Eco-efficient cements: Potential economically viable solutions for a low-CO_2 cement-based materials industry

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Foreword

Across the world, countries face ever-increasing demands for resources. Cement-based materials currently represent more than one-third of the total materials extracted from the earth, on average, each year. They are the backbone of our modern built environment, especially in urban areas. Driven by economic development, a growing middle class and rising populations, many countries are facing problems associated with rapid urbanisation, resource depletion and scarcity, and more broadly, unsustainable patterns of consumption and production.

As a key sector contributing to meeting needs for housing, schools, hospitals, public and commercial developments, the building and construction sector is a large consumer of materials and natural resources. Cement-based materials will remain essential to supply the growth and improvement of our built environment, particularly by those residing in the developing world. However, with current technology, the much needed increase in cement production will imply a substantial increase in CO_2 generation. This is a classical dilemma between the social aspect of sustainability — expansion of the built environment — and the environmental aspect — global warming.

This makes it absolutely critical to find solutions and to identify more resource efficient pathways for the growth of our homes, towns, and cities. To help identify some of these new solutions, in 2015 the Sustainable Buildings and Climate Initiative of the United Nations Environmental Programme (UNEP-SBCI) convened an international group of academic and industry experts, from both developed and developing countries, to investigate new, low-CO_2, low-cost eco-efficient solutions.

It has been UNEP-SBCI's pleasure to support Dr. Karen Scrivener and Dr. Vanderley John as they skillfully lead dedicated researchers through the review of available knowledge to successfully identify scientifically sound technologies that, if further developed, have a potential to contribute to CO_2 mitigation in the cement-based materials industry.

It is my hope that their hard work, as summarised in this report, will bring much needed attention and drive greater policy implication that will enable the further transformation of an industry that plays such a critical role in providing a safe, sustainable, future for all.

—Arab Hoballah, Economy Division, UN Environment

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Executive Summary

This report summarises the main conclusions of an inventory and analysis on low-CO_2, eco-efficient cement-based materials, carried out by a multi-stakeholder working group initiated by the United Nations Environment Program Sustainable Building and Climate Initiative (UNEP-SBCI). The cement industry has already achieved significant reductions in the CO_2 emissions associated with cement production, mainly through increased energy efficiency, use of alternative fuels including a wide range of wastes, as well as through clinker substitution. In addition to these traditional solutions, carbon capture and storage (CCS) has been identified as necessary to achieve the remaining reductions needed to keep global warming to below 2°C vs. pre-industrial levels. This conclusion was drawn from the first sectoral low-carbon technology roadmap developed by the World Business Council for Sustainable Development (WBCSD) for the cement sector in partnership with the International Energy Agency (IEA). Today, some seven years later, the present working group finds that there are several other possible solutions which, even if still requiring substantial efforts in terms of research, education and investment, appear substantially cheaper than CCS and have the potential to deliver a considerable part of the required CO_2 reductions.

Cement is the largest manufactured product on Earth by mass. Combined with water and mineral aggregates it forms cement-based materials (e.g. concrete), the second most used substance in the world after water. The fulfilment of our society's ambition to progress towards a more equitable and sustainable world requires a substantial increase in the built environment. This task will maintain or further increase the demand for cement-based materials. However, under business-as-usual, this would imply an unacceptable increase in CO_2 emissions, contributing to climate change. The technology to implement CCS has improved since 2009, thanks to extensive research programs undertaken by different sectors including cement. Research is also being undertaken to find ways to utilise the captured CO_2 rather than storing it (CCU). In parallel, research on new technologies for cement based materials has progressed, but without adequate estimation of their mitigation potential.

In this context, UNEP-SBCI established a technical working group in 2015 with the objective of reviewing practical, lower-cost alternative technologies specific to cement manufacture and use, capable of reducing CO_2 emissions and increasing materials efficiency throughout the cement value chain. The group's approach was limited to materials solutions, since aspects like renewable fuels and energy have already been analysed in detail. More than 20 world experts, from academia and industry, took part in the work of the group.

The report of the working group indicates that CCS/U is no longer necessarily the most promising technology for the reduction of CO_2 emission related to cement based materials. New material-based solutions, more feasible and cheaper than CCS/U have been developed since the Cement Roadmap was concluded in 2009. However, considering the possible 1.5ºC mitigation scenario, CCS/U remains part of the basket of possible solutions to be developed, including by the production of carbonation-hardening cements, as presented in this report.

To enable the materials-based solutions to enter the market at a scale that would have a significant impact on climate change mitigation, a broader acceptance of new materials in the use phase, associated with new or enhanced standards adapted to applications will be necessary. Both the implementation of existing and the development of new (improved or breakthrough) materials-based technologies will require significant funding to cover the costs of R&D, industrial investments and technical transfer. Better education at all levels from the unskilled user to scientists and engineers is also crucial to progress.

Main conclusions

There are two main areas that can deliver very substantial additional reductions in global CO_2 emissions related to cement and concrete manufacture and use, probably reducing the need for costly investment in CCS over the next 20–30 years:

1. Increased use of low-CO_2 supplements (supplementary cementitious materials or SCMs) as partial replacements for Portland cement clinker.
2. More efficient use of Portland cement clinker in mortars and concretes.

We believe that Portland cement clinker based cements will dominate in the near future due to the economy of scale, level of process optimisation, availability of raw materials and market confidence in these products. In the longer term, other emerging alternative technologies could also play a role in emissions mitigation that consequently merit further investigation.

Increased use of clinker substitutes (SCMs) in Portland cement clinker based cements

Today's cements contain on average only around 20% of SCMs substituting Portland cement clinker — mainly fine limestone, granulated blast-furnace slags (GBFS) and coal fly ashes (FA). GBFS and FA sources of adequate quality are limited globally to only about 15–25% of cement consumption and are unlikely to increase. A recently developed alternative low-CO_2 SCM system uses optimised combinations of calcined clays with ground limestone. Such combinations represent a relatively inexpensive and widely available SCM source capable of replacing up to 50% of clinker while maintaining similar performance to existing cements. Additionally, a significantly-increased filler content above today's average of 6% is technically feasible by combining particle size control and dispersant admixtures, resulting in cements with low water demand. In some applications, filler contents higher than 50% in the cement can offer satisfactory performance. Increasing the average level of clinker substitution in cement to reach 40%, for instance, through the use of the above-mentioned alternatives could avoid up to 400 million tonnes of CO_2 emissions annually.

More efficient clinker use in concrete and mortar

In concretes and mortars a similar magnitude of CO_2 emissions reductions are possible:

- Optimising mix design, facilitated by industrialisation, can improve the eco-efficiency, defined in terms of CO_2 per m^3 per MPa of compressive strength, by a factor of 4 when comparing best practice with worst. Careful optimisation of particle packing, throughout both the coarse and fine fraction of the cementitious materials, coupled with the use of dispersants and the use of fillers can further reduce clinker contents while maintaining product performance.
- Using high strength concrete grades, where appropriate, in structural applications is more efficient and can reduce overall materials consumption.
- Industrialising concrete and mortar production (for example ready-mix concrete, dry-mix mortars) compared to poorly controlled on-site mixing, can provide further substantial savings by avoiding wastage, particularly in urban areas.

- In the long term, savings are possible through the development of more efficient, innovative concrete structures and component design and production methods, which may be accelerated by emerging digital production systems.

New cement technologies could contribute significantlyin the longer term

Non-Portland clinkers may offer promising options for the longer term, but there is as yet no cost-effective alternative to Portland cement clinker in the current economic environment. The most feasible alternative class of hydraulic clinkers is belite-ye'elimite-ferrite (BYF) clinkers, which present substantial CO_2 reductions relative to Portland cement clinker. Though this approach has higher raw materials costs than SCM and filler approaches it is still significantly less than CCS. Further R&D in this area is needed to improve the performance to cost ratio.

Among non-clinker based cements, alkali-activated binder technologies (AAM) also have the capacity to reduce global CO_2 emissions. However, many current AAM technologies require the use of GBFS to give acceptable performance, and in many locations it is simpler to use the limited (global) supplies of GBFS as conventional SCMs. Alkali activated calcined clays are another scalable option. However, this technology requires much larger amounts of alkali metal silicate. Since the production of this alkali metal silicate with current technology is both capital and energy intensive, the contribution of alkali activated calcined clay to mitigation will depend on the successful development of low-CO_2 alkali silicate production methods.

Newly developed clinker technologies, in which concrete products are produced by carbonation rather than hydration have recently been introduced. This is effectively carbon capture and use and can reduce net CO_2 emissions up to 70% compared to Portland cement clinker. Such technologies are already commercially available in some locations. Unfortunately, they suffer from limitations because they require developing a circular economy for captured CO_2, and also because they are limited to factory-made products. We therefore believe that they are unlikely to have a major global CO_2 impact as a direct alternative to Portland cement, as the facility to cast cementitious materials on-site is key to their ubiquitous use in construction.

Finally, we think that there is still some chance for a breakthrough in the area of clinkers made using globally abundant ultramafic rocks instead of limestone as the main raw material. In theory, this approach has the advantage over all limestone-based technologies in that it could be truly carbon-negative; but no feasible energy-efficient industrial manufacturing process has yet been invented, although recently some progress has been made. We consider that this area merits further research in view of its significant potential for CO_2 capture and use.

Requirement for research, coordination and raising awareness

More efficient global use of all possible approaches to low-CO_2 cementitious materials will need, amongst other things, flexible and robust performance-based standards for cement and concrete. Developing such standards will require a well-coordinated international research effort, as well as strong coordination between the industry, standard making bodies, regulators and society at large to raise awareness and create market acceptance for eco-efficient solutions.

Governmental engagement

Governments engagement will be important to the development and implementation of a successful mitigation strategy in the cement industry. The cement value chain makes up a large proportion of all economies, including a range of stakeholders from large companies to individuals. Raising awareness in such a complex environment will require commitment from governments.

Governments also have influence on educational policies, both in undergraduate and graduate civil engineering and architecture courses, which will have to be reconfigured in ways to make it possible for the construction industry, including cement-based materials industries, to cope with the demands of sustainable development.

Research, development and innovation are strongly influenced by governments, not only through funding to academic basic research, but also by promoting alliances between academy and industry and stimulating innovation at the industrial level. Governments are also frequently in a position to influence standardisation processes

Promoting the industrialisation of the cement supply chain most certainly depends on actions of governments. In developing countries this will require actions to reduce the economic advantage associated with the use of aggregates from the informal market, which favours the inefficient use of cement, increasing CO2 footprint. Other options include actions to limit the use of bagged cement, as already done by China.

Finally, the mitigation potential of each technology will depend on its success in the market. Governments are among the largest consumers of cement based materials, especially when investing in infrastructure. Therefore, the use of public purchase power can be decisive in accelerating market penetration of these mitigation technologies.

1. Introduction

Cement is the largest manufactured product on Earth by mass. Combined with water and mineral aggregates it forms cement-based materials (e.g. concrete). It is the second most used substance in the world after water. These materials make up a substantial proportion of the built environment. Impressively engineered bridges and dams, architecturally innovative skyscrapers, roads and railways, high-rise apartments and single-family homes — none of these would be possible without cement. Whether handled by highly skilled tradespeople or do-it-yourselfers, concrete and mortar remain cost- and energy-efficient construction materials. Fulfilling our ambition for a more equitable and sustainable world will require substantial expansion of our built environment, which will in turn increase demand for cement-based materials. Tackling this objective according to business-as-usual practices would involve an unacceptable increase in CO_2 emissions. To mitigate these emissions, the main solution proposed by the International Energy Authority on 2009 was CO_2 capture and storage, (CCS). The technology to implement CCS has improved since 2009, thanks to extensive research programs undertaken by different sectors including the cement one. Research is also being done to find ways of utilising captured CO_2 (CCU). However these are technologies that require energy and are still very expensive at this stage. As most cement is and will be produced and used in developing countries, lower cost alternatives to CCS/U would be highly desirable.

