EFFECT OF FIRE PROTECTION MATERIALS ON FRP STRENGTHENED CONCRETE AXIAL MEMBERS

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ABSTRACT

The present research addresses an issue which is a major concern about the use of fiber reinforced polymers (FRP) in retrofit and strengthening applications. This paper presents an experimental investigation of the effectiveness of different fire protection materials and techniques on the efficiency of concrete axial members strengthened by FRP and subjected to high temperatures such as in the case of fire. Three locally available and economic materials are investigated: ordinary Portland cement mortar, Perlite and Vermiculite. These were applied with different thicknesses over FRP wrapped concrete specimens and subjected to elevated temperature in a closed furnace. For each case, variation of the temperature on the underlying concrete surface and the ultimate load carrying capacity were studied in order to explore and compare the effectiveness of these protection layers. Protective layers were applied over concrete cylinders strengthened using glass or carbon FRP wraps and subjected to elevated temperature to investigate the effect of fire protection materials on ultimate axial load carrying capacity and mode of failure. The results demonstrated that cylinders strengthened with FRP and protected using perlite mortar and ceramic fiber resulted in significant fire protection compared to unprotected FRP strengthened cylinders.

KEY WORDS: Fire Protection, Fiber Reinforced Polymers, repair and strengthening of concrete columns; advanced composite materials; ACM; FRP; CFRP; GFRP; confinement of concrete.

1. INTRODUCTION

The use of fiber reinforced polymer composites (FRP) for strengthening and retrofit of reinforced concrete elements has gained success and proved an attractive alternative to traditional retrofit methods. Effectiveness of FRP as external flexural reinforcement of reinforced concrete beams and slabs and for axial strengthening and ductility enhancement of RC columns is well established by research results and current practice. In addition, design guidelines are available for use in many countries [1, 2].

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However, a major concern about the use of FRP composites in civil engineering applications is the sensitivity of these materials to high temperatures, as is expected in the case of occurrence of fire. For polymer materials and epoxy adhesives, the glass transition temperature, T_g, defined as the temperature at which epoxies changes from relatively hard, elastic, glass-like to relatively rubbery materials, ranges between 60 – 80^{o}C [3]. Temperatures higher than the glass transition point T_g of resins may seriously damage the bond between the FRP and the concrete surface. During fire, if no special measures are taken, FRP-strengthened concrete members are likely to exhibit strength and stiffness degradation and loss of bond at high temperature. Moreover, the externally bonded strengthening may be lost due to the weakening of the adhesive layer between FRP and concrete [3]. This fact is a problematic area that challenges and limits the wide acceptance and application of FRP for strengthening and retrofits applications. Specifications and design guidelines limit the use, increase the load factor or limit the desired strength enhancement in order to meet fire hazard [1]. Fire performance is pointed out as a critical factor requiring more research before FRP can be used with confidence in strengthening applications [3].

Experimental research work investigating the fire performance of GFRP strengthened concrete cylinders [4] and of CFRP strengthened reinforced concrete full-scale columns [5] demonstrated reduction of strength of 50% after 3 hours exposure to temperature of twice T_g, and therefore recommended a minimum of two wrapping layers of GFRP and a conservative value for design residual strength in order to avoid collapse of column. CFRP wrap is concluded to be ineffective during fire unless exterior insulation layer is applied to provide supplemental fire insulation.

Research work involving locally available and economically feasible fire protection materials is needed. Published researches in Egypt studied protective layers such as ordinary Portland cement (OPC) mortar, OPC mortar overlaid by gypsum paste, OPC mortar containing polypropylene fibers and air-entrained cement mortar applied over the externally bonded FRP for fire protection [6,7]. An extensive experimental work conducted recently investigated full scale RC columns subject to fire and protected by layers of different protection materials which were demonstrated to be effective [8]. The same three protection materials are investigated in the current research as fire protection layer for FRP wrapped concrete axial members. The experimental program is explained in the following sections, and the results presented and discussed. Conclusions are drawn regarding the effectiveness of fire protecting materials on ultimate axial load carrying capacity and the mode of failure. Recommendations for further investigation are also pointed out.

2. RESEARCH OBJECTIVE

The current research addresses a major concern about FRP that limits its widespread application for retrofit and upgrading of structures. An experimental program was conducted in order to investigate the effectiveness of different materials applied as an exterior layer around concrete axial members retrofitted using FRP wraps and subjected to elevated temperatures. Three locally available and economic materials were investigated; ordinary Portland cement mortar, Perlite and Vermiculite, applied as exterior fire protection layers over glass and carbon FRP-wrapped concrete specimens. The protection materials investigated are locally available and economic materials, moreover, the application technique is simple and no specialized skill is required for application. The results of the experimental study evaluate and compare the effect of different fire protection materials and techniques on the structural behavior of concrete axial members strengthened with carbon and glass FRP systems.

