Effect of FRP on compressive strength of unheated and post heated concrete

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Abstract: Fire affects the residual compressive strength of concrete. High strength concrete may be reduced to normal or low strength concrete after fire exposure. The experimental work was carried out to investigate the effect of FRP on normal and low strength concrete. The experimental results of unheated concrete were compared with the post-heated published data for normal and low strength concrete confined with carbon fiber reinforced polymer in order to investigate the effect of CFRP confinement on normal and low strength post-heated concrete. It was found that CFRP is more effective for post-heated concrete than un-heated concrete. The unheated experimental work and post heated published data was also compared with the three North American design guidelines (American Concrete Institute ACI 440.2R-2008, Canadian Standard Association CSA-S806-02 and Intelligent Sensing for Innovative Structures Canada ISIS MO4 2001).
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Key words: Compressive Strength, post-heated, unheated.

1. Introduction

Concrete is the most popularly used construction material and it finds its application in almost all the civil engineering disciplines. Its characteristics such as mouldability and high compressive strength have made it a versatile building material. Concrete also offers good resistance to fire than other materials because of its low conductivity and incombustible nature but elevated temperature can affect the concrete adversely. The strength reduction when subjected to elevated temperatures is due to unequal changes between cement paste and aggregates together with deterioration of hydration products like calcium hydroxide and calcium silicate hydrates.

Repair of a fire damaged concrete structure is usually a better option as compared to demolition of structure in most of the fire scenarios. The conventional methods of repair are mostly time consuming and inefficient regarding the increment in strength and method of repairing. Fiber Reinforced Polymer can be used for repairing and strengthening concrete structures. But a limited research exists for increasing the compressive strength of CFRP for fire damaged concrete. Their published work of L.A Bisby and M. Yaqub includes the experimental work conducted for demonstrating the effectiveness of carbon fibre reinforced polymer confinement for fire-damaged/post-heated concrete. They clearly showed the benefits and effectiveness of using carbon fibre reinforced polymer wraps for repairing of post-heated concrete. (A.A.A. De Sooza, 2010; M. Yaqub and C.G. Bailey, 2011; L.A. Bisby, 2011 and J.F. Chen, 2011; M. Kumar Balkacem,2011 ; Metim, 2006; Lee.J, Xi.Y and William.K; Fletcher IA)

The objectives of this paper are as follows: a) the comparison of unheated experimental work with the post heated published data for fibre reinforced polymer confinement. b) Comparison of unheated experimental work and post heated published data with the three well known North American design guidelines (American Concrete Institute ACI 440.2R-2008, Canadian Standard Association CSA-S806-02 and Intelligent Sensing for Innovative Structures Canada ISIS MO4 2001) in terms of confined strength and axial load carrying capacity.

Figure 1 shows the strength reduction curve for assessment of concrete exposed to temperature. (CS TR 68)

2. Methodology

Concrete specimens were prepared in the laboratory for low and normal strength mixes. In the specimens receiving carbon lamination, one layer of the standard CFRP was used. The entire jacket was made of one continuous sheet that was cut to proper length. An additional 4in (100mm) overlap was provided to prevent local failure within the end regions, where load is applied. The carbon fabric (Sika wrap Hex 230 C) used has a tensile strength of 4100

N/mm2 and a modulus of elasticity of 231000 N/mm2. Adhesive used for this project is Sikadur 330 to provide the required bond strength between concrete and carbon. Table 1 shows cured laminate properties of Sikawrap Hex-230 C with adhesive (Sikadur 330). All specimens were capped with sulphur mortar using specially made stands.

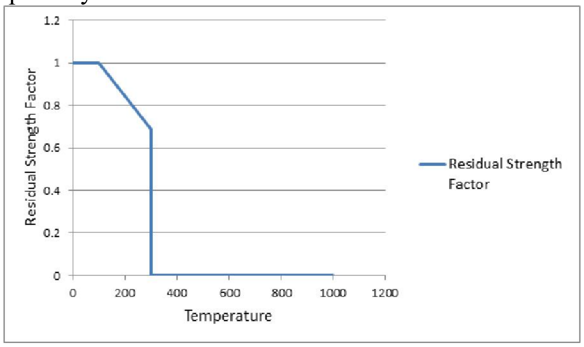

Figure 1: Residual compressive strength of concrete after cooling.

