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Measuring the eco-efficiency of cement use

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ABSTRACT

At present, the cement industry generates approximately 5% of the world's anthropogenic CO_2 emissions. This share is expected to increase since demand for cement based products is forecast to multiply by a factor of 2.5 within the next 40 years and the traditional strategies to mitigate emissions, focused on the production of cement, will not be capable of compensating such growth. Therefore, additional mitigation strategies are needed, including an increase in the efficiency of cement use. This paper proposes indicators for measuring cement use efficiency, presents a benchmark based on literature data and discusses potential gains in efficiency. The binder intensity (*bi*) index measures the amount of binder (kg m^{-3}) necessary to deliver 1 MPa of mechanical strength, and consequently express the efficiency of using binder materials. The CO_2 intensity index (*ci*) allows estimating the global warming potential of concrete formulations. Research benchmarks show that $bi \sim 5$ kg m^{-3} MPa^{-1} are feasible and have already been achieved for concretes >50 MPa. However, concretes with lower compressive strengths have binder intensities varying between 10 and 20 kg m^{-3} MPa^{-1}. These values can be a result of the minimum cement content established in many standards and reveal a significant potential for performance gains. In addition, combinations of low *bi* and *ci* are shown to be feasible.

1. Introduction

According to the Intergovernmental Panel on Climate Change (IPCC), the production of cement in 2003 was responsible for about 5% of anthropogenic CO_2 emissions [1]. This percentage is rapidly increasing largely because cement production increases at a faster rate than the speed at which emissions are presently reduced [1,2]. Global cement production is expected to increase 2.5 times between 2005 and 2050 with the majority of this growth occurring in developing countries [3,4].

The consolidated strategies to reduce CO_2 emissions resulting from the production of clinker are: (a) the substitution of clinker by mineral admixtures like pozzolans and blast-furnace slag; (b) increasing energy efficiency of the production process; and (c) the use of alternative fuels such as bio-fuels and waste [5]. Although they are important, these strategies alone are not capable of reducing the CO_2 emitted by the cement industry to satisfactory levels. Carbon sequestration [6,7], the use of new binders [3,8–10], the use of new raw materials for producing clinker [11], an increase in cement reactivity [10,12] and the substitution of coarse cement particles by limestone filler [13] are other strategies focused on reducing CO_2 emissions from the production of cement.

Another strategy for reducing CO_2 emissions is to improve the efficiency of cement use [3,10]. This would largely depend on the capacity of cement users to formulate more eco-efficient cement based products, but it would also encourage cement manufacturers to develop more efficient products. This alternative has not yet been systematically investigated, but some key options have already been presented: (a) the use of dispersants, better known as superplasticizers [14]; (b) more efficient packing of concrete particles [9]; (c) an increase in compressive strength; and (d) a combination of these strategies leading to the production of a "green concrete" as proposed by [10]. The WWF – Lafarge Report estimates there is a potential for a 15% reduction in cement consumption by the year 2050 which can be achieved by improving the efficiency of cement use [3]. The methodology used to produce this estimate has not been disclosed and thus far there have been no independent confirmations.

On the contrary of strategies focused on cement production – which can act only at the cement scale (substitution, alternative fuel, cement plant efficiency...), strategies that lead with the optimization of cement use can be developed also at concrete scale (use of dispersants, better packing, structural design).

The lack of a set of performance indicators, which would allow professionals and organizations to easily estimate the efficiency of the use of cement, inhibits the adoption of such strategies [15]. Such a set of indicators is also needed to determine a benchmark and establish feasible goals. It is worthwhile to note that the substitution of clinker, energy efficiency and alternative fuels have clearly established, easy to measure, performance indicators.

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The aims of this paper are to propose indicators for measuring the efficiency of cement use, explore the possibility of establishing a benchmark based on literature data and to discuss the potential future gains from the efficient use of cement.

2. Cement use efficiency indicators

There is little discussion found in literature about the efficient use of cement. In a pioneer paper, Popovics [12] presents the f_{eco}, the compressive strength which gives the highest efficiency of strength development (f_r), which is defined as the strength developed by one unit of mass of cement. On the other hand, the economic efficiency of a concrete mix design was defined by Aïtcin [16] as the cost of 1 MPa or 1 year of service life of the concrete structure.

In a more general approach, it is possible to define concrete efficiency in terms of the total amount of binder, the total cost of concrete production or the environmental loads imposed to deliver one unit of functional performance measured by a relevant indicator, e.g. compressive strength, bending strength, modulus of elasticity, carbonation resistance, etc.

