

TEMPERATURE DISTRIBUTION IN BI-MATERIAL SURFACE REINFORCED STRUCTURAL ELEMENTS

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ABSTRACT:

The temperature distribution in bi-material structural elements subjected to high-temperature impacts is examined. The elements are composed of a concrete core reinforced with a coating whose strength and temperature resistance are higher than those of concrete. The obtained results were compared with those of a non-reinforced concrete element. The problem statement is to find the external process temperature at which the boundary/concrete core temperature does not exceed the permissible value according to Eurocode. Results are shown for gluing and diffusion coating depositions. The temperature distribution was determined using the finite difference method.

KEY WORDS: Reinforced bi-material structural elements, temperature distribution, Finite Difference Method.

1 INTRODUCTION

In recent years, researchers have conducted numerous studies on cement and concrete composites exposed to high temperatures. The high temperature and fire response of concrete structural elements depend on the thermal and mechanical properties of concrete. They may vary significantly depending on the temperature, composition, and characteristics of the concrete mix, on the rate of heating, and on some environmental impacts. It is well known that high temperature seriously damages the structure of concrete, leading to its mechanical disintegration. Due to the great importance of the behaviour of concrete at high temperatures, many studies have paid attention to the temperature dependence of various parameters, such as the diffusion coefficient, compressive strength, modulus of elasticity, etc. [1].

In recent decades, technology has been developed to reinforce surfaces by gluing a reinforcing layer to the concrete bulk, alongside the introduction of reinforcement for structural elements and concrete body coatings. On the other hand, diffusive coating is also applied. However, results for concrete elements remain limited. We

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focus our attention on this technology on what follows. Various methods of surface protection for concrete structures are known to have different effects on thermal and mechanical properties and durability [2,3]. In construction, there is a strong interest in using two-material structural elements that are strengthened with coatings, which need to provide fire resistance, thermal insulation, and protection against corrosion and moisture. Yet, the choice of a reinforcing material resistant to high temperatures should consider the material's capability to stick to the concrete surface [4-7].

The advantage of surface reinforcement for a concrete structure is that it helps prevent deterioration and failure under high temperatures, thus extending the concrete's exploitation life. The test results on how concrete acts at high temperatures are shown in [8], considering how the type of aggregate affects the material's properties and the possibility of the material becoming thermally unstable (splitting). The authors test small specimens to determine the basic properties of concrete at high temperatures and its behavior under fire impacts.

Environmental issues of sustainable development of construction require the use of secondary raw and recyclable materials in the design and building of new structures. In [9], the thermal conductivity and thermal diffusivity coefficients of a concrete with natural coarse particles and recycled concrete aggregates are examined. It is demonstrated that the gradual reduction of thermal conductivity and the lowest thermal diffusivity are established in concrete with a higher concentration of recycled concrete aggregates. The results are compared to those in Eurocode [10].

Recently, the use of geopolymer concrete as an alternative to Portland cement has become increasingly important. Hence, one needs to investigate its possible application to building structures. Ref. [11] presents an overview of the actual usage of geopolymer concrete in various structures and related ecology issues. Ref. [12] outlines the major properties of concrete and discusses its fire-resistance. The paper also presents the temperature dependence of the thermal and mechanical properties of different types of concrete. Research [13] shows experimental findings on the physical, thermal, and mechanical properties of refractory concrete made from calcium aluminate and cement.

The tensile strength and modulus of elasticity of refractory concrete under different temperatures are determined by performing thermomechanical tests. The paper [14] talks about a temporary method to measure both the thermal conductivity and specific heat of self-compacting concrete at the same time. Concrete thermal properties are calculated using the Transient Plane Source (TPS) method. The authors of Ref. [15] present the main issues of strength calculation for steel-reinforced concrete buildings, steel structures, etc. that eventually undergo fire impacts. They propose a computational assessment of their behavior, fire protection design, and emergency diagnostics of constructions under high-temperature impacts.