Figure 2 (A): Casting of specimens in laboratory

Fig.2 (B) Rupture of cylinder wrapped with FRP

Table 1: 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 shows the mix properties of the specimen.

Table 2: Mix properties of specimen

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

Review of Design Guidelines for predicting confined strength and axial load carrying capacity:

American Concrete Institute (ACI Committee 440.2R-2008)

This design guideline is used for designing FRP wrap systems for determination of the confined strength and ductility of the members. ACI suggests following formula for axial load carrying capacity of the member. (Hamdy M., 2010)

$$P_u = 0.85 f_{cc'} (A_g - A_{st}) + f_y A_{st}$$

Where

P_U = Axial load carrying capacity

$f_{cc'}$ = Compressive strength of confined concrete

A_g = Cross sectional area of the confined concrete

A_{st} = Longitudinal reinforcing steel area

f_y = Yield strength of longitudinal bars

Formula for confined strength is as follows

$f_{c'}$ = Unconfined concrete compressive strength

f_1 = Lateral confinement pressure

$$f_1 = \frac{2 \in_{fe} E_f n t_f}{D}$$

where

n = number of FRP layers

t_f = Thickness of FRP layer

E_f = Modulus of Elasticity of FRP

$\in_{fe}$ = FRP effective strain

$\in_{fe}$ = FRP effective strain $= k_e \in_{fu}$

$k_\in = 0.55$

CSA-S806-02

The confined strength of concrete is given by the following equation

$$f_{cc'} = 0.85 f_{c'} + k_1 k_s f_1$$

The factor k_1 is dependent on confinement pressure and can be solved using the following equation obtained from tests (CSA 2002)

$$k_1 = 6.7(f_1)^{-0.17}$$

Where k_s is the shape factor which is equal to 1 for circular cross sectional shapes. Confinement pressure f_l can be found out by using the following expression:[14]

$$f_1 = \frac{2 n t_f \in_{fe} E_f}{D}$$

ϵ_{fe} will be least of the following values i.e., 0.004 E_f and 0.75* ultimate FRP strain. (CSA 2002)

Intelligent Sensing for Innovative Structures Canada (ISIS MO4 2001)

The confined strength of concrete can be found out by the expression given below: (ISIS MO4 2001)

$$f_{cc'} = f_{c'}(1 + \alpha_{pc}\omega_w)$$

where

f'_{cc} = Compressive strength of concfined specimen

α_{pr} = Performance coefficient = 1 for circular columns

ω_w = Volumetric strength ratio

ω_w can be found out by

$$\omega_w = \frac{f_1}{f_{c'}}$$

where

f_l = Lateral confinement pressure

f_l can be found out by the following equation:

$$f_1 = \frac{2 N_b f_{frpu} t_{frp}}{D_g}$$

N_b = Number of layers of FRP

f_{frpu} = Ultimate strength of FRP

t_{frp} = Thickness per layeof FRP

D_g = Diameter of the member

ISIS imposes a limitation of minimum confining pressure for design purposes to be taken equal to 4 MPa. (ISIS MO4 2001; Hamdy M., 2010)

3. Results and Discussions

The surface of the ruptured cylinders was observed carefully after achieving failure load. The majority of the specimens failed with an explosive noise followed by cracking sound. CFRP jacket was ruptured in each specimen.

3.1 Effect of Unconfined concrete strength

Table 3 and 4 confirms that FRP is more effective for low strength concrete than normal strength concrete. Tests T-1, T-2, T-3 and T-4 indicate the specimen for low strength concrete whereas normal strength concrete specimens are designated by tests T-5 and T-6 in table in table 3 and 4. The results clearly show 45 to 113 percent increase in confined strength for low strength concrete samples of 8 to 17 MPa unconfined strength. Whereas, 20 to 22 percent strength increment was achieved for normal strength concrete specimens for normal strength concrete samples of 21 and 29 MPa unconfined strength as indicated in table 10. The comparison indicates that FRP is more effective for low strength concrete as compared to normal strength concrete. This is due to the fact that the lateral confinement decreases as the unconfined strength increases. The above mentioned results are in perfect agreement with the available literature. (Mandal et al)

