Effect of carbon fibre reinforced polymer jacketing on low, normal, medium and high strength concrete

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Abstract: This paper presents the experimental results of carbon fibre reinforced polymer (CFRP) jacketing effect on wide range of cylindrical concrete compressive strengths. A total of sixty cylinders were cast and tested under axial compressive loading. The test variable was the compressive strength of concrete. The four grades of concrete compressive strength, low, normal, medium and high strength were used in this experimental study. The results of the carbon fibre reinforced polymer (CFRP) confined specimens of low,normal,medium and high grade strength concrete were compared with the un-confined specimens of low, normal, medium and high grade strength concrete specimens. The comparison was carried out in terms of un-confined to confined compressive strength and the gain in axial load carrying capacity for the low, normal, medium and high grade strength concrete cylinders. The results showed that the carbon fibre reinforced polymer jacketing is more effective for increasing the confined compressive strength and the axial load carrying capacity for low grade strength concrete compared to the high grade strength concrete. It was found that the CFRP confinement effectiveness was reduced with increasing the unconfined compressive strength of concrete.

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1. Introduction

The confinement of the concrete is a well known technique for enhancing the confined compressive strength and the axial load carrying capacity of concrete structural members. Different concrete confinement methods were adopted in the past such as concrete jacketing, steel jacketing, jacketing with reinforcing link bars. However, nowadays, the concrete confinement using the fibre reinforced polymer as a jacketing material is gaining the rapid popularity due to its supremacy over the past conventional methods. There are many benefits of using the fibre reinforced polymer as a strengthening and repairing material because it has high strength to weight ratio, high corrosion resistance, ease of installation and relatively lower cost of maintenance. The previous research has demonstrated that the fibre reinforced polymer (FRP) is the most effective method for enhancing the confined compressive strength and the axial load carrying capacity of the circular concrete cylinders. (Karabinis Al 2001; Matthys S 1999; Pessiki S 2001; Rochette P 2000; Wang YC 2001; Rousakis TC 2002; Rousakis TC 2003). A large number of studies have been published on strength behaviour of FRP-confined concrete. But most of the published research focused on normal strength concrete. (Miyauchi et al. 1996; Berthel et al. 2005; Mandal et al. 2005; Almusallam 2007). Considerable research has also been published for the use of fibre reinforced polymer as a confining material in order to increase the compressive strength. However, most of the experimental published work has been focused on the normal strength concrete.

Although, considerable research has been published in the literature, using the fibre reinforced polymer as a confining material. However, according to author's knowledge very limited or no research has been conducted to investigate the effect of fibre reinforced polymer as a confining material for the strength ranging from low grade to high grade strength concrete. The strengthening of concrete structures having strength ranging from low to high can be encountered in the rehabilitation or repairing of structures. Therefore, there is a strong need to investigate the effectiveness of carbon fibre reinforced polymer for low, normal, medium and high strength concrete. The study provides an insight into the effectiveness of carbon fibre reinforced polymer for the low, normal, medium and high strength concrete.

2. Experimental programme

A total of sixty circular concrete cylinders having standard 150 mm diameter and 300 mm length were cast and tested within the concrete laboratory of University of Engineering and Technology, Taxila,Pakistan. The experimental programme was designed according to following strength grades of compressive strength of circular concrete cylinders.

1) Low grade strength concrete cylinders

A total of twenty four circular concrete cylinders having concrete compressive strength ranging from 7.84 MPa to 16.82 MPa for unconfined and concrete cylinders having CFRP confined compressive strength ranging from 16.71 MPa to 24.38MPa were cast and tested under this category. The low strength concrete was divided into the following further four number of tests.

T1)This category includes the test specimens having un-confined concrete compressive strength 7.84MPa and CFRP confined compressive strength 16.71MPa

T2)This category includes the test specimens having un-confined concrete compressive strength 9.70 MPa and CFRP confined compressive strength 17.54 MPa

T3)This category includes the test specimens having un-confined concrete compressive strength 13.27 MPa and CFRP confined compressive strength 21.65MPa.

