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Effects of concrete cover thickness and concrete strength on temperature transfer in high temperature exposed FRP reinforced concrete

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Abstract: While Fibre-Reinforced Plastics are lightweight, show a high tensile strength, and have no issue with corrosion, they are unfortunately brittle and perform poorly against temperature. Therefore, it is important to know the time and magnitude of the temperature reaching the bars in the high-temperature effect of FRPs produced in the form of bar in reinforced concrete structural elements in concrete. This study set out to examine the time and temperature values of glass fiber reinforced polymer (GFRP) reinforced concrete under high-temperatures. The effects of concrete cover thickness and concrete strength on temperature transfer were researched experimentally. GFRP bars were placed in specimens prepared in three concrete strengths and three different concrete cover thicknesses (20-40-60 mm) exposed to temperature, and temperature-time graphs were created by measuring bar temperature, concrete surface temperature and ambient temperature. The critical time to a glass transition temperature, and optimum cover thickness of GFRPs according to concrete strength and concrete cover thickness were discussed. The study results appeared to indicate that the thickness of the concrete cover is very effective in protecting the bar against temperature in reinforced concrete structural elements, as concrete strength, itself, has only a limited effect.

Keywords: Concrete cover, FRP bar, heat; concrete strength, fire effect.

1. Introduction

Concrete is one of the most widely used materials in buildings in the last century due to its advantages over other building materials. Strength, durability, and fire resistance are among the most notable of these (Abdulrahman & Kadir, 2022). In the reinforced concrete building system, concrete protects the bar placed inside against fire and temperature. Almost all damage in fire-damaged reinforced concrete structures is due to either poor detailing or failure of the steel bar. This is because the bar is usually placed close to the surface of the concrete element. When concrete is exposed to high temperatures, blistering occurs, leading to the development of cracks and loss of concrete cover. Therefore, direct exposure of the steel bar to intense heat exposes the bar to a higher temperature increase compared to the main body of the concrete, and its resistance is affected. The compressive strength and modulus of elasticity of concrete decreases in reinforced concrete elements exposed to high temperatures. In addition, the yield strength, tensile strength, modulus of elasticity, and ductility of steel bar are reduced in such structures, as is the load carrying capacity of the reinforced concrete structure. To improve the fire resistance of reinforced concrete elements, most studies, including building regulations, recommend the traditional design method of increasing the concrete cover thickness of reinforced concrete elements (Gewain et al., 2003; Klingsch, 2014; Kodur & Phan, 2007; Li et al., 2019; Ma et al., 2015; Shi et al., 2004).

Researchers and users require new materials for use in reinforced concrete structures due to the corrosion of steel rebars and damage to reinforced concrete structures. Fibre Reinforced Plastic (FRP) materials, which are produced by combining polymers and high tensile strength fibres that are resistant to chemicals, can be used as reinforcement with the development of production technologies (Aydin, 2018; Aydın & Arslan, 2021). Moreover, FRP bars are non-conductive, lightweight, possess high longitudinal tensile strength and most importantly non-corrosive materials(Remennikov, Goldston, and Sheikh 2016) . A few of the main concerns that prevent the further application of FRP bars in normal buildings include the inductive behavior of FRP-reinforced concrete members (FRP-RC) compared to steel reinforced concrete (SRC) members, the deterioration of the bonding and mechanical properties of FRP bars at high temperatures, and the high susceptibility of FRP-RC members to fire (Chellapandian et al., 2020; Del Prete et al., 2021; Galati et al., 2004). Several building codes exist for the design of FRP-reinforced concrete structures (ACI, 2015; CNR, 2006; CSA, 2002). The Canadian code (CAN/CSA 806-02) provides a design procedure in critical temperature-based fire situations (CSA, 2002; Nigro et al., 2011).

Due to the relatively low glass transition temperature (Tg) and degradation temperature (Td) of the polymer matrix, FRP bars have lower heat resistance than steel bars. The mechanical properties of FRP bars are greatly reduced due to the decomposition of the polymer after exposure to high temperatures; and accordingly, the mechanical properties of FRP reinforced concrete elements are also reduced (Özkal et al., 2018; Rami Hamad et al., 2017; Wu et al., 2011). Glass Fibre Reinforced Polymers (GFRP) are more commonly used in concrete structures due to their affordability compared to other fibrous FRP materials (Nkurunziza et al., 2005). However, some studies have shown that the mechanical properties of GFRP bar are sensitive to high-temperature (Bisby & Kodur, 2007; Gooranorimi et al., 2018; Reid et al., 2014). The behaviors of GFRP bar after exposure to high temperatures are critical for applications in concrete structures potentially subjected to fire (Spagnuolo et al., 2018).

In the literature, there are studies on the behavior of FRP-reinforced ferroconcrete slabs, beams, and columns tested under fire exposure conditions, (Bisby et al., 2005; Nigro et al., 2011; Rafi & Nadjai, 2010; Saafi, 2002), or research on the behavior of concrete elements exposed to standard fire conditions (Abbasi & Hogg, 2005; Gao et al., 2016; Rafi & Nadjai, 2014; H. Wang et al., 2009), or research on the tensile strength of FRP bar at high temperatures (Ashrafi et al., 2017; K. Wang et al., 2011; X. Wang & Zha, 2011; Y. C. Wang et al., 2007). Najafabadi et al. studied the mechanical properties of GFRP and carbon fibre reinforced polymer (CFRP) bar embedded in concrete over a wide high-temperature range (25-800 °C). They found that the concrete cover prevents direct heat and oxygen from reaching the reinforcement and that embedded FRP bar has better tensile performance at high temperatures compared to bare bar exposed to direct heat (Najafabadi et al., 2019). In another study (Ünlüoğlu et al., 2007) steel bars with different diameters were placed in cementitious mortar prepared with fly ash in molds prepared in special sizes with a 25 mm cover and exposed to high temperatures for three hours. As a result of the experiments, it appeared that the 25 mm cover provided with mortar at high temperatures protected the bars, reduced the yield and tensile strength losses, and their resistance was higher than the rebars without a cover. However, the results seemed to indicate that a 25 mm concrete cover does not adequately protect the mechanical properties of the bar at temperatures above 500°C. In all of the studies, it is suggested that increasing the concrete cover will protect the bar more against high temperatures.

Unlike the studies in the literature, this study set out to experimentally research the effects of concrete cover thickness and concrete strength on the heat transfer of GFRP reinforced concrete specimens at high temperatures.

2. Materials and methods

GFRP bars were placed in concrete specimens prepared with different concrete cover thicknesses and strengths and exposed to temperature. The time for the high temperature to reach the bar compared to the concrete surface and the magnitude of the temperature were measured with a thermocouple from the surfaces of the concrete and GFRP bar. According to Turkiye standard concrete cover should be 25 mm and 40 mm at reinforced slabs and column for fire protection respectively (Resmi Gazete,2007). In the experiments, concrete specimens with three different compressive strengths (26.1 -38.6 - 52.0 MPa) and 20 - 40 - 60 mm thick concrete cover prepared for each concrete strength. GFRP bars manufactured with pultrusion process. In this process, the fibers are drawn through a heated die.

