THE PARADOX OF HIGH PERFORMANCE CONCRETE USED FOR REDUCING ENVIRONMENTAL IMPACT AND SUSTAINABILITY INCREASE

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Abstract. The concern about the depletion of natural resources and environmental pollution is increasing in the construction sector. Paradoxically, the society and the main control organizations of sustainability indexes in construction have given little importance to the concrete, which is the industrial product most widely used on the planet, to improve the quality of life of society. Despite the concrete structures are rarely considered in established sustainability programs in construction, several studies have been developed in order to quantify and minimize their environmental impacts, which are related to the structural design and the physical and mechanical properties of the concrete. In this context, this article points out some concepts of environmental management and proposes, with significant examples, the observation of new and interesting sustainability criteria for the use of structural concrete, demonstrating the employment advantage of high strength concrete.

1 INTRODUCTION

Current models of social, economic and industrial development, based on the fast and growing consumption of natural resources, when mismanaged, could result in degradation and environmental pollution. According to Mehta & Monteiro [1], decisions aiming results exclusively in the short term and simplistic goals are contributing to further aggravate the global situation.

On the other hand, in recent decades, it was noticed a growing awareness of society with regard to the limitation of natural resources and the need to adopt practices with less environmental impact and the search for a development model that is more sustainable.

Sustainable development must act in three dimensions [2], as illustrated in Fig. 1:

1. environmental: in order to find a balance between protecting the physical environment and its resources and use these resources so that the planet to continue providing an acceptable quality of life for human beings;
2. economic: requiring the development of an economic system that facilitates access to resources and opportunities, promoting prosperity within what is

environmentally possible and without violating basic human rights;
3. social: seeking the development of fair societies that allow the human development and ensure opportunities for personal improvement and acceptable quality of life.

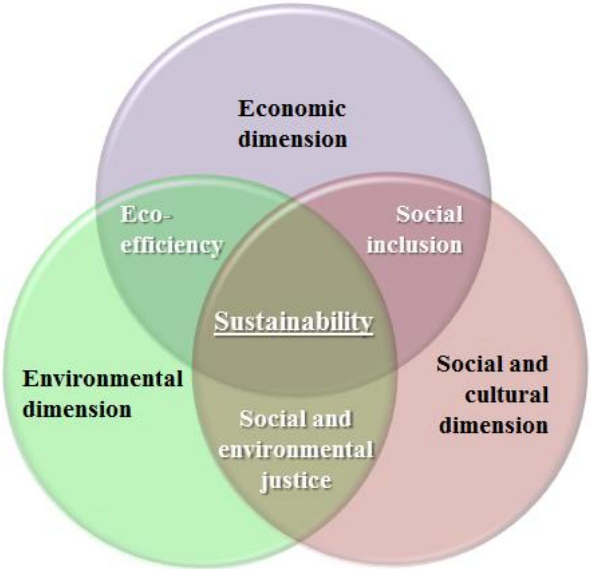

Figure 1: Sustainability dimensions (translated from ELKINGTON [3]).

In the construction industry, a sector that, according to Valdés [4], employs 7% of the world population, uses 2/5 of all energy produced in the world and consumes 50% of the natural resources of the earth's crust, the concrete is the material that occupies the most prominent position, being the manufactured product most used by society, with current global consumption estimated at 19 billion tons per year [1]. The authors emphasize that, with the exception of water, there is no other material consumed in such quantity per capita.

Therefore, the study of the concrete in the context of sustainable construction becomes every day more crucial. This article retrieves the concepts of environmental management and proposes the observation of new sustainability criteria in the design and construction of reinforced concrete structures, employing, paradoxically, high strength concrete with high cement consumption.

2 ENVIRONMENTAL MANAGEMENT

When the chase for economic development started to seriously jeopardize ecosystems and human health through pollution and natural resources depletion, the issue of sustainability has surfaced. Since then, several conferences focusing on this topic took place in order to draw prescriptive standards up, starting in 1992 with the RIO-92 Conference.

In response to this global demand for a more reliable, aware and fair environmental management, the Technical Committee 207 for ISO (TC 207), in 1994, developed the ISO 14000 series of standards, which proposed the concept of Life Cycle Assessment - LCA. This concept involves analyzing and determining the environmental impacts of products or services at all stages of their life cycle: acquisition of raw materials, production, use and after-use treatment, recycling, until final disposal of this product or waste resulting from service.