From a life cycle analysis methodology point of view, this proposition can be understood as changing the functional unit from a **unit of concrete volume or weight** (1 m^3 or kg), which is convenient for measuring the overall environmental impact of any concrete construction, to a **unit of functional performance**, which in many cases is the compressive strength. It must be noted that the definition of unit of volume or weight as a functional unit of concrete is not accurate in most practical situations, since providing volume or mass is not the primary function of concrete in most applications. Therefore, using a performance indicator as a functional unit allows avoiding the distinction between a material scale, where impacts are expressed in kg or m^3, and a structural scale, where the effective volume to provide the function is used. This approach allows comparing the efficiency of concretes with different performances which in turn collaborates in the search for an optimum mix design.

This study proposes a simplified index: the Binder intensity (*bi*), which measures the total amount of binder necessary to deliver one unit of a given performance indicator e.g. 1 MPa of strength

$$bi = \frac{b}{p} \tag{1}$$

where b is the total consumption of binder materials (kg m^{-3}) and p is the performance requirement. In most cases p will be the compressive strength (MPa) at 28 days, but the performance indicator and the age will depend on the application of the concrete. The *bi* index expressed in terms of units of compressive strength (bi_{cs}) is the inverse of Popovics' f_r and gives numbers greater than 1 and seems easier to handle. Many ready-mix concrete companies commonly use the bi_{cs} to measure economical performance. It requires no additional data other than the conventional and therefore the calculation of the indicator is fast and easy. Together, these factors might facilitate the diffusion of this indicator among market practitioners.

As global warming is a major concern of the concrete industry, it is important to develop an indicator which allows comparing concrete formulations in terms of their CO_2 emissions. We propose using a CO_2 intensity (*ci*) indicator defined as the amount of CO_2 emitted to deliver one unit of performance

$$ci = \frac{c}{p} \tag{2}$$

where c is the total CO_2 (kg m^{-3}) emitted to produce and transport all concrete raw materials. In most cases, the p used for *ci* calculation is the compressive strength (ci_{cs}).

Since most CO_2 emissions come from the production of binders [17], CO_2 data from the production of binder allows a close estimation of concrete emissions in most practical situations. There are many life cycle national inventory databases that present typical or average CO_2 emissions from cement production [18]. However, despite being useful, this data does not necessary reflect the actual emissions of any given cement sample, because CO_2 emissions vary widely from plant to plant [19]. For any cement plant, CO_2 emissions frequently oscillate as a result of various factors, like the modification of kiln fuel mix due to market constraints.

In the future, the calculation of this indicator will be based on environmental product declarations from the suppliers of raw materials. In situations where the environmental product declarations are not available, a more feasible approach would be to use data disclosed by the world's leading cement manufacturers, participants in the Cement Sustainability Initiative (CSI) [2], which are based on international standards, independently verified and updated every year.

Combined, the two indicators afford a comprehensive assessment of cement use efficiency. The binder intensity (*bi*) yields the efficiency of using clinker and other hard to find clinker substitutes. The CO_2 intensity (*ci*) permits an estimation of the mix design's global warming potential. Life cycle databases also include other emission data (e.g. SO_x), which can be used to produce a larger series of similar indicators which can allow an even more comprehensive assessment. It should be noted that the data for CO_2 is much more accurate than that provided for pollutants such as SO_2 and NO_2 [20,21].

bi and *ci* incorporate several factors from: (1) the efficiency of cement production; (2) concrete mix design; and (3) selection of concrete materials, which includes the nature and quality of the raw materials (e.g. use of superplasticizers, reactivity of the clinker and the mineral admixtures used). When p value in the Eqs. (1) and (2) is the concrete design strength, the indexes are also sensitive to the variability of the concrete production process. Consequently, these indicators allow an assessment of the efficiency of the entire process. Other popular indicators like the replacement rate of clinker and the energy intensity of the cement or clinker production are not capable of delivering such a comprehensive assessment.

3. Methodology

Literature data related to compressive strength, binder consumption and composition were used to test the indicators. Literature results are considered adequate for exploring future gains in efficiency because they include state-of-the-art laboratory scale technology that most likely will become market feasible in the near future. In this sense, this literature data allows exploring what industrial concrete might become in the future. Compressive strength was selected as the performance indicator because it is the most common mix design criteria.

A total of 156 randomly selected papers published between 1988 and 2009 were analyzed. In order to test the existence of regional influences on the benchmark, two different sets of papers were examined. The first set was composed of 59 Brazilian papers, the majority of which were published during the Brazilian Concrete Institute (IBRACON) yearly conference proceedings. The second set consisted of 97 papers from 28 countries. Selected papers presented 28 days compressive strength results and a clear description of binder composition. A database with 1585 registers was built (Microsoft Excel), including: (a) basic bibliographic reference; (b) amount of each binder fraction (kg m^{-3}); (c) amount and type of dispersants admixtures; (d) 28 days compressive strength for each tested sample; and (e) its geometry. The influence of sample geometry on compressive strength was corrected to the equivalent cylindrical sample (10 × 20 cm) using models from [22–24].

