

## BEHAVIOR OF CONCRETE STRENGTHENED WITH CARBON FIBER REINFORCED POLYMER LAMINATE AT HIGH TEMPERATURE

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### ABSTRACT

In this paper the effect of high temperature on plain concrete strengthened with Carbon Fiber Reinforced Polymer ( CFRP ) sheets and behavior of concrete strengthened after heating were studied for flexure and compression properties . For this purpose a total of 44 prismatic specimens of 100x100x350 mm dimensions were tested . Results indicate that due to high temperature there is a continuous reduction in flexural strength of concrete strengthened with CFRP sheet . Deflection corresponding to flexural strength also reduced for exposure temperature higher than 350°C . The effect of finishing CFRP layers with cement mortar for controlling the reduction of flexural and compressive strengths due to high temperature was found to be not important . According to the obtained results , plain concrete damage by high temperature can be repaired using CFRP sheets for compressive strength of about 74% of that of plain concrete , and flexural strength of about 69% of that of strengthened concrete before heating .

**KEYWORDS:** Bond , CFRP , Compression , Flexure , Heating , High Temperature , Strengthening , Wrapping

### سلوك الخرسانة المقواة بصفائح الكاربون المعرضة الى حرارة عالية

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### الخلاصة

في البحث الحالي تم دراسة تأثير الحرارة العالية على خواص الانحناء والانضغاط للخرسانة المقواة بصفائح الكاربون ودراسة تأثير التقوية على الخرسانة المتضررة بسبب الحرارة العالية . لهذا الغرض تم تهيئة و فحص 44 نموذجاً موشورياً بابعاد 350 x 100 x 100 ملم . النتائج الحاصلة تؤكد بأن هناك نقصان مستمر في مقاومة الانحناء للخرسانة المقواة بصفائح الكاربون مع زيادة درجة الحرارة . الاود المصاحب لمقاومة الانحناء ايضا تأثر بسبب الحرارة لكن بنسبة قليلة لدرجات الحرارة اقل من 350 درجة مئوية . تأثير الانهاء بواسطة مونة السمنت للسيطرة على نقصان مقاومة الانحناء والانضغاط كان قليلاً . حسب النتائج الحاصلة , الخرسانة المتضررة بالحرارة العالية يمكن صيانتها بواسطة الياف الكاربون للحصول على مقاومة انضغاط بنسبة 74% من المقاومة الاصلية و بنسبة 69% من مقاومة الانحناء مقارنة مع مقاومة الانحناء للخرسانة المقواة قبل التعرض .

## 1- INTRODUCTION

Rehabilitating of deficient structural members and old infrastructures damaged as a result of cracking nowadays can be done successfully. Behavior of strengthened concrete members using different materials are well understood through experimental studies, and design proposals was introduced by researchers. Due to developments occurred in the aspect of materials technology, many types of advanced materials like polymers were developed for using as strengthening sheets or fabrics bonded with epoxies to the concrete surface. Polymer laminates are known by their high tensile strength to weight ratio. The structural performance of concrete bonded with fiber reinforced polymers using epoxy is accepted by engineers but the durability of the strengthened concrete needs to be assessed carefully. One of the most pressing problems related to using fiber reinforced polymer FRP is the bond failure lead to premature sheet separation. For this purpose a number of studies were carried out to understand the durability of bonded fiber reinforced polymers to concrete subjected to different environmental conditions.

The effect of freeze - thaw cycling on the bond behavior between carbon fiber reinforced polymer CFRP and concrete was studied by Green et al<sup>[1]</sup>. Their experimental results indicated that the bond between CFRP strips and concrete is not significantly damaged up to 300 freeze – thaw cycles. Tests indicated that the load carrying capacity of beams strengthened with CFRP plates is reduced after long term exposure to 100% humidity, dry heat, freezing and thawing, and thermal expansion environmental conditions<sup>[2]</sup>.

Basically, both the fiber reinforced plastics and epoxies are an organic materials and their performance is good and usable until their combustion at about 300 °C as pointed out by Gaylord<sup>[3]</sup>. If the FRP sheets are provided to concrete for strengthening structural members inside buildings and such buildings subjected to high temperature due to fire, the performance of strengthened concrete be in question .