To seek solutions to this dilemma, in 2015, the United Nations Environment Programme Sustainable Buildings and Climate Initiative (UNEP-SBCI) established a technical working group to review practical alternative technologies for reducing CO_2 emissions and increasing materials efficiency throughout the cement industry value chain, which could reduce the need for CCS. The aim of this report is to demonstrate that there are several potential solutions for CO_2 mitigation that are far less expensive than CCS, that could be used in the short-to-medium term, while significantly impacting net global CO_2 emissions — without making concretes and mortars too expensive for ordinary consumers, particularly those in developing countries where the vast bulk of cement will be produced. Implementing existing-and developing innovative-mitigation technologies will require significant funding. This will in turn require R&D and technical transfer incentives, a greater portion of which must probably come from developed economies. The ultimate long-term benefits, however, will be shared by everyone.

More than 20 international experts from academia and industry took part in this working group (see section 19). Our focus was materials technology, since renewable fuels and energy have already been analysed in great detail. The group explored scientifically informed options with the best potential to be scaled up and make a real contribution, as opposed to niche solutions, and approaches that lack a solid scientific justification.

This report is intended for policy-makers from individual countries and multilateral organisations, industry leaders, research agencies and NGOs, as well as for researchers. It has been condensed from a more substantial body of work produced by group members. Researchers and others who want a deeper understanding of all the options are encouraged to read the complete technical white papers*, which are available as a separate volume on the UNEP-SBCI home page and also in a special issue of Cement and Concrete Research.

We hope that our findings will motivate the cement industry to surpass its CO_2 mitigation goals without greatly increasing costs or risks to the end-user. Our work should

* the full list of white papers is given in section 19, these are referred to in the following text by the names of the authors.

also help broaden multilateral agencies' focus on the mitigation potential for the cement industry; inspire technical education for architects and civil engineers; improve research effectiveness by helping researchers to address the most promising issues; and guide funding agencies to support priority research.

2. Cement and Modern Society

Modern developed societies require a built environment that is unimaginable without the widespread use of cement-based materials that allow construction anywhere, at low cost, of complex and massive shapes from water, gravel, sand and cementitious powder. In the last 65 years, the amount of cement produced increased almost 34-fold, [1, 2], meanwhile the population has increased less than 3-fold [3]. This growth rate is much higher than other commodities such as steel (see Figure 1) [4]. The larger per-capita availability of cement is related to discernably improved living standards in most of the world.

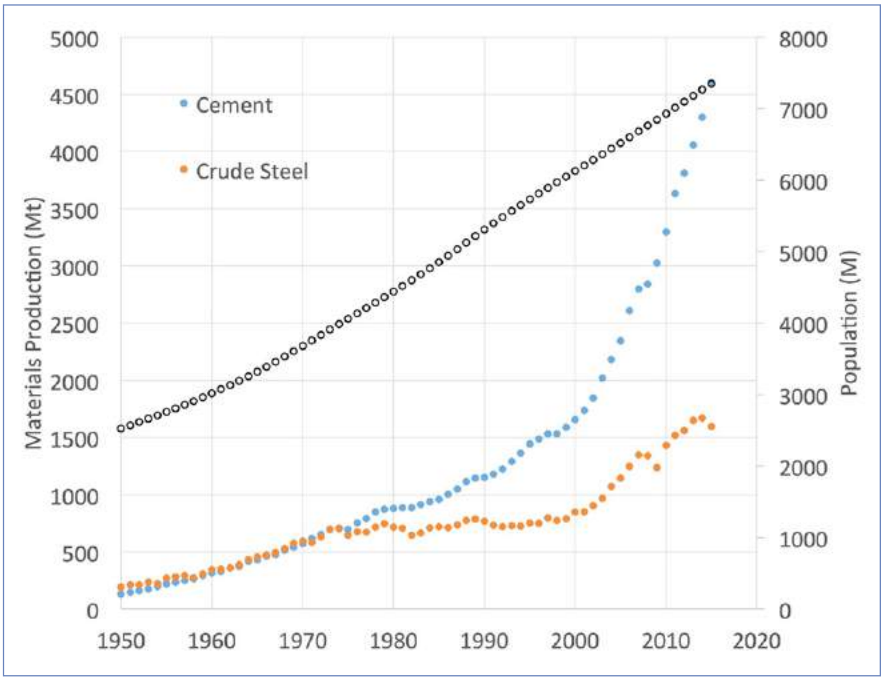


Figure 1. Comparison of cement (data derived from CDIAC[3] and CEMBUREAU[4,5]) and crude steel (World Steel Association [6]) production with population (UN Population Division[7]).

In 2015, the total mass of cement produced was 4,6 billion tonnes [5, 6]. This is equivalent to about 626 kg/per capita, a value higher than the amount of human food consumption [7]. With this cement we can produce around 2.1–2.3 m^3 or 4.8–5.5 t per capita of cement-based materials*. In 2005, cement-based materials represented about 30% of the total global materials use including fossil fuels [8, 9]. In 1950, it represented only 7%. This is a 4-fold increase in proportion in only 55 years.

Figure 2 illustrates how the amounts of other common building materials — such as wood, steel, asphalt, and brick — are very small in comparison to concrete. These materials generally have a higher environmental footprint than cementitious materials. But beyond environmental considerations, the production of these materials could not be sufficiently increased to replace concrete to any significant extent. Additionally, the current production cost of cement is relatively low; a tonne of bulk cement in Europe and North America typically costs USD $100–120, and less than $50 in China. This comparatively low cost and high volume means that it is essentially a local material produced close to the site where it is used, as the cost of overland transportation

* Assuming 1 kg of cement is mixed with 6 to 7 kg aggregates, 0.6 to 0.7 kg water and neglecting the small amount of organic admixtures. Average density was assumed to be 2.3t/m^3.

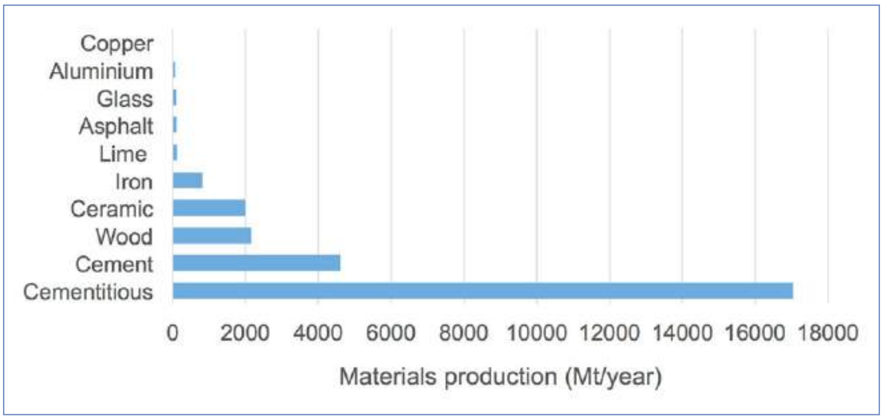


Figure 2. Estimated consumption of common materials 2002–2005. Data from [10,11]. Except from ceramics, asphalt and cementitious, all other materials are shared with other industries. Part of wood is used for fuel and furniture.

rapidly becomes uneconomic†. However, unlike other locally produced materials, cements are treated as commodities and subject to stringent, sometimes inappropriate, national and international standards. This makes it difficult to modify cements to any great extent to adapt them to local economic and environmental needs. This is a significant obstacle to maximising sustainability. If cements could be more easily adapted to local raw materials and to specific applications, this could considerably reduce environmental impact.

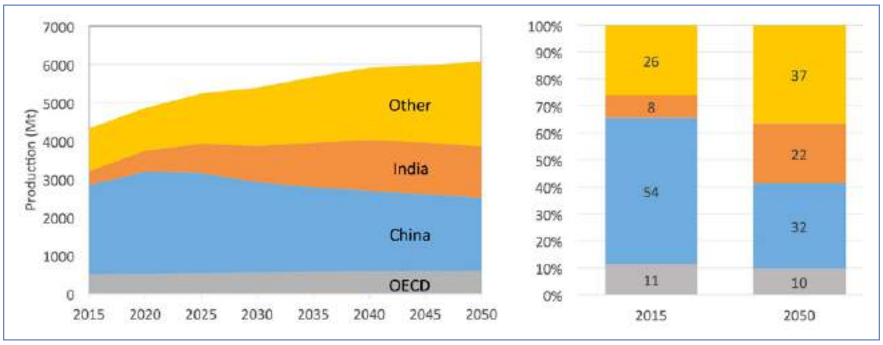


Figure 3. IEA high-consumption scenario for future cement consumption by region [12]. The lower section shows the evolution of cement production distribution among different regions.

Our civilisation has become dependent on the availability of this cheap mineral binder that hardens quickly in almost every habitable environment to produce a wide variety of 3-D structures, and is simple enough to use by unskilled, even illiterate, self-help builders. Cement is so common that we take it for granted. Without decisive action, the beneficial impact of this vital material could fail to be realised.

The World Bank [10] shows that in low-income countries 65% of the urban population lives in slums, more than 60% do not have access to sanitation, and 35% do not have a safe water supply. About 40% of the world's population lives in these low-income countries, where the growth in population is also fastest. A more equitable world demands these deficiencies be remedied and this will require a substantial increase in cement production. It is thus important that the price of cement is affordable for poor communities.

Figure 3 shows the IEA's forecast of cement demand up to 2050 [11]. Even in the high-demand variant, the growth in cement production is only about the same as the rate of population increase. Considering that demand grew at a rate 10 times higher from 1950–2015, it is possible, and perhaps even socially desirable, that future production will surpass these values. About 90% of cement is currently, and will continue to be, produced in non-OECD countries. The proportion of world production in China has already peaked and is expected to diminish from more than 50% today to around 30% by 2050.

† To give an idea the zone around a cement plant which can be economically supplied by road is around 100 km, by rail 300 km, but cement can be transported by sea across an ocean for a roughly similar cost.

WBCSD / CSI

The World Business Council for Sustainable Development (WBCSD) established the Cement Sustainability Initiative (CSI) in 1999.

http://www.wbcsdcement.org/

The CSI is a global effort by 24 leading cement producers, with operations in more than 100 countries. Collectively, these companies account for around 30% of the world's cement production and range in size from very large multinationals to smaller local producers. All CSI members have integrated sustainable development into their business strategies and operations, as they seek strong financial performance with an equally strong commitment to social and environmental responsibility.

The CSI has established a publically accessible data base on production and emissions data from member companies and some other volunteers called "Getting the Numbers Right" (GNR).

http://www.wbcsdcement.org/index.php/en/key-issues/climate-protection/gnr-database

The companies reporting in the GNR data base make up around 70% of world production outside China.

Given the commitment of CSI companies to pursue sustainable development the performance of these companies with respect to sustainability issue is expected to be somewhat better than the industry average.

Growth is forecast to be concentrated mainly in the developing non-OECD countries that combine population growth with a quantitative and qualitative deficit in the built environment. If new solutions for cementitious materials are to be adopted on a significant scale, they must be low cost and used easily by people with minimal training and scientific knowledge.

The traditional form of cement — ordinary Portland cement (OPC) containing >90% Portland cement clinker — is made from abundant raw material cheaply available almost everywhere. The production process requires grinding and calcining (heating to high temperature) a mixture of clay and limestone. The resulting intermediate material, known as *clinker,* is ground to a fine powder with 3–5% gypsum added to form OPC. The production of OPC generates on average 842kg CO_2/t of clinker [12]. Fossil fuel combustion is responsible for less than 40% of total CO_2 emissions, while limestone decomposition ($CaCO_3$ or $CaO.CO_2$) during calcination is responsible for the remainder. This is what makes CO_2 emissions from cement manufacture so different from the emissions produced simply by burning fossil fuels for energy production. Increasing energy efficiency is not enough to significantly impact emissions. Calcination of limestone must also be minimised, which will change the composition of the cementitious products.

Due to the enormous growth in cement demand in the developing world, the share of cement production in total anthropogenic CO_2 emissions has been rising steadily and is now estimated by some sources to be around 10% [13], or about 6% of the total anthropogenic greenhouse gasses (GHG)[15]. This has occurred despite the important improvements in production efficiency and emissions mitigation efforts of the cement industry since the 1970's.

