Protection of RC Beams Strengthened with FRP from Elevated Temperature

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ABSTRACT

The present research work investigates the effect of elevated temperature on the structural behavior of reinforced concrete (RC) beams strengthened with FRP laminates and protected using different external coating layers.. The first phase of this research consisted of testing 81 concrete cubes protected by different coating materials (cement, perlite or vermiculite mortar, Aswan clay, or ceramic fiber blanket) under variable degrees of elevated temperature and for different durations. The second phase consisted of testing 36 beams, strengthened externally by FRP, protected with different coating layers, and subjected to 600^{o}C for two hours duration, left to cool gradually, and then tested till failure.

The obtained experimental results demonstrated the effect of the reduction in flexural capacity of unstrengthens and FRP-strengthened RC beams due to high temperature. All tested beams coating layers showed protection during exposure to 600°C for 2 hours, by reducing heat transfer thus providing higher fire rating and preserving the load carrying capacity. Further enhancement was achieved by using a double layer of ceramic fiber blanket followed by one of the tested materials. Finally, it was concluded that the most efficient protection was achieved by using a double coating system of ceramic fiber and perlite mortar, where the FRP-strengthened beam subjected to 600^{o}C for two hours lost only 5% of the load carrying capacity compared to the control beam which has not been subject to elevated temperature.

KEYWORDS: FRP, Strengthening, Thermal behavior, Fire protection, Reinforced concrete.

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1. INTRODUCTION

In the recent years, there was strong need to repair and strengthen concrete structures due to material deterioration, environmental effects, misuse, overloading or to raise their load-carrying capacity. As alternative to traditional strengthening techniques, Fiber-Reinforced Polymers (FRP) are being increasingly used due to their desirable attributes such as high strength-to-weight ratio, non-corrosive nature, small thickness, lightweight, easy handling, fast application, minimum alteration to dimensions, and reduced need of maintenance, respectively.. Polymer materials exhibit change in mechanical properties if exposed to temperature higher than the glass transition temperature (Tg), which ranges between 80-120^{o}C [1]. In case of a fire, the relatively low Tg of the polymer matrix or resin is easily exceeded which will seriously damage the bond between the FRP and the concrete surface and the structural integrity and effectiveness of the FRP strengthening will be severely threatened or may be totally lost.

Some design specifications such as ACI 440 (2008) [2], do not recommended the use of FRP internal or external reinforcements for structures under high temperatures or for structures in which fire resistance is essential in order to maintain structural integrity. The Egyptian code requires that the capacity of the unstrengthen concrete element should be sufficient to resist service load since FRP strengthening is assumed to be lost in case of fire, and therefore strengthening by externally bonded FRP is limited to raise only 40% of the capacity [3]..

Previous research studies investigated the effect of elevated temperature on RC and FRP-strengthened RC elements (Bisby, 2003 [4] and Mohamed, 2006 [5]). Protection of RC columns from the effect of elevated temperature was attempted through use of layer of thermal-resisting such as Perlite, Vermiculite and Rockwool (Abdel-Razik, et.al, 2004 [6], Nofal and Hamdy, 2005 [7]), or by using a double coating system of ceramic fiber and Perlite-gypsum plaster (Mohamed, 2006 [5]). FRP-strengthened RC beams were also protected using protective layer of Perlite and Vermiculite mortar with different cement contents (Alghareb, 2006 [8], and Hammouda, 2008 [9]).

The present research aims to investigate the effectiveness of applying coating layers of different materials to protect FRP-strengthened beams from elevated temperature. An experimental program of two phases was carried out in order to study the effect of protection layer on the strength of RC beams strengthened by FRP and subjected to high temperature [10]. The experimental program, results and conclusions will be presented.

2. EXPERIMENTAL PROGRAM

2.1. Objective and procedure of experimental program

The main objectives of this research are to study the effect of elevated temperature on unstrengthen or strengthened concrete beams using externally-bonded FRP technique, and the second aim is to investigate the effectiveness of coating layers of different inexpensive and locally-available materials in protection of tested beams from the effect of high temperature.

