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Prediction of Concrete Thickness equivalent to Fire Protection Jackets

Yasmin Hefni and Yehia Abdel Zaher

Department of Structural Engineering, Faculty of Engineering, Ain Shams University
El Sarayat Street, Abbasia, Cairo

ABSTRACT: When concrete structures are exposed to elevated temperatures, concrete cover is considered as a protection layer for reinforcement bars. In some cases, an additional protection is needed to reduce rise o temperature at reinforcement location. Hence, choosing lower thermal conductivity concrete jackets will do the job. In this paper, a mathematical equation to estimate the equivalent thickness of concrete layer that gives the same thermal resistance of various fire protection materials is developed. In the analysis, the equivalent concrete thickness yields same time for the reinforcement bars to attain 500°C as the corresponding thermal protection layer when the structure is exposed to the standard ASTME119 fire rating curve. The analysis has been done with the aid of the finite element temperature analysis software Ansys.

1. INTRODUCTION

A good solution to strengthening old concrete structures is placing jackets around the structural elements. Jackets have been constructed using traditional or precast concrete, steel and FRP wrapping[1,2,3]. Despite concrete jacketing increases the size of the member significantly, it increases the stiffness, the load carrying capacity and the fire resistance.

The main role of improving fire resistance of structures by using concrete jackets is the thermal isolation of the reinforcement by the jacket thickness. Hence, selecting low thermal conductivity concrete jackets will increase the protection of the reinforcement against fire.

Very limited research has investigated the effect of insulation or coating on the fire performance of RC structures[4]. Wickstrom and Hadziselimovic[5] proposed an additional coating layer as an equivalent concrete layer for temperature analysis of insulated RC members after exposure to a standard fire regime. The approach they proposed is suitable only for high density coatings with a large thermal conductivity K (between 0.2 and 0.6 W/m.K). The structure in their study was exposed to the standard ISO 834 fire and the analysis was performed with FE temperature analysis computer program TASEF.

Finite element (FE) analysis by using Ansys is considered a good tool to predict the distribution of temperature and thermal stresses through RC concrete sections[6,7,8,9,10]. Using this FE software package, a regression analysis may be generated for a large amount of temperature data.

2. RESEARCH SIGNIFICANCE

The purpose of this study is to determin the equivalent thickness of concrete layer that gives the same thermal resistance of specific different fire protection materials. The output of this study will help in replacing the costly fire rating materials with a traditional concrete jacket of sufficient thickness to guarantee the protection of the steel reinforcement when the element is subjected to fire.

3. THEORETICAL BACKGROUND

Fourier's differential equation for heat conduction[12] is adopted in Ansys to describe the time-dependent temperature distribution in RC beam. In this equation, the distribution of temperature is described as follows:

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+Q=\varrho c\left(\frac{\partial T}{\partial t}\right)$$

Where: k, ϱ and c denote thermal conductivity, density and specific heat capacity, respectively; Q is the internal generation rate of heat per unit volume; and t is the time variable. The internal generation rate of heat in the analysis of heat of an RC beam exposed to fire is regardless (i.e., Q =0)[15]. Initial temperature distribution and proper boundary conditions are required to solve this differential equation. The initial distribution of temperature in the RC beam at t =0 is described by:

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$T(x,y,t)|_{t=0}=T_0(x,y)$

The free boundary conditions are applied to the top surface of beam specimens. Depiction of the heat fluxes exchange heat with the fire exposed surfaces of the RC beam via convection and radiation, may be described by Robin's boundary condition: [13,14, 15]

$$-k\frac{\partial T}{\partial n}=h_c(T-T_f)^4+\phi\,\varepsilon_m\varepsilon_f\,\sigma\,[(T-T_z)^4-(T_f-T_z)^4]$$

Where n represents the outward normal direction of the beam surface; h_c is the convective heat transfer coefficient; T_f denotes the fire temperature in degree Celsius; T_z is the absolute zero temperature and is equal to -273.15 ^{o}C; ϕ is a configuration parameter; ε_m and ε_f are the emissivity coefficients of the exposed surfaces and of the fire, respectively; and σ is the Stephan–Boltzmann constant. The values for these parameters and constants are recommended in EN 1991-1-2 (2002) as follows:

h_c = 25 or 9 W/(m^2.K) for exposed and unexposed surfaces, respectively; ϕ = 1.0; ε_m = 0.8; ε_f = 1.0; σ = 5.67X10^{-8} W/(m^2.K^4); T_0 (x, y) = 20 ^{o}C.

4. DEVELOPMENT OF TEMPERATURE DATA

4.1 Methodology

The distribution of temperature through a series of jacketed RC beams was obtained by validating FE Ansys software through a parametric study. The data obtained was later used in a regression analysis to derive a simplified predictive method for determining the fire effect on concrete beams. The reise of temperature was also used to evaluate concrete temperature degradation based on the simplified method EN 1992-1-2 2004 that depends on the "500 ^{o}C isotherm method". This method considers that the reinforcement at any location where the concrete exceeds 500 ^{o}C has almost lost its strength.

The thermal load considered in the study was generated by applying a temperature value of 1064^{o}C on the bottom and side surfaces of RC beams (According to ASTME119 fire rating curve after 3 hrs). In Ansys analysis type option, the thermal load was assigned in terms of small time incremental steps, each time step is concluded several smaller sub-steps that are solved using Newton-Raphson's technique. Also, automatic time stepping option is turned on to predict and control time step sizes. At each time (temperature) step end, convergence is achieved by Newton-Raphson's equilibrium iterations when the difference in temperature at each node from each iteration to another is lower than one degree.

