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Fire design of composite ribbed slabs

Projeto de lajes mistas nervuradas de concreto em incêndio


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Abstract

The Brazilian standards of structures in fire prescribe minimum dimensions for the ribbed slabs to ensure fire resistance. However, a new composite ribbed slab is not covered by any of the Brazilian standards in fire. The objective of this work is to present unpublished results from numerical and thermal analyses for this type of slab. Ribbed slabs filled with cell concrete blocks, ceramic bricks and EPS supported by cimentitious board were studied. The constructive element is considerate as thermal insulation if it has the capacity to prevent the occurrence, on the face non exposed to fire, temperature increments greater than 140 °C on the average or greater than 180 ºC at any point. The support function was determined limiting the temperature of the beams and slabs rebars to 500 ºC. The analyses were carried out with the ATERM and Super Tempcalc, software for two-dimensional thermal analysis by means of the finite element method. As a result, tables will be presented that link the fire resistance required time to slab dimensions and position of rebar. Prior to use in designing these results must be confirmed by experimental analysis, which is already being provided.

Keywords: fire, thermal analysis, ribbed slabs, waffled slabs, composite slabs.

Resumo

As normas brasileiras de estruturas em situação de incêndio fornecem dimensões mínimas para as lajes nervuradas para assegurar as funções corta fogo e de estabilidade estrutural. Porém, uma nova laje mista nervurada lançada no mercado brasileiro não é coberta por qualquer das normas brasileiras para a situação de incêndio. O objetivo deste trabalho é apresentar resultados inéditos, frutos de análises numéricas térmicas e estruturais para esse tipo de laje. Foram estudadas lajes com preenchimento de bloco de concreto celular, lajota cerâmica e EPS suportado por placa cimentícia. O sistema construtivo é considerado como isolante térmico se possuir a capacidade de impedir a ocorrência, na face que não está exposta ao incêndio, de incrementos de temperatura maiores que 140 °C na média dos pontos de medida ou maiores que 180 °C em qualquer ponto de medida. A função estrutural foi determinada admitindo a limitação da temperatura das armaduras de vigas e lajes em 500 ºC. As análises foram realizadas com auxílio dos programas ATERM e Super Tempcalc, programas computacionais para análise térmica bidimensional de transferência de calor, por meio do método dos elementos finitos. Como resultado, serão apresentadas tabelas que correlacionarão o TRRF (tempo requerido de resistência ao fogo) às dimensões da laje e posição das armaduras. Antes do uso em projeto, esses resultados deverão ser confirmados por análise experimental.

Palavras-chave: incêndio, análise térmica, laje nervurada, laje mista.

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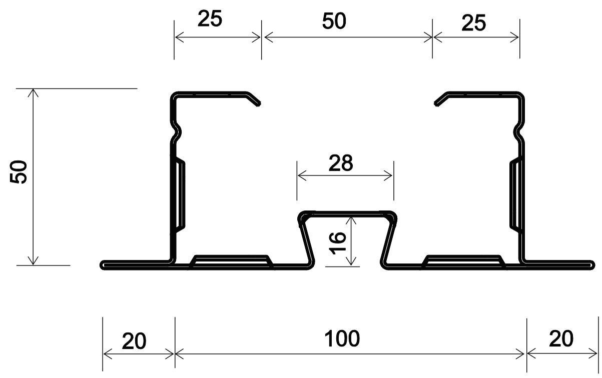
1. Introduction

ABNT NBR 14323:2013 Brazilian standard [1] presents recommendations for steel and concrete composite slabs in a fire situation. ABNT NBR 6118:2007 [2] defines the ribbed slabs and prescribes minimum dimensions for the rib section to waive the verification of flange bending. ABNT NBR 15200:2012 [3] provides minimum dimensions, by means of tables, to ensure fire resistance.
A new kind of steel and concrete composite slab has been released in the market. It is a ribbed slab, manufactured by Tuper, the steel formwork (Figure 1) of which is placed at the base of the rib (Figure 2), working as a formwork and a bottom reinforcement.
Due to the characteristics of this ribbed composite slab, none of the aforementioned standards covers its design in fire situation.
This work aims to investigate the behavior of these ribbed slabs at high temperatures, in order to analyze their thermal insulation, according to the procedure recommended by ABNT NBR 5628:2001 [4] and a fire resistance, based on the 500 °C limit temperature in the reinforcement [5], [6].
The slabs under study are filled with either ceramic tiles (Figure 3), cellular concrete blocks (Figure 4) or EPS on cementitious plates (Figure 5). This study assumes the perfect contact between the filler and the rib wall; hence, all the results should be experimentally confirmed. The advantage of performing a numerical analysis is that the behavior of a large number of alternatives can be previously foreseen, lowering the waste with experimental tests.

Figure 1 – Steel reinforcement (dimensions in mm)



$$\theta_g = \theta_0 + 345\log(8t+1) \quad (1)$$

2. Parameters adopted for the thermal analysis of slabs

2.1 Thermal action

The fire model used in the analysis was the standard fire (ISO-fire) (Equation 1)). According to [4] and [7], the coefficient of heat transfer by convection, α_c, was taken equal to 25 W/m² °C on the faces heated directly by the fire and the resulting emissivity ε_{res}, 0.7.
On the face not exposed to direct heat, a combination of convection and radiation was made, simulated by α_c = 9 W/m² °C. In Equation 1, θ_g is the gas temperature expressed in degrees Celsius (°C), θ_o is the room temperature equal to 20 °C and t is time in min.

2.2 Properties of materials

2.2.1 Concrete

In the thermal analysis of structures, knowledge of thermal properties such as density, thermal conductivity and specific heat is needed. These values vary with temperature and, for concrete, the formulation presented in ABNT NBR 15200:2012 [3] was adopted, and the density at room temperature was equal to 2400 kg/m³, as recommended by ABNT NBR 6118: 2007 [2]. The humidity adopted was equal to 1.5% by weight.

