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Mitigating CO_2 emissions from the cement industry: potential of feasibility *versus* the market challenge

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Abstract Title

Public demands for a larger and better built environment in the developing world are steadily increasing, and will oblige the production of cement to increase at least 2.5 times between 2010 and 2050. Unless affirmative action is taken, the low availability of blast-furnace slag and fly ash, together with the limited potential for gains in energy efficiency, will cause the share of CO_2 emissions from cement production to be as high as 30% by the year 2050. Such recently proposed options as carbon caption and storage are very expensive and could double prices, negatively impacting the costs of infrastructure in developing countries.

This paper presents an additional option for decreasing CO_2 emissions from the cement industry – an environmental demand – without decreasing production – a social demand. An increase in binder use efficiency can be measured by a binder intensity index (mass of binder for each MPa of compressive strength). Laboratory results show that binder content can be reduced by up to 75%, which means that the same amount of concrete could be produced with less than half the clinker content.

Nonetheless, practical market experiments are in general responsible for the lowest binder efficiency found in literature. In this scenario, the contradiction between technical advances and market restrictions to putting them into practice will be discussed to construct a perspective of the future of the concrete and cement chain, as well as identify the main actions required for increasing the sustainability of the chain.

Keywords: global warming, CO_2, cement, binder efficiency, concrete market.

1. Introduction

Cement is essential to almost all built environment production and consequently the world's most used material. Current loads from cement production represent 5-8% of world CO_2 emissions (BERNSTEIN et al, 2007; MÜLLER; HARNISCH 2008). Due to the needs of all sources of infrastructure in developing countries – from housing to basic sanitation and

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highways –, the current production of approximately $2.2x10^9$ t/year is projected to increase to more than $5x10^9$t/year in a high growth scenario (IEA; WBCSD, 2009; Müller; Harnisch, 2008), which would make the cement industry responsible for up to 30% of global CO_2 emissions (BERNSTEIN et al, 2007) if current chain strategies and actions are maintained.

As discussed in Damineli; John (2012), the main industrial strategy to mitigate CO_2 emissions from cement production – replacing clinker with mineral admixtures such as blast-furnace slag (BFS) and fly ash (FA) – does not have long-term potentiality. These materials are not available in scale enough to supply the increasing demand for cement; at best a 22-25% replacement would be reached, and national technical standards allow up to 50% of FA or 70% of BFS in the cement mixture. And this does not take into account the real possibility of a long-term decrease in the availability of the products, as well as it does not consider the possibility of a change in CO_2 allocations in pollutant chains that produce BFS and FA, which could significantly change the current “environmentally-friendly” aspect commonly linked with the use of these wastes as binders for replacing clinker (Chen et al, 2010; Birat, 2011).

This lack of potential for reducing CO_2 emissions in cement production on a worldwide scale is also true of other known mitigating strategies. Even Kilns efficiency, very popular with most of world’s big producers, would not be capable of new gains without huge efforts (Gartner, 2004). The use of alternative fuels also falls within this category (WBCSD, 2007). Together, the three strategies, even if developed to their highest level and commonplace among all cement plants, would just decrease CO_2 emissions by 20-30%, which is clearly unsustainable if compared with targets discussed in the Kyoto Protocol, Stern Review (OCC, 2005), IPCC (2007) and other recent world climate change meetings.

The latest industry strategy for mitigating CO_2 emissions is carbon capture and storage (CCS). Despite its effectiveness – the potential to eliminate 100% of CO_2 emissions–, this strategy is also unsustainable, from a social point of view. CCS is very expensive, with estimated costs varying from USD 40 to 250/t CO_2 (HOENIG; HOPPE; EMBERGER, 2007; ANDERSON; NEWELL, 2004), which could more than double cement’s net price, with a negative impact on the economies of developing countries.

So, to increase concrete production, while at the same time decrease CO_2 emissions, a new strategy is imperative: binder use efficiency. This paper aims to: 1) present solutions already tested in laboratory scale to increase efficiency in the use of binders in structural concrete production; and 2) discuss common market obstacles to the implementation of this technology, and develop a more comprehensive discussion about the feasibility of gains.