Although the resistance of concrete to high temperature is better than that of steel, it is experimentally evident that many important properties of concrete like compressive strength, tensile strength and elastic modulus are deteriorated due to high temperature<sup>[4]</sup>. At about 800 °C the mentioned mechanical properties are rigorously damaged and the concrete not be remain usable .

In this paper the relation between concrete subjected to high temperature and strengthening with CFRP are presented through experimental tests. First, the effect of high temperature on flexural strength of concrete strengthened with CFRP is presented. Later the behavior concrete damaged by high temperature and then strengthened with CFRP is studied through testing prismatic specimens in flexure and compression.

## 2- EXPERIMENTAL

The properties of concrete materials and fiber reinforced polymer used in the present study is shown in Table ( 1 ). Instead of standard prisms of 100 x 100 x 400 mm dimensions a 100 x 100 x 350 mm prism specimens were prepared for testing. Such specimens of smaller length were used due to the limitations of the furnace dimensions used for heating concrete specimens. All specimens were cast from one mix batch and compacted by compacting standard rod. After casting, all specimens were put inside water tank and cured for 28 days. Concrete Specimens were left in open air to dry for another 28 days before strengthening or heating .

Details of prismatic concrete specimens are summarized in Table ( 2 ). Two specimens were prepared for testing for variables shown in the table and accordingly the total number of 44 specimens were tested. After drying, the surface of concrete specimen to be wrapped with CFRP was well cleaned and covered by the epoxy mixture ( 1 part resin and 4 parts hardener ) of Sikadur-330 type, and well leveled to obtained a thickness of about 1 mm. Later a CFRP layer was put on the epoxy surface and covered with hard nylon sheet and pressed so as to saturate the layer with the epoxy mixture . For providing other layers of CFRP the process was repeated . For those specimens having surfaces to be finished , additional layer of epoxy was provided and a medium size sand then sprayed on it and left for 48 hours. Later a cement mortar of 1:2 ( cement : sand ) proportion with water/cement ratio of 0.5 was prepared. The surface of specimen then covered with cement mortar and smoothly finished. After 24 hours the specimen covered with wet cloth and left for 7 days.

**Table ( 1 ) Properties of Concrete Materials and CFRP**

Material	Type	Source	Specific Gravity	Grading
Cement	Ordinary Portland Cement ( Type I )	Kurtlan/Turkey	3.14	-
Fine Aggregate	Medium size river sand	Fishkhabor Quarry	2.71	Passing by 100% on 4.75 mm sieve and of 2.45 fineness modulus
Course Aggregate	Well graded rounded shape river gravel	=	2.76	Passing by 100% on 10 mm sieve

Concrete	Mix Proportion	w/c Ratio	Cement ( kg/m <sup>3</sup> )	Fine Agg. ( kg/m <sup>3</sup> )	Coarse Agg. (kg/m <sup>3</sup> }
Properties	1:1.5:3	0.5	408	812	1224

CFRP Type *	Areal Weight	Fiber Density	Fabric design Thickness	Tensile Strength ( MPa )	Elastic Modulus ( MPa )	Strain at Break of Fibers
SikaWrap-230C ( Unidirectional Fibers )	220 g/m <sup>2</sup>	1.7 g/cm <sup>3</sup>	0.12 mm	4100	231000	1.7%

