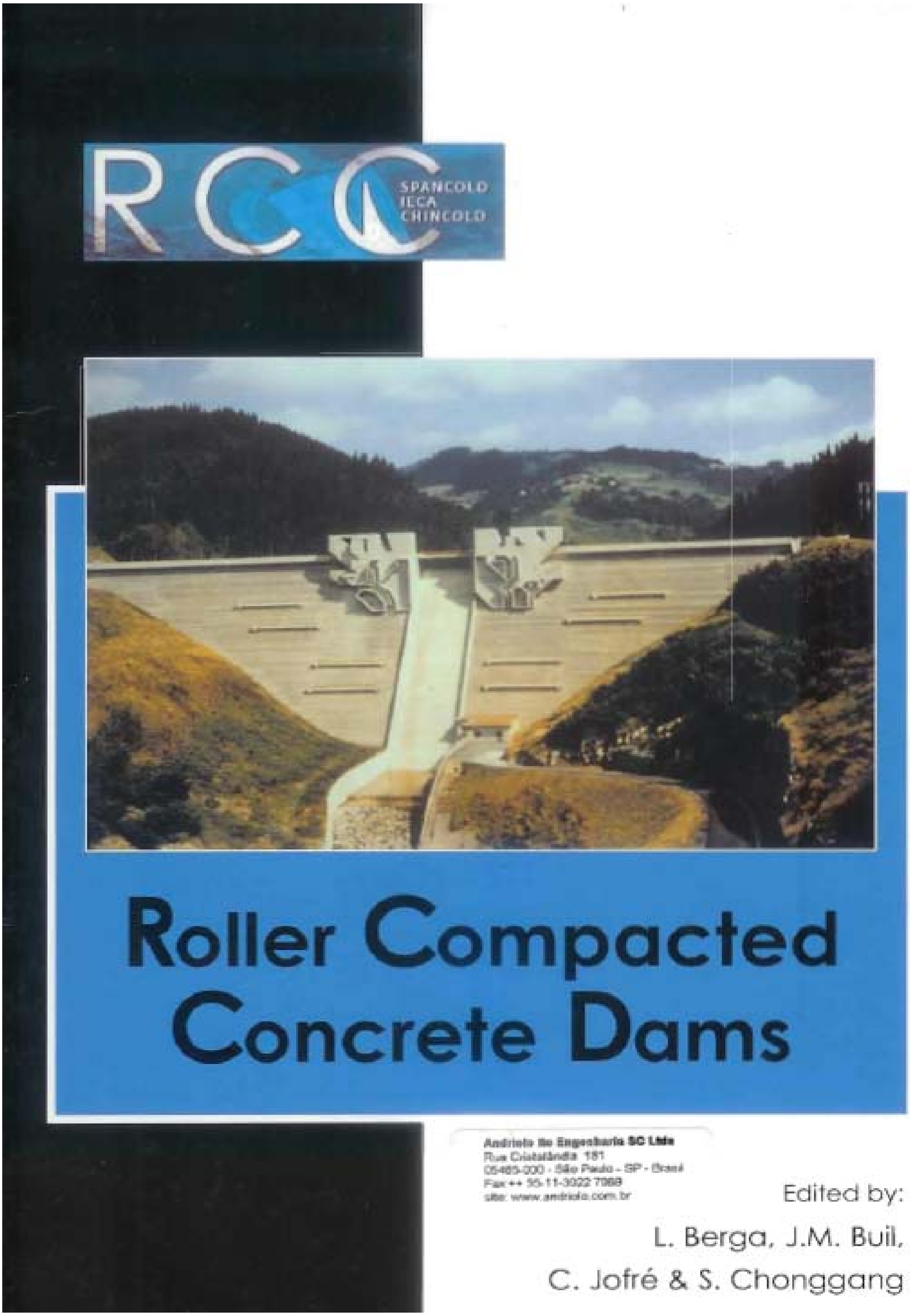

Thermal Analysis of Roller Compacted Concrete

Thermal Analysis of Roller Compacted Concrete

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ABSTRACT : This paper presents a methodology for analyzing temperature evolution in roller compacted concrete. Field temperature calculation can be achieved through the heat dissipation condition in one, two or three directions. Several situations were analyzed and it was observed, in the case of roller compacted concrete, that heat propagation in one direction is more likely. This occurs because the area dimensions of the structure are much larger than the layer thickness. In this case, the influence of the adiabatic rise on the surface of the roller compacted concrete structure can be discarded due to the negligible thickness of the concrete layer in relation to its width. It is worthy of note that the surface concrete can be studied using an independent mesh.