The papers did not present data on CO_2 emissions, which are needed to estimate CO_2 intensity (*ci*). In order to test the indicator, literature data was used to roughly estimate the amount of CO_2 emissions associated to the production of binder. All CO_2 emissions derived from the production and transportation of raw materials and concrete were ignored. The absorption of CO_2 during concrete carbonation was also ignored. In most cases, the contribution of these factors to the CO_2 balance is much lower than from the production of clinker [17]. Therefore, the *ci* results are just a calculation and probably underestimate the actual impact on global warming, but they are still useful for testing the indicator and its sensitivity. Consequently, the amount of CO_2 released by cement was estimated based on a combination of clinker content and literature data. Clinker content was calculated by subtracting the total amount of mineral admixture and assuming a calcium sulfate fraction of 5%. In many cases, Brazilian literature data was related to the use of blended cements. In this case, the fraction of mineral admixtures was estimated as the average between the maximum and minimum content allowed by the national Brazilian standards for the cement class.

CO_2 emissions from clinker production are a function of energy efficiency and fuel, with literature reporting a variation between 821.1 [25] to 1150 kg CO_2/t clinker [5,26]. For the sake of simplicity we assumed an emission of 1 ton CO_2/t clinker, which in many cases is an overestimation due to the fact that many producers currently have the technology for achieving emissions below 800 kg CO_2/t clinker [8,10]. However, no technological advances are taken into account in this study, and a world average (1 ton CO_2/t clinker) is being adopted, a value which is consistent with that adopted by the IPCC in its latest report [1]. Therefore, in this study the CO_2 estimate is a function of clinker content since the CO_2 generated by other binders may be considered negligible in comparison to that produced by clinker [17].

CO_2 emissions from the production process that generate mineral admixture by-products such as fly ash, silica fume and blast-furnace slag are considered equal to zero, which is a common procedure [27,28]. However, this assumption means ignoring CO_2 emissions resulting from phases like classification, drying, grinding and the transportation of these products, which might be significant [17,29], especially when the pozzolan used is calcinated clay. In this sense, the benefits of admixtures are exaggerated. This error varies according to the amount of fossil fuel energy used in these activities.

4. Results and discussion

The consumption of binder tends to increase with compressive strength (Fig. 1). However, dispersion is large, showing that many other factors are influencing the amount of binder needed to deliver a given compressive strength.

4.1. Binder intensity

Fig. 2 presents the calculated binder intensity (bi_{cs}) for Brazilian and international data dispersion. Variability of the data is greatly diminished in comparison with Fig. 1, and dispersion decreases as compressive strength increases. There are no significant differences in the clusters produced with international and Brazilian data. The lower borders of both data clusters are quite similar, even though a wide variety of materials and mix design methods are represented. This shows the bi_{cs} indicator gives consistent results in diverse situations.

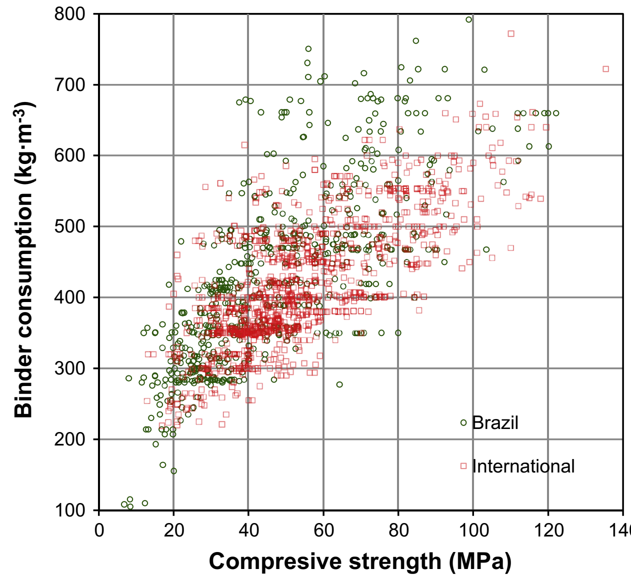

Fig. 1. Compressive strength *versus* total binder consumption. There are 604 results from Brazil (circles) and 981 international (squares).

The minimum observed bi_{cs} tends to decrease with an increase in compressive strength up to 60 MPa. Therefore, high strength concretes tend to be more efficient in terms of the amount of binder required to deliver each unit of mechanical strength, confirming literature data [3,27]. Above 60 MPa, the minimum observed bi_{cs} seems to reach a plateau in the range of 5 kg m^{-3} MPa^{-1}.

