Towards a low-CO_2 concrete chain:

the importance of increasing the quality control of concrete production

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Resumo Concrete has cement in its composition and therefore is a major contributor to global warming. In its chain, several mitigation opportunities are found. This study seeks to present the environmental impacts brought by the lack of quality control in the production of concretes, and possibilities of gains from improvements. Based on the analysis of a state-of-art created from a concrete environmental impact indicator, and simulations of different scenarios, it was shown that, with small improvement in quality control, ~ 7% of CO_2 emissions related to the chain could be mitigated. The lower the compressive strength of concretes, the higher the potential of gains from quality control improvement, which is relevant since most of the commercial concretes have low compressive strength.

Keywords: concrete chain, quality control, low-CO_2 .

Em direção a uma corrente de concreto de baixo CO2: a importância de aumentar o controle de qualidade da produção de concreto

Abstract O concreto tem cimento em sua composição e, portanto, é grande contribuinte ao aquecimento global. Em sua cadeia, encontram-se oportunidades de mitigação. Este estudo busca apresentar os impactos ambientais trazidos pela falta de controle de qualidade na produção de concretos e possibilidades de ganhos. Com base na análise do estado-da-arte criado a partir de um indicador de impacto ambiental de concretos e simulações de diferentes cenários, foi mostrado que, com uma pequena melhoria no controle de qualidade, ~7% das emissões de CO_2 da cadeia poderiam ser mitigadas. Quanto menor a resistência à compressão dos concretos, maior o potencial de ganhos com a melhoria deste controle, o que é relevante já que a maioria dos concretos apresenta baixa resistência à compressão.

Palavras-chave: cadeia do concreto, controle de qualidade, baixo teor de CO_2.

Hacia una corriente de hormigón baja en CO_2: la importancia de aumentar el control de calidad en la producción de hormigón

Resumen El hormigón tiene cemento en su composición y, así, es contribuyente al calentamiento global. En su cadena se encuentran oportunidades de mitigación. Este estudio busca presentar los impactos ambientales que conlleva la falta de control de calidad en la producción de hormigones, y posibilidades de mejoras. Basado en el estado-del-arte creado a partir de un indicador de impacto ambiental y simulaciones de escenarios, se demostró que, con pequeña mejora en el control de calidad, ~7% de las emisiones de CO_2 de la cadena podrían mitigarse. Cuanto menor la resistencia a la compresión de los hormigones, mayor el potencial de ganancias con esta estrategia, lo que es relevante ya que la mayoría de los hormigones tienen baja resistencia a la compresión.

Palabras clave: cadena del hormigón, control de calidad, bajo contenido de CO_2.

_After the Industrial Revolution, greenhouse gas emissions increased unprecedentedly in history. If the planet previously controlled the greenhouse effect to maintain its temperature (KASTING; CASTLING, 2003), the increase in emissions of these gases by human action started to cause imbalance. Thus, these emissions have been the subject of studies, some even awarded Nobel prizes (IPCC, 2007, 2014) that foresee global warming of the atmosphere for the coming years.

The civil construction chain has a major contribution to greenhouse gas emissions, as it is the largest consumer of natural resources in the world (UNEP, 2003). And, within it, concrete is the most used asset (JOHN, 2003). A typical concrete mix for civil construction has 8 to 15% cement and 80% or more aggregates. However, cement alone accounts, on average, for almost 75-80% of NO_x emissions and 85-90% of CO_2 (VARES; HAKKINEN, 1998). Corroborating the data, for the production of 1m^3 of concrete, there is an average emission of 101 kg of CO_2 – cement alone is responsible for 92.1 kg, more than 91% of the total (KJELLSEN; GUIMARAES; NILSSON, 2005). Thus, the greatest environmental impact of concrete – climate change – is directly related to incorporated cement. And demand exacerbates the outlook: based on data from the GCC Association's "Getting the Numbers Right" project, which annually records production and CO_2 emissions data from the world's leading cement producers and makes them available on an online platform, it is estimated that, in 2018, approximately $4.1x10^9$ tons of cement were produced in the globe (GCC ASSOCIATION, 2018). From the same source, in the same year an average of approximately 650 kg of CO_2 per ton of cement was emitted, allowing the estimate that, in 2018, the cement industry emitted something around $2.7x10^9$ t of CO_2. As cement production increase is expected and needed in the coming years due to social demands, the sustainability of the concrete chain needs efforts.