Figure 2 – Ribbed slab with steel reinforcement

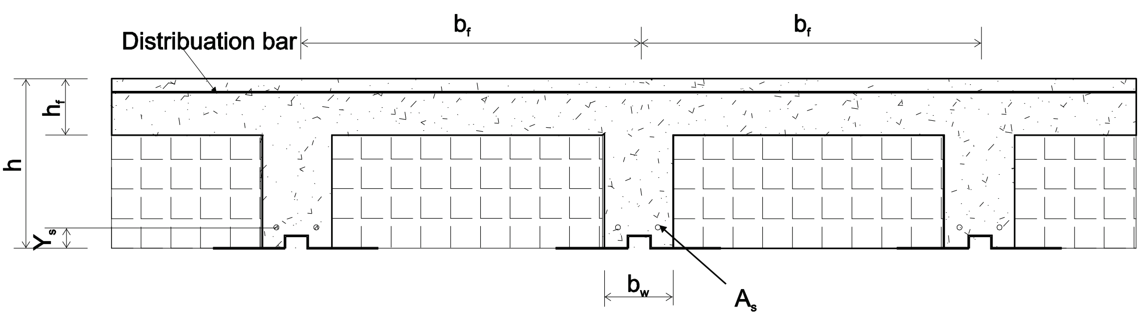
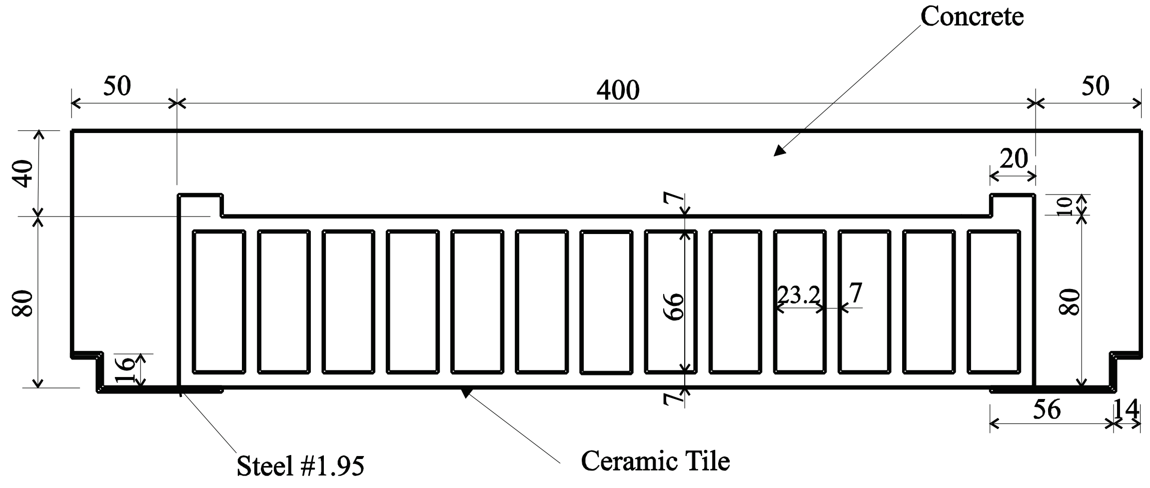


Figure 3 – Model with ceramic tile (dimensions in mm)



2.2.2 Steel

Properties were adopted as recommended by ABNT NBR 14323:2013 [1] and also presented in [6].

2.2.3 Ceramic tile

For ceramic tiles, there is no consensus on the values to be adopted for the properties needed for thermal analysis. Table 1 shows the values of the thermal properties taken from the literature. Where no tests are available, ABNT NBR 15220-2:2005 [8] indicates the properties of the ceramic tiles at room temperature, also shown in Table 1.

The thermal conductivity of the regular concrete decreases with temperature; thus, if it is supposed that the same occurs with the ceramic tile, the conductivity value at room temperature can be considered in favor of safety. Therefore, the highest thermal conductivity (1.05 W/m °C) and the lowest capacitance (density × specific heat = 1000 kg/m^3 × 835 J/kg ºC= 835000 J/m^3 ºC) will be used.

2.2.4 Cellular concrete block

Also, for cellular concrete blocks, there is no consensus on the

Figure 4 – Model with cellular concrete (dimensions in mm)

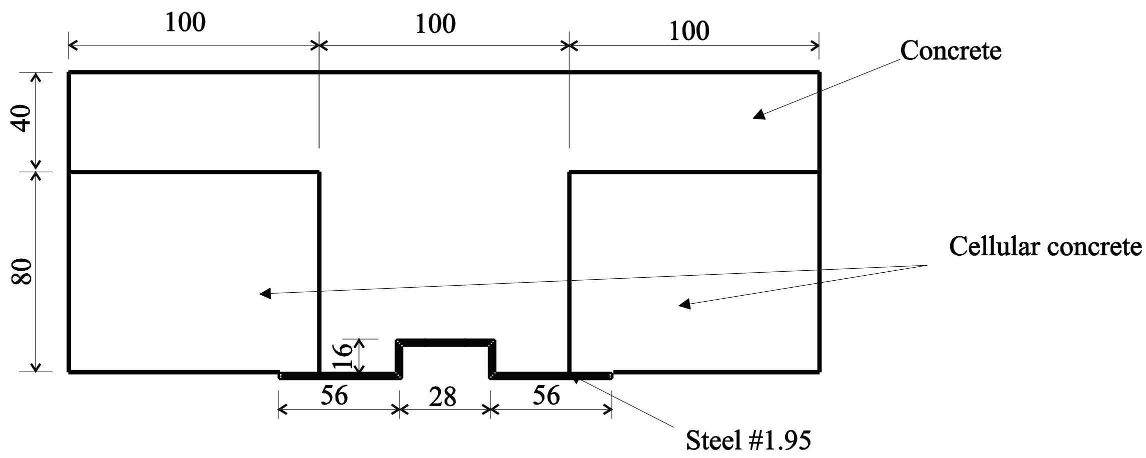
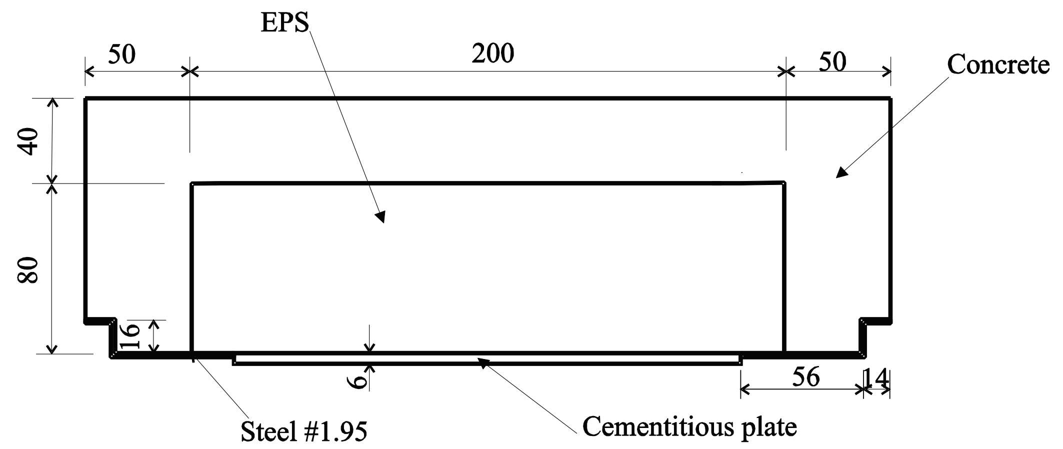


Figure 5 – Model with EPS/cement plate (dimensions in mm)



values to be adopted for their properties in thermal analysis. Table 2 shows the physical and thermal properties provided by some manufacturers and by the literature.

The thermal conductivity of the regular concrete decreases with temperature; hence, if it is supposed that the same occurs with the cellular concrete, the conductivity value at room temperature can be considered in favor of safety. Therefore, the highest thermal conductivity (0.3 W/m °C) and the lowest capacitance (density × specific heat = 300 kg/m³ × 850 J/kg °C= 255000 J/m³ °C) will be used.

2.2.5 Cementitious plate

After extensive research on the physical and thermal properties of cement plates, few results were found, with great variability between them, as shown in Table 3.

Due to the high deviation of values, a study was carried out to verify the influence of the thermal properties on the slab temperature field.