3. EXPERIMENTAL PROGRAM

The experimental program conducted on seventy-five cylinders cast from a 30 MPa concrete mix, was divided into two phases as follows:

Phase I: Fifty-one plain concrete cylinders with diameter 150mm and 300mm long cast using a 30MPa concrete mix. This phase, outlined in Fig.1, was conducted in order to explore the effect of different protective layers on reducing temperature propagation through concrete and on the concrete strength. Three different protective materials were applied (Portland cement mortar, Perlite and Vermiculite) as an external layer on thirty-six cylinders with different layer thicknesses (15 and 30 mm). The concrete cylinders were subjected to elevated temperature of 400^{o}C or 600^{o}C in a closed furnace for duration of two hours. Twelve cylinders without any type of protection were subjected to the same conditions and three cylinders were not subjected to fire and noted as "Control ". The specimens were allowed to cool gradually afterwards in the open atmosphere and tested under axial compression to compare the compressive strength.

Phase II : In this phase, illustrated in Fig.2, twenty-four concrete cylinders were strengthened with one layer of GFRP or CFRP laminates. For each type (GFRP and CFRP wrapped), three specimens were not protected or subjected to fire; three specimens were not protected; three were protected from fire by applying 30mm thick layer of perlite mortar, and three were protected by 30mm thick layer of perlite mortar placed over a sheet of ceramic fiber, as sketched in Fig.3, placed in order to enhance the insulating effect of the protection layer. Specimens were subjected to elevated temperature of 400^{o}C in a closed furnace for two hours then allowed to cool gradually in air or suddenly by water. All samples were tested under axial compression to evaluate compressive strength and compare it to control specimen.