2. Solutions for increasing binder use efficiency: benchmark and technical possibilities

For measuring the potential of the binder use efficiency strategy, three main steps were developed: 1) creation of a Binder Intensity (BI) index, which allows a comparison of different concrete mixtures objectively in terms of binder use; 2) literature research with the aim of establishing a benchmark of BI worldwide; and 3) laboratory research (main part of the PhD thesis of the primary author) to find ways and limits of binder efficiency in concretes. They are summarily presented in the following subject matter.

2.1 Binder Intensity (BI) and the benchmark

Binder Intensity (BI), an index for measuring binder use efficiency (DAMINELI et al, 2010a) was developed. It adapts a concept that is almost universally adopted by the ready mix concrete industry to measure efficiency: the amount of binder per 1MPa of compressive strength at 28 days. This has several advantages: the concept and range of resulting values are familiar to potential users and very simple to estimate, and it is easy to develop a benchmark of current performance. Since the aim was to access the efficiency of using scarce energy intensive material the amount of “cement” was replaced by an equal amount of binder, by removing the amount of limestone filler from the calculation. Therefore, binder intensity (bi_{cs}) is hereby defined as the amount of binder (B, in $kg.m^{-3}$) needed to provide 1MPa of compressive strength (CS, in MPa) at a given age. The concept is to change the functional unit of concrete from one cubic meter to a relevant performance indicator.

bi_{cs}= B/CS

Using the same concept, all series of indicators are easily defined, including the expected service life, changing both impact and performance indexes. One other index was also developed for this research –CO_2 intensity (ci), which measures the amount of CO_2 released for each MPa. To calculate ci, using simplified literature data, clinker was considered as emitting 1 kg of CO_2 per kg of clinker produced, and other binders (fly ash and blast-furnace slag) were considered as zero emissions. This makes ci very dependant on clinker content. So, when clinker is the main binder in the composition, ci tends to be very similar to bi. However, progressively reducing clinker content by replacing it with other alternative binders progressively decreases the ci, whereas bi remains unchanged. Detailed discussions about ci are found in Damineli et al (2010). Since these supplementary binders are scarce (DAMINELI; JOHN, 2012), and their CO_2 emissions are the topic of current discussion, bi analysis is the most important for the aims of the present paper.

For establishing a benchmark of current stage of bi_{cs} worldwide, 156 random papers from 29 countries were used, and also some preliminary data from the real market (one ready-mix concrete company from São Paulo, Brazil). Fig. 1 presents benchmark.

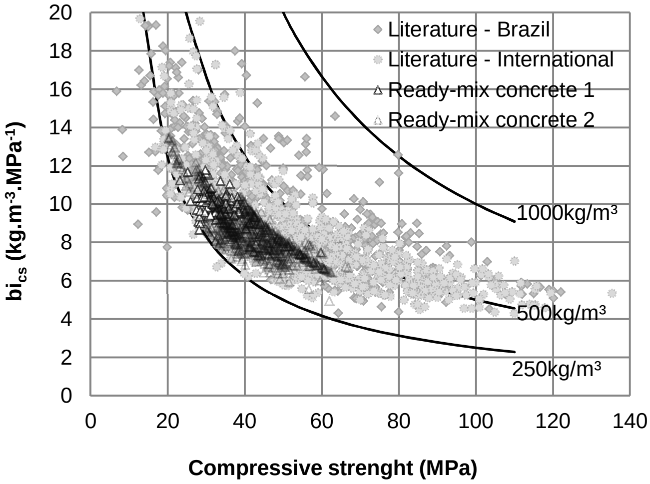

Fig. 1 – Benchmark of bi. This includes data from 29 countries (Damineli et al. 2010) as well as a comprehensive dataset from two ready-mix companies in São Paulo.