1 INTRODUCTION

A method for analyzing temperature evolution in roller compacted concrete in a generic construction is hereby presented and discussed.

The calculation was made with a unidirectional heat dissipation condition. The thicknesses of the placement concrete layers accepted for the calculation were of 20, 30 and 40 cm, with placement breaks of 12, 24 and 48 hours, as this is the most common scenario at construction sites. The placing temperature of the fresh concrete ranged from 15 to 40^{o} C, with 5ºC breaks, and the cement content from 70 kg/m^3 to 250 kg/m^3, with breaks of 30 kg/m^3. Above 160 kg/m^3 it was calculated for 200 and 250 kg/m^3.

A curing period of 14 days was allowed for the concrete.

2. PROPERTIES OF CONCRETES

The thermal properties were admitted in regard to a concrete with a coarse aggregate of quartz mica-schist lythological type, with a maximum diameter of 25 mm. The adiabatic rise of the concrete's temperature was estimated from E-8476, E-8160 and E-8150 mixes [1] from the Concrete Laboratory of Furnas Centrais Elétricas S. A., in Goiânia . In this mix proportion a cement was used with a heat of hydration of 197 J/g^{o}C at 3 days and 228 J/g ^{o}C at 7 days, one of which was a Cement Portland Blast Furnace Slag.

The makeup of the reference mix proportions is shown in Table 2.1.

Table 2.1 – Composition of Reference Mix Proportions

Material	Composition (kg/m³)		
	E-8176	E-8160	E-8150
Cement Portland Blast Furnace Slag (IS)	100	207	346
Silica	---	13	22
Equivalent cement	100	225	377
Water	148	149	162
Natural sand	---	838	704
Artificial sand	1135	---	---
25-mm aggregate	566	613	1097
50-mm aggregate	484	516	---
Specific gravity (Kg/m^3)	2400	2335	2356

For calculation purposes, adiabatic rises derived from data interpolation were estimated for the remaining analyzed mixes, as shown in Table 2.2.

Table 2.2 – Adiabatic rise of Reference Mixes Temperature (^{o}C)

Age (hours)	Rise		
	E-8176	E-8160	E-8150
12	4.25	1.00	0.90
24	7.20	1.10	4.90
48	11.40	13.10	33.85
72	14.25	27.30	39.10
120	17.40	34.60	40.30
240	19.80	36.50	50.25
672	20.90	37.50	41.85

Based on previous studies, it was concluded that the adiabatic rise of the concrete's temperature is directly proportional to content, when the cement type remains unchanged and no additions are employed.

Table 2.3 shows the adopted thermal properties obtained by means of tests performed at the Concrete Laboratory of Furnas Centrais Elétricas S.A, in Goiânia [1]. Figure 2.1 presents an apparatus for thermal characterization.

Table 2.3 – Obtained Thermal Properties

Properties	Symbol	Thermal Parameters
Specific heat (cal/g.^{o}C)	C	0.230
Specific gravity (kg/m³)	γ	2311
Thermal conductivity (kcal/m.h.^{o}C)	K	2.62
Thermal diffusivity (m²/dia)	.h_2	0.1183

For the coefficient of superficial heat transmission, the following values were adopted:

Concrete curing water air: h_c = 300 Kcal/m².d.^{o}C

Concrete air: h_c = 12 Kcal/m².d.^{o}C

Figure 2.1 – Equipment for the Thermal Characterization of Concrete

3. Calculation of the Temperatures

3.1 *Theoretical Formulation*

The problem of heat thermal conduction consists in the numeric resolution of the equation of heat propagation in a solid means, derived from Fourier's Law and the principle of energy conservation [2]. The equation that represents the phenomenon is given below:

$$\delta\theta / \delta t = h^2 . \delta z^2 / \delta t^2 + \delta T / \delta t \qquad (1)$$

where:

θ = temperature of the element
t = time variable;
z = flow direction coordinate;
T = Adiabatic temperature rise in the volume element of the concrete in question
h^2 = thermal diffusivity = k / (d.c), where k is thermal conductivity;
d = specific gravity;
c = specific heat

By applying the Galerkin process, equation (1) may be expressed as follows:

$$T(t+\Delta t) = \left[K + C/\Delta t\right]^{-1} . \left[W(t) + C.T(t)/\Delta t\right] \qquad (2)$$

Where:

$T(t+\Delta t) =$ Temperature

$t+\Delta t =$ age + Calculation Break

[K] = Thermal Conductivity Matrix

$$[K] = \begin{bmatrix} k_1/l_1 & -k_1/l_1 & 0 & \dots & 0 \\ -k_1/l_1 & k_1/l_1 + k_2/l_2 & -k_2/l_2 & \dots & 0 \\ 0 & -k_2/l_2 & \dots & \dots & 0 \\ \dots & \dots & \dots & \dots & -k_{n-1}/l_{n-1} \\ 0 & 0 & 0 & -k_{n-1}/l_{n-1} & k_n/l_n + hc \end{bmatrix}$$

l_i = Element Width
k_i = Element Conductivity
h_c = Heat Transmission Coefficient

$$[C] = \begin{bmatrix} c_1 l_1 \rho_1/3 & c_1 l_1 \rho_1/6 & \dots & 0 \\ c_1 l_1 \rho_1/6 & c_1 l_1 \rho_1/3 + c_2 l_2 \rho_2/3 & \dots & 0 \\ \dots & \dots & \dots & c_{n-1} l_{n-1} \rho_{n-1}/6 \\ 0 & 0 & c_{n-1} l_{n-1} \rho_{n-1}/6 & c_{n-1} l_{n-1} \rho_{n-1}/3 \end{bmatrix}$$

ρ_i = Specific Gravity
c_i = Specific Heat

$$[W(t)] = \begin{bmatrix} c_1 l_1 \rho_1 .(\partial Ta/\partial t)_1 / 2 \\ c_1 l_1 \rho_1 .(\partial Ta/\partial t)_1 / 2 + c_2 l_2 \rho_2 .(\partial Ta/\partial t)_2 / 2 \\ c_2 l_2 \rho_2 .(\partial Ta/\partial t)_2 / 2 + c_3 l_3 \rho_3 .(\partial Ta/\partial t)_3 / 2 \\ \dots \\ c_{n-1} l_{n-1} \rho_{n-1} .(\partial Ta/\partial t)_{n-1} / 2 + h_c . T_{ar} \end{bmatrix}$$

Ta = Adiabatic temperature rise
Tar= Ambient temperature

3.2 Analyzed Hypotheses

In unidirectional calculations, three hypotheses were adopted, considering layer thickness variation in 20, 30 and 40 cm. For each thickness, cement content varied from 70 kg/m³ to 160 kg/m³, with a break of

10kg/m³. The placement break ranged from 12, 24 and 48 hours, while the temperature of concrete placement varied from 15 to 40ºC, with 5 ºC breaks. Ambient temperature was considered as varying from 15, 20 and 25ºC.

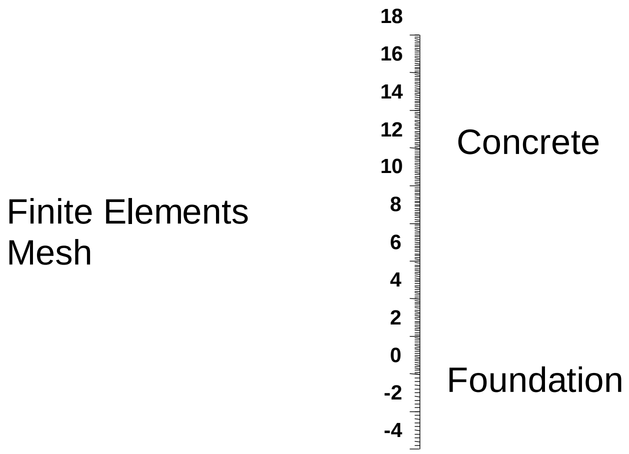


Figure 3.1.1 – Finite Elements Mesh for the Unidirectional Calculation (measured in meters)

The characteristics of the finite elements mesh, discretized along a line, and used in the calculations are presented in Figure 3.1.1 and Table 3.1.2.