Cement production has to grow to meet the demand for decent built environment from citizens in developing, low-income countries. However, according to the WWF/Lafarge Report [14], in a business-as-usual (BAU) scenario, CO_2 emissions from cement production were expected to increase 260% between 1990 and 2050. The 450ppm IPCC mitigating scenario (IEA blue scenario) requires a 50% reduction in anthropogenic CO_2 emissions by 2050 [15]. If new methods are not implemented for reducing CO_2 emissions from cement production, this would leave the cement industry responsible for about one third of this target amount in 2050.

3. Cement Industry Mitigation Strategies, Their Limitations: The IEA / WBCSD: CSI 2009 Roadmap

The cement industry was active in pursuing strategies to reduced CO_2 emissions long before global warming became a priority. Since 1999, with the launch of the Cement Sustainability Initiative (CSI) at the World Business Council for Sustainable Development (WBCSD), the industry has systematically collected evidence and improved its strategies. In 2009 [16], the IEA/WBCSD Roadmap proposed several CO_2 emissions and mitigation scenarios [16}. The IEA study found that the target 50% global emissions reduction goal to keep global warming at less than 2°C of pre-industrial levels would require an overall reduction of 18% in the CO_2 emission of the cement sector (compared to a 2006 baseline) by 2050. Figure 4 shows the CO_2 emission reduction scenarios from the Roadmap and the contribution of each of the mitigation strategies,

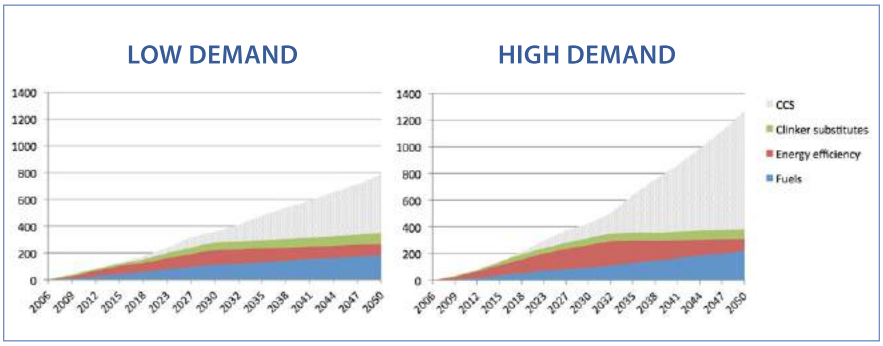


Figure 4. Cement sector CO_2 emissions reductions below base line 2006–2050, adapted from 1.8% [Tam, C and Van der Meer, R, IEA/CSI technology roadmap for the cement industry, 6th International VDZ Congress 2009, pp. 155–157]

grouped under the headings of fuels; Energy efficiency; Clinker substitutes; Carbon capture and storage (CCS). The Roadmap also discussed other technologies, such as novel cement types, which at the time were considered too far from practical application to be included in the quantitative model.

Energy Efficiency

Major efforts to increase energy efficiency began after the energy crisis of the 1970's. A state-of-the art dry-kiln with pre-calciner consumes about 50% less energy than a long wet kiln typically used at that time [1, 17]. The theoretical minimum energy consumption is ~1.9 GJ/t [16], which means state-of-the-art kilns already achieve about 63% efficiency, making such kilns probably today's most efficient thermal machine in wide-scale industrial use. It is unlikely there will be significant gains in best available technology (BAT) [17], but the progressive upgrade of old technology, where economic, was estimated in the IEA/WBCSD Roadmap to provide about 10% (1.8% absolute) of the targeted 18% CO_2 emission reduction [18]. This strategy would require heavy investment, but, since it reduces energy costs, it should not increase the cost of cement.

Fuels

The modern cement kiln is a very flexible machine, which allows the cement industry to change fuels relatively simply. The Brazilian cement industry, for instance, changed from almost 100% fuel oil in the 1970's to a mixture of charcoal (~40%) and coal (~50%) in 1984 and now relies almost entirely on petroleum coke [19]. In Europe, the use of wastes as fuel can be as high as 80% of the thermal demand. Increased use of waste fuels is an efficient means for their disposal, providing a useful and ecologically responsible service to society. This flexibility is an opportunity to reduce CO_2 intensity; there are opportunities to expand the use of biomass and alternative fuels worldwide. The Roadmap expected the worldwide use of "alternative fuels" to grow from 3% in 2006 to about 37% in 2050 and deliver around 15% of the targeted overall reduction in CO_2 emissions.

Clinker substitution by mineral additions/supplementary cementitious materials

Another important and well-established strategy is the replacement of clinker with other materials. This strategy has the advantages of reducing energy consumption as well as increasing production without requiring new kilns.

The most common clinker substitutes (Figure 5) are reactive by-products from other industries: granulated blast furnace slag (GBFS), a by-product of pig-iron production in blast furnaces, whose use in cement dates from before 1900; and fly ash (FA), generated by burning coal to produce electricity. However, the most common supplementary cementitious material is the almost inert limestone filler.

Figure 5. Clinker substitution evolution from companies from the CSI WBCSD [14]. The evolution of the clinker fraction can be deduced by adding 4–5% (added as calcium sulfate, e.g. gypsum) in the total fraction of SCMs.

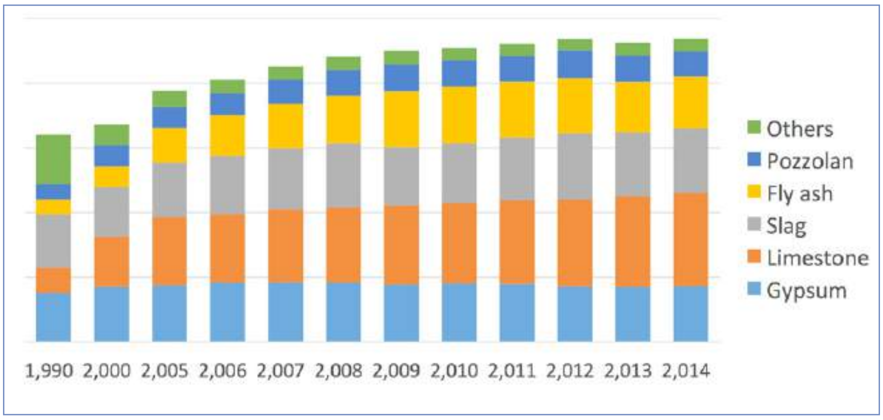


Figure 5 shows the evolution of clinker substitutes over the past 25 years for companies in the CSI's GNR database. It shows that the level of clinker substitution is levelling off. This corresponds to the low estimate of the contribution of clinker substitutes to further CO_2 reduction shown in Figure 5. This arises from the fact that the supply of the most desirable clinker substitutes — particularly blast furnace slags and coal fly ash of adequate quality — is rather modest compared to total cement production. In 2006, (the baseline for the IEA study) a very high proportion of these substitutes were already used in cement or concrete. If new sources of good quality SCMs become available this picture would change significantly. Given the importance of this strategy it is discussed more extensively in Section 8.

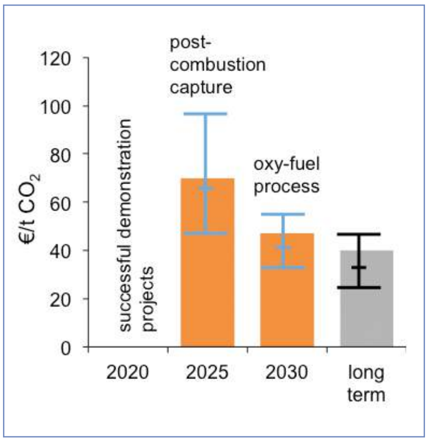


Figure 6. Estimated cost of carbon capture and Storage (CCS) source ECRA

Carbon capture and storage or use

The IEA/WBCSD Roadmap introduced carbon capture and storage (CCS) as the main strategy to reduce CO_2 emissions in an industry that it was expected to be growing: 56% of the planned CO_2 reduction by 2050 would be due to such a strategy (Figure 4). The report estimated it would require between US$ 321 to 592 billion [18] in investment to capture that fraction of the CO_2 from the cement industry. Since 2009 the feasibility of CCS has been extensively studied [19] including several pilot schemes. Figure 6 shows the estimated cost of CCS over the next few decades. These costs would increase the marginal cost of clinker production 2–3 times. Much of the expense results from the large amount of energy required to drive the CCS process.

CCS is still not sufficiently proven for such large-scale use. It was mainly developed for industries burning fossil fuels solely to generate energy — such as coal-fired electricity generation — because these industries have few other options for CO_2 emissions reduction. The process requires scrubbing CO_2 from kiln flue gases, purifying and concentrating it into the highly-pressurised state required to transport it to permanent storage in an underground reservoir. Technology for scrubbing and concentrating the CO_2 is already available on a small scale, although its efficiency could be improved further. Implementing cost-effective transport and safe disposal remain problematic for CSS. Pipeline transport would be efficient relative to road or rail but is capital-intensive and very dependent on the locations of the sources and reservoirs.

Carbon Capture and Use (CCU) is an alternative to CCS that replaces underground storage by another industrial step that transforms CO_2 into commodity chemicals or construction products. CCU has the potential to be significantly less expensive than CCS, provided there is an adequate market for the resulting products. Global demand for specific commodity chemicals requiring CO_2 as a raw material (e.g. formic acid) is often small enough to be satisfied by the emissions from only one cement or power plant. Another method being researched is transforming captured CO_2 into methane (methanisation) using renewable energy. However, this technology is a long way from being economically viable at present. Another possibility is the mineral capture of CO_2 that has the potential to permanently capture globally significant volumes of CO_2 to make useful construction products. Global demand for such products far exceeds that of commodity chemicals. Solidia cements are an example of this approach.

Regardless of the technological challenges, CCS and CCU would significantly impact cement production costs, affecting the price of cement-based materials and the structures built with them — including housing and infrastructure. These costs would have serious social implications in developing countries.

Beyond the 2009 Roadmap

In 2013, the CSI launched its first regional roadmap in India. This targeted 210 Mt of CO_2 reductions compared to a business-as-usual scenario, and further projected a target clinker factor of 58% by 2050. In 2014, it initiated the Brazilian roadmap.

In 2015, at the COP21 in Paris, a landmark government level agreement was reached aimed at restricting increases global average temperature to well below 2° above pre-industrial levels and at pursuing efforts to limit the temperature increase to 1.5°C. The WBCSD has issued a *Global Statement of Ambition* calling for collaborative efforts from all cement companies to reduce CO_2 emissions by 20–25% by 2030 — beyond business-as-usual. The global roadmap, discussed above, will be updated.

While recognising these on-going efforts, this working group takes the quantitative estimations of the 2009 Roadmap as a starting point. We recognise, but do not discuss further, the process related mitigation strategies of alternative fuels and energy efficiency. Our efforts have instead focused on the possibilities to increase the range and supply of clinker substitutes and at any other technologies that have potential to reduce the need for CCS or CCU and the high costs these may entail.

4. Our Working Method

Our group of experts in the field of cementitious materials and environmental assessment began by identifying promising materials-related approaches. Rather than focusing only on the end-of-pipe aspect of the cement production process, it was decided to look for opportunities over the entire life cycle of cement, including, cement applications and recycling. Some of the aspects have been explored systematically for the first time in this report.

In most of these fields a scientific, state-of-the-art white paper (list in section 19) was written by group members and their collaborators. The white papers primarily consolidate the available scientific knowledge, and when possible, integrate market knowledge to develop a consensus for estimating each technology's mitigation potential. To ensure a comprehensive overview of the challenges for introducing new technologies in the typically conservative construction sector, a common template was employed addressing these criteria:

- Description of the technology, its degree of development, scope of application and robustness when used in different climates and by people without formal training;

- Overview of the durability of the solution, a crucial aspect for increasing the resource efficiency of construction;
- State of the development and research needs;
- Assessment of the scalability potential, including raw material availability. Mitigating substantial amounts of CO_2 will require solutions that can potentially be deployed on a large scale in different regions;
- Evaluation of investment and production costs in comparison with Portland cement;
- CO_2 mitigation potential;
- Barriers and incentives predicted for the introduction of the technology in relevant markets;
- Research priorities to further develop the technology.