In this sense, a life cycle analysis (LCA) of concrete material can bring important data to direct the efforts to increase the sustainability of the sector. The LCA can bring elements of analysis to increase the sustainability of this chain, since it can bring important data for evaluations under different approaches, such as: 1) emissions in the production of raw material (in this case, cement and aggregates); 2) the material mixture proportioning project; 3) the quality control of the mixture and production; 4) the design of the structure (sizes and geometry of the pieces); 5) environmental comfort (thermal, visual or spatial); 6) durability; and 7) the recyclability of the material. All these concepts are important for a LCA, as decisions in each aspect imply an increase or decrease in the sustainability of the building. It is known, for instance, that the design focused on the structural aspect can avoid the over-dimensioning of the structure, which results in incorporated material losses, with a consequent increase in the final CO_2 emissions.

This study aims to quantify and discuss the main impacts of this chain in relation to CO_2 emissions. From the analysis of data collected to carry out a benchmark, the potential of actions aimed to mitigate these impacts will be explored, focusing on the concretes proportioning and the quality control of its production process.

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Design For Sustainability (D4S) of concretes

The development of eco-design of a material or component is the search for a new way of producing the same, focused on increasing efficiency, quality, market opportunities and environmental performance. To achieve this, Design for Sustainability (D4S) is a new project concept in which the product is inserted in a more complex system of analysis that considers impacts of the life cycle of the entire production chain, seeking to meet the increase of sustainability (UNEP/DELFT, 2009). The D4S methodology consists of 10 steps.

The application of this methodology on the concrete chain allows to understand the impact of the product in its life cycle, and the definition of strategies to be adopted to improve the process of production / application / use of the concrete in search of the D4S. Due to the greater environmental impact of concrete being related to CO_2 emissions, the environmental analysis adopted will be mono-criteria, privileging this impact in the LCA.

The life cycle of concrete, such as other construction materials, is very comprehensive and, to be studied, it needs to be limited (LIPPIATT, 2002). Important strategies to be adopted at different stages of the life cycle will be presented. In the end, a quantitative analysis of the potential for improvement of the chain will be carried out based on the adoption of stricter quality control criteria in the production of concrete mixtures, a very important phase of the LCA of concrete in terms of the potential for gains towards D4S.

Cement production – industrial stage

Industrial actions to reduce emissions in cement production have been the main focus of conventional approaches to sustainability in the sector and have been the subject of great efforts – as can be seen in several environmental reports of producing companies. Several technical solutions have been developed to reduce the environmental impact in relation to emissions, and good results have been achieved. With regard to fuel consumption, the optimization of the kiln's technologies reduced energy consumption from up to 6Gj / ton of clinker to 4.4Gj / ton spent on the world average (WWF, 2008) with some kilns producing with 3Gj / ton. The estimated potential for reducing emissions through kiln optimization is, however, low: data from the GCC Association (2018) (Figure 1) demonstrated that, although there is a wide variation in energy consumption according to the type of kiln adopted, it appears that the more efficient kilns – that work dry, with pre-heater and pre-calcination – already have their consumption working at values close to the lower consumption, without significant decreases of average energy consumed since 2010. In the current scenario, there is still some possible gain in the migration from wet to dry kilns; however, wet kilns are less and less over time, decreasing these possibilities.

The substitution of traditional energy sources for alternatives, such as biomass renewables, has been going on for some time (CEMBUREAU, 1999) and also reduces emissions, but it is carried out on a small scale. The estimate of the potential for reducing emissions through the substitution of energy sources varies between 6-16%, (HUMPHREYS; MAHASENAN, 2002).