T4)This category includes the test specimens having un-confined concrete compressive strength 16.82 MPa and CFRP confined compressive strength 24.38MPa

2) Normal grade strength concrete cylinders

A total of twelve circular concrete cylinders having concrete compressive strength ranging from 20.88MPa to 28.77 MPa for un-confined and concrete cylinders having CFRP confined compressive strength 25.32MPa to 34.53MPa were cast and tested under this category of tests. The normal strength concrete was further divided into the following further two number of tests both for un-confined and CFRP confined cylinders.

T5) This category includes the test specimens having un-confined concrete compressive strength 20.83MPa and CFRP confined compressive strength 25.32MPa

T6) This category includes the test specimens having un-confined concrete compressive strength 28.77MPa and CFRP confined compressive strength 34.53MPa

3) Medium grade strength concrete cylinders

This section also contains a total of twelve circular concrete cylinders having concrete compressive strength ranging from 36.72 MPa to 48.89 MPa for un-confined and for the CFRP confined compressive strength 44.66 MPa to 55.25MPa were cast and tested under this category of tests. The medium strength concrete was further divided into the following further two number of tests both for un-confined and CFRP confined cylinders.

T7) This category includes the test specimens having un-confined concrete compressive strength 36.72MPa and CFRP confined compressive strength 44.66MPa

T8) This category includes the test specimens having un-confined concrete compressive strength 48.89MPa and CFRP confined compressive strength 55.25MPa.

4**) High grade strength concrete cylinders**

A total of twelve circular concrete cylinders having concrete compressive strength ranging from 56.34MPa to 62.48MPa for un-confined and concrete cylinders having CFRP confined compressive strength 62.76MPa to 67.52MPa were cast and tested under this category of tests. The high strength concrete was further divided into the following further two number of tests both for un-confined and CFRP confined cylinders.

T9) This category includes the test specimens having un-confined concrete compressive strength 56.34MPa and CFRP confined compressive strength 62.76MPa

T10) This category includes the test specimens having un-confined concrete compressive strength 62.48MPa and CFRP confined compressive strength 67.52MPa.

It is worth to mention here that the above ten mentioned tests (T1 to T10) both for the un-confined and CFRP confined concrete, the compressive strength of each test was based on the average of three tests of the un-confined or CFRP confined concrete cylindrical compressive strength.

2.1 Casting of specimens

A total of sixty cylindrical concrete specimens, (thirty CFRP wrapped and thirty unwrapped) were cast in the concrete laboratory for the four grades of concrete (low, normal, medium and high strength concrete). The design concrete mixes for low, medium, normal and high strength concrete were poured into the well oiled cylindrical moulds. Six cylinders at the same time were cast for each low, medium, normal and high strength concrete. All the cylinders for the low, normal, medium and high strength concrete were cast and cured using the procedure described in ASTM C31.The concrete cylindrical specimens after casting are shown in Fig.1 (A). The mix properties of the specimen are shown in Table 2 (B).

2.2 CFRP Jacketing Procedure

All the concrete specimens to be wrapped with the carbon fibre reinforced polymer were taken out of curing tank at least one week before wrapping. The carbon fabric used in this research was Sikawrap Hex 230-C (unidirectional carbon fibre reinforced polymer) with the adhesive Sikadur-330.

The carbon fibre reinforced polymer sheets were cut 50 mm less than the height of specimens and according to circumference of cylinders with 100 mm extra for overlapping in the transverse direction. Only a single carbon sheet was used for wrapping around the cylindrical specimens after saturating with the adhesive. The carbon fibre sheets were wrapped manually around the cylinders using the wet lay up technique. The carbon fabric (Sikawrap Hex 230 C) used in this study has a tensile strength of 4100 N/mm2 and a modulus of elasticity of 231000 N/mm2. Table 2 (A) shows cured laminate properties of

Sikawrap Hex-230 C with adhesive (Sikadur 330) provided by the supplier. All the specimens were capped with the sulphur mortar (at the top and bottom faces) after wrapping with the carbon fibre reinforced polymer in order to apply the uniform axial loading during testing.