The first phase of the experimental work consisted of testing 81 concrete cubes protected by different coating materials under variable degrees of elevated temperature and for different durations. The second phase consisted of testing 36 beams, strengthened externally by FRP, protected with different coating layers, and subjected to 600^{o}C for two hours duration, left to cool gradually, and then tested till failure. Table 1 shows the details of the experimental program.

Table 1: Details of the experimental program

	Protection Type	Stren.	Room temp	Elevated temperature ^{o}C for 2 hours					
			25^{o}C	100^{o}C	200^{o}C	300^{o}C	400^{o}C	500^{o}C	600^{o}C
Phase 1: concrete cubes	Unprotected	No	C4-6	C7-9	C10-12	C13-15	C16-18	C19-21	C22-24
	Type 1	No					C25-27	C28-30	C31-33
	Type 2						C34-36	C37-39	C40-42
	Type 3						C43-45	C46-48	C49-51
	Type 4						C52-54	C55-57	C58-60
	Type 5						C61-63	C64-66	C67-69
	Type 6								C70-72
	Type 7								C73-75
	Type 8								C76-78
	Type 9								C79-81
Phase 2: RC beams	Unprotected	No	B1,B2	B5,B6	B7,B8	B9,B10	B11,B12	B13,B14	B15,B16
	Unprotected	GFRP	B3,B4						B17,B18
	Type 1	GFRP							B19,B20
	Type 2								B21,B22
	Type 3								B23,B24
	Type 4								B25,B26
	Type 5								B27,B28
	Type 6								B29,B30
	Type 7								B31,B32
	Type 8								B33,B34
	Type 9								B35,B36

2.2. The used materials

Concrete mix: The average concrete compressive strength used for cubes and beams was 25 MPa, the mix proportion is: 400 kg/m^3 ordinary Portland cement, washed crushed limestone of nominal maximum size of 20 mm, natural clean sand and water with water/cement ratio of 0.5.

Steel Reinforcement: Ordinary mild steel bars of 8mm diameter with yield stress of 2800 kg/cm^2, ultimate strength of 4100 kg/cm^2, diameter 8mm was used as main longitudinal and stirrups reinforcement for all tested beams.

FRP strengthening: FRP wrap used for external strengthening of concrete beams consists of two parts fiber and resin. Glass FRP used fiber is S-glass fiber (GFRP) sheets of width 1300 mm, thickness 0.36 mm. and density 2500 kg/m^3, having ultimate tensile strength of 4100 MPa, modulus of elasticity of 85 GPa and ultimate strain of 1.4% (Fib, 2001) [11]**.** The resin used for applying the GFRP on the concrete surface is the two-component epoxy adhesive MBRACE Saturant.

Protective coating materials:

The materials used are: mortar of Perlite [12], Vermiculite [12], ordinary Portland cement, red Aswan clay and ceramic fiber. The mix proportions for mortars are given in table 2.

Table 2: Mix proportions of one cubic meter of mortars used as protective layers

Layer	Perlite (lt)	Vermiculite (lt)	Clay (lt)	sand (kg)	cement (kg)	water (lt)	fiber (g)	air-entrained admixture(lt)
OPC mortar	-	-	-	1600	500	200	900	4
Perlite mortar	1 m^3	-	-	-	500	330	900	4
Vermiculite mortar	-	1 m^3	-	-	500	415	900	4
Aswan clay	-	-	1m^3	-	500	500	1800	4

2.3. Preparation of Tests Specimens

Concrete cubes

The concrete mix used to cast all the tested concrete specimens had mix proportions designed to give characteristic compressive strength of 250kg/cm^2. The specimens were concrete cubes of side length 15cm. The wood forms were prepared for casting the concrete cubes and reinforced concrete beams. Concrete was cast at room temperature of 25^{o}C, compacted after casting using electrical vibrator, and then cured with water on the second day. Three cubes where submerged in water and tested after 7 days and three more cubes tested after 28 days to determine the concrete characteristic strength.