By applying a constant pressure while passing through the mold, the resin is melted and impregnated with the fibrous reinforcement (Biswas, Bandyopadhyay, and Sinha 2019). With this process, GFRP bars can have sufficient tensile, bending and compressive strength. The mechanical and physical properties of the GFRP bars can be seen in Table 1. The mix ratios and 28-day compressive strength averages of concretes with three different concrete strengths are given in Table 2. Dimensions and properties of reinforced concrete specimens are provided in Table 3.

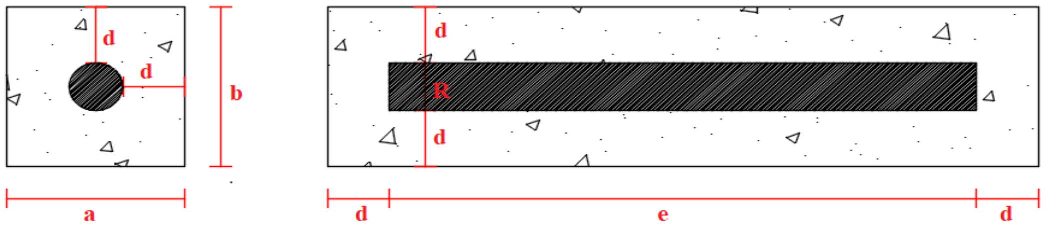
Table 1. FRP bar and resin properties.

E-Glass Fiber		Polyester Resin: Liquid CE 67 HV4	
FWR6		Tensile Strength	Min 50 MPa
Diameter	10 mm	Flexural strength	Min 85 MPa
Modulus of E.	70-80 GPa	Hardness	Min. 45 barcol
Density	2.5-2.6 g/cc	Additive	Min %65
Tensile Strength	2-3.5x103 MPa	Gelation h.(25 oC)	4±1 minute
Elongation Break	%2-5	Acid number	26.0 - 34.0
Fiber/Resin Weight Ratio	2,65	Viscosity	1000±150 Cps

Table 2. Mix proportions of concrete for 1000 dm^3.

Materials (kg)	I	II	III
Water	192	190	172
(CEM I 42,5 R) Ordinary Portland Cement	320	380	430
(Superplasticizer) Additive	-	-	2,15
River Sand	844,3	825,0	837,6
(Crushed) Coarse aggregate (5-12 mm)	521,9	510,0	511,6
(Crushed) Coarse aggregate (12-32 mm)	466,2	455,4	456,8
Total	2344,5	2360,4	2400,0
Average Compressive Strength (MPa)	26,1	38,6	52,0

Table 3. Specimen dimensions (mm).



Concrete Cover (d) (mm)	Section dimensions (a=b)	Bar Length (e)	Bar Diameter (R)	Concrete Length
20	50	210	10	250
40	90	210	10	250
60	130	210	10	250

After the thermocouple ends were attached to the FRP bar surfaces, fresh concrete was placed in the molds. The other thermocouple was mounted on the surface of the cured and strengthened concrete specimens (Figure. 1).

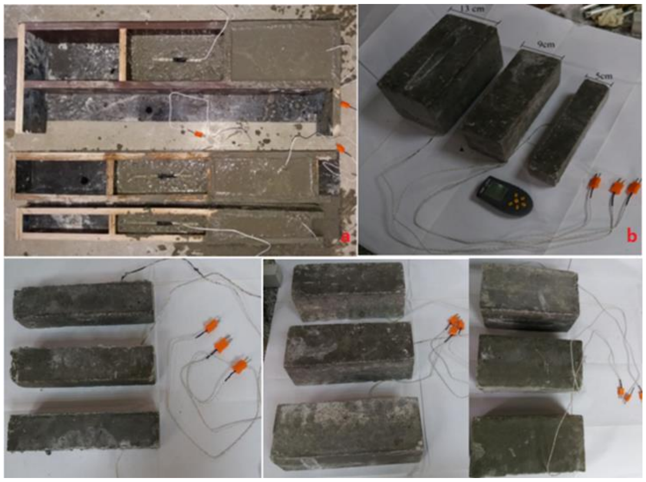


Figure 1. a) Thermocouple attached to GFRP bar b) samples with different concrete covers (20-40-60 mm).

In the high-temperature test of FRP reinforced concrete, the specimens were placed in the furnace and the thermocouples connected to the concrete and FRP bar were taken out to be connected to the thermometer. As the temperature increased in the furnace, a stopwatch was used in the measurements regarding the rate of the temperature of the bar surface, concrete surface, and furnace ambient temperature. The high-temperature experiments continued until the glass transition temperature (Tg), which is the critical temperature value for the bar. The experimental setup and temperature measurements are shown in Fig. 2. Video recordings were taken during the experiments and temperature-time graphs were created and interpreted according to the mat thickness and concrete strength class.

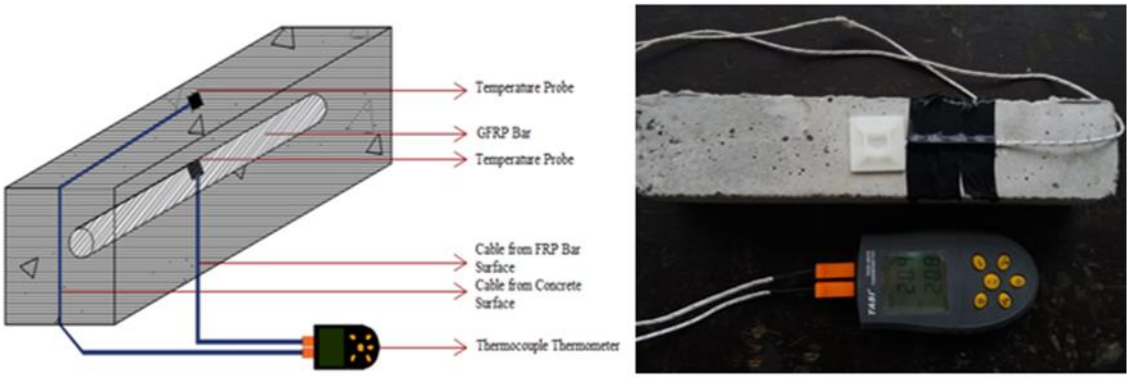


Figure 2. The experimental setup.

3. Experimental results and analysis

In the study researching the time and magnitude of high temperatures reaching the bar in GFRP reinforced concrete, specimens of three concrete strength classes and three concrete cover thicknesses were tested. The experiments continued until the glass transition temperature of FRP bars, Tg: 115 °C, was reached where large strength losses occurred. Temperature time graphs were drawn and interpreted. In the comparison of the graphs, evaluations were made according to the concrete class and the concrete cover.

3.1. Strength class I test results

The average compressive strength of concrete in the first strength class was 26.1 MPa. Temperature-time graphs for strength class I at different concrete cover thicknesses are shown in Fig. 3, 4, 5, and the graph showing the temperature transfer according to the concrete cover thickness is given in Fig. 6.