2.3 Specimen Testing Procedure

The cylindrical specimens were tested in a load compression testing machine having a capacity of $2x10^6$kN using the load control method. The standard procedure of ASTM C39 was followed for the testing of all specimens. All the test data was monitored and recorded through out the testing of specimens.

Figure 1(A): Casting of specimens in laboratory

Fig.1 (B) Rupture of cylinder wrapped with FRP

Table 2 (A): Cured Laminate Properties with of Sikawrap Hex-230 C with Sikadur 330

Property	Value (psi)	Value (MPa)	ASTM Method
Tensile strength	129,800	894	D-3039
Tensile Modulus	9,492,300	65402	D-3039
Tensile Elongation	1.33	1.33	D-3039
Compressive strength	9,724,700	779	D-3039

Table 2 (B) shows the mix properties of the specimen.

Table 2 (B): Mix properties of specimen

Sr. No	Specimen Designation	Strength (MPa)	Slump (mm)	w/c	Mix Ratio
1	T-1	7.84	75	1.08	1:4:8
2	T-2	9.70	60	0.93	1:3:6
3	T-3	13.27	71	0.78	1:2.5:5
4	T-4	16.82	125	0.51	1:2.5:5
5	T-5	20.83	102	0.47	1:2:4
6	T-6	28.77	85	0.40	1:1.3:2.6
7	T-7	36.72	135	0.42	1:1:2
8	T-8	48.89	125	0.42	1:0.8:1.6
9	T-9	56.34	90	0.33	1:0.5:1
10	T-10	62.48	105	0.39	1:0.5:1

3. Test results and discussions

The current research study investigate the effect of carbon fibre reinforced polymer on the wider range of concrete strengths including low and high strength concretes which may encounter in the field of construction industry. The low strength concrete is mostly encountered in the field of repairing and strengthening of concrete structures due to poor or defective construction. The main objective of the present study is to compare the un-confined and CFRP confined compressive strengths for low, normal, medium and high strength concrete. This study also compares the results of un-confined and CFRP confined axial load carrying capacity of low, normal, medium and high strength concrete. The comparison of the results in terms of CFRP confined compressive strength and axial load carrying capacity for the low, medium, normal and high strength concrete are discussed in the following sections.

3.1 Confined versus unconfined strength

3.1.1 Confined versus unconfined strength for low strength concrete

Fig.1 and Table.3 show the results of un-confined and CFRP confined compressive strength for low grade strength concrete. It is evident from the comparison (Fig.1 and Table.3) that the CFRP confined compressive strength is more superior to the un-confined compressive strength. Fig.1 indicates that with increasing the range of compressive strength (T1 to T4) within the low grade concrete strength, the CFRP confinement effectiveness decreases. It can be seen from Fig.1 and Table.1 that the increase in confined strength was found to be to be 113 % to 45 % with respect to the un-confined compressive strength. It is worth mentioning here that the CFRP wrapped cylinders with the least unconfined concrete compressive strength (7.84 MPa) show the maximum increase in compressive strength when wrapped with CFRP jacket. However, the same finding was also observed by (Riad Benzaid, Habib-Abdelhak Mesbah, 2013).

