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Numerical Study of Fiber Reinforced Polymer Reinforced Normal Strength Concrete (FRPNSC) under Hydrocarbon Fire

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Abstract. Main safety requirements in concrete structural are the fire resistance requirements. One of the structural components is Fiber Reinforced Polymer Reinforced Normal Strength Concrete (FRPNSC). FRP reinforcement has been used as the replacement for conventional steel due to anti-corrosion and lightweight characteristics. Severe degradation on chemical bond properties for FRP will be effected when the temperature is rises. It is important to understand the minimum concrete cover thickness and concrete aggregates types to achieve fire resistance requirements. Standard fire equations are commonly used for fire simulations study. However, studies with hydrocarbon (HC) fire equations which fire ignited from petrochemical are limited. Therefore, in order to study the fire resistance of FRPNSC under hydrocarbon fire, temperature at the reinforcement needs to be predicted. In this study, explicit finite difference method (EFDM) used to solve the heat transfer model. The numerical algorithm of EFDM heat transfer model was constructed and used to analyse the concrete thickness and aggregates to achieve fire resistance requirement. The temperature result obtained by the EFDM model successfully validated with test data. FRPNSC under HC for carbonate aggregates give significant effect on the fire resistance compared to standard fire. The carbonate aggregates types also shows better fire performances compared to lightweight aggregates.

1. Introduction

Concrete is the major materials used for building structures. Its advantages compared to among other building materials are on fire-resistive properties. However, concrete structures must still need to be designed for fire effects. The design should consider the structural components which must be able to withstand dead and live loads without collapse even though the rise in temperature causes a decrease in the strength and modulus of elasticity for concrete [1]. Normal Strength Concrete (NSC) was used widely in building constructions. The conventional concrete mixture, NSC types used in reinforcement is classified into three different types, which is carbonate, lightweight and siliceous aggregate. Carbonate aggregate types have been reported as intermediate range in fire resistance performance, while lower performance on fire resistance has been specified to siliceous and lightweight aggregate due to their heat thermal properties [2].

The concrete structure that reinforced by FRP called as FRP reinforced normal strength concrete (FRPNSC). FRP composites are made by incorporating two or more materials into one with the intent of suppressing undesirable properties by fabricated a polymer matrix, for example epoxy, vinyl ester, or polyester and reinforced with various types of carbon, glass, and/or aramid fibers [3]. The application



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of FRP reinforcement in concrete replace the traditional steel reinforcement become interesting in civil engineering members [4]. The advantages of FRP over steel such as strength, anti-corrosion, and durables have shown better integrity on concrete strength. FRP reinforcement also has enhanced the flexural and shear capacity of the concrete structure. In term of cost, FRP has better values compared to steel, then increase the reliability of FRP reinforcement in civil engineering applications [5]. Similar to other building structures, FRP reinforced structural members should also design materials to fulfill the fire resistance requirements and structural requirements based on building codes [6]. The major issue concern is about the weakness of FRP deal with high temperature. The glass transitions temperature (T_g) for FRP within 65°C-82°C where the FRP begin to change its properties such as bond degradation. The polymer resin will be soft and rubbery after the temperature exceeds the glass transition temperature [7]. This will give the impact to concrete reinforcement and the stability of concrete.

In the fire resistance studies, the structural components which used to strengthen the concrete such as FRP also must be taken into account. Most of the fire performances studies applied the (American Society Testing Materials) ASTM standard fire as guidelines for the fire sources. The test procedure was performed by using ASTM fire are widely used among researchers in the world. The fire resistance for FRPNSC defined as where the materials able to withstand the temperature rising before it reach 250°C within 2 hours [8]. At this temperature, the material properties of FRP in the reinforcement reported will change and give a significant effect on the whole of concrete stability. Previous experimental study was successfully conducted by [9] to clarify the fire performance of FRPNSC slab under ASTM fire and provide fire resistance guidelines for one of Japan company, NEFCOM. Beside types of concrete, another factor such as types of fire also gives a significant effect on concrete during fire. For example, a fire which ignited by fuel, petroleum or chemical will produce hydrocarbon (HC) fire [10]. The temperature of HC fire increase over time is different compared to standard fire [11], thus the fire resistance performances also different.