These papers were discussed during the group meetings and open to review by all members. However, ultimately they express the views of the authors not necessarily shared by all group members. The papers will be published in Cement and Concrete Research, one of the most important scientific journals in the field, to broaden discussion within the scientific and technical community.

The white papers have been consolidated in this report to inform a wider readership. The report and the white papers were discussed and commented on by WBCSD CSI member companies and UNEP-SBCI officials. Our objective was to produce a document that reflects a broad consensus. The resulting report represents the group's majority viewpoint.

By including a wide cross section of contributors we believe that the technologies considered here cover all imaginable solutions. Unlike the WBCSD/ IEA study, we did not restrict ourselves to technologies which could be implemented at the cement level, but also considered solutions at the concrete level. Broadly speaking, solutions at the cement (or binder) level are the most practical to implement as they can be put in place by individual cement companies. The solution is "in the bag" — it can be used by anyone, even in the most rustic situations. Concrete solutions generally demand more sophisticated methods for implementation — for example production of concrete in a ready-mix plant. There are also solutions at the structural level, but these necessitate the cooperation of designer and builder. While we do not ignore the potential for CO_2 savings at this level, this has not been analysed in detail for this report. The working group's key findings at the binder- and concrete-levels are discussed in the following sections.

A CO_2 mitigation model was developed, using data from the white papers and report findings along with relevant public data for emission factors and projections for cement production.

5. Overview of Cementitious Materials Use

We tend to assume that concrete is the principal material made from cement, but analysis of the data indicates that its use in concrete accounts for less than half of cement consumption. It is possible to make a relatively robust estimate of the amount of cement used in reinforced concrete; we have good figures for the global production of reinforcing steels and for the average quantity of reinforcement used in concrete. Figure 7 shows the global figures with some breakdown by regions. The regional figures are less reliable as the figures for cement and steel relate to production rather than consumption. They do not account for importation and exportation to other regions between production and use. Nevertheless, it is clear that the proportion of cement used in reinforced concrete globally is only around 25% of the total.

It is difficult to get precise information about the other 75% of cement use. Figure 8 shows the breakdown for Brazil; and South Africa is similar. While it was not possible to obtain reliable figures for all countries, Brazil and South Africa exemplify countries at an intermediate development level. While cement use in reinforced concrete is undoubtedly higher in developed countries‡, it is also probably lower in countries with a low level of development.

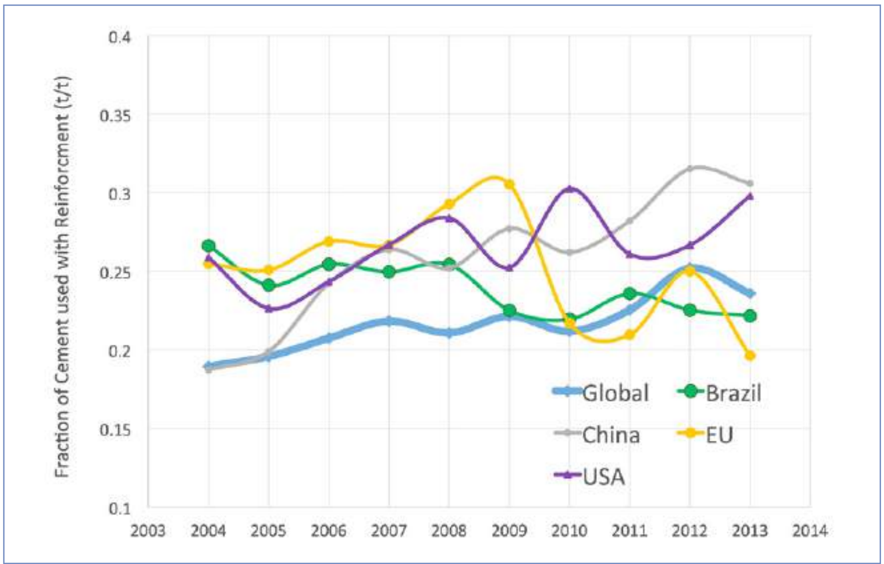


Figure 7. Fraction of cement used in reinforced concrete. Worldsteel 2014, Cembureau 2014

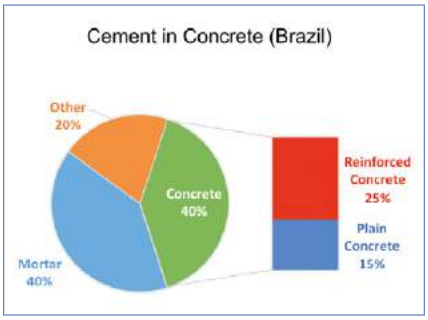


Figure 8. Cement use in different sectors in Brazil.

A comparable amount of cement is used in mortar to that used in concrete. The term "mortar" covers cement-based materials prepared on site, such as renders and mortars for bricklaying. The sector marked "other" in Figure 8 is presumed to be largely accounted for by what can be referred to as "cement-based products," including blocks, pavers, and roof tiles. In developing countries, such cement-based products are used extensively in social housing, so increased demand will be needed to meeting development goals.

This breakdown of cement use is relevant to concerns about carbonation resulting from using materials with lower CO_2 emissions to protect reinforcement. Normally, the high alkaline (pH) environment inside concrete protects steel from corrosion. Two factors may change this protective situation — the ingress of chloride ions and the lowered pH resulting from carbonation. The former is by far the most widespread problem facing reinforced concrete worldwide.

Carbonation is not problematic for the concrete itself, only for the steel inside it. Indeed, carbonation of OPC concrete increases its strength. There are concerns that alternative materials containing increased amounts of ettringite would be weakened by carbonation, due to decreased volume of solid products. Experimental studies on BYF cement indicate this is not the case [20].

CO_2 absorption by cement-based materials can actually be considered a natural form of carbon capture and storage. The cement carbon cycle is shown in Figure 9. "Chemical" CO_2 is emitted during production from limestone decomposition ($CaCO_3 \rightarrow CaO + CO_2$); but the resulting hydration products can then react with

‡ In Europe it is estimated that as much as 58% of cement goes to reinforced concrete (communication Claude Lorea, CEMBUREAU).

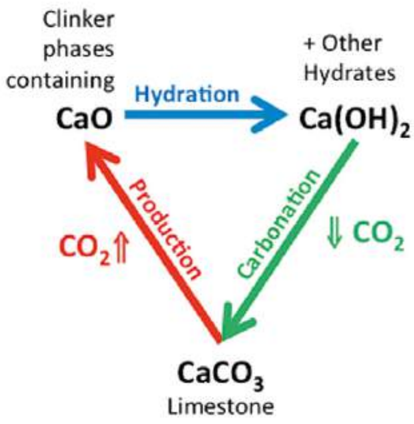


Figure 9. The Cement/Concrete carbon cycle, "chemical" CO_2 emitted during production from limestone breakdown is proportional to CO_2 reabsorption capacity during carbonation.

the same amount of atmospheric CO_2, restoring the calcium in the cement-based materials to calcium carbonate. Some researchers [e.g. 21] have advocated that this process should be considered to offset the production emissions. This has not been widely supported because the rate of carbonation of normal concrete is very slow — complete carbonation of a typical wall would take decades. However, this process would be much more significant for mortars used in thin layers, such as renders, which will carbonate in a few years.

Only a minority of the 25% of cement used with steel will have any significant risk of carbonation-induced corrosion. Carbonation rates reach a maximum at relative humidities around 60%. This RH range, typical of indoor concrete, is much too low for active steel corrosion to be problematic. On the other hand, carbonation is slow at the very high RHs needed for active corrosion. From an environmental standpoint it would be much better to use concretes containing higher calcium with higher CO_2 emissions only in situations where carbonation corrosion is a serious risk. For instance, where periods of intermediate humidity (favouring carbonation) are interspersed with periods of high humidity (favouring corrosion).

Despite the fact that only a small proportion of cement is used with reinforcement, there is strong market attachment to the idea of "general purpose" cement — meaning a cement which can be used in all applications because it makes life simpler for the suppliers and requires a lower level of care and knowledge on the part of the user. The "general purpose" concept, especially with respect to carbonation risk, is built into most modern cement standards. The main exceptions to this are applications in relatively rare environments — such as high sulfate soils — where specially adapted cements are still available. We believe that this "general purpose" approach to cement standards is a serious barrier to environmental optimisation because it requires that the majority of cements be carbonation resistant, when this represents a rather small fraction of real-world applications.

If cement standards could clearly designate a specific category for use with steel in concrete, such cements would almost certainly sell at a premium price because of the higher energy cost for making them. This would discourage their use in the 75% of applications for which do not need this characteristic, and for which cements with a much lower carbon footprint might be better suited.

6. The Limitations of Earth Chemistry

Portland cement did not become the earth's most used material by chance. The processes of nuclear fusion in stars and in planet formation have yielded the 8 elements — oxygen, silicon, aluminium, iron, calcium, sodium, potassium and magnesium — that make up more than 98% of the earth's crust (Figure 10). The vital elements of hydrogen and carbon can be added to this list. These are very abundant in the seas and atmosphere, and so are also commonly found in surface minerals. Minerals containing other elements are not available in the quantities needed to supply the global demand for cementitious materials. Phosphorus is one important example; it is an element essential for life and also chemically suitable for use in hydraulic cements. Global reserves of phosphorus ores are barely sufficient for its primary use as a component of fertilisers. So, any significant diversion of phosphorus into the construction sector would present an enormous problem for the sustainability of modern agriculture!

Because of the high volumes of cement used, the limited availability of most elements is a major constraint to practically viable cement chemistries. However, it also means that an exhaustive analysis and exploration of alternatives can be made. Since cements are basically composed of oxides we can consider the oxides of silicon, aluminium, iron, calcium, sodium, potassium and magnesium, and their potential to form hydrates with cementing properties. The basic principle of hydraulic cements is shown schematically in Figure 11. First, discrete cement particles are dispersed in water. Cement particles (grey) dissolve in the water and then hydrates (shown in red) are precipitated from the aqueous solution. To work as cements these criteria must be met:

- The hydrates must have a higher volume than the dissolving cement
- The ions forming the hydrates must be able to migrate from the original particles into the previously water-filled space
- The hydrates themselves must have low solubility to remain stable over long time periods

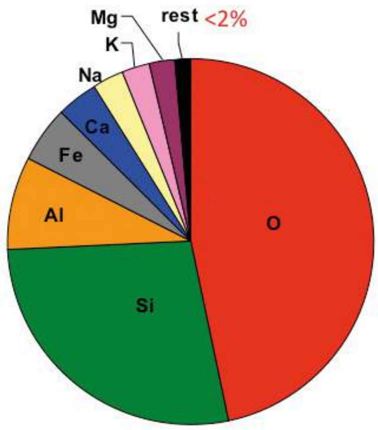


Figure 10. The abundance of elements in the earth's crust [Source: Wikipedia].

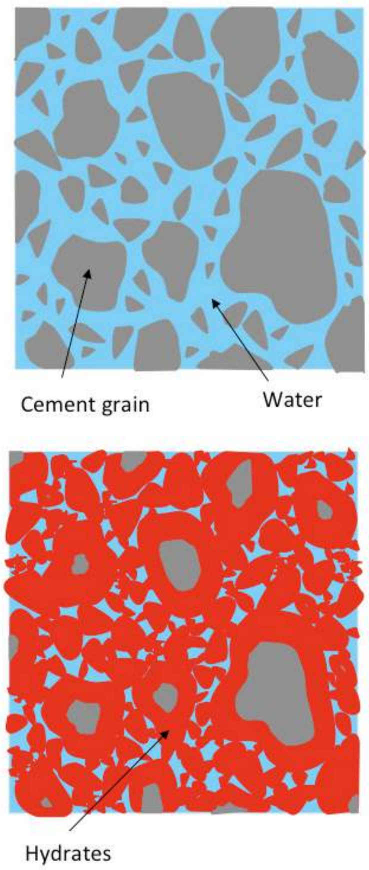


Figure 11. Schematic of cement hydration.