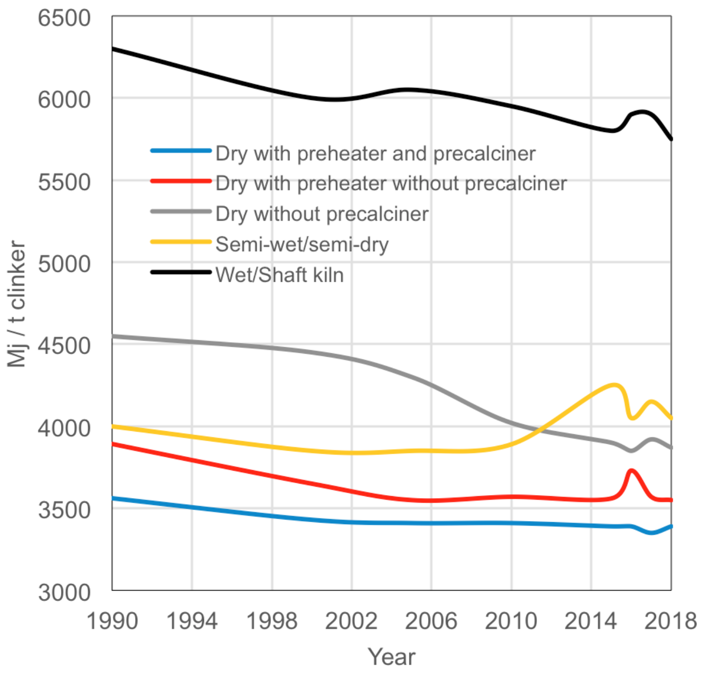


Figure 1: Evolution of the reduction in energy consumption related to cement production according to the type of kiln. Data from GCCAssociation, 2018. Source: Author.

A third solution is to replace part of the cement clinker with mineral additions, such as blast-furnace slag (BFS) or fly ash (FA). This replacement already occurs on a large scale in Brazilian cements: CP III can contain up to 75% BFS, while CP IV admits a maximum content of 50% FA (NBR 16697: 2018). In many other countries, BFS and FA are applied directly to the concrete mixing as a substitute for cement. Nevertheless, it has already been demonstrated that the global supply of BFS and FA does not have the capacity to replace clinker in these percentages on a worldwide scale, as this supply is in the order of 10 to 15% in relation to the total cement produced (DAMINELI; JOHN, 2012). In other words, the use of cements with high rates of substitution, despite being a solution acclaimed even by some environmental certifications – which give points to those who do – is not feasible on a large scale, which makes it a sustainable solution only occasionally – mainly in locations around the globe where these materials are widely available. For instance, the Brazilian AQUA certification for residential buildings version 2016 points to the use of CP III and CP IV cements (FUNDACAO VANZOLINI, 2016); in turn, LEED certification version 4.1 for single-family buildings rewards the use of fly ash in concrete (US GREEN BUILDING COUNCIL, 2020).

Thus, the actions mentioned, added up, are insufficient to mitigate the impact to a satisfactory level. For a D4S in the concrete chain, solutions beyond the cement production stage should be sought.

Concrete production – cement use stage

The reduction in emissions related to the concrete chain can also be obtained in other stages of the material's life cycle. In this sense, acting in the stage of using cement –

the production of concrete – can decisively contribute to increasing sustainability. A LCA focused on the environmental impacts determined at this stage can bring data for the actual implantation of D4S in concrete mixtures, both by improving the mixture proportioning processes – with a reduction in the consumption of cement from tools such as dispersion and packaging of particles (DAMINELI, 2013) – and the increase in quality control – the main focus of this paper.

To assess the environmental performance of concretes in an objective, parameterized and easy-comparable manner, an environmental indicator was created to analyze the parameters of cement consumption (impact indicator since CO2 of concrete chain is mostly related to cement production process) and compressive strength (performance indicator) of concrete. In a D4S analysis, the need to relate environmental impact to product performance is indispensable, as there is no sustainability in low-impact solutions that have no technical value, and vice-versa. In building construction technology, the concept of sustainability should bring solutions with low environmental impact, but without losing technical performance – or even increasing it – and even at a low cost, which brings prospects for real application in the market.