Table 3.1.2 – Characteristics of the Finite Elements Mesh - Unidirectional

Material	Number of elements	Element thickness (m)
Concrete	180	0.1
Foundation	20	0.2

3.2.1. Influence of Layer Thickness

The thickness of concrete placement layers is a factor of great influence on the temperature that the concrete will reach in the structure. The thicker the layer, the higher the temperature of the concrete. Figure 3.2.1 presents the concrete temperature evolutions. Placement hypotheses were calculated considering a concrete with a binder content ranging from 70 kg/m^3 to 250 kg/m^3, a placement break between layers of 12 hours, fresh concrete temperature equivalent to the ambient's of 20ºC and layer thickness ranging between 20 , 30 and 40 cm.

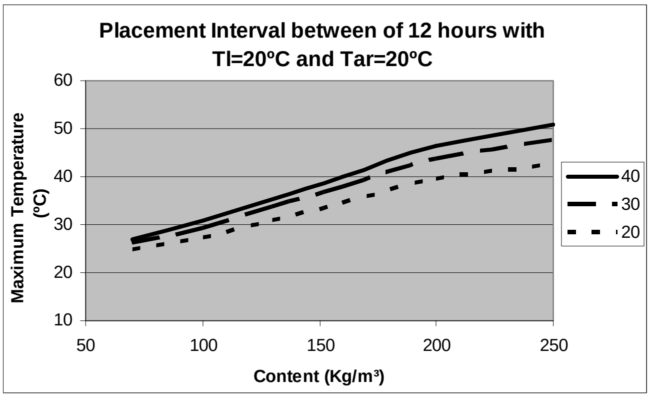


Figure 3.2.1 – Influence of thickness between layers

3.2.2. Influence of Layer Placement Break

Figure 3.2.2 illustrates the influence of placement break by showing the evolutions in the concrete's temperature. Placement hypotheses were calculated for a concrete with a binder content of between 70 kg/m^3 and 250 kg/m^3, a placement break between layers ranging from 12 to 48 hours, fresh concrete temperature equivalent to the ambient's at 20ºC and thickness of layers equal to 30 cm.

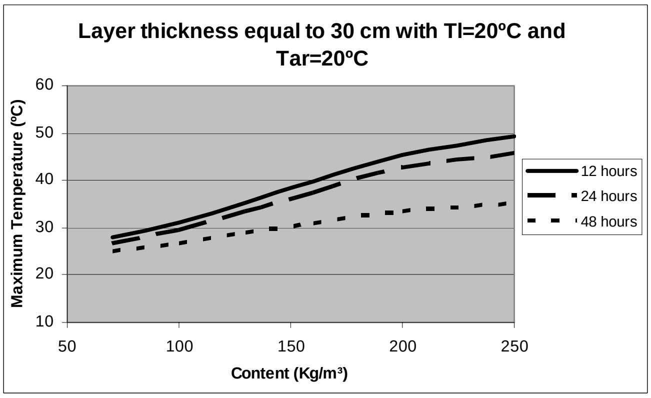


Figure 3.2.2 – Influence of placement break

3.2.3. Influence of Cementitious Content

The types and contents of binders greatly affect the final temperature of the concrete in the structure [3]. The binder types, characterized by different types of cements and additives (that may include natural or artificial pozzolans, fly-ash, crushed blast furnace slag or even the aggregate itself in a fraction finer than sieve nr. 200), will also influence on the temperature of the concrete in the structure. In the present case, only the effect of cement featuring blast furnace slag with aggregate filler will be considered. Figure 3.2.3 illustrates the influence of binder content in the evolution of concrete temperatures. Placement hypotheses were calculated for concrete with binder content varying from 70 kg/m^3 to 250 kg/m^3, a placement break between layers ranging from 12 to 48 hours, temperature of the fresh concrete equal to the ambient's, at 20ºC and layer thickness equal to 40 cm.