Below 60 MPa the minimum bi_{cs} somewhat follows the line that corresponds to a total binder content of 250 kg m^{-3}. Only 36 out of 1585 data points (~2.2%) were produced using less than 250 kg m^{-3} of total binder. This is probably a result of the minimum binder content values established in most national standards, supposedly to ensure durability, a very important performance requirement for a sustainable concrete. For example, Brazilian standard [30] establishes a minimum consumption of 260 kg m^{-3} for structural concrete while the European standard requires a minimum cement content of 240 kg m^{-3} for concrete subjected to the risk of corrosion [31]. However, Wassermann et al. [32] shows that durability performance indicators are not affected (carbonation depth, shrinkage) or even improved (chloride penetration and capillary absorption coefficient) when binder content is reduced within the limits investigated. Dhir et al. [33] conducted a comprehensive investigation and concluded that "specifying minimum cement content for concrete durability was not necessary". Additionally Popovics [12] shows that for the same *w/c* ratio an increase in binder content results in a decrease in compressive strength. Therefore, considering its environmental and economical implications, it is possible to conclude that "the minimum cement (i.e. binder) content requirement should be revisited" [32] and additional research is needed.

Another possible cause for higher bi_{cs} for concretes below 60 MPa is the need for a minimum amount of fines [27,32] to ensure adequate rheology and the bond between the concrete and steel. It may also be simply a result of the standard aggregate grading curves. However, a definitive answer to the question of minimum cement content will depend on a comprehensive investigation of how it affects all the relevant aspects of concrete performance.

A binder intensity (bi_{cs}) of 5 kg m^{-3} MPa^{-1} should not be seen as an absolute minimum since the set of data presented in Fig. 2 includes values below that number. International data revealed 16 results below 5 kg m^{-3} MPa^{-1}, and Brazilian data, eight results. In

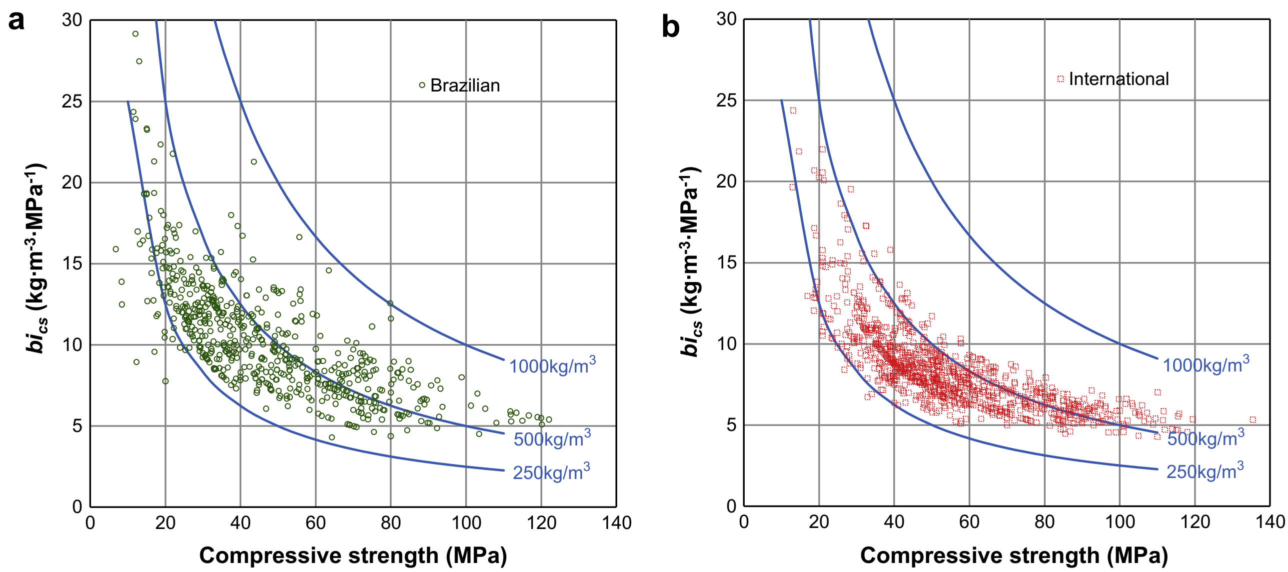

Fig. 2. Binder intensity (bi_{cs}) *versus* 28 day compressive strength for: (a) Brazilian data; (b) international data. The lines represent concretes with the same amount of total binder. Few data points are not shown because *bi* is above 25 kg/m**3** MPa.

all cases, the minimum bi_{cs} observed is 4.3 kg m^{-3} MPa^{-1} [34,35]. The strategy of paper [35], Brazilian, is a combination of high aggregate packing density with a very reactive blended cement from Holcim Brazil (Duracem AD300, with >60 MPa 28 days on standard test) and commercial superplasticizer. Ductal, the only commercial ultra-high performance concrete (UHPC) available has a total binder of 1194.5 kg m^{-3}, 230 MPa compressive strength and a bi_{cs} of 5.2 kg m^{-3} MPa^{-1} [36,37]. However, with the use of high pressure packing and thermal curing, compressive strength goes up to 800 MPa and bi_{cs} falls to ~1.5 [37]. So, in the long term it is possible to achieve lower bi_{cs} values, especially when considering that in UHPC about 50% of the cement grains remain unhidrated [36].