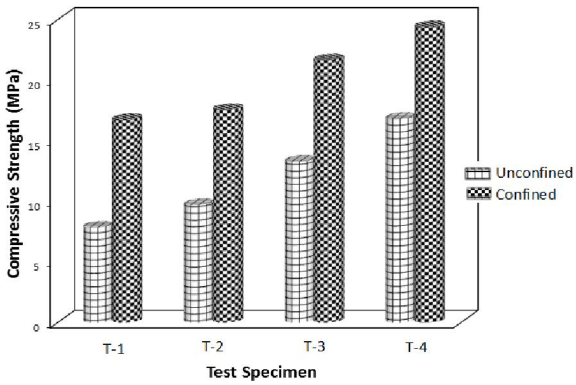

Figure 1: Comparison of confined versus unconfined Compressive Strength for low strength concrete circular cylinders

Table 3: Percentage increase in confined versus unconfined strength for low strength concrete circular cylinders

Test. No	f'_c (MPa)	f'_{cc} (MPa)	$\frac{f'_{cc}}{f'_c}$	$\frac{f'_{cc}-f'_c}{f'_{cc}}$ (%)
T-1	7.84	16.71	2.13	113
T-2	9.70	17.54	1.80	81
T-3	13.27	21.65	1.63	63
T-4	16.82	24.38	1.45	45
Avg	11.91	20.07	1.69	69

3.1.2 Confined versus unconfined strength for normal strength concrete

Fig.2 and Table 4 compares the results of un-confined and CFRP confined compressive strength for the normal strength concrete circular cylinders. The Fig.2 and Table.4 clearly shows that CFRP is more effective for lower strength (T5) compared to higher strength (T6) within the range of normal grade strength concrete. It was also observed that CFRP confined strength was higher compared to un-confined compressive strength for the normal grade strength concrete. The Fig.2 and the Table.4 shows that the increase in the confined compressive strength was 22% to 20% with respect to the un-confined compressive strength. This indicated that the CFRP confinement effective was more in case of low grade strength concrete compared to the normal grade strength concrete. This could be due to the fact that CFRP confinement provides more restraining effect in case of low grade strength concrete compared to the normal grade strength concrete.

3.1.3 Confined versus unconfined strength for medium strength concrete

Fig.3 and Table.5 compares the results of CFRP confined and unconfined compressive strength for the medium grade strength concrete. It is interesting to note that the CFRP confinement effectiveness decreases with increasing the un-confined compressive strength within the range of medium strength concrete.Fig.3 and Table.5 shows that the percentage increase in the confined compressive strength was 22% to 13% with respect to the un-confined compressive strength for the medium grade concrete. It is worth mentioning that the CFRP confinement is more effective for the normal grade strength concrete compared to the medium grade strength concrete in terms of confined compressive strength.

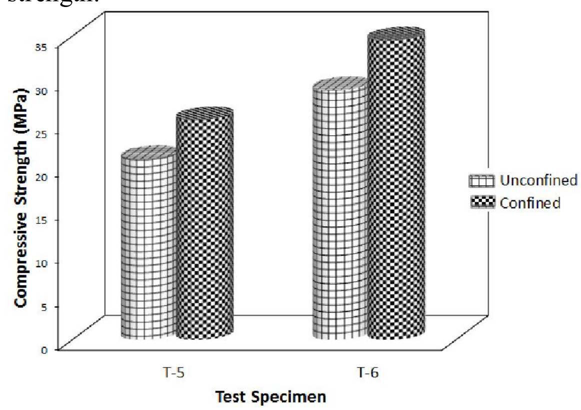

Figure 2: Comparison of confined versus unconfined Compressive Strength for normal strength concrete circular cylinders

Table 4: Percentage increase in confined versus unconfined strength for normal strength concrete circular cylinders

Test. No	f'_c (MPa)	f'_{cc} (MPa)	$\frac{f'_{cc}}{f'_c}$	$\frac{f'_{cc}-f'_c}{f'_{cc}}$ (%)
T-5	20.83	25.32	1.22	22
T-6	28.77	34.53	1.20	20
Avg	24.80	29.93	1.21	21