Through the Life Cycle Assessment it is also possible to produce Environmental Product Declaration (Environmental Product Declaration - EPD), considered one of the best and most complete references of sustainability today.

The EN 15804:2012 establishes three types of EPD, described below, based on the life cycle stages covered in the study of each product or service (Fig. 2):

1. *cradle to gate*: mandatory, only comprehends the production stage (supply of materials, transportation, manufacturing and associated processes);
2. *cradle to gate with options*: optional, comprehends the stage of production and other additional stages, chosen by the product or service provider;
3. *cradle to grave*: optional, involves production processes, installation, use, maintenance, repair or replacement, demolition, treatment for reuse, reconstruction, recycling and final disposal, considered the most correct option but more laborious analysis.

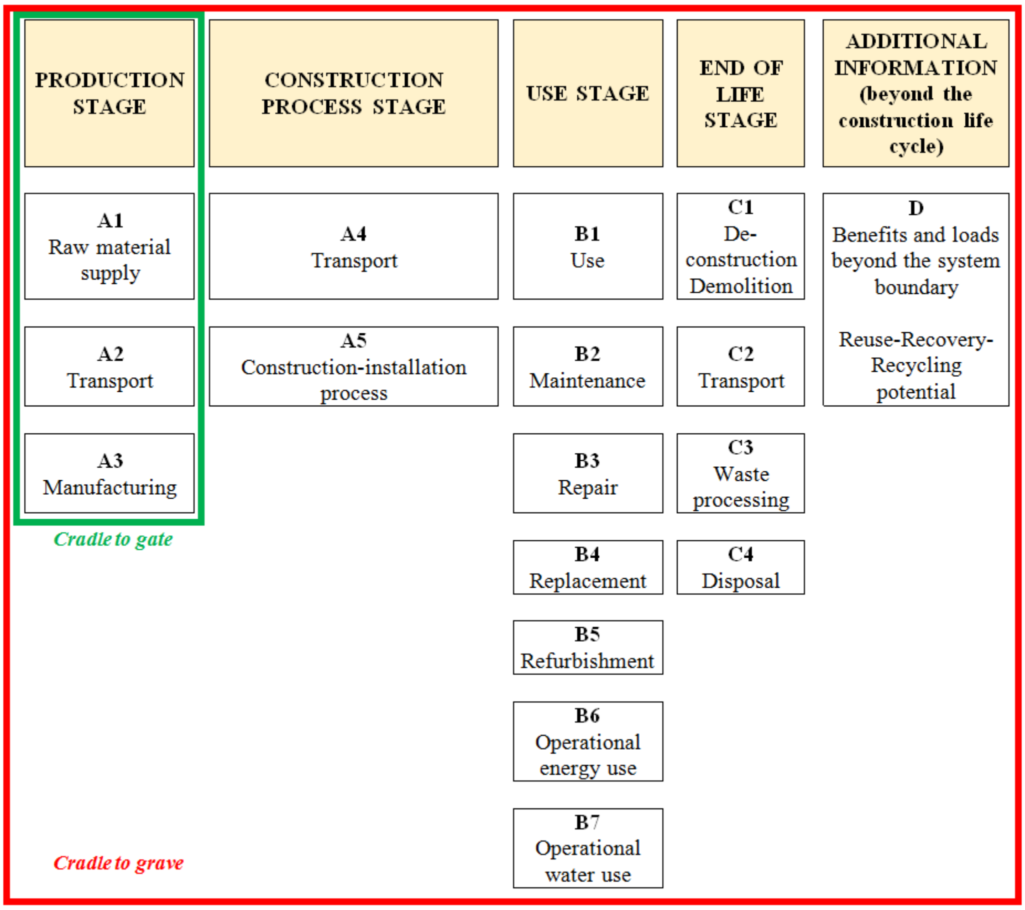

Figure 2: Stages of the life cycle of a product or service (adapted from EN 15804:2012 [5]).

Yet, according to EN 15804:2012 [5], environmental impact indicators, quantified in different categories at each stage of EPDs involve the analysis of the following listed parameters:

a. global warming potential, in kg of CO_2 equivalent;
b. the stratospheric ozone layer depletion potential, in kg of equivalent CFC 11;
c. ground and water acidification potential, in kg of equivalent SO_2;
d. eutrophication potential, in kg of $(PO_4)^{3-}$ equivalent;
e. tropospheric ozone formation potential, in kg of equivalent ethylene;
f. abiotic resources (elements) depletion potential, in kg of equivalent Sb;
g. abiotic resources (fossil fuel) depletion potential, in MJ.