\* Data provided by the manufacturer

Table ( 2 ) Detail of Specimens Properties

Specimen	Type of Test	CFRP Configuration	Strengthening and Burning Relationship	Exposure Temp. (°C)	Remark
F F-1	Flexure =	Plain Concrete One Layer at Tension Face	- Strengthened Without Heating	- -	- Figure (1a )
F-1-250	=	=	Strengthened Before Heating	250	=
F-1-300	=	=	=	300	=
F-1-350	=	=	=	350	=
F-1-400	=	=	=	400	=
F-1-450	=	=	=	450	=
F-2	Flexure	Two Layers at Tension Face	Strengthened Without Heating	-	Figure (1b)
F-2-250	=	=	Strengthened Before Heating	250	=
F-2-300	=	=	=	300	=
F-2-350	=	=	=	350	=
F-2-400	=	=	=	400	=
F-2-450	=	=	=	450	=
FFT-2-500	Flexure	Two Layers at Tension Face +Finishing Tension Face	Strengthened Before Heating	500	Figure ( 1c )
FFTC-2-500	=	Two Layers at Tension Face +Finishing All Sides	Strengthened Before Heating	=	Figure ( 1d )
FT-1-500	Flexure	One Layer at Tension Face	Strengthened After Heating	500	Figure ( 1e )
FTS-1-500	=	One Layer at Tension Face and Strips in Compression Zone	=	=	Figure ( 1f )
C C-500	Compression =	Without Strengthening =	- Heated Without Strengthening	- 500	- -
CFF-1-500	=	Fully Wrapping with One Layer+ Fully Finishing	Strengthened Before Heating	500	Figure ( 2a )
CP-1-500	=	Partially Wrapped with One Layer	Strengthened After Heating	500	Figure ( 2b )
CF-1-500	=	Fully Wrapped with One Layer	=	500	Figure ( 2c )