An investigation of Brazilian data revealed that the highest bi_{cs} values found (above 20 kg m^{-3} MPa^{-1}) occurred due to the use of high volumes of some weak or low elastic modulus waste materials as aggregates or reinforcement, including reclaimed vulcanized rubber tire fibers [38,39], PET pellets as fine aggregate [40] or granulated foundry slag as fine aggregate [41]. This demonstrates that bi_{cs} can also be an indicator of the environmental performance of concretes produced using waste as its raw material. Conversely, the lowest bi_{cs} values (below 5 kg m^{-3} MPa^{-1}) are linked to improved packing of aggregates [35] or a combination of a very low *w*/*c* ratio with 10% silica fume content [42–44] and superplasticizers, resulting in concretes with compressive strengths above 60 MPa.

For international data, the highest bi_{cs} values are related to a high rate of clinker substitution by mineral admixtures. In most of the data more than 50% of the clinker has been replaced with fly ash [45–47] or volcanic ash [48]. Nonetheless, the more efficient concretes (bi_{cs} under 5 kg m^{-3} MPa^{-1}) are those with compressive strengths above 80 MPa, superplasticizer, very low *w*/*c* ratios and 6–10% of silica fume [34,49–53]. However, it is possible to achieve a bi_{cs} under 5 kg m^{-3} MPa^{-1} by replacing 10% of the clinker with very fine fly ash, which suggests that improving the packing is decisive [54].

The data gives reason to suggest 5 kg m^{-3} MPa^{-1} as a feasible goal for normal strength (<50 MPa) concrete in the not too distant future. In the long term, significantly lower binder intensity will probably be feasible. An international benchmark using results from commercial concretes would be necessary to establish more accurate targets. More than that, the overall performance, including the durability and fracture behavior, of these very low binder concretes must be systematically investigated, as the minimum bi_{cs} for low strength concretes may be governed by parameters other than compressive strength.

Fig. 3 shows no clear trends on the amount of clinker and compressive strength during 20 years analysis. Thus, the "time" factor appears to have no influence on the conclusions.

4.2. CO_2 intensity

Fig. 4 presents total CO_2 emissions (kg m^{-3}) of the sample *versus* 28 day compressive strength. The results show a comparatively higher dispersion than the total binder content data (Fig. 1), with total CO_2 emission estimated between 100 and 600 kg m^{-3}. The data sample shows no evidence that the maximum CO_2 emission is a function of square root of compressive strength, as suggested by [27]. This is probably due to the presence, in this research, of several different types of cement, clinker fractions and raw materials.

Fig. 5 presents the estimated CO_2 intensity (ci_{cs}) *versus* 28 day compressive strength. The data trend is similar to that observed for the binder intensity results (Fig. 3), since high strength concretes tend to present lower intensities and less data dispersion. However, the estimated minimum CO_2 intensity is around 1.5 kg m^{-3} MPa^{-1} for all ranges of concrete strength. These values contain a certain inaccuracy since the actual CO_2 emissions of clinker production vary widely and also because mineral admixtures and aggregates were considered as having zero CO_2 emissions.

The focus on clinker substitution as the major tool for achieving sustainable concrete, combined with the assumption that waste recycled as mineral admixtures have zero CO_2 emission, may lead to the formulation of concretes with high bi_{cs} but low ci_{cs}, as shown in Fig. 6. As an example taken from the Brazilian data, a 90% replacement rate of the clinker with fly ash (70%) and blast-furnace slag (20%) resulted in concretes with ci_{cs} < 1.6 but with bi_{cs} between 12.6 and 16.9 [55]. International data also reveals low ci_{cs} (below 5) obtained with formulations having high bi_{cs}, between 15 and 20.6 [45,47,56]. In these concretes, all clinker substitutions (mostly with fly ash) were above 69%. However, the global amount of waste that can be recycled as mineral admixtures – mainly

