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Confinement effectiveness of CFRP strengthened concrete cylinders subjected to high temperatures

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Abstract. The current study investigated experimentally the effectiveness of Carbon Fiber Reinforced Polymer (CFRP) in confining concrete cylinders after being subjected to high temperature. Parameters examined were: (a) the exposing temperatures (20, 100, 200, 400 600and 700°C) and (b) the number of CFRP layers (1 and 3 layers). A uniaxial compressive testing was carried out on 36 concrete cylinders with dimensions of 150 mm×300 mm. The results obtained show that the compressive strength reduced with the increased of temperature compared to that measured at 20°C. In particular, the reduction in the compressive strength was more observed when the temperature exceeded 400°C. Further, the concrete cylinders confined with one and three layers of CFRP significantly increased the compressive strength compared to the counterpart unconfined specimen tested at the same temperature. Also, the average percentages of the increase in the compressive strength were approximately 112% and 158% when applying 1 and 3 layers of CFRP, respectively, compared to the counterpart un-strengthened specimen tested at the same temperature.

Keywords: concrete cylinders; confining; CFRP; high temperatures

1. Introduction

Fiber reinforced polymer (FRP) has been found to be an effective solution in retrofitting and upgrading of concrete structures. The main reason behind that is the superior properties offered by these materials, in specific; their resistant to corrosion, the high strength compared to its weight and ease of application (Raoof and Bournas 2017). FRP has been widely used for flexural strengthening of RC beams and slabs; shear strengthening of RC beams and confining of RC columns (Moshiri *et al* 2015, Al-Karaghool 2013, Radnić *et al.* 2013, Chikh 2012, Quiertant and Clement 2011, Gajdošová, and Bilcˇík 2011, Benzaid, *et al* 2009, Al-Salloum 2007, Elsanadedy 2011, Elsanadedy *et al* 2012, Siddiqui 2014). However, FRP showed a poor performance at moderate and high temperatures as the epoxy resins lose their tensile strength when the temperature reaches the glass transient temperature (T_g) (Raoof and Bournas 2017). Thus, in real fire scenario, if FRP left without protection, it may ignite causing evolution of fire.

According to the previous studies, it is found that the concrete can loss its strength at high temperatures, particularly, when the temperature of the concrete exceeded 400°C (Antons *et al*. 2012, Zhang *et al.* 2014, Belouadah *et al*. 2018). This may raise question on its structural performance after being exposed to a fire. Past studies, have mainly focused on evaluating the effectiveness of FRP strengthened concrete columns when exposing to high temperatures (Saafi and Romine 2002, Cleary *et al*. 2003, El-Karmoty 2012, Creeet *et al.*2012, Shaikh and Taweel 2015).

Saafi and Romine (2002) investigated experimentally the performance of GFRP-confined concrete cylinders subjected to high temperatures. The results have been showed that the GFRP system significantly lose its confinement effectiveness when the temperature reaches above or equal to the glass transient temperature (T_g). The same results were also observed by Cleary *et al*. (2003) in which concrete cylinders strengthened with GFRP were heated up to 120°C and 180°C and subjected to uniaxial compression loadings.

To maintain the performance of FRP- confining concrete columns at high temperature, fire protections were used by El-Karmoty et al 2012. This study tested concrete columns strengthened with CFRP and provided with two types of protection systems namely, (a) cement plaster and (a) perlite, gypsum and ceramic fiber. The specimens were exposed to a temperature of 600°C for 2 hrs and then left to cool down at the room temperature. All specimens were subjected to a uniaxial compressive load up to failure. The results showed that providing insulation system could enhance the CFRP confining performance. Creeet *et al.* (2012), tested two full-scale columns with different cross-section (circular and square cross-section). These samples are wrapped and strengthened with CFRP and provided with a thermal insulation system comprised cement mortar. Parameters investigated were; thermal insulation thickness (40 mm for square column and 44 mm for circular column) and the number of CFRP layers (two for circular column and three for square column). The results have shown that the provided insulation system was efficient in maintaining the specimen’s strength up to 4 hrs. fire endurance.

