

# Reinforced short columns designed in accordance with the regulations fib Model Code 2020 Eurocode 2:2023 and ABNT NBR 6118:2023. sustainability study

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**Abstract:** This study presents an investigation into sustainability in the design of short reinforced concrete columns, following the guidelines of four technical regulations: fib Model Code 2020, Eurocode 2:2023, ABNT NBR 6118:2014, and ABNT NBR 6118:2023. The design considered two reinforcement ratios, with a minimum ( $\geq 0.4\%$ ) and a maximum lap splice ( $< 4.0\%$ ), and two strength classes, C20 and C50. The characteristic strength ( $f_{ck}$ ) was referenced at three different ages: 28, 56, and 91 days, resulting in 16 possible scenarios for the column segment. The concrete mix included two types of cement: CR, with a high clinker content ( $> 90\%$ ), and CS, with about 30% clinker. The comparative analysis focused on sustainability and dematerialization, considering only  $\text{CO}_{2\text{eq}}$  emissions. The results indicate that, according to the Eurocode 2 (EN 1992-1-1) criteria, concretes made with CS class cement and  $f_{ck}$  controlled at 56 days consistently achieve greater dematerialization and lower greenhouse gas emissions. This study demonstrates how design choices, combined with advanced concrete technology, can significantly enhance the sustainability of a structure.

**Key words:** column design; dematerialization; sustainability; greenhouse gases;  $\text{CO}_{2\text{eq}}$  emission

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## 1 Introduction

This paper presents a study of sustainability considering  $\text{CO}_{2\text{eq}}$  emissions and dematerialization, determined in accordance with the available Environmental Product Declarations, focused on the design of short reinforced concrete columns while adhering to the premises of four rules—technical standards: fib Model Code 2020 [1], Eurocode 2:2023 [2], ABNT NBR 6118:2014 [3], and ABNT NBR 6118:2023 [4]. For the design of the column section, different amounts of reinforcement, types of cement, and concrete strength classes were considered, with  $f_{ck}$  referring to various ages.

The design assumptions adopted for the sizing of the short, solid, square-section reinforced concrete column were based on data from a real-world case of a residential building<sup>1</sup>, with 2 basement levels, a ground floor, 24 standard stories, a machine room, an elevated water tank, and a roof. Only the column section between the 1st floor and the 2nd floor is considered, with a ceiling height of 2.88 m, the structure being subject to environmental aggressivity classes ranging from CAA I for C20 concrete to CAA II for C50 concrete columns, according to ABNT NBR 12655:2022 [5].

For wind loads, the building was designed considering the basic wind speed  $V_0 = 40$  m/s, topographic factor  $S_1 =$

1.00, roughness category IV (S<sub>2</sub>), building class C (S<sub>2</sub>), and statistical factor S<sub>3</sub> = 1.00, parameters in accordance with ABNT NBR 6123:1998 [6]. For seismic actions, the ABNT 15421:2023 [7] standard was followed for buildings located in seismic zone 0. For vertical actions, the values described in ABNT NBR 6120:2019 [8] were adopted for residential buildings. Regarding fire and fire safety requirements, the provisions of ABNT NBR 15200:2012 [9] were used as a basis, considering a TRRF of 90 minutes and the corresponding requirements regarding column detailing. The total number of column spans in this building is 1,008 (one thousand eight segments), and the standard floor area per floor is 365 m<sup>2</sup>.

The total characteristic normal force (NS<sub>k</sub>) for the design of this column section used as a representative example was 4000 kN, and the total characteristic moments to which it will be subjected were M<sub>xSk</sub> = M<sub>ySk</sub> = 120 kN·m. It was assumed that accidental actions correspond to 25% of the total characteristic normal force.

The objective of this study is to quantitatively demonstrate that design decisions, together with concrete technology, influence greenhouse gas emissions and the sustainability of a structure.

## 2 Short column design

The model for calculating compressive strength prescribed for the design of a new project, based on a specific assumed value for the characteristic compressive strength of concrete,  $f_{ck}$ , according to the new version of the fib Model Code for Concrete Structures 2020 (MC 2020) [1], is:

$$f_{cd} = \alpha_{cc} \cdot \eta_{cc} \cdot \frac{f_k}{\gamma_c} \quad (2.1)$$

Where:

$f_{cd}$  → design compressive strength of concrete;

$f_{ck}$  → characteristic compressive strength of concrete, at ages ranging from 28 to 91 days;

$\gamma_c$  → reduction factor for the characteristic strength of concrete;

$\alpha_{cc}$  → coefficient that accounts for opposing effects: on one hand, the increase in strength due to cement hydration, and on the other hand, the reduction in this strength caused by sustained high-level<sup>2</sup> long-term<sup>3</sup> loading;

$\eta_{fc}$  → reduction factor for strength<sup>4</sup> that takes into account the increase in brittleness with increasing concrete strength, calculated by:

$$\eta_{cc} = \left( \frac{40}{f_{ck}} \right)^{1/3} \leq 1.0 \quad (f_{ck} \text{ in MPa}) \quad (2.2)$$

According to MC 2020 [1], under normal design conditions, it can be assumed that the increase in strength after 28 days compensates for the effects of long-term loading, such that, for new structures loaded at 28 days or later, and with  $f_{ck}$  referring to 28 days, this coefficient can be taken as  $\alpha_{cc} = 1.0$ . In this study,  $\eta_{fc} = 1.0$  for  $f_{ck} = 20$  MPa and  $\eta_{fc} = 0.93$  for  $f_{ck} = 50$  MPa.

For structures loaded at ages greater than 91 days and where the reference and control date for  $f_{ck}$  is greater than 28 days but equal to or less than 56 days, according to Eurocode 2 [2], it is correct to continue considering  $\alpha_{cc} = 1.0$ , provided that the cement class is CS.

For  $f_{ck}$  ages greater than 28 days in the case of MC 2020 [1] and for  $f_{ck}$  ages greater than 56 days in the case of Eurocode 2 [2], up to 91 days, the code recommends considering  $\alpha_{cc} = 0.85$ . Eurocode 2 [2] also allows the value of  $\alpha_{cc}$  to vary from 0.8 to 1.0, depending on the provisions of the National Annex<sup>5</sup> of each European Union country, and it is recommended to adopt the value  $\alpha_{cc} = 1.0$  for general cases.

In the case of the ABNT NBR 6118:2023 standard [4], the coefficient is more conservative and is set at 0.85, noting

that the coefficient appears in the calculation of the maximum design stress  $\sigma_{cd}$  rather than in the calculation of the design resistance  $f_{cd}$

The text of standard ABNT NBR 6118:2014 [3] did not consider the fragility coefficient  $\eta_{fc}$  whereas the new text of ABNT NBR 6118:2023 [4] considers this fragility coefficient using the same model as MC 2020 [1]. The Brazilian standard, in both the 2014 version [3] and the current 2023 version [4], specifies  $f_{ck}$  referring only to 28 days of age.

