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Experimental Investigation of Concrete Cylinders Confined with PBO FRCM Exposed to Elevated Temperatures

Reem Talo [1], Farid Abed [1,*], Ahmed El Refai [2] and Yazan Alhoubi [1]

[1] Department of Civil Engineering, American University of Sharjah, Sharjah 26666, United Arab Emirates
[2] Department of Civil Engineering, Laval University, Québec City, QC G1V 0A6, Canada; ahmed.elrefai@gci.ulaval.ca
* Correspondence: fabed@aus.edu; Tel.: +971-6-515-2493

Abstract: Externally bonded fiber-reinforced polymers (FRPs) have been widely used for strengthening and retrofitting applications. However, their efficacy is hindered by the poor resistance of their epoxy resins to elevated temperatures and their limited compatibility with concrete substrates. To address these limitations, fabric-reinforced cementitious matrix (FRCM), also known as textile reinforced mortar (TRM), systems have emerged as an alternative solution. In this study, experimental tests were performed on concrete cylinders confined with FRCM systems that consisted of mineral mortar and poliparafenilenbenzobisoxazole fabric (PBO). The cylinders with concrete strengths of 30, 45, and 70 MPa, were confined with one or two FRCM layers, and were subjected to different target temperatures (100, 400, and 800 °C). The experimental results highlighted the confinement effect of FRCMs on the compressive strength of the tested cylinders. Cylinders exposed to 100 °C exhibited a slight increase in their compressive strength, while no specific trend was observed in the compressive strength of cylinders heated to 400 °C. Specimens heated up to 800 °C experienced a significant reduction in strength, reaching up to 82%.

Keywords: composites; confined concrete; columns; elevated temperatures; fire; FRCM; PBO

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1. Introduction

Fiber composite systems have been recognized as effective strengthening techniques for reinforced concrete (RC) structures. Concrete is the most used construction material due to its many advantages including its high compressive resistance, high durability, and the sufficient supply of raw materials. However, RC structures have been proven to deteriorate at some point in their lifetime and therefore need to be strengthened. Retrofitting and/or reinforcing RC elements are performed for various reasons such as increasing the load-carrying capacity of the structure to withstand higher loads, counteracting the effects of inadequate maintenance, addressing steel reinforcement corrosion, and numerous other factors.

Fiber-reinforced polymers (FRPs) are one of the most common externally bonded composite systems used for strengthening and repair. Commercially available FRPs usually consist of unidirectional or bidirectional fibers that are applied and bonded to concrete with the use of polymer adhesive matrix. FRPs are highly efficient in strengthening applications due to their corrosion resistance, their large deformation capacity, their high strength-to-weight ratio, and their ease of installation. However, FRPs have several drawbacks including the poor compatibility of their organic matrices with the concrete substrate and their poor resistance to elevated temperatures, which creates a serious concern during fire events. Organic resins lose their mechanical properties under high temperatures and release toxic fumes when temperature levels exceed their glass transition temperature (T_g), which is usually around 50–120 °C [1].

To overcome the drawbacks linked to the organic matrices used for FRPs, the fabric-reinforced cementitious matrix (FRCM) strengthening systems, also known as textile-reinforced mortars (TRMs), were introduced. In these systems, open mesh textile fibers are embedded into inorganic mortar-based matrices, which are used as an alternative to the FRP organic matrices [2–10].