Available data indicates that the minimum bi is around 5 kg.m^{-3}.MPa^{-1} for concretes above 50MPa, using current technology. Below that, minimum bi follows the 250kg.m^{-3} binder content line, which corresponds roughly to the minimum cement content found in many national standards (ABNT, 2006; Grube; Kerkhoff, 2004). Since most of the concretes are below the 50MPa class, actual bi is much higher than the possible minimum. More detailed discussions about bi potentials for assessing binder use efficiency are found in Damineli et al (2010a).

2.2 Laboratory results

Preliminary laboratory results presented in Fig. 2 show that by controlling dispersion and packing of the system (ORTEGA et al, 1999; BONADIA et al, 1999) and replacing binder with engineered inert fines (MOOSBERG-BUSTNES; LAGERBLAD; FORSSBERG, 2004; VOGT, 2010) it is possible to mix concretes with compressive strengths between 20 and 40MPa (same as market requirements) and *bi* between 5 to 7 kg.m^{-3}.Mpa^{-1}, which fills in an empty area of the graph– the area with binder consumption under 250kg.m^{-3}. This implies in mixtures with binder contents lower than that required by national standards yet still having good strength, which shows that national standards can be a big hindrance in the search for increased binder efficiency. Also, most of these concretes are self-compacting, which means, in practice, that lower *bi* results could be achieved if rheological requirements were decreased to allow the production of concretes with higher yield stress.

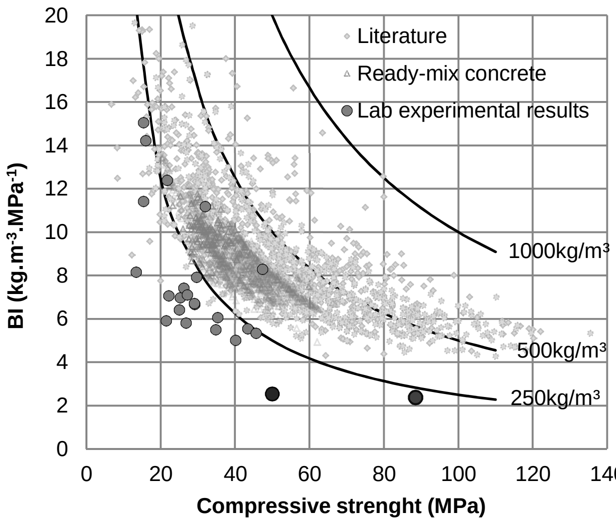

Fig. 2 – Examples of the potential to reduce bi of concretes. Concretes formulated and produced in lab at USP as well as in collaboration with CBI/Sweden. Most concretes are self-compacting. The two with bi below 3 have slumps above 180mm.

A serious limitation to introducing packing strategies is the large number of controlled fillers. Taking advantage of the large variety of these raw materials in Sweden, we were able to produce some highly efficient concretes. One formulation, using only 210 kg.m^{-3} of total binder (including 10 kg of silica fume), slump of 180mm, reached 88.4MPa (100x200mm cylinder) at 28 days. This corresponds to a *bi*o f 2.37 kg.m^{-3}.MPa^{-1} – less than half that of the best practices found in the literature benchmark[3]. Compared to marketable concretes this means cutting total binder consumption by a factor of 4. In the same project another concrete having only 126.3 kg.m^{-3} of total binder content was also designed and achieved 190mm of slump and 28 day-compressive strength of 50MPa, which delivered a *bi* of 2.53kg.m^{-3}.MPa^{-1}.

These essays show that the restrictions to designing concretes with very low cement content can be overcome by employing scientific methods of packing and dispersion of particles, requiring lower binder content for achieving rheological parameters.

3. Market challenges, trends and potential

However, introducing the highest binder use efficiency concretes, such as those presented above into the market, would involve enormous obstacles. This subject matter will discuss the most important related issues, which must to be overcome for a real, more sustainable concrete/cement chain.