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Table 1 Proportions of concrete mix

Cement (kg/m^3)	Sand (kg/m^3)	Coarse aggregate (kg/m^3)	Water/ cement (%)	Slump (mm)
350	700	1050	34	71

However, the insulation system did not keep the temperature of the CFRP- strengthened system below the glass transient temperature.

Al-Salloum *et al.* (2016) tested forty-two FRP-strengthened concrete cylinder to evaluated the effectiveness of FRP when exposed to high temperatures. Type of fabric materials (carbon and glass), exposing temperature (100 and 200°C) and time of exposure (1, 2 and 3 hrs.) was examined. The specimens heating to the pre-defined temperature and time, then subjecting the specimen to a uniaxial compression loading up to failure. The test results indicate that the temperature was the main factor affecting the confining effectiveness of FRP and the loos of strength for specimens exposed to 200°C was more pronounced than of the corresponding specimens subjected to 100°C for the same exposure time.

According to the previous studies, it is found that there is a limited work for the effect high temperatures on the performance of FRP in retrofitting concrete columns. This paper examined experimentally the effect of CFRP confining concrete cylinders subjecting to high temperatures. In the present study, two factors were studied at high temperatures: the exposure temperatures (20, 100, 200, 400, 600 and 700°C) and number of CFRP layers (1 and 3 layers). In the next section, the experimental program will be presented.

2. Experimental program

2.1 Materials and methods

The targeted concrete compressive strength was 20 MPa. This compressive strength was chosen to simulate a real concrete condition in deficient concrete structures. Type I Portland cement, sand with fineness modulus of about 2.42 and coarse aggregate was used in mix proportions shown in Table 1. A slump test was conducted to check the consistency of the concrete mix within ACI concrete design method.

A total of 36 concrete cylinder with dimensions of 150 mm diameter and 300 mm height were casted, cured, hated up to the pre-defined temperature, strengthened with CFRP and subjected to uniaxial compressive loading up to failure.

Two specimens were tested for each case to reduce the uncertainty of the obtained results. Twelve specimens were left un-strengthened, and serves as reference specimens. These specimens were subjected to the pre-specified temperatures to examine the effect of the temperatures on the concrete strength. Twelve specimens were strengthened with one layer of CFRP to investigate the effectiveness of FRP-confining system in retrofitting of concrete cylinder after exposing to the pre-defined temperatures. The rest twelve specimens were wrapped with three layers of FRP for the same purpose of the corresponding specimens strengthened with one layer.

Table 2 Details of tested specimens

Specimen name	Temperature (°C)	No. of CFRP layers
C_20	20	-
C_100	100	-
C_200	200	-
C_400	400	-
C_600	600	-
C_700	700	-
C1_20	20	-
C1_100	100	1
C1_200	200	1
C1_400	400	1
C1_600	600	1
C1_700	700	1
C3_20	20	-
C3_100	100	3
C3_200	200	3
C3_400	400	3
C3_600	600	3
C3_700	700	3

Full details of tested specimens are presented in Table 2.

The specimen’s notation follows CN_T; C refers to a concrete cylinder, N stands for the number of CFRP layer and T represents the exposure temperature. For example, C3_500 refers to a specimen strengthened with three layers of CFRP after being subjected to 500°C. Whereas, C_100 denotes to un-strengthened specimens subjected to 100°C.

2.2 Material properties and strengthening procedure

2.2.1 Concrete

All specimens were casted using the same concrete mix design. The procedure of casting included; preparing the raw materials namely, (a) cement, fine and coarse aggregate, (b) mixing them in an electrical mixer, (c) pouring the mix in steel molds (three layers) and (d) compacting each concrete layer using shaking plate for 1-minute. After 24 hrs. the specimens were removed from the molds and cured in water for 7 days.