Trapko [11] investigated the performance of concrete cylinders confined with carbon FRPs (CFRPs) and carbon FRCMs (C-FRCMs) under elevated temperatures. The specimens were exposed to temperatures of 40, 60, and 80 °C for 24 h and directly tested until failure. According to the results, the CFRP-confined cylinders suffered a 10% drop in their load-bearing capacity for every 20 °C rise in temperature. However, the temperature increase had a slight impact on the capacity of the C-FRCM-confined cylinders, which dropped by 5 and 10% when exposed to 40 and 80 °C, respectively. Ombres [12] analyzed the structural performance of thermally conditioned concrete cylinders confined with a PBO-FRCM. The parameters of the study were the temperature used for the thermal conditioning, the fiber reinforcement ratio, and the concrete strength. Over a period of five days, the cylinders were exposed to a constant temperature ranging between 20 and 250 °C daily for four hours and cooled to room temperature. The specimens were then tested at room temperature until failure. The author reported that the load bearing capacity decreased with the elevated temperatures, yet the decrease was limited and was a result of the subsequent heating and cooling performed during the thermal conditioning stage. Although the results of the study clearly showed the effectiveness of the PBO-FRCM confinement at elevated temperatures, the author concluded that further experimental and analytical investigations were still needed. In another study, a series of tests were conducted by Cerniauskas et al. [13] on CFRP- and TRM-confined concrete cylinders exposed to temperatures up to 400 °C. The cylinders were kept at the target testing temperature for one hour prior to testing and then loaded concentrically to failure. The test results demonstrated that the efficiency of the CFRP confinement decreased significantly with increased temperatures, particularly after exceeding the glass transition temperature of the epoxy adhesive. On the other hand, the TRM confining system displayed superior performance compared to the FRP system at 400 °C. Moreover, there was a minor loss of the strengthening action of the TRM wrapping system at temperatures between 100 and 200 °C. However, the TRM-wrapped cylinders showed an unexpected enhancement in their strength at 400 °C. The discrepancy in the tests results suggested that more tests should be conducted to fully understand the behavior of the FRCM confinement under high temperatures.

In this research, experiments were performed on PBO-FRCM-confined cylinders subjected to different target temperatures (100, 400, and 800 °C) with different concrete strengths (30, 45, and 70 MPa) and number of FRCM layers (0, 1, and 2). The cylinders were heated to the target temperature and then tested in axial compression until failure after cooling to room temperature. The confinement effect was analyzed, and the results are presented and discussed. PBO-FRCM is emerging as a new and promising strengthening system, with no previous work investigating its performance under elevated temperatures.

2. Experimental Program

Experimental tests were performed on PBO-FRCM-confined cylinders heated to several target temperatures and then loaded axially in compression until failure occurred. The aim of the performed experiments was to gain a better understanding of the performance and the confinement effect of the PBO FRCM systems under elevated temperatures (up to 800 °C).

2.1. Test Matrix

The test matrix, which was divided into 3 groups, is presented in Table 1. The investigation was carried out on a total of 34 cylinders cast with normal strength concrete of 30 MPa, medium strength concrete of 45 MPa, and high strength concrete of 70 MPa. After 28 days of curing, the cylinders were confined with 1 or 2 layers of PBO-FRCM systems or left unconfined to act as controls, to investigate how the behavior of the cylinders changes when adding more strengthening layers and using concrete mixes with different strengths. All the tested cylinders had a length of 300 mm and a diameter of 150 mm before confining. The cylindrical specimens in this research were exposed to different target temperatures (100, 400, and 800 °C) in order to observe how the FRCM confinement effect changes with the exposure to different elevated temperatures.

Table 1. Test matrix.

Group	Concrete Strength (MPa)	Number of PBO-FRCM Layers	Exposure Temperatures (°C)
1	30	0	RT, 100, 400, 800
		1	RT, 100, 400, 800
		2	RT, 100, 400, 800
2	45	0	RT, 100, 400, 800
		1	RT, 100, 400, 800
		2	RT, 400
3	70	0	RT, 100, 400, 800
		1	RT, 100, 400, 800
		2	RT, 100, 400, 800

A special identification scheme was created in which the first part referred to the temperature of the specimen during conditioning. The second part of the identification referred to the number of FRCM layers used, and the last part referred to the compressive strength of the concrete. For instance, specimen 100_2L_45 had a target compressive strength of 45 MPa, was strengthened with 2 layers of FRCM, and was exposed to a temperature of 100 °C.