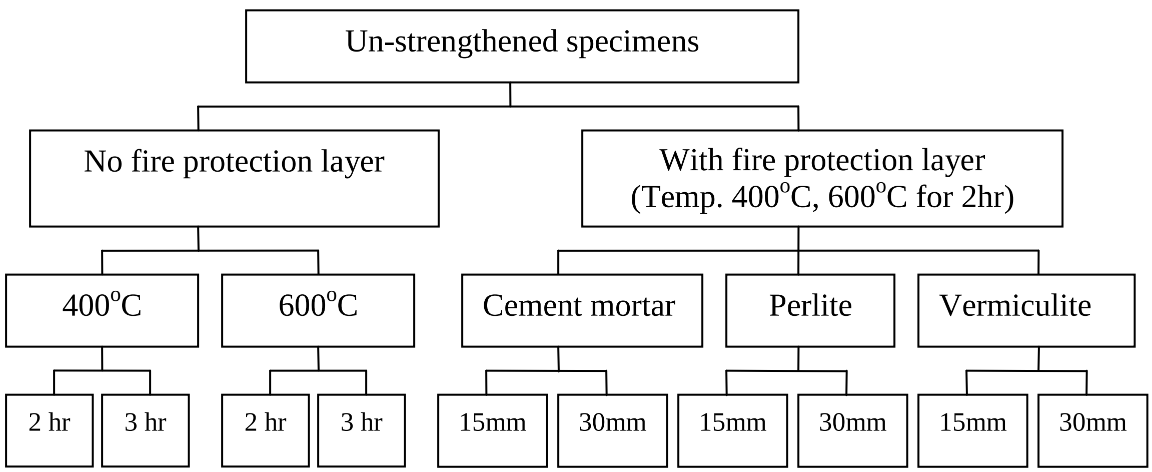


Fig.1 Experimental Program for unstrengthened specimens

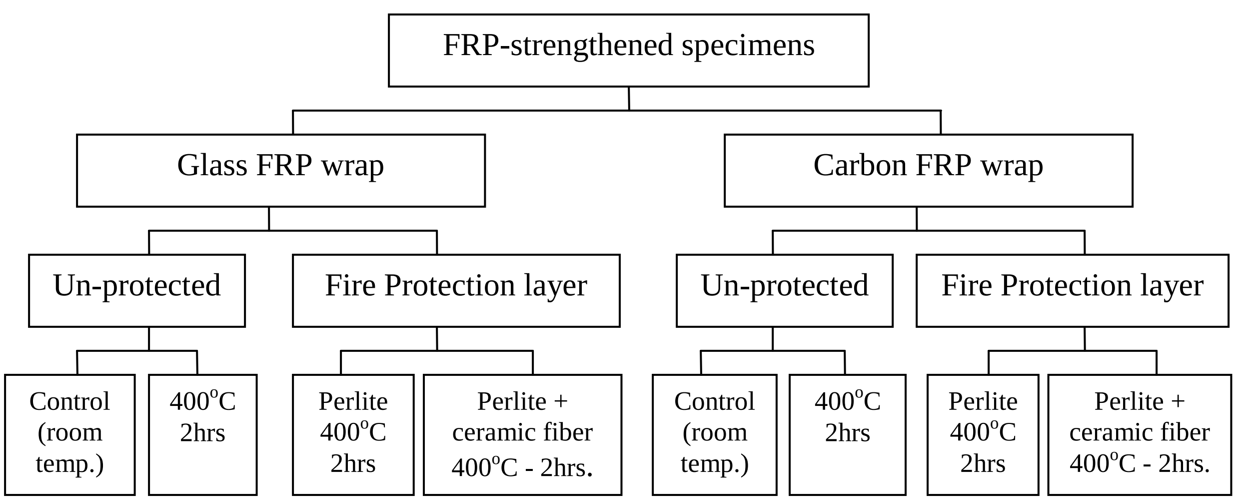


Fig.2 Experimental Program for FRP strengthened (confined) specimens

4. EXPERIMENTAL WORK

4.1. Concrete Mix

A 30 MPa concrete mixture was used to cast seventy-five concrete cylinders with diameter 150mm and 300mm long. The coarse aggregate used was washed crushed limestone with a nominal maximum aggregate size of 25 mm, while natural sand was used as fine aggregate. Ordinary Portland cement of 350 kg for each cubic meter of concrete and was used with water/cement ratio of 0.43. Superplasticiser was added in 58% of cement weight. Table 1 presents the concrete mix proportions. The concrete specimens were cured for 28 days.

Table 1: Concrete Mix Proportions

Cement	Course Agg. (25mm max.diam.)	Fine Agg.	Admixture (superplasticiser)	w/c ratio
1	1.76	3.54	0.58	0.43
350 kg	615 kg	1240 kg	58% cement wt.	150 lt.

4.2. FRP Strengthening Materials

Strengthening of concrete specimens was made through confinement by FRP wraps. Twelve cylinders were strengthened by unidirectional roving of high strength carbon fiber (CFRP) wraps (SikaWrap®HEX-230C), available from SIKA®Egypt. Twelve specimens were wrapped with unidirectional roving type E-glass fiber (GFRP) wraps (SikaWrap® HEX-430G VP). Sikadur-330®™ epoxy was used for both types. Table 2 presents properties of FRP materials [9]. The outer surface of the concrete cylinders was grind and cleaned. Epoxy resin and hardener were mixed, brushed on concrete surface and applied to the GFRP or CFRP sheets wrapped on the cylinders with 50mm overlap, and then a final coating of epoxy was applied.

Table 2: Mechanical and Physical Properties of GFRP and CFRP strengthening systems [9]

	GFRP	**CFRP**
Fiber Type	E-Glass fibers	High strength carbon fibers
Fiber orientation	Unidirectional (0^o)	Unidirectional (0^o)
Fiber weight (gm/m^2)	430	225
Fabric design thickness-fiber (mm)	0.17	0.13
Tensile strength (MPa)	2250	3500
Tensile Modulus	70000	230000
Elongation at break (%)	3.1	1.5

4.3. Fire Protection Layers

Concrete specimens were protected from fire by applying 15 mm or 30 mm thick layer of three different types of mortar: ordinary Portland cement (OPC) mortar, perlite-OPC mortar with glass fibers, and vermiculite-OPC mortar containing glass fibers. Mix proportions and physical properties of mortars are given in Table 3 and 4. [10]

a) Cement Mortar

Mix proportions, given in Table 4, shows that cement: fine aggregate 1:3. Water added as 10% of cement and sand by weight.

b) Perlite plaster

Perlite is a term for naturally occurring siliceous volcanic rock. It is chemically inert and has excellent insulating properties at low and high temperatures. Thermal properties are stable for long time and not affected by environment. Perlite aggregate conforming to requirements of ASTM Designation C-35 is available in Egypt for a fairly low price.

c) Vermiculite plaster

Vermiculite is a member of the phyllosilicate group of minerals, resembling mica in appearance. When heated it expands many times its original volume, a property known as exfoliation. Vermiculite aggregate conforming to requirements of ASTM standard C-332 is also locally produced and available in Egypt for a fairly low price.

Table 3. Physical Properties of Perlite and Vermiculite [10]

Property	**Perlite**	**Vermiculite**
color	white	gold-brown
Free moisture (max.)	0.5%	0.5%
pH	6.5-8.0	7.0-9.5
Specific gravity	2.2-2.4	2.5
Bulk density	32-40 kg/m^3	75-90 kg/m^3
Softening point	871-1093 ^{o}C	
Fusion point	1260-1343 ^{o}C	2200-2400 F
Specific heat	837 J/ kg K	1080 J/ kg K

Table 4. Mix design of fire protection plasters

Plaster type	Cement (kg)	Sand (kg)	Water (lt)	Perl or Verm. (lt)	Glass fiber (g)	Admixture (lt)
Cement plaster	50	150	20	-----	------	-----
Perlite	50	----	33	33	500	----