Reinforced concrete beam samples

The RC beam samples dimensions were chosen so as to fit with the dimensions of the furnace and the testing machine. The dimensions and reinforcement of beams are shown in figure 1. Some of the beams were strengthened with FRP laminates, and some were coated with a layer of coating materials, as mentioned in the experimental program.

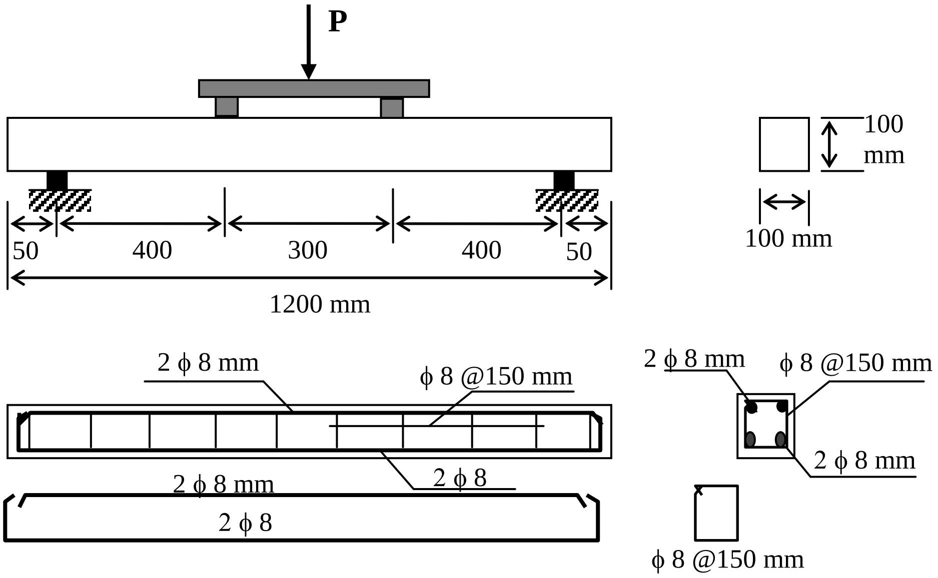

Figure 1. Dimensions and reinforcement of tested beams.

Figure 2: RC beams strengthened by FRP

2.4. Testing of specimens

Electric Furnace: The electric furnace was designed and specially fabricated for this research work. The furnace consists of two parts, and was designed to allow two cubes or one beam to be placed inside it after connecting the two parts of the furnace together, as shown in figure 3. During testing, the surface of the furnace is wrapped with ceramic fiber sheet to keep the temperature.

Figure 3: Installation of concrete cubes and beams in the electric furnace.

Subjecting cubes and beams to elevated temperature: The temperature scheme was chosen to resemble the temperature-time curve specified by ASTM [13] and ISO834 [14], representing fire in a residential building. The beams were exposed to temperature raised gradually at a rate of 20^{o}C/minute until reaching the target temperature then remain constant according to the chosen duration (2 hours). Type (K) thermo-couple was put on the surface of the specimens beneath the coating material to measure the temperature every 10 minutes. After switching off the furnace, the cube or beam specimens were left to cool gradually till reaching the room temperature, and then placed in the loading machine to determine the failure load and evaluate the residual strength.

Determination of failure load of cubes and beams and measuring instruments: The load capacity of cubes was determined by using compression machine shown in figure 4. The RC beams were tested by carrying out 4-point loading till failure using 200-ton hydraulic machine shown in figure 4, to determine failure load and study the failure mode and crack pattern. For measuring temperature on the surface of the concrete a temperature data measurement system was used by using type (K) thermo-couple. Data acquisition system by linear variable displacement transducers (LVDT) was used to measure the rate of deflection.