The current study investigates the temperature distribution within surface-reinforced bi-material structural elements subjected to high-temperature impacts. The elements are composed of a concrete core reinforced with a coating whose strength and temperature resistance are higher than those of concrete. The selected coating is a geopolymer that can be applied to the concrete volume in two ways: by gluing and by diffusion, where a transition coating/core area occurs during the latter. The temperature distribution within the cross-section of the element using the finite difference method (FDM) is found and compared it to that of unreinforced concrete. The problem statement is to find the external process temperature at which the boundary/concrete core temperature does not exceed the permissible value according to Eurocode [10]. We introduce a novel approach by examining the temperature impact on surface-reinforced concrete structural elements, accounting for a smooth temperature change in the transition area between two materials.

2 STATEMENT OF THE THERMAL PROBLEM

A simple beam with a reinforcing coating applied to both sides, having known thermal and strength characteristics, is considered. The simple beam is subjected to temperature loading along its upper and lower sides with temperature θ_m (Figs. 1 and 2). The one-dimensional thermal problem is addressed.

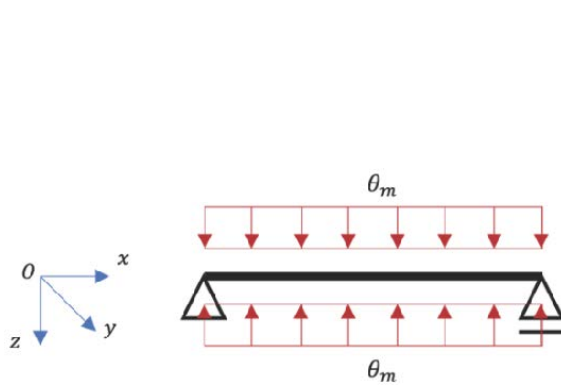


Fig. 1. Reinforced beam.

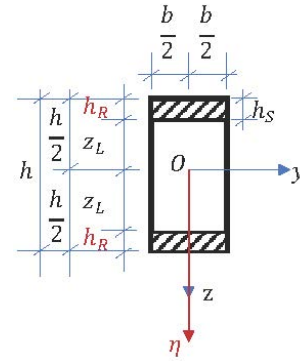


Fig. 2. The geometry of a cross-section of the beam.

Two methods of applying the coating are considered: case (i) involves gluing without diffusion, and case (ii) involves diffusion with the formation of a transition area. The temperature distribution in the cross-section of the structural elements using the finite difference method was calculated. Furthermore, a comparison of the outcome of both cases to the results for a surface unreinforced structural element was made.

Symbols in Fig. 1 and Fig. 2: l – beam length; b – beam width; h – beam height. For case (i): $\frac{h}{2} = h_S + z_L$ and for case (ii): $\frac{h}{2} = h_R + z_L$; $h_S = \text{const}$ – layer thickness, made of coating material and concrete. The thickness of the transition area is represented by h_R , which consists of material that has penetrated a concrete volume; A local coordinate system η is assumed for case (i) only. The thickness of the concrete core is z_L and the temperature θ_m is applied symmetrically and uniformly to both surfaces of the beam at level at $z = \pm \frac{h}{2}$. The initial temperature is denoted with θ_0 .

The thermal equation is expressed as follows:

$$(1) \quad \rho(\theta) c_T(\theta) \frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left[\lambda(\theta) \frac{\partial \theta}{\partial z} \right]$$

or

$$(2) \quad \rho[\theta(z, t)] c_T[\theta(z, t)] \frac{\partial \theta(z, t)}{\partial t} = \frac{\partial}{\partial z} \left[\lambda[\theta(z, t)] \frac{\partial \theta(z, t)}{\partial z} \right],$$

where $\theta = \theta(z, t)$ represents temperature, t denotes time, $\rho(\theta)$ indicates density, $c_T(\theta)$ stands for specific heat, and $\lambda(\theta)$ refers to thermal conductivity.

The equation is applied to the concrete core, reinforcing layer, and transition area, using their respective thermo-physical parameters ρ , c_T and λ , or with a coefficient of thermal diffusivity $\alpha[\theta(z, t)] = \frac{\lambda[\theta(z, t)]}{\rho[\theta(z, t)] c_T[\theta(z, t)]}$.