Hydrates formed primarily from the alkali metals sodium and potassium have very high solubility. These ions stay in solution and contribute little to the strength-giving hydrates. On the other hand, the ions of iron and magnesium have low mobility in alkaline solutions, so hydrates from these elements are mainly precipitated within the boundaries of the original cement grains and make little contribution to filling the previously water-filled space. From the standpoint of hydraulic cement, this means that the most important oxides are those of silicon, calcium and aluminium — which make up about 90% of a typical Portland cement. In this lime (CaO), silica (SiO_2), alumina (Al_2O_3) system the only reactive minerals are the calcium silicates and the calcium aluminates or sulfo-aluminates (discussed further in the next section). From the standpoint of CO_2 emissions, the most important characteristic of these minerals is the calcium content. The calcium comes from calcium carbonate (limestone) and the first step of producing clinker is the decarbonation of the limestone:

$$CaCO_3 \rightarrow CaO + CO_2$$

This is the chemical reaction that accounts for some 60% of CO_2 emissions from the manufacture of traditional Portland cement. Since no large-volume concentrated sources of calcium exist other than limestone, the manufacture of calcium-based cements inevitably leads to substantial "chemical" CO_2 emissions associated solely with the decarbonation reaction, and not with the fuel burned in the process. It is exactly for this reason that the cement industry is such a significant CO_2 emitter. This also a cause for optimism — it is clearly possible to reduce these emissions in a relatively inexpensive way, simply by changing the composition of cements.

7. Cements Made from "Alternative Clinkers"

The white paper by Gartner and Sui [4], offers a comprehensive discussion of the alternatives to Portland cement clinker as the basis for hydraulic cements. This paper's central conclusions are presented here. As previously explained, the most viable chemistries for practical hydraulic cements derive from the CaO-SiO_2-Al_2O_3 system. The only minerals in this system with significant hydraulic activity are the high-lime calcium silicates, C_3S (alite) and C_2S (belite), and the calcium aluminates, C_3A, $C_{12}A_7$, CA and $C_4A_3\$$ (ye'elimite). Assuming that the main calcium source is limestone, the amounts of chemical CO_2 released by raw materials' calcination to create the clinker minerals found in Portland cement clinker, or other clinkers discussed in this section, are compared in Table 1, which reveals the very significant differences among them.

CEMENT CHEMISTS' NOTATION

As cement is composed of oxides a particular notation is used to shorten chemical formulae:

Calcium oxide or lime	CaO = C
Silicon dioxide or silica	SiO_2 = S
Aluminium oxide or alumina	$Al2O_3$ = A
Iron oxide	$Fe2O_3$ = F
"Sulfate"	SO_3 = $\bar{S}$ or $
Water	H_2O = H

Examples:

Tricalcium silicate or alite	Ca_3SiO_5 = C_3S
Ye'elimite	$Ca_4Al_6SO_{16}$ = $C_4A_3\$$
Calcium silicate hydrate	$Ca_XSiH_YO_{(X+2Y)}$ = C-S-H

Hyphens indicate variable ratios of lime silica and water

Belite-rich Portland cement clinkers

Belite-rich Portland clinkers are produced with the same process as ordinary Portland cement clinkers, but with less limestone in the clinker raw material mix, so CO_2 generation is reduced. However, this emission reduction of around 10% is rather modest relative to OPC. Belite-rich Portland cements and clinkers are chiefly covered by existing cements norms and so should not be considered as a new class of cement. A key reason they are not currently widely used is that they gain strength much more slowly than most OPCs. Such cements are well suited for niche markets where the strength-gain after a few days is not critical. They are mainly employed for reasons of their low heat of hydration in the construction of massive concrete dams and foundations. Over the past 15 years, belite-rich Portland cements have been used in concrete engineering projects in China.

TABLE 1

Clinker compound	**Chemical CO_2 emissions (kg/tonne)**
Alite (C_3S) [typically, >60% of Portland cement clinker]	579
Belite (C_2S)	512
Tricalcium Aluminate (C_3A)	489
Tetracalcium Alumino-Ferrite (C_4AF, "Ferrite")	362
Quicklime (CaO)	786
Wollastonite (CS) [a major component in Solidia clinkers]	379
Ye'elimite ($C_4A3\$$) [made with $CaSO_4$ as sulphur source]	216
Periclase (MgO) [made from magnesium carbonate]	1100
Periclase (MgO) [made from basic magnesium silicate rocks]	0

Belitic clinkers containing ye'elimite (CSA)

A promising lower-carbon alternative to belitic Portland clinkers is belitic clinkers containing ye'elimite (also known as calcium sulfoaluminate or CSA). These clinkers can be made in conventional Portland cement plants, requiring only changes in the proportions of the main raw materials — for example, less limestone and more aluminium sources. The CO_2 emissions associated with making such clinkers decrease as their ye'elimite content increases, but unfortunately their cost also increases very significantly at the same time because higher ye'elimite contents require more expensive aluminium-rich raw materials. The high cost of high-ye'elimite clinkers is the main reason why modern CSA cement technology, developed primarily in China over the last 4 decades, is still restricted to specialty niche applications where the additional cost can be justified. Recent research in Europe has focused on "Belite-Ye'elimite-Ferrite" (BYF) clinkers, in which belite is the major component, ye'elimite content is below about 35%, and ferrite (C_4AF) levels are also significant. Manufacture of such clinkers therefore requires much smaller amounts of the most expensive aluminium-rich raw materials than conventional CSA clinkers. BYF clinkers [e.g. "Aether" or "Ternocem"] have the potential to replace Portland cement clinker in cements formulated for many major applications, with CO_2 savings of 20% or greater per unit of clinker in the cement due mainly to the lower limestone content of the kiln feed. BYF cements could also replace Portland-slag cements in many applications, thus supplementing the very limited global supply of granulated blast-furnace slag, which is itself a very valuable low-CO_2 hydraulic binder. The major barrier to commercialisation of current BYF technology remains its high raw materials costs. An exception to this is cases where cheap aluminium- and iron-rich raw materials, like bauxite wastes, can be used. BYF cements seem unlikely to be produced on a large scale until the cost of emitting CO_2 becomes significantly higher than it presently is. Nevertheless, the BYF approach is still much less expensive than CCS.

Hydraulic calcium silicate clinkers manufactured by hydrothermal processing

At least two research groups are currently trying to develop CO_2-efficient approaches to the manufacture of belite-like hydraulic binders by hydrothermal processing [22, 23]. At the heart of these approaches is the observation that a hydrated calcium silicate compound (α-C_2SH) can easily be made by low-temperature autoclaving of lime-silica mixtures. The α-C_2SH can then be activated — and at least partially dehydrated — by intergrinding with hard fillers (Celitement) and/or heating at low temperatures to give a material which is very close to belite (C_2S) in composition though far more reactive. In the case of intergrinding with hard filler, the resulting reactive material is equivalent to a filled activated belite cement with good bonding between the filler and the hydrates. The overall manufacturing process is complex due to the need for more processing steps than required for OPC production — specifically the preparation of lime, grinding of silica sources, blending, autoclaving, low-temperature drying, and blending/grinding with fillers. Because these approaches are still under development at the laboratory level, no reliable estimates can yet be made for their overall energy- and CO_2- efficiencies in a real-world industrial context. Simple thermodynamic arguments, however, imply that manufacturing the reactive belite component is itself unlikely to be significantly more CO_2-efficient than producing an equivalent amount of belite in a belite-rich Portland Cement clinker. Thus, the main interest of this type of binder appears to lie in the very significant increase in the rate of strength development relative to what is currently possible with equivalent binders made from belite-rich Portland cement clinkers, and the resultant increased level of dilution with low-CO_2 fillers that may be made possible by this increased reactivity.

Magnesium-based cements

Hydraulic cements based on magnesium oxide (MgO) have recently been claimed to offer great potential for reducing CO_2 emissions. However, most of the research has been done with MgO produced by calcination (decarbonation) of magnesium carbonates, for which the CO_2 emissions are extremely high (see Table 1) so this approach is clearly unsustainable. Nonetheless, there is still some chance for breakthrough in the area of MgO-based clinkers made using globally abundant ultramafic rocks (basic magnesium silicates) instead of limestone as the main raw material. Because these rocks are rich in basic MgO but contain no CO_2, they have the inherent capacity to capture CO_2 as stable magnesium carbonates. In theory, this approach has the advantage over limestone-based technologies because it could be truly carbon-negative if enough magnesium carbonate forms in the resulting hardened binder. As yet, no viable energy-efficient industrial manufacturing process has been invented, although there has been some recent progress [24]. We consider this area merits further research based on its potential for substantial CO_2 reduction — but only in the very long term, owing to the difficulty associated with developing and implementing the necessary process methodology.

Carbonation-hardening cements

There has been a considerable research on the manufacture of concrete products by carbonation instead of hydration. Partial carbonation curing of conventional Portland clinker-based concretes is already used in some precast concrete plants — making use of waste flue gases, etc. — providing a small strength boost compared to ordinary humid curing. But minimal CO_2 is consumed in this way. What is new is the development of special calcium silicate clinkers (CCSC) made specifically for carbonation curing (Solidia, USA). These clinkers, comprising low-lime calcium silicate minerals such as wollastonite, can be made in conventional cement kilns using common raw materials (limestone and silica) and are no more expensive to make than

ordinary Portland cement clinker; in fact, energy costs and CO_2 emissions are lower due to lower limestone contents in the kiln feed. These clinkers are too unreactive to harden by hydration and can only be cured rapidly in an atmosphere of almost pure CO_2, with controlled relative humidity well below 100%. This requires some modification of the concrete curing chambers typically used for precast products, to allow for CO_2 gas circulation (at atmospheric pressure) and condensation of any evaporated water from the fresh concrete. Solidia cements have recently been commercialised for fabricating certain non-reinforced precast cement-based products, but the CO_2 gas for curing currently comes from industrial gas suppliers. The long term goal is to use recycled industrial CO_2 from industrial flue gases, which can be considered to be part of the market for CCU, as discussed in section (3). The global effectiveness of this approach will depend on the extent to which a circular economy for CO_2 develops. Due to the need for specialised curing procedures, and the fact that the hardened cement does not protect steel against corrosion, this approach seems best suited for the unreinforced precast cement-based products market — specifically, with products made in factories where curing conditions can be properly controlled.

The carbonatable calcium silicate clinker referred to above must usually be manufactured, because there are insufficient amounts of naturally occurring carbonatable calcium silicates available. Their manufacture requires the decarbonation of limestone in the cement kiln, so the CO_2 captured during curing only represents that part which was released by decarbonation of the limestone in the kiln, and not that part resulting from the fuel combustion. There has also been a considerable amount of published research on the carbonation of high-calcium industrial wastes with poor cementitious properties, including steel slags. However, simple calculations show that the most energy- and CO_2-efficient way to use the uncarbonated calcium in these wastes is to substitute them for raw material components in the kiln feed for making Portland cement clinkers. This can already be done today, provided that the wastes can easily be transported to a cement plant.

Additionally, the carbonation-curing approach could be applied to MgO-based cements made from abundant natural magnesium silicates (MOMS as discussed above) with even greater benefits for net CO_2 capture, because in this case the raw materials contain no chemical CO_2, so the CO_2 captured during curing would represent a true net CO_2 capture as soon as it exceeds the CO_2 emitted by the combustion of the fuel required to drive the manufacturing process.

Finally, we mention the possibility of making binders from precipitated calcium or magnesium carbonates derived from natural brines — for example, from deep aquifers. An American company (Calera) has demonstrated this process. Besides requiring high electrical energy input, this method is problematic because the calcium and magnesium ions in the resulting brines occur almost entirely as chlorides — so it produces an equivalent amount of a chloride-rich waste stream (dilute hydrochloric acid) which in turn presents a significant disposal problem because there are insufficient large-scale uses for this by-product.