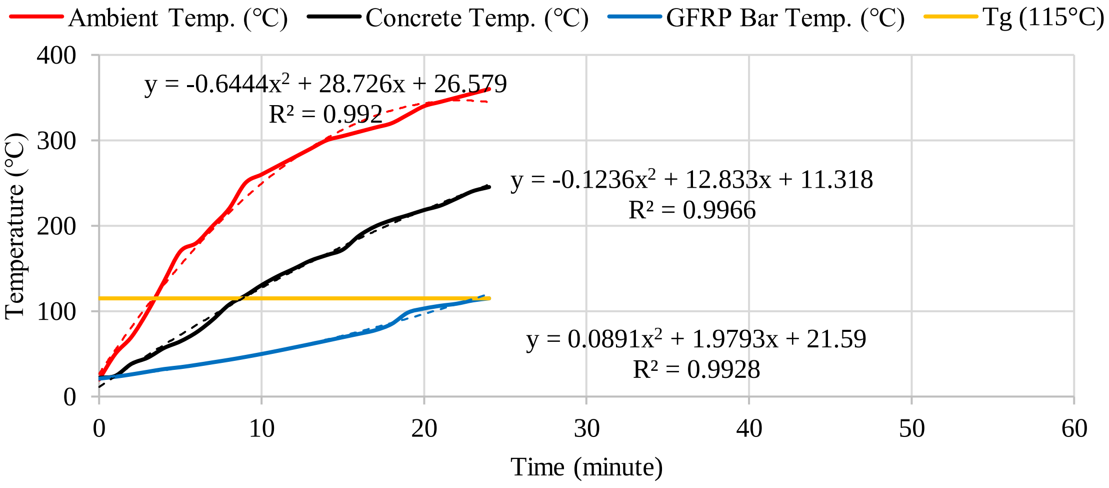


Figure 3. Temperature-time graph for strength class I and cover thickness 20 mm.

In strength class I concretes with 20 mm concrete cover thickness, when the FRP bar Tg temperature reached 115 °C the concrete surface temperature was 245 °C and the ambient temperature was 360 °C. The average compressive strength of 26 MPa and 20 mm concrete cover thickness reduced the temperature at the concrete surface by 130 °C, that is, the effect of surface temperature was reduced by 53%.

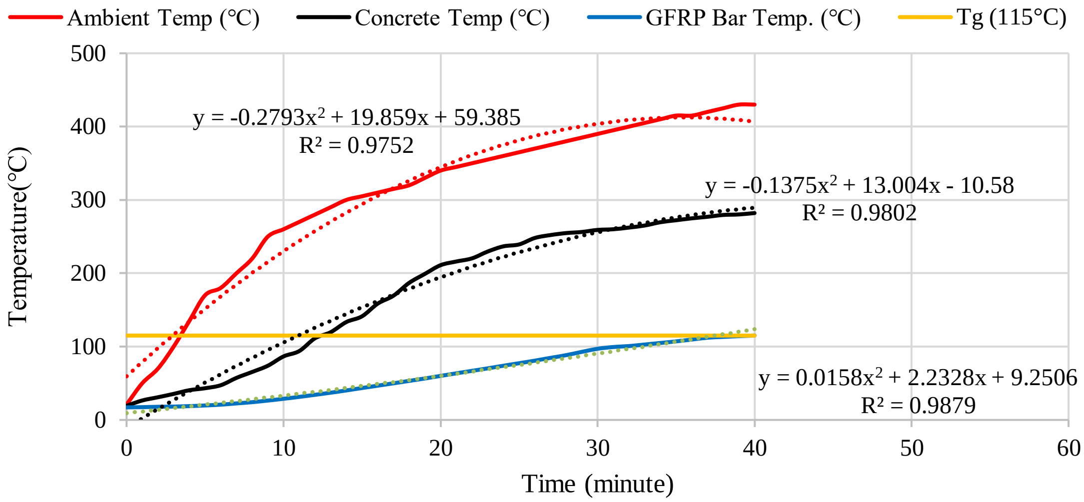


Figure 1. Temperature-time graph for strength class I and cover thickness 40 mm.

In specimens with 40 mm concrete cover thickness, the concrete surface temperature was 282 °C and the ambient temperature was 430 °C while the bar was at 115 °C . In concretes of this strength class, 40 mm concrete cover thickness reduced the surface temperature reaching the FRP bar by 59% in terms of critical temperature.

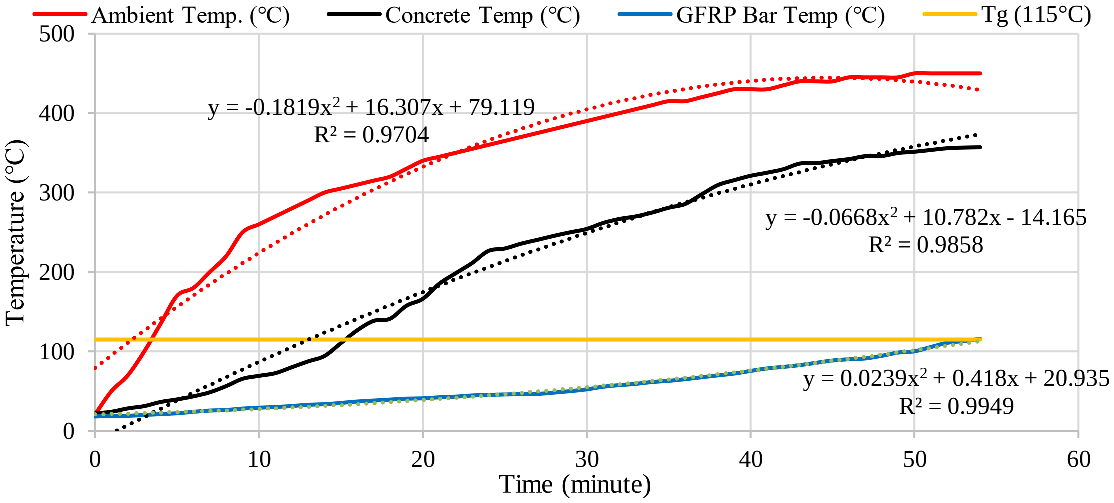


Figure 2. Temperature-time graph for strength class I and cover thickness 60 mm.

For the maximum concrete cover thickness of 60 mm for strength class I concretes, the concrete surface temperature was 357 °C and the ambient temperature was 450 °C when the bar was at Tg temperature. The 60 mm concrete cover thickness reduced the surface temperature reaching the FRP bar by 68% for the critical temperature.

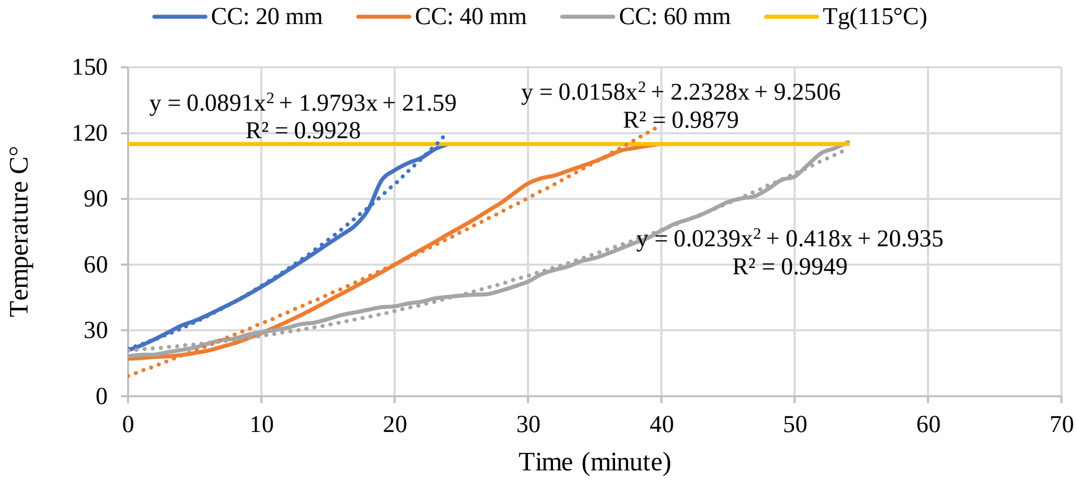


Figure 3. Effect of cover thicknesses for strength class I (CC: Concrete cover).