In fire performances studies, temperature across concrete must be determined. However, it is difficult to measure the temperature across the concrete structure with various factors such as types of fire, concrete thickness and aggregate types of concrete [12]. Previous research for theoretical and experimental had been conducted to understand the fire resistance requirements for FRPNSC materials but the factors improve over years. Its time and cost problems to conducts multiple experiments.

In order to encounter these problems, the temperature across the concrete will be represented by heat transfer equations. The numerical method based on explicit finite difference method (EFDM) had been used to solve the heat transfer equation and predict the temperature across FRPNSC [2, 8, 13]. Thermal properties for NSC have been set up in EFDM models and was successfully produced the temperature across FRPNSC under standard fire. However, in the previous models, the authors did not consider HC fire as the source of temperature. The experimental studies for FRPNSC under HC fire are also limited in previous study since hard to simulate the real HC fire. In addition, the numerical study for the new FRPHSC also limited.

Therefore, the fire-resistance study for FRPNSC and FRPHSC under HC fire will be conducted. In this present study, 1D heat transfer equations will be used to represent the heat transfer across concrete slab during the fire. Explicit Finite Difference Method (EFDM) models will be used to solve 1D heat transfer equations to predict the temperature across FRPNSC thickness. The temperature result obtained from the models will be used to determine the required concrete thickness for FRPNSC achieved the fire resistance. Finally, the summary between types of fire and concrete thickness data will be used to provide the new fire resistance guidelines for FRPNSC.

2. Governing heat transfer equations

The heat transfer across concrete structure can be represented by the heat transfer equations. The following governing Equation (1) obtained by considering that the net rate of heat flow should be equal to the rate of internal energy increase. The heat flow was given by the Fourier law related to temperature gradients presented by [2],

$$\frac{\partial}{\partial x} \left(k \frac{\partial T}{\partial x} \right) + q = \rho C_p \frac{\partial T}{\partial t} \quad (1)$$

where k is the thermal conductivity of the concrete, T is the temperature, t is time, ρ is the material's density, C_p is the heat capacity and q is a term representing the heat generation within the material. The physical significance of the terms in Equation (1) presents the mathematical description of the conservation energy principles. On the left-hand side, the terms represent heat transfer into or out of the differential of plane due to heat conduction while on the right hand sides represent the energy stored generated by heat. The Equation (1) can be used by right simplification and boundary conditions to optimize the usage of heat transfer equations in this study. The contributions of heat transfer in internal reinforcing steel assumed to be minimal and neglected due to more portion of concrete than steel.

The change in energy was stored and represented as (ΔQ_{store}) in difference of time on the right hand-side of equation. At the element surface, the energy changes must be equal to the difference between the heats into the element. It is because the radiation process represented by heat generation (Q_{gen}) and the heat out of the element (Q_{cond}) caused by the conduction in the x-direction. The difference presented as,

$$\Delta Q_{store} = Q_{gen} + Q_{cond} \quad (2)$$

In Equation (2), the convection is ignored as one of mechanism for heat transfer from surrounding to the surface of slab. The convection contributes less than 10% for heat transfer at the surface of slab in standard fire endurance tests [14]. Therefore, it can be ignored for numerical fire modelling. The Equation (1) and Equation (2) can be described as,

$$\Delta Q_{store} = \rho C_p \frac{\partial T}{\partial t} \quad (3)$$

and can be rewrite as,

$$\Delta Q_{store} = \rho C_p \frac{\Delta T}{\Delta t} \quad (4)$$

where ΔT is the difference change in time interval Δt , ρC_p is the specific heat capacity of concrete (based on the aggregate types). For a differential across the element, the heat conduction equation, for x-direction by using the relation presented in Equation (5),