Once the design compressive strength of the concrete ( $f_{cd}$ ) is defined, the concrete stress ( $\sigma_{cd}$ ) is obtained according to the stress-strain diagram presented in MC 2020 [1], ABNT NBR 6118 [4], and Eurocode 2 [2], represented by the following equation:

$$\sigma_{cd} = f_{cd} \cdot \left[ 1 - \left( 1 - \frac{\varepsilon_c}{\varepsilon_{c2}} \right)^n \right] \quad (2.3)$$

For concrete with a characteristic strength of up to 50 MPa according to ABNT NBR 6118:2023 [4], and for concrete ranging from 12 MPa to 100 MPa, MC 2020 [1] and Eurocode 2 [2] prescribe:

- $\varepsilon_{c2} = 0.20\%$ , specific shortening strain of the concrete at the onset of the creep plateau;
- $\varepsilon_{cu} = 0.35\%$ , specific shortening strain of the concrete at failure;
- $n = 2$ , dimensionless parameter.

For concretes with characteristic strength between 55 MPa and 90 MPa, not analyzed in this study, only according to ABNT NBR 6118:2023 [4] and its previous version ABNT NBR 6118:2014 [3]:

- $\varepsilon_{c2} = 0.20\% + 0.0085\% (f_{ck} - 50) 0.53$ ;
- $\varepsilon_{cu} = 0.26\% + 3.5\% [(90 - f_{ck}) / 100]^4$ ;
- $n = 1.4 + 23.4 [(90 - f_{ck}) / 100]^4$

The limitations on specific strains reflect the greater brittleness of concretes with a compressive exceeding 50 MPa. From the authors' perspective, in Brazilian standards, as long as these limitations on specific strains are maintained, there is no technical reason to also introduce or maintain the fragility coefficient  $\eta_{fc}$ . For didactic and conceptual reasons, it is preferable to maintain the specific strain limitations and eliminate the fragility coefficient  $\eta_{fc}$  from the Brazilian standard ABNT NBR 6118:2023 [4].

Partial safety factors, also known as weighting coefficients, aim to introduce safety into the design of reinforced concrete structures, on the one hand by increasing the applied forces and on the other by reducing the characteristic strengths of the materials to be used. This procedure is known as the semi-probabilistic method in Brazil and the partial coefficient method in MC 2020 [1] and Eurocode 2 [2].

The definition of the values of these partial safety factors is primarily determined by the probabilistic analysis of the structure's conditions and risks, its uses, simplifications, and uncertainties in the calculation model, as well as variations in these parameters. In practice, the semi-probabilistic or partial factor method is only probabilistic in its consideration of the distribution of material strengths and actions, because once the weighting coefficients are introduced, the analysis is entirely deterministic [10]. Table 2.1 shows the different values of the partial safety factors recommended by the under consideration.

Table 2.2 shows the combinations considered in this study for the design of short columns with two classes of characteristic compressive strength of concrete (C20 and C50).

The classic criteria for the design and detailing of columns were followed, taking into account the differences in the calculation of deformation specific requirements according to each standard. A nominal cover of  $c = 30$  mm was adopted

for C20 concrete and  $c = 25$  mm for C50 concrete.

Table 2.1. Partial safety factors according to MC 2020 [1]; EN 1992:2023-1-1 [2], EN 1990:2002 [12], ABNT NBR 6118:2023 [4], and ABNT NBR 8681:2003 [11]

ABNT NBR 6118:2023 [4] and ABNT NBR 8681:2003 [11]		MC 2020 [1]; EN 1992:2023-1-1 [2] and EN 1990:2002 [12]	
Materials ( $\gamma_m$ )	Actions ( $\gamma_f$ )	Materials ( $\gamma_m$ ) <sup>(1)</sup>	Actions ( $\gamma_f$ ) <sup>(1)</sup>
$\gamma_c$ (concrete) = 1.4	$\gamma_g$ (permanent actions) = 1.4	$\gamma_c$ (concrete) = 1.4 to 1.6	$\gamma_g$ (permanent loads) = 1.3 to 1.4
$\gamma_s$ (steel) = 1.15	$\gamma_q$ (variable actions) = 1.4	$\gamma_s$ (steel) = 1.1 to 1.175	$\gamma_q$ (variable loads) = 1.3 to 1.7

<sup>(1)</sup> In this study, the following values were adopted:  $\gamma_c=1.5$ ;  $\gamma_s=1.15$ ;  $\gamma_g=1.35$ ; and  $\gamma_q=1.5$ , which correspond to the consequence class CC2 of the 2020 MC [1].

Table 2.2. Combinations used in this study

Regulation	Strength class	$\eta_{ic}$	$\alpha_{cc}$	$\gamma_c$	$\gamma_s$	$\gamma_f$ (Permanent action)	$\gamma_f$ (Variable action)	$f_{cd}/f_{ck}$ (%)
ABNT 6118:2023 [4] 28 days	C20	1.00	0.85	1.4	1.15	1.4	1.4	61%
	C50	0.93	0.85	1.4	1.15	1.40	1.40	56%
MC 2020 [1] 28d EC 2 [2] 28d to 56d	C20	1.00	1.00	1.5	1.15	1.35	1.50	67%
	C50	0.93	1.00	1.5	1.15	1.35	1.50	62%
MC 2020 [1] >28d EC 2 [2] 57d to 91d	C20	1.00	0.85	1.5	1.15	1.35	1.5	57%
	C50	0.93	0.85	1.5	1.15	1.35	1.50	53%

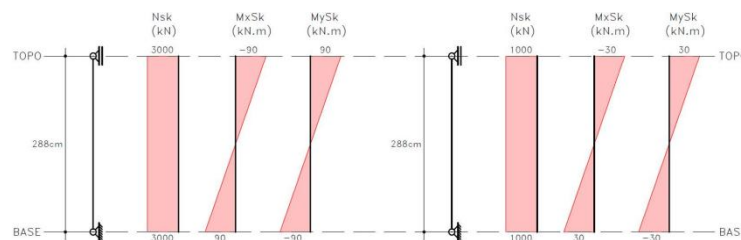


Figure 2.1. Characteristic design load on the column: dead load (left side) and live load (right side)

All design alternatives for this column section were considered prismatic columns with a square cross-section and short length ( $\lambda \leq 35$ ) with a length  $l_c = 2.88$  m, where two column details were extracted from each strength class: one alternative with minimum reinforcement close to the required limit ( $\geq 0.4\%$ ) and another with details close to the maximum allowable amount of steel in a section with an overlap joint (around 4% of  $A_s/A_c$ ).

For the nominal load, the characteristic load was defined as shown in Figure 2.1.

Table 2.3 shows the dimensions, reinforcement quantities, and slenderness ratios, detailed for each possible design alternative for the column section.

As the concrete strength class increases, the decrease in column area from the minimum reinforcement configuration to the maximum reinforcement configuration does not maintain the same proportion as the reduction in concrete area. This is due to the loss of the initial lever arm, which subtly shifts from domain 5 to domain 4 as the concrete strength class increases. The design of minimum reinforcement for columns requires that the steel area be at least 15% of the  $N_d/f_{yd}$  ratio, which results in the reinforcement for columns in strength class C50 having a minimum amount of approximately 0.90% rather than the 0.40% for C20.