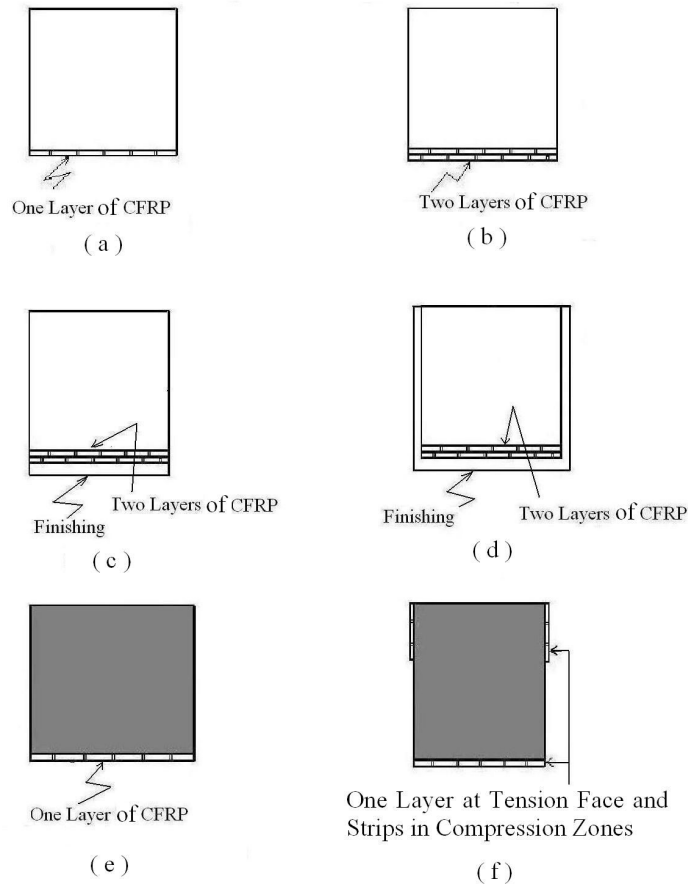


Figure ( 1 ) Detail of Cross Section of Flexural Specimens

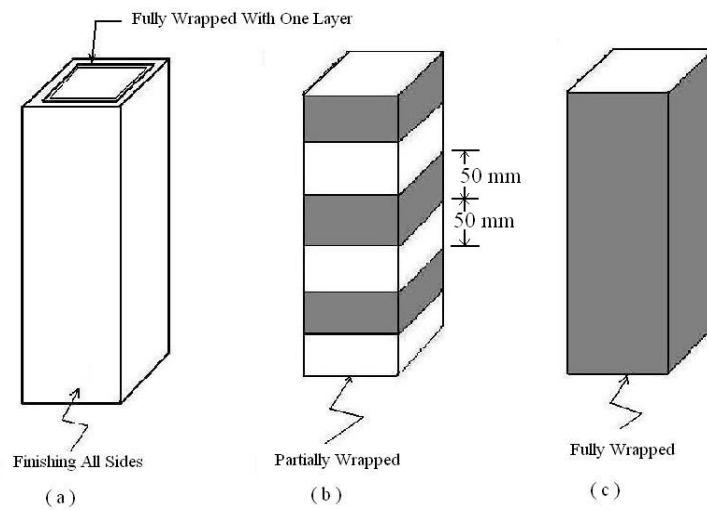


Figure ( 2 ) View of Strengthened Compression Specimens

After strengthening and finishing, all specimens were dried before subjecting to high temperature at 105°C temperature for 24 hrs. Those specimens exposed to high temperature were put horizontally inside the heating furnace and subjected to various temperatures according to the detail shown in Table ( 2 ). The rate of temperature increase was 380 °C / hr and after reaching the desired temperature heating was continued for 1 hr. After burning, all specimens were left in the laboratory and tested after 24 hrs for flexural strength or compressive strength or strengthened with CFRP layer and then tested, all according to the configuration shown in Table(2 ). All flexural specimens were tested to ultimate load by the mean of two central point loads over a clear span equal to 270 mm and shear span equal to 90 mm and the results of flexural strength and the corresponding deflection were taken from the output of the device. The rate of load increment used for testing flexural and compression specimens was 5 kN / min. After testing photographs were taken to illustrate the cracking pattern and the appearance due to physical changes take place as a result of high temperature .

### 3- RESULTS AND DISCUSSION

Table ( 3 ) shows the results of flexural strength, corresponding central deflection, and compressive strength of concrete specimens for different wrapping configuration. The values shown in the table are the average result obtained from testing two identical specimens. The role of different parameters affecting the strength and deformation of concrete strengthened with CFRP sheets in contact with high temperature in some detail is discussed in the following paragraphs.

#### 3-1 Effect of High Temperature on Flexural Strength

Flexural strength of plain concrete was 3.77 MPa and found to fail at the central zone of the specimen as a result of a single crack. Oppositely those specimens strengthened with one and two layers of CFRP were failed in shear [ Figure ( 5 ) ]. This occurs due to high flexural capacity as a result of strengthening tension face of the specimen with CFRP. After strengthening, the flexural strength of concrete was increased to 299% and 443% due to strengthening with one layer and two layers of CFRP, respectively. Figure ( 3 ) shows the variation of flexural strength of strengthened concrete with one layer and two layers of CFRP with temperature increase . As the flexural strength results are compared with that of control specimens one can found that the flexural strength of concrete is affected with the temperature increase and rigorously damaged when the temperature be higher than 350°C. The percentage of residual flexural strength is 29% and 32% for specimen strengthened with one and two layers, respectively at 400°C and 24% at 450°C compared with that of plain concrete. Such percentages are only 8% and 5% of the strengthened control specimen . Observing the nature of heated specimens indicates that due to high temperature and after 350°C the color of epoxy bonding is changed from grey to black as shown in Figure ( 6 ) and at 450°C it changed to white powder deposit [ Figure ( 7 ) ]. Comparing results of specimens strengthened with one layer and two layers of CFRP shown in Figure ( 3 ) indicate that the flexural strength of specimens with two layers is lower than that strengthened with one layer of CFRP at all exposure temperatures. Therefore flexural strength and hence the performance of concrete is reduced more due to high temperature when the amount of CFRP layer is increased. This can be argued from the fact that the epoxy material which is flammable not affected only by high temperature but can act as an enhancement tool for

burning plain concrete and affecting concrete through flam blows lead to more reduction in flexural strength .

