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RESEARCH

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Experimental Study of the Effect of Different Insulation Schemes on Fire Performance of FRP Strengthened Concrete: FIRECOAT and REALROCK

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Abstract

The past two decades have witnessed rapid advances in the use of fiber-reinforced polymer (FRP) composites in different engineering fields. Advantages such as high strength-to-weight ratio, corrosion resistance, and tailority have led to immense interest in the use of FRPs in wide spectrum repair and strengthening of structures. Despite their many advantages, FRPs are highly sensitive to high temperatures, which pose a major concern for fire potential structures such as buildings. Applying proper thermal insulation can enhance the fire performance of FRP and reduce the possible fire damage to the FRP strengthened element. This study set out to experimentally investigate the effectiveness of two insulation systems, "FIRECOAT" and "REALROCK" on fire performance of CFRP and GFRP strengthened concrete specimens. Various configurations and exposure durations were considered to evaluate the effectiveness of insulating materials. To perform the experiments, cylindrical concrete specimens were fabricated and strengthened using CFRP or GFRP. After insulating the specimens, they were exposed to a standard fire curve for two different durations of 30 and 60 min. The results indicate that less than 30 min of fire, both insulation systems can provide the required protection. During long exposure duration of 60 min, only REALROCK can provide the required thermal resistance for FRP-strengthened concrete. Within the tested materials, Fire Set 60 outperformed other insulating materials. It was observed that implementing Fire Set 60 in the innermost layer of thermal insulations has crucial importance in preventing the fire induced reductions in strength of FRP-strengthened concrete elements.

Keywords Concrete, Damage, Fire, FRP, High temperature, Insulating material, Strengthening, Thermal insulation

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1 Introduction

Recently, there has been growing interest in extending the service life of structures by adopting new materials with better performance and lower life-cycle costs (Jain & Lee, 2012; Lee & Jain, 2009). Fiber-reinforced polymer (FRP) composites have gained significant attention due to their distinctive characteristics such as high performance at low weight, corrosion resistance, ease of transportation and application, and tailorability (Balla et al., 2023; Liu et al., 2022; Saafi, 2000; Zhang et al., 2017). A considerable amount of literature has been published on the use of FRP in construction applications and exhibits the performance of FRP under various loading conditions along with different structural materials (Abdullah & Bailey, 2018; Alotaibi et al., 2022; Ghazizadeh et al., 2018; Kim, 2019; Li & Harries, 2018; Lin et al., 2022; Louk Fanggi & Ozbakkaloglu, 2015; Muc et al., 2020; Noël, 2019; Sun et al., 2022; Wei et al., 2019). Properties such as the type of resin, fiber, and fiber placement are the main contributors to the performance of FRPs. Enormous efforts to develop FRP composites have led to the development of new types of FRPs such as carbon fiber-reinforced polymers (CFRP) and glass fiber-reinforced polymers (GFRP). Each type of FRP composite and application can provide different levels of improvement in the bearing capacity of the strengthening elements. For different purposes, FRP composites can be applied using different techniques, such as external bonding or internal reinforcement bars with different resin matrices.

Although the use of FRP significantly enhances the carrying capacity of the elements, the low fire performance of this material poses a major concern, particularly in buildings (Mosallam et al., 2008; Protchenko & Szmigiera, 2020). FRP has a low glass transition (65–120 ℃) and low decomposition temperature (300–500 °C). When the temperature of the FRP exceeds its glass transition temperature, the resin undergoes a phase change and becomes rubbery. Exceeding the decomposition threshold breaks the chemical bonds of the resin and deteriorates the fiber bonds (Bai et al., 2007, 2008; Firmo et al., 2012; Rami Hamad et al., 2017). This poses a legitimate concern from environmental and structural perspectives due to the release of significant toxic gases and major strength loss in FRP. Therefore, to maintain the functionality of FRP, it is important to prevent the temperature rise in FRP, and its temperature must remain below the glaion threshold.

To enhance the high-temperature performance of FRP, many experimental and numerical studies have focused on different possibilities to improve the fire behavior of FRP composites. Since numerical models are advantageous due to their time, cost, and energy efficiency, numerous research works have used numerical and analytical methods to obtain the fire behavior of FRP under different conditions. However, a numerical analysis cannot fully represent the complexity of a real fire under different external parameters. Therefore, performing experimental evaluations that can better demonstrate the real fire behavior of FRPs is crucial. As a result, the literature has widely addressed the fire behavior of FRP-strengthened reinforced concrete (RC) elements using numerical (Adelzadeh et al., 2014; Bilotta et al., 2020; Guo et al., 2022; Hajiloo & Green, 2019; Jia et al., 2021) and experimental methods (Al-Kamaki et al., 2015, 2017; Cao et al., 2022; Ferrier et al., 2016; Hamad et al., 2019; Hawileh et al., 2015; Leone et al., 2009; Nigro et al., 2012).

Studies on the fire performance of FRPs have highlighted the necessity of employing appropriate fire insulation to prevent fire-induced losses to FRP strengthened structures (Firmo et al., 2015). In this regard, various scholars have attempted to characterize the performance of different insulation techniques for various types of elements and structures. Williams et al., (2006) performed an experimental study on FRP-strengthened concrete slabs and examined the effectiveness of four different insulation schemes for improving the fire performance of the elements. They observed that 38 mm of the tested insulation system protected the elements from 4 h of the standard fire curve. Their results indicated the importance of thermal insulation schemes on the fire responses of FRP-strengthened concrete elements and in delaying fire damage. Green et al., (2006) also highlighted the impact of thermal insulation on fire performance of FRP strengthened RC columns. They have exposed the strengthened RC columns to extremely low and high temperatures and observed that using proper insulation can slow down the temperature developments within concrete section. Although the utilized insulation could not protect the FRP for the entire fire exposure, it increased the fire performance of RC columns for up to 4 h. Cree et al., (2012) have conducted full scale fire tests to evaluate the performance of circular and square RC columns strengthened with FRP and thermal insulation. The constructed columns were exposed to 4 h of standard fire curves and observed that the tested thermal insulations could provide satisfactory fire protection. Although the utilized insulation could not prevent the epoxy from reaching its glass transition temperature, it could effectively protect the concrete and reinforcements from temperature rises. They used numerical analysis to validate their findings. Ji et al., (2013) attempted to develop new thermal insulation to improve the fire performance of FRP-strengthened RC beams. From the performed experiments, they observed that the developed insulation could improve the fire performance of strengthened beams and significantly increase their post-fire residual strength. Guruprasad & Ramaswamy, (2019) experimentally evaluated the fire performance of two different insulation materials to protect CFRP-wrapped concrete specimens and used finite element methods to assess the participation of insulation with four different thicknesses. From the experimental tests, they observed that both insulation materials could effectively protect the specimens from high temperatures up to 715 °C. Numerical analysis results indicated the effectiveness of the insulation layer thickness and showed that under a high-temperature exposure of 715 °C, thermal insulation with a maximum thickness of 90 mm can delay epoxy deterioration. A review by Kodur et al., (2019) emphasized the importance of thermal insulation in protecting FRP-strengthened concrete elements from high-temperature effects. The properties of the insulation material significantly affect the fire behavior of the element. However, the thermal properties of FRP do not significantly contribute to the thermal resistance of strengthened elements. Imran & Mahendran, (2020) focused on the fire performance of CFRP-strengthened short steel columns and evaluated the effect of spray-applied thermal insulation on their fire performance using experimental tests. They evaluated the fire performance and remaining axial compression capacity of insulated and non-insulated columns. They observed that during 30 min of fire, the utilized thermal insulation could maintain the column temperature below 100 °C and their bearing capacity for 60 min of fire. Sobia et al., (2022) focused on the impact of applying FRP and thermal insulation on the fire performance of RC square columns. They fabricated full-scale columns to evaluate their fire performance with and without CFRP and then assessed the effectiveness of ultra-high-performance fiber-reinforced cementitious material as an insulation layer. Their results showed that applying FRP could delay the temperature increase in the core of the columns. In addition, insulation can considerably enhance the fire endurance of strengthened RC columns.