In addition to these indicators of environmental impact, the same standard also sets parameters describing the use of natural resources (renewable or not), energy and water.

The EPDs are valid for 5 years and after this period, must be reviewed and verified. It is not necessary to recalculate them if the underlying information does not present substantial changes. If either environmental impact indicators suffer change of at least 10% (for more or less), the EPD should be updated.

Also in the context of sustainable buildings, various international organizations, aiming to encourage this construction segment, created certifications to enhance and guide the transformation of conventional projects in environmentally friendly projects. Among these certifications, can be highlighted the LEED (Leadership in Energy and Environmental Design), Casa Azul Seal (Brazilian certification system developed by Caixa Econômica Federal), HQE (Haute Qualité Environmentale), BREEAM (Building Research Establishment Environmental Assessment Method) and DGNB (German Sustainable Building Council).

However, the evaluation criteria of the certifications, mistakenly, do not contemplate the use of high-strength concrete in the positive composition of the scores.

Although it seems a paradox, throughout this article, the many advantages involved in the adoption of this type of concrete will be presented, aiming to support the proposal for its inclusion in certification systems.

3 SUSTAINABLE CONCRETE?

As already discussed, concrete is the building material widely used worldwide, mainly due to its resistance, flexibility, durability, easy implementation and low cost. However, as with any other product to be used in construction, production of concrete and its components (especially cement) requires energy, consumes water and results in CO_2 generation [6].

According to Isaia and Gastaldini [7], cement production consumes 5,5GJ energy and releases around of 1ton of CO_2 per ton of clinker. Levy [8] points out that cement production is responsible for about 6% to 7% of total CO_2 emissions in the world. Brazil, with annual production of 40 million tons of cement and about 16 million tons of clinker, contributes with about 1% to 2% of total carbon emissions in Brazil.

The environmental impact of the concrete, however, is not caused only by the cement. For the production of concrete, materials and non-renewable natural resources such as sand and gravel are also used, bordering the amount of consumption of 12 billion tons annually. Considering the impact of exploration, processing and transport of this raw material, it is observed that all specific concrete manufacturing process seems to adversely affect the environment [9], although its essential for the improvement of human life quality through building houses, bridges, roads, viaducts, harbors, water and wastewater treatment plants, schools, hospitals, etc.

The concrete industry also uses large amounts of potable water, about 1 trillion liters each year, just as concrete water content, to which are added large portions of concrete mixers and equipment wash water and curing water of the concrete [10].

Thus, in order to reduce the consumption of potable water, natural resources and energy, reducing environmental impact, there is a need to consider the service life, durability and strength of concrete structures, taking into account the long-term (more than 50 years) of constructions in concrete.

However, according to EN 15804:2012 [5], only the cradle to gate life-cycle assessment is currently recommended and even required in certain circumstances. Therefore, the concreting service companies, for example, are concentrating on accomplishing it, discouraging, mistakenly, the use of high-strength concrete. Corresponding to this mistaken view, the environmental impacts exposed in Tab. 1 refers only to the production of ready-mix concrete.

Table 1: Environmental impacts for 1m³ of ready-mixed concrete produced by concreting services company *Allied Concrete* [11].

Parameter	**Impact / m³**						
Compressive strength (MPa)	**20**	**25**	**30**	**35**	**40**	**45**	**50**
Global warming potential (kg CO_2 eq)	333	366	395	445	513	539	609
Stratospheric ozone layer depletion potential (kg CFC 11 eq 10^{-5})	1,10	1,19	1,26	1,39	1,57	1,56	1,83
Ground and water acidification potential (kg SO_2 eq)	1,42	1,56	1,68	1,89	2,18	2,29	2,60
Eutrophication potential (kg $(PO_4)^{3-}$ eq)	0,339	0,372	0,402	0,451	0,519	0,548	0,620
Tropospheric ozone formation potential (kg ethylene eq)	0,0688	0,0756	0,0818	0,092	0,106	0,112	0,127
Potential depletion of non-fossil resources (kg Sb eq$\cdot 10^{-4}$)	1,10	1,18	1,25	1,41	1,44	1,49	1,83
Potential depletion of fossil resources (MJ)	3080	3390	3650	4090	4700	4900	5570

However, this incomplete and misplaced analysis does not reflected the overall environmental impacts of a concrete structure. Contrary to this view, Levy [8] explains that the high performance concrete (HPC) have a more compact pore structure and, in its formulation, superplasticizers additives and mineral additions that react with the free lime and improve its strength. Thus, in these HPCs, the water/cement ratio is lower than in a conventional concrete, which increases their mechanical properties and durability.