Table 2.3. Summary of options for detailing the column section

Regulation	Strength class	Dimensions (cm)	Steel area (cm <sup>2</sup> )	Steel ratio	Slenderness ratio $\lambda$	Concrete volume (m <sup>3</sup> )	Steel consumption (kg)
NBR 6118:2023 [4] (28 days)	C20	69 × 69	19.63	0.41% <sup>4</sup>	14	1.37	82
		49 × 49	96.51	.02%	20	0.69	235
	C50	48 × 48	19.63	0.85% <sup>3</sup>	21	0.66	65
		41 × 41	64.34	.83%	24	0.48	160
MC 2020 [1] Eurocode 2 [2] (28 to 56 days)	C20	66 × 66	19.63	0.45% <sup>3</sup>	15	1.25	80
		48 × 48	91.07	.95%	21	0.66	235
(28 to 56 days)	C50	45 × 45	19.63	0.97% <sup>3</sup>	22	0.58	55
		40 × 40	57.30	.58%	25	0.46	144
MC 2020 [1] (29 to 91 days)	C20	71 × 71	19.63	0.39% <sup>3</sup>	14	1.45	82
		50 × 50	96.51	.86%	20	0.72	236
Eurocode 2 [2] (57 to 91 days)	C50	49 × 49	19.63	0.82% <sup>3</sup>	20	0.69	66
		42 × 42	64.34	.65%	24	0.51	170

For comparison, Figure 2.3 shows the concrete volume ( $V_c$ ) for each of the design alternatives for this column section with minimum reinforcement.

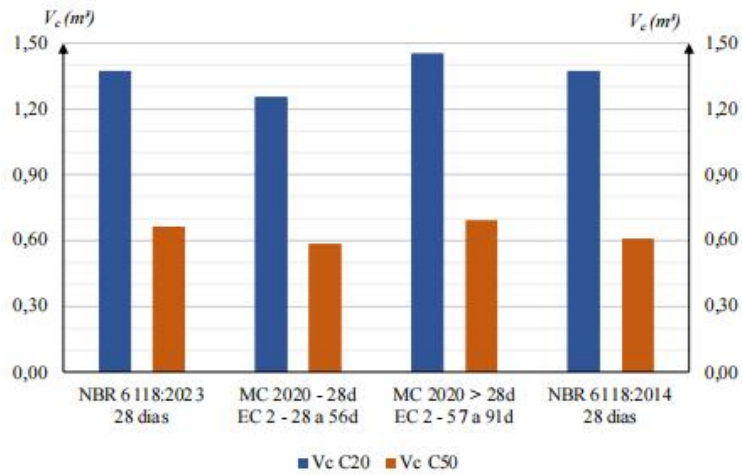


Figure 2.3. Bar chart indicating the volume of concrete corresponding to each design alternative of the column segment, for a minimum reinforcement ratio ( $\geq 0.4\%$ )

Figure 2.4 shows the volume of concrete ( $V_c$ ) with the maximum reinforcement (around 4%), showing a significant reduction in the total concrete volume of each design alternative for the column segment.

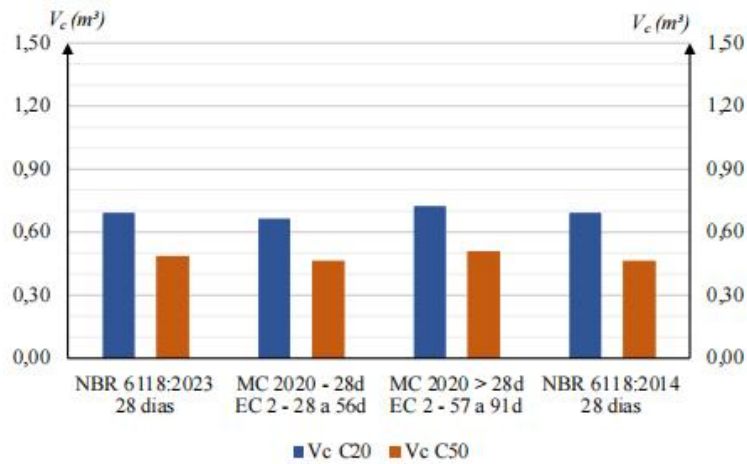


Figure 2.4. Bar chart indicating the volume of concrete corresponding to each design alternative of the column segment, for a maximum reinforcement ratio (around 4%)

In order to show the influence of concrete strength, C20 or C50, Figure 2.5 presents the bar chart of longitudinal steel area ( $A_s$ ) for the maximum reinforcement ratio,  $< 4\%$ .

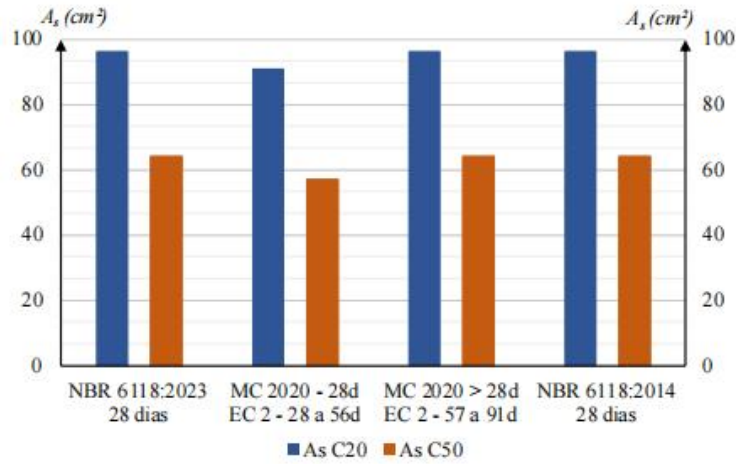


Figure 2.5. Bar chart indicating the steel area corresponding to each design alternative of the column segment, considering the maximum reinforcement ratio (around 4%)

To complement the study of column section design alternatives based on various code criteria and concrete strength classes, the section with a fixed square cross-section of 50 x 50 cm was also analyzed for concrete classes C20 and C50, simulating an architectural design requirement.

In this case, since the volume of concrete is a constant, Figure 2.6 shows the variation in the steel area ( $A_s$ ) as a function of the concrete strength class.

It is observed that, for the case under study, sizing according to the requirements of MC 2020 [1] with  $f_{ck}$  at 28 days and Eurocode 2 [2] with  $f_{ck}$  at 28 days or 56 days leads to more economical columns regardless of the strength class considered. The requirements of the Brazilian standard ABNT NBR 6118:2023 [4] result in bulkier columns; that is, it is a more conservative standard, which is inconsistent with a country whose socioeconomic indicators are lower than those of European countries.