It was noted that R2 values were above 97% in all of the graphs created as a result of experimental studies in strength class I concretes. In this concrete strength group, FRP bars with 20, 40, 60 mm concrete cover thickness reached Tg temperature in 24, 40, 54 minutes respectively. When the FRP bars reached the critical temperature, the ambient temperature was 360, 430, 450 °C and the concrete temperature was 245, 282, 257 °C, respectively. The critical temperature value, which is extremely important for the safety of the structure during a fire, reached 67% more time in 40 mm and 125% more time in 60 mm compared to structural elements with 20 mm concrete cover.

3.2. Strength class II test results

For strength class II concretes with an average compressive strength of approximately 39 MPa, the temperature-time graphs according to the concrete cover thicknesses are given in Fig. 7, 8, 9 and the graph evaluating the effect of concrete cover thickness is provided in Fig. 10.

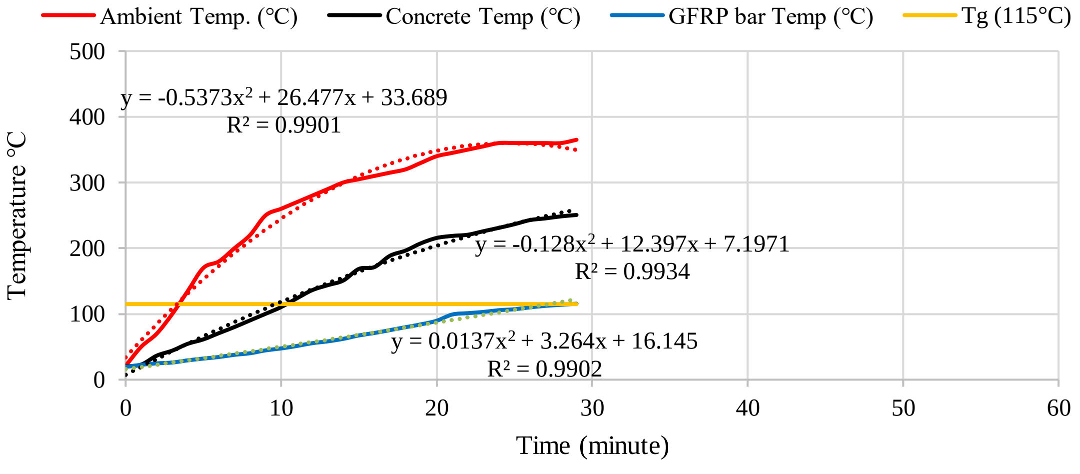


Figure 7. Temperature-time graph for strength class II and cover thickness 20 mm.

In this strength class, at 20 mm concrete cover thickness, the FRP bar was at 115 °C, the concrete surface was 251 °C and the ambient temperature was 365 °C. The 20 mm concrete cover thickness between the bar and the concrete surface reduced the temperature at the concrete surface by 136 °C, approximately 54%.

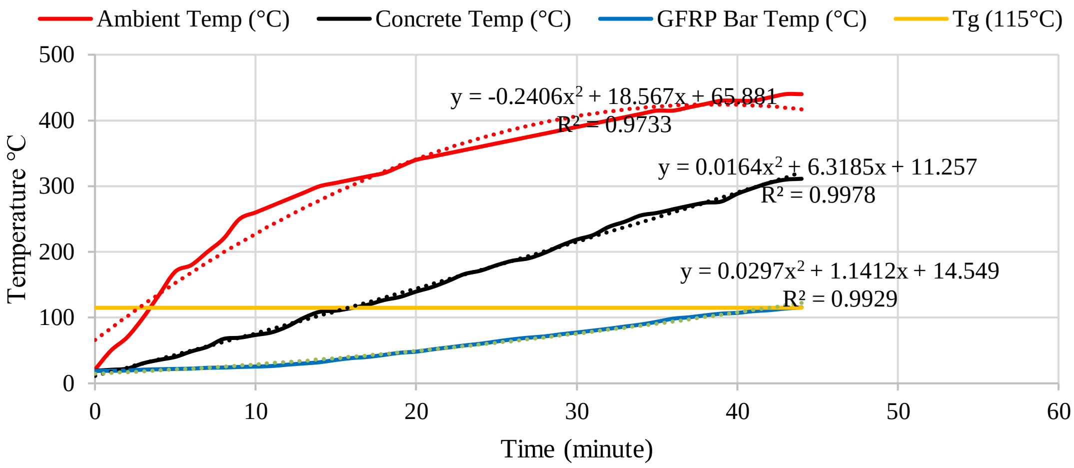


Figure 8. Temperature-time graph for strength class II and cover thickness 40 mm.

At 40 mm concrete cover thickness, when the FRP bar reached Tg temperature, the concrete surface temperature was 311 °C and the ambient temperature was 440 °C. In concretes of this strength class, 40 mm concrete cover thickness reduced the surface temperature by 63% in terms of the critical temperature to reach the FRP bar.

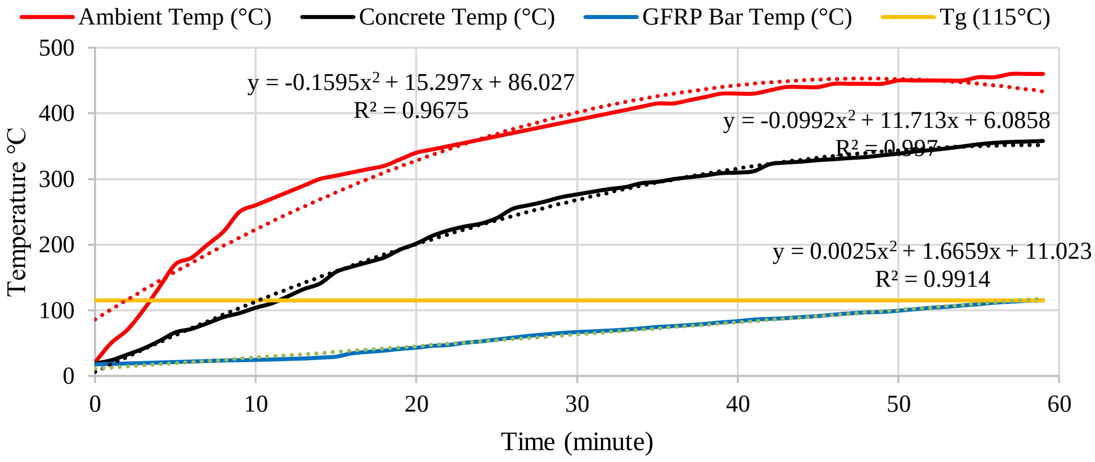


Figure 9. Temperature-time graph for strength class II and cover thickness 60 mm.