According to the thermal properties presented in this item, seven simulations were performed, in which the properties of the cementitious plates were varied, as shown in Table 4. In the sixth

Table 1 – Properties of ceramic tiles at room temperature

Source	Density (kg/m³)	Conductivity (W/m°C)	Specific heat (J/kg K)
CADORIN (9)	1600	0.7	840
INCROPERA; DEWITT (10)	1920	0.72	835
ABNT NBR 15220-2:2005 (8)	1000 – 2000	0.70 – 1.05	920

Table 2 – Properties of cellular concrete blocks at room temperature according to manufacturers

Manufacturer	Density (kg/m³)	Conductivity (W/m°C)	Specific heat (J/kg °C)
SIPOREX (11)	300 – 650	0.12 – 0.15	1000 – 1100
CONSTRUPOR (12)	400 – 800	0.28	1008
SICAL (13)	430 – 500	0.097	–
BARREIRA e FREITAS (14)	525	0.30	1050
GAWIN et al (15)	400 – 600	0.115 – 0.162	850
ABNT NBR 15220-2:2005 (8)	400 – 500	0.17	1000

Table 3 – Thermal properties of cement plates at room temperature, according to manufacturers and Brazilian standard

Manufacturer	Density (kg/m³)	Conductivity (W/m°C)	Specific heat (J/kg °C)
DUROCK – KNAUF (16)	1200	2.22	–
BRASILIT (17)	1700	0.35	–
ETERNIT (18)	1700	0.48	–
AQUAPANEL – KNAUF (16)	1150	0.35	–
ABNT NBR 15220-2:2005 (8)	1400 – 2200	0.65 – 0.95	840

Table 4 – Thermal properties of the cementitious plate analyzed

Simulation	Density (kg/m³)	Conductivity (W/m°C)	Specific heat (J/kg K)
1	1200	2.22	840
2	1700	0.35	840
3	1700	0.48	840
4	1150	0.35	840
5	1400	0.95	840
6	Concrete properties – see 2.2.1.		
7	Absence of cementitious plate		

simulation, thermal properties of concrete were adopted for the cementitious plate. In the seventh simulation, the presence of the cementitious plate was disregarded, i.e., the side faces of the rib and the lower face of the flange were directly exposed to fire.

To check the influence of the physical and thermal properties on the slab temperature field, the temperature variation was analyzed at three points, as shown in Figure 6: point A – rib upper left corner, point B - midpoint of the upper concrete face (flange) and point C – steel plate.

By means of Super Tempcalc thermal analysis software [19], the graphs showing the temperature variation versus fire exposure time for points A, B and C were plotted. See Figures 7 and 8.

As can be seen in Figures 7 and 8, the protection provided by the cementitious plate is, despite its small thickness, not negligible when