The boundary condition for temperature is $\theta_m = \theta(\pm \frac{h}{2}, t) \leq \theta_{pr}(t)$, where $\theta_{pr}(t)$ represents the process temperature.

Such non-linear problems can be solved with the finite element method. However, due to simple geometry, this research uses the finite difference method. This approach allows controlled linearization and has been effective in previous work for determining structural elements' load-bearing capacity [16].

3 SOLUTION OF THE PROBLEM WITH FDM

A discrete value Δz for the concrete core and coating along z or z_j with a specified n number of steps, $j = 1, 2, \dots, n$ is assumed. Additionally, a discrete value Δt of time t or t_k for m number of steps $k = 1, 2, \dots, m$. For one chosen step of incrementing values Δz and Δt , equation (2) takes the following form:

$$(3) \quad \rho[\theta(z_j, t_k)] c_T[\theta(z_j, t_k)] \frac{\theta(z_j, t_k) - \theta(z_j, t_{k-1})}{\Delta t} \\ = \frac{1}{\Delta z} \left\{ \lambda[\theta(z_{j+1}, t_k)] \frac{\theta(z_{j+1}, t_k) - \theta(z_j, t_k)}{\Delta z} - \lambda[\theta(z_j, t_k)] \frac{\theta(z_j, t_k) - \theta(z_{j-1}, t_k)}{\Delta z} \right\}.$$

Within a discrete interval, λ varies concerning z and t . To linearize equation (3), it is assumed that λ depends only on z_j and t_{k-1} , which are known. Thus, a double linearization for λ is performed as follows:

$$(4) \quad \lambda [\theta (z_{j+1}, t_k)] \approx \lambda [\theta (z_j, t_k)] \approx \lambda [\theta (z_j, t_{k-1})] .$$

Within a discrete interval, ρ and c_T vary only over time t . To linearize equation (3), it is assumed that they depend on z_j and t_{k-1} , which is known. In this scenario, the linearization takes the following form:

$$(5) \quad \begin{aligned} \rho [\theta (z_j, t_k)] &\approx \rho [\theta (z_j, t_{k-1})] \\ c_T [\theta (z_j, t_k)] &\approx c_T [\theta (z_j, t_{k-1})] . \end{aligned}$$

This linearization is valid when λ does not vary significantly in discrete intervals Δz and Δt . This imposes certain restrictions on the choice of the discrete intervals. Hence, the choice of these intervals must adhere to certain limitations according to the specific practical task.

The term “controlled linearization” is used to describe this process. Upon completing the linearization, equation (3) takes the following form:

$$(6) \quad \begin{aligned} &\rho [\theta (z_j, t_{k-1})] c_T [\theta (z_j, t_{k-1})] \frac{\theta (z_j, t_k) - \theta (z_j, t_{k-1})}{\Delta t} \\ &= \frac{1}{\Delta z^2} \left\{ \lambda [\theta (z_j, t_{k-1})] (\theta (z_{j+1}, t_k) - \theta (z_j, t_k)) \right. \\ &\quad \left. - \lambda [\theta (z_j, t_{k-1})] (\theta (z_j, t_k) - \theta (z_{j-1}, t_k)) \right\} . \end{aligned}$$

Equation (6) transforms into

$$(7) \quad \begin{aligned} \theta (z_j, t_k) - \theta (z_j, t_{k-1}) &= \frac{\Delta t}{\Delta z^2} \frac{\lambda [\theta (z_j, t_{k-1})]}{\rho [\theta (z_j, t_{k-1})] c_T [\theta (z_j, t_{k-1})]} \\ &\quad \times (\theta (z_{j+1}, t_k) - 2\theta (z_j, t_k) + \theta (z_{j-1}, t_k)) . \end{aligned}$$

The coefficient of thermal diffusivity, when considering linear discretization for various parameters λ , ρ or c_T is as following:

$$(8) \quad \alpha [\theta (z_j, t_{k-1})] = \frac{\lambda [\theta (z_j, t_{k-1})]}{\rho [\theta (z_j, t_{k-1})] c_T [\theta (z_j, t_{k-1})]} .$$