In this study, thermal load is applied directly to the bottom and side surfaces of the developed FE model which means heat is transferred mainly by conduction [16,17,18]. This approach was examined to successfully verify an experimental study.[19]

4.2 Finite Element Type Used

FE type used in the analysis is 8-node element "PLANE77". It is a modified version of the 4-node, 2-D thermal element "PLANE55". This element has one degree of freedom, for temperature, at each node. The elements with 8-node are more suited to curved model boundaries since they possess compatible temperature shapes. Also, it is valid to the transient or steady-state 2-D or thermal analysis. Figure 1 shows PLANE77 geometry. [20]

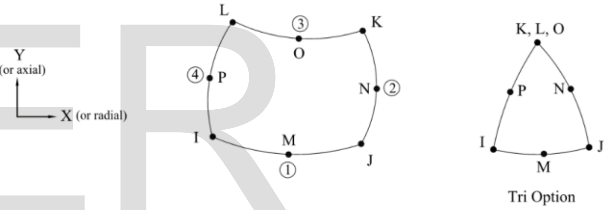

Figure 1: FE PLANE77 geometry [20]

4.3 Software Input Data

To obtain temperature data for different thermal properties, four categories of concrete are used to simulate four different insulation materials in the Ansys models. Table 1 shows thermal conductivity and density with temperature for the used types of concrete. Note that material 1properties in the table are equal to those of traditional concrete. The next rules are considered for the software input data:

- Thermal conductivity at 800 ^{o}C = 50% the thermal conductivity at 20^{o}C. [13,14]
- Thermal conductivity is constant after 800 ^{o}C. [11,21]
- Specific heat is constant for all concrete types at all temperatures. The specific heat =1.00 for materials (1,2) and 0.84 kJ/kg.K for materials (3,4) for simplicity. [9,11]
- Thermal conductivity of concrete is derived from the relation $k = 0.072\, e^{0.00125\rho}$ according to ACI 122R 02 but with changing the constant in the relation from 0.072 to 0.0865

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to provide for a 20% increase in k for air-dry concrete (Valore 1980).[22]

- Concrete density changes with temperature in EN1992-1-2: 2004 as follows:

For 20°C ≤ T ≤ 115°C:

ρ = Reference density "ρ_{20}"

For 115°C < T ≤ 200°C:

$\rho = \rho_{20}\,(1 - 0.02(T - 115)/85)$

For 200°C < T ≤ 400°C:

$\rho = \rho_{20}\,(0.98 - 0.03(T - 200)/200)$

For 400°C < T ≤ 1200°C

$\rho = \rho_{20}\,(0.95 - 0.07(T - 400)/800)$

Table 1: Thermal properties of the materials in the input data

Material No.	Tempe °C	Thermal Conductivity K (W/m.K)	ρ Density (kg/m³)
1	20	1.53	2300
	600	0.90	2140
	800	0.80	2100
	1100	0.80	2040
2	20	1.04	2000
	600	0.75	1865
	800	0.50	1830
	1100	0.50	1780
3	20	0.74	1720
	600	0.56	1600
	800	0.37	1570
	1100	0.37	1530
4	20	0.56	1500
	600	0.41	1400
	800	0.28	1373
	1100	0.28	1420

Temperature data generated by Ansys for jacketed beam models was used to help predict a simplified equation to estimate the traditional concrete thickness used in the original beam equivalent to that of jacket material with different thermal conductivity. The following procedure was followed to attain this objective:

- 2D Finite element models were constructed. A set of beams with cross section dimensions 60x60cm made of traditional concrete (material 1 in Table 1) were considered as original beams.
- Concrete jackets of thickness (t) equal to 2.0, 4.0 and 6.0 cm around the bottom and side surfaces of original beam were constructed using materials No. 2, 3 and 4 for all thicknesses.
- The three jacketed surfaces of the beams were exposed to constant temperature value T_f. equals 1064.11°C (According to ASTME119 fire rating curve after 3 hrs).

$$T_f = T_o + 750\,(1 - e^{-0.49\sqrt{t}}) + 22.0\sqrt{t}$$

- Relying on the "500 °C isotherm method", the time required for reaching a temperature value of 500°C at the reinforcement location (0.02m inside the original beam) for each jacket material type and thickness was determined.
- The equivalent thickness of jackets made of traditional concrete (material No. 1) d_e was evaluated to reach the 500°C at same location and time.
- One and two dimensional heat transfer were considered separately for each jacket type and thickness.
- The wide width of beams (60 cm) was chosen to study one dimensional heat transfer where the heat developed at the reinforcement position along the vertical midline was a result of exposure to fire from the bottom surface only.[15]
- The two dimensional case was studied by measuring the temperature at the corner of the beam cross section where it receives the heat from side and bottom surfaces of the beam[15]. Figure 2 shows one dimensional and two dimensional heat transfers.

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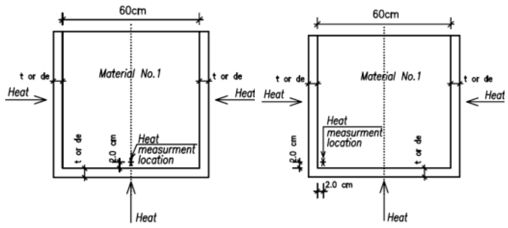
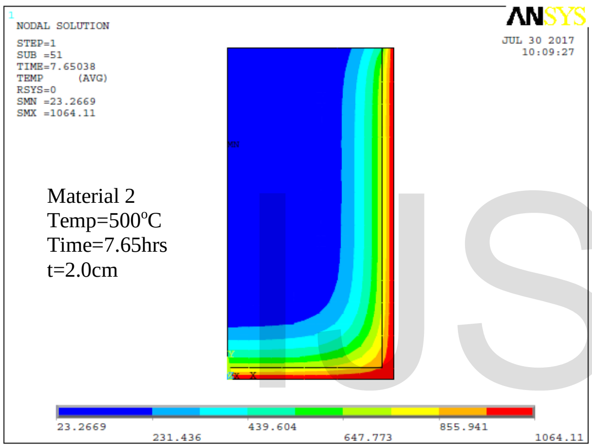


One dimensional **Two dimensional**

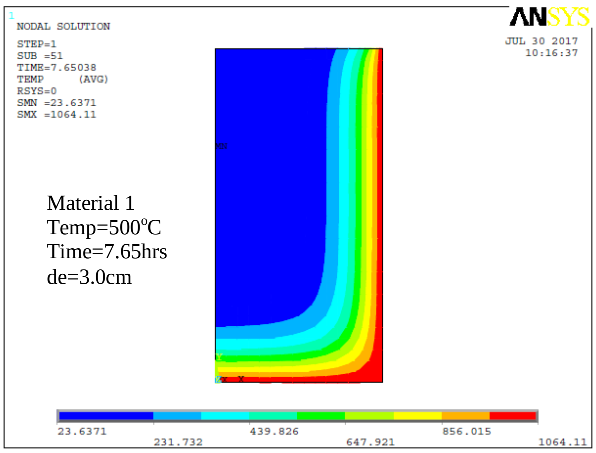
Figure 2: Measurement of temperature by one dimensional and two dimensional heat transfers