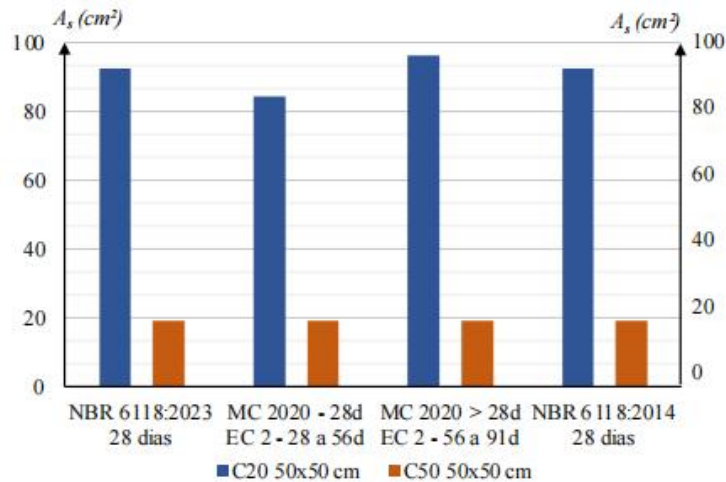


Figure 2.6. Bar chart indicating the variation of steel area ( $A_s$ ) when fixing the dimension of the column segment and changing the concrete strength class

With the goal of sustainability, which aims to produce more with less—that is, it is necessary to dematerialize—for the same load and with optimized geometry, using concrete with  $f_{ck} = 50$  MPa in a column instead of concrete with  $f_{ck} = 20$  MPa, the concrete volume can be reduced from 1.45 m<sup>3</sup> (in the case of minimum reinforcement and C20 concrete) to just

0.46 m<sup>3</sup> (with maximum reinforcement ratio and C50 concrete), contributing significantly to dematerialization.

By the same reasoning, the reinforcement for this column section can be reduced from 236 kg for C20 to just 55 kg when using C50, representing a significant savings in steel, taking dematerialization into account.

Similarly, considering the same stresses and fixing the geometry of the column section at (50 cm x 50 cm), by using concrete with  $f_{ck} = 50$  MPa instead of concrete with  $f_{ck} = 20$  MPa, the total steel mass can be reduced from 96 kg for C20 to just 20 kg for C50, representing a massive savings in steel—approximately four times less material—for the same volume of concrete and formwork area.

The influence of the control or reference date for the  $f_{ck}$  must also be considered. Mix proportions for the same materials—whether based on 56 days or 91 days—for the same  $f_{ck}$  value will result in concrete mixes with lower cement consumption per cubic meter, which can yield even greater sustainability benefits, as demonstrated in the sequence of this study.

### 3 Material consumption as a function of the $f_{ck}$ reference date

MC 2020 [1] in section 14.6.1.6.1 "Development of strength with time," as well as Annex B of Eurocode 2 [2] "Time-dependent behavior of materials: strength, creep, shrinkage, and elastic strain of concrete and relaxation of prestressing steel," recommend the use of an exponential expression to represent the growth of concrete compressive strength as a function of time, namely:

$$\frac{f_{c(t)}}{f_{c(t_{ref})}} = e^{\left\{ s_c \cdot \left[ 1 - \sqrt{\frac{t_{ref}}{t}} \right] \cdot \left( \sqrt{\frac{28}{t_{ref}}} \right) \right\}} \quad (3.1)$$

Where:

$s_c$ : dimensionless coefficient ranging from 0.1 to 0.6, as shown in Table 3.1.

Table 3.1. Values of  $s_c$  according to fib (MC 2020) [1] and Eurocode 2 [2]

Concrete strength (MPa)	Class CR	$s_c$ Class CN	Class CS
$f_{ck} \leq 35$	0.3	0.5	0.6
$35 < f_{ck} < 60$	0.2	0.4	0.5
$f_{ck} \geq 60$	0.1	0.3	0.4

Note: The CR, CN, and CS classes are determined based on the type and strength class of the cement. To determine the CR, CN, and CS classes, refer to Table 14.6-8 "Strength development classes of concrete" in MC 2020 [1], as well as standards EN 197-1 [13] "Cement–Part 1: Composition, specifications and conformity criteria for common cements" and EN 206 [14] "Concrete–Specification, performance, and conformity." Simply put, the following can be associated with the Brazilian context: CR (concrete with CP V cement); CN (concrete with CP II cement); and CS (concrete with CP III or CP IV cement).

$f_{c(t)}$ : compressive strength at age  $t$ , expressed in MPa;

$t$ : age of concrete in days, calculated according to the expression:

$$t = \sum_{i=1}^n \Delta t_i e^{\left[ \frac{13.65 - \frac{4000}{273 + T_{(\Delta t_i)}}}{\Delta t_i} \right]} \quad (3.2)$$

Where:

$t$ : adjusted concrete age as a function of temperature, in days;

$\Delta t_i$ : number of days during which the temperature  $T$  prevails;

$T_{(\Delta t_i)}$ : mean temperature in °C during the time interval  $\Delta t_i$ ;

$t_{ref}$ : control and reference age for  $f_{ck}$ , in days, which may vary from 28 to 91 days;

$f_{c(t_{ref})}$ : mean compressive strength at age  $t_{ref}$ , expressed in MPa.

As a premise of this study, it was assumed that the concrete will always be at a temperature of  $T_{(\Delta t_i)} = 20^\circ\text{C}$  during the days up to the control age, regardless of the use of this formulation.

The authors also disagree with this formulation, since accelerating and maintaining concrete at temperatures above  $20^\circ\text{C}$  leads to lower long-term final strengths than those obtained from the same concrete cured at  $20^\circ\text{C}$  during the early ages. Accelerated curing processes with initial temperatures above  $30^\circ\text{C}$  lead to higher early-age strengths, but in the long term—28 days or more—the final results end up being lower than those of concrete maintained at temperatures around  $20^\circ\text{C}$  to  $25^\circ\text{C}$ . High temperatures lead to larger, brittle microstructural grains at the interfaces, while lower temperatures lead to grain refinement and, consequently, higher ultimate strengths.

For simplicity, this study considers concrete produced with CR and CS cements, as shown in Table 3.1. The strengths  $f_{c(28)}$ ,  $f_{c(56)}$ , and  $f_{c(91)}$  were also adopted as a reference for concrete strength [ $f_{c(t_{ref})}$ ], for the purposes of comparative analysis.

The  $f_{ck}$  values adopted in this study were 20 MPa and 50 MPa. The values for concrete mix design,  $f_{cm}$ , should be 26.6 MPa and 56.6 MPa, respectively, assuming a constant standard deviation of 4 MPa. It should be noted that both MC 2020 [1] and Eurocode 2 [2] prescribe a constant standard deviation equal to 4.8 MPa, that is, they consider greater variability in concrete strengths than that provided for in Brazilian standards.

In this way, it was possible to determine the compressive strength required at 28 days for the different strength classes studied (C20 and C50), for the different control ages  $f_{ck}$  (28, 56, and 91 days), and for the two types of cement considered, CR and CS, as detailed in Table 3.2.

Table 3.2. Average compressive strength values at 28 days [ $f_{cm}(28)$ ], calculated according to Equation 3.1, for the strength classes (C20 and C50), according to the control age (28, 56, and 91 days), for concretes produced with CR and CS cement

$t_{ref}$ (days)	Strength class	$f_{cm(t_{ref})}$ (MPa)	Cement type (MPa)	$s_c^{(1)}$	$f_{cm(28)}^{(2)}$
28	C20	26.6	CS	0.6	26.6
			CR	0.3	26.6
	C50	56.6	CS	0.5	56.6
			CR	0.2	56.6
56	C20	26.6	CS	0.6	22.3
			CR	0.3	24.4
	C50	56.6	CS	0.5	48.9
			CR	0.2	53.4
	C20	26.6	CS	0.6	20.4
			CR	0.3	23.3
91	C50	56.6	CS	0.5	45.3
			CR	0.2	51.8

Notes:

<sup>(1)</sup>  $s_c$  value obtained from Table 3.1.