Figure 6 – Checking points for the analysis

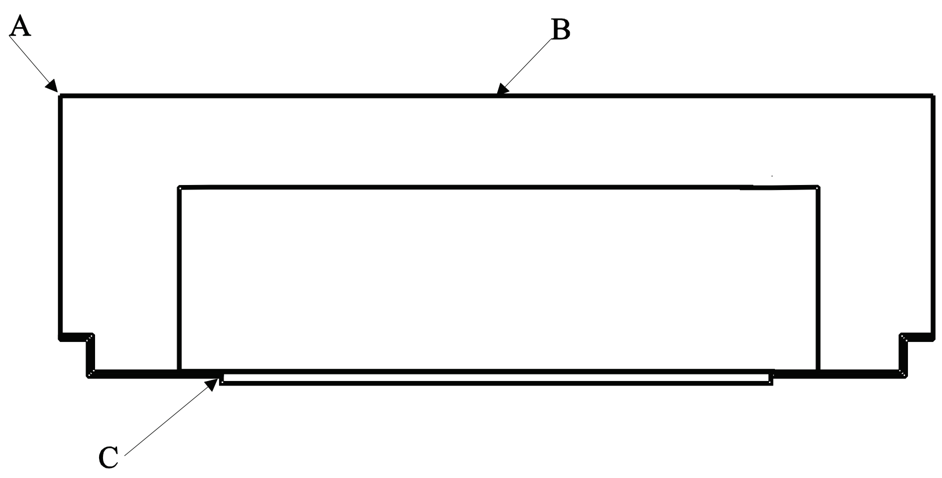


Figure 7 – Point A temperature variation

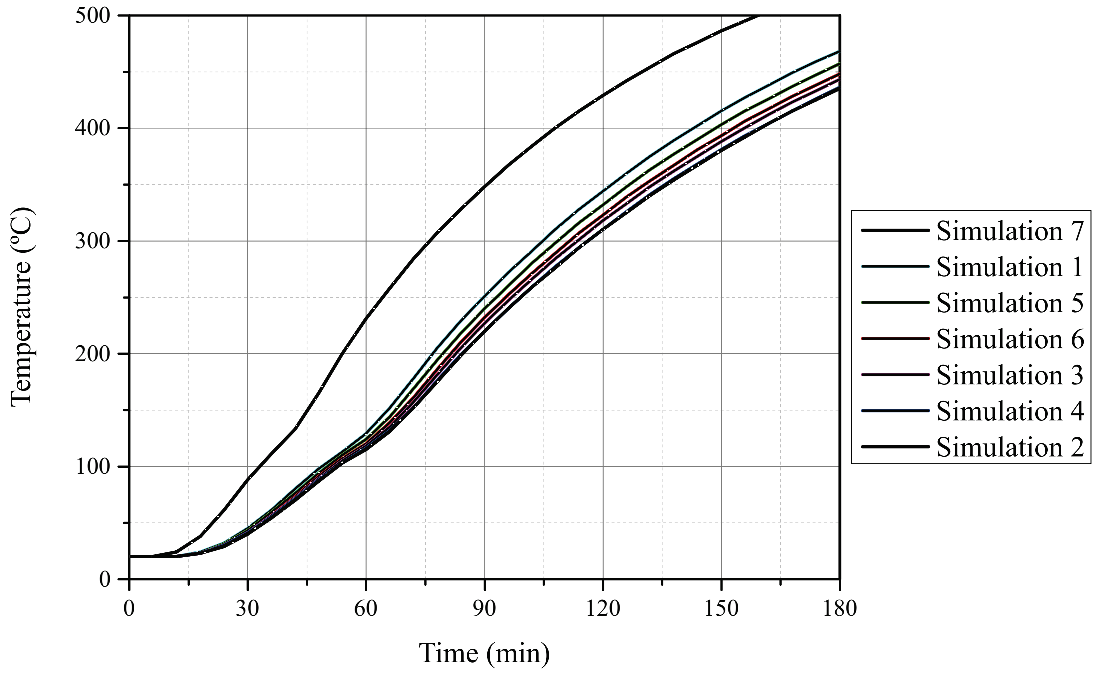


Figure 8 – Point B temperature variation

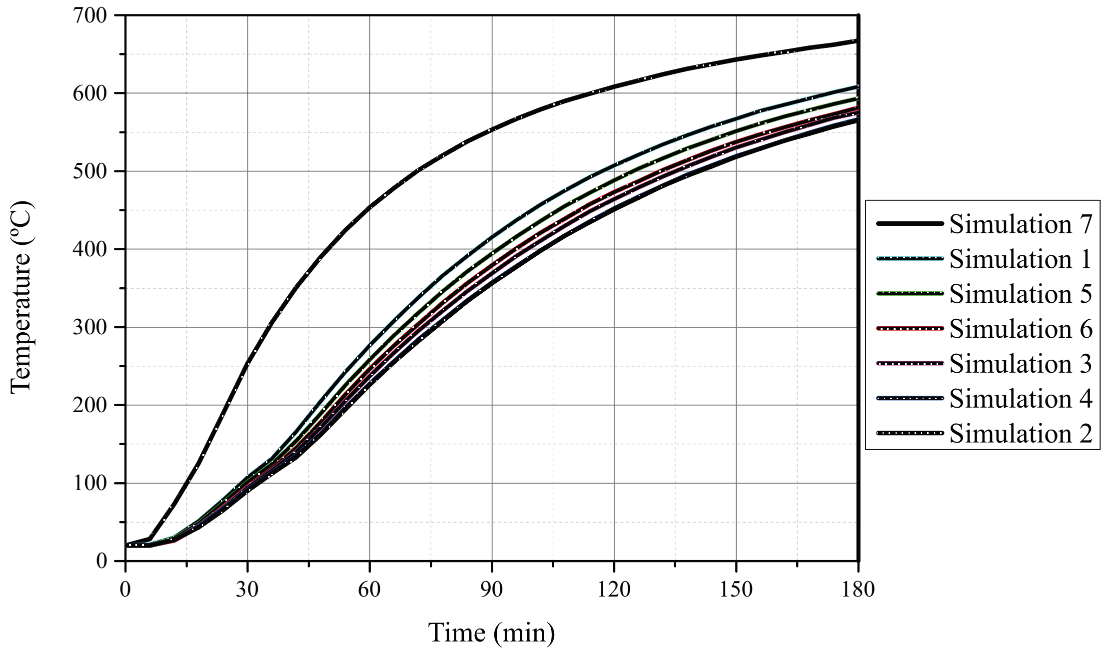
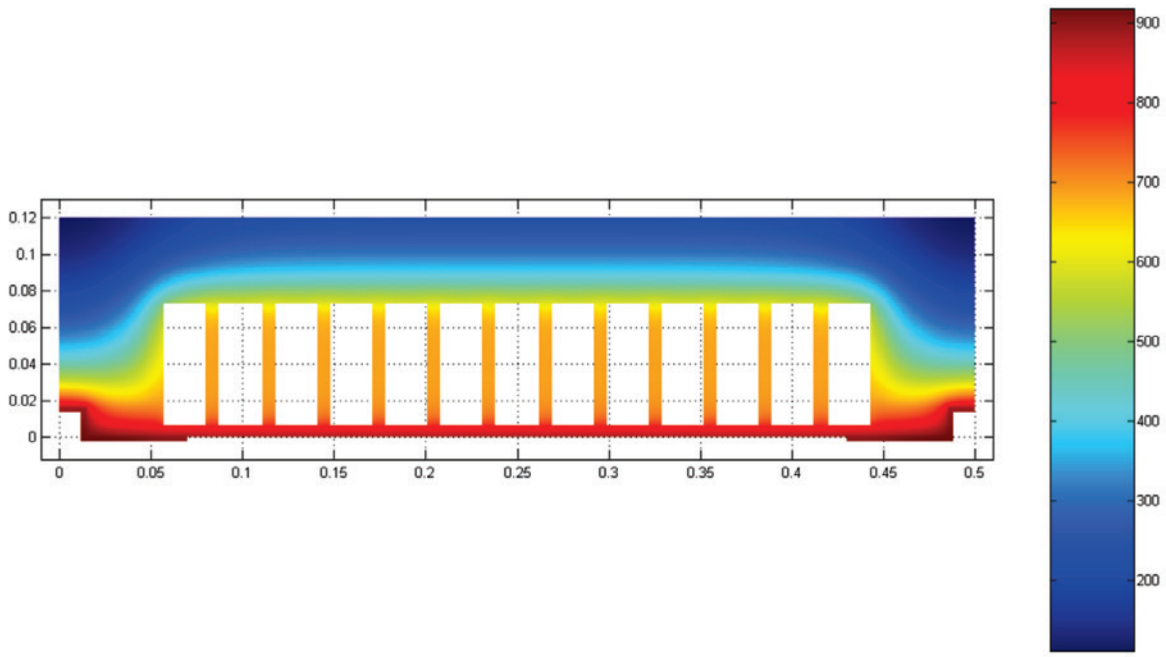


Figure 9 – Temperatures field after 60 minutes of fire



compared to simulation # 7 (no cementitious plate). On the other hand, the physical-thermal properties, simulations # 1 to 6, do not profoundly affect the results. For this being a numeric study and the wide variability found in the values of the plate properties, we decided to admit the properties of simulation # 1 in favor of safety.

3. Analyses of slabs with ceramic tile

3.1 Type 12-4 slab

Making use of Super Tempcalc thermal analysis software [19], the thermal behavior of a ribbed concrete slab filled with ceramic tile was analyzed. Initially, the following were considered (see Figure 3): thickness of the flange equal to 4 cm, rib height from the flange equal to 8 cm, rib width equal to 10 cm, 8.0 cm high ceramic tile and 1.95 mm thick metal joist. The holes of the ceramic tile were supposed to be filled with air. The temperature fields were analyzed for 30, 60, 90, 120, 150 and 180 minutes of exposure to standard fire. As an example, Figures 9 and 10 show

Figure 10 – Isotherms after 60 minutes of fire

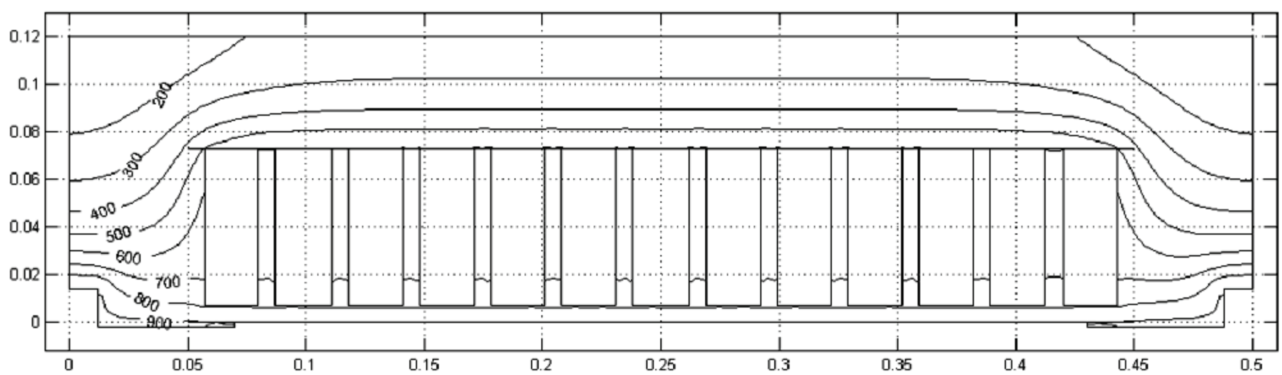


Table 5 – Maximum and average temperatures on slab upper face with flange between 4 and 6 cm

Time (min)	4 cm flange		5 cm flange		6 cm flange	
	θ_{max} (°C)	θ_{ave} (°C)	θ_{max} (°C)	θ_{ave} (°C)	θ_{max} (°C)	θ_{ave} (°C)
30	92	78.9	64	56.0	46	41.1
60	238	206.7	171	150.3	126	113.3
90	365	327.8	288	257.2	226	200.3
120	454	417.3	374	342.6	307	280.1
150	517	481.7	439	407.6	370	343.0
180	560	528.1	487	457.0	419	392.9

the thermal field and isotherms, respectively, for 60 minutes.

3.2 Other flange or flange+lining thicknesses

In order to evaluate the thermal insulation provided by the ceramic tile, the concrete flange thickness was varied from 4 to 8 cm. Since the thermal and physical properties of cement and sand mortar are similar to those of concrete, the thickness of the flange used in computer models may be substituted, in practice, by the actual flange thickness plus one layer of cement and sand mortar. The rib height with no flange was maintained equal to 8 cm. The maximum and average temperatures obtained on the slab upper surface for 4, 5, 6, 7 and 8 cm flange thicknesses are presented in Tables 5 and 6. Table 7 was constructed from Tables 5 and 6 associating the flange thickness to the time of fire resistance for thermal insulation. Table 8 presents the distances between the lower face of the rib and the lowest (d_1) and the highest (d_2) points of the isotherm of 500 °C and the minimum distance between the isotherm of 500 °C and the top of the steel recess (d_3), as shown in Figure 11.