5 FORMATION OF THE SIMPLIFIED EQUATION

Model 1



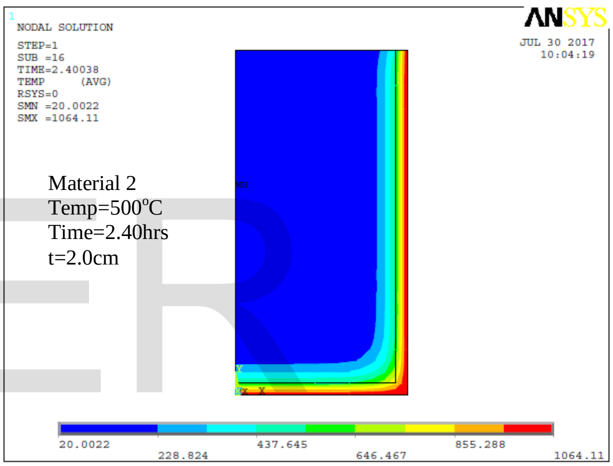
Model 2



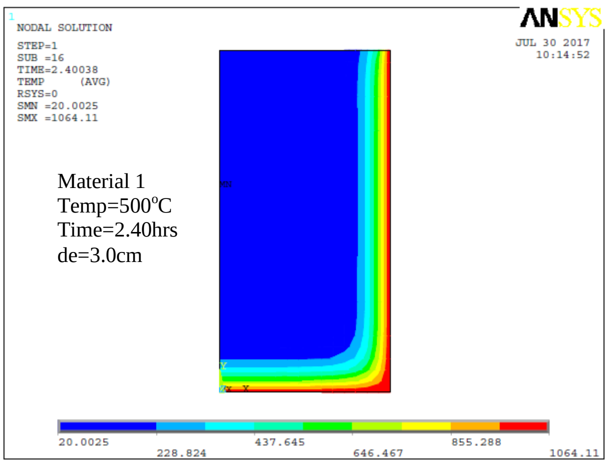
a. One Dimensional Heat Transfer

The output of the temperature data using the methodology illustrated in previous section is introduced as temperature survey for the jacketed beams cross section. Figures from 3 to 11 shows the temperature contours for the cross section of the jacketed beams made with materials 2, 3 and 4 with the corresponding contours of original beam cross section showing the equivalent thickness for all jacket materials. In each figure and for the two types of heat transfer, the equivalent thickness of traditional concrete de (the right contour) is obtained by allocating the position that has a temperature of 500 °C at a time similar to the temperature and time of corresponding isolation material (the left contour, i.e. 2, 3 or 4).

Model 1



Model 2



b. Two Dimensional Heat Transfer

Figure 3: Temperature contours for material 2 of jacket thickness 2.0cm

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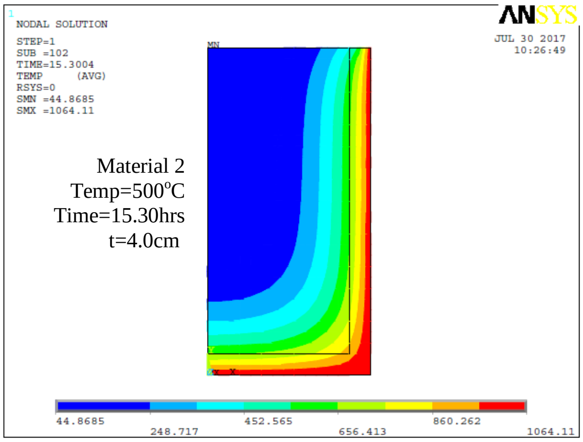
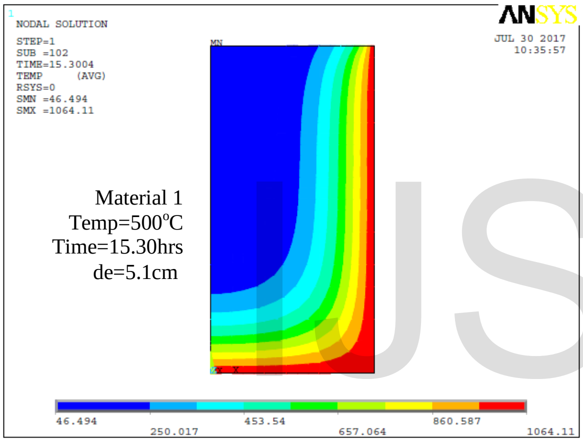
Model 3