The superior mechanical behavior of HPCs also allows significant reductions of structural sections, generating large cement, steel, water and aggregates economy, as well as possible economic gain by increase in useful areas for use, rental and parking on enterprises.

An important example of the application of this concept in Brazil is the colorful HPC with f_{ck} 80MPa, used in *e-Tower* building in São Paulo, which enabled a significant reduction in the area occupied by columns in parking areas [12], as shown in Fig. 3.

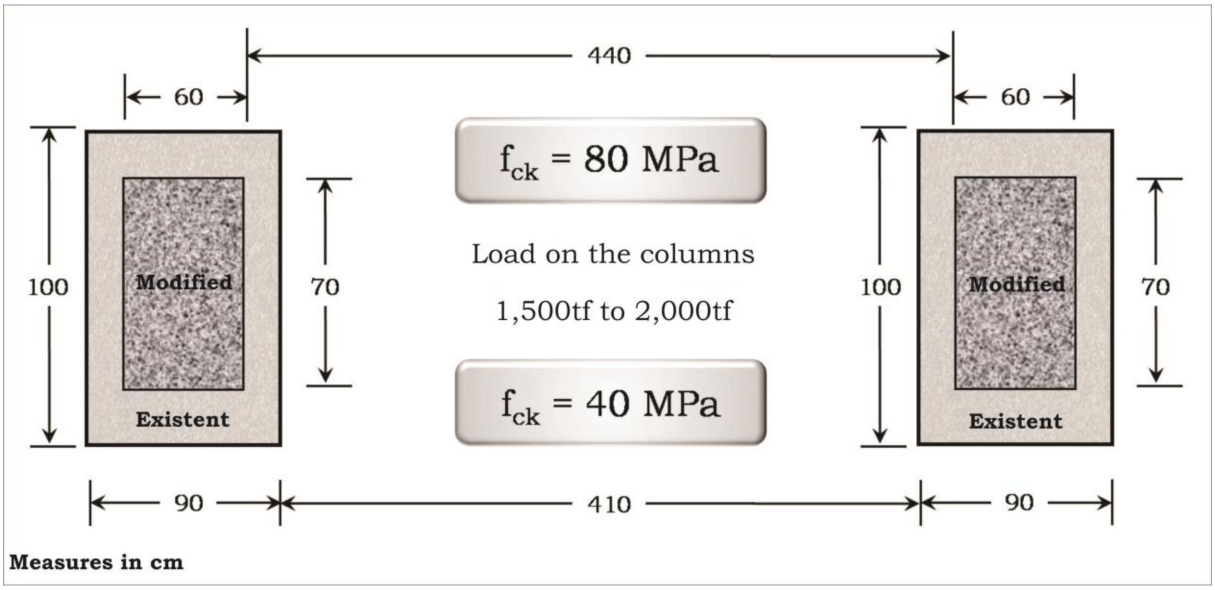

Figure 3: Project design of *the e-Tower:* existing columns on the original design with 40MPa f_{ck} (90cm x 100cm) and modified columns with 80MPa f_{ck} (60cm x 70cm)

This modification (reduction in the size of the columns) made the project compatible with the architectural requirements and made it possible to meet the criteria of a sustainable structure. Under the service life and sustainability point of view, one of the main deleterious mechanism of a concrete structure is the corrosion of steel, very unlikely phenomenon in structures built with high strength concrete.

All carbon steel is eternally protected by a high alkaline environment with a pH greater than 11.5. This fact is legitimately observed in the case of chloride free Portland cement concrete structures, since the hydration products of the curing reaction between the anhydrous grains of cement and water release large quantities of $Ca(OH)_2$, NaOH and KOH, which are strong bases [13], able to chemical and effectively protect steel from deleterious corrosion.

This protection capability by passivation can be lost over time due to various actions of which the most important are the chloride penetration and the reaction of carbon dioxide CO_2

with the hydration products of these alkalis, resulting in low alkaline salts, a phenomenon known by carbonation of concrete.