By substituting eq. (8) into equation (7) and transforming, we obtain

$$(9) \quad a_{j+1} \theta (z_{j+1}, t_k) + a_j \theta (z_j, t_k) + a_{j-1} \theta (z_{j-1}, t_k) = -\theta (z_j, t_{k-1}) ,$$

where

$$(10) \quad \begin{aligned} a_j &= - \left(\frac{2\Delta t}{\Delta z^2} \alpha [\theta(z_j, t_{k-1})] + 1 \right) = -(2a_{j+1} + 1) \\ a_{j+1} &= a_{j-1} = \frac{\Delta t}{\Delta z^2} \alpha [\theta(z_j, t_{k-1})] . \end{aligned}$$

3.1 CASE (I) – WITHOUT DIFFUSION

This scenario considers structural elements consisting of a concrete core surface reinforced by a layer with specific thickness h_S , composed of composite material and concrete. The composite is glued to the concrete core, creating a bi-material element, as shown in Fig. 2.

Equations (9) and (10) apply to both layers using their thermal diffusivity values.

For the reinforcing layer:

$$\alpha [\theta(z_j, t_{k-1})] = \alpha_R [\theta(z_j, t_{k-1})] \quad \text{for } j = 1, 2, \dots, f ,$$

where f is the final step of Δz from the layer at $k = 1, 2, \dots, m$; $\alpha_R [\theta(z_j, t_{k-1})]$ represents the thermal diffusion coefficient of the reinforcing substance.

For the concrete core:

$$\alpha [\theta(z_j, t_{k-1})] = \alpha_C [\theta(z_j, t_{k-1})] \quad \text{for } j = (f + 1), \dots, n ,$$

where $(f + 1)$ is the first step of Δz from the concrete core, at $k = 1, 2, \dots, m$; $\alpha_C [\theta(z_j, t_{k-1})]$ represents the thermal diffusion coefficient of the concrete.

3.2 CASE (II) – WITH DIFFUSION

This scenario considers structural elements consisting of a concrete core and surface reinforced by an insulating material applied through diffusion, forming a transition area. In this instance, the thickness of the transition zone, occurring during the material's penetration into concrete, is the thickness of the reinforcing material, denoted by h_R . In the transition area, a local coordinate system with an axis η , as shown in Fig. 2, is introduced as follows:

$$(11) \quad \begin{aligned} \eta &= \frac{z - z_L}{h_R} , \quad \eta \in [0, h_R] \\ \theta &= \theta(\eta_i, t_k) \end{aligned}$$

A discrete value $\Delta\eta = \Delta z/h_R$ is assumed for the transition area along axis η or η_j for n number of steps, $j = 1, 2, \dots, n$ and a discrete value Δt of time t or t_k , for m steps $k = 1, 2, \dots, m$.

For transition area eq. (9) and eq. (10) have the following form:

$$(12) \quad a'_{j+1}\theta(\eta_{j+1}, t_k) + a'_j\theta(\eta_j, t_k) + a'_{j-1}\theta(\eta_{j-1}, t_k) = -\theta(\eta_j, t_{k-1})$$

for

$$(13) \quad a'_j = - \left(\frac{2\Delta t}{h_R^2 \Delta \eta^2} \alpha^* [\theta(\eta_j, t_{k-1})] + 1 \right) = - (2a'_{j+1} + 1)$$

$$a'_{j+1} = a'_{j-1} = \frac{\Delta t}{h_R^2 \Delta \eta^2} \alpha^* [\theta(\eta_j, t_{k-1})]$$

$$(14) \quad \alpha^* [\theta(\eta_j, t_{k-1})] = \alpha_R [\theta(\eta_j, t_{k-1})] \left(1 - \sqrt{1 - \eta_j^2} \right) + \alpha_C [\theta(\eta_j, t_{k-1})] \left(\sqrt{1 - \eta_j^2} \right),$$

where $\alpha^* [\theta(\eta_j, t_{k-1})]$, $\alpha_R [\theta(\eta_j, t_{k-1})]$ and $\alpha_C [\theta(\eta_j, t_{k-1})]$ denote the generalized thermal diffusivity coefficient and the thermal diffusivity coefficients of the reinforcing substance and the concrete core, respectively.