2.2.2 Materials and strengthening procedure

A directional high tensile strength carbon fiber strip was used as a strengthening material. The average ultimate tensile strength of the carbon fiber was 801 MPa, whereas the corresponding tensile strain was 1.01% and the modulus of elasticity was 74.7 GPa. Other standards of the used carbon fiber reinforcement are presented in Fig. 1. Two-parts epoxy resin (Sikadur®-330) was used to bind the carbon fiber to the concrete surface. The tensile strength was 30 MPa, the modulus of elasticity was 4.5 GPa. All the above data of the carbon fiber and epoxy resin was according to the manufacturer datasheets.

The strengthening procedure included; (a) a thin layer of

Weight: 230 g/m^2
Nominal thickness: 0.381 mm
Density: 1.8 g/cm^3
Direction: unidirectional

Fig. 1 Carbon fiber used as external strengthening

concrete was removed using a grinding machine (Fig. 2(a)); (b) the resulted concrete surface was cleaned using compressed air, (c) the two part of the epoxy resin was mixed with a ratio of 1:4 (as recommended by the manufacture), (d) the epoxy resin was applied to the concrete surface using a roller (Fig. 2(b)) and (e) the first layer of the carbon layer was applied (Fig. 2(c)). The procedure in (e) was repeated until the required number of layers was applied (Fig. 2(d)). Finally, the specimens were left at the room condition for seven days to insure a proper curing for the epoxy.

2.3 Test setup

The specimens were fixed inside a furnace that was operated by a gas. The level of temperature inside the furnace was controlled by a thermocouple that can be set to the required temperature. In addition, all specimens were instrumented with a high temperature thermocouple that fixed at the core of specimens during the casting (Fig. 3(a)). The specimens were subjected to a direct fire till reached the pre-defined temperature (Fig. 3(b)) for approximately 90 minute. Thereafter, the specimens were left to cool down at the room temperature. Finally, the specimens were strengthened with CFRP and left 7 days for curing.

Before the test, the specimens were fixed in the testing ring. Two dual gages were attached to measure the axial strain. The specimens were subjected to uniaxial compressive loading using a universal machine (with capacity of 1000 kN) up to failure (Fig. 4).

Table 3 Summary of test results

Specimen	Compressive strength (MPa)	Compressive strength reduction (%)	Failure mode
C_20	17.8	-	CC+
C_100	17.2	3	CC+
C_200	16.3	8	CC+
C_400	13.8	22	CC+
C_600	9.50	47	CC+
C_700	8.10	54	CC+
C1_20	35.5	-	CCFR++
C1_100	33.9	5	CCFR++
C1_200	32.7	8	CCFR++
C1_400	31.4	12	CCFR++
C1_600	20.6	42	CCFR++
C1_700	18.8	47	CCFR++
C3_20	41.6	-	CCFR++
C3_100	41.3	6	CCFR++
C3_200	39.2	9	CCFR++
C3_400	38.5	39	CCFR++
C3_600	25.2	43	CCFR++
C3_700	23.9	43	CCFR++

+CC- Concrete crushing
++CCFR- Concrete crushing followed by carbon fiber rupture.

3. Results and discussion

3.1 Results

Table 3 presents the main obtained results included; (1) the ultimate compressive strength (average of two specimens), (2) the reduction in the compressive strength (%) due to the high temperature and (3) The observed failure mode.

3.2 Temperature-time diagram

Fig. 5 presents the time- temperature relationships obtained from the thermocouple's reading for the specimens

(a) Removing a thin layer of concrete (b) Application of the epoxy resin to the resulted concrete surface (c) Application of the first layer of the CFRP (d) Application of the required number of layers.