Vermiculite	50	----	33	38	500	----

d) Glass fiber

These are alkali resistant chopped strand fibers produced from 100% coated fiberglass. Characterized by low thermal conductivity, it provides high resistance against cracking and minimizes shrinkage in concrete. The product used herein is 17 microns in diameter, 12 mm in length and dosage is 0.5 kg for every 50 kg of cement.

e) Ceramic Fiber

Ceramic fiber mats (such as rock wool, etc.) is a non-combustible material that can withstand high temperatures. It is thus used for thermal and acoustic insulation and as fireproof filling for irregular cavities, such as furnaces and vehicle exhaust.

f) Wire mesh

A square galvanized wire mesh 20x20 mm complying with British Standards 1369 Part1 and BSEN 10142 with density 1.61 kg/m^2 was fixed around the concrete specimens for ease of placement of plaster layers.

4.4 Application of Protection Layers

Specimens were protected using different protection layers. Thermocouples were placed in order to measure temperature on the concrete surface as sketched in Fig. 3. Thermocouples of Type J, resisting up to 1000^oC, are fixed at the outer surface of each specimen before applying the protection layer. The final appearance of the protected cylinders is seen in Fig.4.

4.5. Temperature Profile and Cooling Schemes

The concrete specimens were subjected to elevated temperature in a closed electrical heat treatment furnace, shown in Fig. 5. The furnace was heated up from room temperature to 400^oC or 600^oC with a rate of 999^oC/hr, then the temperature was kept constant over a two- or three-hour period [11]. After that, the specimens were allowed to cool slowly in air. To investigate the effect of cooling scheme, two strengthened cylinders were suddenly cooled by water.

4.6. Experimental Test Set-Up

The concrete cylinders were subjected to axial compression using a 300 ton testing machine till failure, shown by Fig.6. The ultimate load carrying capacity was recorded from the machine dial. The mode of failure for each specimen was observed and photographed.

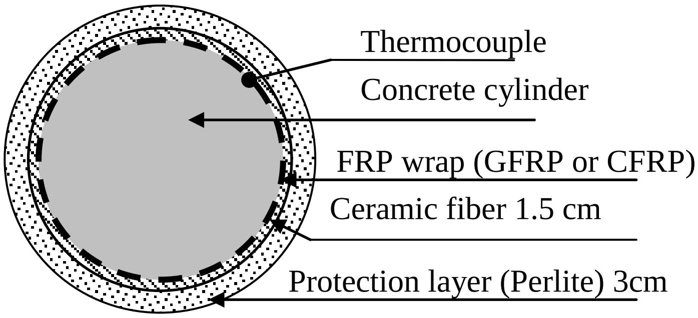


Fig.3 : Scheme of strengthening and protection layers applied to concrete cylinders.

Fig.4: Concrete cylinders with different protection layers before subjecting to fire.

Fig.5 Heating Furnace

Fig.6: Experimental test set-up for testing the concrete cylinders.

5. EXPERIMENTAL RESULTS

5.1 Effect of Elevated Temperature on Concrete Strength (Phase I)

The results of the experimental investigation conducted on unstrengthened concrete specimens (phase I) are presented in Table 5, It shows the compressive strength for different temperatures and exposure durations compared to control specimen. The compressive strength was decreased by 20% and 31.4% when subjected to elevated temperature of 400^{o}C for 2 and 3 hours respectively. When exposed to temperature of 600^{o}C, the compressive strength decreased by greater values of 48.5% and 60% for duration of 2 and 3 hours respectively, as shown in Fig.7. Similar results were observed through a research conducted recently and gave the explanation that temperature higher than 500^{o}C cause a rapid deterioration in the cement paste and some types of aggregates producing a considerable amount of gaseous products [10]. Gases entrapped in concrete pores increase the pore pressure and accelerate propagation of internal cracks reducing concrete properties [10].

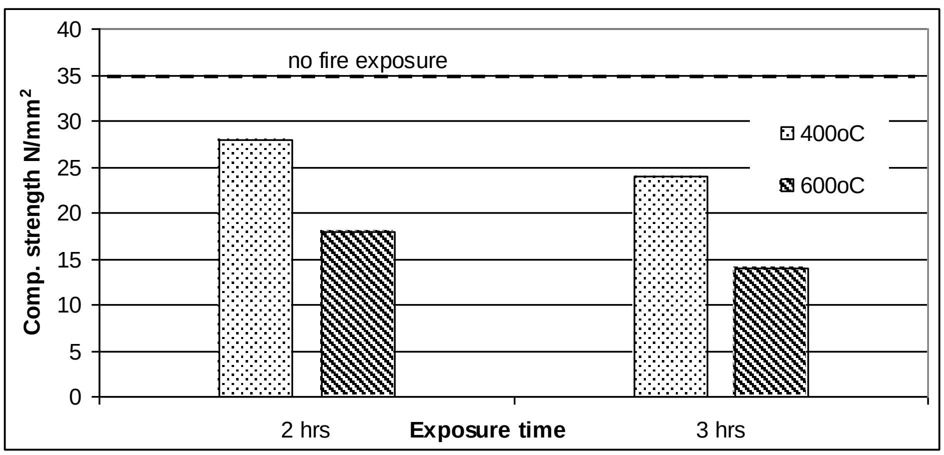


Fig 7: Effect of fire exposure on ultimate capacity of unprotected concrete specimens