For strength class II concretes, the concrete surface temperature was 358 °C and the ambient temperature was 460 °C when the FRP bar was at Tg temperature at 60 mm concrete cover thickness. In this group, it was concluded that the thickness of the concrete cover can reduce the surface temperature reaching the FRP bar by approximately 68%.

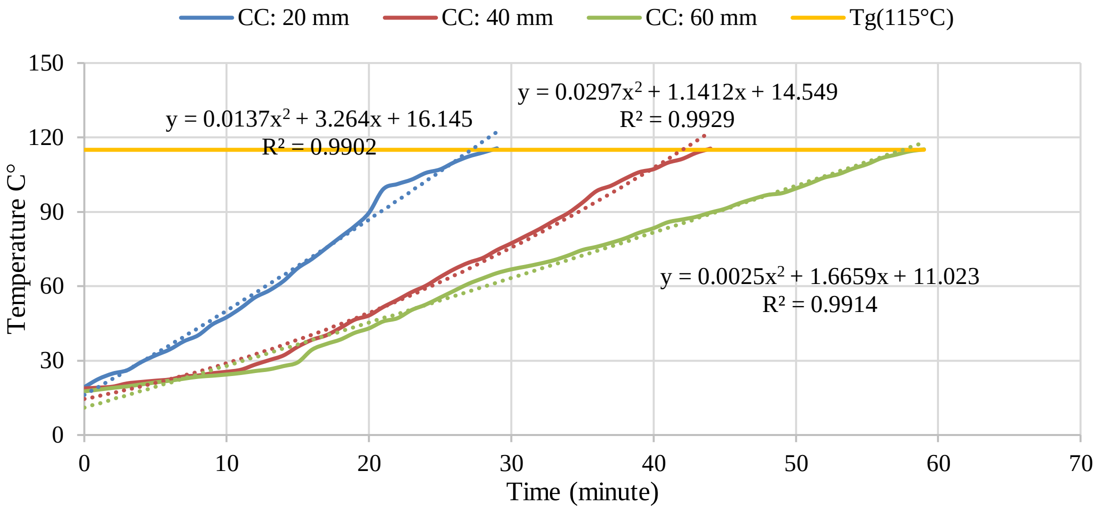


Figure 10. Effect of cover thicknesses for strength class II. (CC:Concrete cover).

In all graphs created in this strength class, R2 values were above 96% and there is good consistency in the data. In this group, FRP bar with 20, 40, and 60 mm concrete covers reached Tg temperature in 29, 44, and 59 minutes respectively. When FRP bars reach the critical temperature 115 °C, the ambient temperature was 365, 440, 460 °C and the concrete temperature was 250, 311, 357 °C respectively. In terms of time to reach the critical temperature, FRP bars saved 52% and 103% more time for 40 mm and 60 mm bars compared to 20 mm bars.

3.3. Strength class III test results

For strength class III concretes with an average compressive strength of 52 MPa, the temperature-time graphs for 20, 40, and 60 mm for concrete covers are shown in Fig. 11, 12, 13 for 20, 40, and 60 mm, respectively, and the comparison of concrete cover thicknesses is given in Fig. 14.

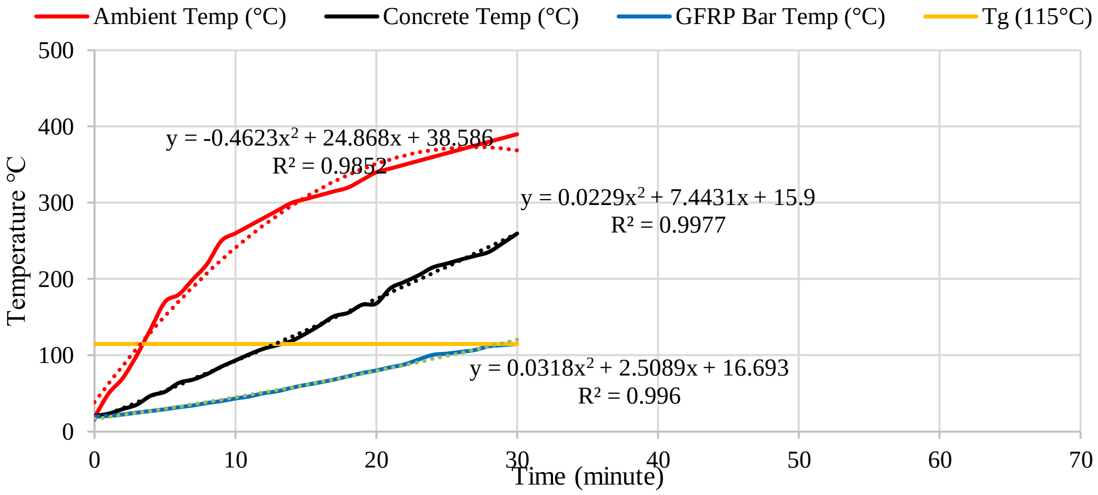


Figure 11. Temperature-time graph for strength class III and cover thickness 20 mm.

In the group with the highest concrete strength, at 20 mm concrete cover thickness, the concrete surface was 260 °C and the ambient temperature was 390 °C while the FRP bar was at the critical temperature. This concrete cover thickness reduced the temperature at the concrete surface by approximately 56%.

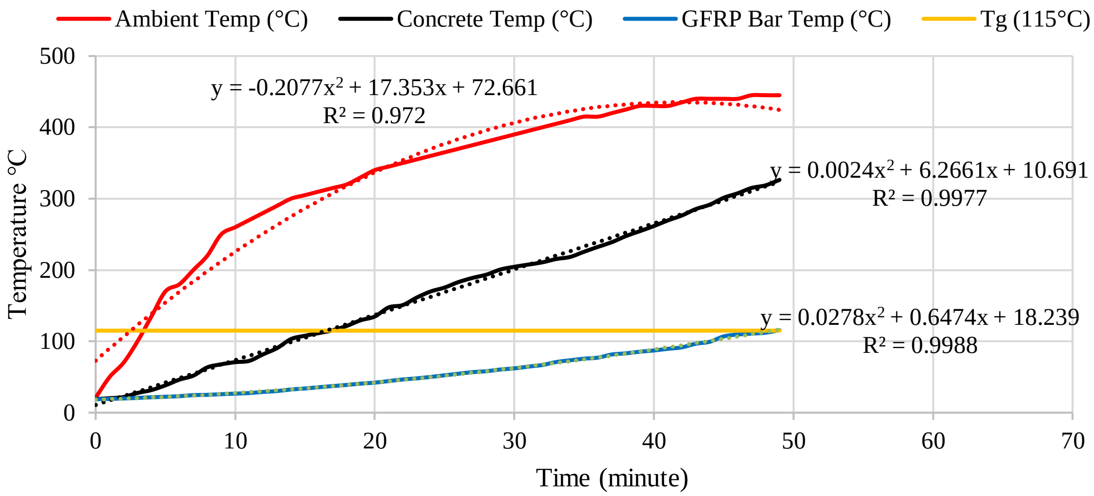


Figure 12. Temperature-time graph for strength class III and cover thickness 40 mm.

At 40 mm concrete cover thickness, the concrete surface temperature was 326 °C and the ambient temperature was 445 °C. In concretes of this strength class, the concrete cover reduces the surface temperature reaching the FRP bars by 65%.