The indicator is Binder Intensity (*BI*), and is calculated by Equation 1:

$$BI = \frac{\boldsymbol{total\ binder\ content\ (\frac{kg}{m^3})}}{\boldsymbol{28\text{–}day\ compressive\ strength\ (MPa)}} \qquad (1)$$

This indicator, expressed in kg.m^{-3}.MPa^{-1}, allows the assessment of the amount of binder (the main one is cement) required to generate each MPa of compressive strength. Hence, when comparing different concrete mixtures, the higher the BI, the higher the cement content (impact) was required to obtain the same compressive strength (performance), or less compressive strength was obtained with the same cement content. In both cases, the eco-efficiency is lower.

The BI indicator is, therefore, an important tool for analyzing concrete sustainability, and allow the assessment of the problem based on an important tool of the D4S: the benchmark, which consists of the identification of quantitative data of a given market (in this case, BI data from market mixes) to establish a database that allows comparison of performance. The creation and application of the benchmark allows the establishment of processes to increase product performance through the identification, understanding and adaptation of the best existing market practices, and therefore it is an important stage of D4S (UNEP/DELFT, 2009). The benchmark of the current technology of concrete carried out through the environmental indicators created, therefore, provides valuable information for the improvement of the D4S, in several acting fronts.

A more comprehensive study on the meanings and variations of BI related to the efficiency of concrete mixture proportioning processes is widely discussed in Damineli et al. (2010), where a comprehensive benchmark was developed. The present paper will use that benchmark data to estimate and discuss the influence of the concrete production quality control process in the sustainability of concrete chain for the next years.

Methodology

The BI are calculated using the fcj – real compressive strength of the specimens – and not to the fck – resistance adopted in large scale productions, using standard deviation (S_d) to control production variation and quality. The relationship between fck and fcj, in the quality control of concretes, is established by the well-known Equation 2 (NBR 12655: 2015):

$$fck = fcj - 1.65\, Sd \qquad (2)$$

The Sd of a concrete is determined by the higher or lower precision in the quality control carried out in the material mixing phase, which includes, among others: 1) precision of the weighing of the materials for the mixing in the proportions determined in the dosage; 2) control of the characteristics of the aggregates, such as water absorption, granulometric distribution, moisture content present in the reception (and in use); 3) control of the water content added to the mixture; 4) efficiency of the mixing process (a manual process is less efficient than using a concrete mixer, for example, and implies higher variability).

Sd, therefore, is directly related to the control performed and conditions available in the production process. It is used, in practice, to ensure that> 95% of the concretes produced will have compressive strength equal to or higher than the design fck – thus ensuring the safety of the building. Therefore, the higher the Sd, the greater the variability that the concretes produced by that process / production line will have, so that the target resistance must be greater for the real resistance to be guaranteed.

Sd can be calculated from a historical series of concrete data with the same production process (a concrete company can calculate its own process Sd, as well as a simple bricklayer who mixes concrete in construction sites). In cases where these data are not available, there is the possibility of adopting estimated values from NBR 12655: 2015 (ABNT 2015), which presents Sd numbers to be considered based on some parameters adopted in production, such as: 1) measurement of aggregates and cement in mass (more accurate) or by volume (less accurate); 2) measurement of mixing water in mass or volume with a metering device (more accurate) or without this device (less accurate); 3) amount of water corrected according to the humidity of the aggregates (more accurate) or according to the desired consistency for concrete in the fresh state (less accurate). Different combinations of these factors arrive at conditions A, B or C for preparing the concrete, with respective adoption of Sd in 4 (condition A, more precise), 5.5 (condition B, intermediate) or 7 (condition C, less precision and control).