For the concrete core:

$$\alpha^* [\theta(\eta_j, t_{k-1})] = \alpha_C [\theta(\eta_j, t_{k-1})] \quad \text{for } j = (f + 1), \dots, n,$$

where $(f + 1)$ is already the first step of Δz from the concrete core, $k = 1, 2, \dots, m$.

4 NUMERICAL RESULTS

The discrete values Δz introduced for the concrete core and layer, as well as for time Δt , are selected to ensure that the values ρ , c_T and λ do not vary significantly within the chosen discrete intervals. It was achieved by running a series of calculations and finding a slight change in the results (under 3%) for the required process temperature $\theta_{pr}(t)$.

4.1 SURFACE UNREINFORCED CONCRETE STRUCTURAL ELEMENT

The geometrical assumptions for ordinary concrete element are as follows:

$$(b \times h) = (0.20 \times 0.28); \quad z_L = h/2 = 0.14 \text{ m}; \quad \Delta z = 0.002 \text{ m}$$

$$\Delta t = 600 \text{ s (const)}; \quad \theta_0 = 20^\circ\text{C}; \quad j = 70 \text{ steps.}$$

Our goal is to find the process temperature, at which the critical temperature causing thermal degradation of concrete is attained at steps $j = 1$ and $k = 1$, i.e. $\theta(z_j, t_{k-1}) \approx 100^\circ\text{C}$.

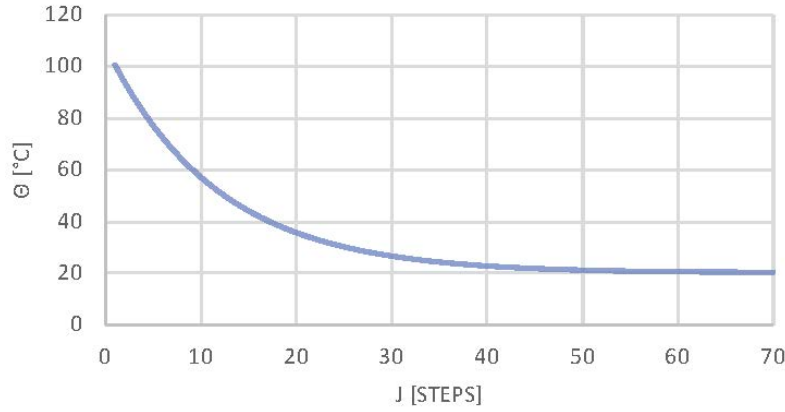


Fig. 3. The temperature distribution for a surface unreinforced ordinary concrete element.

Using the equations (9) and (10) the process temperature for ordinary concrete was calculated. The thermal diffusivity for concrete has been taken from [10] - $\alpha_c = 0.9 \times 10^{-6} \text{ m}^2/\text{s}$ for $\theta_0 = 20^\circ\text{C}$. The process temperature in this case is found to be $\theta_{pr}(t) = 108^\circ\text{C}$. At this process temperature, the temperature in the concrete reaches 100.75°C at step $j = 1$, Fig. 3.

4.2 A GEOPOLYMER-COATED REINFORCED CONCRETE ELEMENT

Regarding surface concrete element reinforcement, we examine two scenarios: (i) Geopolymer layer (without diffusion) and (ii) Geopolymer layer (with diffusion).

The geometry of both scenarios is as follows:

$$(b \times h) = (0.20 \times 0.30) \text{ m}; \quad h_S = h_R = 0.01 \text{ m}; \quad z_L = 0.14 \text{ m}; \\ \Delta z = \Delta \eta = 0.002 \text{ m}; \quad \Delta t = 600 \text{ s (const)}; \quad \theta_0 = 20^\circ\text{C}; \quad j = 75 \text{ steps}.$$

Our goal is to find the process temperature at which the critical temperature causes thermal degradation of concrete, $\theta(z_j, t_{k-1}) \approx 100^\circ\text{C}$, [10].