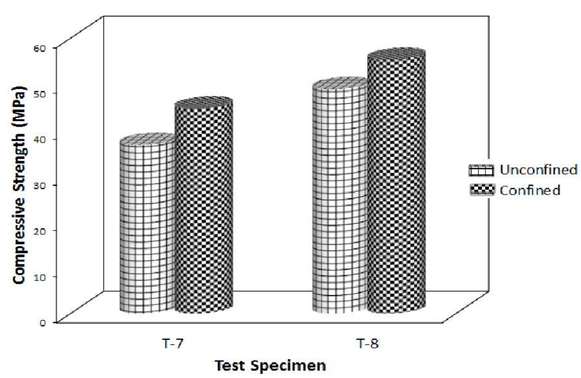

Figure 3: Comparison of confined versus unconfined Compressive Strength for medium strength concrete circular cylinders

Table 5: Percentage increase in confined versus unconfined strength for medium strength concrete circular cylinders

Test. No	f'_c (MPa)	f'_{cc} (MPa)	$\frac{f'_{cc}}{f'_c}$	$\frac{f'_{cc}-f'_c}{f'_{cc}}$ (%)
T-7	36.72	44.66	1.22	22
T-8	48.89	55.25	1.13	13
Avg	42.81	49.96	1.17	17

3.1.4 Confined versus unconfined strength for high strength concrete

Fig.4 and Table.6 highlight the comparison of CFRP confined and unconfined tested results of compressive strength for high grade strength concrete. It was found that the increase in CFRP confined compressive strength was 8% to 11% with respect to the un-confined compressive strength. It is noteworthy to mention here that CFRP confinement is less effective for increasing the confined compressive strength compared to the low, normal and medium grade concrete strength. This could be attributed to fact that the low, normal and medium grade strength concrete displayed more lateral expansion as compared to high grade strength concrete.Since, the restraining action of CFRP depends on the lateral expansion of concrete Therefore, the CFRP becomes more effective in terms of increasing the confined compressive strength for the low, normal and medium grade strength concrete compared to high grade strength concrete.

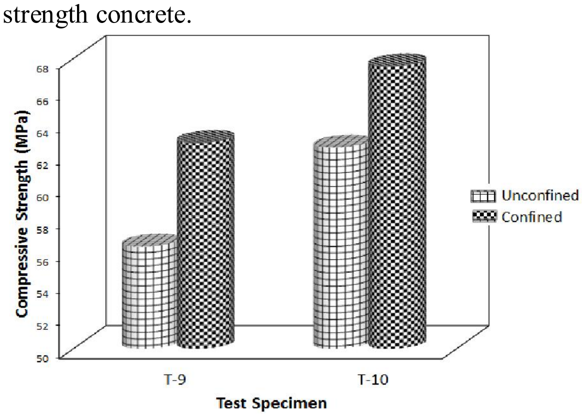

Figure 4: Comparison of confined versus unconfined Compressive Strength for high strength concrete circular cylinders

Table 6: Percentage increase in confined versus unconfined strength for high strength concrete circular cylinders

Test. No	f'_c (MPa)	f'_{cc} (MPa)	$\frac{f'_{cc}}{f'_c}$	$\frac{f'_{cc}-f'_c}{f'_{cc}}$ (%)
T-9	56.34	62.76	1.11	11
T-10	62.48	67.52	1.08	8
Avg	59.41	65.14	1.10	10

3.1 Confined versus unconfined axial load carrying capacity

3.2.1 Confined versus unconfined axial load carrying capacity for low strength concrete

Fig.5 indicates that the CFRP confinement significantly enhanced the axial load carrying capacity for low strength concrete compared to un-confined low grade concrete. The percentage increase was found in the range of 113 %, to 45 % with respect to the un-confined low grade concrete.. The summary of the results for axial load carrying capacity for CFRP confined and un-confined low grade concrete strength is shown in Table 7.