$$\Delta Q_{cond}^x = -kA \frac{\partial T}{\partial x} \quad (5)$$

Since the heat transfer problem is one-dimensional, the conduction carries out the heat from elementary layer of material per unit time is given by,

$$\Delta Q_{cond}^x = -kA \frac{\Delta T}{L} \quad (6)$$

where k is the thermal conductivity, surface area A and thickness L . The heat transferred into a surface element with surface area A , due to radiation can be approximated as follows

$$Q_{gen} = A \sigma \varepsilon_{surf} \left[(T_{surr} + 273)^4 - (T_{surf} + 273)^4 \right] \quad (7)$$

where σ is the constant of Stephan-Boltzman, ε_{surf} is the emissivity of the slab surface, T_{surr} is the surroundings temperature, and T_{surf} is the temperature surface being heated.

3. Numerical Method

3.1. Discretization Process for Time Derivatives

For the surface element, the time derivation in Equation (1) is discretized with finite difference scheme given in [8] for (ΔQ_{store}) presented as,

$$\Delta Q_{store} = \rho C_p \frac{[T_i^{j+1} - T_i^j]}{\Delta t} \quad (8)$$

where T_i^{j+1} is the temperature for the element of current time step and T_i^j is the temperature for the element of previous time step.

3.2. Discretization Process for Spatial Derivatives

From Equation (5), A is equal to 1 and the spatial derivatives which consider heat conduction along x -direction is as in [12] which given by

$$\Delta Q_{cond}^x = - \left[\frac{k_i^j + k_{i+1}^j}{2} \right] \left[\frac{T_i^j - T_{i+1}^j}{(\Delta x)^2} \right] \quad (9)$$

where T_{i+1}^j the temperature for elementary layer next to surface element at previous time step k_i^j , and k_{i+1}^j are the thermal conductivities of the surface and elementary layer next to surface at their previous time step respectively.

3.3. Initial Conditions, Boundary Conditions and Time Steps

Initial conditions provided in this study follow from the previous successful study [15], which is 20°C.

$$T(x, 0) = 20^\circ C \quad (10)$$

In this study, the temperature is in elevated situation, which will give different values of boundary conditions. Radiation from the fire, transfer the heat to boundary at room temperature. After several arrangements, two equations are obtained to predict the temperature at the boundary. For the boundary exposed by fire at $x = 0$, the formulation presented in Equation (11), where ε_n is the emissivity of concrete given by 0.9 and σ is Stefan Boltzmann constant given by $5.67 \times 10^{-8} \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-4}$.

$$T_i^{j+1} = T_i^j + \frac{2\sigma\varepsilon_n}{(\rho C_p)_i^j \Delta x} \left[(T_f^j + 273)^4 - (T_i^j + 273)^4 \right] \Delta t \quad (11)$$

$$- \frac{(k_1^j + k_2^j)}{(\rho C_p)_i^j (\Delta x)^2} (T_1^j - T_2^j) \Delta t$$

On the other side, FRPNSC has been exposed to air. The convective process between concrete and air situation at $x = m$ are imposed by the following equations

$$T_m^{j+1} = T_m^j + \frac{(k_{m-1}^j + k_m^j)}{(\rho C_p)_m^j (\Delta x)^2} \Delta t - \frac{2\sigma\varepsilon_n \left[(T_m^j + 273)^4 - (T_0^j + 273)^4 \right] \Delta t}{(\rho C_p)_m^j \Delta x} \quad (12)$$

$$+ \frac{\gamma (T_m^j - T_0^j)^{1.25}}{(\rho_n c_n)_m^j \Delta x}$$

where

$$\gamma = 3600(1.32) \left[\frac{(T_m^j - T_0)}{10.7} \right]^{0.25} \quad (13)$$

represents the coefficient of convective heat transfer between concrete to air. Both Equations (11) and (12) will be used to obtain the boundary temperatures by taking the ρC_p as the thermal capacity for concrete.