**Table ( 3 )** Test Results of Specimens

Specimen	Ultimate Stress ( MPa )	Central Deflection (mm)	Ratio of Stress to Plain Concrete Stress ,%	Ratio of Stress to Strengthened Concrete Stress ,%	Ratio of Deflection to Plain Concrete Deflection ,%	Ratio of Deflection to Strengthened Concrete Deflection, %
F	3.77	2.0	100	33	100	57
F-1	11.28	3.48	299	100	174	100
F-1-250	11.41	3.6	303	101	180	103
F-1-300	8.1	3.25	215	72	163	93
F-1-350	7.24	2.9	192	64	145	83
F-1-400	1.10	1.21	29	10	61	35
F-1-450	0.89	0.8	24	8	40	23
F-2	16.70	3.5	443	100	175	100
F-2-250	8.62	3.3	229	52	165	94
F-2-300	4.64	2.8	123	28	80	80
F-2-350	3.93	3.46	104	24	173	99
F-2-400	1.22	1.16	32	7	58	33
F-2-450	0.91	0.81	24	5	23	23
FFT-2-500	0.38	0.40	10	2	20	11
FFTC-2-500	0.49	0.65	13	3	33	19
FT-1-500	6.78	2.3	180	60	115	66
FTS-1-500	7.8	4.9	207	69	245	141
C	21.46	-	100	-	-	-
C-500	1.85	-	8	-	-	-
CFF-1-500	2.53	-	12	-	-	-
CP-1-500	2.07	-	10	-	-	-
CF-1-500	15.9	-	74	-	-	-

### 3-2 Effect of High Temperature on Deflection

Results of central deflection corresponding to the ultimate load are shown in Table ( 3 ). Ratios of deflection of flexural specimens exposed to high temperature to that of plain concrete and

strengthened concrete specimens before heating are also shown in the table. Figure ( 4 ) shows the variation of deflection with temperature increase. It is shown that the deflection is reduced slowly for temperatures lower than 350°C and there is sudden reduction between 350°C and 400°C. At 400°C temperature the ratio is 61% for one layer CFRP and 58% for two layers of the plain concrete deflection and only 35% and 33% of that of strengthened concrete. At 450 °C such ratio for most of the specimens is 23%. As compared to the ratio of residual flexural strength the percentage reduction in deflection is lower especially for temperature lower than 350°C. As the results of Table ( 3 ) are compared one can observe that the role of the addition of other layers to strengthened concrete is not important on the reduction of deflection with temperature. In general the effect of high temperature on the deflection corresponding to flexural strength is lower than the flexural strength itself .

### ***3-3 Effect of Finishing on Flexural Strength and Deflection***

To study the effect of protecting CFRP layer with cement mortar finishing , two specimens strengthened with CFRP layer and covered with cement mortar at the tension face and at three sides ( specimens FFT-2-500 and FFTC-2-500 ) are tested for ultimate load and deflection. Results of these specimens are shown in Table ( 3 ). As the results compared with those specimens without protection or finishing , the role of finishing can be considered negligible. The reason of this observation can be argued from the fact that due to high temperature both CFRP layer and epoxy are damaged and their physical properties are changed and left the weak space between the mortar layer and concrete specimen to be easily separated from concrete even at small deformation. Before testing all finishing layers were fall down due to debonding. Figure ( 7 ) shows the view of specimen with finishing after testing .

### ***3-4 Effect of Strengthening on Flexural Strength of Concrete Exposed to High Temperature***

In order to study the effect of strengthening concrete subjected to high temperature with CFRP four specimens were tested, two in flexure and others in compression. These specimens were previously subjected to 500°C temperature, cooled down to room temperature and then strengthened with one layer of CFRP. Percentage of flexural strength for those specimens strengthened at tension face is 180% and 60% compared with that of control plain and strengthened concrete specimens, respectively. Such percentages are increased to 207% and 69% when strips of CFRP are provided to compression zone of flexural specimens in addition to that at tension face. The difference of 27% and 9% were occurred due to the increase of shear strength of concrete as a result of strengthening sides of specimen in compression zone. According to the obtained results any plain concrete damaged by high temperature can be repaired successfully with layers of CFRP. Results of Table( 3 ) also indicate that the percentage of deflection of concrete specimen corresponding to ultimate load is 115% of that of plain concrete and 66% of that of strengthened concrete when the specimen bonded with one layer of CFRP at tension face. For those specimens strengthened with strips in compression zone the ratio of deflection is 245% and 141%. The later deflection is higher than 100% because comparison was made with that of specimen strengthened with CFRP layer at tension face only ( specimens F and F-1 ). The later two deflections is higher than the previous value due to ductility increase as a result of strengthening compression zone with CFRP strip.