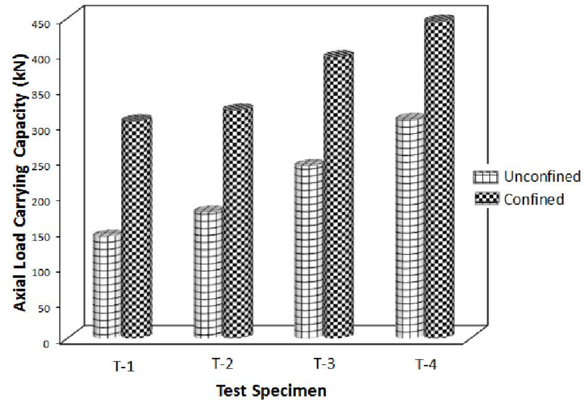

Figure 5: Comparison of confined versus unconfined axial load carrying capacity for low strength concrete circular cylinders

Table 7: Percentage increase in confined versus unconfined axial load carrying capacity for low strength concrete circular cylinders

Test. No	P_{uo} (kN)	P_{ucc} (kN)	$\frac{P_{ucc}}{P_{uo}}$	$\frac{P_{ucc}-P_{uo}}{P_{ucc}}$ (%)
T-1	143	305	2.13	113
T-2	177	320	1.81	81
T-3	242	395	1.63	63
T-4	307	445	1.45	45
Avg	217	366	1.69	69

3.2.2 Confined versus unconfined axial load carrying capacity for normal strength concrete

Fig.6 compares CFRP confined and un-confined axial load carrying capacity for the normal strength concrete. It is interesting to note that the percentage increase in the confined axial load carrying capacity was less for the normal grade strength concrete compared to low grade strength concrete. It can be seen from Fig.6 and Table.8 that percentage increase in the axial load carrying capacity for the normal grade concrete was 22% to 20% with respect to the un-confined normal grade concrete strength.

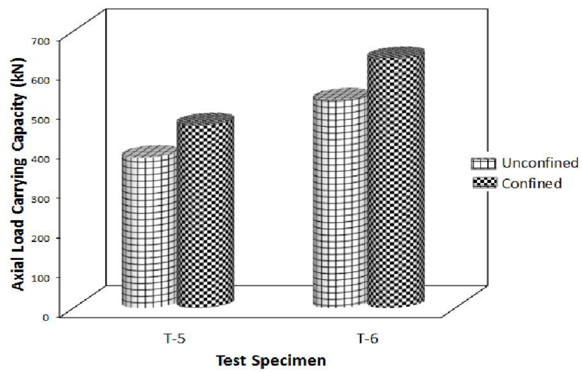

Figure 6: Comparison of confined versus unconfined axial load carrying capacity for normal strength concrete circular cylinders

Table 8: Percentage increase in confined versus unconfined axial load carrying capacity for normal strength concrete circular cylinders

Test. No	P_{uo} (kN)	P_{ucc} (kN)	$\frac{P_{ucc}}{P_{uo}}$	$\frac{P_{ucc}-P_{uo}}{P_{ucc}}$ (%)
T-5	380	462	1.22	22
T-6	525	630	1.20	20
Avg	453	546	1.21	21

3.2.3 Confined versus unconfined axial load carrying capacity for medium strength concrete

Fig.7 displays the comparison of axial load carrying capacity of CFRP confined and un-confined medium grade concrete strength. Comparing Fig.6 with Fig.7, it is clear that the effect of CFRP confinement on increasing the load carrying capacity was more pronounced for normal grade concrete as compared to medium grade concrete strength. The results of gain in axial load carrying capacity of CFRP confined and un-confined compressive strength for medium grade concrete is shown in Table.9. The percentage increase in confined axial load capacity with respect to the unconfined axial load capacity for medium grade concrete was found to 22 %to 13%.