Fig. 2 Strengthening procedure for test specimens

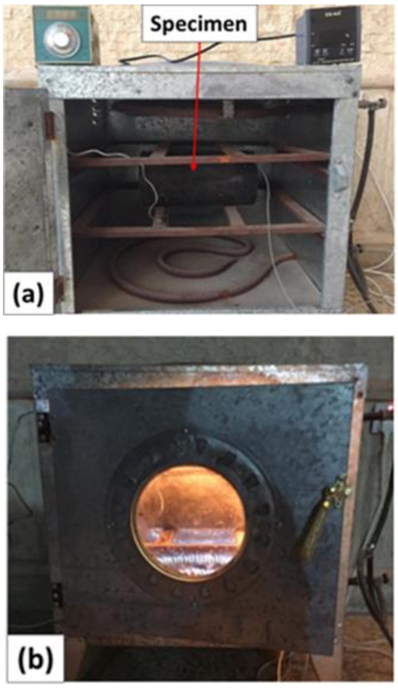

Fig. 3 Heating system; (a) Thermocouple location, (b) Direct fire

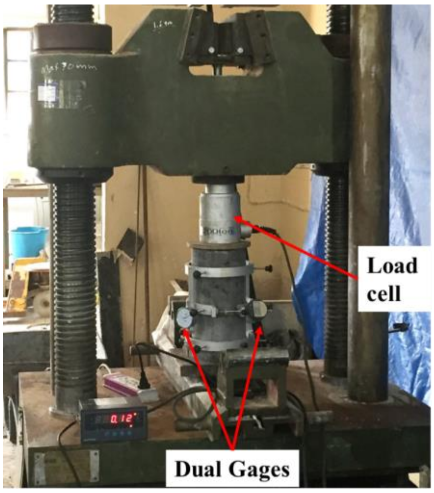

Fig. 4 Test setup

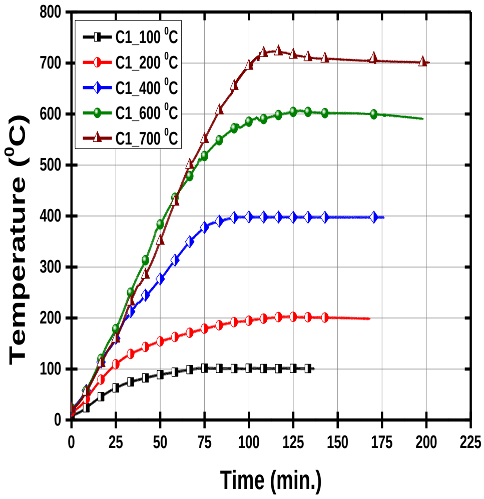

Fig. 5 Time- temperature profile for the test specimens

strengthened with 1-layer of CFRP. It can be seen from this figure that the temperature was rapidly increased at the begging of heating the specimens and then decreased with the increase of exposure time. Thereafter, the temperature was kept approximately constant for about 90 minute.

3.3 Stress-strain curve

Fig. 6 shows the stress- axial strain relationship for all tested specimens (average of two specimens). The stress-axial strain curves were characterized by two stages namely;

- A linear stage with decreasing in the stiffness
- And non-linear stage due to concrete cracking and activation of CFRP until failure occurred.

For the strengthened specimens, it can be seen that, as the number of CFRP layers increased, the stiffness of the specimens was also increased.

3.4 Ultimate load and failure mode

Table 3, lists the values of the ultimate compressive stress and the reduction in strength is due to the high temperate. The results here will be presented based on the exposure temperature. Starting from the control specimens (i.e., group C_T; the un-strengthened specimens tested at different pre-defined temperatures). The ultimate compressive strength recorded was 17.8, 17.2, 16.4, 13.8, 9.5 and 8.1 MPa for specimens exposed to 20, 100, 200, 400, 600 and 700°C, respectively. The typical failure mode noted for this group was concrete crushing at this mid-height of the specimens.

Similarly, the specimens strengthened with one layer of CFRP (i.e., C1_T group), the maximum compressive strength attended was 34.5, 33.6, 32.8, 31.4, 20.6 and 18.9 MPa, for specimens subjected to 20, 100, 200, 400, 600 and 700°C, respectively. The observed failure mode of this group was concrete crushing followed by rupture of CFRP at the mid-height of the specimens due to concrete expansion at this location.