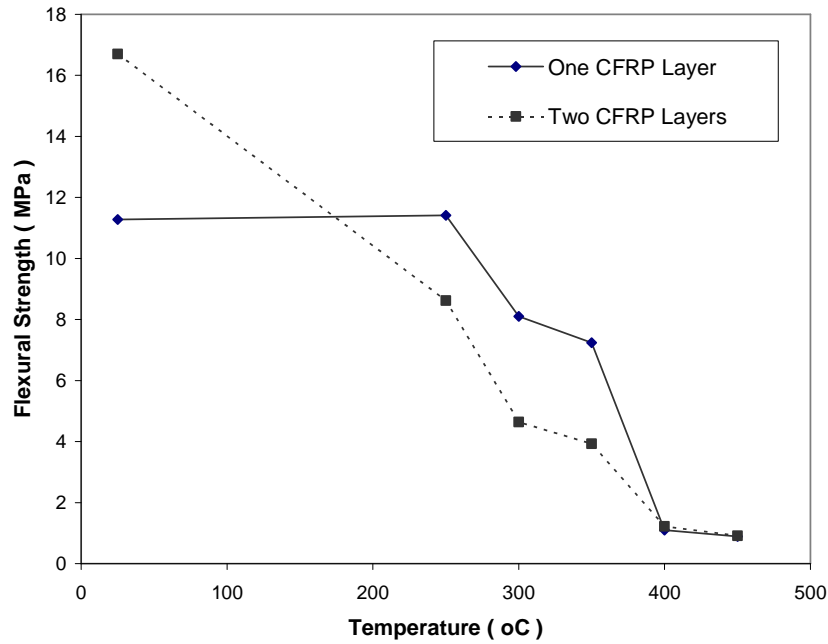


Fig.( 3 ) Variation of Flexural Strength With Temperature Rise

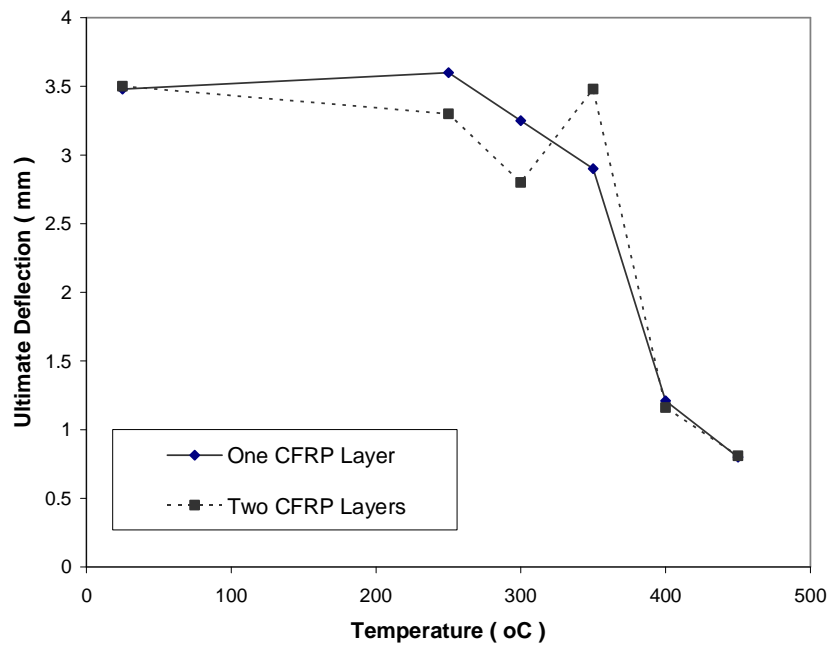


Fig.( 4 ) Variation of Central Deflection With Temperature Rise

### ***3-5 Compressive Strength of Wrapped Concrete Exposed to High Temperature***

According to the results of Table( 3 ) the performance of strengthened concrete in compression subjected to high temperature is not better than that in flexure. Percentage of compressive strength of specimen subjected to 500°C is 12% and 8% of that of control plain concrete, for heated plain and strengthened concrete specimens, respectively. This result indicates that due to high temperature the confinement effect which is responsible to increase the compressive strength diminishes as a result of reducing the bond between CFRP and concrete. Therefore the compressive strength is similar to that of plain concrete subjected to high temperature. The difference is only 4% remains for the effect of strengthening which is too small and can be considered not important. It should be noted that the strengthened specimen has also surfaces protected against high temperature with cement mortar finishing but was found to affect no on controlling damaging the strengthened concrete by high temperature. After heating and before testing a few number of cracks was seen along the specimen [ Figure ( 11 ) ] resulted from thermal expansions due to the low tensile strength of thin section finishing mortar. After testing, stresses will produce axial and lateral deformations and due to weak bond of epoxy material as a result of high temperature the finishing layer will easily separate from the specimen and disrupts. Figure ( 12 ) shows the view of such specimen after testing .

### ***3-6 Strength of Concrete Subjected to High Temperature then Wrapped***

Two specimens were tested to study the effect of wrapping on concrete subjected to 500°C temperature. One specimen was partially wrapped ( after heating with 500°C ) with CFRP strips 50 mm in width and of 50 mm spacing between them and the other specimen was fully wrapped. Table( 3 ) contains results of such specimens after testing for compressive strength. For partially wrapped specimen the ratio of compressive strength is only 10% increase of that of plain concrete while for the fully wrapped concrete the ratio is 74%. In that specimen partially wrapped with CFRP when the specimen is stressed under