3.1 The lack of inert filler production and technical knowledge

Concretes with very high binder use efficiency (experimental lab data shown in Fig. 2) are produced with a significant content of clinker replacement by inert fillers, which are not produced under high temperature and release much less CO_2 emissions than clinker or other heat-processed binder. Inert filler CO_2 emissions result from their production at mills and subsequent transport.

A simple comparison of the pros and cons of inert filler production versus clinker production would seem to indicate that the first is cheaper and more environmentally-friendly. But, this scenario changes drastically when market regulations are added to the equation. At present, the demand and production of clinker is much greater than fillers, and good inert fillers are still very expensive in contrast and could, if used in a short-time perspective, increase concrete costs. Just for comparison, when cement production surpassed 2x109 tons in 2004 (WBCSD, 2009), limestone filler production was 6.9x10^{6} tons, for all industrial uses (BRITISH GEOLOGICAL SURVEY, 2006) – a 10^{3} tons magnitude of a lower order.

This production difference has a direct impact on prices. One ton of cement costs, on average, USD 75 in Asia (lowest price), USD 90 in Europe, USD 120 in America or Africa, and USD 148 in Oceania (SNIC, 2011) – world average near USD 100-110. Similar data is found on the website of the Massachusetts Department of Transportation, which quotes USD 105 as the price of cement (http://www.mhd.state.ma.us/default.asp?pgid=content/fuelPrices&sid=about), October 2012. But these prices can more than double due to transport and other market costs – one

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[3]Research in collaboration with Prof. Björn Lagerblad (CBI -KTH). One of the concretes formulated in this research won the “Starkast Betong” (The strongest concrete) international competition, which was held in CBI Betonginsituten, 2012. This competition established a maximum cement content of 200 kg.m^{-3} and did not limit the use of supplementary materials. The winning concrete just used 200kg.m^{-3} of cement and 10 kg.m^{-3} of silica fume as total binders.

bag of 50kg in Brazil costs from USD 9 to 10 to the final consumer, which makes the per ton cost (20 bags) from USD 180 to 200.

In Brazil, bagged limestone filler, , can cost the final consumer between USD 40 and USD 500 per ton, depending on the production control process, particle grain size , purity of raw material and other variables. So, these variations in price can have a heavy impact concrete's final cost. Therefore, a good understanding of filler characteristics is fundamental when choosing the material for use in concrete, avoiding high costs at the same time that high efficiency in binder use is reached.

However, even though demand is low, cost-competitive inert fillers are becoming more familiar on the concrete market. If in some countries inert fillers are still very expensive and uncommon, Europe, to the contrary, already has some inert filler producers that are supplying the concrete chain with high quality, bagged fillers at competitive prices. The concrete chain is now offering these materials as a replacement for clinker, although comprehensive instruction as to their potential is still lacking. The authors' opinion here is that this will only occur when the cement industry begins developing its own technology for producing fillers that are adequate and compatible with clinker, a very singular material in terms of physic-chemical characteristics. The envisioned concrete/cement chain for this end is one that understands clinker interactions, and also the only one that has a process line developed, in terms of size and organization, required for this task. The large scale production of inert fillers could result in a substantial reduction in the cost of cement/concrete and even be added to new lower clinker and binder cements.

3.2 Quality of aggregates

The quality of aggregates has been continuously investigated since the beginning of concrete technology. Forty years ago, Renninger (1969) said that the quality of aggregates had already been an extensively covered subject in concrete technology, showing that the rounder the aggregate, the lower the water content required for the same formulation and same slump, which implies in lower w/c ratio and higher compressive strength – and so, higher binder use efficiency. The study still links aggregate quality to concrete durability, showing that even when concrete paste is very low in voids content, aggregate quality can influence durability indexes.

Rached; De Moya; Fowler (2009), another example of work which studied the correlation between aggregate shape, texture and grading, found that these are characteristics which require control when minimum cement content in concrete is required.

A detailed analysis of studies that vary the quality of aggregates in concrete while maintaining other formulation parameters unchanged can give a better understanding of how binder use efficiency and the aggregate quality are linked. Fig. 3 presents data from Angulo et al (2010) analyzed under bi_{cs} index concept.