These studies have significantly contributed to the enhancement of the fire performance of FRP-strengthened elements from various perspectives. However, due to the complexity of fire and its effects on composite systems, finding the best solution for the use of FRP in structures with fire risks requires further study. In addition, the existing solution for improving the thermal performance of FRP systems has posed some challenges from aesthetic, thickness, and extra loading perspectives (Selvaratnam & Gamage, 2021). Therefore, the thermal performance of FRP strengthening systems requires further investigation before reaching the optimum solution. Moreover, most studies have focused on improving the fire performance of CFRP-strengthened elements, whereas comparatively less attention has been paid to the fire performance of GFRP-strengthened members. To this end, this paper has focused on the performance of two different thermal insulation systems “FIRECOAT” and “REALROCK” recently developed by Dymat© on protecting CFRP and GFRP, two of the most preferred strengthening composites, from high temperature induced strength losses. The FIRECOAT system comprised epoxy as a primer and Firefree 88 as the coating layer. This water-based fire resistance material is used as the coating layer and is designed to provide fire resistance for various materials such as concrete, steel, and FRP. The REALROCK thermal insulating system comprised Fire Set 60, a fire-resistant joint compound, and Vella Fino, which was used as coating layer. The Fire Set 60 is a gypsum-based fire resistance setting compound designed to slow down the fire spreading path and protect the underlying materials. Vella Fino is a low-VOC acrylic paint with high durability and crack resistance properties that can provide an ultra-smooth finish on the fire set layer. To obtain the performance of the materials, cylindrical concrete specimens with different strengthening materials and insulation configurations were subjected to ASTM E119 (ASTM E119, 2012) standard fire curve with different exposure durations. The fire performance of each system was evaluated based on the post-fire residual strengths of the specimens.

2 Conducted Experiments

The experimental tests were conducted to evaluate the effectiveness of two insulation systems on fire protection of CFRP and GFRP wrapped concrete elements. The tested insulation systems constituted FIRECOAT and REALROCK. In the experiments related to FIRECOAT, CFRP/GFRP, FCI-APP11 A&B Components, and Firefree 88 (Dymat®D8) were used. In the REALROCK related experiments, CFRP/GFRP, Fire Set 60 and Acrylic Vella Fino were used. To evaluate the effectiveness of each fire protection system, two different exposure durations of 30 and 60 min were considered. Some of the fabricated specimens were selected as reference samples, and the rest were divided into two equal groups: in the first group, specimens were CFRP-wrapped, and the second group of specimens was GFRP-wrapped. For each system, these tests aimed to determine the effectiveness of four different insulation methods on thermal resistance and strength loss of FRP materials. Based on the results obtained from uniaxial compression test of samples, and resulting changes in their performance, the effectiveness of the methods was evaluated.

The naming convention for samples consists of three parts representing the parameters considered in each test (Table 1). The first part indicates the strengthening material of the specimen. The second part, denoted by T1, T2, or T3 represents the type of thermal insulation scheme. The third part of the label represents the exposure durations, with the values of “30” and “60” representing the high temperature exposure durations of 30 and 60 min.

2.1 Fabrication of Test Specimens

To perform the experiments, 66 cylindrical concrete specimens with a length of 45 cm and a diameter of 20 cm were fabricated. To control the moisture loss of the freshly placed concrete, specimens were moist

Table 1 General overview of test samples and their naming

References			Set 1 (CFRP)			Set 2 (GFRP)		
	Test 1	Test 2		Test 1	Test 2		Test 1	Test 2
20 °C	60 min	30 min	20 °C	60 min	30 min	20 °C	60 min	30 min
Ref	Ref-60	Ref-30	CFRP	CFRP-60	CFRP-30	GFRP	GFRP-60	GFRP-30
				CFRP-T1-60	CFRP-T1-30		GFRP-T1-60	GFRP-T1-30
				CFRP-T2-60	CFRP-T2-30		GFRP-T2-60	GFRP-T2-30
				CFRP-T3-60	CFRP-T3-30		GFRP-T3-60	GFRP-T3-30

T insulation type

Fig. 1 Constructed specimens

cured by spraying for 7 days. The fabrication stages of these specimens are given in Fig. 1.

To determine the concrete specifications, standard cubic samples were cast and subjected to uniaxial compression tests after 28 days. The average compressive strengths of the samples were determined as 25.49 MPa.

2.2 Strengthening Procedure

All constructed specimens, except reference samples, were reinforced using fiber polymer composites. Set-1 specimens were wrapped using CFRP and Set-2 specimens were GFRP wrapped. In both sets, 2 layers of FRP were wrapped and an overlap length of 200 mm has been considered. The epoxy matrix is comprised of epoxy resin (DYMAT® BT-D "A") and hardener (DYMAT® BT-D "B"). The mechanical properties of the tested CFRP, GFRP, and epoxy resin are listed in Table 2. In all mixes, the weight of resin and fabric were equal while for resin and hardener, a mixing ratio of 1:3 has been used. The utilized strengthening materials are described in Table 3. CFRP and GFRP strengthened specimens are shown in Fig. 2.

Table 2 Properties of strengthening fabrics and epoxy

	Fibers	
	DYMAT® Carbon fiber system DHC-190	DYMAT® Glass fiber system DHE-272
Tensile strength (GPa)	4.83	3.73
Tensile modulus (GPa)	280.0	83.3
Ultimate elongation (%)	1.65	4.50
Density (g/cm^3)	1.74	2.55
Weight (g/m^2)	644	922
Fiber thickness (mm)	0.37	0.36
	2-Part Epoxy	
Tensile strength (MPa)	90.0	
Shear modulus (GPa)	5.0	

2.3 Insulation Systems and Application Procedures

In this section, the procedures related to the preparation and applying the insulation materials used for FIRECOAT and REALROCK insulation systems are presented. To precisely evaluate the effectiveness of each system, the insulating materials with various combinations were applied to some of the strengthened specimens

Table 3 Utilized materials for strengthening the specimens

Scope	Materials		
	Component	**Name**	**Image**
Strengthening	Fiber reinforced polymers	DYMAT® Carbon fiber system DHC-190	
		DYMAT® Glass fiber system DHE-272	
	Epoxy matrix	DYMAT® BT-D "A" Epoxy Resin	
		DYMAT® BT-D "B" Curing Agent—Hardener	

(Figs. 3 and 4). Table 4 shows the materials used for each system. The preparation and application procedures relevant to each insulating system are described in the below subsections. Layer information and schematic representations of the considered insulation types are presented in Table 5.

2.3.1 FIRECOAT

FIRECOAT insulation system consists of Dymat®DCF-D approved test by ICC-AC125 by IAPMO. FCI-APP11 A&B components and final coating Firefree 88 (Dymat®D8) were used for this system. To evaluate the fire protection performance of this system two different insulation methods were considered. Group T1 specimens were insulated using 1 layer of A&B mix and 3 layers of Firefree 88, while group T2 specimens were insulated using 2 layers of A&B mix and 6 layers of Firefree 88.

Mix A&B contains Dymat®DCF "A" Epoxy Resin and Dymat®DCF "B" Curing Agent (Hardener). Prior to the application of mix A&B, the specimens' surfaces were cleaned. To prepare the mix, A and B materials were mixed using a mixer with a ratio of 1:1 by volume and with the use of a brush rolled on specimens with an equal amount of 310.56 g for each layer (0.225 lb/ft^2).

a) CFRP b) GFRP

Fig. 2 FRP wrapped specimens

Fig. 3 Preparation and application of the FIRECOAT components

Once the first layer was thoroughly dry, following the same procedure the next layer was applied.

As soon as the surface was dry enough to touch, the preparation for Firefree 88 was started. To prepare the Firefree 88 a clean wooden stick was used to stir the material and using a roller was applied on the outer surface of the specimens with the amount of 55.2 g (0.04 lb/ft^2) for each layer. When the first layer reached a gel-like state the second layer was applied.