So, if different Sd (which can be considered as a good indicator of the concrete production quality control process) were applied to the fcj compressive strength of concretes, a fck value can be achieved. For the purpose of analyzing the impact of S_d on the environmental efficiency of concretes, all the BI found in the benchmark cited were recalculated using three scenarios for comparison: SD = 0 (without standard deviation, therefore the result of compressive strength achieved in concretes); Sd = 3 (which would be the standard deviation for a production process with good-medium control) and Sd = 7 (the largest standard deviation presented in the standard, generally used in production processes with very little quality control in almost all stages and processes that increase variability).

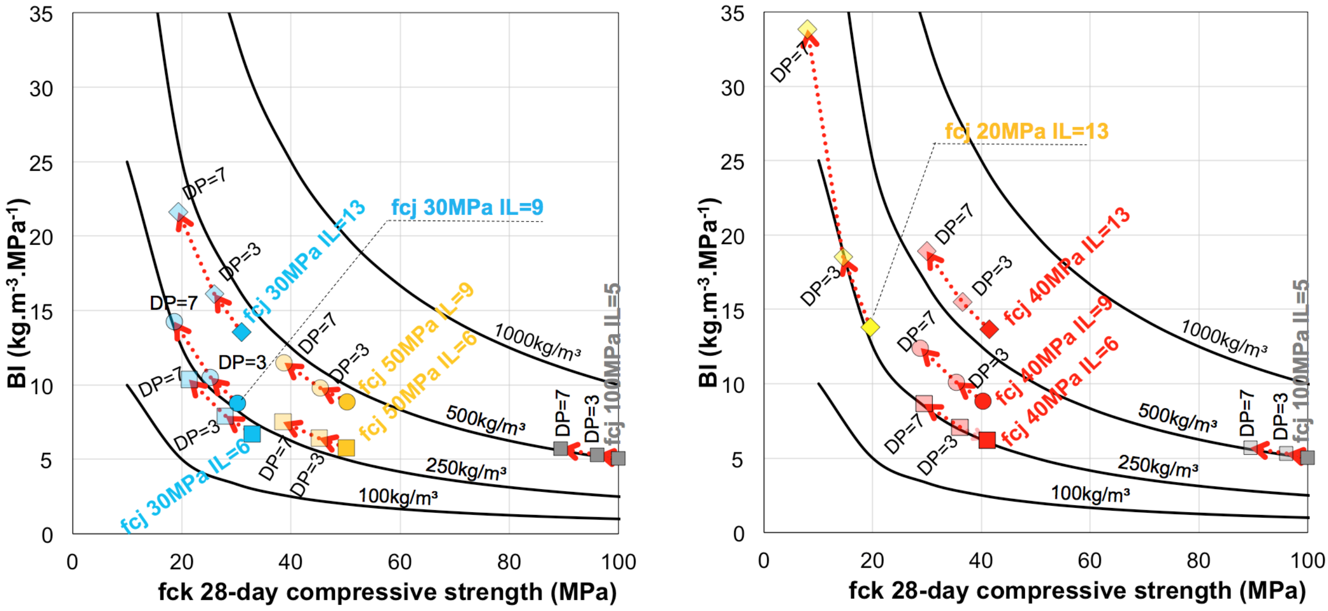
In addition to the variation of the S_d, the analysis also adopted the variation of resistance bands of the analyzed concretes from 30 MPa (ordinary resistance in the market), 40 MPa and 50 MPa (a high resistance already used in the market), as well as their proportioning efficiency (determined, as previously discussed, by the BI). With these variables, it becomes possible to see how changing the S_d (or process quality control) modifies the BI (or environmental efficiency) of concretes of different ranges of compressive strength, and also different efficiencies of the proportioning process.

Results and discussion: estimating the gains from increasing the quality control process in the concrete chain

Figure 2 presents an analysis of the variation of the eco-efficiency of the studied concretes according to the application of different standard deviations (S_d) on the compressive strength of the concretes.