<sup>(2)</sup> Average compressive strength at 28 days calculated using the formula specified in fib MC 2020 [1] and EUROCODE 2 [2] (Equation 3.1), varying  $t_{ref}$ : 28, 56, and 91 days.

To estimate the performance index, expressed in kg of cement per MPa, a reference average performance of 9/10 kg of cement/MPa was adopted for  $f_{cm}$  from 20 to 30 MPa and of 7/7.5 kg of cement/MPa for  $f_{cm}$  of 40 to 60 MPa, for CR and CS cements, respectively, based on the authors' experience, the literature on the subject [15], and the dosages commonly used in concrete plants. It should be noted that this study proposes to discuss sustainability in a simplified manner,

disregarding the regulatory limits on minimum cement consumption per m<sup>3</sup> and maximum water-to-cement ratio set forth in the aforementioned standards.

Thus, considering the volume of concrete used in each of the alternatives studied for this column section, sized according to the criteria of the different regulations and the same performance index adopted, a summary of the cement consumption obtained is presented in Table 3.3, detailing the cement consumption per m<sup>3</sup> of concrete in each of the alternatives for the design of the column section under study.

Table 3.3. Material consumption and cement savings relative to concrete mixes controlled at 28 days of age, for the different design alternatives

Regulations reference age	Concrete strength class	Concrete volume (m <sup>3</sup> ) <sup>(1)</sup>	Cement type	Cement consumption per m <sup>3</sup> of concrete (kg/m <sup>3</sup> )			Cement mass for column construction (kg)		
				28 days kg/m <sup>3</sup>	Reference age (28, 56, or 91 days) kg/m <sup>3</sup>	Cement savings 28 days <sup>(2)</sup> kg	28 days kg	Reference age (28, 56, and 91 days) kg	Cement savings compared to 28 days <sup>(2)</sup> kg
NBR 6118:2023 [4] 28 days	C20	1.37	CS	266	266	0	364	364	0
			CR	239	239	0	328	328	0
		0.69	CS	266	266	0	184	184	0
			CR	239	239	0	165	165	0
	C50	0.66	CS	425	425	0	280	280	0
			CR	396	396	0	262	262	0
		0.48	CS	425	425	0	204	204	0
			CR	396	396	0	190	190	0
MC 2020 [1] 28 days	C20	1.25	CS	266	266	0	333	333	0
			CR	239	239	0	299	299	0
		0.66	CS	266	266	0	176	176	0
			CR	239	239	0	158	158	0
	C50	0.58	CS	425	425	0	246	246	0
			CR	396	396	0	230	230	0
		0.46	CS	425	425	0	195	195	0
			CR	396	396	0	182	182	0
Eurocode 2 [2] 56 days	C20	1.25	CS	266	223	43	333	279	54
			CR	239	220	19	299	275	24
		0.66	CS	266	223	43	176	147	29
			CR	239	220	19	158	145	13
	C50	0.58	CS	425	367	58	246	213	33
			CR	396	374	22	230	217	13
		0.46	CS	425	367	58	195	169	26
			CR	396	374	22	182	172	10
MC 2020 [1] 91 days and Eurocode 2 [2] 91 days	C20	1.45	CS	266	204	62	386	296	90
			CR	239	210	29	347	304	43
		0.72	CS	266	204	62	192	147	45
			CR	239	210	29	172	151	21
	C50	0.69	CS	425	340	85	293	234	59
			CR	396	363	33	273	250	23
		0.51	CS	425	340	85	217	173	44
			CR	396	363	33	202	185	17

<sup>(1)</sup> Value obtained considering the column dimensions indicated in Table 3.1 and a height of 2.88 m.

<sup>(2)</sup> Value obtained by subtracting the cement consumption at 28 days of age from the cement consumption at the reference age (28, 56, or 91 days)

#### 4 Emissions and CO<sub>2EQ</sub> intensity (IC)

The objective of this article is to present a comparative analysis of CO<sub>2eq</sub> emissions for the different design alternatives considered in this study. Therefore, for each of the alternatives studied, the corresponding CO<sub>2eq</sub> emissions and

the associated eco-efficiency indicators in kg CO<sub>2</sub>/MPa were calculated; the latter are referred to as CO<sub>2eq</sub> intensity (IC).

To quantify CO<sub>2eq</sub> emissions, the values from the EPDs (Environmental Product Declarations) available in the "EPD documents" on the website [www.environdec.com/home](http://www.environdec.com/home), the data provided by the "Construction Environmental Performance Information System – Sidac" available at [www.sidac.org](http://www.sidac.org), and the data obtained by CECarbon energy consumption and carbon emissions calculator for buildings available on the website [www.cecarbon.com.br](http://www.cecarbon.com.br) were used.

Table 4.1. Amount of CO<sub>2</sub> released in kg CO<sub>2eq</sub>, depending on the material used, considering product stages A1, A2, and

A3

Material	Sidac <sup>(1)</sup> (kg CO <sub>2eq</sub> .)	CECarbon <sup>(2)</sup> (kg CO <sub>2eq</sub> .)	ArcelorMittal Piracicaba (kg CO <sub>2eq</sub> .) <sup>(3)</sup>	EPD Documents Votorantim Santa Elena (kg CO <sub>2eq</sub> .) <sup>(4)</sup>	Gerdau Araçariçuama (kg CO <sub>2eq</sub> .) <sup>(4)</sup>
Steel CA-50, per t	425.9 – 1,061.0	-	786	-	1,070
Cement CP III (CS), per t	235.3 – 681.7	-	-	384	-
Cement CP V (CR), per t	776.4 – 994.3	-	-	852	-
Pine wood, per m <sup>2</sup> <sup>(5)</sup>	0.3 – 0.7	-	-	-	-
Plywood, per m <sup>2</sup> <sup>(6)</sup>	-	6.8	-	-	-
Cross-laminated timber (CLT), per m <sup>2</sup> <sup>(7)</sup>	-	3.1	-	-	-
Glued-laminated timber, per m <sup>2</sup> <sup>(8)</sup>	-	3.3	-	-	-
Rough sawn wood (planted), per m <sup>3</sup> <sup>(9)</sup>	-	50.6	-	-	-

<sup>(1)</sup> Source: [www.sidac.org.br/busca](http://www.sidac.org.br/busca)

<sup>(2)</sup> Source: [www.cecarbon.com.br](http://www.cecarbon.com.br)

<sup>(3)</sup> Source: Environmental Product Declaration No. EPD-ARC-20170124-CBD1-EM (valid until 03/22/2023), available at: [www.ibu-epd.com](http://www.ibu-epd.com). According to the LCA calculation rules presented in this document, the CO<sub>2</sub> emissions indicated are valid for ArcelorMittal's plants in Brazil located in: Cariacica, Itaúna, João Monlevade, Juiz de Fora, and Piracicaba, although this EPD has expired.

<sup>(4)</sup> Source: [www.environdec.com/library](http://www.environdec.com/library)

<sup>(5)</sup> The amount of CO<sub>2</sub> released was calculated based on a formwork thickness of 18 mm. Sidac indicates, for pine wood, a CO<sub>2</sub> release ranging from 19.06 kg CO<sub>2eq</sub>. to 39.15 kg CO<sub>2eq</sub>. per m<sup>3</sup> of wood.