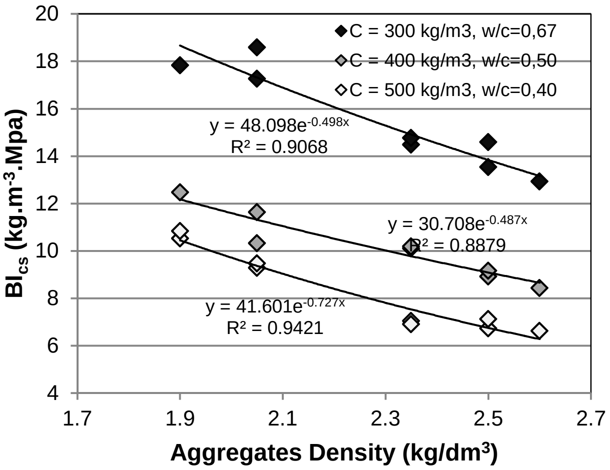

Fig. 3 – Recycled aggregatedensity versus binder intensity (Angulo et al, 2010).

As shown in Fig. 3, the density of aggregates is a good parameter for controlling their quality. This study divided Construction and Demolition Waste (CDW) recycled aggregates by density and mixed concretes with different binder contents (C) and water/cement ratios (w/c). The tests revealed that bi increases (lower efficiency of binder use) as well as the aggregates density decreases, for the same w/c and C (total binder consumption) curves. Since aggregate densities determine the different levels of quality of recycled aggregates, the real environmental balance of the use of these aggregates in concrete can be negative in terms of binder consumption unless they are used with some caution. Poor quality aggregate decreases binder use efficiency, and requires increasing binder consumption to reach the same levels of mechanical properties, which, in turn, will produce more CO_2 emissions and additional costs, binder being the most expensive component of ordinary concretes. Notwithstanding, it is also shown that controlling the quality of aggregates – recycled or not – makes it possible (and so is a condition) to mix real more eco-efficient concretes.

The main obstacle to achieving this is the size of the aggregate chain worldwide. Concrete consists of 15-20% cement and the remaining 80-85% is basically, aggregates. This huge amount, combined with the very distinct aggregate mineralogical sources, makes controlling the quality of aggregates very difficult in the market practice, as previously discussed by Damineli et al (2010b).

The authors believe that the main obstacle to introducing some aggregate control tools, as aggregate selection is currently practiced, is mainly a lack of knowledge as to the real benefits it will bring. If binder use efficiency is increased, costs can decrease for the same mix, which will produce beneficial impacts for the economy and the environment.

3.3 Cement market share: a portrait of binder use inefficiency

Ready mix concrete will continue to be the fastest-growing market for cement through 2015, when it will account for 27 percent of global demand. Construction contractors will be the second largest market, followed by consumers, concrete products and other markets (THE FREEDONIA GROUP, 2011). Despite continual growth of the ready-mix concrete business, the biggest share of the market is composed of local concrete producers who do not exercise nor have the same technological control that ready-mix producers do. And this is even more conspicuous in developing countries, where informal do-it-yourself construction is still one of most popular ways to construct. So, as ready- mix concrete dominates the demand for cement in developed, world markets, but in many developing countries sales to consumers or construction contractors are more common. As a good example, India, the second largest cement producer in the world, sold only 11% of its total cement production to ready-mix concrete producers, while 53.7% was sold directly to independent consumers (see Fig. 4.a). Forecasts predict the growth of the ready-mix business up to approximately 13.7% by 2020, when consumers will buy 50.1% of total cement consumption (Fig. 4.b). THE FREEDONIA GROUP, 2011, demonstrates that the change in market will occur very slowly and the trend of using cement in informal construction will continue.