5.2 Effectiveness of Protection Layers on Insulation and Concrete Strength (Phase I)

The temperature of concrete surface underneath the different protection layers 1.5 or 3 cm thick was measured while the specimens were being exposed to elevated temperatures of 400^{o}C or 600^{o}C for two hours. The temperature gradients are plotted in Figure 8. It was observed that large fragments of cement mortar and vermiculite protective layers completely fell off after the specimens were exposed to air and left to cool, while in the case of perlite protective layer, few cracks were observed in these layers as shown in Fig.10 compared to unprotected. This might be attributed that when vermiculite is heated to high temperature, particles of vermiculite exfoliate by expanding at right angles due rapid conversion of contained water to steam. While when perlite is exposed to elevated temperature it reaches chemically combined water in the form of vapor, which maintains the plaster temperature at about 100^{o}C until the water has been driven off as steam. The insulating action of perlite aggregate delays the release of steam and retards the transmission of heat, thus highly improving the fire retardant quality [10].

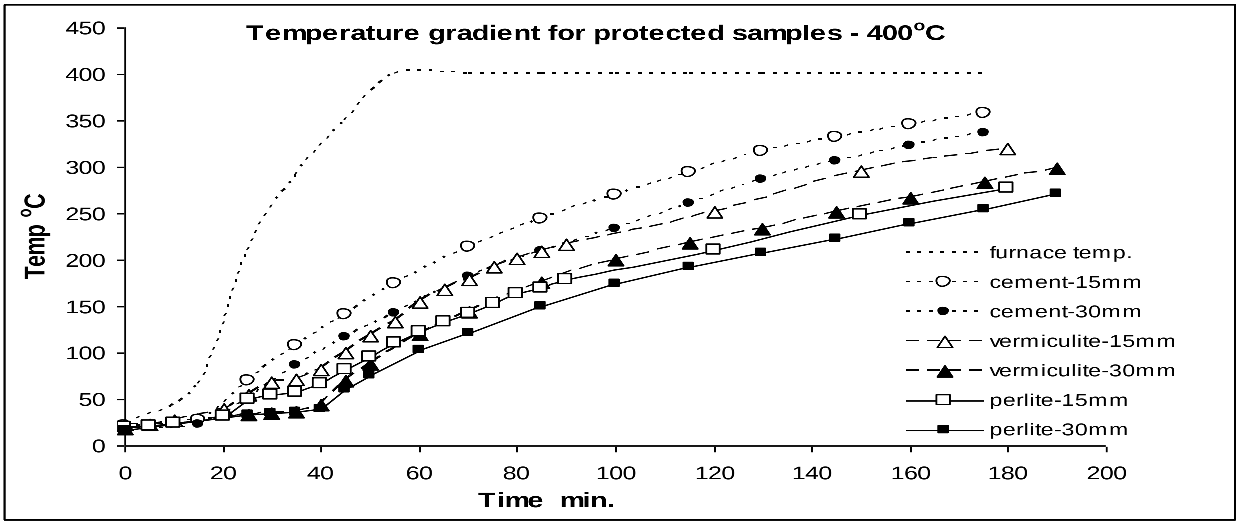
The experimental results of the compressive strength of concrete cylinders protected by the three tested protection layers are given in Table 5 and Fig.11 compared to control specimen. For all protection materials, the fire resistance of concrete improves with increase of layer thickness.

Table 5: Experimental Results: Effect of Elevated Temperature on Unstrengthened Cylinders

Protection layer	Thickness (mm)	Temp. (^{o}C)	Duration (hrs)	Compressive strength (N/mm^2)	Comp. strength decrease (%)
Unprotected	0	No fire	0	35	--------
Unprotected	0	400	2	28	20
		400	3	24	31.4
		600	2	18	48.5
		600	3	14	60
Cement Mortar	15	400	2	29	17
	30	400	2	30	14.2
	15	600	2	19	45.7
	30	600	2	21	40
Perlite	15	400	2	30	14.2
	30	400	2	32	8.6
	15	600	2	22	37
	30	600	2	24	31.4
Vermiculite	15	400	2	28	20
	30	400	2	30	14.2
	15	600	2	19	45.7
	30	600	2	21	40

- All results given are the average of three specimens

This might be explained that the increase in thickness increases the thermal resistance (R-value) of the plaster and the amount of free and bonding water increase as well. Thus the amount of heat dissipated in the decomposition of the hydration reaction, and the heat stored in the plaster increases, and the amount of heat passing through the plaster to reach the concrete surface decreases. Perlite is shown to be the most effective; this might be due to the insulating action of perlite aggregates which delay the release of steam and retards the transmission of heat, thus highly improving the fire retardant quality [10].