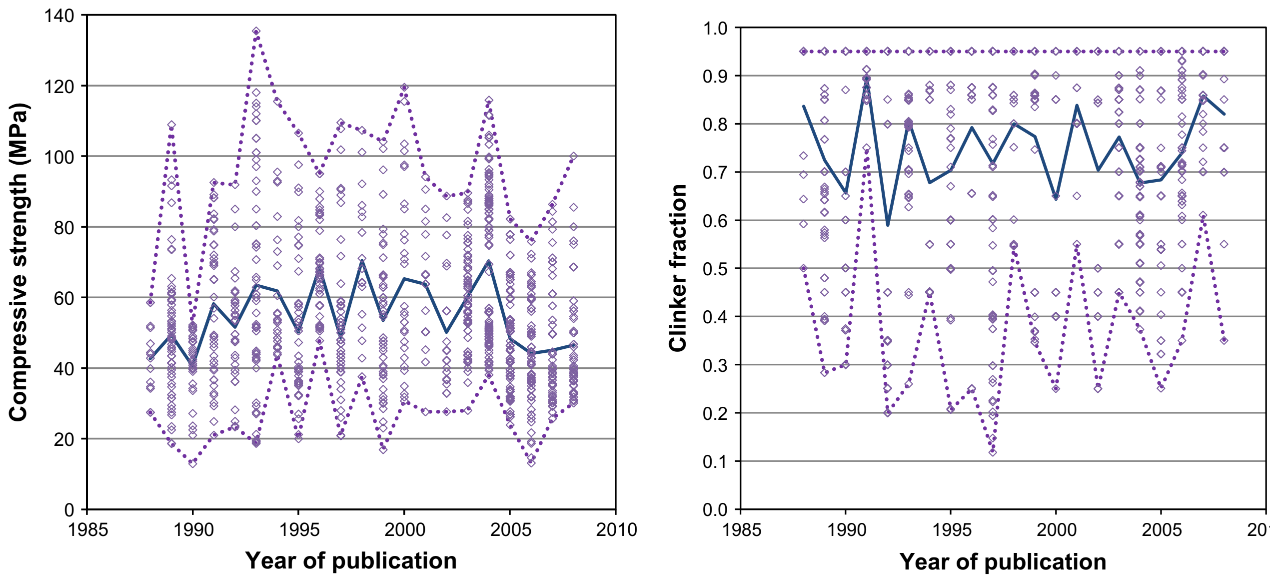

Fig. 3. Dispersion of observed values of compressive strength (left) and clinker fraction (right) over the time of analysis. Lines denote minimum, maximum and average values for each year.

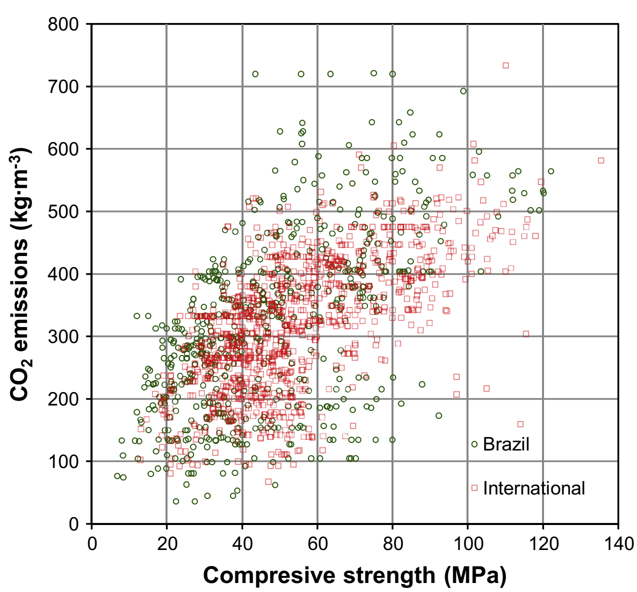

Fig. 4. Estimated total CO_2 emissions *versus* 28 day compressive strength.

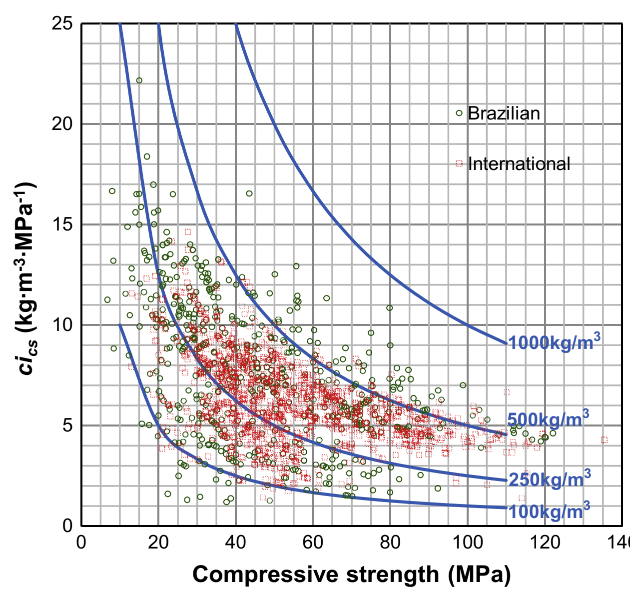

Fig. 5. Estimated CO_2 intensity (*ci*) *versus* 28 day compressive strength. The lines represent concretes with the same amount of total CO_2.

blast-furnace slag and fly ash – is limited [5]. For example, the forecast for global coal consumption, which generates fly ash, shows a production peak by the year 2030, around 15% above the 2009 values. After 2030 fly ash production is expected to decrease [57]. In this same period, cement production is projected to increase 216% [4]. There is a well established notion currently embedded in some green building certification schemes that the higher the clinker replacement rate is, the more sustainable concrete is. The application of this concept can lead to a depletion of scarce non-renewable mineral admixtures. In view of this, it might be wise to consider conserving this scarce material for future use. Consequently, the amount of clinker substitutes, even those which are recycled, must be considered in *bi* calculations.