With the increase in concrete strength, there is an important reduction of the risk associated with the reinforcement corrosion, given the high difficulty of aggressive agents penetration. According to Levy [8], with smaller and not connected pores, the high strength concrete is less subject to the action of aggressive agents present in the atmosphere and water, which increases its durability and hence service life of the structure.

From the point of view of sustainable construction, some important parameters were achieved with this design change: increase of the service life, reduction of natural resources use, environmental impacts, energy and the total volume of the work concrete (even with a cement consumption per cubic meter of concrete top to the original design of concrete - with f_{ck} 40MPa).

Specifically about the elevation of service life, some standardized values from enshrined bibliographies[1] were adopted to illustrate the magnitude of the growth, as shown in Table 2, where it can be seen an increase of ten times on the service life of project.

Table 2: Data collected in the case study on the concrete pillars of the building and high strength-Tower, for the growth of life.

Element	**Design characteristic cover (1) (cm)**	**Carbonation constant adopted(2): k_{CO_2} (mm/ year $^{1/2}$)**	**Estimated design service life (years)**
Structural column (90cm x 100cm) with f_{ck} = 40MPa	3,0	2,45	150
Structural column (60cm x 70cm) with f_{ck} = 80MPa	3,0	0,77	1500

(1) It was considered as the design characteristic cover within the tolerance of the NBR 6118:2014, i.e. the minimum admitted covering.

(2) This value was adopted depending on the Prática Recomendada do IBRACON only for the purpose of demonstrating that the structure service life increases tenfold when the concrete strength changes. It is noteworthy, however, that these coefficients were estimated.

As for saving natural resources, it was found that there was a considerable reduction of all materials used in the concrete composition and design of comlumns with f_{ck} = 80MPa, compared to the f_{ck} = 40MPa. The volume of aggregates was reduced by 70%, while the cement in 20%, according to Table 3.

[1] The value of the carbonation coefficient was estimated based on literature: ***Prática recomendada IBRACON – Comentários Técnicos NB-1***, produced in 2003. The adopted model has been simplified based on the structure deterioration mechanism of carbonation, through the formula: $e = k_{CO2} \cdot \sqrt{t}$, where ***e*** is the concrete cover in cm, $\boldsymbol{k_{CO2}}$ is the carbonation constant in cm/year$^{1/2}$ and ***t*** is the time, in years.

Table 3: Data collected in a study about *e-Tower* high-strength concrete columns, referring to the reductions of materials and concrete.

Material	Reduction
Sand	70%
Gravel	70%
Cement	20%
Water	53%
Steel	43%
Formwork	31%
Concrete	**53%**

Confirming this view, Couto [14] studies showed that the design of buildings of 41 floors with high strength concrete is advantageous, both from an economic and sustainable point of view, compared with those designed with conventional concrete. It was observed that it is possible to obtain a reduction of approximately 11% in the overall cost of the structure, changing the strength from a f_{ck} 25MPa to a f_{ck} 50MPa.

So, with holistic and long-term vision, it is necessary to perform the concrete life cycle analysistaking into account the whole life cycle of this material and not only from the "cradle to gate".

Bento e Rossignolo [15] shows in their doctoral research the importance of a holistic view, result of a cradle to grave analysis of a residential building hypothetically designed, consisting of eight floors and a ground floor type. Were analyzed in this study the strength classes with f_{ck} of 25MPa, 30MPa, 35MPa, 40MPa, 45MPa and 50MPa, as explained in Table 4.

Table 4: Overall balance of impact categories with results obtained for each structure strength [15].[continue]

Impact category	C25	C30	C35	C40	C45	C50
Eutrophication (g NO_3^-)	$(2,33 \cdot 10^2)$	Larger $(2,43 \cdot 10^2)$	$(2,15 \cdot 10^2)$	Minor $(2,09 \cdot 10^2)$	$(2,10 \cdot 10^2)$	$(2,13 \cdot 10^2)$
Photochemical ozone formation (g C_2H_4 eq)	$(4,03 \cdot 10^4)$	Larger $(4,10 \cdot 10^4)$	$(3,83 \cdot 10^4)$	Minor $(3,55 \cdot 10^4)$	$(3,61 \cdot 10^4)$	$(3,72 \cdot 10^4)$
Consumption of material resources (kg)	Larger $(6,93 \cdot 10^2)$	$(6,56 \cdot 10^2)$	$(5,43 \cdot 10^2)$	$(5,00 \cdot 10^2)$	Minor $(4,95 \cdot 10^2)$	$(4,90 \cdot 10^2)$
Consumption of energy resources (kWh)	$(4,20 \cdot 10^1)$	Larger $(4,30 \cdot 10^1)$	$(4,01 \cdot 10^1)$	Minor $(2,17 \cdot 10^1)$	$(2,20 \cdot 10^1)$	$(2,26 \cdot 10^1)$