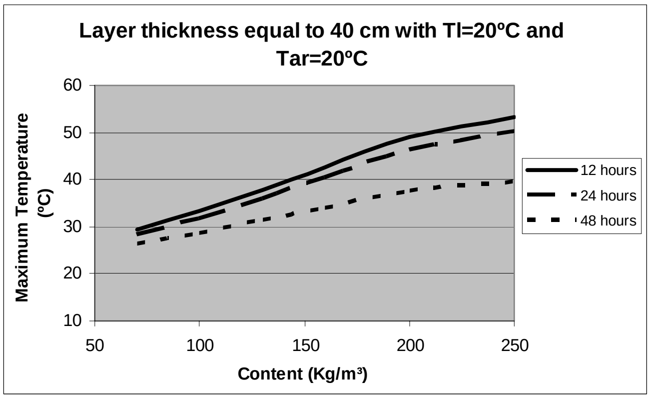
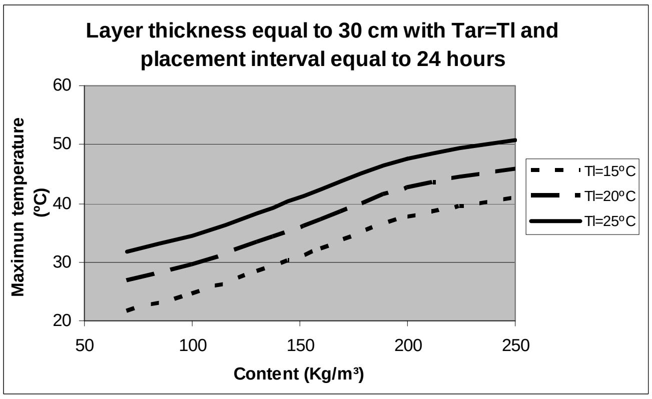


Figure 3.2.3 – Influence of layer thickness on maximum temperature reached in the structure.



3.2.4. Influence of Placement Temperature on maximum temperature reached in the structure.

3.2.4 Influence of Placement Temperature on maximum temperature

Figure 3.2.4 illustrates the influence of placement temperature in the evolutions of concrete temperature. Placement hypotheses were calculated for concrete with binder content ranging from 70 kg/m^3 to 250 kg/m^3, a placement break between layers ranging from 12 to 48 hours, temperature of the fresh concrete equal to the ambient's, at 20ºC and layer thickness equal to 30 cm.

3.2.5 Abacus for Estimating Maximum Temperature

The attached table shows values for maximum temperature in the structure for one of the hypotheses, whose results were obtained by correlating concrete placement temperature, thickness and waiting time

Table 3.2.5 - Maximum temperature in a structure using pozzolan cement.