Finally, the specimens which have been strengthened with three layers of CFRP, the calculated ultimate compressive strength was 41.6, 4.3, 39.2, 38.1, 25.3 and 23.9 MPa, for specimens subjected to 20, 100, 200, 400, 600 and 700°C, respectively. The failure mode of this group was similar to the corresponding group strengthened with one CFRP layer (i.e., C1_T group). This type of failure mode is attributed to the effect of high temperature on the concrete strength, hence the concrete had pre-mature failure due to deterioration of its strength as a result of high temperature, then, the stresses were transferred to the CFRP which failed due to rapture as a result of hoop stresses.

3.5 Discussion

3.5.1 Effect of high temperature on compressive strength

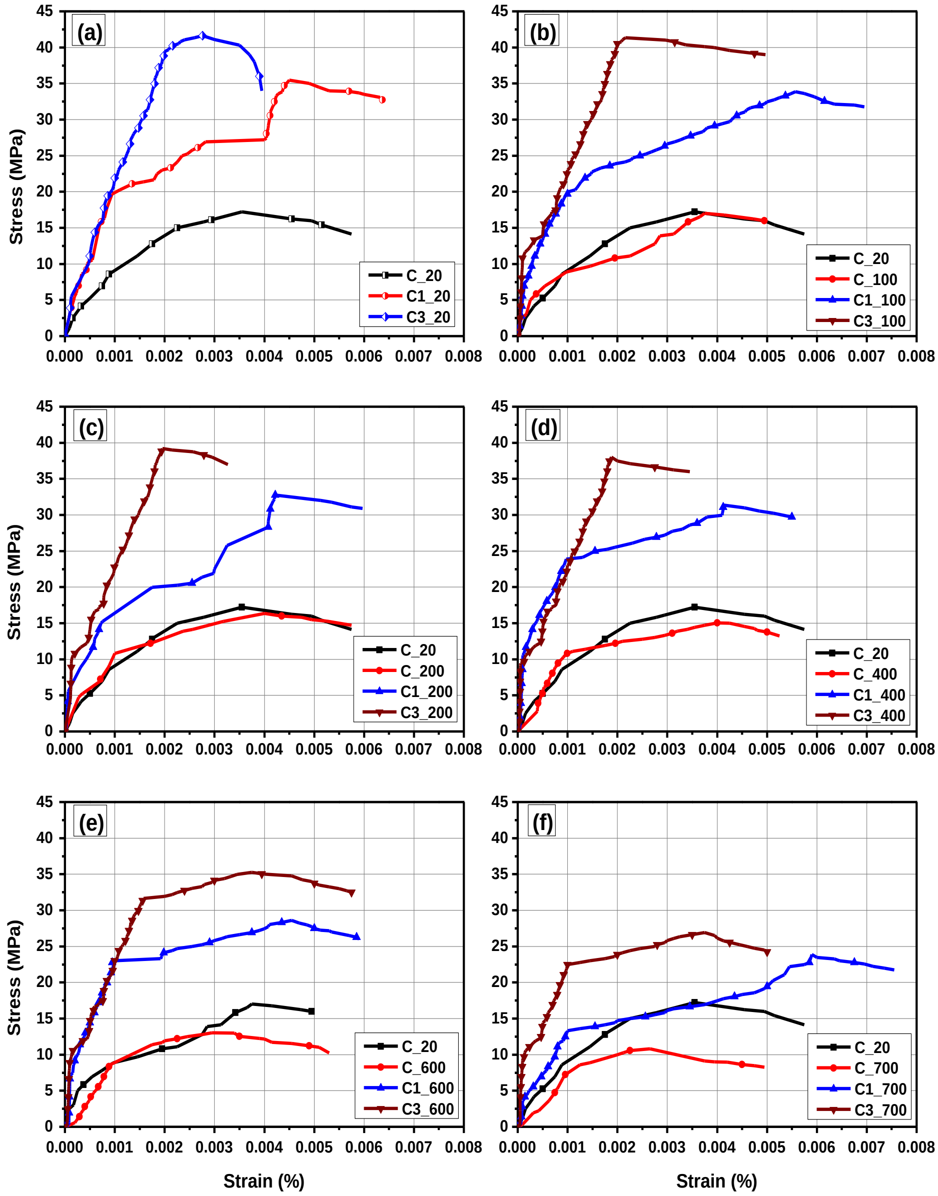

Fig. 6 Stress- axial strain curves of the test specimens

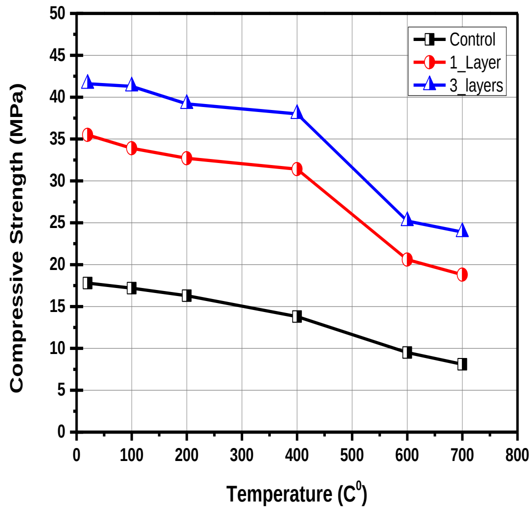

Fig. 7 Variation of compressive strength with the increase of temperature