Table 3: Percentage increase in confined and unconfined compressive strength for low strength (unheated) concrete

Test No.	No. of samples	Test condition	Test days	Test Value Avg (MPa)	Percentage increase
T-1	3	Unwrapped	37	7.84	113
	3	Wrapped	37	16.71	
T-2	3	Unwrapped	37	9.70	89
	3	Wrapped	37	17.54	
T-3	3	Unwrapped	37	13.27	63
	3	Wrapped	37	21.65	
T-4	3	Unwrapped	37	16.82	45
	3	Wrapped	37	24.38	

Table 4: Percentage increase in confined and unconfined compressive strength for normal strength (unheated) concrete

Test No.	No. of samples	Test condition	Test days	Test Value Avg (MPa)	Percentage increase
T-5	3	Unwrapped	37	20.83	22
	3	Wrapped	37	25.32	
T-6	3	Unwrapped	37	28.77	20
	3	Wrapped	37	34.53	

3.2 Predicted versus measured confined strength and axial load carrying capacity

3.2.1 Predicted versus measured Confined strength

Table 5, 6 and 7 shows the predicted confined strengths for low and normal strength unheated concrete samples using three North American design guidelines (American Concrete Institute ACI 440.2R-08, Canadian Standards Association CSA S806-02 and Intelligent Sensing for Innovative Structures Canada ISIS MO4 2001). ACI 440.2R-08, CSA S806-02, ISIS MO4-2001underestimate the results of confined strength with respect to the experimental results for low strength unheated concrete. The percentage increase in compressive strength of experimental results over theoretical results is 2, 8 and 19 percent respectively for ACI 440.2R-08, CSA S806-02, ISIS MO4-2001. The confined compressive strength is best predicted by ACI 440.2R-08 with a different of just 2 percent with respect to experimental results for low strength concrete.

ACI 440.2R-08 overestimates the results of confined strength with respect to experimental results for normal strength unheated concrete. Whereas CSA S806-02 and ISIS MO4-2001 underestimate the results for normal strength concrete. The percentage increase in compressive strength of theoretical results over experimental results is 9 percent for ACI 440.2R-08. It is also clear that CSA S806-02 and ISIS MO4-2001 underestimate the results by 2 percent for normal strength concrete. The confined compressive strength is best predicted by CSA S806-02 with a different of just 2 percent with respect to experimental results for normal strength unheated concrete.

Table 8, 9 and 10 shows the predicted confined strengths for low and normal strength post-heated concrete samples using three North American design guidelines (American Concrete Institute ACI 440.2R-08, Canadian Standards Association CSA S806-02 and Intelligent Sensing for Innovative Structures Canada ISIS MO4 2001). The symbol (*) shows the published experimental work of L.A Bisby. ACI 440.2R-08, CSA S806-02, ISIS MO4-2001underestimate the results of confined strength with respect to the experimental results for low strength post heated concrete. The percentage increase in experimental results is 143, 162 and 190 percent for ACI, CSA and ISIS.

ACI, CSA and ISIS underestimate the results of confined strength with respect to the experimental results for low strength post heated concrete. The percentage increase in experimental results is 83, 103 and 106 percent for ACI, CSA and ISIS.

The results clearly shows that the North American design guidelines are very conservative for predicting the confined compressive strength of post heated concrete.

Table 5: Experimental values versus theoretical values for confined concrete compressive strength predicted by ACI 440. 2R-08 for unheated (low and normal strength) concrete

fc'	fcc' theo (MPa)	fcc' exp (MPa)	fcc'/fc' (theo)	fcc'/fc' (exp)
7.84	15.37	16.71	1.96	2.01
9.70	17.55	17.54	1.81	1.81
13.27	21.15	21.65	1.59	1.59
16.71	24.32	24.38	1.48	1.48
20.83	28.71	25.32	1.37	1.22
28.77	36.66	34.53	1.26	1.20