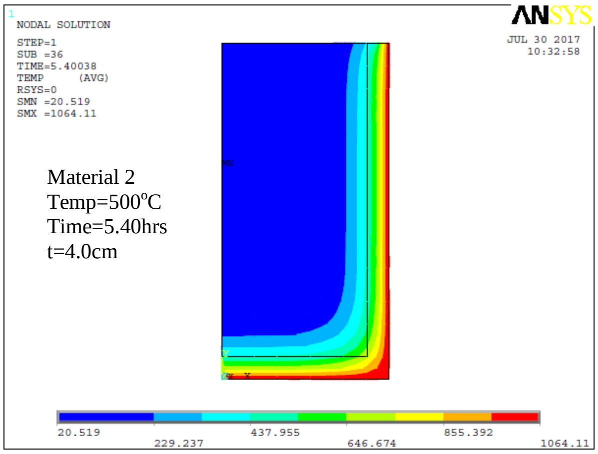


Model 4

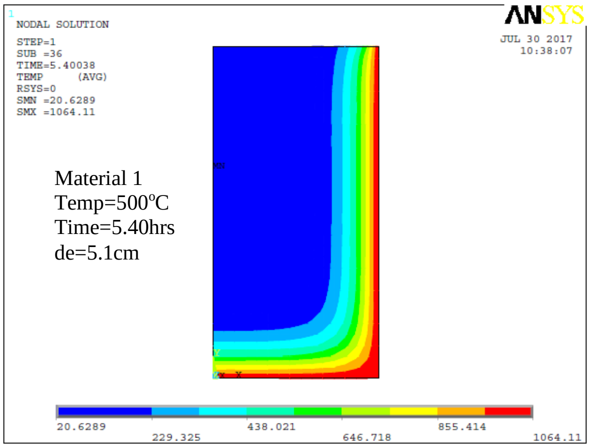


a. **One Dimensional Heat Transfer**

Model 3



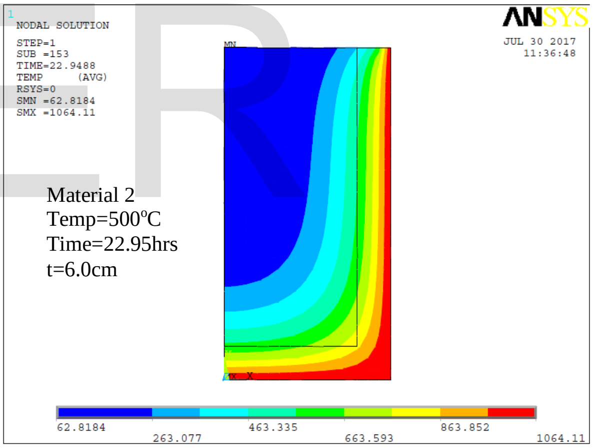
Model 4



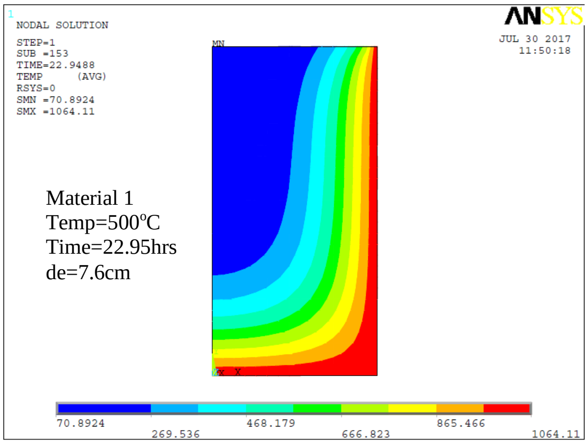
b. Two Dimensional Heat Transfer

Figure 4: Temperature contours for material 2 of jacket thickness 4.0cm

Model 5



Model 6



.a. One Dimensional Heat Transfer

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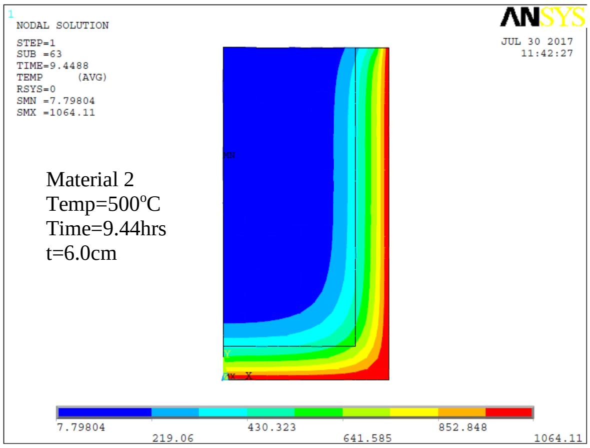
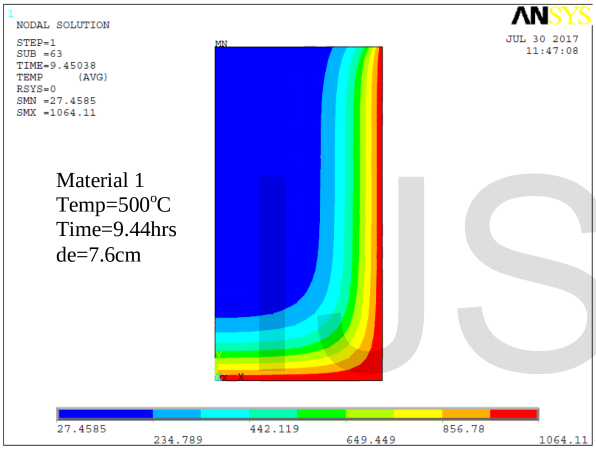
Model 5