For an analysis that could address the influence of the level of quality control on different types of concretes, from the benchmark original data, some representative points were selected to compose the Figure 2. These points aimed at concretes with different resistance ranges and, within of each resistance band, different efficiency of use of the binder (BI). There are: 1) concrete with high compressive strength and low BI (fcj = 100 MPa, IL = 5 kg.m^{-3}.MPa^{-1}) – there were no found high-strength concretes with medium or high BI; 2) concrete with 3 average compressive strength ranges (50,

Figure 2: Influence of the application of S_d = 3 and S_d = 7 on the BI of concretes of varied compressive strength and BI. a) 100MPa, 50 MPa and 30 MPa concrete families; b) 100 MPa, 40 MPa and <20 MPa concrete families. Source: Author.



40 and 30 MPa), and within the universe of each of these groups, representatives with low BI (~ 6 $kg.m^{-3}.MPa^{-1}$), medium (~ 9 $kg.m^{-3}.MPa^{-1}$) and high (~ 13 $kg.m^{-3}.MPa^{-1}$); and 3) concrete of compressive strength considered low (up to 20 MPa), and within this group, representatives were sought again with low (not found), medium (not found) and high BI (~ 13 $kg.m^{-3}.Mpa^{-1}$ and ~ 22 $kg.m^{-3}.Mpa^{-1}$). For better visualization and comparison, these were divided in the graphs of Figures 3.a (concrete families with 100 MPa, 50 MPa and 30 MPa) and 3.b (concrete families with 100 MPa, 40 MPa and <20 MPa). Both graphs are on the same scale on both axes, to allow direct comparisons by viewing in a horizontal line. Following the discussion on production quality control, the standard deviation values 3 (medium) and 7 (high) were applied to each of these concretes. A low S_d would be something close to the point itself (this would, in theory, be the point where $S_d = 0$). To visualize the influence of S_d on the points, each of them is followed by a red dotted line that leads to two more opaque new points, which represents the design of the same concrete with the variation of quality control (S_d).

In this sense, Figure 2 allows us to affirm that an important tool for the effectuation of the concept of D4S on the production of concretes is the increase of control in the production of mixtures. The designed compressive strength (fck) is significantly decreased by increasing S_d (decreased quality control), which brings a consequent increase in BI – since, on the other hand, the consumption of binders is fixed in the mixture and therefore does not vary according to the BI variation. This, in practice, means that, in order for the designed compressive strength to be achieved in a process with low quality control, a higher content of binders – cement being the main one in general – must be used, without any increase in performance. Cement, in this case, ends up acting as a compensator for the lack of quality control, which, in turn, reduces eco-efficiency. The opposite, fortunately, is also valid: increased quality control has the ability to decrease the cement content needed to guarantee the performance proposed by fck.

This trend is higher as it is applied to concretes of lower strength and with higher BI (low efficiency in the use of cement). In a 100 MPa and IL 5 $kg.m^{-3}.MPa^{-1}$ concrete (high strength, low BI) for example, the application of $S_d = 7$ (as large as possible) increased the BI from 5.0 to 5.7 $kg.m^{-3}.MPa^{-1}$. In concrete with 50 MPa and IL = 5.8 $kg.m^{-3}.MPa^{-1}$ (medium-high strength, low BI), $S_d = 7$ increased the BI to 7.5 $kg.m^{-3}.MPa^{-1}$. The concrete of 30 MPa and BI = 6.7 $kg.m^{-3}.MPa^{-1}$ (medium strength, low BI) had the BI increased to 10.4 $kg.m^{-3}.MPa^{-1}$ with the application of $S_d = 7$, markedly higher increase. Note that we are comparing concretes with different strengths, similar BI. The BI increased ~14% in the 100 MPa concrete, but near to 55% in 30 MPa concrete.