Common fire resistance study will use standard fire ASTM as the source of temperature. However, in different cases, this study consider the fire ignited by fuel, petroleum or chemical where hydrocarbon fire will be produced and increased over time [10]. In 2000, the hydrocarbon gas exploded and ignited the fire which destroyed the structure of British Petrol (BP) [16]. Therefore, the standard fire ASTM is not reliable to be applying for all situations. The application of HC fire curve has been presented as follows:

$$T_{hcf} = 20 + 1080 \times (1 - 0.325 \times e^{-0.167t} - 0.675 \times e^{-2.5t}) \quad (14)$$

where T_{hcf} is the temperature from HC fire and t time in hours. Therefore, the expression in Equations (14) will be used in this study.

4. Test problem

4.1. Validation of FRPNSC under ASTM fire

The validation process for this numerical model performed against experimental data has been done in our previous works [17]. The duration of fire follows the fire protection guidelines which is 2 hours protection [9]. 120 mm FRPNSC slab sample has been exposed to standard fire [11] for 120 minutes. Thermal properties relations for Carbonate aggregate have been applied in this model.

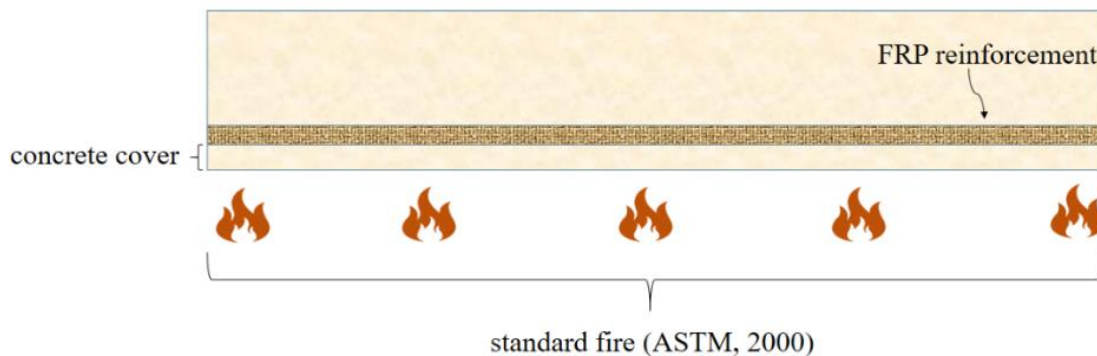


Figure 1. FRPNSC slab with carbonate aggregates under standard fire

The temperature predicted through the concrete thickness had been compared with the test data [9]. In order to avoid concrete spalling, the temperature will be simulated at minimum thickness of concrete.