Table 6: Experimental values versus theoretical values for confined concrete compressive strength predicted by CSA S806-02 for unheated (low and normal strength) concrete

fc'	fcc' theo (MPa)	fcc' exp (MPa)	fcc'/fc' (theo)	fcc'/fc' (exp)
7.84	14.89	16.71	1.90	2.01
9.70	16.56	17.54	1.71	1.81
13.27	19.60	21.65	1.48	1.59
16.71	22.61	24.38	1.35	1.48
20.83	26.03	25.32	1.25	1.22
28.77	32.82	34.53	1.14	1.20

Table 7: Experimental values versus theoretical values for confined concrete compressive strength predicted by ISIS MO4-2001 for unheated (low and normal strength) concrete

fc'	fcc' theo (MPa)	fcc' exp (MPa)	fcc'/fc' (theo)	fcc'/fc' (exp)
7.84	12.30	16.71	1.57	2.01
9.70	14.16	17.54	1.46	1.81
13.27	17.73	21.65	1.34	1.59
16.82	21.27	24.38	1.26	1.48
20.83	25.38	25.32	1.22	1.22
28.77	33.22	34.53	1.15	1.20

Table 8: Experimental values versus theoretical values for confined concrete compressive strength predicted by ACI 440. 2R-08 for post heated (low and normal strength) concrete*

fc'	fcc' theo (MPa)	fcc' exp (MPa)	fcc'/fc' (theo)	fcc'/fc' (exp)
11.67	19.56	51	1.68	4.37
14.67	22.56	51.33	1.54	3.50
20	27.89	54	1.39	2.70
27	34.89	61	1.29	2.26

Table 9: Experimental values versus theoretical values for confined concrete compressive strength predicted by CSA S806-02 for post heated (low and normal strength) concrete*

fc'	fcc' theo (MPa)	fcc' exp (MPa)	fcc'/fc' (theo)	fcc'/fc' (exp)
11.67	18.24	51	1.56	4.37
14.67	20.79	51.33	1.42	3.50
20	25.32	54	1.27	2.70
27	31.27	61	1.16	2.26

Table 10: Experimental values versus theoretical values for confined concrete compressive strength predicted by ISIS MO4-2001 for post heated (low and normal strength) concrete*

fc'	fcc' theo (MPa)	fcc' exp (MPa)	fcc'/fc' (theo)	fcc'/fc' (exp)
11.67	16.13	51	1.38	4.37
14.67	19.13	51.33	1.30	3.50
20	24.46	54	1.22	2.70
27	31.46	61	1.17	2.26

3.2.2 Predicted versus measured axial load carrying capacity

Table 11, 12 and 13 shows the predicted axial load carrying capacity for low and normal strength unheated concrete samples using three North American design guidelines (American Concrete Institute ACI 440.2R-08, Canadian Standards Association CSA S806-02 and Intelligent Sensing for Innovative Structures Canada ISIS MO4 2001). ACI 440.2R-08, CSA S806-02 and ISIS MO4 2001 underestimate the results of axial load carrying capacity with respect to the experimental results for low strength unheated concrete. The percentage increase in experimental results of low strength unheated concrete is 21, 33 and 50 percent for ACI 440.2R-08, CSA S806-02, ISIS MO4-2001. ACI best predicted the results with a difference of 21 percent with respect to the experimental results.

ACI 440.2R-08, CSA S806-02, ISIS MO4-2001 underestimate the results of axial load carrying capacity with respect to the experimental results for normal strength unheated concrete. The percentage increase in experimental results over theoretical results is 9, 36 and 38 percent of normal strength unheated concrete for ACI 440.2R-08, CSA S806-02, ISIS MO4-2001. ACI 440.2R-08 best predicted the results with a different of 9 percent with respect to the experimental results.

Table 14, 15 and 16 shows the predicted axial load carrying capacity for low and normal strength post-heated concrete samples using three North American design guidelines (American Concrete Institute ACI 440.2R-08, Canadian Standards Association CSA S806-02 and Intelligent Sensing for Innovative Structures Canada ISIS MO4 2001). ACI 440.2R-08, CSA S806-02, ISIS MO4-2001 underestimate the results of axial load carrying capacity with respect to the experimental results for low strength post-heated concrete. The percentage increase in experimental results over theoretical results of low strength post-heated concrete is 190, 221 and 255 percent for ACI 440.2R-08, CSA S806-02, ISIS MO4-2001 respectively.