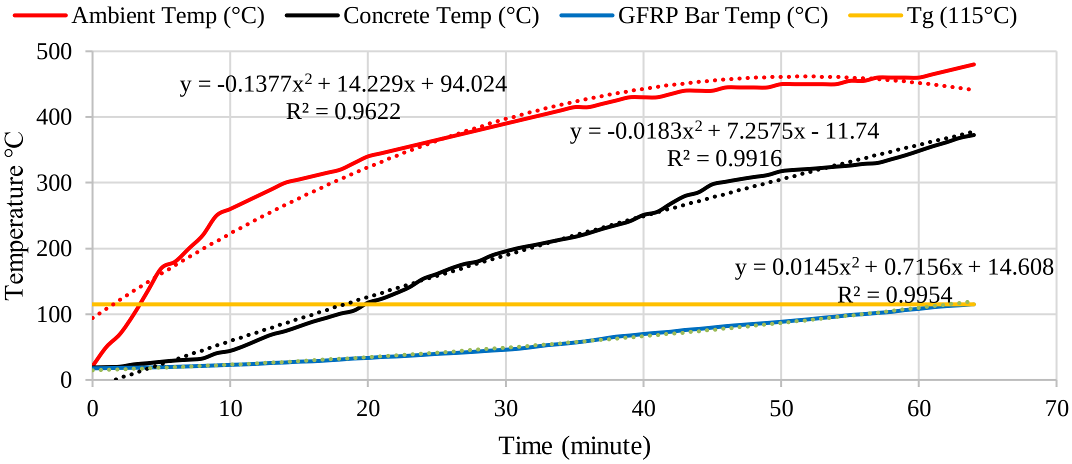


Figure 13. Temperature-time graph for strength class III and cover thickness 60 mm.

For strength class III and 60 mm concrete cover, the concrete surface temperature was 373 °C and the ambient temperature was 480 °C when the bar was at Tg temperature. It was concluded that the thickness of the concrete cover can reduce the surface temperature reaching the FRP bar by approximately 69%.

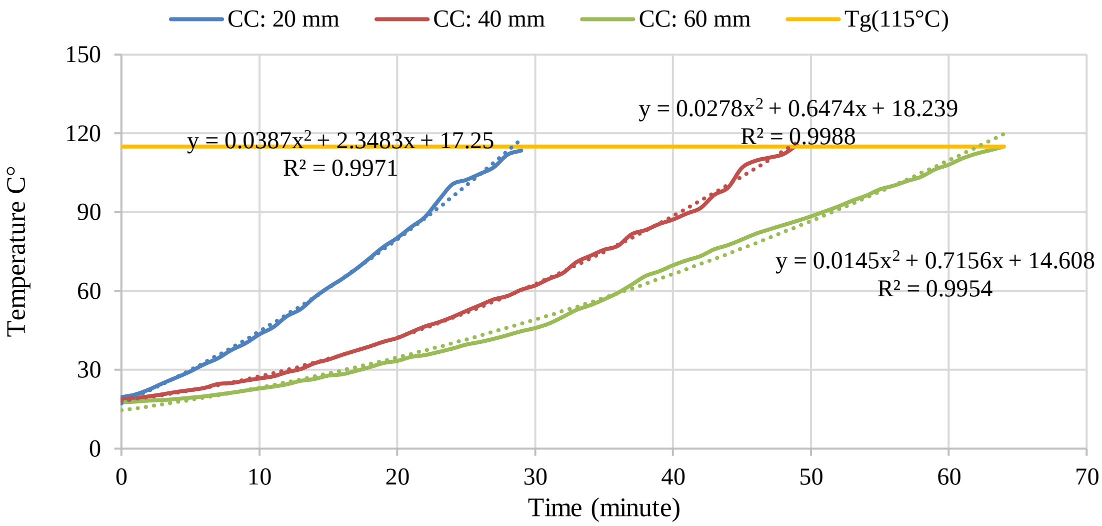


Figure 14. Effect of cover thicknesses for strength class III (CC:Concrete cover).

In this strength class, FRP bars with 20, 40 and 60 mm concrete covers reached Tg temperature in 30, 49, and 64 minutes respectively. When the FRP bars reached the critical temperature, the ambient temperature was 390, 445, 480 °C and the concrete temperature was 260, 326, 373 °C, respectively. When the FRP bars reach the critical temperature, the increasing concrete cover thicknesses reach the critical temperature in 63% and 113% more time for 40 mm and 60 mm concrete covers, respectively, compared to 20 mm concrete covers.

3.4. Findings and discussion

The temperature-time graphs of concretes with the same concrete cover but different strength classes for 20, 40, and 60 mm mat are given in Fig. 15, 16, 17. In these graphs, temperature data up to Tg temperature were collected and evaluated.

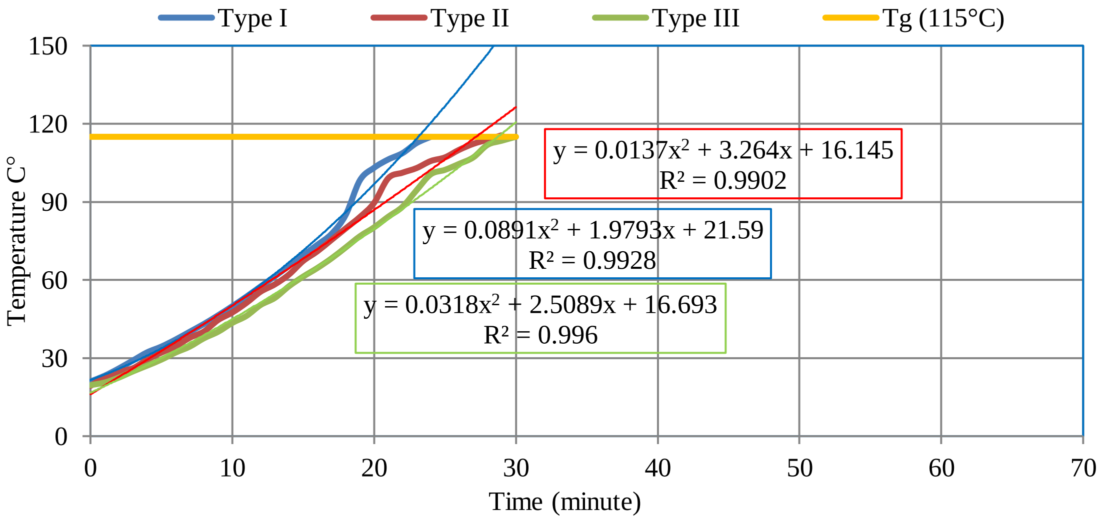


Figure 15. Temperature-time graph at 20 mm concrete cover (Type: Concrete class).

For specimens with 20 mm concrete covers, the critical times required for FRP bars to reach Tg temperature in concrete strength classes I, II, and III are 24, 29, 30 minutes, respectively, for 40 mm concrete covers 40, 44, 49 minutes, respectively, and for 60 mm concrete covers 54, 59, 64 minutes, respectively (Fig. 18). It was determined that the increase in concrete strength classes saved a smaller amount of time in terms of bar protection compared to the increase in concrete cover thickness. The time difference between low and high concrete strength classes is 25%, 22%, and 18% for 20, 40 and 60 mm concrete cover thickness, respectively. These ratios are 125%, 103%, and 113% for strength classes I, II, and III when the concrete cover thickness increases from 20 mm to 60 mm. Therefore, concrete cover thickness protects FRP bars against fire to a great extent at higher temperatures. It is thought that the limited amount of time saved as the concrete strength increases is due to the increased heat storage of the concrete density with increasing strength.