2.3.2 REALROCK

REALROCK insulation system consists of 60 min fire-resistant setting compound Fire Set 60 (Dymat®Fireset) and %100 acrylic interior/exterior plaster Acrylic Vella

Fig. 4 Preparation and application of the REALROCK components

Table 4 Utilized materials for thermal insulations

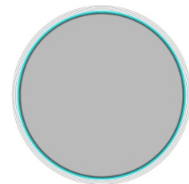
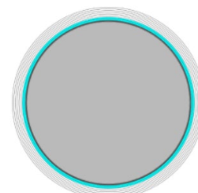
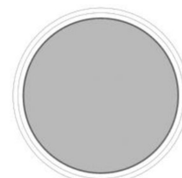
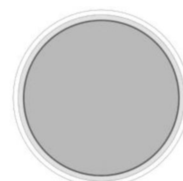
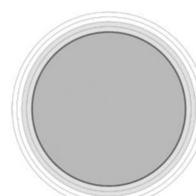
Scope	Materials		
	Component	**Name**	**Image**
FIRECOAT Insulation system	FCI-APP11 A&B components	DYMAT® DCF "A" Epoxy Resin	
		DYMAT® DCF "B" Curing agent—Hardener	
	Final coating firefree 88	Dymat®D8	
REALROCK Insulation system	DYMAT® Plaster (acrylic paint)	Acrylic vella fino coating	
	DYMAT® Fire-Resistant joint compound (60 min)	Fire set 60 (DYMAT® fire set)	

Fino as coating material. To evaluate the effectiveness of this system 3 different insulation schemes were considered. In group T1 specimens only 2 layers of Acrylic Vella Fino were applied, and no setting compound was used. In group T2, each of Fire Set 60 and Acrylic Vella Fino materials was applied for 1 layer, while in group T3, each of these materials was applied for two layers.

To prepare the Fire Set 60 setting compound, 0.615 L of clean water and 1 kg of setting compound were poured into a clean mixing trough and mixed with a plastering trowel. Then, using a plastering spatula it was applied to the prepared specimens as a single layer of 0.25 inches thick for T2 specimens and two layers of 0.5 inches thick for T3 specimens.

Upon complete drying of Fire Set 60 layers, preparation of Acrylic Vella Fino material was started. Using a mechanical mixer, Acrylic Vella Fino was mixed and applied to the dried surface of the specimens with an equal layer thickness of 0.25 inches. While applying the paint, special attention was taken to maintain the

Table 5 Utilized insulation schemes

insulation system	Insulation Type ID	Layer information (*from inner to outer layer*)		Schematization
FIRECOAT Insulation system	T1	FCI-APP11 A&B Components 1 layer	FireFree 88 (Dymat®D8) 3 layers	
	T2	FCI-APP11 A&B Components 2 layers	Firefree 88 (Dymat®D8) 6 layers	
REALROCK Insulation system	T1	✗	Acrylic Vella Fino 2 layers	
	T2	Fire Set 60 1 layer	Acrylic Vella Fino 1 layer	
	T3	Fire Set 60 2 layers	Acrylic Vella Fino 2 layers	

uniform layer thickness. When the first layer was partially dried the second layer was applied.

2.4 Temperature Tests and Measurements

To assess the thermal performance of each configuration and the effectiveness of each insulation material, all specimens have undergone a high-temperature test. To perform the high temperature tests, an electrical car-bottom furnace with a chamber size of 2000 × 1500 × 2000 (W × L × H) mm, a heating power of 210 kW, and an operating temperature of 1100 °C was used. The prepared specimens for FIRECOAT and REALROCK tests are shown in Fig. 5.

As the heating resistances are located on three sides of the furnace, it was tried to place the CFRP and GFRP wrapped specimens on the furnace car-bottom as symmetrically as possible. The specimens used in each test and their furnace positions are illustrated in Fig. 6. As demonstrated in this figure, in each test for FIRECOAT and REALROCK, 7 and 9 specimens were used respectively. To have a better evaluation of the effectiveness of each system, ceramic fiber caps were used to cover the uninsulated top surface of the specimens.

All temperature tests were performed with respect to ASTM E119 standard fire curve. In this set of experiments, two different exposure durations were considered. The duration of fire exposure for the first and second groups was 60 and 30 min respectively. During the temperature tests, the data related to furnace

Fig. 5 Prepared specimens

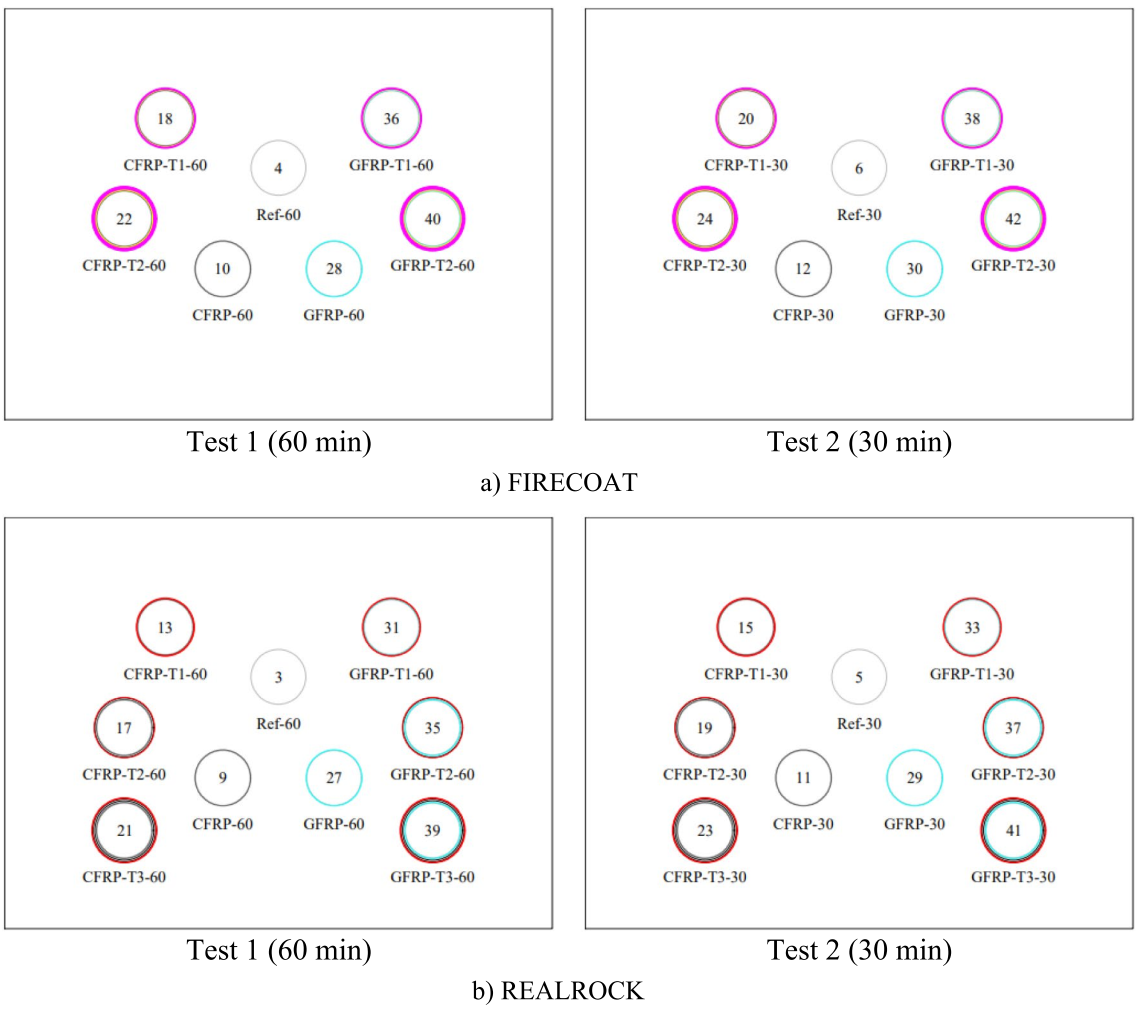


Fig. 6 Location of specimens in the furnace

interior temperature was recorded and transformed into graphs (Fig. 7).