2.2. Specimen Preparation

After casting, the concrete cylinders were left in the curing tanks for 28 days prior to confinement. The PBO fabric was cut into sheets with a width of 300 mm (total height of the cylinder) and length of 471 mm (equivalent to the cylinder's perimeter) plus an additional 100 mm to account for the overlap length. The properties of the PBO fabric and the inorganic matrix used are presented in Tables 2 and 3, respectively.

Table 2. Material properties of the PBO as provided by Ruregold.

Property	Ruregold PBO
Nominal thickness (mm)	0.05
Young's modulus (GPa)	270
Tensile strength (MPa)	5800
Mesh elongation at rupture (%)	2.5

Table 3. Material properties of the inorganic matrix as provided by Ruregold.

Property	Ruregold Matrix
Density (kg/m^3)	1800
Max application time (min)	45
Mortar 28-day compressive strength (MPa)	40
Mortar 28-day flexural strength (MPa)	4
Mortar young's modulus (GPa)	15

Prior to confinement, an electric grinder was used to roughen the outer surface of the cylinder to ensure good bonding between the binding cementitious matrix and the concrete substrate. According to the manufacturer, the cementitious matrix had a compressive strength of 40 MPa. An initial layer of the cementitious matrix was applied with an approximate thickness of 3 mm. To ensure the desired thickness, the cementitious layer was placed in 3 mm thick acrylic frames before wrapping the PBO fabric as shown in Figure 1.

Figure 1. Preparation of the first cementitious layer.

The matrix was smoothed with a metal rod to ensure an overall uniform thickness. After demolding the cement layer, it was applied to the cylinder using the rolling technique shown in Figure 2.

Figure 2. Wrapping process of the first layer of cementitious matrix.

After applying the cement layer, a layer of PBO fabric was applied as shown in Figure 3. The fabric was slightly pressed and impregnated in the mortar before the second mortar layer and fabric were applied when necessary, using the same procedure as shown in Figure 3. The cylinders were then left to cure by wrapping a wet burlap around them until the day of testing.

Figure 3. Process of applying the PBO sheet and the second layer of cementitious matrix.

2.3. Thermal Exposure

A 500 × 400 × 400 mm electric furnace with a heating capacity of 1000 °C was used to heat the specimens. To ensure proper heat distribution within the furnace, a maximum of 5 specimens were heated at a time as shown in Figure 4.

Figure 4. The electric furnace used in this study.

All cylinders were heated to steady-state temperatures up to 800 °C at a heating rate of 10 °C/min. Once the target temperature was reached, the cylinders were kept in the furnace at the target temperature for 1 h after which they were removed from the oven and left to cool to room temperature. Figure 5 shows the curves of temperature vs. time as adopted during testing.

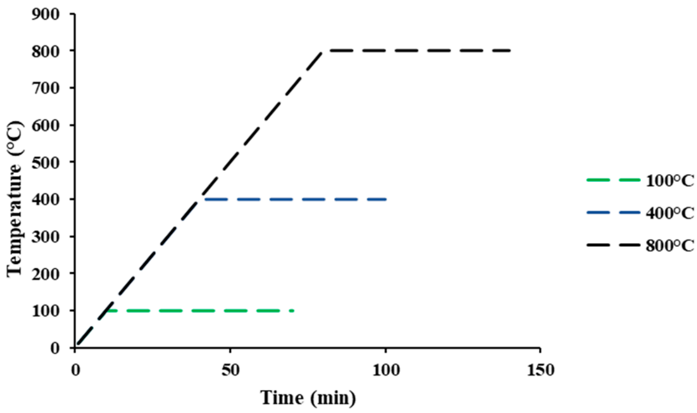


Figure 5. Individual temperature-time curves.