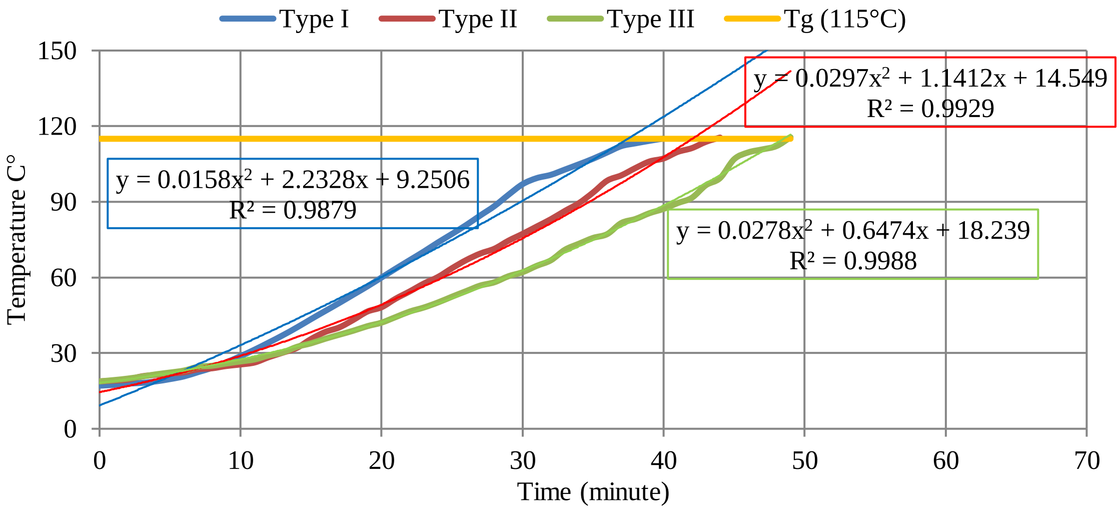


Figure 16. Temperature-time graph at 40 mm concrete cover (type: concrete class).

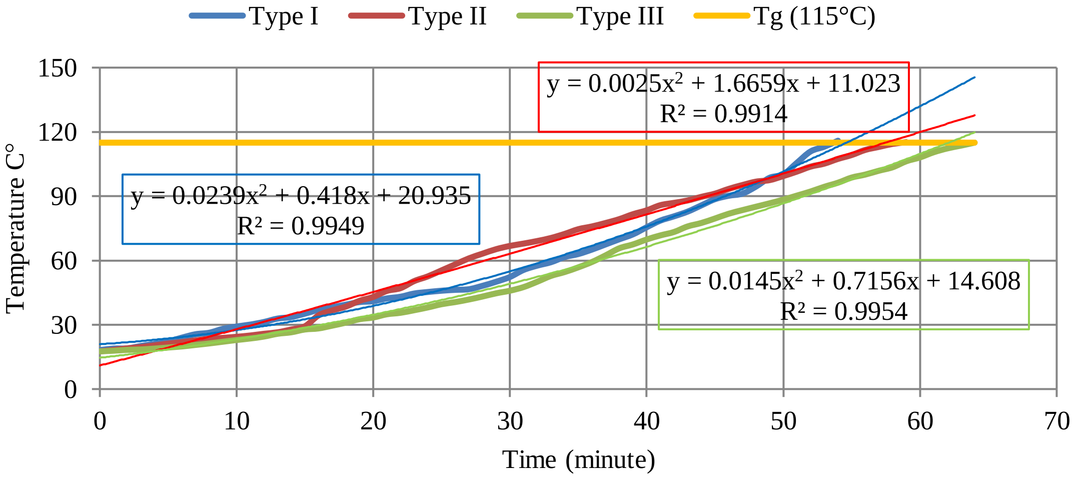


Figure 17. Temperature-time graph at 60 mm concrete cover (type: concrete class).

The fire resistance of a steel structural element and the time required to evacuate the building is specified in the standards according to the importance of the building, and this time is 60 minutes for a normal residential building made of steel profile (Aykut & CIRPICI, 2018). Considering that the coefficient of thermal conductivity of steel is very high compared to GFRP, it can be said that the 60 mm concrete cover is especially important when it comes to saving time.

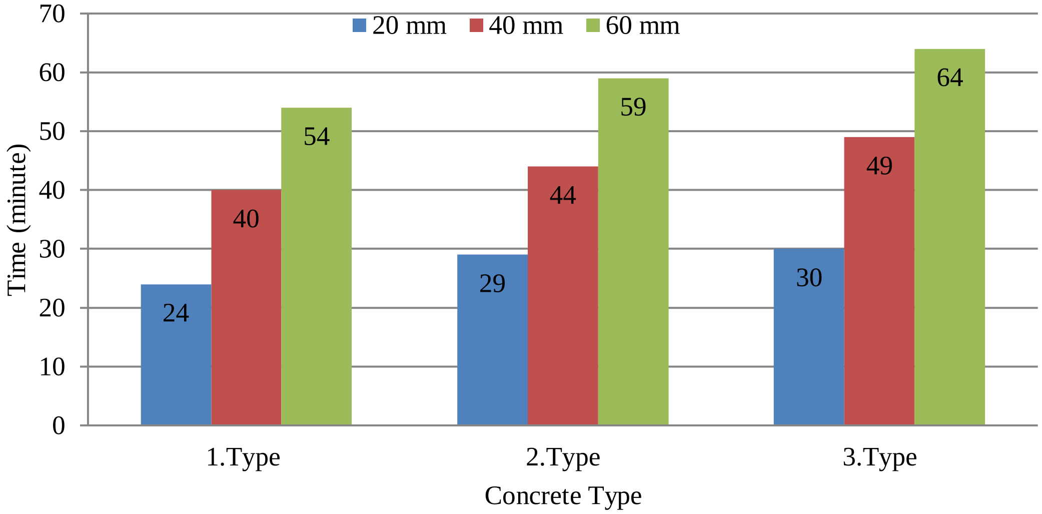


Figure 18. Critical time according to concrete type and cover.

The graphs of concrete surface temperature required for FRP bar to reach Tg temperature according to concrete cover thickness and concrete strength are given in Fig. 19. The increasing concrete cover is more effective while the effect of concrete strength is limited. Between 20 mm and 60 mm concrete covers, a temperature difference of more than 100 °C was observed for each concrete strength class.