During fire exposure of 60 min, some specimens experienced severe damage. So, they were excluded from the rest of the experiment. Upon completion of the fire test, the furnace door was opened, and using a dual laser portable pyrometer (AST TI 1500), the surface temperature of specimens was measured. Then, the samples were placed outside the furnace and cooled naturally to be prepared for compression tests. In this stage, visual observations of tested specimens were recorded and backed up using photographs and video so that can be used in further evaluations. Using the data obtained from compressive tests and recorded visual observations, the effectiveness

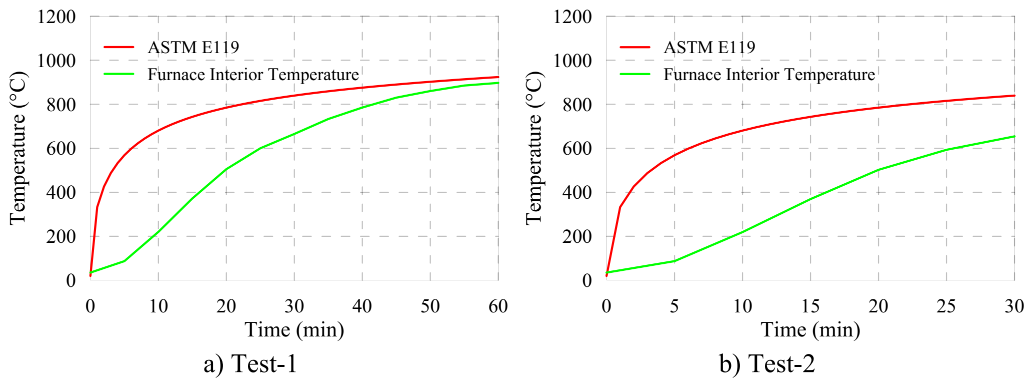


Fig. 7 ASTM E119 fire curve and furnace interior temperatures during the tests

of each insulation method was evaluated. The overview of the conducted fire tests is depicted in Figs. 8 and 9.

2.5 Uniaxial Compression Tests

Subsequent to the cooling phase, all specimens were subjected to a uniaxial compression test using a servo-hydraulic compression testing machine with a capacity of 3000 kN. A constant loading rate of 0.6 MPa/s was used to determine the residual strength of the specimens (BS EN 12390-2:2009, 2009; BS EN 12390-3:2009, 2009). The pre- and post-test conditions of the FIRECOAT and REALROCK specimens are shown in Figs. 10 and 11, respectively. Entries marked with "---" denote specimens where compression tests orphotographic documentation were not possible.

2.6 Results and Discussion

2.6.1 Temperature Measurements

After the fire test, a pyrometer was used to determine the specimens' surface temperature at two different stages; first, it was measured immediately after opening the furnace door, and second measurement was done upon removal of specimens from the furnace. The measured temperatures are shown in Fig. 12. The temperature values in the red and blue squares represent those obtained from the first and second set of temperature measurements.

2.6.2 Visual Observations

During the cool down period, the effects of fire exposure to the specimens and the post test condition of the materials were visually evaluated (Fig. 13). The direct exposure of the FRP-strengthened specimens to fire significantly damaged the carbon and glass fibers and deteriorated the epoxy matrix due to exceeding its glass transition temperature. After 60 min epoxy was completely deteriorated and almost no trace of epoxy has been observed on the specimens.

Implementing Firefree 88 in the FIRECOAT-insulated specimens effectively increased the fire performance for up to 30 min. After this period, swelling was observed on the surfaces of the samples insulated with six layers of Firefree 88 (T2). From 30 to 60 min, Firefree 88 lost all its fire-resistant properties. In addition, because of the long exposure duration, the components of the REALROCK system became brittle and flaked off from the specimen surfaces.

Post-fire test observations showed that during fire exposure for 30 min, the FIRECOAT insulation system could prevent FRP deterioration and the explosive spalling of concrete. For the REARLOCK-insulated specimens, it was observed that the T3 configuration with two layers of Fire Set 60 and Acrylic Vella Fino could prevent any type of spalling for up to 60 min. This system adequately protected the epoxy matrix for up to 30 min of fire and provided a partial protection for longer exposure. During the long fire exposure, specimens with a more layers of insulation demonstrated better performance.

2.6.3 Uniaxial Compression Tests

To assess the effectiveness of each insulation method, all FRP wrapped specimens as well as reference specimens were subjected to a uniaxial compression test. The obtained data are presented in Table 6. The fire induced decreases in strength of non-insulated specimens are demonstrated in Fig. 14.

- As can be seen in Table 6, the compressive strength of the reference specimen was measured as 30.09 MPa, while this value reached 86.10 and 68.23 MPa after applying CFRP and GFRP to the specimens respectively.