Table 4: Overall balance of impact categories with results obtained for each structure strength [15]. [conclusion]

Impact category	C25	C30	C35	C40	C45	C50
Ecotoxicity (m^3 compartment)	($2{,}54 \cdot 10^2$)	Larger ($2{,}64 \cdot 10^2$)	($2{,}20 \cdot 10^2$)	Minor ($2{,}10 \cdot 10^2$)	Minor ($2{,}10 \cdot 10^2$)	Minor ($2{,}10 \cdot 10^2$)
Global warming (g CO_2 eq)	Larger ($6{,}75 \cdot 10^3$)	($6{,}67 \cdot 10^3$)	($6{,}12 \cdot 10^3$)	($5{,}74 \cdot 10^3$)	Minor ($5{,}71 \cdot 10^3$)	Medium ($5{,}67 \cdot 10^3$)
Human toxicity (m^3 compartment)	Larger ($1{,}80 \cdot 10^8$)	($1{,}78 \cdot 10^8$)	Minor ($1{,}68 \cdot 10^8$)	($1{,}76 \cdot 10^8$)	($1{,}76 \cdot 10^8$)	($1{,}76 \cdot 10^8$)
Acidification (g SO_2^- eq)	($9{,}52 \cdot 10^1$)	Larger ($1{,}00 \cdot 10^2$)	($9{,}19 \cdot 10^1$)	Minor ($8{,}90 \cdot 10^1$)	($9{,}03 \cdot 10^1$)	($9{,}23 \cdot 10^1$)
Waste (kg)	Larger ($2{,}30 \cdot 10^{-1}$)	Larger ($2{,}30 \cdot 10^{-1}$)	($1{,}90 \cdot 10^{-1}$)	($1{,}70 \cdot 10^{-1}$)	Minor ($1{,}68 \cdot 10^{-1}$)	Minor ($1{,}68 \cdot 10^{-1}$)

This study considered the section reduction in two stages, in C35 and C45 classes. It was concluded that, in this case, the strength class with less environmental impact would be the C40. Thereafter, increasing the resistance would not result in a significant decrease of resistant section of flexed elements and it would not be advantageous for the loading determined initially.

The study of Schmidt and Teichmann [16], aiming the construction of a bridge with lattice structure in prestressed concrete (work of art), also concluded that the ultra high performance concrete (UHPC), with f_{ck} = 200MPa, proves to be much more sustainable than the conventional concrete, resulting in a lower consumption of raw materials and energy, as shown in Tab. 5.

Table 5: Demand for materials (in tons) and energy (in MJ) for the construction of a bridge with lattice structure with conventional concrete and high performance concrete [16].

Material	C25/C30	High performance f_{ck} 200MPa
Cement	120	98
Aggregates	620	170
Water	60	21
Silica fume	-	18
Steel (passive reinforcement)	70	22
Steel Fibers	-	10
Steel (active reinforcement)	10	12
Total energy (MJ)	2.050.256	1.148.517

Indeed, it is clear that the use of high performance concrete (paradoxically, with higher cement consumption per cubic meter) brings significant advantages, not only with respect to mechanical properties, but also in environmental and sustainable aspect. However, as already explained, these benefits appear only in the long term and over a review of the service life of the material, when a full analysis (cradle to grave type) is performed.

Besides the importance of high resistance in reducing total input demand, it is also important to investigate the specific emissions by concreting service companies in m^3 of the product supplied. The concrete generally have CO_2 at around 7% to 15% of the produced concrete mass [6], depending on the designed proportions.

These values are closely related to the clinkering of used cement, the optimization of the production process of the plants and also the quantity of cement per m^3 calculated for the concrete mixes. Along with analysis of the total energy used for the entire structure, a proper study and the optimization of the inputs of the m^3 of concrete can also help to mitigate their environmental impact.