8. Extending Clinker Substitution with Mineral Additions / Supplementary Cementitious Materials

The preceding section demonstrates that cements based on Portland cement clinker will continue to be dominant for the foreseeable future. Such cements have the following advantages:

- Economy of scale of production and optimised processing, affecting both cost and energy requirements
- Widespread availability of raw materials
- Ease of use enabled by workability time before setting
- Confidence in long term durability based on wide-ranging and prolonged usage

In the light of this, a very effective strategy to reduce CO_2 emissions is to substitute some of the Portland cement clinker with other materials (as already discussed in section 3). These are known variously as mineral additions or supplementary cementitious materials (SCMs), and also include almost inert materials, which may also be called fillers. Here we will use the term SCM for materials reacting to some extent. Limestone is usually regarded as a filler, though it is now clear [25, 26] that it can react with available alumina. For this reason, there is increasing interest in coupled substitutions of limestone with alumina-rich SCMs, as discussed later in this section.

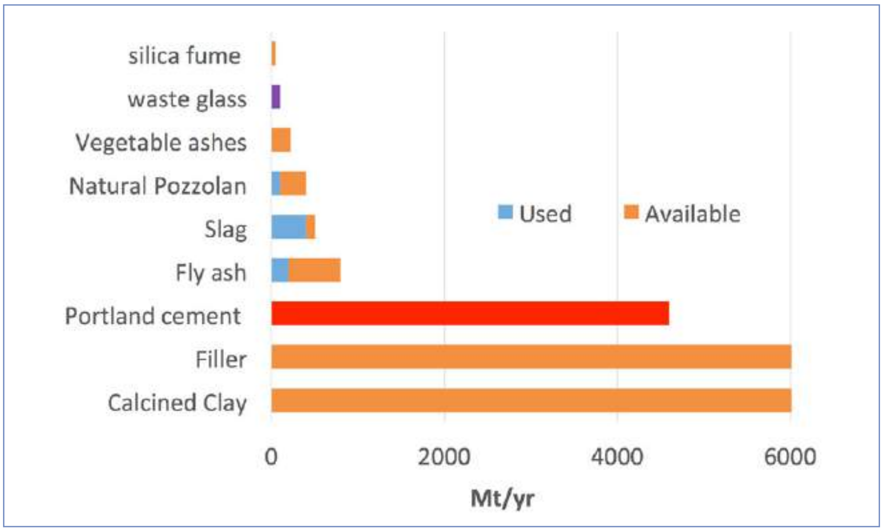


Figure 12. Use and estimated availability of possible SCMs and fillers. Actual possible use will depend on logistics, exact chemical and mineralogical composition, contamination, local availability of other raw materials, etc.

As shown previously in Figure 5, just three materials: limestone, granulated blast furnace slag (GBFS), and fly ash (FA) presently constitute the overwhelming majority of mineral additions. The IEA /WBCSD Roadmap identified limited potential for further CO_2 reduction by clinker substitutes because of the limited supplies of slag and fly ash (Section 3). However, new sources of SCMs would radically change this situation. Figure 12 shows the estimated availability of possible SCMs and fillers in comparison to the amount of cement produced.

Blast furnace slags

Granulated blast furnace slag can be substituted up to high levels (70% is common), but the amount of blast furnace slag available globally is only around 330Mt/year. This availability has decreased from 17% of cement production in 1980 to only 8% in 2014. Despite the fact that growth in steel production is projected at about the same

pace as cement production, blast furnace production of iron and slag is expected to diminish. This is due to the increased availability of scrap steel for recycling and the introduction of more efficient steel-making technologies. Over the long term, blast furnace slag availability is expected to be below 8% of cement production. Furthermore, iron production is concentrated predominantly in industrialised countries, conversely to where the demand for cement is expected to grow most — in developing countries.

To be effective as SCMs, blast-furnace slags must be quenched rapidly from the liquid state, usually with excess water in a granulator. Thus, the actual SCM used is a distinct industrial product, "granulated blast-furnace slag" (GBFS). Granulators are installed and operated in iron-making factories dedicated to producing GBFS as a by-product sold at a profit as an SCM. Because this involves capital investment, GBFS should not be considered a waste product — it often sells for appreciably more on the open market than it costs a cement maker to make Portland clinker. Before GBFS became valuable for use as a cement, blast-furnace slags were typically air-cooled, involving minimal investment, and then often crushed and sold as hard dense aggregates with much less value than GBFS.

Currently, more than 90% of blast furnace slag is already used as an SCM either in cement blended at cement plants or as an addition to concrete or other cement-based mixes [12, 27]. For these reasons, there is little potential for further CO_2 reduction from the use of blast furnace slag.

Fly ash

Fly ash results from coal combustion in power plants, and so may be truly regarded as a waste product. There are greater amounts than slag available, around 900 Mt/yr, but the quality is very variable, such that only about one third of this amount is currently used in cement and concrete. There is probably some scope for increasing this proportion, through better characterisation and classification. Converting unreactive fly ash into reactive material by adjusting the chemistry is unlikely to be economically viable.

It should also be considered that burning coal to produce electricity is by far the largest source of anthropogenic CO_2 and in some countries coal fired electricity production is being phased out. On a global-level, coal will continue to be a substantial part of the energy mix in the medium term — largely due to a lack of incentives for using alternatives. However, it bears noting that the recent availability of shale gas in North America has led to a shortage of fly ash there.

Since fly ash and blast furnace slag are by-products, the availability varies regionally. Originally, they were sold at a low price, thereby reducing the cost of cement. This is now changing in many regions due to heightened demand. They also were considered to be CO_2 free, but allocation of environmental loads is now under discussion. If CO_2 reallocation discouraged their reuse in cement, this would be counterproductive for total global CO_2 emissions. Presently, in many regions, there is a scarcity of these materials and a significant increase in the proportion of Portland cement clinker that they can replace in cement is not expected.

Natural pozzolans

In addition to slag and fly ash, other pozzolans — reactive amorphous or poorly-crystalline siliceous materials from natural sources — are available in a few regions. The CSI GNR database indicates around 75 Mt/y of pozzolans are currently used as clinker substitutes. Available reserves are plentiful, but localised. Reactivity varies considerably. Moreover, the angular particle shape and internal porosity of some materials can lead to greater water demand and workability problems.

Calcined clays

The practice of partially substituting calcined clay for clinker has been known for a long time — it was used in 1932 for bridge construction in San Francisco, USA [29], as well as in many of Brazil's large dams. Since the 1970's Brazil has a constant production of calcined clay of about 2Mt annually.

Clays, especially those containing some kaolinite, produce reactive materials when calcined to around 700–850°C [28] Clay reserves are so vast as to be effectively unlimited compared to the amount of cement produced. In countries such as India and China with established ceramic industries, substantial reserves of suitable clays are currently stockpiled as waste — the over- or under- burden from existing quarrying operations. Exploitation of these reserves represents an enormous potential to increase the global supply of SCMs. Clay reserves in other countries may be less accessible, and the cement industry must also respect the need to preserve natural resources. For the sake of sustainability, clay usage should parallel the trend of fly ash and slag — either by using waste materials from other industries, or carrying-out onsite calcination in cement plants using local materials and avoiding long distance transport.

High surface area and high water demand, along with colour control, have been problems that recent technologies are progressively solving.

Calcined kaolinitic clays have the advantage of reacting quite rapidly, more rapidly than siliceous fly ashes and even faster than slag. The high alumina content of calcined kaolinitic clays makes them particularly suitable for co-substitution with limestone [30] as discussed below and in the white paper by Scrivener.

Vegetable ashes

The white paper by Martirena and Monzo discusses the question of biomass or vegetable ashes. The total availability is probably around 100–200 Mt/y assuming an average ash content of 5% [31] on crop residues reported by [9]. Ash production tends to be dispersed in small quantities and close to agricultural areas.

The most studied is rice husk ash (RHA). If properly processed, this ash results in a silica-rich pozzolan, with high chemical reactivity thanks to its high surface area. The performance of RHA may be very good, despite its very high surface area, which in some applications could increase water demand for good flowability.

Several obstacles impede more widespread use of RHA and other vegetable ashes in cement and concrete — notably, seasonable and geographical variability, and the difficulty of producing reactive ashes while at the same time exploiting the agricultural wastes for fuel. High temperatures and long residence times during burning tend to produce unreactive crystalline quartz. Carbon contamination may also be problem from incomplete combustion.

Furthermore, ashes have other applications, such as soil amendment (mineral fertiliser), which is generally logistically convenient, and in landscaping and other industrial applications [32].

Globally it is not considered that there is a lot of potential for further CO_2 mitigation through the use of agricultural ashes, although there may be some interest on a regional level.

Other reactive products

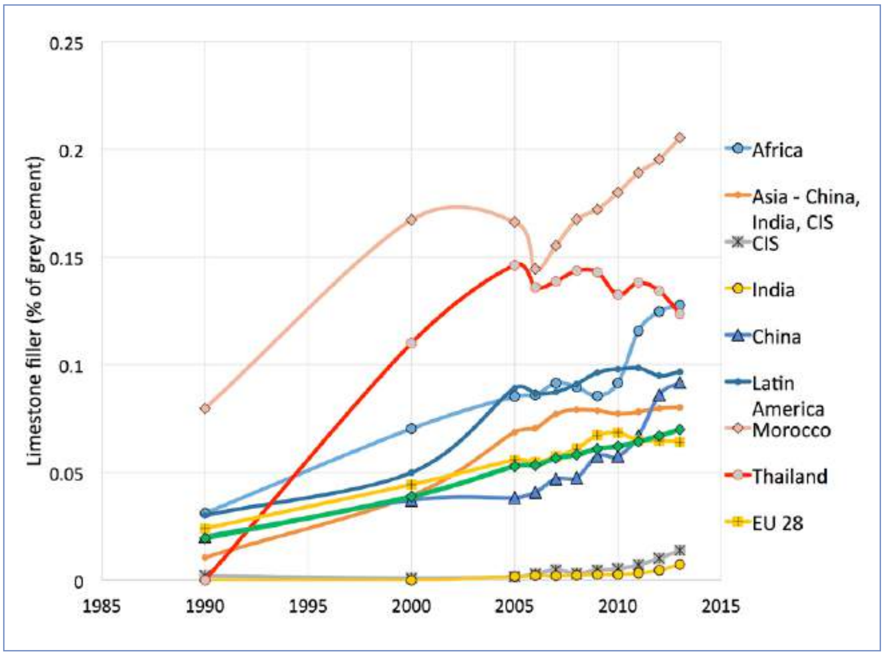
Any amorphous or imperfectly crystalline material containing silica, alumina and/or lime can be potentially a reactive SCM. Although the dominant sources have been blast furnace slag and fly ash, there are others, including natural or industrial residues like slags from steel and other metals.

Among the issues to be considered are available quantities, presence of contaminants, (such as calcium oxide and other minerals that undergo large and slow expansion when exposed to humidity), elevated alkali levels, and the existence of competitive uses for the product, as in the case of waste glass. These issues, combined with logistical costs and availability of other alternatives in each region, effectively limits actual use of such materials. Addressing environmental concerns in the coming decades will necessitate using different SCMs according to local availability.

Potential clinker replacements have been reviewed by Snellings [27]. One of the most plentiful is steel slag, of which about 200 Mt is available annually. Slags from steel production differ from those produced during the reduction of iron in a blast furnace (GBFS, as discussed above). Most slag from the LD process is rich in CaO and other expansive phases, and so better utilised as a raw material for clinker production. If all CO_2 from the decomposition of limestone, added to the blast furnace charge, is allocated to steel production it could be considered a source of CaO free from "chemical" CO_2. The presence of heavy metals in some slags may also restrict their application.

Smaller amounts of non-ferrous slags also exist. Currently, few of these are quenched or otherwise treated to improve reactivity, because the required investment is not justified by any demonstrable improvement in performance. More research is needed if these are to be used as SCMs.

Figure 13. Limestone filler content in grey cement for selected regions. Data from WBCSD GNR [14]. GNR coverage varies between regions.



Fillers as SCMs

Fillers are fine particulate materials, inert or weakly reactive, produced by grinding, that can partially replace clinker or other reactive SCMs. The use of fillers to dilute or extend more valuable raw materials is widespread in other industries, including plastics. Fillers are also a convenient clinker substitute for the cement industry. Because they do not require calcining, filler use could be very interesting from an economic and environmental perspective. Their production needs only energy for grinding. Since many minerals can be used as fillers, they are available everywhere in effectively unlimited quantities. The use of fillers is discussed further in the white paper by John et al.