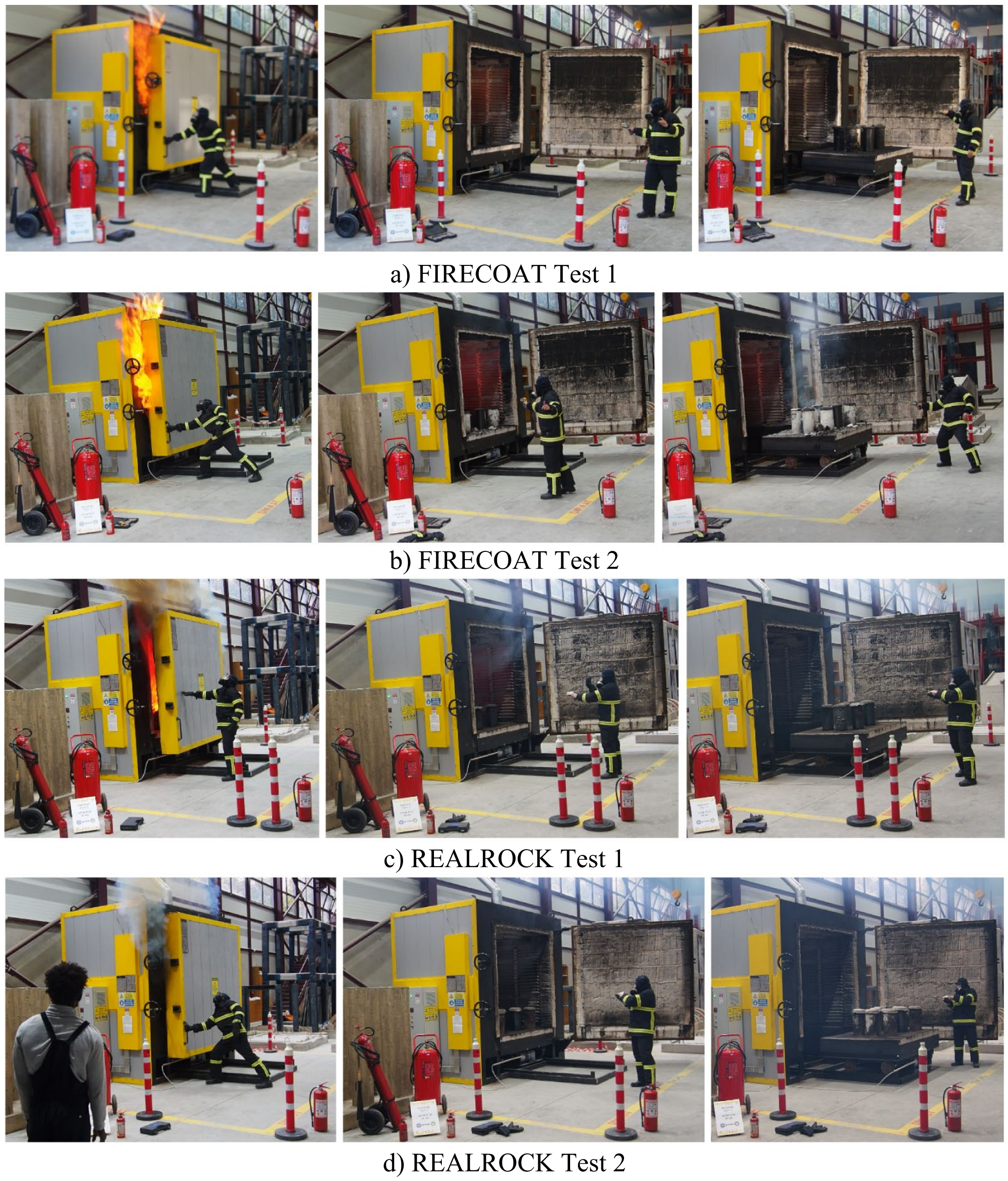


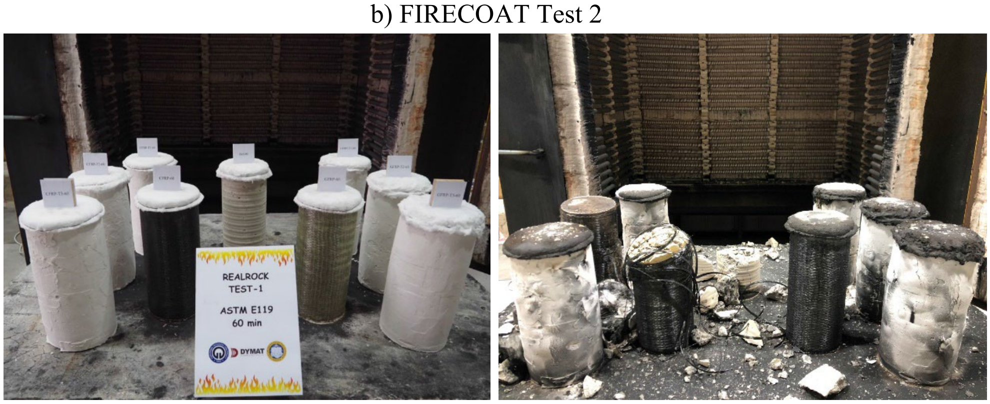
Fig. 8 Opening furnace door and surface temperature measurements

- High-temperature exposure has decreased the compressive strength of the specimens.
- After fire exposure for 30 and 60 min, the compressive strength of the reference specimens decreased and reached 17.58 MPa and 17.09 MPa respectively.
- For CFRP wrapped specimens, 30 min of fire exposure decreased their compressive strength to 37.21 MPa, and 60 min of fire exposure decreased this value to 18.36 MPa.
- For GFRP wrapped specimens, 30 min of fire exposure decreased their compressive strength to 24.37 MPa, and 60 min of fire exposure decreased this value to 20.13 MPa.

The changes in compressive strength of the FIRECOAT and REALROCK insulated specimens were compared and the performance of each system was evaluated. Figs. 15 and 16 compare the compressive strength of the tested specimens in each system. The

a) FIRECOAT Test 1

b) FIRECOAT Test 2



c) REALROCK Test 1

d) REALROCK Test 2

Fig. 9 Pre and post-test conditions of the specimens

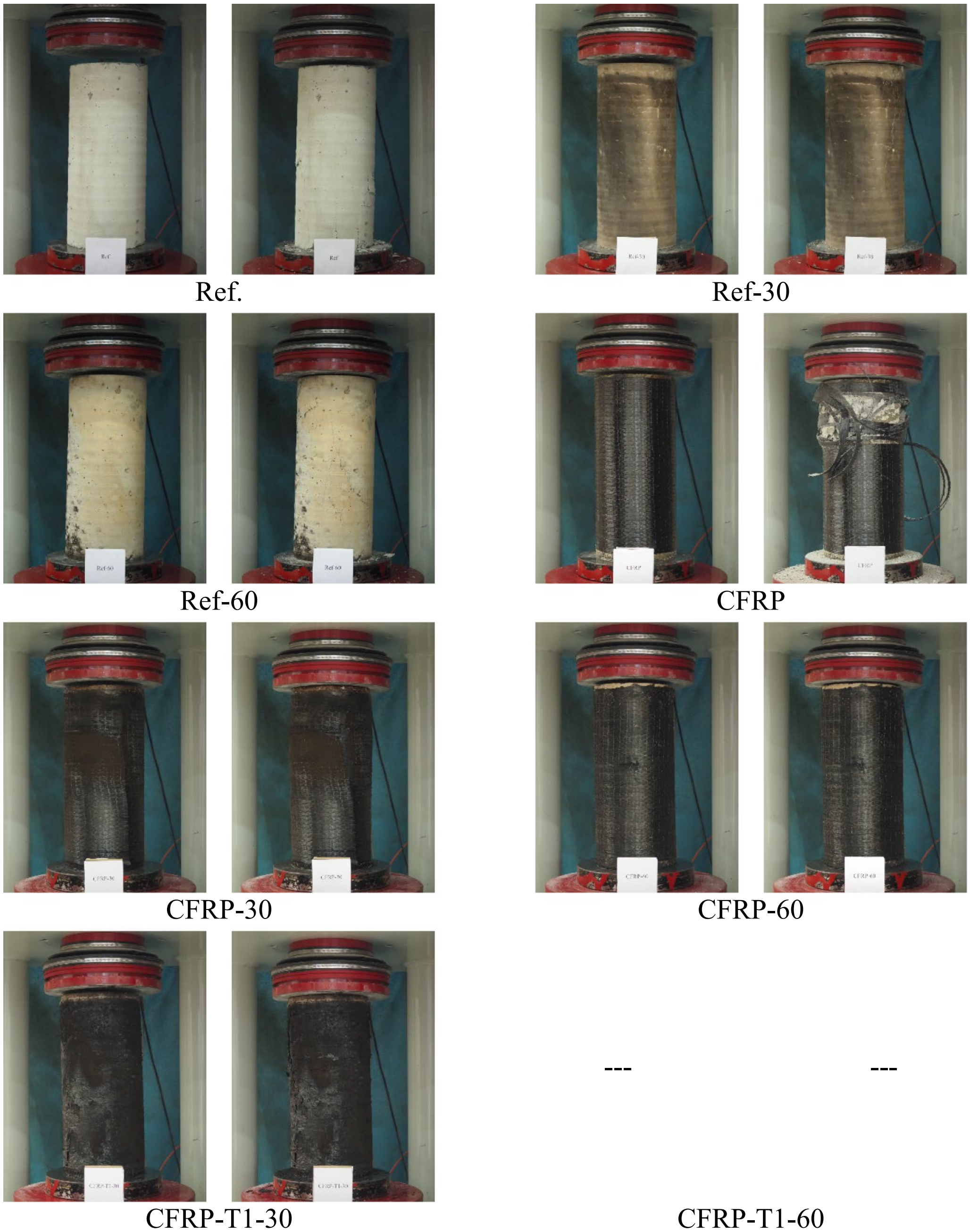


Fig. 10 Testing compressive strength of FIRECOAT samples before and after the fire tests

efficacy of each insulation system in protecting the FRP from high temperatures is depicted in Fig. 17. From this data it was observed that:

2.6.3.1 FIRECOAT 2.6.3.1.1 Set-1 (CFRP)

- Although the use of CFRP significantly improved the compressive strength of specimens (from 30.09 to 86.10 MPa), a fire exposure of 30 min decreased the compressive strength of insulated specimens by 58% and 12% and reached to 36.20 MPa and 75.49 MPa (T1 and T2 respectively).
- Fire exposure of 60 min has caused a decrease of 78% in compressive strength of the T1 specimen and reached 18.70 MPa. This exposure duration resulted

Fig. 10 continued

Fig. 11 Testing compressive strength of REALROCK samples before and after the fire tests

in explosive spalling of the T2 specimen. Hence, post-fire data relevant to this specimen was not obtained.

