvärd & Björn Täljsten, "Strengthening of concrete structures with cement based bonded composites",	Beam size 180 mmX500 mm X4000 mm,	Tensile strength =3800 N/mm^2 , E = 284 Gpa, G 30 concrete, f_y = 460 N/mm^2	110%	99%	debonding	Rupture of fibre

No	Research and Author	Description of sample	Material Properties	Strength gain in flexure		Observed failure mode	
				Using Epoxy	Using cement based adhesive	Using Epoxy	Using cement based adhesive
9	E,Ferrier,A.Si Labri,J.F. Georging,J.Ambroise,April 2012,"New hybrid cement based composite material externally bonded to control RC beam cracking".	Beam size 150 mmX250 mm X2000 mm,	Tensile strength =2300 N/mm^2 , E = 130 Gpa, G 30 concrete, f_y = 460 N/mm^2	55%	63%	debonding	Rupture of fibre
10	Luciano Ombres,June 2011,"Debonding analysis of RC beams strength with FR cementanious mortar"	Beam size 150 mmX250 mmX2700 mm,	Tensile strength =5800 N/mm^2 , E = 270 Gpa, G 27 concrete, f_y = 460 N/mm^2	38%	30%	debonding	Rupture of fibre
11	Luciano Ombres,June 2011,"Debonding analysis of RC beams strength with FR cementanious mortar"	Beam size 150 mmX250 mmX2700 mm,	Tensile strength =5800 N/mm^2 , E = 270 Gpa, G 23 concrete, f_y = 460 N/mm^2	23%	40%	debonding	Flexural failure

Appendix C: Details of Cement adhesive mix ratios

	Research & Author	Cement bond						Test type
		material	**Mix proportion (kg)**				**bond thickness(mm)**	
			1	**2**	**3**	**4**		
1	S.L. Sveinsdottir, "Experimental research on strengthening of concrete beams by the use of epoxy adhesive and cement-based bonding material"	Sand	20250	20250	20250		10	flexure
		Water	3119	3153	3448			
		Cement	11250	11250	11250			
		Silica fume	1125	1125	1125			
		Omnicon(SP)	373	314	112.2			
		Fibers		106				
		Acryl			380			
		SP	1.30%					
2	"Investigation on allternative bonding agents for CFRP concrete composites",S.R. Adhikarinayake,K.D.J.A.Gayan,N.G .T.T.Thathsarani,J.C.P.H.Gamage,U OM,Sri Lanka	cement grout					3	flexure
		cement grout					6	flexure

	Research & Author	Cement bond						Test type
		material	**Mix proportion (kg)**				**bond thickness(mm)**	
			1	**2**	**3**	**4**		
3	Hashemi S, Al-Mahaidi, "Cement based bonding material for FRP", 11th inorganic-bonded fiber composites conference, November 5-7, 2008 Madrid – Spain.	cement	888	813	776	613		flexure
		micro cement				153		
		water	426	406	310	427		
		Silica fume	754.8	691	659	651.5		
		SBR latex			194			
		Viscocrete5-500 (SP)	8.9	40.6	3.9	42.2		
4	Siavash Hasmi,Riadh Al Mahandi,May 2011, "Flexural performacne pf CFRP textile-retrofitted RC beam using cement based adhesive at high temperature"	cement	674.3				20	flexure
		micro cement	168.6					
		water	354					
		Silica fume	84.3					
		Filler(Silica200G)	716.6					
		Viscocrete5-500 (SP)	75.9					

	Research & Author	Cement bond						Test type
		material	**Mix proportion (kg)**				**bond thickness(mm)**	
			1	**2**	**3**	**4**		
5	Siavash Hasmi,Riadh Al Mahandi,June 2011, "Experiment and finite element analysis of flexure behaviour of FRP-strengthened RC beams uisng cement based adhesive"	cement	674.3				20	flexure
		micro cement	168.6					
		water	354					
		Silica fume	84.3					
		Filler(Silica200G)	716.6					
		Viscocrete5-500 (SP)	75.9					
6	Al-Abdwais, R. Al-Mahaidi, K. Abdouka, "Modified cement-based adhesive for near-surface mounted CFRP strengthening system", Fourth Asia-Pacific Conference on FRP in Structures, Melbourne, Australia, Melbourne, Australia, 2013.	cement	674.3	674.3	674.3	674.3	4	pull-out
		micro cement	168.6	168.6	168.6	168.6		
		water	354	354	354	354		
		Silica fume	84.3	84.3	84.3	84.3		
		Filler(Silica200G)	716.5	716.5	716.5	716.5		
		Viscocrete5-500 (SP)	42.1	33.7	25,.3	16.9		
		Primer	227.4	151.2	101.1	88.6		

	Research & Author	Cement bond						Test type
		material	Mix proportion (kg)				bond thickness(mm)	
			1	2	3	4		
7	Heshamdiab,Apri 2015,"Efficiency of cement based bonding agent for FRP sheets vs epoxy"	Cement	888				One layer	flexure
		water	426					
		fine sand	755					
		SP	8.9					
8	Thomas Blanksvärd & Björn Täljsten, " Strengthening of concrete structures with cement based bonded composites",	mortor					One layer	flexure
9	E,Ferrier,A.Si Labri,J.F. Georging,J.Ambroise,April 2012,"New hybrid cement based composite material externally bonded to control RC beam cracking".	Cement	742				35	flexure
		Silica fume	44					
		Basalt sand	698					
		sand	523					
		water	222					
		SP	22					
		Accelataor	10					
		Matalic fiber	131					
		Welam gum	0.262					

	Research & Author	Cement bond						Test type
		material	Mix proportion (kg)				bond thickness(mm)	
			1	2	3	4		
10	Luciano Ombres,June 2011,"Debonding analysis of RC beams strength with FR cementanious mortar"	mortor(compressive strength 30.4 Mpa)					22.5	bending test
11	Luciano Ombres,July 2011, "Flexural analysis of RFC beams strength with the cement based high strength composite materials"	mortor(compressive strength 29 Mpa)						bending test

Appendix D: Details of testing data

Applied loads (MT)	Deflection of beam specimens (Dial gauge readings)									
	C1	C2	A-E1	A-E2	B-C1	B-C2	C-PC1	C-PC2	D-PC1	D-PC2
0	0	0	0	0	0	0	0	0	0	0
0.2	30	40	25	11	15	10	20	4	8	22
0.4	50	62	35	22	29	30	27	12	15	33
0.6	70	76	59	42	37	38	35	20	21	42
0.8	110	100	78	60	43	43	37	26	28	50
0.98	198									
1		200	96	80	48	46	47	32	30	56
1.02		202		94						
1.2			125		52	50	51	38	33	62
1.4			166		56	53	55	43	38	68
1.48			198			55				
1.6					60	58	60	46	40	71
1.8					65	62	67	50	44	75
2					140	67	73	134	48	126
2.2					148	136	118	158	111	142
2.4					160	218	150	180	135	158
2.46						220				
2.6					190		235	205	150	182
2.8					205		268	248	182	198
3					230		302	300	208	214
3.12					232					
3.16							305			
3.2									240	236
3.4									280	248
3.6										273
3.8										296
4										328