The situation is aggravated when high BI is high. The concrete of 50 MPa and BI = 8.8 $kg.m^{-3}.MPa^{-1}$ (medium-high strength, high BI) changed to BI of 11.5 $kg.m^{-3}.MPa^{-1}$ with the use of Sd = 7 – appreciably higher increase than its brother of 50 MPa and BI = 5.8 $kg.m^{-3}.MPa^{-1}$, which, as already seen, increased to 7.5 $kg.m^{-3}.Mpa^{-1}$. Similarly, the 30 MPa concrete with BI = 8.8 $kg.m^{-3}.MPa^{-1}$ saw its BI rise to 14.2 $kg.m^{-3}.MPa^{-1}$ (~61% increase) with the same S_d – considerably higher increase compared to its sibling 30 MPa and BI = 6.7 $kg.m^{-3}.MPa^{-1}$, which rose to 10.4 $kg.m^{-3}.MPa^{-1}$, and also considerably higher than the concrete of 50 MPa and BI = 8.8 $kg.m^{-3}.MPa^{-1}$, which reached BI = 11.5 $kg.m^{-3}.MPa^{-1}$ (~31% increase). An even more accentuated increase

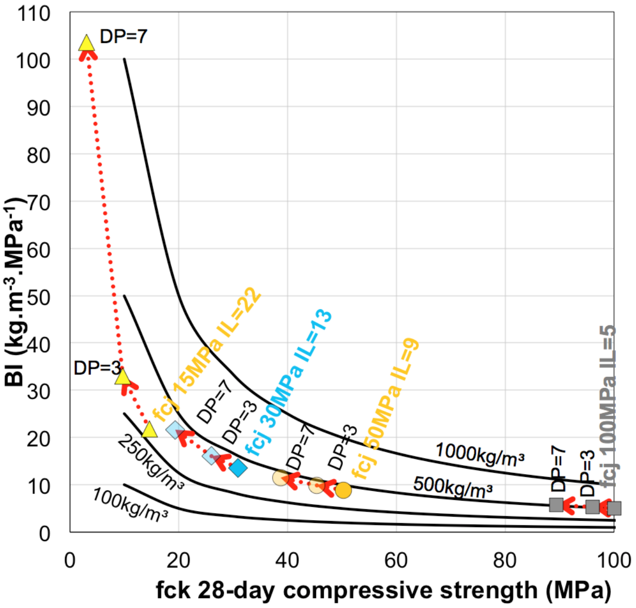


Figure 3: Extreme case shows the influence of the application of $S_d = 3$ and $S_d = 7$ on the BI of concretes of low resistance (<20 MPa) and high BI. The scale of the graph's y-axis needed to be changed to demonstrate the BI level reached. Source: Author.

was observed in the concrete of 30 MPa and BI = 13.5 kg.m^{-3}.MPa^{-1}; with $S_d = 7$, this reached an BI of 21.6 kg.m^{-3}.MPa^{-1}, an extremely high value for an ordinary strength concrete in concrete production plants.

As extreme cases, we still have the concrete with compressive strengths below 20MPa. The first, with 20 MPa and BI = 13.8 kg.m^{-3}.MPa^{-1}, had its BI increased to 33.8 kg.m^{-3}.MPa^{-1} (~145% increase) when the $S_d = 7$ was applied. Within the universe of the concrete chain, this value is absolutely out of any sustainability perspective, as well as a 15 MPa concrete with a high BI of 21.9 kg.m^{-3}.MPa^{-1}: this last, already of low resistance and a very bad proportioning design, would jump to an BI of no less than 103.6 kg.m^{-3}.MPa^{-1} if it was still applied with poor quality control, S_d=7 (see Figure 3).

Figure 4 shows the BI data from the benchmark originally obtained (right side), and the same data modified by the application, in all of them, of the coefficient of S_d = 7 (considering, therefore, a low-quality control during production and mixing). It is possible to have an idea of the eco-efficiency loss of the chain as a whole as the quality control processes are inadequate.