After all specimens were cooled to ambient temperature, they were tested for axial compression until failure. A 3000 kN SANS compression machine was used to load the cylinders according to ASTM C39 standards [14]. Load–time graphs were obtained for each specimen. To prevent premature failure during testing, 2 layers of CFRP strips were applied on the top and bottom of the cylinders with an average height of 30 mm, as shown in Figure 6. It is important to note that it was challenging to ensure perfect alignment of the fabric during the specimens' preparation and to maintain a uniform thickness of the cementitious layers. Such imperfections and nonuniformity in the FRCM systems might explain the discrepancy in some of the test results, as detailed later. It was also observed that the FRP strips were not perfectly aligned or bonded to the substrate.

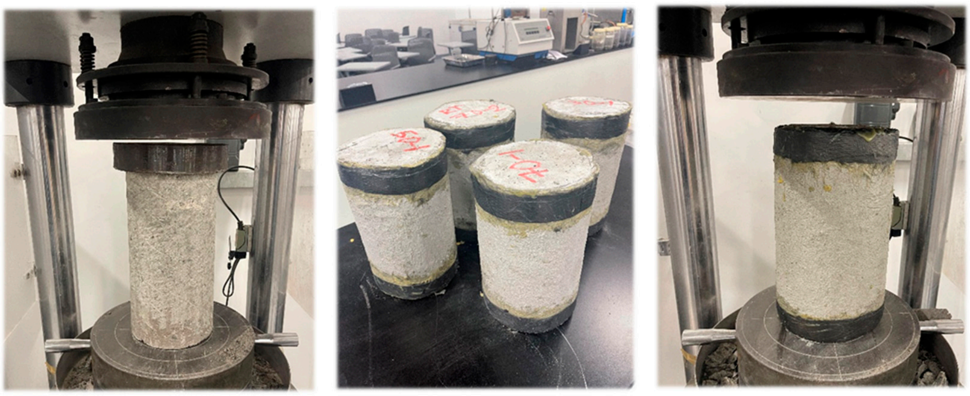


Figure 6. Unconfined and confined cylinder setup.

3. Results and Discussion

The results of the performed tests are presented in Table 4 in terms of ultimate axial load and compressive strength.

Table 4. Compression test results.

Group	Specimen ID	Ultimate Load (kN)	Compressive Strength (MPa)
1	RT_0L_30	527.7	29.9
	100_0L_30	613.1	34.7
	400_0L_30	461.0	26.1
	800_0L_30	97.7	5.5
	RT_1L_30	729.4	41.3
	100_1L_30	786.7	44.5
	400_1L_30	518.2	29.3
	800_1L_30	282.5	16.0
	RT_2L_30	935.0	52.9
	100_2L_30	750.0	42.5
	400_2L_30	859.6	48.7
	800_2L_30	368.0	20.8
2	RT_0L_45	743.0	42.1
	100_0L_45	877.1	49.7
	400_0L_45	676.3	38.3
	800_0L_45	344.6	19.5
	RT_1L_45	838.1	47.5
	100_1L_45	906.8	51.3
	400_1L_45	903.0	51.1
	800_1L_45	587.3	33.3
	RT_2L_45	938.9	53.2
	400_2L_45	983.7	55.7
3	RT_0L_70	1218.3	69.0
	100_0L_70	1430.0	81.0
	400_0L_70	1306.9	74.0
	800_0L_70	848.6	48.0
	RT_1L_70	1406.8	79.6
	100_1L_70	1692.8	95.8
	400_1L_70	1312.8	74.3
	800_1L_70	1024.2	58.0
	RT_2L_70	1455.0	82.4
	100_2L_70	1434.7	81.2
	400_2L_70	1511.8	85.6
	800_2L_70	1026.8	58.1

3.1. Failure Modes

Figures 7–9 show the failure modes of selected specimens from Group 1, Group 2, and Group 3, respectively. It is important to note that the specimens were prepared using the hand layup method, which cannot ensure perfect alignment of the fibers, a uniform cement thickness, proper impregnation of the fibers, and an exact overlap length for all the specimens. Such imperfections and nonuniformity in FRCM systems can influence the failure modes of the cylinders.