In the case of simplistic analysis of $1m^3$ concrete alone, the environmental impact can be evaluated through the concept of *yield*, expressed by the ratio of compressive strength (MPa) / cement consumption (C_{cim}). The fact that the efficiency of a concrete is closely linked to the amount of cement required to achieve the desired strengths is evident. For Helene and Tutikian [17], the yield has a great peak for each concrete mix and must be studied through the dosage diagram, in order to obtain the most sustainable concrete, which must also be an economically viable solution.

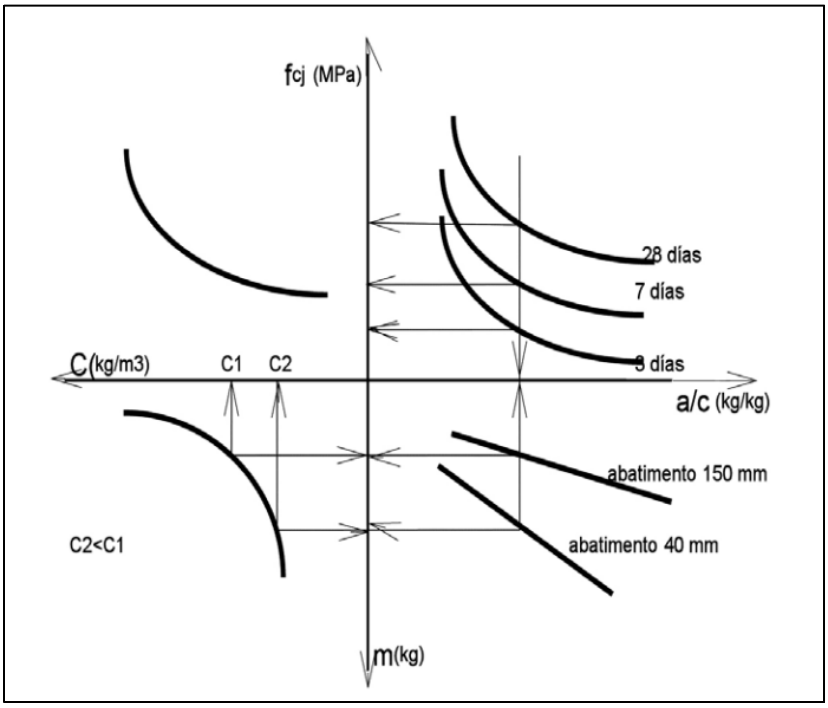

Figure 4: Dosage diagram of Portland cement concrete.

That said, studies of Boggio [18] bring an assessment of the efficiency factor or concrete yield calculated for concrete with strengths between 20MPa and 40MPa, dosed according to IBRACON method (Table 6).

Table 6: Efficiency factor or concrete yield evaluation for different strengths (adapted from Boggio [18]).

Strengths f_{c28} **(MPa)**	**Efficiency factor**	
	$f_{c28}/C_{cim}\left(\frac{MPa}{kg/m^3}\right)$	$C_{cim}/f_{c28}\left(\frac{kg/m^3}{MPa}\right)$
20	0,082	12,20
25	0,091	10,93
30	0,099	10,10
35	0,109	9,18
40	0,109	9,14
80*	0,174	5,75

* Data collected in the study of high strength concrete columns of *e-Tower* building.

Given the importance of concrete in constructive chain and at the development of a nation and given the benefits of high strength concrete employment, it is paradoxical to use consumption of cement as environmental degradation index, because the correct would be thinking about the construction life cycle with a global and holistic view, not only about cement consumption of concrete.

4 FINAL CONSIDERATIONS

As shown, even having a higher consumption of cement per m^3, and hence, a larger amount of CO_2 emission per m^3, the reduction in the volume of concrete and a considerably increased service life justify the use of high strength concrete from the point of view of sustainability. As pointed out by Hajek, Fiala and Novotna [19], using materials with better physical and mechanical characteristics is a realistic mean of achieving substantial advantages from the perspective of materials and energy savings, allowing, in the case of concrete, the preparation of designs with optimized sections, increased durability and strengths and, ultimately, the generation of less environmental impact. In this context, it is suggested that the use of high-strength concrete also compose the score of existing seals for sustainable construction, such as LEED, Casa Azul Seal, HQE, BREEAM and DGNB, considering that its employment offers high performance in environmental quality, productivity, global economy of materials and resources.

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