The first recorded uses of fillers to replace binder were the Arrowrock and Elephant Butte Dams, built by the US Bureau of Reclamation between 1912 and 1916 [28]. Coarse cement was inter-ground with local rock (granite and sandstone), producing a cement with 50% filler. A hundred years later these dams are still in use. The technical feasibility and durability of such filler cements were demonstrated by a 10-year long investigation conducted by the University of California Berkeley [33, 34] in 1930's–1940.

After this, it took 40 years for fillers to become widely used in the cement industry. Since the 1980's substituting limestone filler for clinker has become a common practice in the cement industry. Nowadays, most countries' standards allow filler substitution, with maximum filler values ranging from 5-35% (John et al). Limestone filler has become the most widely used clinker substitute (Figure 5) with an average content (among GNR companies) of around 7% that has remained constant since 2010. Because a fraction of the limestone does react with available alumina to form carbo aluminate phases which contribute to strength and durability [25, 26], up to 10% limestone can be added without the negative effect of dilution on properties; lower levels of addition, typically around 5%, may even improve properties. However, increasing filler content using the current typical intergrinding technology, will reduce the strength class of the cement and so will increase the amount of cement needed to achieve a desired strength. Higher filler contents are typically used in unsophisticated applications, where optimisation of the cement content is poor and it reduces the tendency for over dosage of clinker.

The average of limestone filler used in cement varies from 1–20% from country to country (Figure 13). Several factors influence the uptake of filler: a history of poor-quality, counterfeit high-filler cement, or other cultural circumstances may keep standard limits low; the existence of local over-capacity of clinker productions may make filler less attractive to cement producers, etc. There seems to be higher filler content in the bagged cement markets — users of bagged cement often use cement-rich mix designs and rarely require very high strength concrete. In this situation, high filler contents are an effective way to minimise clinker use. Since industrial users prefer high-strength cements, markets where these users dominate have proportionately lower filler fractions. Nevertheless, the wide variation indicates that filler levels could certainly be increased to reduce clinker use.

Recent developments in Germany and Brazil show that it is possible to produce cements with acceptable performance with higher filler content than the current 35% maximum in many standards. More sophisticated grinding processes to optimise particle size distribution, along with adding dispersant chemical admixtures at the cement plant to reduce water demand to reach good workability are needed to avoid the strength reduction caused by dilution [35].

Recent studies also confirm the possibility of using other minerals as fillers in place of high purity limestone, which currently dominates standards. Limestone unsuitable for clinker production, such as with fairly high dolomite content, performs well as an additive [36]. There is no calcination of dolomite to yield periclase (MgO) and so there is no risk of unsoundness. Dedolomitisation may occur slowly, but there is no evidence of deterioration caused by this reaction[§]. More widespread use of limestone unsuitable for clinker manufacture would lead to more efficient exploitation of limestone quarries with and significant extension of quarry life.

In addition to limestone, any other mineral may be used that is volumetrically stable when exposed to hydrated cement paste and has no negative influence on long-term durability. This may be important for regions where the availability of limestone is limited, such as Brazil's Amazon region and in India [37]. However, for some minerals such as quartz [38], care must be taken to avoid the health risks of respirable crystalline silica dust.

CLINKER FACTOR

The clinker factor is the fraction of cement which is made up of Portland cement clinker. The traditional ordinary Portland cement (OPC) or CEMI according to European norm EN 197-2 has a clinker factor of > 90% the remainder being made of calcium sulfate (e.g. gypsum) and fine limestone.

Current World Average	0.78
2050 target in IEA/WBCSD 2009 roadmap	0.72
2050 target in WBCSD CSI Indian regional roadmap	0.58
Our estimate as "reasonable" global average for 2050	0.60

What is the limitation on average clinker factor?

If we can solve the problem of SCM availability, the question then arises of what is the technical limit to the average level of clinker substitution. To reiterate, granulated blast furnace slag, which has latent hydraulic activity and an overall composition similar to calcium silicate hydrate, may be used up to levels of 70% or more. Pozzolans, such as fly ash and calcined clays require calcium hydroxide (from the hydration of the clinker component) to react and react slower than clinker. Average accepted substitution rates in many applications are generally defined by the client's requirement for a reasonable early strength. However, the issue of early strength can be partially addressed at the production level by replacing intergrinding with separate grinding

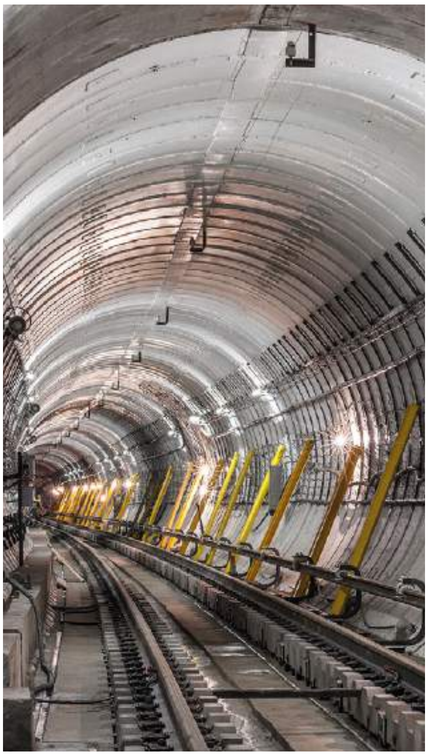
Even so, the clinker factor must be minimised in a way that the overall amount of clinker needed to deliver the required performance is reduced. Current intergrinding technology means that, limestone contents above ~10% will result in a cement of lower strength class because of clinker dilution. This strength reduction has little practical implication for the bag-cement market (as previously discussed). However, in better-optimised concrete mixes, it may increase the amount of cement necessary to achieve the desired concrete or mortar strength, which may also increase the environmental impact in the final application.

Combining particle size distribution engineering with the use of dispersants (e.g. superplasticisers) allows for filler contents to be increased to above 50% without losing, and sometimes even gaining, mechanical strength. This can be done if the water demand for adequate workability is reduced. Less water means there is more solid (binder + fillers) to fill the space between sand grains so good mechanical properties are maintained. This new technology will require separate grinding of clinker and fillers and mixing and the addition of dispersant admixtures. The reactive clinker fraction should be concentrated in the fine fraction of the blend, favouring its earlier strength gain. With such technology, the increase in the cement content needed to maintain mechanical properties means that the proportional CO_2 reduction will be lower than suggested by the clinker factor. This technology could also be adopted at the concrete level, as discussed in section 10.

Another promising technology is the coupled addition of SCMs containing alumina, such as calcined clay, fly ash and slags. The alumina reacts with the calcium carbonate (limestone) to form carbo aluminate hydrates, which contribute to space filling, improving strength and durability. This development is recognised in the recently

§ Dedolomitisation is sometimes considered the cause of expansive and deleterious reaction with carbonate aggregates referred to as alkali carbonate reaction. This is not the case here as the reaction results in a small volume decrease. It is most likely that ACR is caused by fine particles of reactive silicates embedded in the carbonate rocks.

proposed European standard extension allowing up to 55% clinker substitution. This synergetic addition is particularly effective for fast reacting calcined clays containing metakaolin — there is no strength decrease going from a 30% solely calcined clay substitution to a 45% substitution with 30% clay and 15% limestone [30]. Some aspects of durability, such as resistance to chloride ion penetration may even be improved.



If optimised particle size distribution and combinations of fillers and SCMs are fully exploited, we consider that an average clinker substitution level of above 40% (clinker factor <0.6) is realistic worldwide. CO_2 reduction would then be more than currently ascribed to CCS in the 2009 IEA /WBCSD Roadmap. However, realising this level of clinker substitution will require increased research and education efforts, particularly with users.

9. Alkali Activated Materials

On the research side, alkali activated materials (AAMs) have received much attention as materials with lower CO_2 emissions. The first alkali activated materials were alkali-activated slags, developed and widely used in the Ukraine during the 1970s. Subsequently, it has been demonstrated that materials, also known as "geopolymers," could also be obtained from alumina silicate sources such as fly ash.

In the white paper by Provis, this technology is described in detail. Currently, global commercial use of these materials remains extremely small. Substantial technical obstacles exist for more widespread use. On the resource side, there are major limitations. These materials use the same substances as those used to substitute clinker in blends, whose limited availability was discussed in the previous section. In the case of slag — the main component of nearly all real-world applications — almost all suitable quality slag is already used in conventional Portland based cement or concrete. If slag is diverted from use in Portland based blends to be used in alkali activated materials, it may be that the CO_2 emission per tonne (or m^3) of the alkali activated material will be lower than those of an equivalent standard OPC-based material. But there will be no decrease, and likely an increase in the overall global CO_2 emissions of the cementitious materials sector because (a) the CO_2 per tonne of Portland based materials will increase due to the lack of slag for blending, and (b) any CO_2 emissions associated with the production of the alkali activator must also be factored into the equation.

Therefore, AAMs can only contribute globally to the reduction of CO_2 emissions in the sector if they primarily use minerals or industrial by-products not currently used as clinker substitutes in blended cements. Broadly speaking, the effectiveness of materials in AAMs is roughly correlated to their reactivity in blended cements. The "best" materials are granulated blast-furnace slags, which can be used to produce AAMs at room temperatures. Fly ash with good reactivity would allow production of alkali activated cements with CO_2 footprints lower than Portland cement. However, thermal curing is required for the most abundant, class F fly ash, which limit its market penetration to precast components and diminishes its mitigation potential. The availability of reactive fly ash is limited to some regions and it is already diminishing due to climate change related policies. The only materials with substantial potential to extend the availability of suitable minerals for AAMs are calcined clays. However, at present, considerable quantities of sodium silicate (water glass) are needed to activate calcined clays. The total CO_2 emissions from clay calcination and large quantities of sodium silicate may result in cements with high CO_2 emissions. The current

global production of sodium silicate worldwide is less than 10 Mt per year (enough to make only around 40–50 Mt of AAMs) and the energy and CO_2 emission of the production process used at present are very high. Materials that could truly reduce CO_2 emission in the sector require the invention of a lower energy production process and substantially increased production, requiring significant investment.

10. CO_2 Mitigation by Improving Efficiency of Cement Use

In exploring ways to increase the cement use efficiency, we will first consider improvements in binder efficiency possible in industrialised applications. Secondly, we discuss the mitigation possible through promoting more industrialised production of concrete and minimising the inefficient use of cement by untrained and ill-equipped personnel. These aspects are both discussed in more detail in the white paper by John et al.

Reducing CO_2 by improving binder efficiency.

It is possible to make considerable improvements in the efficiency of cement use and this has considerable potential for CO_2 emission reduction. The decisions and skills of the user in formulating cement-based mixtures determine the amount of cement used for a given application. An appropriate indicator of cement use efficiency can be either "binder intensity," which signifies the amount of binder (clinker and also reactive SCMs but not fillers), or the "CO_2 intensity" per m^3 and per strength unit (MPa), a concept proposed by Damineli et al [39]. Figure 14, shows an example of the data collected and published by those authors, plus examples of recent developments, including data from concretes formulated with up to 70% replacement of binder by filler.

The amount of binder used to produce concretes of a given strength varies enormously, (a fact that is neglected by typical life-cycle inventory databases). This dispersion shows that there is a substantial potential for CO_2 mitigation by simply improving the cement use efficiency. The minimum binder intensity is 5 kg/m^3.MPa above 50 MPa. For lower strengths it follows a line that corresponds to the 250 kg/m^3 limit present in most reinforced concrete standards. This minimum binder content reflects the need for sufficient fine particles to fill the space between aggregates to ensure good rheological behaviour. For concretes with 30 MPa compressive strength the minimum binder intensity is around 8 kg/m^3.MPa, but the average is around 12 kg/m^3.MPa, a 44% difference. In general, the lower binder intensities are for concretes made with pure Portland Cement.