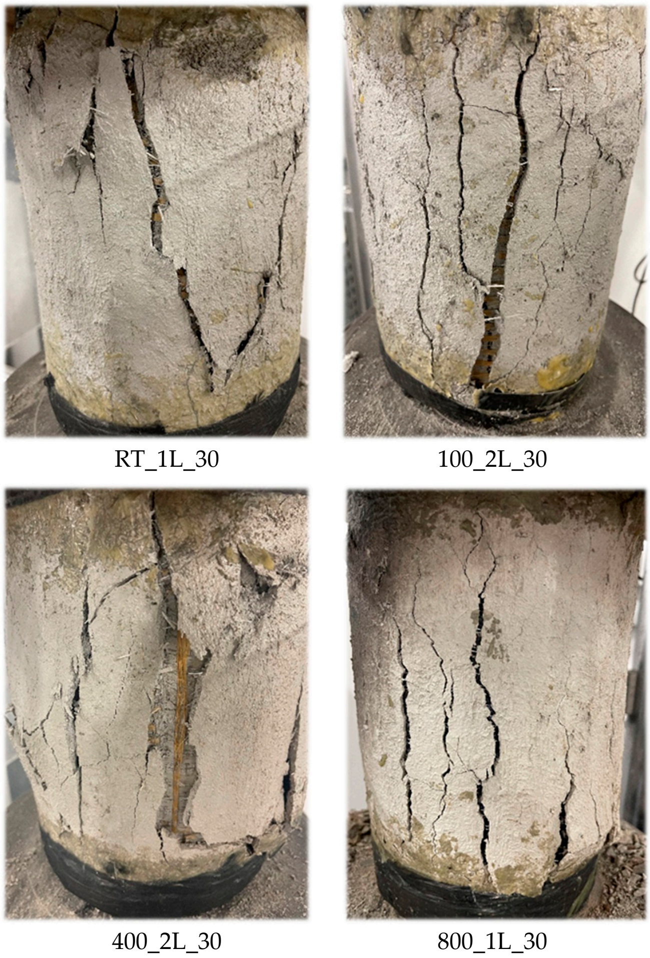


Figure 7. Failure modes of specimens of Group 1.

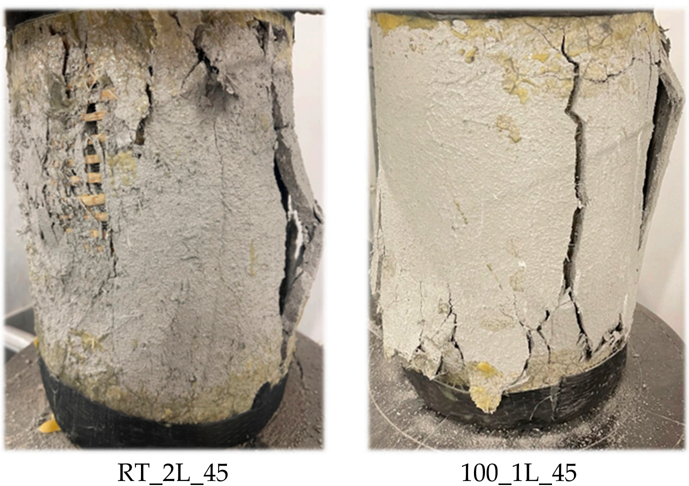
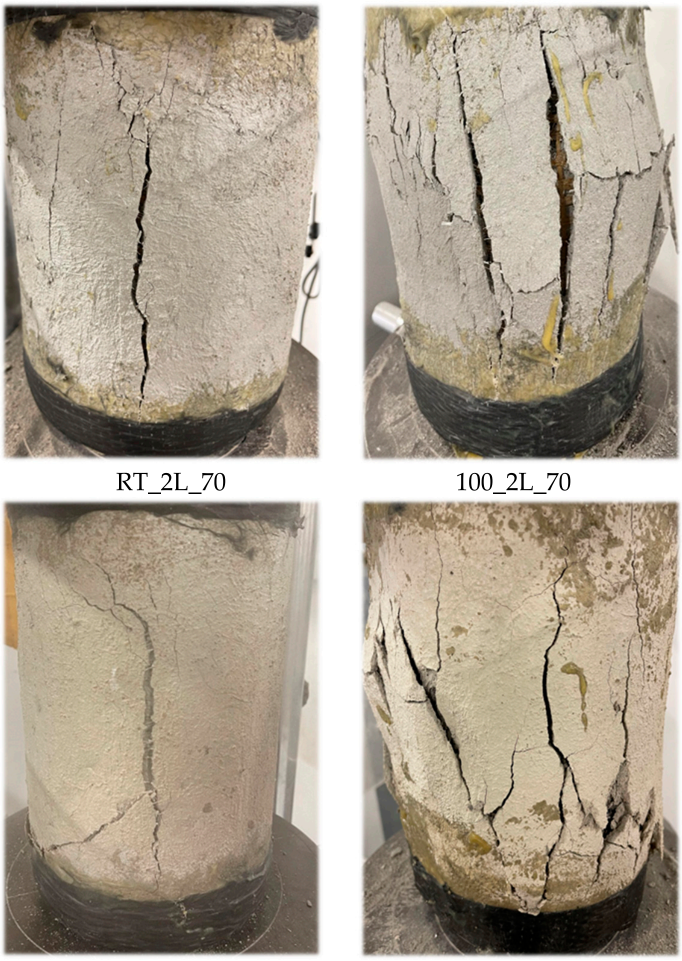