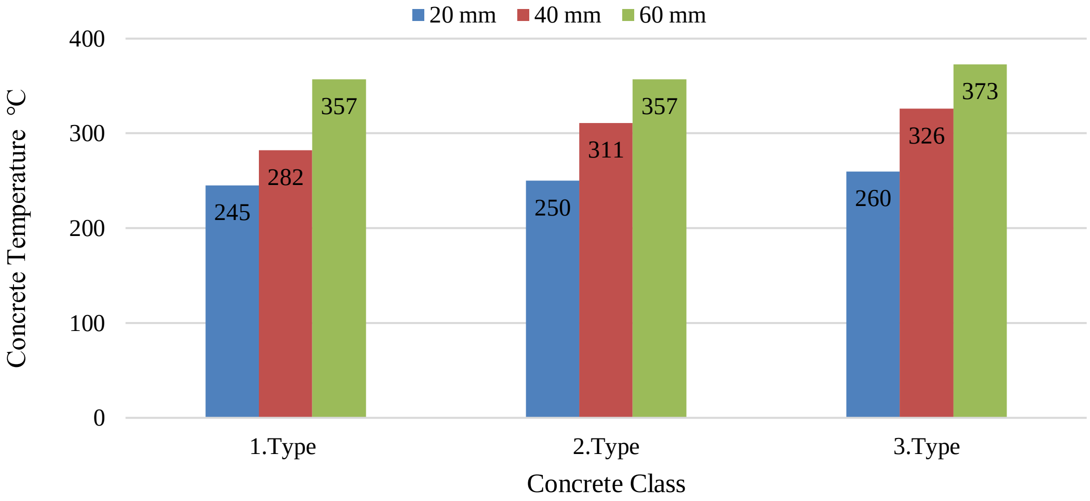


Figure 19. Concrete surface temperature according to concrete cover and concrete type.

Much work has been done in the literature on the change in mechanical properties of concrete at high temperatures. One of the most recent studies was done by Ahmad et al. In the study, concretes with different strengths were produced by being exposed to different mixing ratios and high temperatures. As a result of the study, it was seen that the strengths decreased as the temperature increased. It can be stated that concrete loses 30% of its strength at approximately 400 ℃, 50% of its strength at 600 ℃ ,and 80% of its strength at 800 ℃. (Ahmad et al. 2021).

As a result of experiments carried out in earlier studies, analytical model expressing mechanical changes in concrete were developed (1) (Lie, Chabot, and Irwin 1992). In the equation below, fct represents the strength of the concrete at T temperature, fc the strength of the concrete at room temperature, and Tc the changing temperature. (Bisby 2005).

$$0 \leq Tc \leq 450 \ : \ fct = fc$$

$$Tc \geq 450 : \ fct = fc\left[2{,}011 - 2{,}3353x\left(\frac{Tc-20}{1000}\right)\right] \tag{1}$$

$$\varepsilon_m = 0{,}0025 + (6xTc + 0{,}04xTc^2)x10^{-6}$$

In this study, the temperature of the concrete varies between 200-400 ℃. According to the equation (1), there was no significant loss in strength since the temperature remained between 0-450 ℃. By looking at the concrete properties of Ahmad's work (Ahmad et al. 2021), it can be stated that the concretes used in this study still maintain 70%-90% of their compressive strength.

Studies on temperature changes in FRP bars are much less than in construction materials such as steel rebar and concrete. However, for FRP bars, mathematical models related to strength changes in temperature changes were proposed, albeit limited, in the literature. Two examples of different mathematical models taken from the literature are shown here. The equation proposed by Wang is given in (2) (Wang, Young, and Smith 2011) and the equation suggested by Nadjai is given in (3) (Ashrafi et al. 2017; Nadjai, Talamona, and Ali 2005). With these equations, the ratio of the tensile strength at temperature T to the strength at room temperature can be found.

$$22 \leq T(°\mathrm{C}) < 150 \ , \qquad 1 - \frac{(T-22)^{0,9}}{200} \tag{2}$$

$$100 \leq T < 475, \ 1.267 - 0.00267T, \tag{3}$$

In this study, since the bars were exposed to Tg (115 °C), FRP bars lost 30% of their strength according to Wang's equation and 4% according to Nadjai's equation. However, the effect of the matrix was not taken into account in the equations. Since the glass transition temperature is different for each matrix, the changes in strength also differ. While no significant change is observed in FRP bars until the glass transition temperature, the matrix deteriorates after this temperature, leaving the fibers bare. In this case, the external forces cannot be distributed to the fibers, and the bars lose their load-bearing properties. In different studies in the literature, it has been seen that more than 20% strength losses occur in GFRP bars at 250 ℃, and that GFRP bars that reach 400 ℃ lose about 80% of their strength (Hajiloo, Green, and Gales 2018; Kumahara et al. 1993).

In the literature, while significant effects on the tensile properties of bare steel bar after 600 °C were observed, this critical limit for bare GFRP bars was determined to be 300 °C (Özkal et al., 2018). In another study, (Ellis et al., 2018) GFRP bar was found to maintain 83% of its original tensile strength after being heated to 400 °C and cooled to ambient temperature. In addition, concrete-bar adhesion deteriorates significantly with temperature. Most of the reduction in GFRP-concrete interaction was above Tg for ribbed bar and below Tg for sand-coated bar (Rosa et al., 2019, 2021). It is stated in the study (Mouritz & Arthur, 2007) that the mechanical and bonding properties of GFRP bar deteriorate at high temperatures, especially those close to the glass transition temperature of the polymeric matrix (typically between 65 °C and 150 °C). Because the FRP bars are thermoset resin, difficulties in homogeneous production, and not an isotropic material like steel bar, it is necessary to be careful when using these materials as reinforcement in structural elements in reinforced concrete. It should not be forgotten that the concrete cover effect is very important in reaching the glass transition temperature limit of FRPs under the influence of fire or temperature.

4. Conclusions and comments

The results of the experimental research on the effect of concrete cover thickness and concrete strength on heat transfer in structural elements with FRP bar under high-temperature effect are summarized below:

1. In low-strength concrete specimens with a compressive strength of 26 MPa, FRP bars in concrete reached the critical Tg temperature in 24, 40, 54 minutes for 20, 40, 60 mm concrete cover thicknesses, respectively. Therefore, 40 mm concrete cover thickness saves 67% and 60 mm concrete cover thickness saves 125% more time compared to 20 mm concrete cover thickness
2. In specimens with a strength of 39 MPa, FRP bars with 20, 40 and 60 mm concrete cover thicknesses reached the critical temperature in 29, 44, and 59 minutes, respectively. In terms of critical temperature time, 40 mm and 60 mm concrete covers save 52% and 103% more time than 20 mm concrete covers.
3. The specimens with the highest compressive strength, with an average compressive strength of 52 MPa, reached the critical temperature in 30, 49, and 64 minutes for 20, 40 and 60 mm concrete covers, respectively. Increasing concrete cover thicknesses reached the critical temperature in 63% more time for 40 mm and 113% more time for 60 mm concrete cover compared to 20 mm concrete covers.
4. In terms of protecting the bar against temperature, the increase in the thickness of the concrete cover significantly delays the bar from reaching the critical temperature. Experimental studies have revealed that the change in concrete strength class has a limited effect. The time difference between low and high concrete strength classes at 20, 40 and 60 mm concrete cover thickness is around 20% proportionally.
5. Compared to steel reinforced concrete structural elements, the concrete cover thickness should be increased in structures where FRP bars are used. These polymer matrix reinforcements are more affected by high temperatures due to the low critical temperature Tg (115 °C) at which they lose most of their mechanical strength. As a result of this study, 60 mm concrete cover thickness is recommended because it increases the time to reach the critical temperature by more than 2 times compared to 20 mm concrete cover thickness.

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