Fig. 6 shows that the minimum ci_{cs} is highly independent of the bi_{cs} value. Therefore it is possible to formulate concretes which present low ci_{cs} and low bi_{cs} simultaneously. This is because ci_{cs} is not directly related to clinker fraction (Fig. 7) since it is possible to formulate a concrete with a high amount of clinker and, at the same time, a low clinker fraction. Fig. 7 also shows that for "pure" cement, it is possible to have an estimated ci_{cs} as low as 4.3 kg m^{-3} MPa^{-1} if the bi_{cs} is minimized. Clinker substitution is crucial to any further reduction of ci_{cs}. Practical examples of $bi_{cs} < 6$ conjugated with $ci_{cs} < 3$ were found in Brazilian [35,43,44] and international [34,58–60] data. These concretes always had compressive strengths above 50 MPa and more than 50% clinker replacement. It must be noted that the difference between these concretes in relation to those cited earlier – with low ci_{cs} but high bi_{cs} – is the use of blast-furnace slag as clinker replacement instead of fly ash.

Contrasting with the above, higher ci_{cs} values (above 15 kg m^{-3} MPa^{-1}) from Brazilian data are related to high bi_{cs} with little or no clinker replacement and sometimes combined with the use of some type of recycled waste as aggregate or some regional

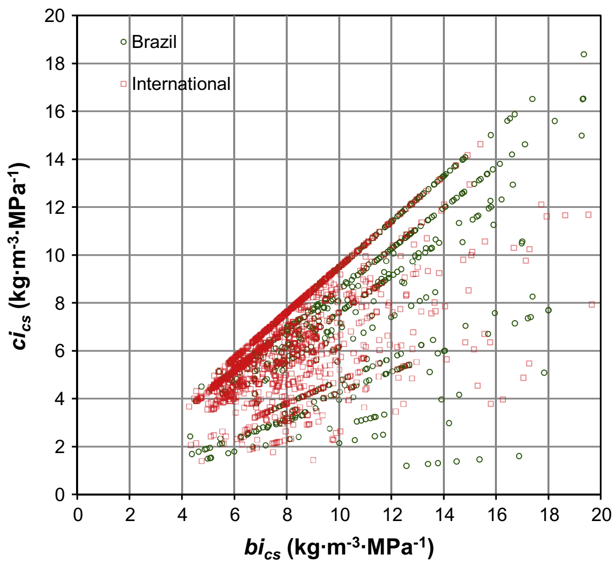

Fig. 6. Binder intensity (*bi*) *versus* estimated CO_2 intensity (*ci*).

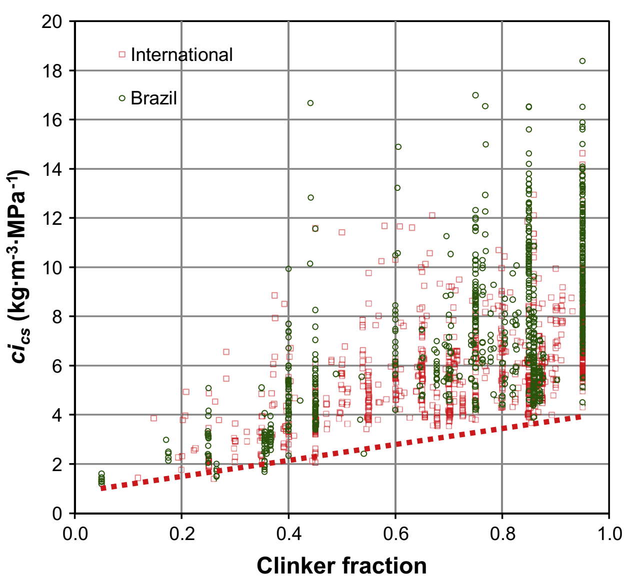

Fig. 7. Clinker fraction *versus ci* intensity.

aggregate [38,39,41,61–64]. The maximum ci_{cs} values found in international data remain below 15 kg m^{-3} MPa^{-1}. All ci_{cs} values above 13 kg m^{-3} MPa^{-1} presented high bi_{cs} value and no clinker replacement [65–68].