ACI 440.2R-08, CSA S806-02, ISIS MO4-2001 underestimate the results of axial load carrying capacity with respect to the experimental results for normal strength post-heated concrete. The percentage increase in experimental results over theoretical results of normal strength post-heated concrete is 118, 365 and 177 percent for ACI 440.2R-08, CSA S806-02, ISIS MO4-2001 respectively.

Table 11: Experimental values versus theoretical values for axial load carrying capacity predicted by ACI 440. 2R-08 for unheated (low and normal strength) concrete

Pu	Pu theo(kN)	Pu exp(kN)	Pu(theo)/Pu	Pu(exp)/Pu
143	240	305	1.68	2.13
177	269	320	1.52	1.81
242	324	395	1.34	1.63
307	378	445	1.23	1.45
380	439	462	1.16	1.22
525	561	630	1.07	1.20

Table 12: Experimental values versus theoretical values for axial load carrying capacity predicted by CSA S806-02 for unheated (low and normal strength) concrete

Pu	Pu theo(kN)	Pu exp(kN)	Pu(theo)/Pu	Pu(exp)/Pu
143	226	305	1.58	2.13
177	249	320	1.41	1.81
242	293	395	1.21	1.63
307	336	445	1.09	1.45
380	384	462	1.01	1.22
525	418	630	0.80	1.20

Table 13: Experimental values versus theoretical values for axial load carrying capacity predicted by ISIS MO4-2001 for unheated (low and normal strength) concrete

Pu	Pu theo(kN)	Pu exp(kN)	Pu(theo)/Pu	Pu(exp)/Pu
143	186	305	1.30	2.13
177	213	320	1.20	1.81
242	265	395	1.10	1.63
307	316	445	1.03	1.45
380	373	462	0.98	1.22
525	417	630	0.79	1.20

Table 14: Experimental values versus theoretical values for axial load carrying capacity predicted by ACI 440. 2R-08 for post heated (low and normal strength) concrete*

Pu	Pu theo(kN)	Pu exp(kN)	Pu(theo)/Pu	Pu(exp)/Pu
213	299	931	1.03	4.37
268	345	937	1.29	3.50
365	427	985	1.17	2.70
493	534	1113	1.08	2.26

Table 15: Experimental values versus theoretical values for axial load carrying capacity predicted by CSA S806-02 for post heated (low and normal strength) concrete*

Pu	Pu theo(kN)	Pu exp(kN)	Pu(theo)/Pu	Pu(exp)/Pu
213	276	931	1.30	4.37
268	306	937	1.14	3.50
365	370	985	1.01	2.70
493	456	1113	0.92	2.26

Table 16: Experimental values versus theoretical values for axial load carrying capacity predicted by ISIS MO4-2001 for post heated (low and normal strength) concrete

Pu	Pu theo(kN)	Pu exp(kN)	Pu(theo)/Pu	Pu(exp)/Pu
213	242	931	1.14	4.37
268	285	937	1.06	3.50
365	361	985	0.99	2.70
493	459	1113	0.93	2.26

3.3 Comparison of unheated versus post heated data

Table 3 shows the percentage increase in confined and unconfined compressive strength for low strength (unheated) concrete. It is clear from the table 3 that the increase in compressive strength of unheated low strength concrete specimens is 45 to 113 percent for 8 to 17 MPa unconfined strength whereas 250 to 337 percent increase in confined compressive strength can be observed for low strength post-heated concrete specimens of 15 and 12 MPa unconfined strength as indicated in table 10. It is to be noted that the post heated data used in the tables is taken from the published research work conducted by L.A Bisby. Table 4 shows that the increase in compressive strength of normal strength unheated concrete specimens is 20 to 22 percent for 21 and 29 MPa unconfined strength whereas 126 to 170 percent increase in confined compressive strength can be observed for normal strength post-heated concrete specimens of 20 and 27 MPa respectively as indicated in table 10.

The above results indicate that fiber reinforced polymers are very effective for post heated concrete as compared to unheated concrete.