Ambient temperature			15 ºC			20 ºC			25 ºC		
Layer thickness (cm)			20	30	40	20	30	40	20	30	40
C (kg/m³)	PB (days)	PT (ºC)	Max. Temp. (ºC)			Max. Temp (ºC)			Max. Temp. (ºC)		
70	0.5	15	21.03	22.84	24.30	24.71	26	26.97	28.61	29.37	29.75
100			23.51	26.11	28.21	27.14	29.24	30.83	30.94	32.49	33.58
130			27.02	30.36	32.90	30.75	33.52	35.36	34.56	36.7	37.89
160			30.60	34.64	37.64	34.41	37.85	40.11	38.24	41.05	42.57
200			35.48	40.44	43.96	39.31	43.64	46.42	43.13	46.86	48.92
250			38.66	44.34	48.27	42.37	47.37	50.76	46.20	50.51	53.27
70	1		19.89	21.69	23.17	23.92	25.23	26.24	28.04	28.91	29.5
100			21.87	24.45	26.58	25.89	27.91	29.64	29.91	31.58	32.74
130			24.82	28.31	30.75	28.87	31.73	33.79	32.94	35.16	36.92
160			27.85	32.26	35.21	31.93	35.68	38.03	36.00	39.11	41.15
200			31.93	37.52	41.15	36.00	40.95	43.98	40.08	44.37	46.81
250			34.21	40.78	45.1	38.28	44.2	47.93	42.36	47.62	50.75
70	2		18.30	19.78	21.16	22.58	23.76	24.81	27.03	27.86	28.47
100			19.56	21.67	23.65	23.79	25.57	27.3	28.12	29.67	30.95
130			20.9	23.69	26.24	25.14	27.57	29.68	29.48	31.46	33.31
160			22.24	25.72	28.89	26.49	29.6	32.33	30.84	33.48	35.78
200			24.03	28.42	32.46	28.29	32.30	35.9	32.63	36.21	39.34
250			25.04	30.00	34.47	29.39	33.91	37.91	33.73	37.82	41.36
70	0.5	20	22.54	24.95	26.83	26.03	27.84	29.31	29.71	31.00	31.97
100			24.99	28.19	30.73	28.51	31.11	33.22	32.14	34.24	35.83
130			28.41	32.38	35.43	32.01	35.36	37.89	35.75	38.51	40.36
160			32.92	36.64	40.18	35.6	39.64	42.64	39.41	42.85	45.11
200			36.65	42.32	46.49	40.48	45.44	48.96	44.31	48.65	51.42
250			40.02	46.33	50.81	43.66	49.34	53.27	47.37	52.37	55.76
70	1		21.08	23.30	25.19	24.89	26.69	28.17	28.92	30.22	31.24
100			23.02	26.06	28.55	26.87	29.45	31.58	30.89	32.91	34.64
130			25.82	29.91	32.92	29.82	33.31	35.75	33.87	36.73	38.79
160			28.78	33.84	37.38	32.85	37.26	40.2	36.93	40.68	43.03
200			32.85	39.09	43.33	36.93	42.52	46.15	41.00	45.95	48.98
250			35.13	42.35	47.27	39.21	45.76	50.10	43.28	49.20	52.93
70	2		19.26	20.97	22.67	23.30	24.78	26.16	27.58	28.76	29.82
100			20.52	22.82	25.14	24.56	26.67	28.65	28.79	30.58	32.30
130			21.86	24.85	27.79	25.9	28.69	31.24	30.14	32.57	34.68
160			23.2	26.90	30.44	27.24	30.72	33.89	31.49	34.60	37.33