Table 6 – Maximum and average temperatures on slab's upper face with 7 and 8 cm flange

Time (min)	7 cm flange		8 cm flange	
	θ_{max} (°C)	θ_{ave} (°C)	θ_{max} (°C)	θ_{ave} (°C)
30	35	32.0	28	26.4
60	101	90.1	79	70.5
90	173	154.3	134	122.1
120	251	227.0	203	182.2
150	312	287.5	261	239.8
180	360	336.3	308	287.1

Table 7 – Fire resistance values for thermal insulation

Flange thickness + cement and sand mortar (cm)	Fire resistance Thermal insulation (min)
4	49
5	62
6	76
7	92
8	108

Table 8 – Distances from 500 °C isotherm

Time (min)	d_1 (cm)	d_2 (cm)	d_3 (cm)
30	1.6	2.4	0.9
60	3.6	3.6	2.2
90	5.1	5.1	3.7

Figure 11 – Composite slab. checked distances included

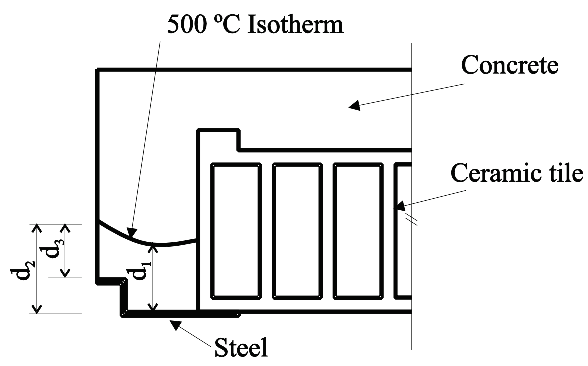


Table 9 – Minimum c_1 for type 12-4 ribbed slab

Time (min)	c_1 vertical (cm)	c_1 horizontal (cm)
30	2.5	2.5
60	3.5	5.0
90	5.0	5.0

For fire resistance higher than 120 minutes, the 500 °C isotherm crosses the flange. The reinforcement should be placed in the flange and in the middle of the rib, which is not feasible. From the analyses performed, Table 9 is proposed. Values were rounded in view of the difficulty of attaining millimeter precision in the construction work.
It is observed that the values of c_1 in Table 9 are considered high. However, for structural purposes, they can be compensated by increasing the rib height. This will in no way affect the results found herein.

4. Analyses of slab with cellular concrete blocks

Figure 12 – Field of temperatures after 60 min

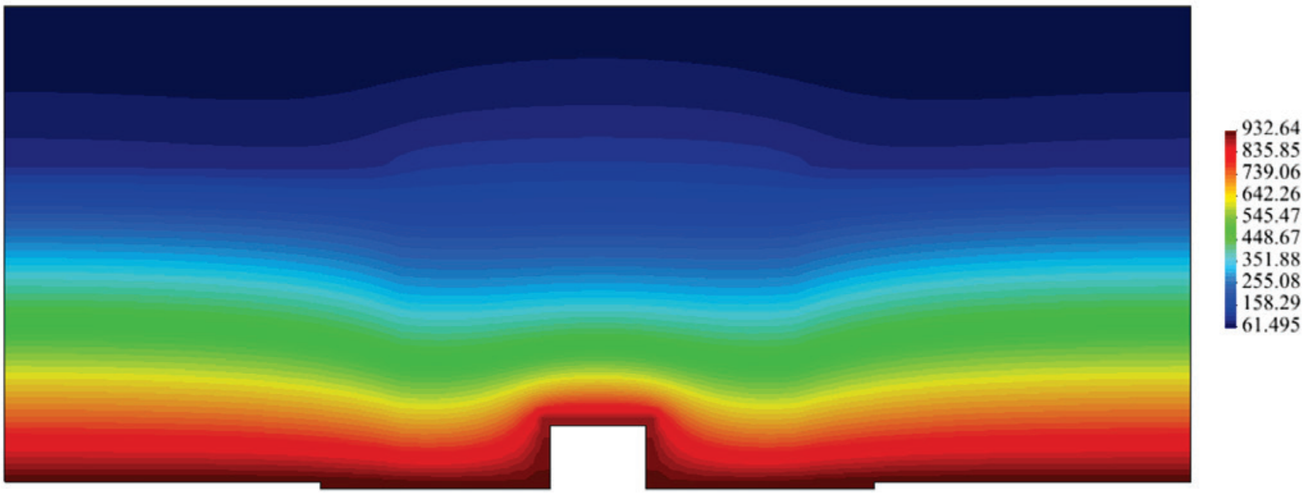


Figure 13 – 60-minute Isotherms

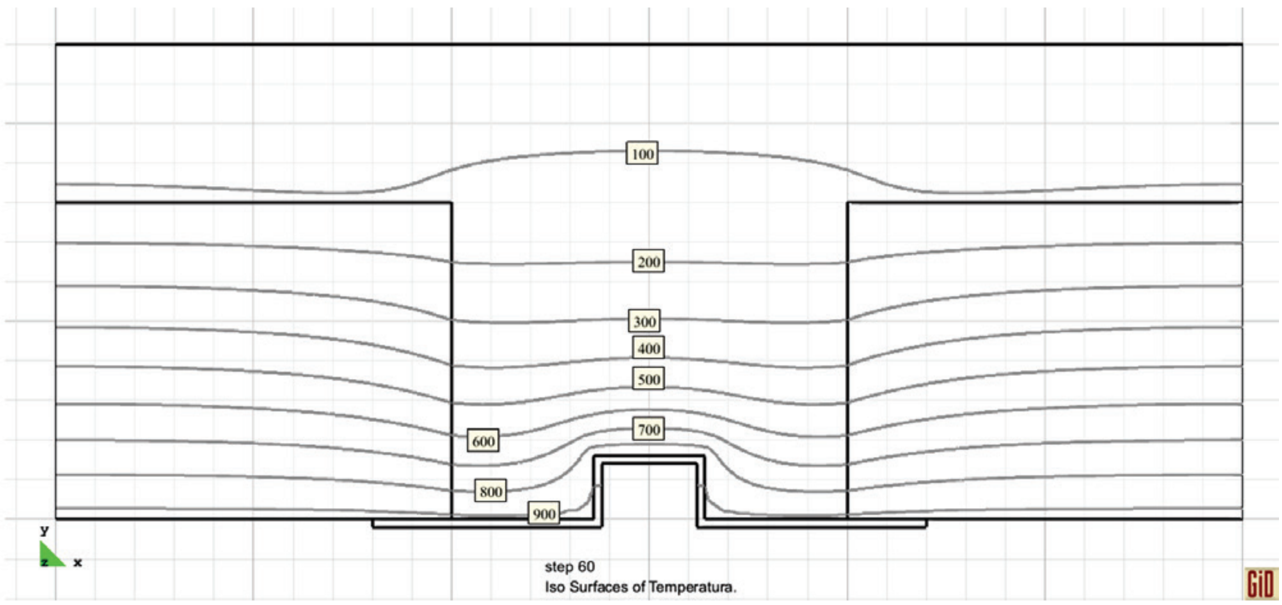


Table 10 – Temperatures on the upper face for 4, 5 and 6 cm flanges

Time (min)	4 cm flange			5 cm flange			6 cm flange		
	θ_{max} (°C)	θ_{ave} (°C)	θ_{ave} (°C) rib	θ_{max} (°C)	θ_{ave} (°C)	θ_{ave} (°C) rib	θ_{max} (°C)	θ_{ave} (°C)	θ_{ave} (°C) rib
30	28.9	27.2	26.3	24.9	23.9	23.3	22.6	22.0	21.6
60	69.5	64.2	67.8	54.5	51.2	53.3	43.6	41.7	41.7
90	115.2	104.7	112.7	96.0	87.0	93.7	78.4	71.8	76.7
120	159.9	137.5	154.4	129.5	115.6	125.9	109.8	99.6	107.4
150	204.1	174.0	197.3	166.7	144.1	161.3	137.3	122.2	133.6
180	239.5	207.6	232.5	201.2	174.5	195.3	167.5	147.1	162.9