The available data suggests that achieving ci_{cs} ~4 kg m^{-3} MPa^{-1} with no clinker replacement is not too far off. A ci_{cs} below 2 kg m^{-3} MPa^{-1} is a plausible medium term goal, at least for locations having a sufficient supply of waste admixtures like blast-furnace slag. For locations with no waste mineral admixtures, using low CO_2 clinker and artificial pozzolans (produced with bio-fuels) combined with improved packing, can allow for the production of concretes with equivalent low ci_{cs} values. Considering the uncertainty of CO_2 emissions used to estimate ci_{cs}, these numbers must be taken very cautiously.

4.3. Implications for global warming targets

An accurate estimate of the potential contribution of increasing the efficiency of cement use (reducing *bi*) to mitigate cement supply chain CO_2 emissions requires an international benchmark based on actual market results, which must include measuring the fraction of cement used in structural concrete. It is also necessary to systematically investigate all the possible consequences of producing concretes with very low binder content, such as modifications in its long term performance, because other aspects can limit bi_{cs} and ci_{cs} targets.

Exploratory data from the Brazilian market suggests that ready-mix concretes below 40 MPa, which consume the most cement, have a bi_{cs} ~10–12. Admitting that the formulation of a durable and structurally safe concrete with $bi_{cs} = 5$ is possible, a potential reduction of binder content around 50% can be estimated. For mixed on site concretes – which are predominant in developing countries like Brazil – the potential is significantly higher than for ready mix ones. The WWF – Lafarge Report [3] estimates that a more efficient use of cement can lead to a 15% reduction in its global consumption.

An estimate of CO_2 emissions from concrete is even more complex, because it is influenced not only by the clinker replacement rate and emissions associated to the admixtures, but also by the concrete formulation efficiency (bi_{cs}). The average estimated ci found in literature was 7.1 for international data and 9.1 kg m^{-3} MPa^{-1} for Brazilian data. The minimum estimated ci_{cs} was around 1.5–2 kg m^{-3} MPa^{-1}. Since this estimate was made without taking in consideration the emissions from clinker replacement admixtures, the benefits of clinker replacement are overestimated, especially for high replacement rates and low ci_{cs} formulations. In Brazil the potential of increasing the clinker replacement rate is rather limited, since today the average replacement rate is nearly 30% [2] and the amount of slag and fly ash is limited. Globally, the WWF report estimates there is a potential for reducing current CO_2 emissions of around 14% by clinker replacement only.

5. Conclusions

In the near future, without the introduction of technological innovations, the ever increasing demands for cement based materials in developing countries will most certainly provoke a significant increase in the cement industry's percentage of global CO_2 emissions.

In this study, two indicators are proposed which allow measuring the eco-efficiency of cement use, binder intensity and CO_2 intensity. Both indicators have performance, e.g. mechanical strength, as a functional unit, an innovation which might allow the development of an entire family of new indicators. Both indicators were tested using two sets of data from literature, one Brazilian and the other from 28 different countries. The results produced from the two sets of data are consistent.

Binder intensity (bi_{cs}) allows measuring the amount of binder necessary to deliver a unit of strength, and consequently the efficiency of the use of binders. For concretes having more than 60 MPa at 28 days, minimum bi_{cs} stabilizes around 5 kg m^{-3} MPa^{-1}. As concrete strength decreases, the minimum bi_{cs} increases progressively, closely following the line that represents a total binder content of 250 kg m^{-3}. This is probably a result of minimum cement content established in most national standards. For 20 MPa concrete, the minimum observed bi_{cs} is around 13 kg m^{-3} MPa^{-1}.

CO_2 intensity (ci_{cs}) allows measuring the amount of CO_2 needed to deliver a unit of strength and hence, its contribution to global warming. CO_2 emissions data used in this work are only approximate and the following numbers should be considered cautiously. The minimum ci_{cs} is not affected by compressive strength and remains around 1.5 kg m^{-3} MPa^{-1}. Without substituting clinker it is possible to produce concretes with CO_2 intensities as low as 4.3 kg m^{-3} MPa^{-1}. For lower CO_2 intensities clinker replacement has shown to be necessary. The data suggests that mix design and raw materials selection allows reducing ci_{cs} by a factor of 10, from a ci_{cs} ~15 kg m^{-3} MPa^{-1} to a minimum ~1.5 kg m^{-3} MPa^{-1}.

Data also shows that is possible to produce concretes which, simultaneously, have low bi_{cs} and ci_{cs} values. In laboratory conditions, concretes with bi_{cs} ~4 kg m^{-3} MPa^{-1} and ci_{cs} around 2 kg m^{-3} MPa^{-1} were produced.

An international benchmark based on commercial concrete data is essential for establishing the actual benefits of increasing the efficiency of cement use to mitigate CO_2 emissions proceeding from the concrete supply chain. Further research on the implications of significant reductions of cement content in long term performance is also needed. The first exploratory results presented here are encouraging.

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