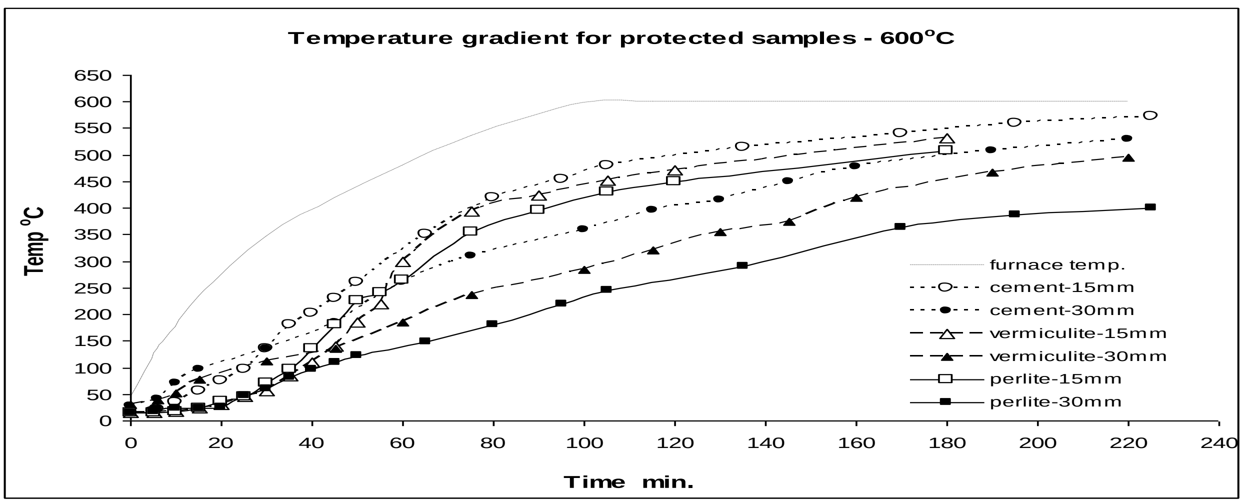


Fig.8: Temperature profile in protected unstrengthened specimens

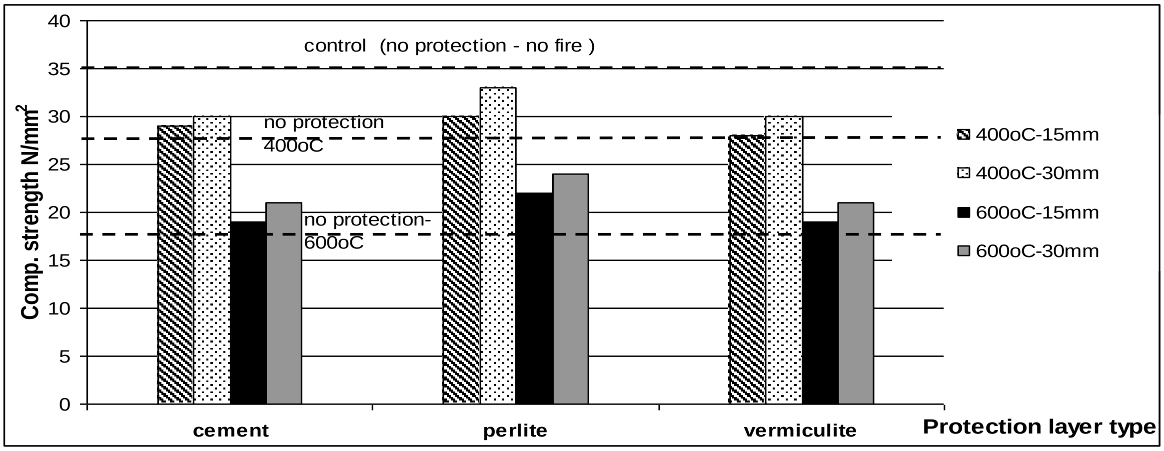


Fig 9: Effect of protection material and layer thickness on concrete strength

a) Control Unprotected specimens

b) Protected Specimens

Fig 10: Concrete specimens with and without protection after subjecting to fire

5.3 Effectiveness of Protection Layer on FRP Strengthened Specimens (Phase II)

The experimental results of the axial compression test of FRP strengthened cylinders protected by different materials and exposed to elevated temperature of 400^{o}C for two hours are presented in Table 6. Strengthening the tested concrete cylinders increased the compressive strength by 43% and 100% for GFRP and CFRP respectively. The compressive strength of GFRP wrapped cylinders without any protection layer decreased by 30% than the control values (those for FRP wrapped cylinders not exposed to elevated temperature), and by 42.8% for CFRP wrapped cylinders. Smoke and bad-smelling gases were emitted throughout the experiment.