Figure 4: Compression machine for testing cubes and 4-point bending test for beams

3. EXPERIMENTAL RESULTS

3.1. Experimental Results of Phase one: concrete cubes

Phase one consists of 51 cubes divided into 3 groups, the studied parameters are degrees of temperature (100, 200, 300, 400, 500, 600°C) and different materials used as coating layers.

a. Unprotected concrete cubes subjected to temperature 100-600°C:

In order to study the effect of elevated temperature on concrete, 18 concrete cubes were exposed to elevated temperature in the electric furnace for 2 hours, left to cool gradually in air then tested under compression till failure. The experimental results, given in Figure 5 as the average value of compressive strength for 3 cubes, shows decrease in compressive strength of concrete cubes subjected for two hours to temperatures of 100°C, 200°C, 300°C, 400°C, 500°C and 600°C, by 2, 15, 32, 43, 57 and 80%, respectively, compared to control cubes, accompanied by change in the color of concrete and excessive cracking for 500 and 600°C. Similar conclusion was reported in published research (Bisby, 2003[4])

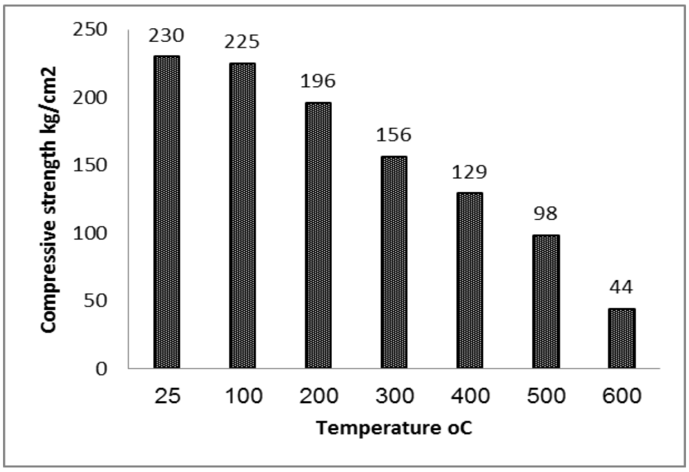

Figure 5: Compressive strength of unprotected cubes after exposure to elevated temperatures.

b. Thermally protected concrete cubes subjected to temperature 400, 500 and 600°C:

The tested 45 cubes were coated with a layer 30 mm thick of different coating materials (type 1 to type5) and subjected to different degrees of temperature (400, 500, 600°C) for 2 hours, left to cool gradually in air, then tested in compression till failure. The temperatures measured below coating layer are plotted in figure 7 to demonstrate the effectiveness of the coating layer in retarding temperature from reaching the concrete surface. Also, the values of the compressive strength as average of three cubes are plotted in Figure 8 to compare the ability of the coating layers to maintain the residual strength of the structural element. Results show that coating material type 5 is the best material for protection for the cubes, when exposed to 400°C, 500°C and 600°C for two hours, followed by type 1 then type 2.