Figure 14 – Temperatures along the upper face of a slab with 8 cm block and 4 cm flange

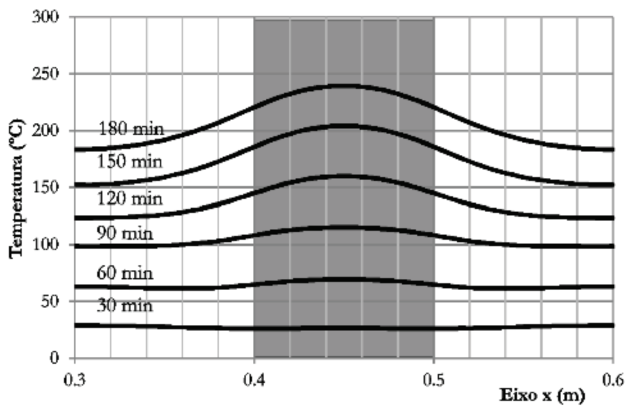


Table 11 – Distances from 500 °C isotherm

Time (min)	d_1 (cm)	d_2 (cm)	d_3 (cm)
30	1.4	2.4	0.6
60	2.8	3.3	1.6
90	3.8	4.1	2.4
120	4.6	4.8	3.1
150	5.2	5.3	3.8
180	5.8	5.9	4.4

4.1 Type 12-4 slab

The analysis of the thermal behavior of ribbed concrete slab filled with cellular concrete blocks was performed. Initially, the following was considered (see Figure 3): concrete slab thickness equal to 4 cm, height of the concrete block equal to 8 cm, width of the beam equal to 10 cm and metal joist thickness equal to 1.95 mm. Due to the slab continuity, only one rib was modeled, with flange collaborating width equal to 30 cm. By means of ATERM program [20], the thermal analysis of the slab was performed for 30, 60, 90, 120, 150 and 180 min. As an example, the field of temperature and isotherms for 60 min of standard fire is presented in Figures 12 and 13.

Figure 15 – Composite slab studied

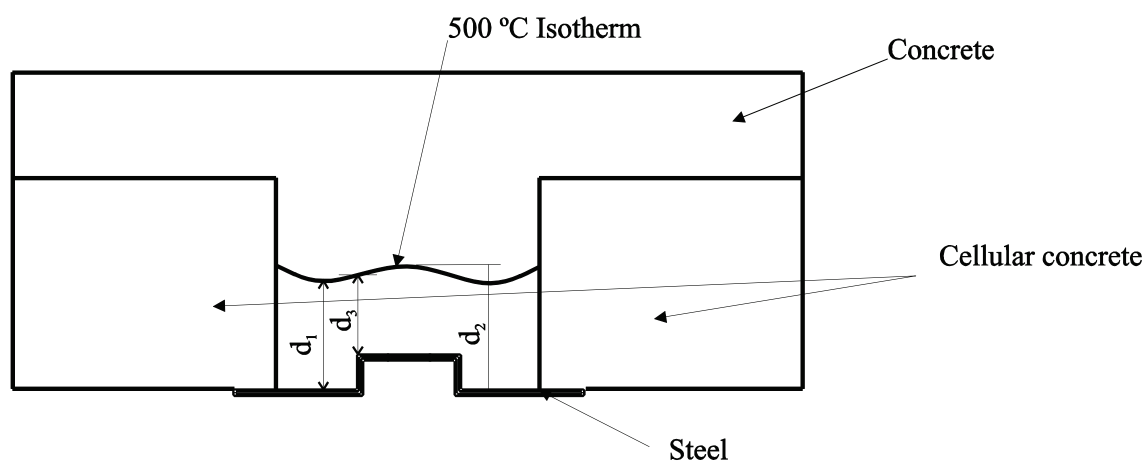


Table 12 – Temperatures on the upper face of 16-4, 20-4 and 25-4 slabs

Time (min)	16-4 slab			20-4 slab			25-4 slab		
	θ_{max} (°C)	θ_{ave} (°C)	θ_{ave} (°C) rib	θ_{max} (°C)	θ_{ave} (°C)	θ_{ave} (°C) rib	θ_{max} (°C)	θ_{ave} (°C)	θ_{ave} (°C) rib
30	21.4	20.9	20.5	20.2	20.1	20.0	20.1	20.0	20.0
60	34.8	32.8	31.9	24.4	23.2	22.4	23.2	22.2	21.5
90	57.1	54.9	56.3	34.0	32.5	31.8	31.0	29.4	28.7
120	85.5	79.9	83.9	47.3	46.0	46.8	41.7	40.8	41.1
150	110.3	102.6	108.5	65.0	61.4	63.9	57.0	54.3	56.2
180	133.0	120.5	129.8	82.7	77.2	81.2	73.1	68.5	71.9

Table 13 – Distances from 500 °C isotherm for 16-4, 20-4 and 25-4 slabs

Time (min)	16-4 slab			20-4 slab			25-4 slab		
	d_1 (cm)	d_2 (cm)	d_3 (cm)	d_1 (cm)	d_2 (cm)	d_3 (cm)	d_1 (cm)	d_2 (cm)	d_3 (cm)
30	1.4	2.3	0.6	1.4	2.3	0.6	1.4	2.3	0.6
60	2.9	3.3	1.5	2.9	3.3	1.5	2.9	3.3	1.5
90	3.9	4.1	2.4	3.9	4.1	2.4	4.0	4.1	2.5
120	4.8	5.0	3.3	4.8	4.9	3.3	4.8	4.9	3.2
150	5.5	5.5	3.9	5.6	5.6	4.0	5.6	5.6	4.0
180	6.0	6.0	4.4	6.2	6.2	4.6	6.2	6.2	4.6

Table 10 shows the maximum and average temperatures obtained on the upper surface for times equal to 30-180 min of exposure to fire. Average temperatures on the rib area of the upper face are also shown. The temperature variation along the upper face for periods of 30 to 180 minutes is shown in Figure 14, where the shaded area indicates the rib region. The highest temperatures are observed to occur in this region.

The ribbed slab under study with 4 cm flange and filled with 8 cm high cellular concrete blocks is found to meet the requirements of thermal insulation for fire resistance up to 120 min.

4.2 Other thicknesses of flange or flange+linings

For a better evaluation of the slab thermal insulation, a concrete flange thickness of 5 cm was adopted. Thermal analysis was redone and it was found that, as shown in Table 10, the slab studied meets the requirements for thermal insulation for fire resistance up to 150 min. Further analysis performed for a thickness of 6 cm proved that the condition of thermal insulation is met for fire resistance up to 180 min, as shown in Table 10.