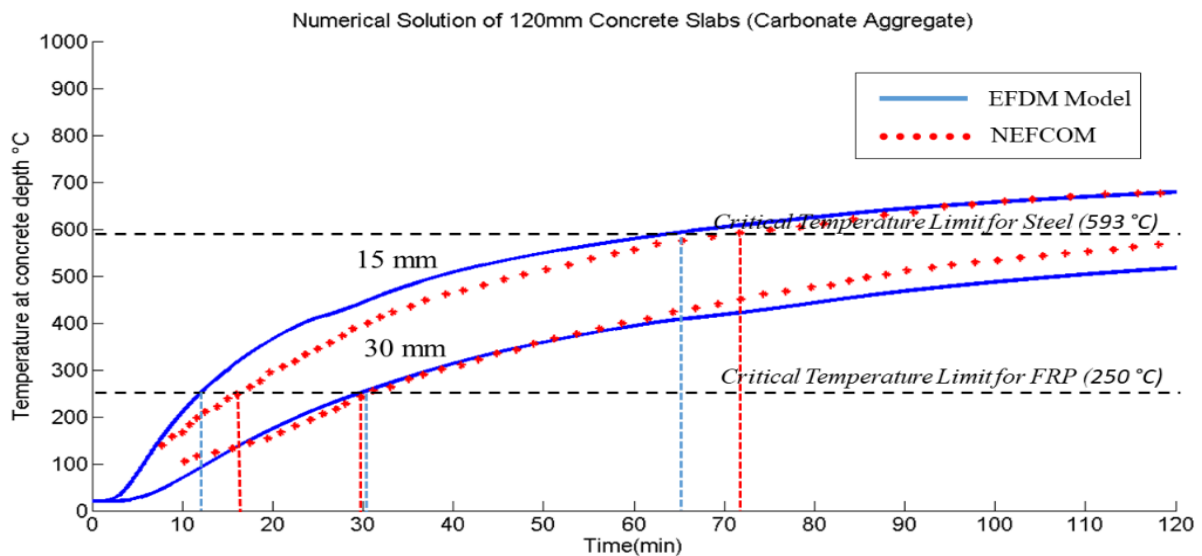


Figure 2. The validation of EFDM model against NEFCOM data (FRPNCS under Standard Fire)

From figure 2, small discrepancies between EFDM against NEFCOM data have been shown during 120 minutes of simulations. The critical temperature limit for FRP at 250 °C has been reached within 12.12 minutes and 29.732 minutes for 15 mm and 30 mm concrete cover thickness respectively. The percentage of errors at 250 °C are 24.72 % for 15 mm concrete cover thickness and 4.41 % for 30 mm concrete cover thickness. EFDM model has overestimated the temperature for 15 mm concrete cover thickness.

EFDM has predicted the material failure occurs at steel temperature limit, 593 °C in 64.97 minutes after heating for 15 mm concrete cover. While for 30 mm depth of concrete, the steel temperature limit does not even reach. It is because of the larger concrete cover thickness factors that delay the heat transfer across materials. A good agreement between numerical and test data through concrete cover thickness shown in figure 2. The validation was successfully conducted and EFDM model able to be used for further discussion. The investigations continue to predict the temperature for FRPNCS with carbonate and lightweight aggregate types under HC fire.

4.2. Simulation of FRPNCS under HC fire

The EFDM models has been used to predict the temperature of FRPNCS under HC fire. The results show that the carbonate aggregates types show poor fire performance under HC compare to the simulation under standard fire (figure 1). The poor fire performances causes by the excessive heat generation produce by HC fire compare to standard fire. 3 different depth of concrete applied; and show the critical temperature limit for FRP reach at 5.92, 19.84 and 42.72 minutes respectively.