200			24.99	29.63	34.01	29.03	33.42	37.45	33.29	37.30	40.9
250			25.75	31.10	36.02	30.04	35.00	39.47	34.39	38.91	42.91
70	0.5	25	24.26	27.16	29.54	27.54	29.95	31.82	31.03	32.84	34.31
100			26.59	30.39	33.32	29.99	33.19	35.73	33.52	36.11	38.22
130			29.81	34.39	37.96	33.41	37.38	40.43	37.01	40.36	42.89
160			33.32	38.65	42.71	36.92	41.64	45.18	40.6	44.64	47.64
200			37.99	44.33	49.02	41.65	47.31	51.49	45.47	50.43	53.96
250			41.42	48.34	53.33	45.02	51.33	55.8	48.66	54.34	58.27
70	1		22.38	24.99	27.37	26.08	28.3	30.19	29.89	31.69	33.17
100			24.32	27.67	30.71	28.02	31.06	33.54	31.87	34.45	36.58
130			27.12	31.52	35.11	30.82	34.91	37.93	34.82	38.31	40.75
160			29.92	35.41	39.55	33.78	38.84	42.38	37.85	42.26	45.21
200			33.78	40.68	45.44	37.86	44.09	48.32	41.93	47.52	51.15
250			36.22	43.93	49.44	40.13	47.36	52.27	44.21	50.77	55.1
70	2		20.48	22.33	24.23	24.26	25.97	27.66	28.3	29.78	31.16
100			21.48	24.15	26.70	25.52	27.82	30.15	29.56	31.67	33.65
130			22.82	26.2	29.34	26.86	29.86	32.79	30.9	33.69	36.24
160			24.16	28.25	31.99	28.2	31.9	35.44	32.24	35.72	38.89
200			25.95	30.98	35.57	29.99	34.63	39.01	34.03	38.42	42.45
250			26.71	32.28	37.58	30.75	36.1	41.02	35.05	40.00	44.47
70	0.5	30	26.16	29.56	32.41	29.26	32.16	34.55	32.54	34.95	36.82
100			28.41	32.65	36.12	31.59	35.39	38.32	34.99	38.19	40.73
130			31.21	36.5	40.52	34.81	39.38	42.96	38.42	42.38	45.43
160			34.72	40.66	45.24	38.32	43.65	47.71	41.92	46.64	50.18
200			39.39	46.34	51.55	42.99	49.33	54.02	46.65	52.32	56.49
250			42.82	50.35	58.87	46.42	53.34	58.33	50.02	56.32	60.81
70	1		23.72	26.93	29.55	27.38	29.99	32.37	31.08	33.30	35.19
100			25.63	29.45	32.89	29.33	32.67	35.71	33.02	36.06	38.55
130			28.43	33.12	37.28	32.12	36.52	40.11	35.82	39.91	42.93
160			31.23	36.99	41.72	34.93	40.42	44.55	38.78	43.84	47.38
200			34.98	42.25	47.67	38.78	45.68	50.49	42.86	49.09	53.33
250			37.52	45.51	51.62	41.22	48.93	54.45	45.13	52.36	57.28
70	2		22.08	24.70	26.57	25.48	27.33	29.23	29.26	30.97	32.67
100			22.91	25.66	28.28	26.48	29.15	31.70	30.52	32.82	35.14
130			23.78	27.54	30.89	27.82	31.2	34.34	31.86	34.86	37.79
160			25.12	29.59	33.55	29.16	33.25	36.99	33.20	36.9	40.44
200			26.91	32.33	37.15	30.95	35.98	40.57	34.99	39.63	44.01
250			27.67	33.62	39.14	31.71	37.28	42.58	35.75	41.10	46.02
70	0.5	35	28.37	32.17	35.28	31.16	34.56	37.41	34.26	37.16	39.55
100			30.27	35.04	38.98	33.41	37.64	41.12	36.59	40.39	43.32
130			32.74	38.69	43.22	36.21	41.5	45.52	39.81	44.38	47.96
160			36.11	42.67	47.77	39.72	45.66	50.24	43.32	48.65	52.71
200			40.79	48.35	54.09	44.39	51.34	56.55	47.99	54.33	59.02
250			44.22	52.36	58.4	47.82	55.35	60.87	51.42	58.34	63.34
70	1		25.54	28.86	31.81	28.72	31.93	34.55	32.39	34.99	37.37
100			26.96	31.39	35.07	30.63	34.45	37.89	34.33	37.67	40.71
130			29.73	34.73	39.47	33.43	38.12	42.29	37.12	41.52	45.11
160			32.53	38.59	43.89	36.22	41.99	46.72	39.93	45.41	49.55
200			36.26	43.83	49.95	39.98	47.25	52.67	43.78	50.67	55.49
250			38.83	47.08	53.79	42.52	50.51	56.62	46.22	53.93	59.45
70	2		23.82	27.11	29.45	27.08	29.71	31.57	30.48	32.33	34.23
100			24.51	28.06	30.61	27.91	30.67	33.28	31.49	34.15	36.7
130			25.29	28.94	32.56	28.77	32.54	35.89	32.82	36.20	39.34
160			26.08	30.93	35.23	30.12	34.59	38.55	34.16	38.24	41.99
200			27.87	33.66	38.82	31.91	37.32	42.15	35.95	40.98	45.57
250			28.63	34.96	40.69	32.67	38.62	44.14	36.71	42.28	47.58
70	0.5	40	30.58	34.81	38.31	33.37	37.17	40.28	36.16	39.56	42.41
100			32.44	37.58	41.85	35.27	40.04	43.98	38.41	42.64	46.12
130			34.34	40.89	45.91	37.74	43.7	48.22	41.21	46.50	50.52
160			37.52	44.81	50.43	41.11	47.67	52.78	44.72	50.66	55.24
200			42.19	50.36	56.62	45.79	53.35	59.09	49.39	56.34	61.55
250			45.62	54.37	61.00	49.22	57.36	63.40	52.82	60.35	65.87
70	1		27.44	31.22	34.24	30.54	33.87	36.81	33.72	36.93	39.55
100			28.60	33.33	37.29	31.96	36.38	40.07	35.63	39.45	42.89
130			31.03	36.54	41.65	34.73	39.73	44.46	38.42	43.12	47.29
160			33.83	40.19	46.06	37.53	43.59	48.89	41.22	46.99	51.72
200			37.56	45.40	52.02	41.26	48.83	54.84	44.98	52.25	57.67
250			40.12	48.66	55.97	43.83	52.08	58.79	47.52	55.51	61.62
70	2		25.56	29.51	32.33	28.82	32.11	34.45	32.08	34.71	36.57
100			26.22	30.47	33.48	29.51	33.06	35.61	32.91	35.66	38.28
130			26.89	31.00	34.31	30.29	33.94	37.56	33.78	37.54	40.89
160			27.67	32.35	36.98	31.07	35.93	40.23	35.11	39.59	43.55
200			28.82	35.00	40.55	32.87	38.66	43.82	36.91	42.32	47.16
250			29.58	36.31	42.37	33.62	39.96	45.69	37.67	43.62	49.14