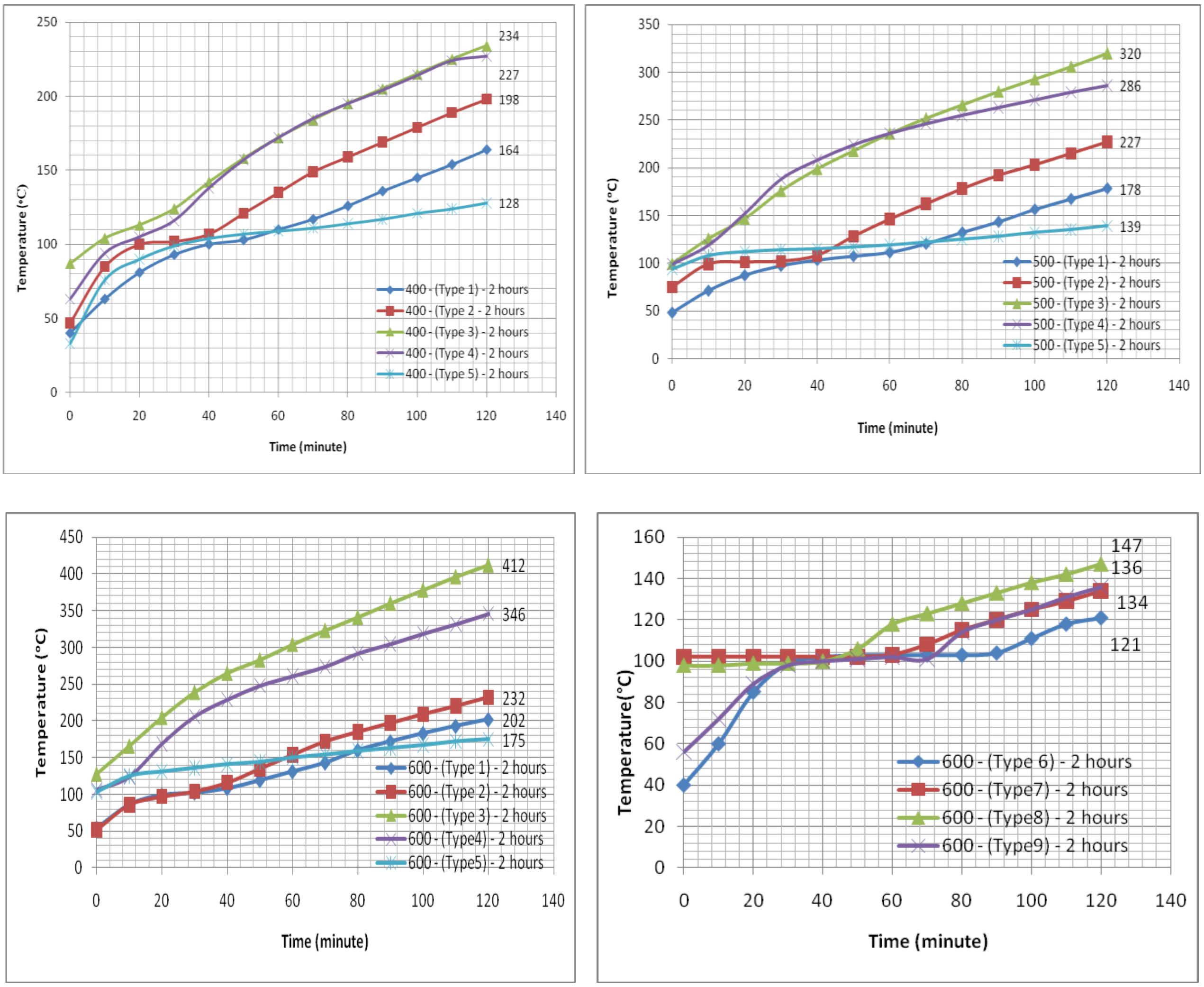

Figure 6: Temperature measured under coatings exposed to 600°C for 2 hours.

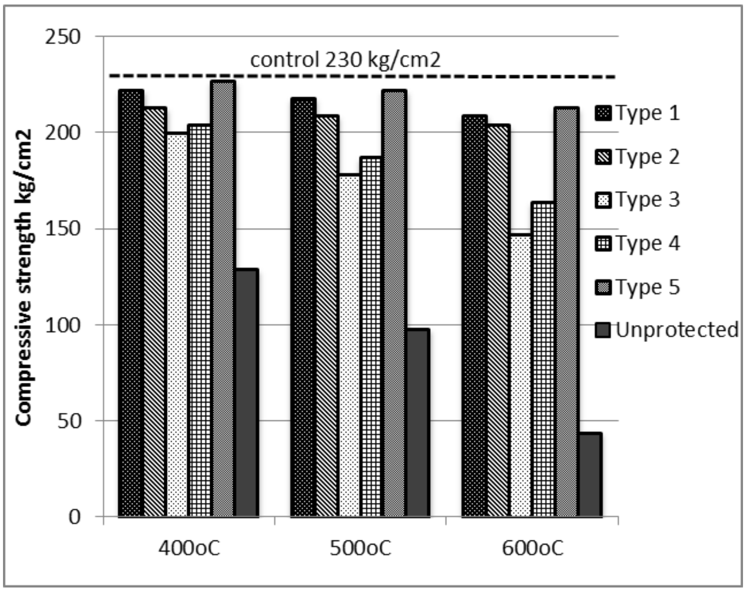

Figure 7: Compressive strength for protected cubes with coating types 1-5 when exposed to 400, 500 and 600°C 2 hours.