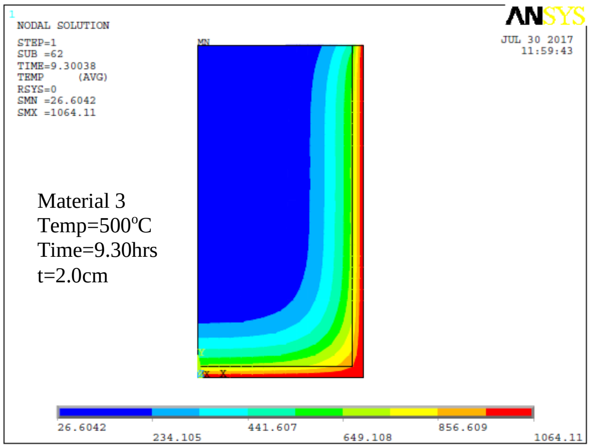
Model 6



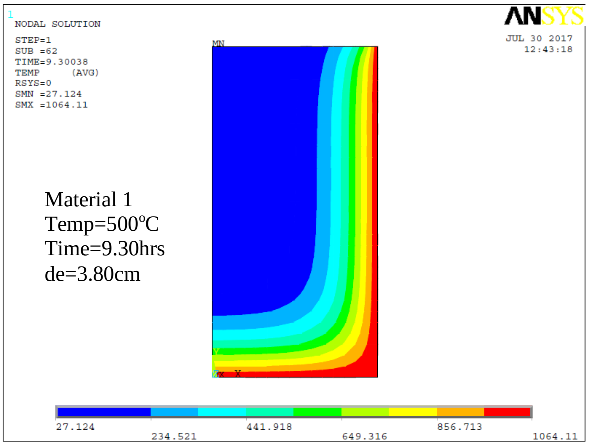
b. Two Dimensional Heat Transfer

Figure 5: Temperature contours for material 2 of jacket thickness 6.0cm

Model 7

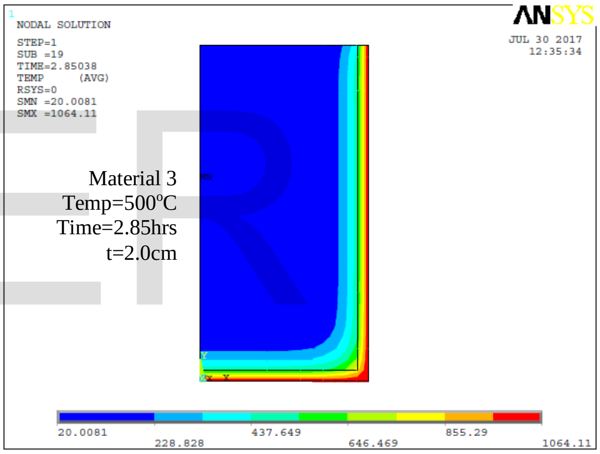


Model 8

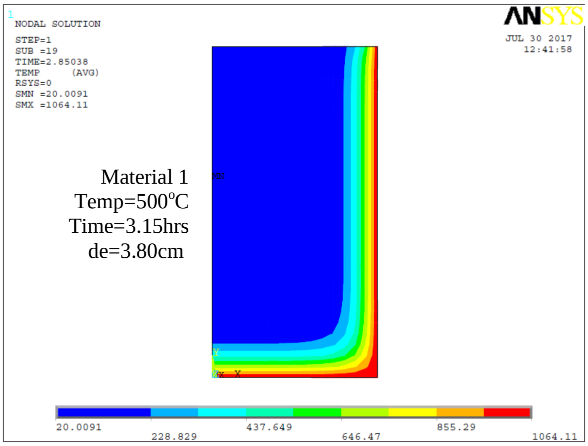


a. One Dimensional Heat Transfer

Model 7



Model 8



b. Two Dimensional Heat Transfer

Figure 6: Temperature contours for material 3 of jacket thickness 2.0cm

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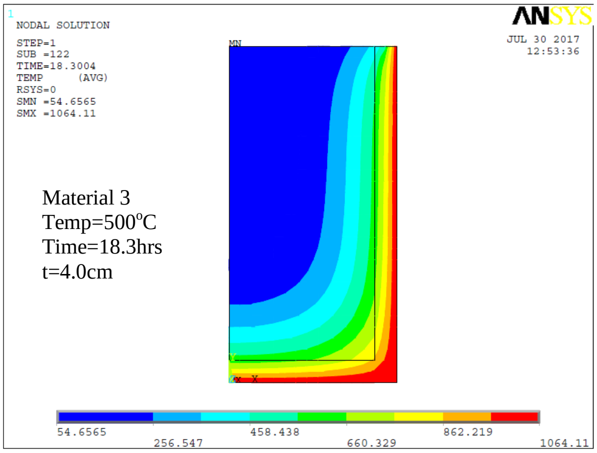
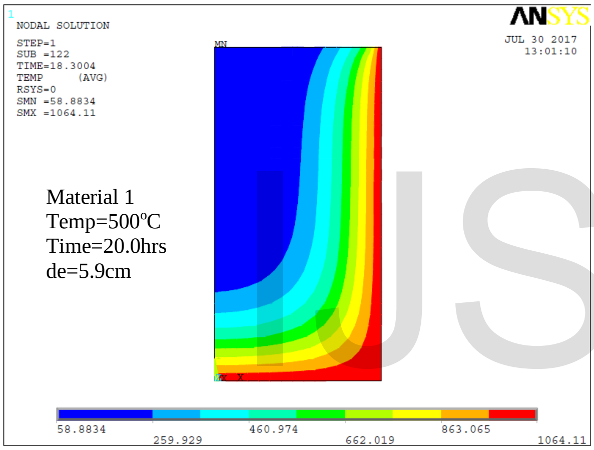
Model 9