C= content

PB = Placement break

PT= Placement temperature

4. PROPOSAL FOR CRACKING CRITERION

An interesting proposal for a criterion for assessing the cracking situation, which is at once simple but very useful for critical decision making in the field, is to check temperature drops in comparison to the structure´s temperature of stabilization.

By gaining practical knowledge of an admissible temperature drop, the following criterion can be established:

$$\nabla T = T\max - Tamb \leq \nabla Tadm$$

$$T\max = Maximum \ \ Temperature \ \ in \ \ the \ \ structure$$

$$Tamb = Ambient \ \ Temperature$$

$$where \ \ \nabla Tadm = admissible \ \ drop$$

$$\nabla T = Temperature \ \ Drop$$

By analyzing the temperature drop in a structure one can establish a critical alert limit and a limit that would indicate a high likelihood of thermal-originated cracking.

5. CONCLUSIONS

The temperature control of roller compacted concrete in the structure is to be constantly investigated by using real data, that is, by means of strict mix proportion studies from which the characterization of the properties of the concrete will be obtained. From this point on, the parametric study shown in this paper should be repeated.

A rather simple analysis can be made by building an abacus as proposed in 3.2.5, which will permit applications at the construction site.

The analysis of cooling temperatures indicates the likely risks of thermal –originated cracking of the concrete.

It is believed that the methodology shown above is a simple means of assessing the thermal behavior of roller compacted concrete structures. It must be noted that the face concrete [7] is not contemplated here, as it requires separate investigation due to being a region that is highly prone to thermal-originated cracking.

The figures in the abacus in Table 3.2.5 show that:

- For binder contents < 130kg/m3 the maximum temperatures occur below 45^{o}C (a limit that is quite acceptable for concrete structures), for most situations, except placement regimens at every 12 hours with a placing temperature of 35^{o}C, and at each 12 and 24 hours if placed at 40^{o}C;
- For binder contents ~ 200kg/m3 the maximum temperatures occur below 45^{o}C (a limit that again is quite acceptable for concrete structures), only for placement breaks above 1 day;
- For placement breaks of between 1 and 2 days (a more usual situation in RCC jobs) a maximum temperature of 45^{o}C (a usual limit condition for concretes) concern will begin when content is higher than 160kg/m3 and the placement temperature tops 30^{o}C;
- For RCC placement breaks of 12 hours, even when the RCC is placed at temperatures below the ambient´s, the Maximum Temperatures may be higher than 45^{o}C.
- It must be highlighted in this parametric study there were no considerations on the variation of the condition of “Restriction”, as distance grows from the foundation, as well as with respect to the height of the structure.

It is important to note that the verifications herein aim only to provide a preliminary risk analysis of the occurrence of cracks of a thermal origin. For more in-depth study, a more detailed analysis of each case is advised, adopting parameters that are suitable to the concrete and the ambient and construction conditions that better apply to the in-situ conditions of the structure to be analyzed.

6. REFERENCES

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