Protecting the FRP wrapped cylinders by a 30mm thick layer of perlite mortar was observed to reduce the temperature recorded on the concrete surface as shown by the temperature gradient plotted in Fig.10. Addition of a layer of ceramic fiber was shown to further improve the thermal insulation. Experimental results of axial compression test showed that protection by perlite layer resulted in compressive strength less than by 20% and 25.7% than control values for glass and carbon FRP wrapping, respectively, as shown in Table 6. While in the case of protection by perlite plaster and ceramic fiber it decreased by 10% and 14% for air cooling and water cooling, respectively for GFRP and by 14.2% and 22.9% for air cooling and water cooling respectively for CFRP wrapped cylinders. The specimens after testing are shown in Fig.12. The results plotted in Fig.13 compare the results of different protection and cooling schemes. It can be deduced that protection with ceramic fiber and perlite plaster gave the best results regarding both thermal insulation and ultimate carrying capacity of FRP wrapped axial members. The effect of the protection material on the axial load carrying capacity is expected to be more obvious if the specimens were subjected to higher temperatures and for longer durations. The cylinders axially loaded till failure through the axial compression test demonstrated high ductility due to confinement by FRP wrapping. This ductility was not observed in the unprotected cylinders, but was still highly pronounced in the protected specimens subjected to high temperature.

Fig. (11): FRP confined specimens subject to fire and axially loaded till failure

Table 6. Experimental Results: Effect of elevated temperature on strengthened cylinders

Strength-ening	Protection layer (plaster)	Temp. (^oC)	Compressive strength (N/mm^2)	Comp. strength % decrease	Observ.
GFRP	Unprotected	No fire	50	---	.
	Unprotected	400	35	30	
	Perlite	400	40	20	
	Perlite + ceramic fiber	400	43	14	water cool
	Perlite + ceramic fiber	400	45	10	air cool
CFRP	Unprotected	No fire	70	----	
	Unprotected	400	40	42.8	
	Perlite	400	52	25.7	
	Perlite + ceramic fiber	400	59	22.9	water cool
	Perlite + ceramic fiber	400	60	14.2	air cool