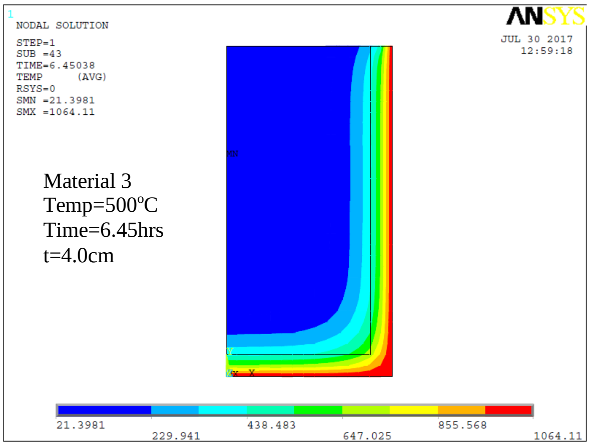


Model 10

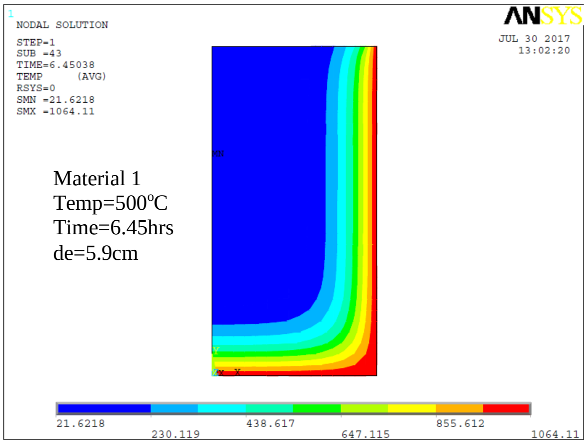


a. One Dimensional Heat Transfer

Model 9



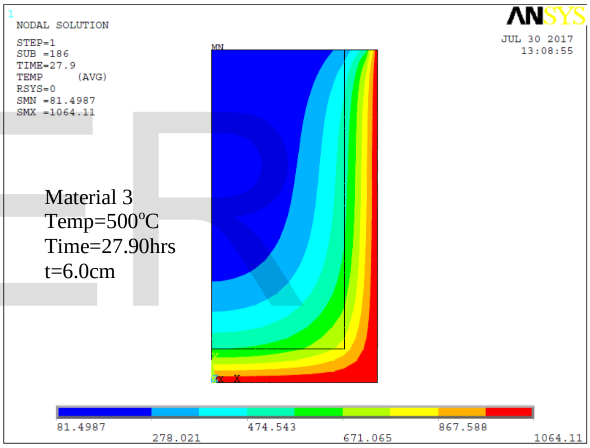
Model 10



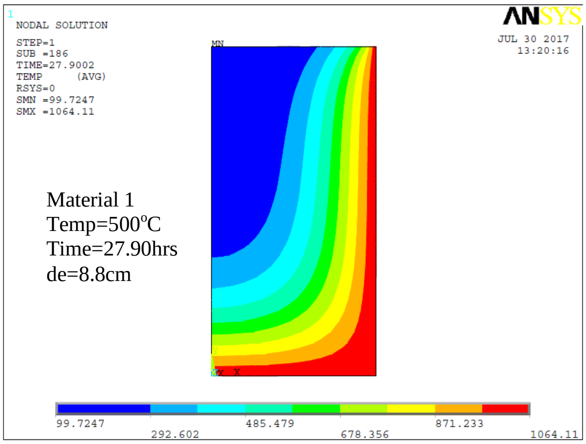
b. Two Dimensional Heat Transfer

Figure 7: Temperature contours for material 3 of jacket thickness 4.0cm

Model 11



Model 12



a. One Dimensional Heat Transfer

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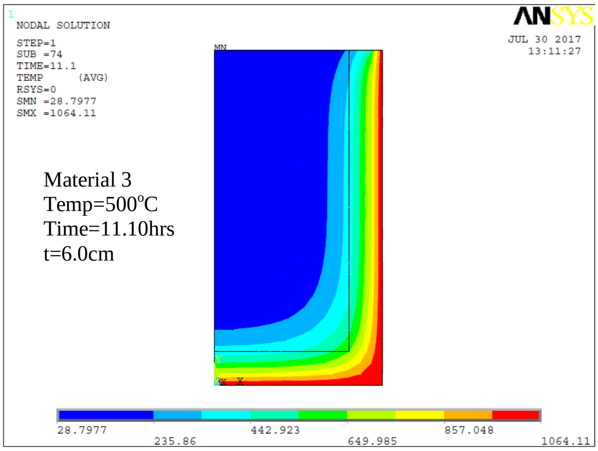
Model 11



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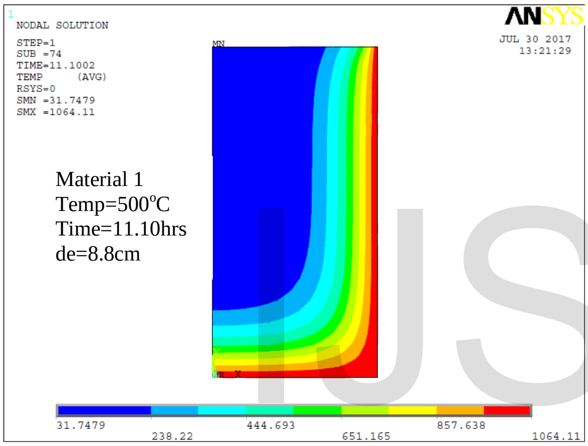
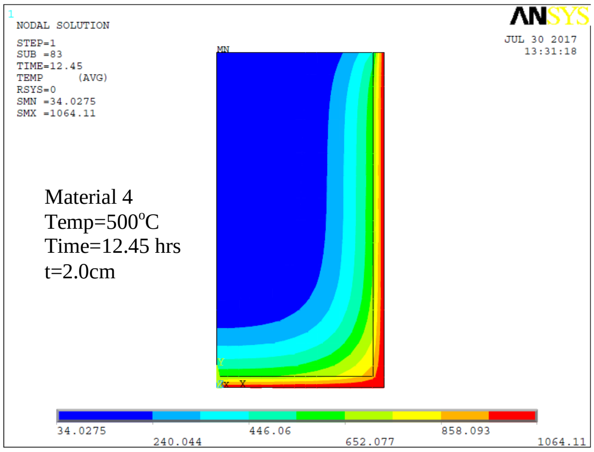


b. Two Dimensional Heat Transfer

Figure 8: Temperature contours for material 3 of jacket thickness 6.0cm

Model 13



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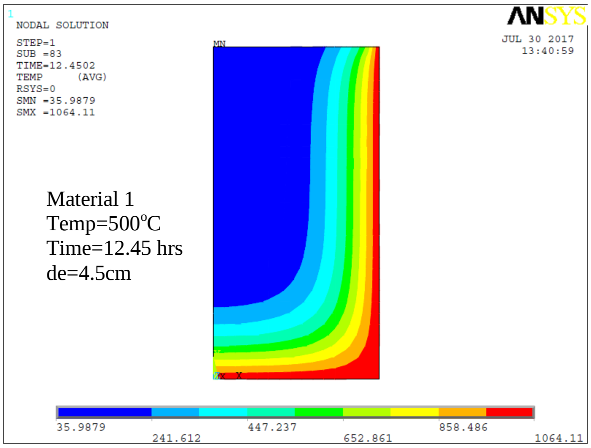
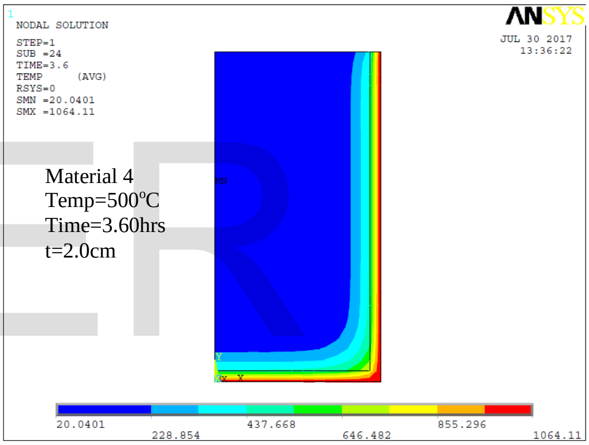