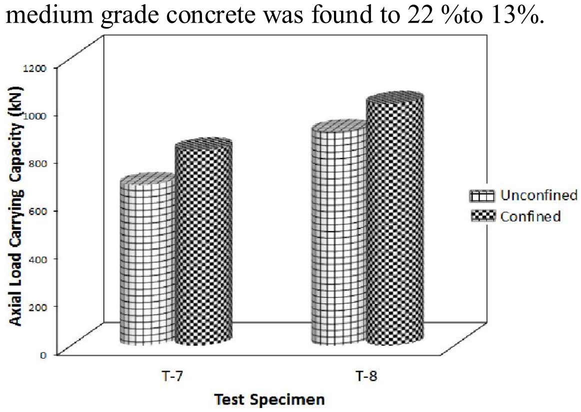

Figure 7: Comparison of confined versus unconfined axial load carrying capacity for medium strength concrete circular cylinders

Table 9: Percentage increase in confined versus unconfined axial load carrying capacity for medium strength concrete circular cylinders

Test. No	P_{uo} (kN)	P_{ucc} (kN)	$\frac{P_{ucc}}{P_{uo}}$	$\frac{P_{ucc}-P_{uo}}{P_{ucc}}$ (%)
T-7	670	815	1.22	22
T-8	892	1008	1.13	13
Avg	781	912	1.68	17

3.2.4 Confined versus unconfined axial load carrying capacity for high strength concrete

Fig.8 indicates the test results for confined versus unconfined axial load carrying capacity for high grade concrete strength. It is interesting to note that the increase in the CFRP confined axial load carrying capacity was found comparatively smaller compared to the low, normal and medium grade concrete strength. This indicated that the CFRP confinement is less effective in case of high grade concrete strength compared to the low, normal and medium grade concrete strength in terms of gain in axial load carrying capacity. It be seen from Table.10 that the CFRP confinement for high grade concrete strength could enhance the axial load carrying capacity from 11% to 8% when compared to the un-confined axial load carrying capacity of high grade concrete strength.

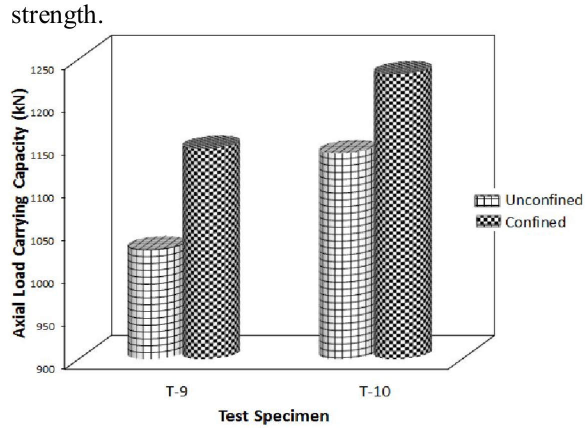

Figure 8: Comparison of confined versus unconfined axial load carrying capacity for high strength concrete circular cylinders

Table 10: Percentage increase in confined versus unconfined axial load carrying capacity for high strength concrete circular cylinders

Test. No	P_{uo} (kN)	P_{ucc} (kN)	$\frac{P_{ucc}}{P_{uo}}$	$\frac{P_{ucc}-P_{uo}}{P_{ucc}}$ (%)
T-9	1028	1145	11.38	11
T-10	1140	1232	8.07	8
Avg	1084	1189	9.69	10

3.3 Comparison of low, normal, medium and high strength concrete for confined strength and axial load carrying capacity

3.3.1 Comparison of low, normal, medium and high strength concrete for confined versus unconfined strength

Fig.9 depicts the overall comparison of the effectiveness of CFRP confinement for the low, normal, medium and high grade concrete strength. Fig.9 clearly shows that CFRP is most effective for low grade strength concrete and least effective for high grade strength concrete in terms of confined compressive strength The low grade concrete strength with the minimum unconfined concrete compressive strength 7.84 MPa was increased to the maximum value 16.74MPa when wrapped with the single layer of CFRP jacket. This is the maximum increase (113%) in the confined strength with respect to the un-confined strength when compared to the other grades of normal, medium and high strength concrete. However, the minimum increase (8%) was observed in case of CFRP confined high grade concrete strength with respect to the un-confined high grade concrete strength.