2.6.3.1.2 Set-2 (GFRP)

- The use of GFRP has significantly improved the compressive strength of the specimens (from 30.09 to 68.23 MPa). But fire exposure of 30 min decreased the compressive strength of the insulated specimens by 55% and 24% and reached to 30.96 MPa and 52.08 MPa (T1 and T2 respectively).
- Fire exposure of 60 min has caused a decrease of 68% in compressive strength of the T1 specimen and reached 21.51 MPa. The strength value obtained from T2 specimen (14.03 MPa) deviates significantly

Fig. 11 continued

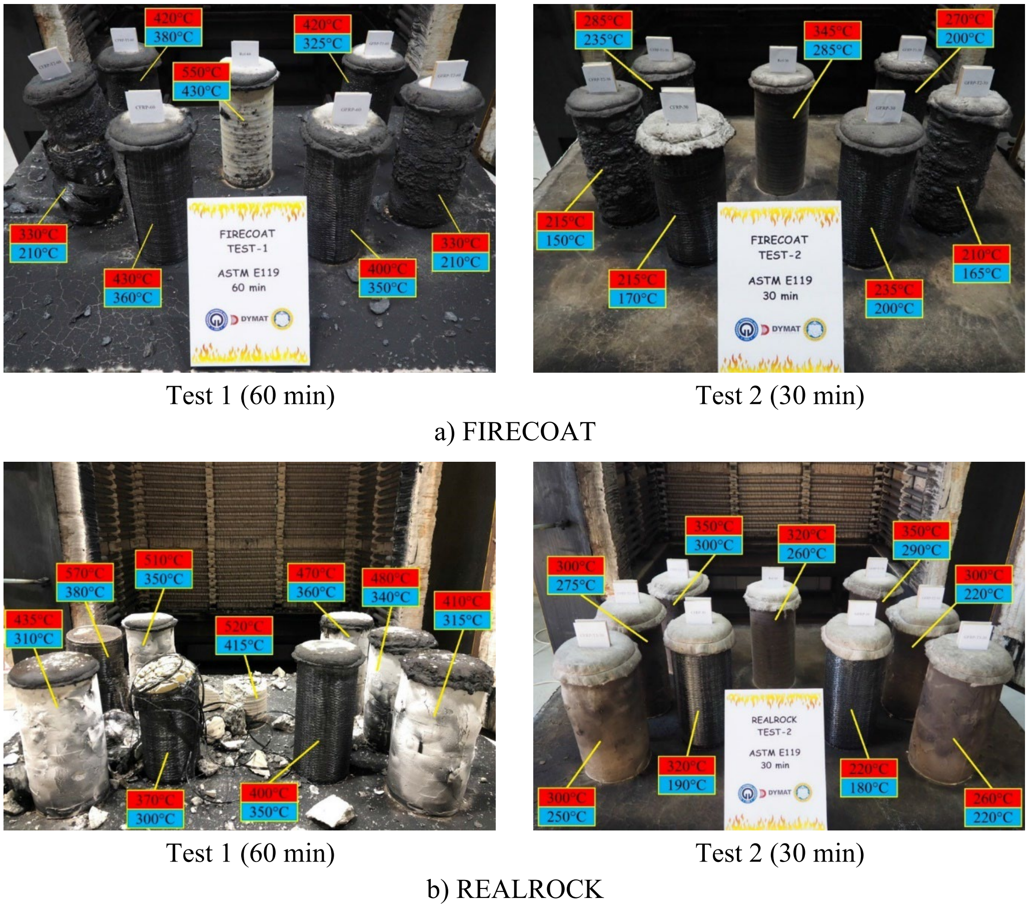


Fig. 12 Measured values of surface temperatures

from the expected results, indicating that due to failure caused by long fire exposure the specimen might not adequately capture the performance of this configuration.

2.6.3.2 REALROCK 2.6.3.2.1 Set-1 (CFRP)

- Although the use of CFRP significantly improved the compressive strength of specimens (from 30.09 to 86.10 MPa), fire exposure of 30 min decreased the compressive strength of the insulated specimens by 20%, 17%, 14% and reached to 69.01 MPa, 71.17 MPa, and 74.45 MPa (T1, T2 and T3 respectively).
- Fire exposure of 60 min has caused a decrease of 78% and 38% in the compressive strength of T1 and T3 specimens and reached their compressive strength to 19.09 MPa and 53.38 MPa respectively. This exposure duration resulted in explosive spalling of the T2 specimen. Hence, post-fire data relevant to this specimen was not obtained.

2.6.3.2.2 Set-2 (GFRP)

- The use of GFRP has significantly enhanced the compressive strength of specimens and reached to 68.23 MPa. But fire exposure of 30 min decreased the compressive strength of REALROCK insulated specimens by 34%, 13%, 5%, and reached to 44.83 MPa, 59.41 MPa, and 64.96 MPa (T1, T2, and T3 respectively).
- Fire exposure of 60 min has caused a decrease of 64%, 34%, and 25% in compressive strength of T1, T2, and T3 specimens and reached their compressive strength to 24.50 MPa, 45.08 MPa, and 51.17 MPa respectively.

The results obtained from the performed fire and compressive strength tests indicate that:

- The application of carbon and glass fiber composites to concrete specimens increased the compres-