From this, the improvement of methods and management of the quality control of concrete production (which includes everything from the reception and characterization of raw materials to the mixing, transport and application process) stands out as a tool of fundamental importance for obtaining D4S from concretes, as well as increasing the eco-efficiency of the chain as a whole. Taking into account the S_d influence analysis on the BI of the data in this work; the fact that, in the concrete production chain, most of the mixed concretes have intermediate strengths, in the order of 20 to 40 MPa; and

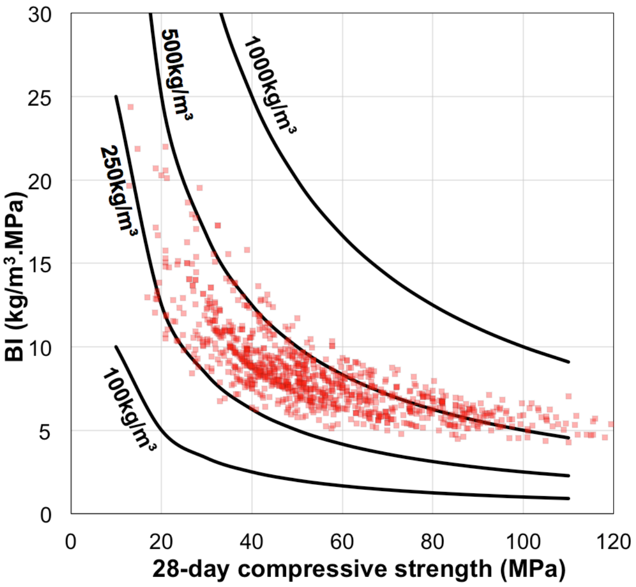


Figure 4: BI data from the original benchmark (Damineli et al, 2010) (right) modified to fck with the adoption of $S_d = 7$ (left). Source: Author.

also adopting that an average S_d for the chain should be around 4, a simulation of an earning potential was made from the improvement of quality control. In this scenario, approximately 23% of the cement produced worldwide is being used to guarantee the project fck against an inefficient quality control system. The simple reduction of this S_d to 3, something easily achievable with the simple adoption of some control measures, could reduce this value to around 16%, bringing savings of 7% of the world's cement. The difficulty lies in being able to scale these control measures globally.

Conclusions

The application of the D4S methodology (UNEP; DELFT, 2009) on the concrete life cycle resulted in the creation of environmental indicators for comparative assessment of the environmental performance of different concrete mixtures, in an analysis focused on the impact on global warming (emissions of CO_2). The use of these indicators – BI and CI – on a database of 100 international articles resulted in a benchmark of concrete, which allowed the development of discussion of various scenarios and actions that could increase D4S in this chain, with a special focus on the optimization of mixture proportioning of concrete and improving the quality control of the production process.

Simulations of changes in the standard deviation (S_d) to be used in quality control, which depends on factors such as characterization of aggregates, mixing technology and component weighing precision, among others, showed that the low-quality control – which it is a reality in most concrete manufacturing processes – tends to greatly increase the consumption of cement, which is, in this case, used to maintain the concrete design fck so that it can guarantee its structural safety. Similarly, the discussion shows that the increase in quality control has great potential to mitigate the environmental impacts of the chain, based on the reduction of the cement content necessary to achieve the fck. The possible gain is proportionally higher as the compressive strength range of the concrete is reduced, as the quality control influences the mixtures more significantly as they present lower strengths. This was evidenced by comparing concretes with S_d = 0 (theoretical, in which fck = fcj) with S_d = 7 (the largest described by the NBR 12655 standard, in case of concretes with very poor-quality control). The fact is relevant since concretes of medium-low resistance (20-40 MPa) are the most used in practice, which delegates to the increase in quality control a great importance on the mitigation of CO_2 emissions from the concrete chain. For concretes mixed in loco, which account for a considerable part of concrete production in developing countries, and which normally have low resistance and very low-quality control, this discussion gains even more fundamental importance.

With a simulation on the data, it was built a scenario that shows that it can be possible to reduce approximately 7% of cement consumption in mixtures of 20-40 MPa by simply reducing the S_d of mixtures from 4 to 3, something that can be applied without great efforts. As cement is the component with the highest cost of concrete, it is evident that this action, in addition to environmental benefits, also has social importance as it increases the access of the low-income population to the material.

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