For using the simplified method of 500 °C limit temperature in reinforcement, Table 11 presents the distance between the underside of the rib and the lowest point (d_{1}) and the highest point (d_2) of the 500 °C isotherm and the minimum distance between the 500 °C isotherm and the top of the steel recess (d_3), for the slab with 4 cm flange, as shown in Figure 15.

From the study performed, one can infer that safety is obtained if the bars centroid keep a distance from the rib underside face greater than 2.4 cm. For 60 min of fire resistance, this rises to 2.8 cm. For fire resistance higher than 90 min, the values found are not of practical use. Thus, the next analysis will cover blocks of greater height.

Table 14 – Fire resistance for cellular concrete filled slabs

Slab type	Total height (mm)	Flange height (mm)	Fire resistance (min)
12-4	120	40	120
12-5	120	50	150
12-6	120	60	180
16-4, 20-4, 25-4	160 a 250	40	180

Table 15 – c_{1min} for ribbed slabs filled with cellular concrete blocks and minimum rib height equal to 100 mm and 80 mm, respectively

Time (min)	c_1 (cm)
30	2.5
60	3.5
90	4.0
120	5.0
150	5.5
180	6.5

Type 16-4, 20-4, and 25-4 slabs were also analyzed, which corresponds to 4 cm thick flange and 16, 20 and 25 cm rib + flange height (respectively, 12, 16 and 21 cm high blocks). Table 12 shows the maximum and average temperatures obtained on the slab upper face, for times equal to 30-180 minutes of exposure to fire. Average temperatures on the rib area of the upper face are also shown.

Table 13 presents the distances between the rib lower face and the lowest (d_1) and highest (d_2) points of the 500 ºC isotherm as well as the minimum distance between the 500 ºC isotherm and the top of the steel recess (d_3), as shown in Figure 15. Based on Table 13, one can build Table 14, related to thermal insulation.

By observing Table 13, the values of d_1 are verified to be quite the same, i.e. slightly dependent on the rib height. Thus, the minimum values of $c_{1,\ the}$ distance from the reinforcement CG to the rib base shown in Table 15 are proposed. The values were rounded due to the difficulty in obtaining millimeter precision in the field.

It is observed that the values of c_1 from Table 15, considered high for structural purposes, can be compensated by increasing the rib height. This in no way affects the results herein.

5. Analyses of slabs with EPS blocks on a cementitious plate

5.2 Type 12-4 slab

Analyses were made on the thermal behavior of ribbed concrete slab filled with EPS block resting on cementitious plate, employing Super Tempcalc [19] software. The presence of EPS was disregarded due to the fact that this material is quickly consumed by the heat. Initially, the following was considered (see Figure 5): thickness of the concrete slab equal to 4 cm, rib height from the flange equal to 8 cm, rib width equal to 10 cm, cementitious plate thickness equal to 6.0 mm and thickness of the metal joist equal to 1.95 mm. The temperature fields were analyzed for 30, 60, 90, 120, 150 and 180 minutes of exposure to standard fire. As examples, Figures 16 and 17 show, respectively, the thermal field and isotherms for 60 minutes.

5.2 Other flange or flange+lining thicknesses

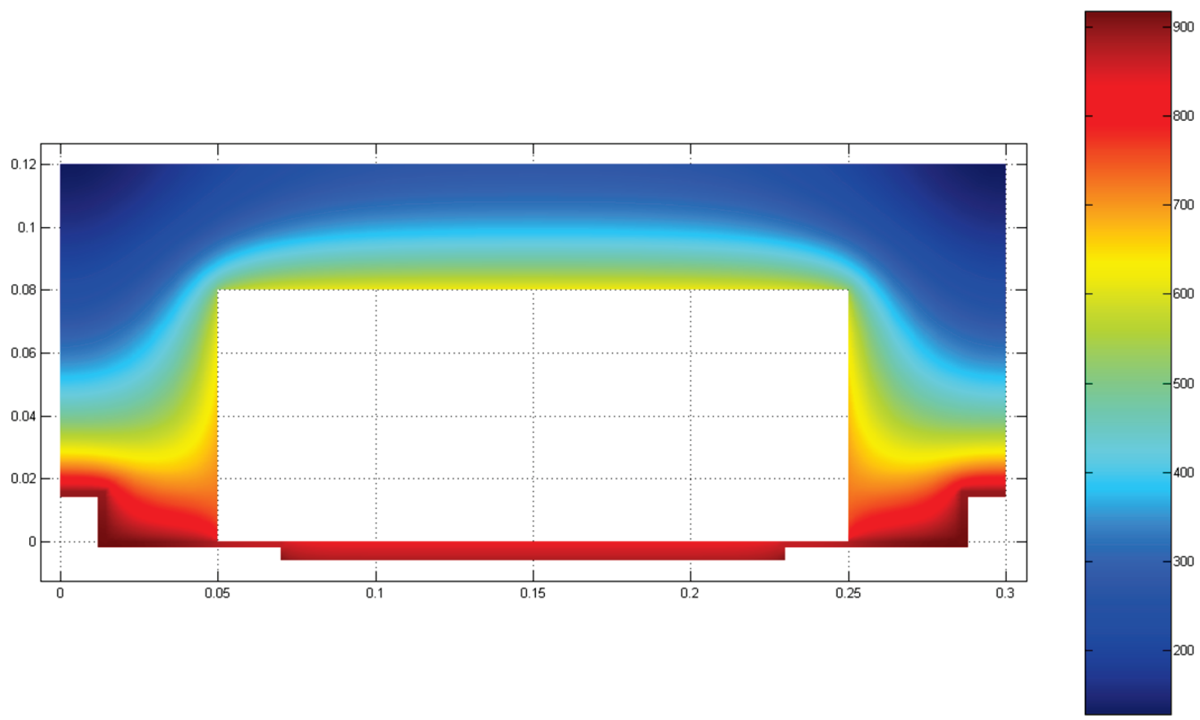
To evaluate the thermal insulation of the slab with cementitious plate, the thickness of the concrete flange was varied from 4 to 8 cm. Having in mind that the thermal and physical properties of cement and sand mortar are similar to those of concrete, the flange thickness used in computer models can be substituted, in practice, by the flange actual thickness plus one layer of cement and sand mortar. The rib height was supposed equal to 8 cm. The maximum and average temperatures on the upper surface of the slab, for thicknesses of 4, 5, 6, 7 and 8 cm, are presented in Tables 16 and 17. From Tables 16 and 17, Table 18 was constructed for thermal insulation. For information, the values standardized by ABNT NBR 15200:2012, for the case of lack of the cement plate, are provided.

Table 19 was built for use with the simplified method of 500 °C limit temperature in the reinforcements and presents the distances between the rib lower face and the lowest (d_1) and the highest (d_2) points of isotherm 500 °C and the minimum distance between 500 °C isotherm and the top of the steel recess (d_3), as shown in Figure 18.

For fire resistance higher than 120 min, the 500 °C isotherm crosses the flange. The reinforcement should be placed in the flange and in the middle of the rib which is not feasible. Observing Table 8, Table 20 is proposed. Values were rounded in view of the difficulty in attaining millimeter precision in the field.

The values of c_1 from Table 20 are considered high but, for struc-

Figure 16 – Field of temperatures after 60 minutes of fire



tural purposes, can be compensated by increasing the rib height. This does not at all affect the results yielded in this work.