Fig. 7 shows the reduction of compressive strength with the increase of temperatures for both the un-strengthened and strengthened specimens. In general, as the temperature increase, the reduction in compressive strength of the tested specimens also increase. In particular, for the un-strengthened specimens and compared to the control specimens (i.e., C_20), the average reduction in the compressive strength was 3.4, 8.4, 22.5, 46.6 and 54.5% for the specimens exposed to 100, 200, 400, 600 and 700°C, respectively. Similarly, compared to the control specimen (i.e., C1_20), the corresponding reduction in the compressive strength for the one layer of CFRP strengthened specimens (i.e., C1_T group), was 4.5, 7.9, 11.5, 42.0 and 47.0%, for the specimens subjected to 100, 200, 400, 600 and 700°C, respectively. Finally, the average compressive strength was reduced by 0.7, 5.8, 8.7, 39.4 and 42.5% compared to the control specimen (C3_20) for the specimens strengthened with three layers of CFRP and

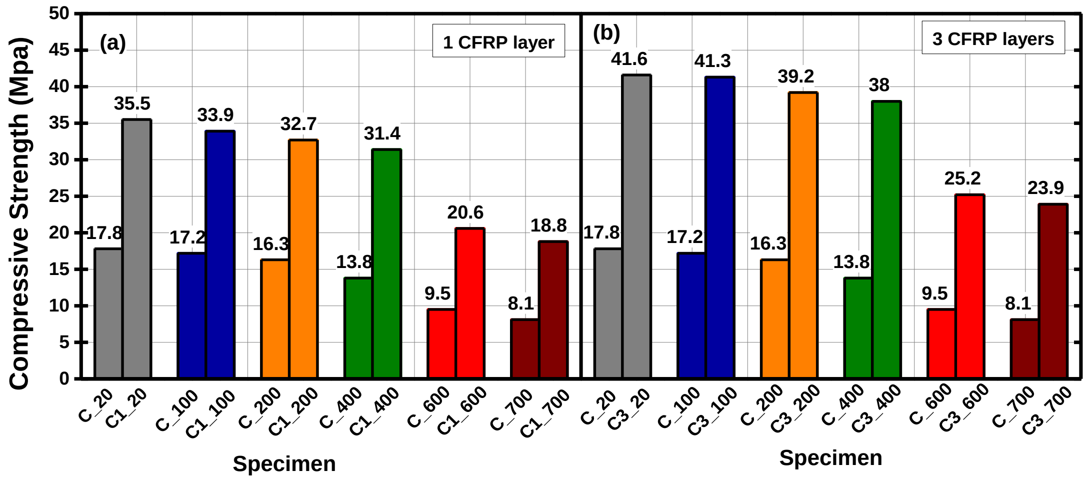

Fig. 8 Effect of number of CFRP layers on the compressive strength increase; (a) 1_layer strengthened specimens and (b) 3_layer3 strengthened specimens