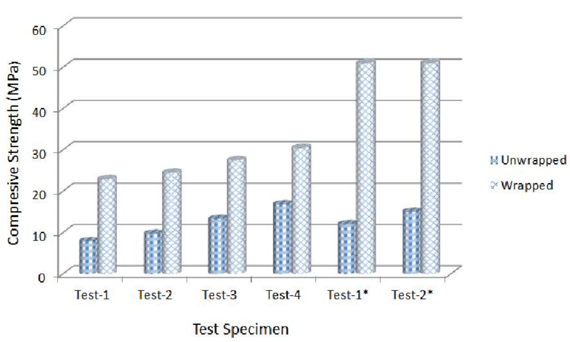

Figure 2: Comparison of unheated experimental work versus post heated published data* for low strength concrete

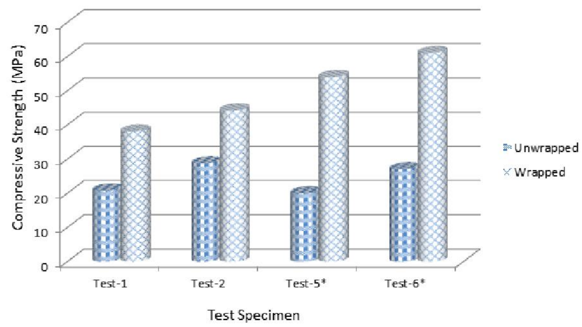

Figure 3: Comparison of unheated experimental work versus post heated published data for normal strength concrete

Table 17: Percentage increase in confined and unconfined compressive strength for low and normal strength (post-heated) concrete

Test No.	Exposure Temperature (^{0}C)	Unwrapped Test value Avg (MPa)	Wrapped Test vale Avg (MPa)	Percentage increase
T-1*	686	11.67	51	337
T-2*	686	14.67	51.33	250
T-5*	500	20	54	170
T-6*	300	27	61	126

Table 18: Percentage increase in axial load carrying capacity for low strength (unheated) concrete

Test No.	No. of samples	Test condition	Test days	Test Value Avg (kN)	Percentage increase
T-1	3	Unwrapped	37	143	113
	3	Wrapped	37	305	
T-2	3	Unwrapped	37	177	81
	3	Wrapped	37	320	
T-3	3	Unwrapped	37	242	63
	3	Wrapped	37	395	
T-4	3	Unwrapped	37	307	45
	3	Wrapped	37	445	

Table 19: Percentage increase in axial load carrying capacity for normal strength (unheated) concrete

Test No.	No. of samples	Test condition	Test days	Test Value Avg (kN)	Percentage increase
T-5	3	Unwrapped	37	380	22
	3	Wrapped	37	462	
T-6	3	Unwrapped	37	525	20
	3	Wrapped	37	630	

Table 20: Percentage increase in axial load carrying capacity for post heated samples of low and normal strength concrete (Published data of L.A Bisby)

Test No.	Exposure Temperature (^{0}C)	Unwrapped Test value Avg (kN)	Wrapped Test vale Avg (kN)	Percentage increase
T-1*	686	213	931	337
T-2*	686	268	937	250
T-5*	500	365	985	170
T-6*	300	493	1113	126

5. Conclusions

The confinement effectiveness decreases as the unconfined strength increases.

Carbon Fiber Reinforced Polymer is very effective for enhancing the confined compressive strength and axial load carrying capacity for low strength concrete as compared to normal strength concrete.

Carbon Fiber Reinforced Polymers significantly enhance the confined compressive strength of post heated concrete (low and normal strength) as compared to unheated concrete (low and normal strength).

The North American design guidelines (ACI 440.2R-08, CSA S806-02, ISIS MO4-2001) give very conservative predictions for confined compressive strength and axial load carrying capacity of post heated concrete (low and normal strength).

The North American design guidelines (ACI 440.2R-08, CSA S806-02, ISIS MO4-2001) underestimate the results for confined compressive strength for low strength unheated concrete cylinders.

The design guideline of ACI overestimates the results for confined compressive strength of normal strength unheated concrete whereas CSA and ISIS underestimate the results.

The North American design guidelines (ACI 440.2R-08, CSA S806-02, ISIS MO4-2001) underestimate the results of axial load carrying capacity for low and normal strength unheated concrete.

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