4.2.1 GEOPOLYMER-LAYERED REINFORCED CONCRETE ELEMENT WITHOUT TAKING DIFFUSION INTO CONSIDERATION

According to [4], the geopolymer layer's thermal diffusivity is assumed to be $\alpha_s = 0.57 \times 10^{-6} \text{ m}^2/\text{s}$. It is constant for the entire thickness of the layer h_S and does not change when the temperature changes over time, that is, we solve the problem without considering diffusion. The results are illustrated in Fig. 4.

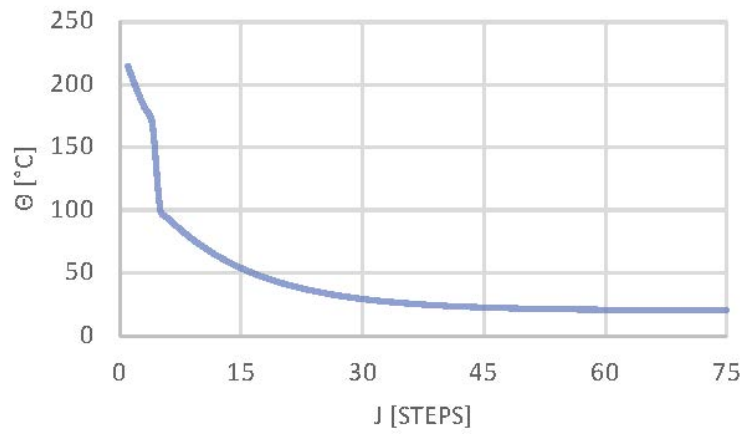


Fig. 4. The temperature distribution for a geopolymer-layered concrete element without considering diffusion – case (i).

4.2.2 CONCRETE ELEMENT REINFORCED WITH A GEOPOLYMER, CONSIDERING DIFFUSION

Thermal diffusivity of the geopolymer layer is taken from [4], but it is now assumed to be initial or valid only for step $j = 1$. On the other hand, the geopolymer layer is assumed to be a geopolymer liquid gradually diffusing into the concrete core and forming a transition area with thickness h_R .

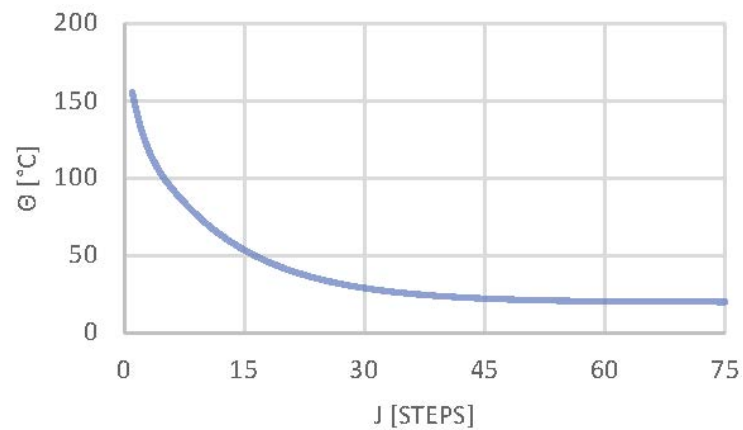


Fig. 5. The temperature distribution for a geopolymer-layered concrete element with considering diffusion – case (ii).

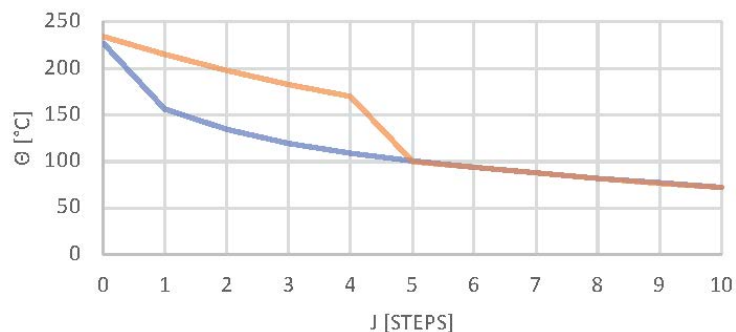


Fig. 6. A detailed view of the temperature distributions, highlighting the differences between the two situations.