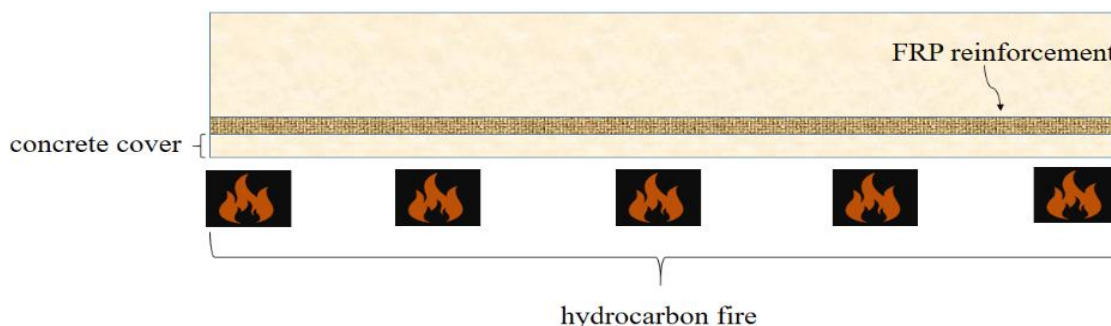


Figure 3. FRPNCS slab with carbonate aggregates under HC fire

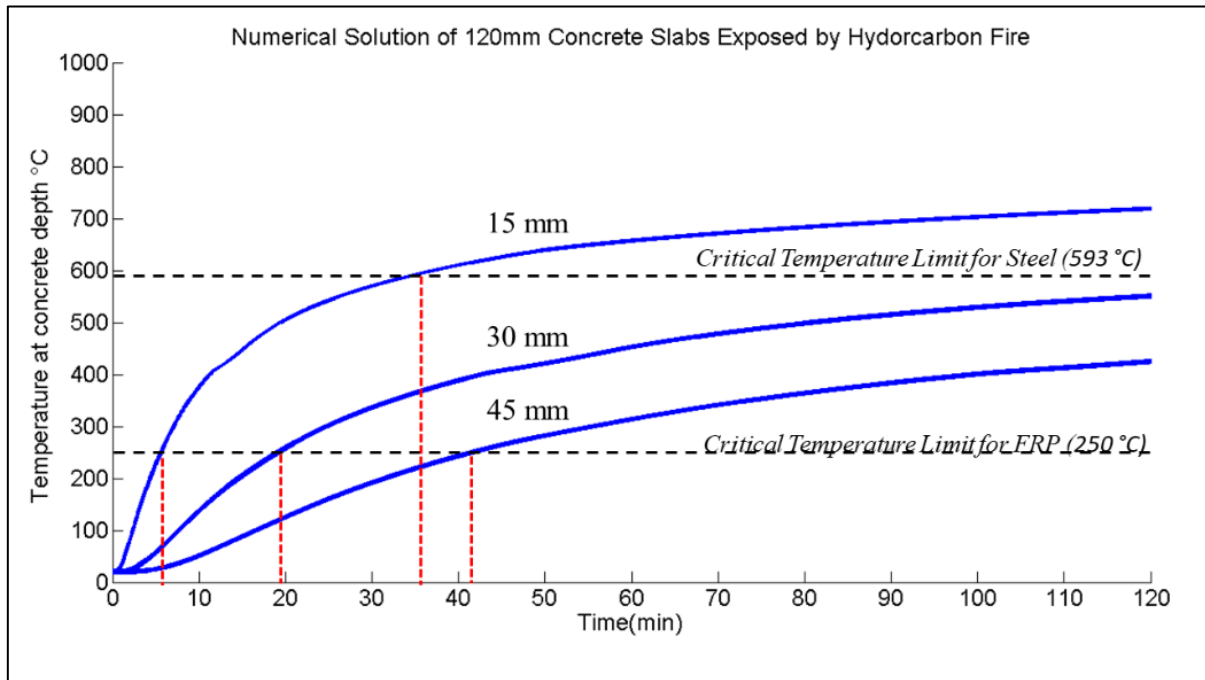


Figure 4. Temperature at concrete depth of FRPNSC under hydrocarbon fire (Carbonate aggregates)

For material failure at critical temperature of steel in 36.32 minutes for 15 mm, while for 30 mm and 45 mm concrete cover, the temperature does not reach within 120 minutes under the exposure of HC fire. Therefore, 30 mm concrete cover thickness is enough to protect the structural within 120 minutes under HC fire. Furthermore, EFDM also used to simulate the temperature for lightweight aggregates concrete slab.