<sup>(6)</sup> The amount of CO<sub>2</sub> released was calculated based on a formwork thickness of 18 mm. For plywood, CECarbon indicates a CO<sub>2</sub> release of 378 kg CO<sub>2eq</sub>. per m<sup>3</sup>.

<sup>(7)</sup> The amount of CO<sub>2</sub> released was calculated based on a formwork thickness of 18 mm. For cross-laminated timber, CECarbon indicates a CO<sub>2</sub> release of 171.12 kg CO<sub>2eq</sub>. per m<sup>3</sup>.

<sup>(8)</sup> The amount of CO<sub>2</sub> released was calculated based on a formwork thickness of 18 mm. For glued laminated timber, CECarbon indicates a CO<sub>2</sub> release of 183.6 kg CO<sub>2eq</sub>. per m<sup>3</sup>.

<sup>(9)</sup> The amount of CO<sub>2</sub> released was calculated using 75 mm x 75 mm battens and raw sawn timber with a specific mass of 550 kg/m<sup>3</sup> (according to Table 1 of ABNT NBR 6120:2019 [8] "Actions for the calculation of building structures, considering solid coniferous wood, strength class C25"). CECarbon indicates, for the case of raw sawn (planted) wood, a CO<sub>2</sub> emission of 92 kg CO<sub>2eq</sub>. per ton.

Table 4.1 shows the CO<sub>2eq</sub>. values per ton of material produced in Brazil for steel and cement, and per m<sup>2</sup> of formwork, assuming that the formwork was made of 18 mm thick plywood, reinforced with 75 mm x 75 mm (strips) of untreated

wood [16] spaced every 35 cm.

Likewise, for the construction of the support for securing the column formwork (lower frames), 25 mm thick and 100 mm wide wooden slats were used. Horizontal bracing (metal profile guides), tie-downs with anchor bars, plumb lines, squares, etc., were not considered in this study since they are components of the formwork system that can be reused several times.

Based on the data presented, it was possible to obtain the expected average volume of rough-sawn lumber (in m<sup>3</sup>) per m<sup>2</sup> of plywood panel, which is 0.025 m<sup>3</sup>/m<sup>2</sup>. Therefore, in this study, a factor of 8.0 kg CO<sub>2eq</sub>/m<sup>2</sup> of formwork was adopted, in accordance with the calculations detailed below:

$$\text{CO}_{2\text{eq.}} \text{ emissions formwork} = [6.8 \text{ kgCO}_{2\text{eq.}}/\text{m}^2] + [(0.025 \text{ m}^3/\text{m}^2) \cdot 50.6 \text{ kgCO}_{2\text{eq.}}/\text{m}^3]$$

$$\text{CO}_{2\text{eq.}} \text{ emissions from formwork} = [6.8 \text{ kg CO}_{2\text{eq.}}/\text{m}^2] + [1.2 \text{ kg CO}_{2\text{eq.}}/\text{m}^2]$$

$$\text{CO}_{2\text{eq.}} \text{ emissions from formwork} = 8.0 \text{ kg CO}_{2\text{eq.}}/\text{m}^2$$

Based on the data presented in Table 4.1 and the quantities of materials (steel, cement, and formwork), it was possible to calculate the amount of CO<sub>2eq</sub> for each of the design alternatives for the column section under study, as well as the CO<sub>2eq</sub> intensity (IC) for each  $f_{cm(t_{ref})}$  resistance, which is presented below in Table 4.2.

For a better visualization of the figures presented in Table 4.2, Figures 4.1 and 4.2 graphically present the CO<sub>2eq</sub> emissions for each studied alternative, considering designs with minimum and maximum amounts of reinforcement, respectively.

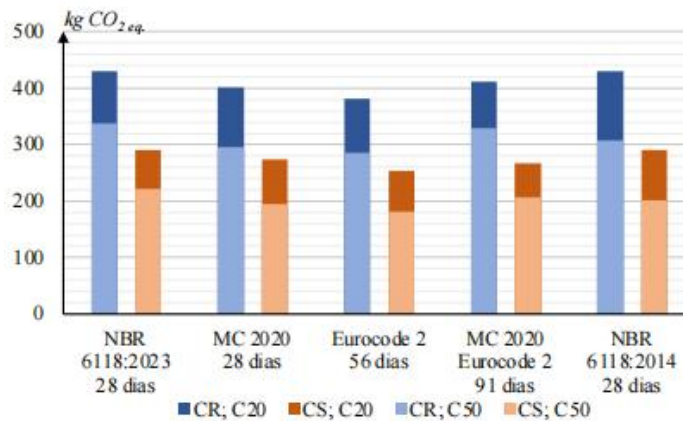


Figure 4.1. Bar chart showing CO<sub>2</sub> emissions in kg CO<sub>2eq.</sub> for alternative column designs with minimum steel quantities

Table 4.2. Amount of CO<sub>2eq.</sub> released per studied alternative in kg CO<sub>2eq.</sub>

Regulations	Strength class	Steel consumption (kg) <sup>(1)</sup>	Formwork area (m <sup>2</sup> ) <sup>(2)</sup>	Cement mass in the column (kg) <sup>(3)</sup>	CO2 emissions per column (kg CO <sub>2eq.</sub> )	IC per column (kg CO <sub>2</sub> /MPa)
NBR 6118:2023 [4] 28 days	C20	82	7.95	364 kg CS 328 kg CR	291 431	10.9 16.2
		235	5.64	184 kg CS 165 kg CR	367 437	13.8 16.4
		65	5.53	280 kg CS 262 kg CR	221 337	3.9 6.0
	C50	160	4.72	204 kg CS 190 kg CR	287 371	5.1 6.6
		80	7.60	333 kg CS 299 kg CR	274 401	10.3 15.1
		235	5.53	176 kg CS 158 kg CR	363 430	13.6 16.2
MC 2020 [1] 28 days	C20	55	5.18	246 kg CS 230 kg CR	195 296	3.4 5.2
		144	4.61	195 kg CS 182 kg CR	266 346	4.7 6.1
		80	7.60	279 kg CS 275 kg CR	254 381	9.5 14.3
	C50	235	5.53	147 kg CS 145 kg CR	352 419	13.2 15.8
		55	5.18	213 kg CS 217 kg CR	182 285	3.2 5.0
		144	4.61	169 kg CS 172 kg CR	256 338	4.5 6.0
Eurocode 2 [2] 56 days	C20	82	8.18	296 kg CS 304 kg CR	267 412	10.0 15.5
		236	5.76	147 kg CS 151 kg CR	355 427	13.3 16.1
		66	5.64	234 kg CS 250 kg CR	206 329	3.6 5.8
	C50	170	4.84	173 kg CS 185 kg CR	287 378	5.1 6.7

<sup>(1)</sup> According to the document "Environmental Product Declaration Reinforcing Steel Bar Gerdau GG 50," 1,070 kg of CO<sub>2</sub> per ton of steel (kg CO<sub>2eq.</sub>), a value obtained by summing the emission values in stages A1 (Raw material supply), A2 (Transportation), and A3 (Core process).