c. Concrete cubes protected by dual system and subjected to 600°C:

Twelve concrete cubes were protected using a dual system consisting of ceramic fiber mat wrapped around the cube followed by applying a coating layer of 30 mm thickness type 1, 2, 3 or 4, and are indicated as type 6, 7, 8 and 9, respectively. The cubes were subjected to elevated temperature of 600°C for 2 hours. The temperatures measured below coating were shown in Figure 6, and some cubes are shown in figure 8, after exposure to 600^{o}C for 2 hours. The values of compressive strength as average of three cubes are given in table 3. Results show that the dual system can protect the surface of the cube during exposure to 600°C for 2 hours, and maintain residual compressive strength 98.7% compared to control cubes, as shown in table 3.

Table 3: Compressive strength of cubes protected by dual system.

Type of coating	Temperature (^{o}C)	Failure load (ton)	Compressive strength (kg/cm^{2})	Ratio to control (%)
Type 6	600	51	227	98.7
Type 7	600	51	227	98.7
Type 8	600	50	222	96.5
Type 9	600	51	227	98.7

Figure 8: Concrete cube with protection type(6) and type(8) after 2-hour exposure to 600C°.

3.2. Experimental Results for phase 2: RC beams

a. Unprotected RC beams subjected to temperature 100-600^{o}C:

Two unstrengthened and two FRP-strengthened beams, not subjected to high temperature, were tested by 4-point bending test. The failure load was 3.0t and 3.8t for unstrengthened and strengthened beams, respectively, thus increasing by 27% due to GFRP strengthening. To study the effect of high temperature, 12 RC beams were subjected to temperatures (100, 200, 300,400, 500 and 600°C). Results are given in Table (4). When subjected to 600^{o}C, the GFRP system fell from the beams due to burning of resin above the glass transition temperature (Tg), and the failure load was (1.03 t).

Table 4: The failure load of unprotected RC beams.

Beam	Strengthening	Temperature (°C)	Protection layer	Failure load (ton)	Ratio to control (B_1, B_2) (%)
B_1, B_2	------	25	-----	3.0	100
B_3, B_4	GFRP	25	-----	3.8	126.67
B_5, B_6	------	100	-----	3.0	100
B_7, B_8	------	200	------	2.71	90.33
B_9, B_{10}	------	300	-----	2.28	76.00
B_{11}, B_{12}	------	400	-----	1.87	62.33
B_{13}, B_{14}	------	500	-----	1.56	52.00
B_{15}, B_{16}	------	600	-----	1.03	34.33
B_{17}, B_{18}	GFRP	600	-----	1.03	34.33

b. Thermally protected RC beams subjected to temperature 400, 500 and 600°C:

Ten RC beams, strengthened with GFRP laminates, were protected with different types of coating layers (from type1 to type 5) and exposed to temperature 600°C for 2 hours. The temperature measured beneath the coating layer (on the surface of GFRP laminates) is shown in figure 9. The beams, such as shown in figure 10 were tested by 4-point flexure loading till failure. The ultimate loads for protected beams are compared in figure 11.