loading, there is already locations available without wrapping and therefore remain without confinement and considered weak zones that concrete crushes in a lower stress level compared with strengthened zones. As a result of such weak zones other strengthened zones remains useless. Therefore for obtaining better results of strengthening , the concrete must be fully wrapped. In the case of full confinement, the concrete acts in its biaxial stress state and can carry higher load capacity. The ratio of compressive strength for the fully wrapped concrete is 74% and as compared with that of flexural strength which is 180% and 207% ( specimens FT-1-500 and FTS-1-599 ) the performance of heated concrete in compression is lower than that in flexure when strengthened with CFRP sheets as a repairing material.



Figure ( 5 ) Specimen F-2



Figure( 6 ) Specimen F-2-300



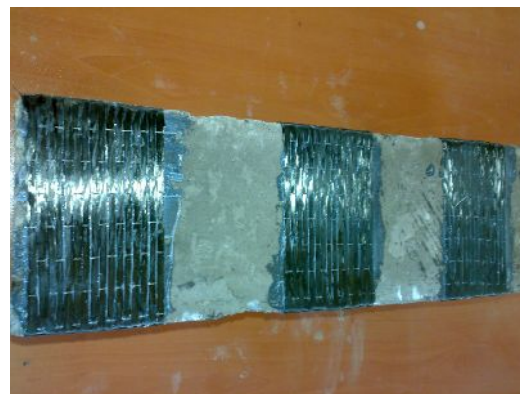
Figure( 7 ) Specimen FFT-2-500



Figure( 8 ) Specimen F-1-250



Figure( 9 ) Specimen FTS-1-500



Figure( 10 ) Specimen CP-1-500



Figure( 11 ) Specimen CF-1-500 (Before Testing)



Figure( 12 ) Specimen CF-1-500 (After Testing)

#### 4- CONCLUSIONS

From the experimental study presented in this research the following conclusion can be drawn :

- 1- There is a continuous reduction in flexural strength of plain concrete strengthened with CFRP sheets with temperature rise. The ratio of flexural strength to that of plain concrete is reduced to 24% and to that of strengthened concrete reduced to 5% at 450°C.
- 2- The deflection corresponding to flexural strength was not considerably reduced for temperature exposure lower than 350°C but suddenly reduced to about 23% at 450°C.
- 3- The role of additional layers of CFRP bonded to the strengthened layer was found to be not important for controlling the reduction in flexural strength and the corresponding deflection.
- 4- The role of cement mortar finishing provided to CFRP layer for controlling damages due to high temperature was found to be not important.
- 5- Plain concrete damaged by high temperature can be repaired using CFRP laminate for flexural strength of about 69% of that of strengthened concrete and about two times of that of plain concrete.
- 6- Plain concrete damaged by high temperature can be repaired for compressive strength of about 74% of that of plain concrete provided that the concrete fully wrapped with CFRP sheets.

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