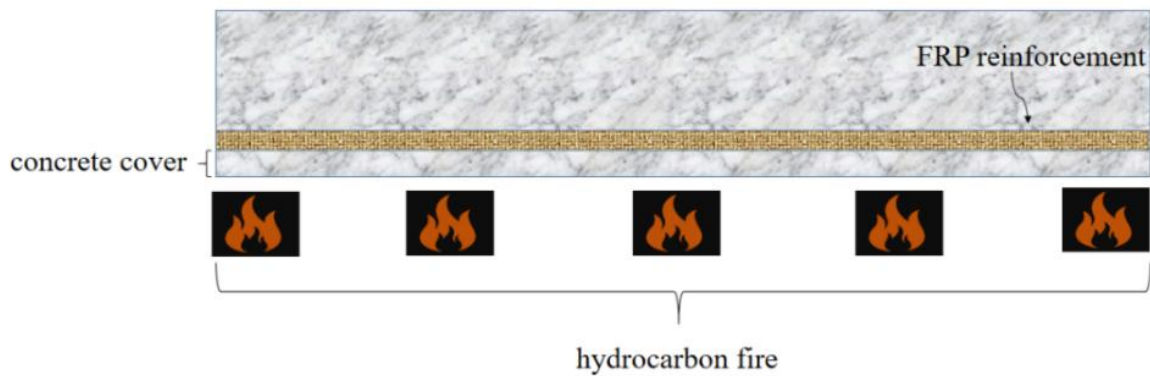


Figure 5. FRPNSC slab with carbonate aggregates under HC fire

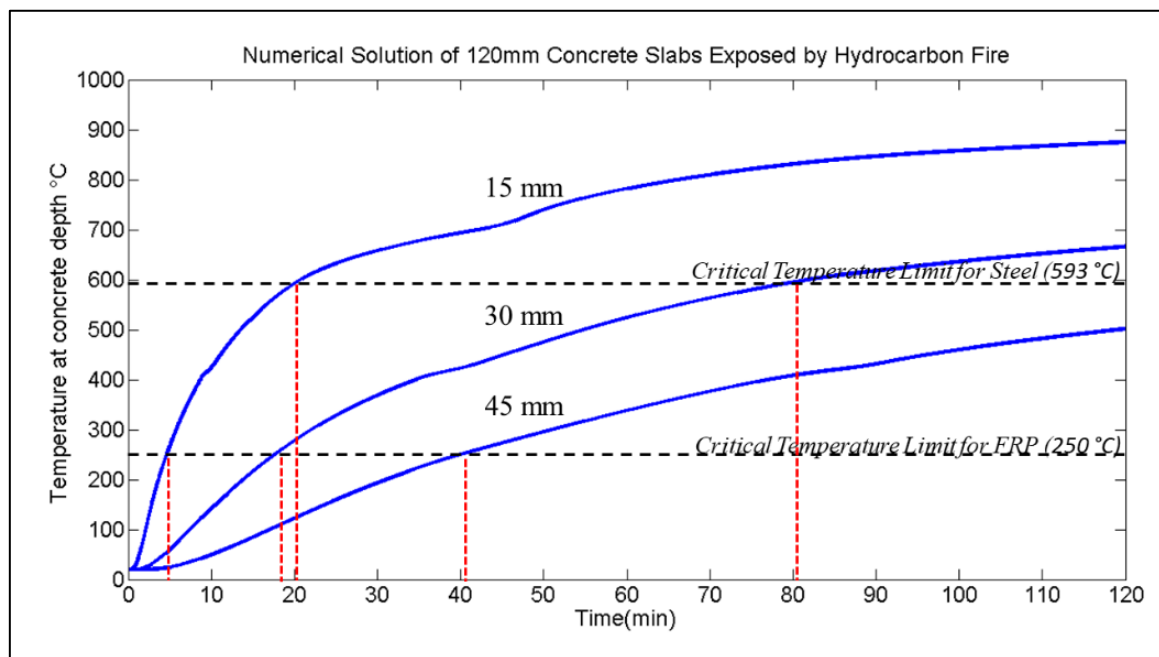


Figure 6. Temperature at concrete depth of FRPNSC under HC fire (Lightweight aggregates)

In figure 6 shows that, the FRP start to degrade at 15 mm, 30 mm and 45 mm within 4.80, 18.24 and 41.12 minutes respectively. The temperature increases rapidly across the concrete thickness.

From all concrete thickness presented, only 45 mm concrete cover thickness does not reach critical temperature of steel. Therefore, it can be determined as the minimum concrete cover thickness needed for lightweight aggregate of FRP RC exposed with HC fire.

5. Conclusion

In conclusion, the EFDM in this study has been successfully predicted the temperature across FRPNSC slab under both standard and HC fire. The temperature profile obtained from FRPNSC with carbonate aggregate show better fire performances compare to lightweight aggregate under HC fire conditions. The results also show the poor fire performances of concrete slab under HC due to excessive temperature produced compare to standard fire. Therefore, EFDM models developed can be further used in fire resistance study for FRP reinforced concrete study.

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