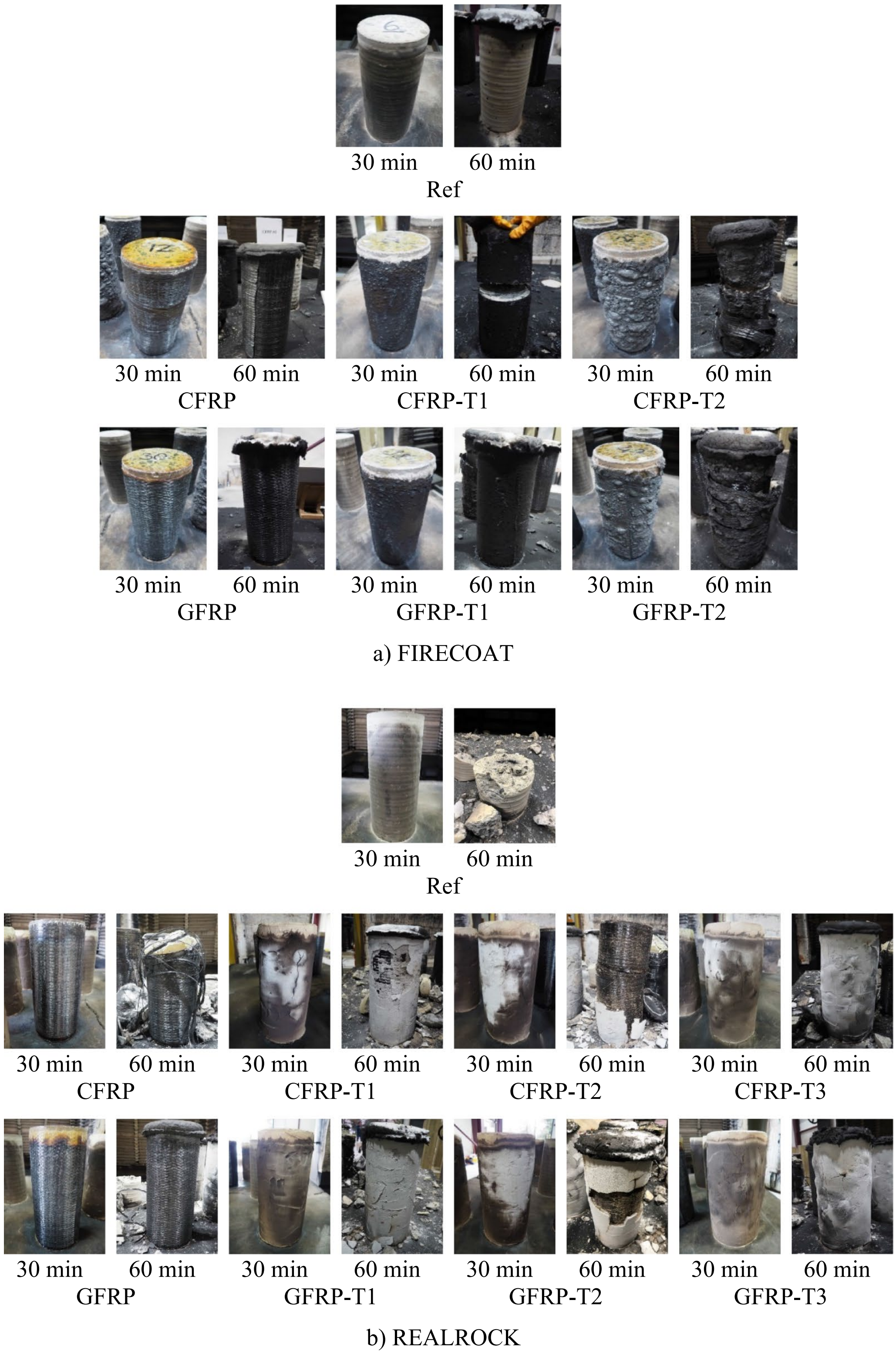


Fig. 13 Post-test visual observations

Table 6 Comparison of compression test results from each insulation system

a) FIRECOAT

Specimen ID		No	Max. Load (N)	Max. Stress (N/mm^2)
Ref.	Ref	1	945281.56	30.09
	Ref-30	6	560723.19	17.85
	Ref-60	4	536824.31	17.09
Set-1	CFRP	7	2705007.00	86.10
	CFRP-30	12	1088490.13	34.65
	CFRP-60	10	576904.00	18.36
	CFRP-T1-30	20	1137223.13	36.20
	CFRP-T1-60	18	587583.44	18.70
	CFRP-T2-30	24	2371450.25	75.49
	CFRP-T2-60	22	–	–
Set-2	GFRP	25	2143591.00	68.23
	GFRP-30	30	734890.63	23.39
	GFRP-60	28	603850.81	19.22
	GFRP-T1-30	38	972557.44	30.96
	GFRP-T1-60	36	675841.88	21.51
	GFRP-T2-30	42	1636213.25	52.08
	GFRP-T2-60	40	440795.81	14.03*

b) REALROCK

Specimen ID		No	Max. Load (N)	Max. Stress (N/mm^2)
Ref.	Ref	1	945281.56	30.09
	Ref-30	5	543543.69	17.30
	Ref-60	3	536824.31	17.09
Set-1	CFRP	7	2705007.00	86.10
	CFRP-30	11	1249386.13	39.77
	CFRP-60	9	576904.00	18.36
	CFRP-T1-30	15	2167975.00	69.01
	CFRP-T1-60	13	599746.44	19.09
	CFRP-T2-30	19	2235780.75	71.17
	CFRP-T2-60	17	–	–
	CFRP-T3-30	23	2338961.50	74.45
	CFRP-T3-60	21	1676887.50	53.38
Set-2	GFRP	25	2143591.00	68.23
	GFRP-30	29	796519.69	25.35
	GFRP-60	27	661006.13	21.04
	GFRP-T1-30	33	1408400.38	44.83
	GFRP-T1-60	31	769538.19	24.50
	GFRP-T2-30	37	1866427.63	59.41
	GFRP-T2-60	35	1416181.88	45.08
	GFRP-T3-30	41	2040831.63	64.96
	GFRP-T3-60	39	1607563.50	51.17

* Deviation due to specimen failure

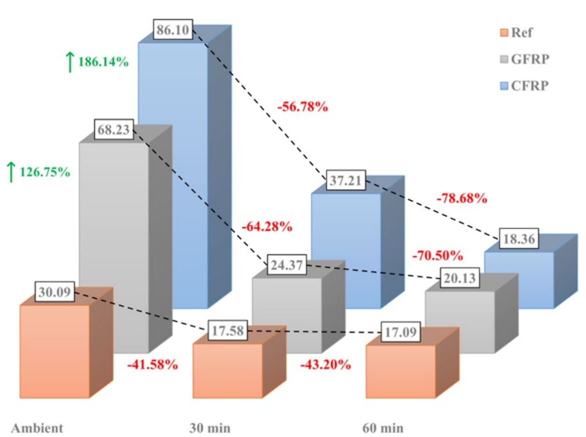


Fig. 14 Changes in compressive strength of the non-insulated specimens

sive strength of the specimens by 2.9 and 2.3 times, respectively.

- The results from the tests on non-insulated FRP-strengthened specimens showed that under 60 min of fire, FRP loses all its strengthening properties, and concrete experience a significant loss in its strength. After 30 min of fire exposure, CFRP demonstrated a better performance than GFRP. Although FRPs could survive 30 min of fire exposure, the remaining strengthening effect on the compressive strength of the concrete was negligible.
- Under 30 min of fire, both the FIRECOAT and REALROCK insulation systems adequately protected FRPs and preserved their strengthening effects on concrete. However, within the tested configurations, the overall performance of T1 in the FIRECOAT system was unsatisfactory. A comparison of the other results from this system shows that this poor performance was attributed to the insufficient thickness of Firefree 88.
- Within 60 min of fire exposure, two of the REALROCK configurations, with an inner layer of Fire Set 60 (T2 and T3), could adequately protect the FRP and control the fire-induced performance losses. Within the tested configurations in this system, the T1 specimens with no inner layer of Fire Set 60 could not provide any protection. This highlights the major contribution of Fire Set 60 in