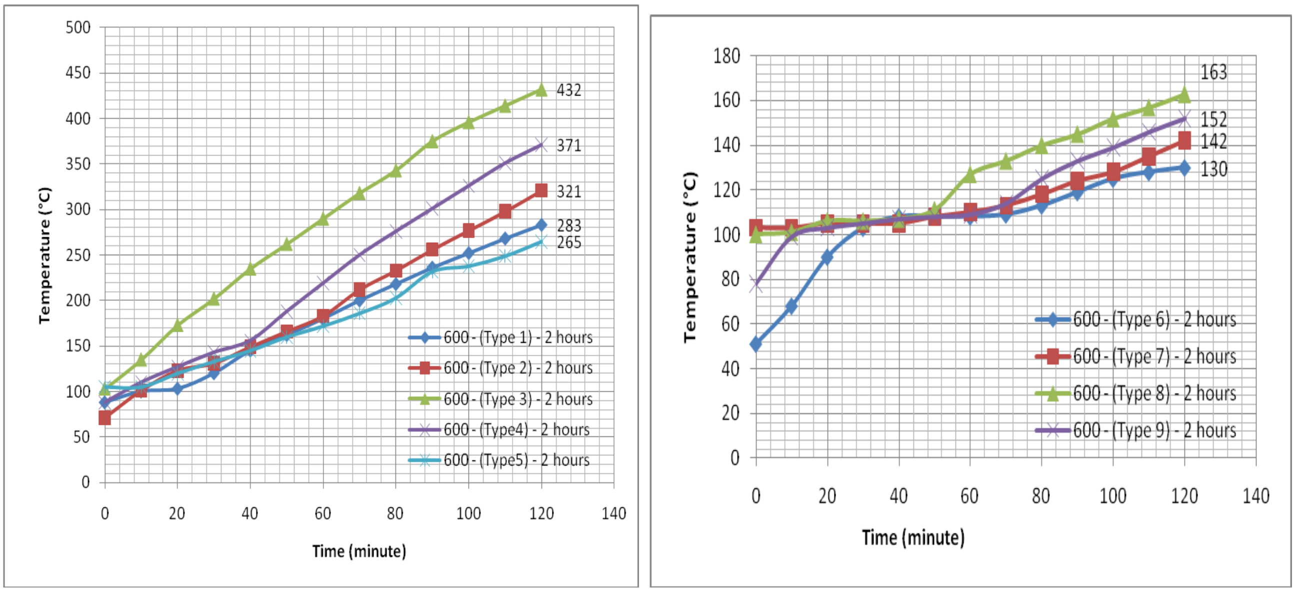

Figure 9: Temperature measured under coating types 1-5 when exposed to 600°C for 2 hours.

Figure 10: FRP-strengthened RC beams protected using type 1 and 4 after exposure to 600°C.

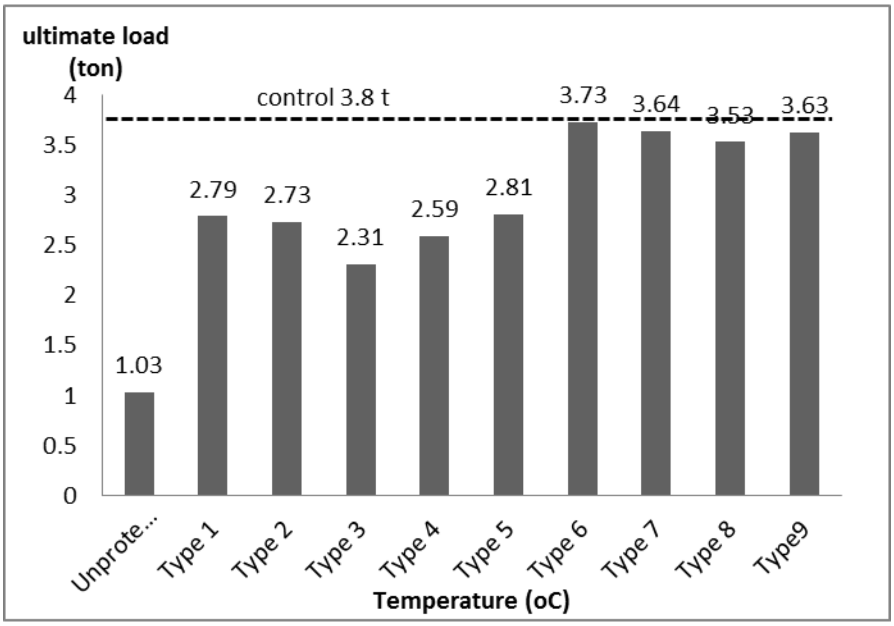

Figure 11: Failure loads for protected FRP-strengthened RC beams exposed to 600°C.

c. RC beams protected by dual system and subjected to 600°C:

This group consists of 8 beams strengthened with GFRP, coated with dual system of coating layers (type6 to type9) and exposed to a temperature of 600°C for two hours. The measured temperature under the coating layer (above the surface of the GFRP laminates), were shown in figure 9. The beams were tested by 4-point flexure loading till failure, and ultimate loads were plotted in figure 11. Form the above results it can be concluded that the four protective coat types of (type 6, type 7, type 8 and type 9) can protect the surface of the GFRP system as the temperature below the coating materials in the four types is less than the (Tg) for the resin present. Also, only 1 to 5% of the residual strength is lost.