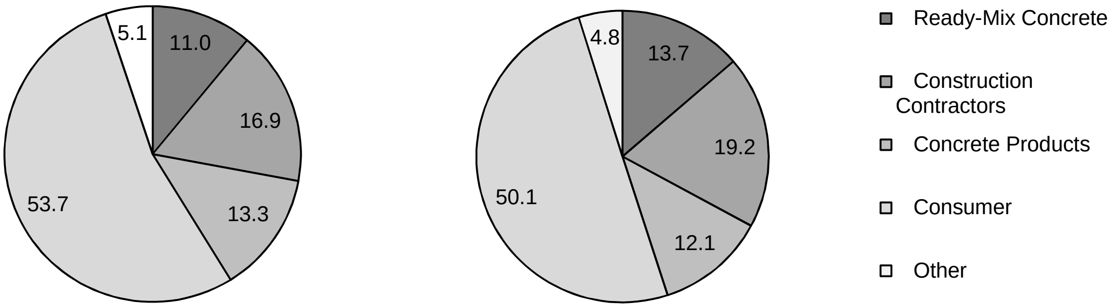

Fig. 4 – Cement market share in India: a) left – in the year 2010; b) right – forecast for the year 2020 (The Freedonia Group, 2011).

In Brazil, another developing country with a big share of total world cement production, direct sales to the final consumer were, in 2011, 54% of the total cement market, while 19% was sold to ready-mix producers, as shown in Fig. 5 (SNIC, 2011).

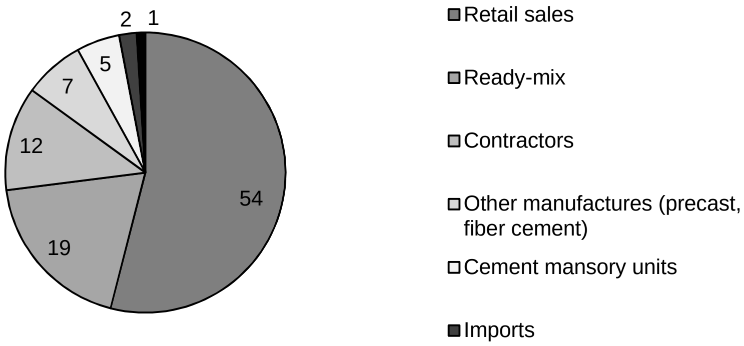

Fig. 5 – Cement market share in Brazil in the year 2011 (SNIC, 2011).

As cement used for informal concrete mixtures is not only sold to final consumers, total bagged cement sold in 2011 was 68% of market share, against 32% sold in large quantities to industrial users (including ready-mixers) (SNIC, 2011).

As bagged cement is sold in small quantities to final consumers, the main purpose being to supply small and informal constructors, there is a great variety of manuals containing instructions for mixing concrete filled with very simple proportioning and mixing methods that fill the technological gap in these markets. A rough assessment of these manuals (calculation of bi) showed that the concrete mixes presented are very inefficient in terms of binder use – one of the evaluated mixes used more than 350kg.m^{-3} of cement to deliver a 25 MPa 28-day compressive strength, which results in bi>14kg.m^{-3}.MPa^{-1}. And this scenario is most likely even much worse, considering not all informal constructions follow a manual or some previously established concrete proportioning design.

Therefore, the authors consider the size of bagged cement market share as a good measurement parameter for binder use inefficiency. The larger the share of bagged cement, the greater the amount of wasted cement embedded in inefficient concrete formulations, which will require, on a large scale, an increase of cement – and clinker – production, directly affecting CO_2 emissions.

3.3.1 Changing binder use efficiency by changing cement market share: ready-mixbagged concrete

On a long term perspective, the authors believe that only a complete restructuring of the cement chain will lead to an increase in cement use efficiency. So, instead of selling pure cement and shrinking from the responsibility of proportioning efficient cement-based materials to the final consumer, who is usually not qualified to perform this task, the authors recommend that cement be sold already inserted in cement-based- materials such as concrete ready-mix formulations. The industrial sector, which has the most technological knowledge and the best quality control, is the only sector able to design more efficient mixtures. This means a decrease in the bagged cement market share and an increase in the production of ready-mix concrete, which could even be sold from ready-mix producers or as new ready bagged materials, such as bagged concrete, where all the final consumer has to do is add water– no proportioning care is needed, this task will be developed in controlled industrial processes. Perhaps this is the best way to increase binder efficiency on a large scale since it would very difficult to change the informal, cultural aspects embedded in developing country constructions.