subjected to 100, 200, 400, 600 and 700°C, respectively. It is noted the reduction in the compressive strength of the three layers strengthened specimens was slightly less than that of the corresponding reduction for the one layer strengthened specimens that subjected to the same temperature. Hence, when the number of CFRP layers increased, a better confinement effectiveness can be achieved. It was also noted that the reduction in the compressive strength was more pronounced when the temperature exceeded 400°C. This noticeable decrease in the compressive strength was due to the deterioration of the concrete itself as a result of the high temperature. The same results were also observed by Raoof and Bournas (2017) and Hashemi and Al-Mahaidi (2012). Reduction in compressive strength of concrete after 400°C would typically range from 55% to 70% of it is original value. Calcium hydration takes place after these temperature and aggregate also begins to deteriorate. For example, quartz expands at a higher rate around 300°C (Georgali and Tsakiridis 2005).

Finally, an attempt was made to examine the CFRF effectiveness at 800°C; however, during the heating, the specimen exploded inside the furnace.

3.5.2 Number of layers

Fig. 8 shows the effect of the number of CFRP layers on the compressive strength increase of the tested specimens. Comparison of the results was made based on the counterpart un-strengthened specimen that exposed to the same temperature. In general, applying CFRP resulted in a noticeable increase in the compressive strength compared to the un-strengthened specimens subjected to the same temperature. In specific, the average enhancement in the compressive strength was 1.99, 1.97, 2.01, 2.28, 2.17, 2.32 times for the specimens strengthened with 1_layer of CFRP and subjected to 20, 100, 200, 400, 600 and 700°C respectively (Fig. 8(a)). Similarly, the corresponding enhancement in the compressive strength when tripling the number of layers was 2.34, 2.40, 2.4, 2.75, 2.65 and 2.95 times for the specimens exposed 20, 100, 200, 400, 600 and 700°C, respectively (Fig. 8(b)). It is noted that the enhancement in the compressive strength was not proportional when shifting from one to three layers of CFRP. This can be attributed to the failure mode which was mainly due to concrete crushing, hence the CFRP in the case of three CFRP layers strengthening did not fully utilized.

Moreover, Touhari and Kettab (2014) stated that the enhancement in strength and strain of CFRP confined concrete cylinders is not proportional to the number of CFRP layers. This is mainly due to lateral confining pressure effect which is mainly depends on FRP hoop stress.

4. Conclusions

From the results obtained, the following conclusions can be drawn:

- In general, for both the un-strengthened and strengthened specimens, as the exposing temperature increased, the concrete compressive strength decreased in non-proportional way. In particular, above 400 0C, decrease in the compressive strength significantly.
- Regardless the exposure temperature, application of CFRP confining materials resulted in a significant enhancement in the compressive strength. In particular, the average increase in the compressive strength was about 2.1 and 2.6 times for the specimens strengthened with one and three layers of CFRP, respectively, compared to the identical un-strengthened specimens tested at the same temperature.
- For all the un-strengthened specimens subjected to the pre-defined high temperatures, the observed failure mode concrete crushing at the mid-height of the specimens. Whereas, the corresponding failure mode of the one and three CFRP layers strengthened specimens was due to concrete crushing flowed by CFRP rupture at the middle height of the strengthened specimens. This type of failure can be attributed to the deterioration of the concrete strength of strengthened specimens as a result of high temperature.

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