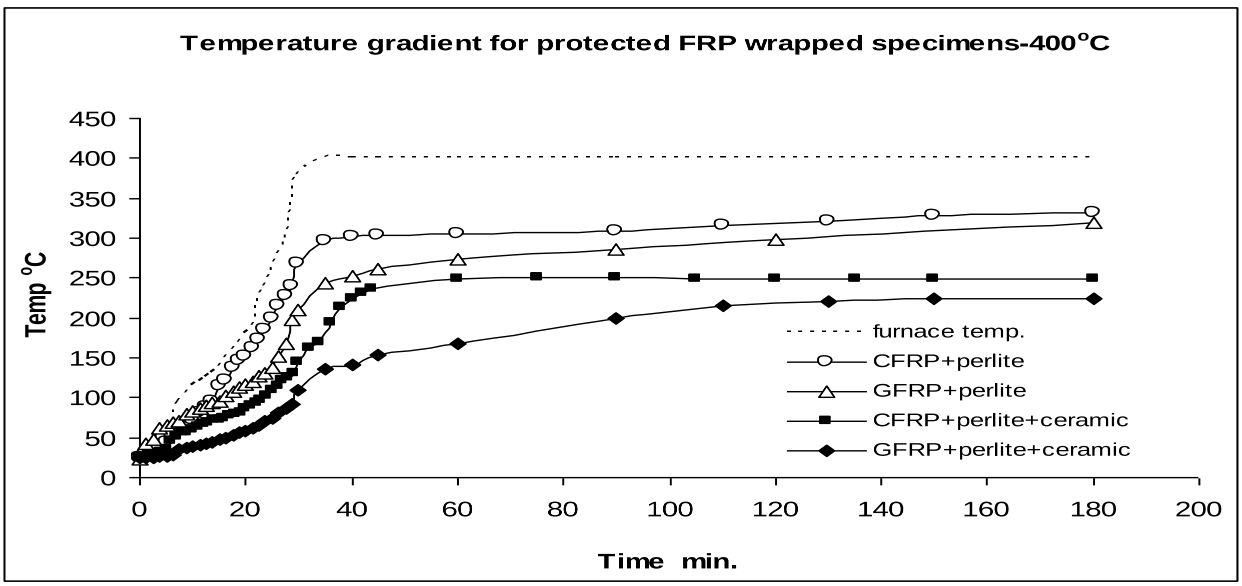


Fig.12: Temperature profile in protected FRP wrapped specimens

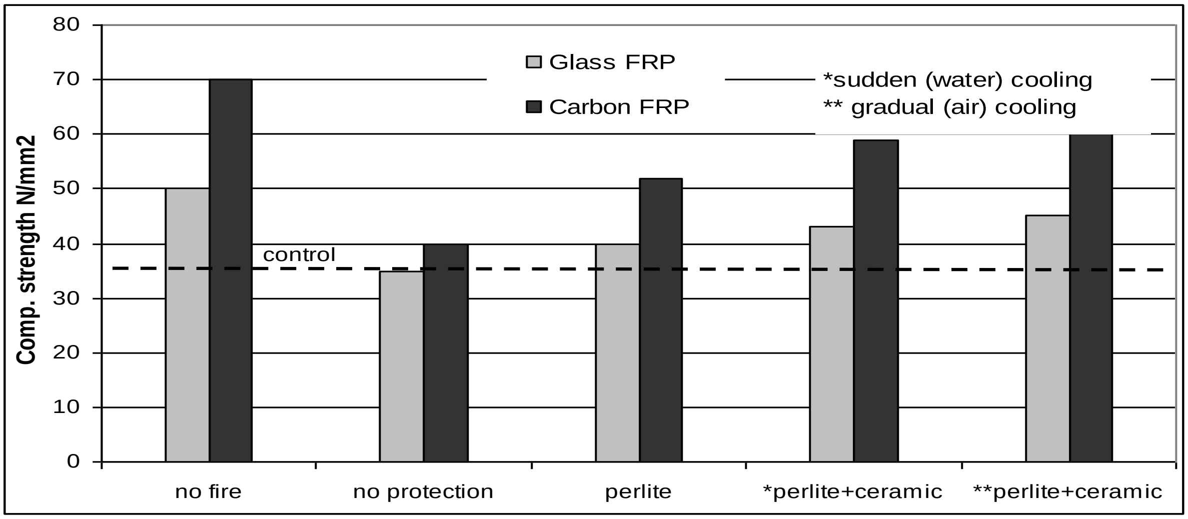


Fig 13: Effect of protection material on ultimate capacity of wrapped concrete specimens

5. CONCLUSIONS AND RECOMMENDATIONS

The current research presents the results of an experimental program conducted in order to investigate the effectiveness of different materials applied as an exterior layer around concrete axial members retrofitted using FRP wraps when subjected to elevated temperatures.

The experimental results of the current research program suggest the following conclusions;

1. The concrete compressive strength was reduced to almost one half when subjecting to elevated temperature more than 500^{o}C for two hours, deterioration increased with increasing time of exposure.

2. The strengthening of concrete cylinders through confinement by FRP wrapping is considered an easy retrofitting process and resulted in significantly enhancing the load carrying capacity for concrete cylinders.

3. If FRP wrapped axial members are exposed to elevated temperature of 400^{o}C for 2 hours without any protection, considerable loss of strength is inevitable.

4. External protective layers of a fireproof insulating material proved to be effective in protecting the concrete cylinders from the deteriorating effect of the fire scheme used in the experimental program, with improved results with increasing layer thickness.

5. External protective layers of proved to be effective in protecting concrete cylinders wrapped with glass and carbon FRP from the deteriorating effect of the fire.

6. The investigated protection materials are all locally available and economic. Moreover, the technique is simple; no special skill is required for application.

7. Perlite plaster and cermic fiber layer proved to produce the best protection performance as well as the least expensive protection material. It is strongly advised that retrofitting RC columns using FRP wraps should be protected with at least 3 cm thick perlite and 2cm thick ceramic fiber.

8. The research may be extended to investigate the effectiveness of the recommended protection material and scheme for higher temperatures and for longer duration, and also on full-scale columns.

9. It is also suggested to explore the possibility of using other locally available materials as protection layers through a similar investigation.

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تأثير طبقات الحماية من الحريق على عناصر الضغط المحوري الخرسانية المدعمة بالبوليمرات المسلحة بالألياف

يعتبر التأثر السلبي للبوليمرات المسلحة بالألياف بدرجات الحرارة العالية أحد عيوب هذه المواد مما يحد من استخدامها في مجالات التدعيم خشية حدوث حريق. ويقدم هذا البحث نتائج برنامج معملي تم تنفيذه بهدف دراسة مدى كفاءة طبقات الحماية المطبقة خارجيا على العناصر الخرسانية المعرضة لضغط محوري والمدعمة بالبوليمرات المسلحة بالألياف، لدى تعرض هذه العناصر لدرجات الحرارة العالية.ولقد تم دراسة كفاءة العزل لثلاث أنواع مختلفة من الحماية و تم اختيار افضل هذه ا لأنواع لدراسة سلوك الخرسانة المدعمة بأنواع مختلفة من البوليمرات المسلحة بالألياف تحت تأثير درجات الحرارة المرتفعة، وذلك بهدف دراسة ومقارنة كفاءة العزل وتأثير ذلك علي تحمل الخرسانة. ويقدم البحث استعراض النتائج المعملية واستخلاص الاستنتاجات وتقديم التوصيات في هذا الشأن.