<sup>(2)</sup> The value of 8 kg of CO<sub>2</sub> per m<sup>2</sup> of formwork was considered, as justified in the text.

<sup>(3)</sup> According to the document "Environmental Product Declaration for Cement CP III 40 RS," 384 kg of CO<sub>2</sub> per ton of cement (kg CO<sub>2eq.</sub>), a value obtained by summing the emission values in stages A1 (Raw material supply), A2 (Transportation), and A3 (Core process). According to the document "Environmental Product Declaration for Cement CP V ARI," 852 kg of CO<sub>2</sub> per ton of cement (kg CO<sub>2eq.</sub>), a value obtained by summing the emission values in stages A1 (Raw material supply), A2 (Transportation), and A3 (Core process).

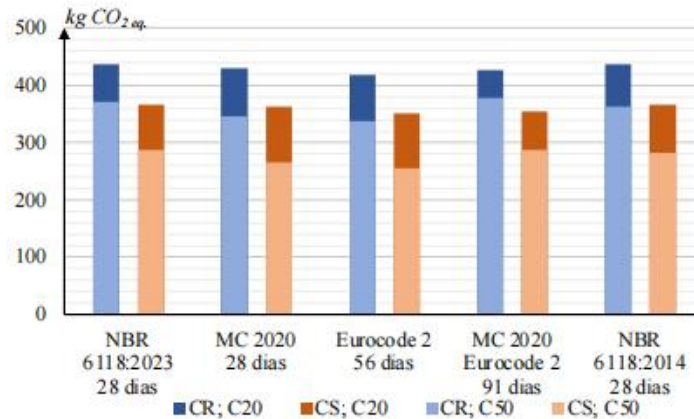


Figure 4.2. Bar chart showing CO<sub>2</sub> emissions in kg CO<sub>2eq.</sub> for the alternative column design with the maximum amount of steel

As shown, a column section designed for the same function and load can emit between 182 kg CO<sub>2eq.</sub> (IC = 3.2 kg CO<sub>2</sub>/MPa) and 437 kg CO<sub>2eq.</sub> (IC = 16.4 kg CO<sub>2</sub>/MPa), depending on a design decision made by the structural engineer during the design phase, combined with concrete technology for mix optimization and the use of different cements. In relative terms, this range can vary from 1 to 2.4 times, which is quite significant.

Figure 4.3 schematically presents the two alternatives for calculating the column sections in this study that exhibit the highest and lowest CO<sub>2</sub> emissions. This figure also includes detailed emissions by material used, as well as the rest of the information characterizing each of the alternatives for sizing and constructing the same column.

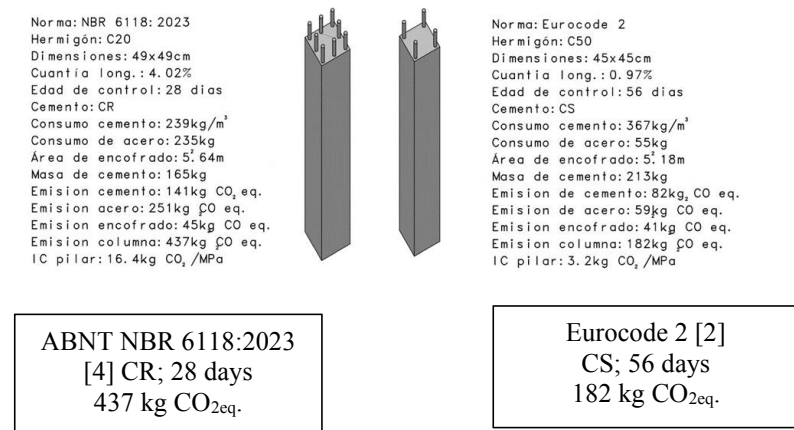


Figure 4.3. Alternatives for calculating column spans in this study that result in higher and lower CO<sub>2eq.</sub> emissions

This enormous advantage can only be achieved under ideal conditions of design freedom. Under normal conditions, with architectural and construction constraints, the benefits may be more limited.

In any case, it can be said that by using CS cement instead of CR cement, for any situation and even taking into

account that 0.5 to 1 kg more CS cement is needed per MPa, the structure will emit fewer greenhouse gases.

It was also observed that columns designed with a minimum amount of reinforcement emit fewer greenhouse gases.

The adoption of a reference age for  $f_{ck}$  of 56 days instead of 28 days in this study always led to a reduction in greenhouse gas emissions.

It is also possible to perform a similar analysis of CO<sub>2</sub> emissions by fixing the dimensions of this column section and varying the steel area ( $A_s$ ), the type of cement, as well as the concrete strength class (C20 or C50).

Table 4.3 shows the CO<sub>2eq</sub> emissions, with the column section dimensions fixed at 50 x 50 cm and a ceiling height of 2.88 m, simulating architectural constraints.

As shown in Table 4.3, a column intended for the same function, under the same load, with the same geometry and square cross-section, can emit from 201 kg CO<sub>2eq</sub>. (IC = 3.6 kg CO<sub>2</sub>/MPa) to 439 kg CO<sub>2eq</sub>. (IC = 16.5 kg CO<sub>2</sub>/MPa), depending on a design decision made by the structural engineer during the design phase and combined with concrete technology in the optimization of the mix and different cements. In relative terms, this can range from 1 to 2.2 times, which is very significant.

Table 4.3. Amount of CO<sub>2</sub> released for each studied alternative, considering fixed dimensions (50 x 50 x 288 cm<sup>3</sup>), in kg

CO<sub>2eq</sub>

Regulation	Strength class	Steel consumption (kg)	Formwork area (m <sup>2</sup> )	Cement mass per column (kg)	CO <sub>2</sub> emissions per column (kg CO <sub>2eq</sub> .)	Carbon index (IC) per column (kg CO <sub>2</sub> /MPa)
NBR 6118:2023 [4](28 days)	C20	230	5.76	192 kg CS	366	13.8
				172 kg CR	439	16.5
	C50	58		306 kg CS	226	4.0
				285 kg CR	351	6.2
MC 2020 [1](28 days)	C20	228	5.76	192 kg CS	364	13.7
				172 kg CR	437	16.4
	C50	50		306 kg CS	217	3.8
				285 kg CR	342	6.0
Eurocode 2 [2](56 days)	C20	228	5.76	161 kg CS	352	13.2
				158 kg CR	425	16.0
	C50	50		264 kg CS	201	3.6
				269 kg CR	329	5.8
MC 2020 [1] & Eurocode 2 [2](91 days)	C20	236	5.76	147 kg CS	355	13.3
				151 kg CR	427	16.1
	C50	60		245 kg CS	204	3.6
				261 kg CR	333	5.9

This enormous advantage achieved in a single column section, if extrapolated simplistically and multiplied by the total of 1,008 column sections in this structure, could save 240 t of CO<sub>2eq</sub>. In other words, conservatively speaking, if a careful analysis of the columns were to reduce, for example, just 30 kg of CO<sub>2eq</sub>. per section, the reduction in greenhouse gases in this structure could be in the order of 30 tons of CO<sub>2eq</sub>., in the columns alone.