Figure 8. *Cont.*

400_1L_45 800_1L_45

Figure 8. Failure modes of specimens of Group 2.



RT_2L_70 100_2L_70

400_1L_70 800_2L_70

Figure 9. Failure modes of specimens of Group 3.

For all the tested cylinders, a gradual formation of cracks in the outer mortar layer was observed. Most cylinders failed due to the fabric separation at the fabric–matrix interface while other cylinders, namely 100_2L_30 and 100_1L_45, failed prematurely after the debonding of the FRP strips occurred.

3.2. Effect of the Concrete Strength and the Number of FRCM Layers

The variation in the compressive strength of the control and the confined cylinders with the exposure temperatures are presented in Figure 10. As indicated from the obtained results, the effect of FRCM confinement on the compressive strength was more pronounced in the specimens of Group 1, which represents cylinders having a compressive strength of 30 MPa.

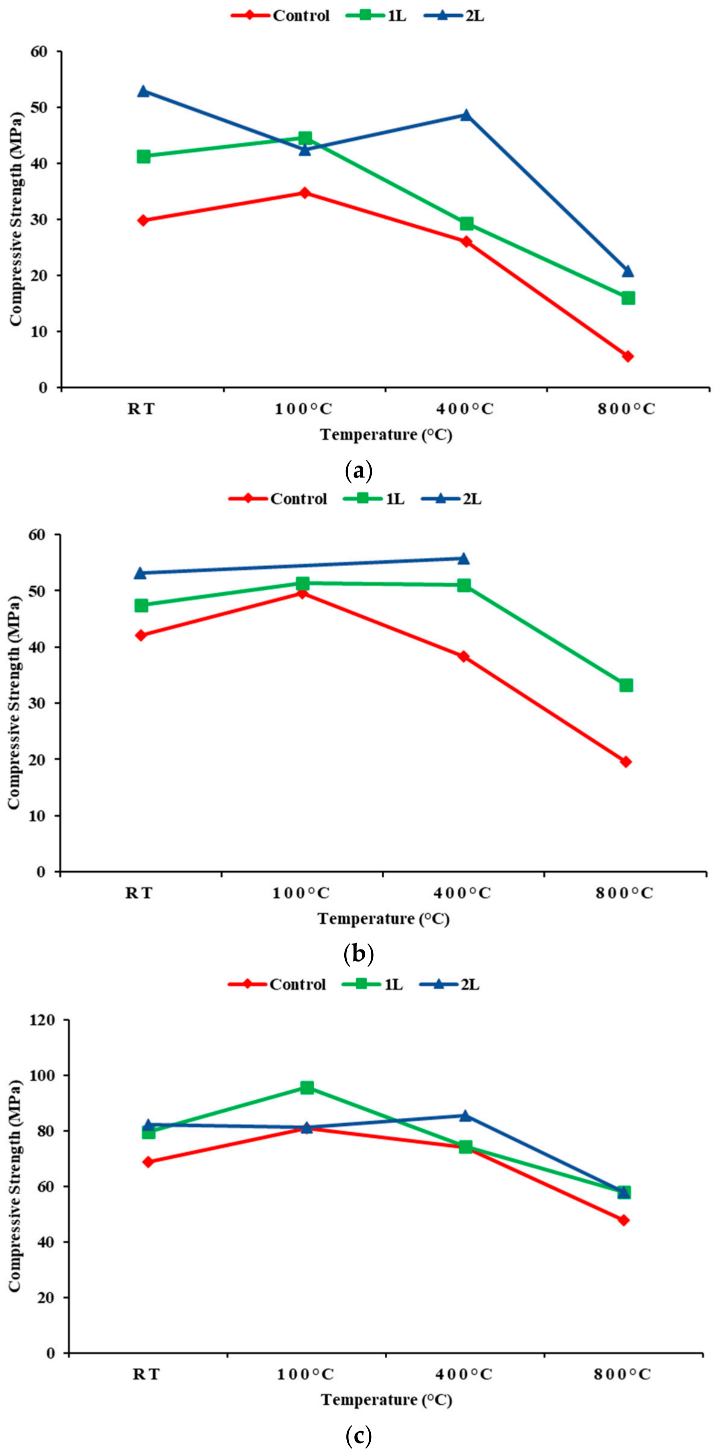


Figure 10. Compressive strength vs. temperature for (**a**) Group 1, (**b**) Group 2, and (**c**) Group 3.

At room temperature, confining the tested specimens with one and two layers of FRCM increased the compressive strength by 38 and 77%, respectively, as compared to the control cylinder (RT_0L_30) in Group 1. Specimens of Group 2 showed an increase in their compressive strength that ranged between 13 and 26% while those of Group 3 showed an increase between 16 and 19%, which can be attributed to the relatively high concrete strengths in specimens of Groups 2 and 3. Despite some discrepancies, it can be concluded that confining the specimens with one and two layers impeded the effect of temperature on the compressive strength of the tested specimens as detailed below.

It is important to note that specimens 100_2L_30 of Group 1 and 100_2L_70 of Group 3, which were confined with two layers of FRCM and heated to 100 °C, showed compressive strengths lower than their counterparts 100_1L_30 and 100_1L_70, respectively, which were confined with one layer (Figure 10). This finding was attributed to the premature rupture and debonding of the lower FRP strip as observed during testing and is shown in Figure 7 for specimen 100_2L_30.

3.3. Effect of Elevated Temperatures

The effect of the exposure temperature on the compressive strength of all the tested cylinders is shown in Table 5 and summarized as follows.

Table 5. Percentage decrease/increase in compressive strength.