a. One Dimensional Heat Transfer

Model 13



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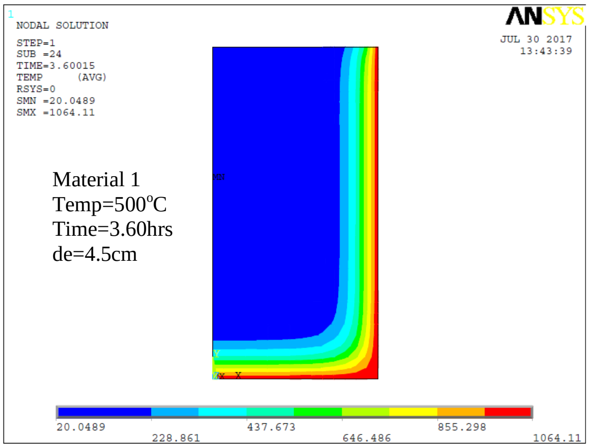
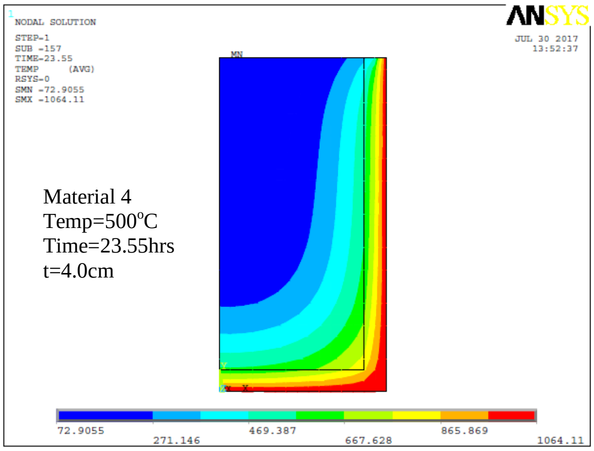


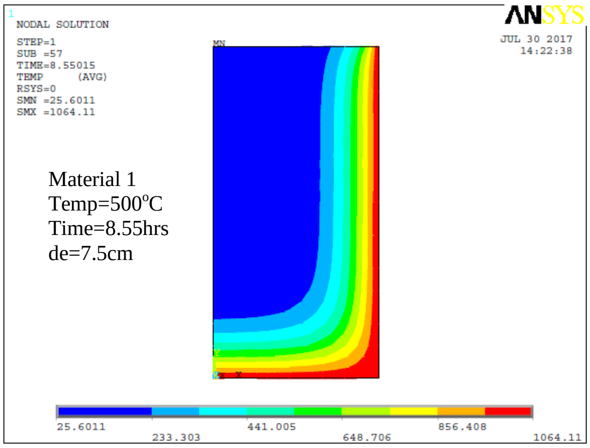
b. Two Dimensional Heat Transfer

Figure 9: Temperature contours for material 4 of jacket thickness 2.0cm

Model 15



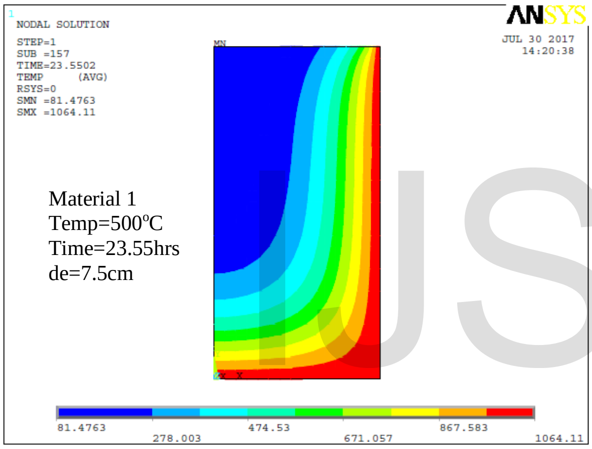
Model 16



b. Two Dimensional Heat Transfer

Figure 10: Temperature contours for material 4 of jacket thickness 4.0cm

Model 16



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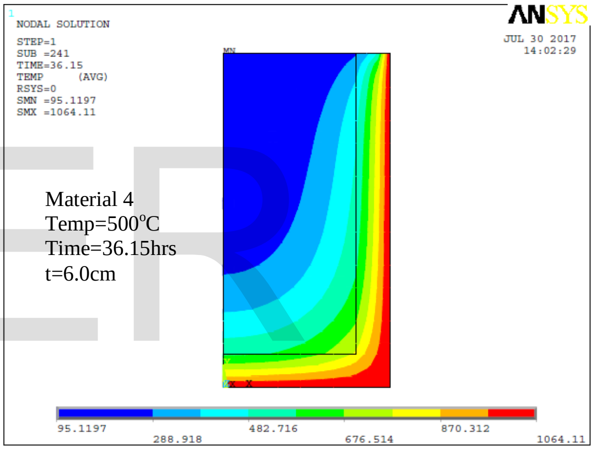
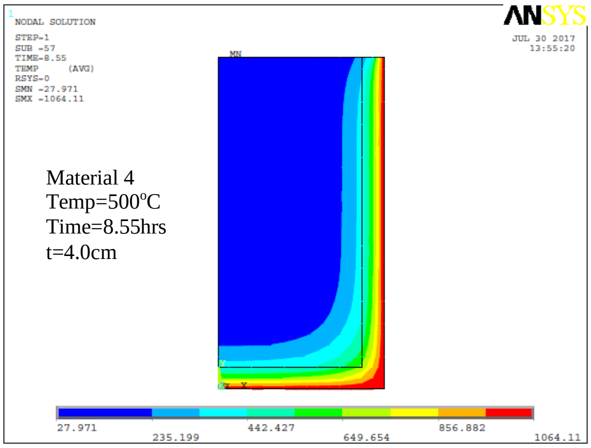


a. One Dimensional Heat Transfer

Model 15



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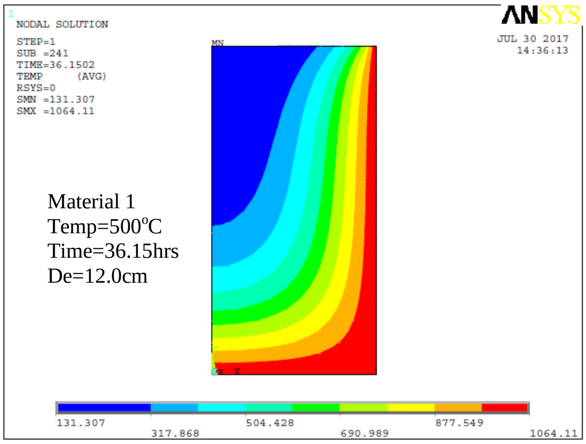
Model 18