## 5 Conclusion

The text of the MC 2020 standards [1] and Eurocode 2 [2] result in columns with a lower volume of concrete, steel, and formwork, since they prescribe the coefficient  $\alpha_{cc} = 1.0$  for  $f_{ck}$  at 28 days, whereas Eurocode 2 [2] prescribes  $\alpha_{cc} = 1.0$  even for  $f_{ck}$  at 56 days. On the other hand, ABNT NBR 6118 of 2023 [4], which adopts a fixed value of  $\alpha_{cc} = 0.85$ , resulted in a design with higher material consumption.

In this study, for  $f_{ck} = 50$  MPa at 56 days and 0.9% reinforcement ratio, Eurocode 2 [2] resulted in a column section with a concrete volume of 0.58 m<sup>3</sup>, 55 kg of steel, and 5.2 m<sup>2</sup> of formwork, whereas for  $f_{ck} = 20$  MPa at 28 days, 0.4%

reinforcement ratio, ABNT NBR 6118 [3] [4], resulted in a column section with 1.37 m<sup>3</sup> of concrete, 82 kg of steel, and 7.95 m<sup>2</sup> of formwork. Roughly extrapolating to the total of 1,008 column sections, the intelligent selection of design options in this building could lead to material savings, that is, eliminating the use of 796 m<sup>3</sup> of concrete, 27 t of steel, and 2,772 m<sup>2</sup> of formwork.

In general, design alternatives for the column section with a minimum amount of reinforcement, regardless of the standards used, resulted in lower CO<sub>2eq.</sub> emission values. Specifically, Eurocode 2 [2], which assumes  $\alpha_{cc} = 1.0$  with  $f_{ck}$  at 56 days, leads to better eco-efficiency indicators (IC) for any design detail compared to the other standards.

The design performed according to the current Brazilian standard ABNT NBR 6118:2023 [4] presented the worst IC indices; that is, in this study, in particular, it was the standard that contributed least to the sustainability of short columns.

In this study, for  $f_{ck} = 50$  MPa at 56 days, 0.9% reinforcement ratio, Eurocode 2 [2] resulted in a column section with an emission of 182 kg CO<sub>2eq.</sub> (IC = 3.2 kg CO<sub>2</sub>/MPa), whereas for  $f_{ck} = 20$  MPa at 28 days, 4% reinforcement ratio, ABNT NBR 6118 [3] [4], for the same load, function, and safety, resulted in a greenhouse gas emission of 437 kg CO<sub>2eq.</sub> (IC = 16.4 kg CO<sub>2</sub>/MPa) of greenhouse gases. A rough extrapolation to the total of 1,008 column sections in this building could imply a reduction in greenhouse gas emissions of up to 257 tons of CO<sub>2eq.</sub>

This study also demonstrated that the use of CS cement, regardless of the different standards considered here, resulted in lower CO<sub>2eq.</sub> emissions compared to high-early-strength CR cement, even though more CS cement was required to achieve the same strength and age.

In fact, in a structural project intended for a specific architectural design, there is not as much freedom as considered in this study, because architectural and functional constraints often do not allow for the optimal dimensions from a structural standpoint. Certainly, in real-world cases, the gains will be smaller, but they cannot be disregarded or omitted in studies to verify the safety and optimization of the project during the design phase.

This study sought to demonstrate that design decisions, intelligently combined with concrete technology, can significantly influence sustainability; that is, they can effectively contribute to the dematerialization and reduction of greenhouse gas emissions from the finished structure.

Finally, based on the results obtained in this study, the authors conclude that to achieve lower greenhouse gas emissions, the design strength calculation guidelines established in Eurocode 2:2023 [2], using the highest concrete strength classes (thus allowing for lower material consumption) and testing at a reference age of 56 days leads to more sustainable results.

As a suggestion, it is understood that studies that include, in addition to short columns, other types of structural elements (beams, slabs, foundations, among others) could be the subject of similar studies, in order to verify the conclusions mentioned here.

### **Conflicts of interest**

The author declares no conflicts of interest regarding the publication of this paper.

### **References**

- [1] Fédération Internationale du Béton – fib (CEB-FIP). fib Model Code for Concrete Structures 2020. Lausanne, Switzerland, 2023. 1256 p.
- [2] EUROPEAN COMMITTEE FOR STANDARDIZATION. EN 1992-1-1: Eurocode 2: Design of concrete structures - Part 1-1: General rules and rules for buildings, bridges and civil engineering structures. Brussels, 2023. 402 p.
- [3] ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS ABNT NBR 6118:2014. Projeto de Estruturas de Concreto -Procedimento. 3 ed. Rio de Janeiro, 2014. 238 p.

- [4] ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS ABNT NBR 6118:2023. Projeto de Estruturas de Concreto. Rio de Janeiro, 2023. 242 p.
- [5] ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS ABNT NBR 12655: 2022. Concreto de cimento Portland. Preparo, controle, recebimento e aceitação- Procedimento. Rio de Janeiro, 2022. 6 p.
- [6] ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS ABNT NBR 6123:1998. Forças devidas ao vento em edificações. Rio de Janeiro, 1998. 110 p.
- [7] ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS ABNT NBR 15421:2023. Projeto de estruturas resistentes a sismos. Rio de Janeiro, 2023. 27 p.
- [8] ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS ABNT NBR 6120:2019. Ações para o cálculo de estruturas de edificações. Rio de Janeiro, 2019.
- [9] ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS ABNT NBR 15200:2012. Projeto de estruturas de concreto em situação de incêndio. 2 ed. Rio de Janeiro, 2012. 48 p.
- [10] HELENE, Paulo. Contribuição ao Estabelecimento de Parâmetros para Dosagem e Controle dos Concretos de Cimento Portland. São Paulo, Universidade de São Paulo, Escola Politécnica, Programa de Pós-graduação em Engenharia Civil, Departamento de Engenharia de Construção Civil, 1987. 278 p. (Tese de Doutorado)
- [11] ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS ABNT NBR 8681:2003. Ações e segurança nas estruturas - Procedimento. Rio de Janeiro, 2003. 18 p.
- [12] EUROPEAN COMMITTEE FOR STANDARDIZATION. EN 1990:2002+A1:2005: Eurocode - Basis of structural design. Brussels, 2002. 116 p.
- [13] EUROPEAN COMMITTEE FOR STANDARDIZATION. EN 197-1:2011: Cement – Part 1: Composition, specifications and conformity criteria for common cements. Brussels, 2011. 38 p.
- [14] EUROPEAN COMMITTEE FOR STANDARDIZATION. EN 206:2013+A2:2021: Concrete - Specification, performance, production and conformity. Brussels, 2013. 92 p.
- [15] DAMINELI, B.L.; PILEGGI, R. G.; JUAN, V. M. Eco eficiência do uso de cimento em concreto: estado atual, possibilidades e tendências. 54º Congresso Brasileiro do Concreto 54CBC2012. Maceió. Instituto Brasileiro do Concreto IBRACON, 2012.
- [16] ZORZI, Antonio C. Sistemas de Fôrmas para Edifícios: recomendações para a melhoria da qualidade e da produtividade com redução de custos. 2. ed. São Paulo: Ibracon, 2015. 195 p.