Using equation (14), the generalized thermal diffusion coefficient $\alpha^* [\theta(\eta_j, t_{k-1})]$ was calculated for all steps, $j = 1, 2, \dots, f$ in the transition area. The results are illustrated in Fig. 5.

Figure 6 shows a detailed view of the temperature distributions, highlighting the differences between the two cases for $j = 0, 1, \dots, 10$.

For both cases the process temperature was found to be $\theta_{pr}(t) = 234^\circ\text{C}$ and $\theta_{pr}(t) = 227^\circ\text{C}$, respectively.

Figure 7 shows the temperature distribution in the cross-section of the structural element in terms of time without accounting for diffusion, before reaching the critical temperature for concrete $\theta(z_j, t_{k-1})$, [10]. Temperature $\theta_m = 170^\circ\text{C} < \theta_{pr}(t)$ or $\theta_m = 170^\circ\text{C} < 234^\circ\text{C}$ was chosen, and equations (8), (9) and (10) were used in this case. In the Wolfram Mathematica, macros were generated, and the problem was solved for as many k as needed to attain $\theta(z_j, t_{k-1}) \approx 100^\circ\text{C}$.

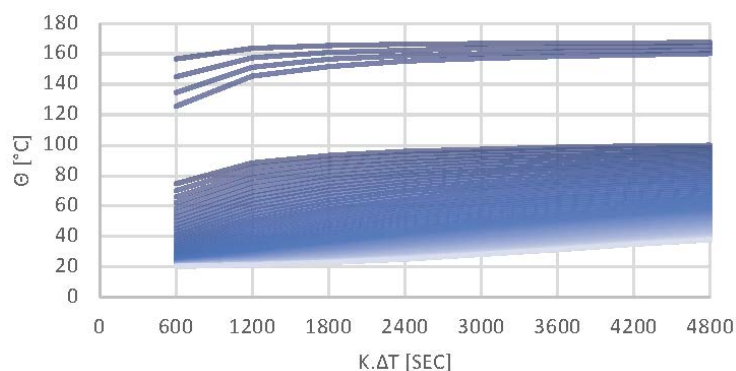


Fig. 7. The temperature distribution in the cross-section in terms of time – case (i).

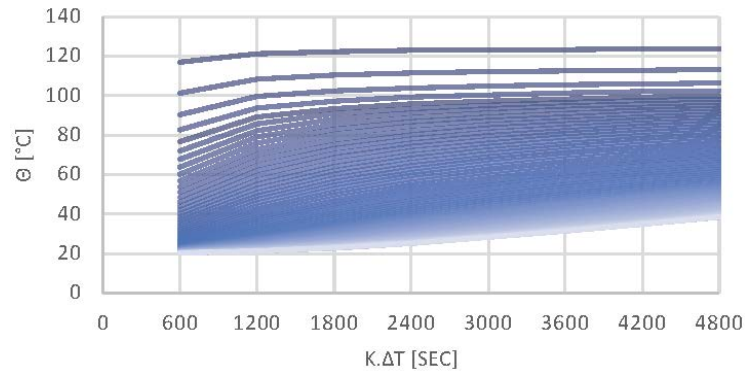


Fig. 8. The temperature distribution in the cross-section in terms of time – case (ii).

Figure 8 shows the temperature distribution in the cross-section of the structural element in terms of time accounting for diffusion. For this case the same temperature $\theta_m = 170^\circ\text{C} < \theta_{pr}(t)$ or $\theta_m = 170^\circ\text{C} < 227^\circ\text{C}$ was chosen.

5 CONCLUSION

The finite difference method was used to determine the temperature distribution in the cross-section of the bi-material surface-reinforced structural element and compare it to that in unreinforced concrete elements. It used a coating specifically designed for concrete with higher strength and thermal properties.

The authors consider the proposed research, together with the mathematical solution found, to be beneficial for engineering practice. The accuracy of the solution is very important when quickly checking how well a surface-reinforced structural element can handle high temperatures. Note that the coatings under consideration are relatively novel in civil engineering, while subsequent literature is scarce.

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