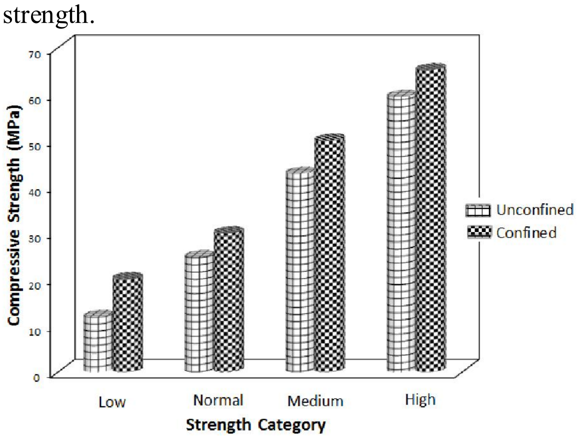

Figure 9: Comparison of confined versus unconfined compressive strength for low, normal, medium and high strength concrete circular cylinders

3.3.2 Comparison of low, normal, medium and high strength concrete for confined versus unconfined axial load carrying capacity

Fig.10 provides the overall comparison for the low, normal, medium and high grade concrete strengths in terms of gain in axial load carrying capacity. All grades of CFRP confined concrete strengths showed the similar trend in creasing the axial load carrying capacity as it was observed in Fig.9 in terms of confined compressive strength.

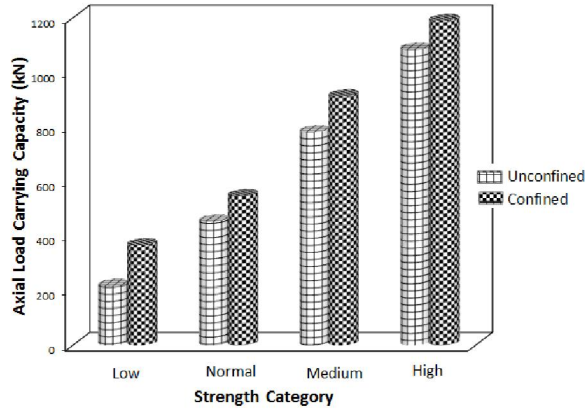

Figure 10: Comparison of confined versus unconfined axial load carrying capacity for low, normal, medium and high strength concrete circular cylinders

4. Conclusions

This study addresses the effectiveness of carbon fibre reinforced polymer for the wider range of concrete compressive strengths. A comparative experimental investigation was carried out to study the effect of carbon fibre reinforced polymer on the low, normal, medium and high grade concrete compressive strength in terms of confined compressive strength and the gain in axial load carrying capacity. Based on the results the following conclusions were drawn from this experimental investigation.

1) The carbon fibre reinforced polymer confinement effectiveness reduces with increasing the unconfined compressive strength of concrete

2) The maximum CFRP confined compressive strength (113%) was achieved with respect to the un-confined compressive strength for the low grade strength concrete when compared to the normal, medium and high grade strength concrete. However, the minimum CFRP confined compressive strength (8%) was achieved with respect to the un-confined compressive strength for high grade concrete strength when compared with the other grades of low, normal and medium strength concrete.

3) The maximum load carrying capacity was achieved for the low grade concrete CFRP confined concrete cylinders when compared to the other normal, medium and high grade strength concrete. However, the trend of CFRP confinement effectiveness was found similar in terms of gain in axial load carrying capacity as it was observed in terms of confined compressive strength for all the low, medium, normal and high grade strength concrete.

Based on the above mentioned conclusions it is found that the carbon fibre reinforced polymer jacketing is very effective for the repairing, strengthening and retrofitting of low grade concrete strength which usually encountered in the field of construction industry due to use of faulty or poor quality concrete or extreme loading.

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Notations

The following symbols are used in this paper:

f_c'= characteristic concrete compressive strength determined from standard cylinder

f_{cc}' = compressive strength of confined concrete

P_{uo} = experimental axial load carrying capacity of unconfined cylinder

P_{ucc} = experimental axial load carrying capacity of confined cylinder

w/c = water cement ratio

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