4. CONCLUSIONS

From the results of the experimental work, the following main conclusions can be drawn.

1. Concrete subjected for two hours to temperatures of 100^{o}C, 200^{o}C, 300^{o}C, 400^{o}C, 500^{o}C and 600^{o}C, had compressive strength reduced by 2, 15, 32, 43, 57 and 80%, respectively, compared than control cubes.

2. Concrete protected by a 30mm-thick layer of cement, perlite, vermiculite or clay mortar, or a layer of ceramic fiber blanket was demonstrated to give good thermal insulation and retain concrete compressive strength when exposed to elevated temperature 400, 500 and 600^{o}C for two hours.
3. The experimental results showed that best protection was given by applying a layer of ceramic fiber blanket or perlite mortar over the surface of concrete which preserved 97% and 93% of concrete compressive strength during 2-hour exposure to 500^{o}C and 600oC, respectively.

4. Using a double coating system (Ceramic fiber + Perlite plaster or Vermiculite plaster or OPC plaster or Aswan clay with overall total thickness of about 50mm), was demonstrated to give better protection for concrete exposed to elevated temperature 600^{o}C for two hours. The residual compressive strength was nearly equal to that of the control samples.

5. Subjecting RC beam samples to a temperature of 200^{o}C, 300^{o}C, 400^{o}C, 500^{o}C and 600^{o}C for two hours, gradually cooling, then loading in a 4-point testing machine till failure, recorded a decrease in the failure load of 10% 24%, 38%, 48% and 66% compared to control beams at room temperature, accompanied by change in the color of concrete and cracking for 600^{o}C two-hour exposure.

6. RC beams strengthened with externally bonded GFRP sheets and tested till failure had ultimate strength higher than control beams by 27%.

7. RC beams strengthened with GFRP when subjected to elevated temperature, the epoxy of GFRP strengthening system burned and evaporated, and the GFRP sheets totally separated from the beams. Exposing the GFRP strengthening system to elevated temperature higher than that of the glass transition temperature (Tg) of the resin, destroys the mechanical properties of the resin, then by higher temperature it burns which leads to falling of the GFRP sheets.

8. RC beam samples strengthened with GFRP were protected using a layer of different materials (the same types as mentioned above) and were exposed to elevated temperature 600^{o}C for two hours, left to cool gradually then tested in 4-point load scheme till failure. The recorded failure

load was 61%, 68%, 72% and 73% of that of the control beam sample (GFRP strengthened beam kept at room temperature) for beam samples coated by layers of OPC, Aswan clay, vermiculite and perlite mortars, respectively. Beam protected by ceramic fiber blanket retained 74% of failure load of control beam, this means giving protection nearly the same as the perlite layer.

9. When GFRP strengthened RC beams were protected using double coating system (ceramic fiber + Perlite plaster or Vermiculite plaster or OPC plaster or Aswan clay) and were exposed to elevated temperature 600^{o}C for two hours, the GFRP system was not affected by elevated temperature and the beams had the same residual strength, i.e. about 98% of the failure load of control samples strengthened by GFRP but kept at room temperature. This means that the protection layer gave complete thermal protection to the FRP strengthening of the beams.

10. It can be concluded that perlite, vermiculite or cement mortars or a plaster of Aswan-clay that were used as coating layers proved to effectively contribute to reduce heat transfer and thus provide higher fire rating and keep the load carrying capacity of the structural member after being exposed to elevated temperature (61% to 80% of residual strength kept). Higher level of capacity can be achieved by adding ceramic fiber blanket then followed by any of the above mortars, especially perlite mortar, which gives 95-98% of the original carrying capacity maintained.

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