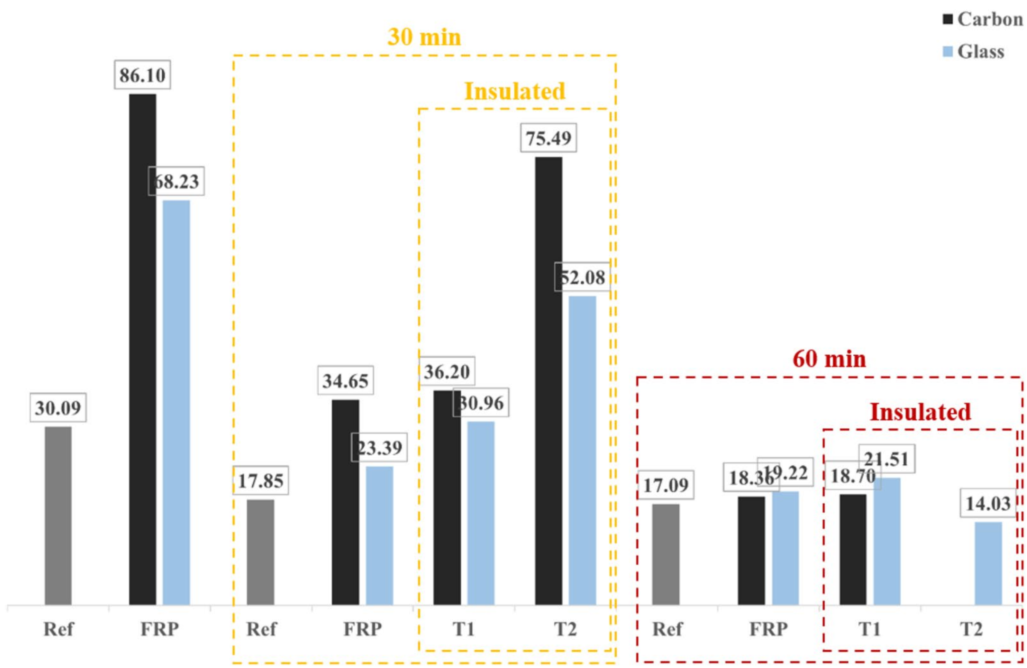


Fig. 15 Compressive strength of the tested specimens for FIRECOAT

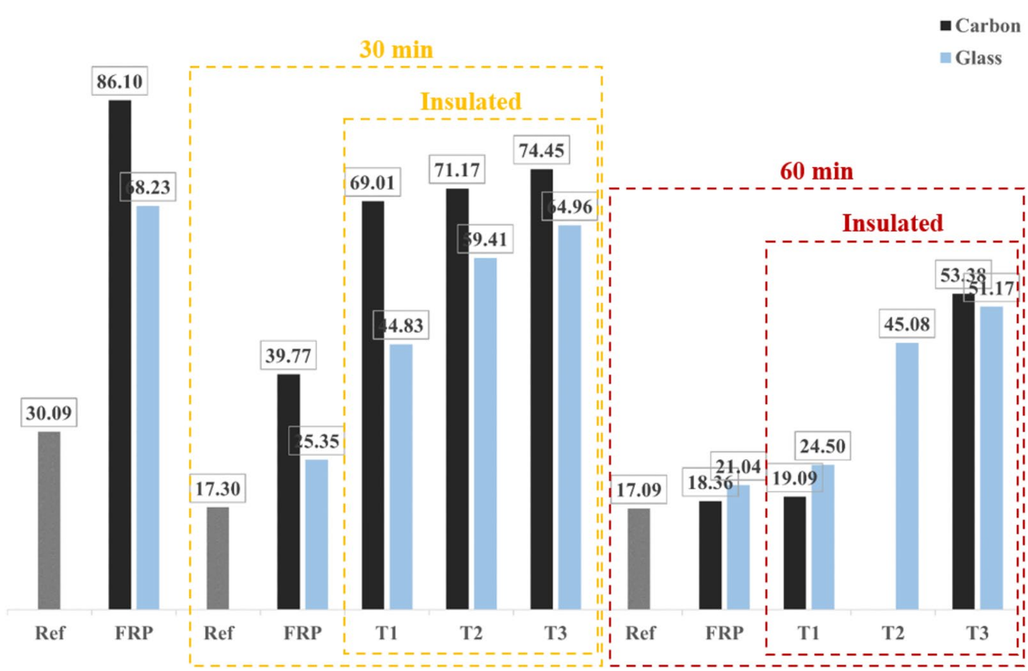


Fig. 16 Compressive strength of the tested specimens for REALROCK

protecting the FRP strenghtened concrete specimens from fire exposure effects. Evaluating different configurations of the FIRECOAT system shows that none of the tested configurations can provide the required protection for the entire duration of a 60 min fire.

- To improve the performance of the FIRECOAT system, the application of Firefree 88 with a minimum

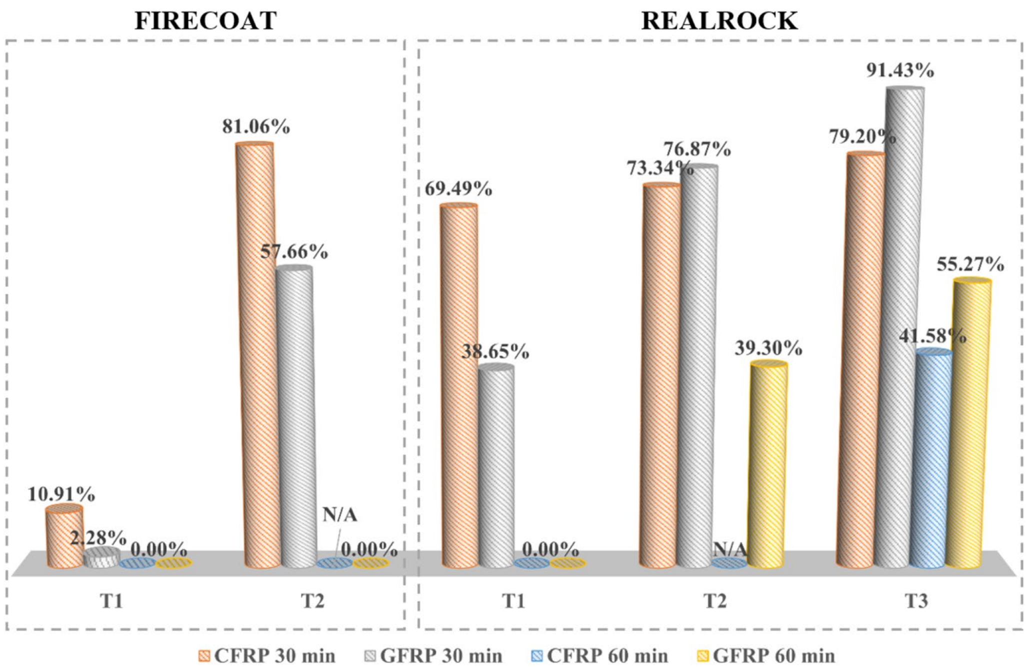


Fig. 17 The success of insulation systems in maintaining the strength provided by FRP

of six layers is suggested. Using this configuration can delay high-temperature losses for up to 30 min and effectively protect the elements from fire-induced damage during this exposure period.

- The results indicated that using Fire Set 60 as the innermost layer of REALROCK-insulated specimens can have a major impact on improving the fire performance of the specimens for up to 60 min.

3 Conclusions

The present experimental study was designed to determine the effectiveness of two insulation systems, "FIRECOAT" and "REALROCK" on protecting CFRP and GFRP strengthened concrete specimens from fire exposure. The main goal was to determine the performance of the insulation materials in protecting the strengthened specimens, and the second goal was to determine the best configuration for each insulation system. The fire load was applied in accordance with the ASTM E119 standard fire curve for two exposure durations of 30 and 60 min. In summary, the key findings of this study are as follows:

- Strengthening concrete specimens with CFRP or GFRP composites increased their compressive strength by 2.9 and 2.3 times, respectively.
- After 60 min of fire exposure, the non-insulated FRP-strengthened specimens exhibited a loss of strength properties for both CFRP and GFRP layers, as well as a significant loss of in strength of concrete.
- Within 30 min of fire exposure, CFRP demonstrated a better performance than GFRP; FRPs sustained the fire load but had a negligible effect on the compressive strength of the concrete.
- Both the FIRECOAT and REALROCK insulation systems adequately protected the FRPs from 30 min of fire exposure and preserved their strengthening effects on the concrete specimens.
- The REALROCK system with an inner layer of Fire Set 60 can adequately protect the FRP and reduce fire-induced strength losses for 60 min. The use of Fire Set 60 as the innermost layer of this insulation system can have a major impact on enhancing the fire performance of the specimens for up to 60 min.
- None of the tested configurations in the FIRECOAT system could provide the desired protection for the entire 60 min of fire; the application of Firefree 88 with a minimum thickness of six layers is suggested to improve the system performance.

In summary, the findings of this study confirm those of previous research on the strengthening effects of CFRP and GFRP on concrete elements and their susceptibility to fire exposure. The results highlight the critical role of thermal insulation in improving the fire performance of FRP-strengthened concrete elements. The insulation systems tested in this study can effectively protect FRP layers from fire while providing several advantages over commonly used insulation materials. In these systems, the simultaneous use of multiple objects with low thicknesses offers a more flexible aesthetics and provides high temperature protection. The reduced thickness of the tested systems can also decrease the additional dead load imposed on the strengthened structure. In addition, the simple application procedure has the potential to significantly reduce material and labor costs. These findings provide insights into the effectiveness of different fire insulation systems and offer recommendations for optimizing their configurations to improve the fire performance of FRP-strengthened elements.

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Author contributions
ACA, SA and AM contributed to methodology, formal analysis, conceptualization, funding acquisition, investigation, project administration, resources, validation, and writing. MG was involved in supervision, writing—review and editing. YEA and SM contributed to software and writing original draft. All the authors read and approved the final manuscript.

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Availability of data and materials
The data and materials used to support the findings of this study are available from the corresponding author upon request.

Declarations

Ethics approval and consent to participate
The authors state that the research was conducted according to ethical standards. Informed consent was obtained from all individual participants included in this study.

Consent for publication
All the authors agree that the article will be published after acceptance.

Competing interests
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