a. One Dimensional Heat Transfer

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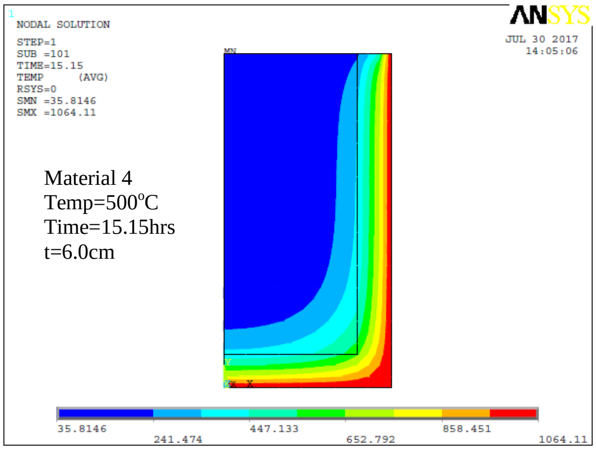
Model 17



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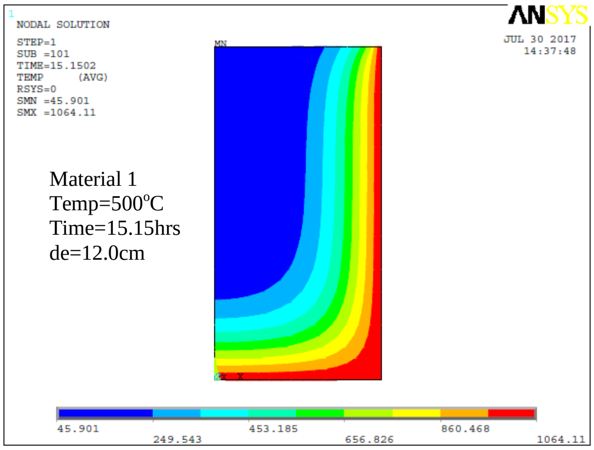

b. Two Dimensional Heat Transfer

Figure 11: Temperature contours for material 4 of jacket thickness 6.0cm

In the above figures, it is clear that the equivalent depth of traditional concrete (material 1) d_e needed to reach 500°C at a certain location is equal in the two cases of heat transfer for all jackets material type (i.e. 2, 3 or 4). But, the time needed to reach 500°C at a certain location is smaller for two dimension heat transfer when compared with one dimension heat transfer in all cases.

In addition, it is clear that required time to reach 500 °C for the same material type increased when the jacket thickness increased for the same material type. Also, this time increased when the thermal conductivity reduced for the same jacket thickness. This means that concrete sections with lower thermal conductivity and/or greater reinforcement cover thickness will sustain a longer time without failure when exposed to fire.

The values of thermal resistance of the jacket layer (R = t/K (m^2K/W)), where t denotes the jacket thickness, K is the thermal conductivity at 20 °C and the equivalent control material (material 1) thickness is summarized in Table 2 and plotted in Figure 12. In the figure, the x-axis represents the thermal properties of the three isolation materials considered in the study and the y-axis shows the equivalent thickness of the traditional control material.

Table 2: Summary of the output of temperature data

Material No.	$K_{at\ 20}$ (W/m.K)	t (m)	$R_{at\ 20}$ (t/K)	Equivalent de (m)
2	1.00	0.020	0.020	0.032
		0.040	0.040	0.051
		0.060	0.060	0.076
3	0.75	0.020	0.027	0.038
		0.040	0.053	0.059
		0.060	0.080	0.088
4	0.56	0.020	0.036	0.045
		0.040	0.071	0.075
		0.060	0.107	0.120

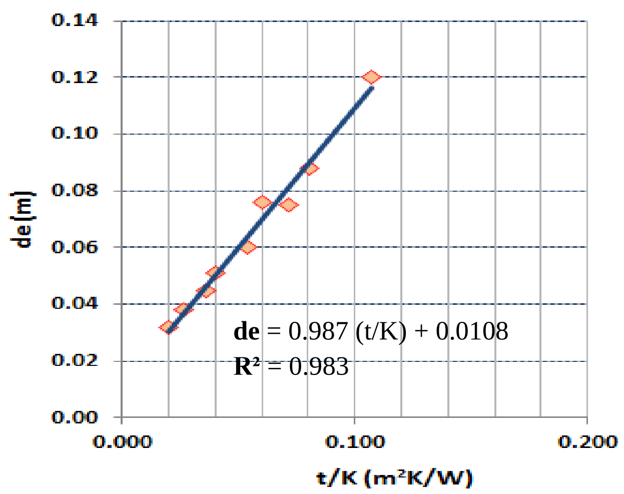

Figure 12: Relationship between the thermal resistance of isolation materials and the equivalent thickness de

The relationship in Figure 12 between thermal resistance of the protection layer (t/k) and equivalent concrete layer thickness d_e is approximately linear directly proportional, i.e when the thermal resistance increases the protection layer thickness increases. Therefore, materials with lower thermal resistance are preferred in fire isolation. The predicted equation representing the relation in Figure 12 is:

$$de = 0.987\ t/K + 0.0108 \quad \text{Where:}$$

$$0.56 \leq K \leq 1.00 \quad (W/\ mK)$$

$$0.020 \leq t \leq 0.060 \quad (m)$$

$$0.02 \leq t/K \leq 0.107 \quad (m^2K/W)$$

6. CONCLUSION

Based on numerical results obtained using Ansys validated finite element models, this paper concluded that:

1- The relationship between the thermal resistance of the protection layer (t/K) and the equivalent concrete layer thickness d_e when exposing the structure to the standard fire curve according to ASTME119 is linear.

2- The calculations showed that the relationship which was valid in the one-dimensional case can be used with the same constants for the two-dimensional condition as well.

3- The thermal protection layer by using concrete jackets of low thermal conductivity to a concrete structure can be expressed in terms of an equivalent traditional concrete layer.

4- The time required to reach 500 °C for the same material type increased when the jacket thickness increases and/or when the thermal conductivity reduces.

5- Concrete sections with lower thermal conductivity and/or greater reinforcement cover thickness will sustain a longer time without failure when exposed to fire

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