Diverse initiatives of developing ready-mixed bagged concrete are already available in some countries (http://www.cemix.co.nz/bagged-concrete-guide; http://www.quikrete.com; http://www.spec-west.com/pd12069/buddy-rhodes-new-buddys-ultra-green-concrete-mix). But, these initiatives are still small scale and an effective increase in binder use efficiency will demand an enormous effort in the development of this strategy.

4. Conclusions

This paper presents laboratory results that prove refining binder use efficiency in concrete is possible and already attainable by applying the concepts of packing and dispersion of particles to mix designs. The authors of this research created the Binder Intensity (BI), an index for measuring binder use efficiency that measures the ratio between the total amount of binder, in kg.m^{-3}, and compressive strength, in MPa. Results show that it is possible, in laboratory essays, to produce concretes with 88MPa of 28-day compressive strength using only 210 kg.m^{-3} of binder, resulting in a concrete with bi = 2.37 kg.m^{-3}.MPa^{-1}, which is more than 2 times as efficient as that currently used by the market to produce the same strength. Also, a concrete of 51 MPa was delivered – a bi = 2.47 kg.m^{-3}.MPa^{-1} using 126 kg.m^{-3} total binder, which is a concrete within the parameters of those used by the market to produce common strengths but, by using less than half of the total binder commonly consumed.

Although the goal of producing highly efficient concretes in terms of binder use efficiency was reached in PhD research by the first author, the biggest challenge is yet to come – conducting the market to an implementation of this technology, which is a huge challenge due to the size of the market. This is a completely different scale on which to work, where there are many obstacles related to the variability of raw materials and the way the concrete business is commonly practiced. Some of these obstacles are presented and discussed in the second part of this paper and give a better understanding of what is needed to do, such as: 1) changing the inert fillers market and technological knowledge; 2) changing quality control parameters for aggregates; and 3) changing how the cement market is currently shared.

In first case,, increasing the use of inert fillers in concrete depends on a market strategy for increasing the production of high quality fillers, a solution that depends on greater technological comprehension of clinker-filler interactions, which, once implemented, would lead to a decrease in prices . The solution enables the cement industry to increase cement production without needing to increase clinker production or invest in new expensive kilns. And, benefits in terms of sustainability are equally high. Social sustainability will benefit since the costs of cement-based materials will not rise and can even be reduced. Environmental loads of the cement industry can be greatly reduced. The cement industry can benefit economically since, it seems improbable that more sophisticated and energy intensive grinding could be more costly than operating a kiln or capturing and storing carbon.

Second challenge, improving the quality control of aggregates is another strategy also dependant on profound changes in the market. And, the benefits of better aggregates for concrete – which would increase binder use efficiency – need to be better understood by the market. The size of this chain – more than 80% of the world's production of concrete is aggregates – as well as the enormous variations found in the different sources of aggregates -- are certainly the worst enemies of this strategy. But again, high environmental benefits can be achieved by increasing the quality of aggregates, mainly by decreasing the binder content required for the same mix.

The third involves changing the method of selling cement. Pure bagged cement is the most inefficient way of using the material since the final consumer has to design proportioning mixtures relying on his usually, poor technical knowledge – which is quite the norm in the informal constructions of developing countries. In order to change this, the responsibility for designing mixes needs to be an industrial competence, which can use the accumulated expertise derived from high technological efforts to increase the efficiency of binder use. The more cement is sold in final mix proportioned materials, such as bagged, ready-to-use concrete, the higher the binder use efficiency on a global scale, with real benefits for sustainability since more concrete will be produced with less clinker. This allows to supply increasing social demands for infrastructure in developing countries at the same time that environmental loads are decreased.

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