Group	Number of Layers	% Decrease/Increase in Compressive Strength			
		RT	100 °C	400 °C	800 °C
1	0	-	+16%	−13%	−82%
	1	-	+8%	−29%	−61%
	2	-	−20%	−8%	−61%
2	0	-	+18%	−9%	−54%
	1	-	+8%	+8%	−30%
	2	-	-	+5%	–
3	0	-	+17%	+7%	−30%
	1	-	+20%	−7%	−27%
	2	-	−1%	+4%	−29%

For the control unconfined cylinders, a minor increase in strength (an average of 17%) was observed when the specimens were heated to 100 °C. This trend was true for specimens of all concrete strengths (Groups 1, 2, and 3). This finding agreed well with the provisions of Eurocode 2 that states that the compressive strength of concrete undergoes a negligible change in strength when it is heated to 100 °C [15]. A minor increase in the compressive strength of normal concrete has been reported by Kodur [16] while other studies showed that heating concrete to 100 °C caused a slight drop in its compressive strength [17–19]. In the current study, an increase in strength was observed in specimens of all groups and was almost consistent. This finding may be attributed to the prolonged curing of concrete, which simulated steam curing or hot air curing, in which concrete is exposed to hot water vapor (up to 100 °C) to accelerate its strength development [20], despite the fact that the cylinders were heated after more than 90 days after their casting day. On the other hand, heating the control cylinders to 400 °C slightly affected their compressive strength, which agreed well with the results reported by Kodur [16]. The highest loss in strength of the tested specimens was 13% and was encountered in specimen 400_0L_30 of Group 1. Specimen 400_0L_45 of Group 2 lost around 9% of its capacity; however, specimen 400_0L_70 experienced a minor increase in strength of 7%.

At 800 °C, all control specimens suffered from a significant decrease in their compressive strength. The highest decrease in strength, 82%, corresponded to specimen 800_0L_30 of Group 1, which agreed well with the test results of Chan et al. [21]. Specimens 800_0L_45 and 800_0L_30 of Groups 2 and 3 lost 54 and 30% of their capacity, respectively.

The elevated temperature had a similar effect on the specimens confined with one layer of FRCM compared to the unconfined specimens. A minor increase in strength was also observed at 100 °C. At 400 °C, the highest decrease in strength was about 29%, which corresponded also to the specimen 400_1L_30 in Group 1. Specimens heated at 800 °C also experienced significant decreases in their strength.

The residual strengths of the cylinders confined with two layers of FRCM and heated at 100 °C indicated that the elevated temperatures did not have the same effect on their strength as on the unconfined cylinders and the cylinders confined with one layer of FRCM. Heating the cylinders to 100 °C resulted in a 20% decrease in capacity for specimens 100_2L_30 in Group 1 and almost no decrease in capacity for specimens 100_2L_70 in Group 3. This suggested that the FRCM might have impeded the effect of the elevated temperature, which resulted in different behaviors. Up to 400 °C, the temperature exposure did not have a significant effect on the residual capacity as observed for the unconfined specimens and the specimens confined with one layer of FRCM. The cylinders heated to 800 °C also experienced significant drops in capacity, indicating that at high temperatures, the number of confinement layers did not affect the decrease in strength.

4. Conclusions

The present study aimed to investigate the performance of PBO-FRCM-confined cylinders after being exposed to elevated temperatures. The following conclusions can be drawn from the performed tests:

1. Delamination between the fibers and the cement matrix was the most common failure mode for the FRCM-confined cylinders. However, specimens 100_2L_30 and 100_1L_45 experienced rupture or debonding of the FRP strips, leading to premature failure.
2. The effect of the PBO-FRCM-confinement was more pronounced in cylinders with a low concrete strength (30 MPa) regardless of the exposure temperature.
3. Heating the cylinders to 100 °C resulted in a slight increase in strength, possibly due to prolonged curing of the concrete at this temperature. Increasing the temperature to 400 °C resulted in marginal differences in strength; however, no consistent trend was observed. Some specimens experienced an increase in strength while others experienced a drop in their axial capacity.
4. Heating the confined cylinders to 800 °C resulted in a significant reduction in their capacity that reached 82%. This finding emphasized the necessity of insulating the externally bonded composite materials.

It should be stated here that the above conclusions are based the experimental test results conducted on only one specimen per loading condition, and therefore, further tests on large-scale FRCM-strengthened columns are going to be conducted by the authors as part of a large-scale project to provide more details about the fire response of RC columns strengthened with FRCM.

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