6. Comparisons to the brazilian standard

By comparing the filled slabs to the unfilled ones, they should follow the recommendations of ABNT NBR 15200:2012 [3]; Table 21 presents a summary of the results of this study and, in the last column, the requirements of the Brazilian standard for

Figure 17 – Isotherms after 60 minutes of fire

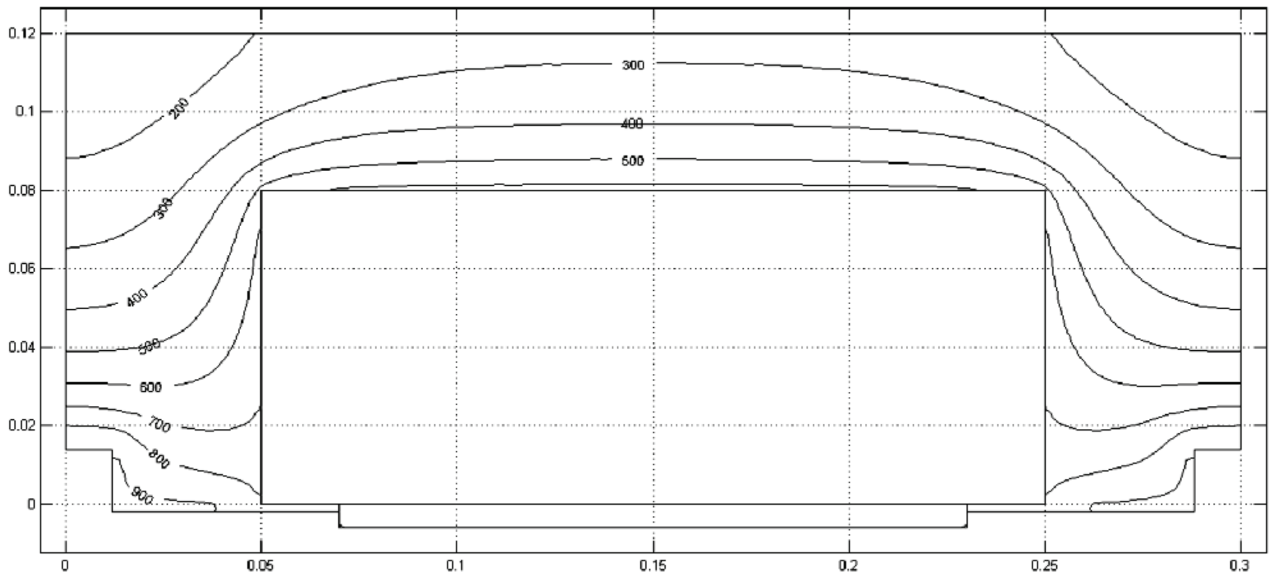


Table 16 – Maximum and average temperatures on the upper face of slab with 4 and 6 cm flange

Time (min)	4 cm flange		5 cm flange		6 cm flange	
	θ_{max} (°C)	θ_{ave} (°C)	θ_{max} (°C)	θ_{ave} (°C)	θ_{max} (°C)	θ_{ave} (°C)
30	107	85.4	76	61.1	54	44.9
60	276	222.5	200	162.9	143	121.3
90	415	354.0	327	278.5	256	216.7
120	507	446.9	418	368.4	342	301.8
150	567	511.1	483	434.9	407	367.0
180	608	556.3	529	484.1	456	417.6

Table 17 – Maximum and average temperatures on the upper face of slab with 7 and 8 cm flange

Time (min)	7 cm flange		8 cm flange	
	θ_{max} (°C)	θ_{ave} (°C)	θ_{max} (°C)	θ_{ave} (°C)
30	40	34.5	31	28.1
60	112	95.7	88	75.1
90	197	166.9	149	130.5
120	278	245.5	224	197.1
150	340	308.2	284	257.4
180	390	358.2	332	306.1

fire resistance in function of the thermal insulation.
Table 22 presents a summary of the results of this study and, in the last column, the Brazilian requirements for minimum c_1.

7. Conclusions

This paper examined ribbed composite slabs filled with ceramic tiles, cellular concrete blocks and EPS on cement plate at high temperature. Conditions of thermal insulation and resistant capacity were analyzed.
The presence of any of the 3 types of filler studied improves the performance of the slab in fire, increasing the fire resistance time and decreasing the value of $c_{1\ minimum}$ in relation to similar slabs with no filling. Based solely on thermo-structural numerical analysis, values of fire resistance time are proposed, as a function of thermal insulation capacity and c_1, assuming the limit temperature at reinforcement equal to 500 °C.
In view of the unprecedented nature of this research, and, especially, of the existence of the large space filled with heated air inside the holes of the ceramic tile and the vacuum caused by the burning of EPS, the results for thermal insulation and reinforcement position presented here should be experimentally confirmed before being used in design. Similarly, tightness warranty must be analyzed experimentally, since it has not been targeted in this study. The numerical procedure led to results that may be useful to guide future studies.

8. Acknowledgments

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Table 18 – Fire resistance values for thermal insulation

Flange thickness + cement and sand mortar (cm)	Fire resistance thermal insulation (min)	Fire resistance no plate (min)
4	30	–
5	59	–
6	72	30
7	87	45
8	103	60

Figure 18 – Composite slab. checked distances included

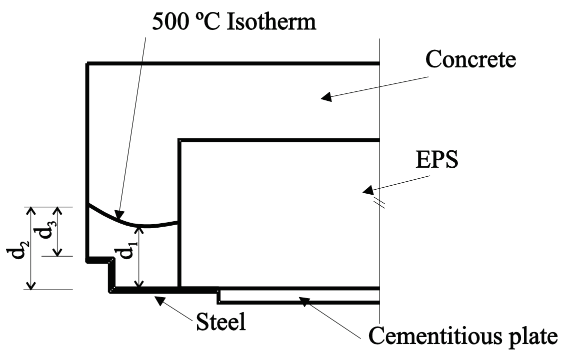

Table 19 – Distances from 500 °C isotherm

Time (min)	d_1 (cm)	d_2 (cm)	d_3 (cm)
30	1.6	2.4	0.9
60	3.8	3.8	2.4
90	5.8	5.8	4.4

Table 20 – minimum c_1 for the ribbed slab studied

Time (min)	c_1 vertical (cm)	c_1 horizontal (cm)
30	2.5	2.5
60	4.0	5.0
90	6.0	5.0

Table 21 – Fire resistance values (min) for thermal insulation of Type 12-4 composite ribbed slabs

Flange thickness + cement and sand mortar (cm)	Ceramic tile	Cellular concrete block	EPS on cement plate	NBR 15200:2012 (3)
4	49	120	30	Not allowed
5	62	150	59	Not allowed
6	76	180	72	30
7	92	180	87	45
8	108	180	103	60

Table 22 – Minimum c_1 for Type 12-4 ribbed slab

Time (min)	Ceramic tile		EPS on cement plate		Cellular concrete block	NBR 15200:2012 (3)
	c_1 vertical (cm)	c_1 horizontal (cm)	c_1 vertical (cm)	c_1 horizontal (cm)	c_1 (cm)	c_1 (cm)
30	2.0	2.0	2.0	2.0	2.0	2.0
60	3.5	4.5	4.0	4.5	3.5	4.5
90	5.0	5.0	6.0	5.0	6.0	> 6.0
120	–	–	–	–	–	> 6.5
150	–	–	–	–	–	> 7.0
180	–	–	–	–	–	> 8.0

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