A consequence of the variation in binder intensity is a variation in CO_2 intensities of more than four times for concrete of the same strength — the "worst" concrete results in more than four times the CO_2 emissions of the "best" concrete. The minimum CO_2 intensity is around 2kg CO_2/ m^3.MPa for concretes above 40–50 MPa and increases exponentially for lower strengths. Lower CO_2 intensities can be achieved by replacing clinker with reactive SCMs — such as granulated blast furnace slag and fly ash — assuming they are carbon neutral. The clinker portion of the total binder is not necessarily a good indicator of the CO_2 footprint of the concrete, some concretes made with "pure" cements (~0.95 clinker factor) have lower CO_2 intensity than concretes made with cement with clinker factors 40% and lower.

The most effective way to reduce cement dosage, without compromising strength, is by selecting the aggregate amounts in different fractions to optimise packing, reducing the void space to be filled by cement paste. Reducing the cement dosage

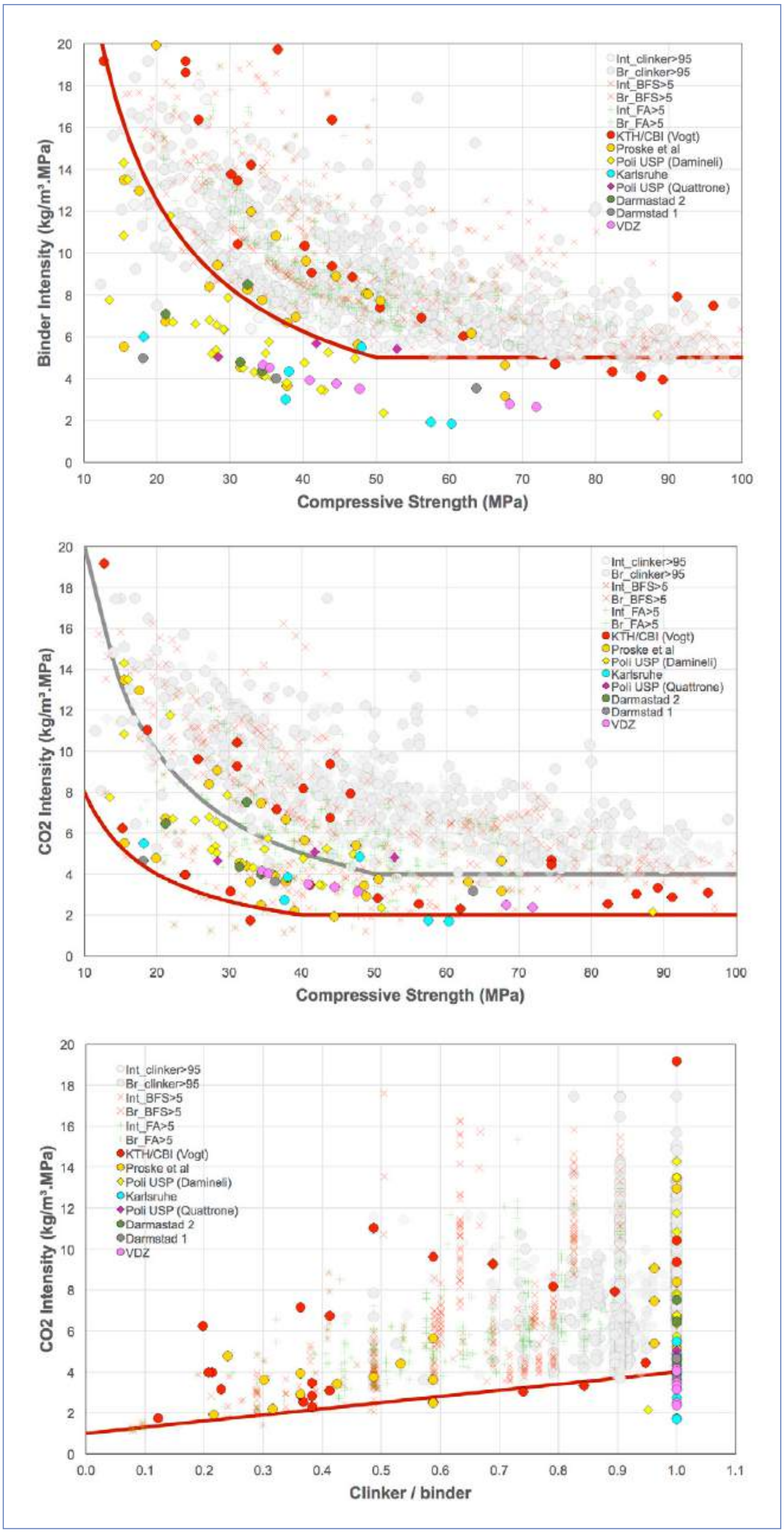


Figure 14. Potential CO2 mitigation by optimising binder use with current (light colours) and high-filler, low-water technology. Binder intensity (bi) as function of 28-day strength (a, top); Estimated CO2 intensity (ci) as a function of 28 days strength (b center). Benchmark data from 29 countries (Damineli et al [28]) are represented in light colours. Red tick lines are the best practice results of current technology. The green line on the CO2 intensity graph separates CO2 intensity of cements of less 5% of SCMs from those with high amount of SCMs. Dots and diamonds in darker colours show the mitigation potential of using high-filler, low water concrete formulations from various authors.

while maintaining good flow and compaction also depends of the use of adequate dispersants (admixtures). Generally speaking, it is only practical to implement such technologies with industrialised production (e.g. Ready mix plant)

This wide scatter observed for concrete, is also likely to occur in other concrete applications, like concrete blocks.

Potential of filler to reduce binder and CO_2 intensities of concrete

Recent advances in engineering particle size distributions combined with the use of dispersants allow a binder replacement of up to 70% by inert fillers without the negative effects of dilution. Since fillers can be made from a variety of materials and require no calcination, they can be cheaper than Portland cement, which makes the technology attractive. The combination of particle size distribution and dispersant use reduces the amount of mixing water needed to obtain good flow (Figure 15). With less mixing water, fewer hydration products are needed to fill the space between particles, improving strength. Because there is less water, there is more solid (binder plus filler), even up to 50% more. Nevertheless, binder intensity can be reduced by more than 50%, as indicated by the red line in Figure 14. Binder intensities around 4–5 kg/m^3.MPa can be achieved for 30 MPa concretes in comparison with values higher than 8 kg/m^3.MPa typical with current technology. For strengths above 50 MPa, binder intensities are about 2 kg/m^3.MPa, compared to 5 kg/m^3.MPa with the best current technology. Similar technology can be deployed for mortars, concrete blocks and other cement-based products.

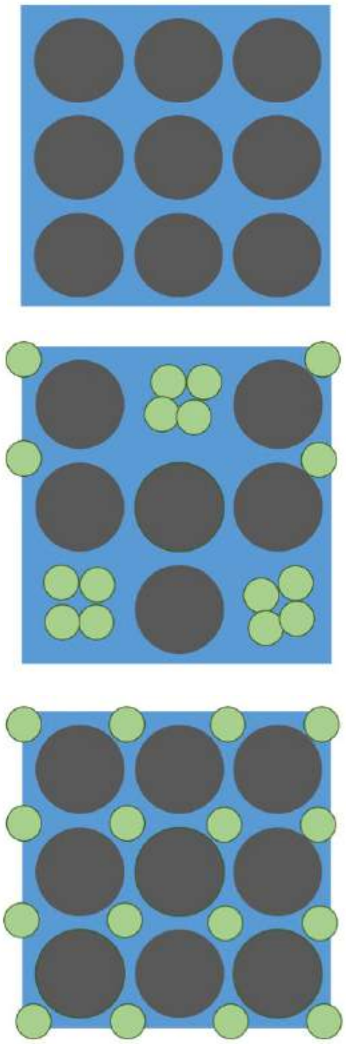


Figure 15. The effect of the combination of binder replacement by inert fillers. Without the presence of the dispersant admixture (centre), as is usual in today's cement industry, ultrafine filler agglomerates may increase the water demand. Dispersants destroy the agglomerates (right), and if the particle size distribution is adequately engineered, will reduce the amount of water needed to fill intergranular space and separate the particles.

The refractory castables industry has more than 20 years of experience with this technology [40]. In the Portland cement field, the technology is still in its infancy, with a limited amount of published research, although there are some patents in the area [e.g. 41]. The recent publication of ASTM C1797M-16 [42], *standardising filler for use in concrete,* and ACI 211.7R-15 [43], *a practical guide for proportioning concrete mixtures with fillers* attest to growing interest in the market. The robustness of combining cement with dispersants, and the limited time stability of mixed dispersants and cement, particularly in hot climates, are issues requiring further research. The specification of minimum cement contents in current standards is another restriction [44]. Such requirements are most relevant where carbonation induced corrosion is an issue (see section 5). Unreinforced concrete, concrete components such as blocks, levelling, rendering and bricklaying mortars, are applications comprising a large proportion of cement use in some developing markets and offer considerable potential for CO_2 reduction.

CO_2 reduction through industrialised cement use

One of the appeals of cement is its robustness and inherent simplicity of use. Untrained personnel can produce concrete using as much as 90% locally available sand and gravel. This means that only cement (in bags) needs to be transported significant distances. On the other hand, such untrained personnel tend to use more cement than necessary, due to non-optimal grading of aggregates, lack of dispersants and low intensity mixing. Since industrial clients, in most regions, prefer bulk delivery, the market share of bagged cement is a rough estimate of inefficient use of cement that is typically higher in the developing world (Figure 19). Cement wastage is also a

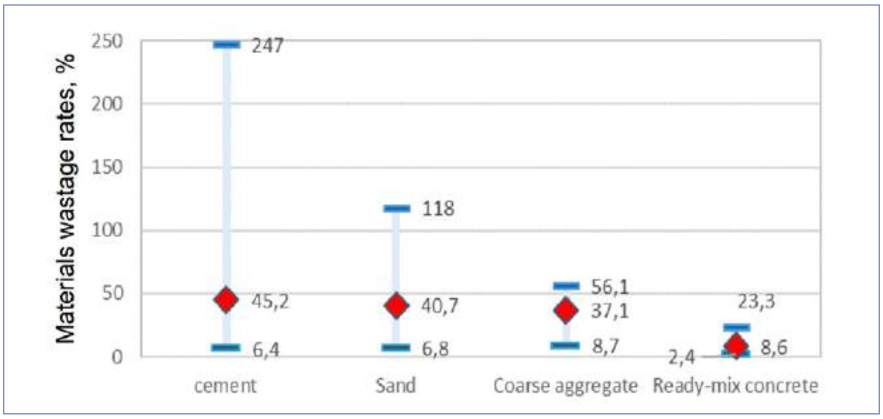


Figure 16. Materials wastage rates (max, min and median) in more than 40 high-rise building sites from different Brazilian regions. Data from [45].

consequence of poor planning, inappropriate storage or transportation — like exposing cement bags to rain or humidity, storing them for too long, all of which is exacerbated by the fact that paper is the most common cement-bag material. Figure 16 shows data from Brazil, illustrating that poorly controlled concrete production at building sites leads to higher materials wastage rates, defined as the percentage of materials actually used at the building site exceeding the amount in the project design.

For these reasons promoting more industrialised cement usage has the potential to reduce cement waste, and therefore overall cement consumption, which would also reduce the environmental impact. Other environmental benefits include reducing illegal aggregate extraction, which is very common in the developing world [46–50].

It is reasonable to assume that increased industrialised production of cement and cement-based materials could reduce wastage by at least 20–30%. Best estimates for the global bag market are around 42% (Figure 19). If these saving were realised on this amount, overall cement consumption could be reduced by around 10%. The challenge is making industrial products competitive compared to informal markets — which avoid costs such as restoration of quarries and payment of social security and taxes for workers — ensuring adequate return rates on the capital needed to build plants and logistical infrastructure. Governments must be encouraged to make industrialised cement products — ready-mixed concrete, dry mix mortar, and precast concrete components — more competitive.

For example, China included industrialisation of cement use in the Chinese National Climate Change Program [51] by seeking to "discourage the production of bagged cement and encourage the development of bulk cement." In October 2003, the Chinese central government issued Decree 341, banning concrete mixing operations on job sites in 124 cities across the country [52]. In June 2007, mortar mixing operations on job sites were banned in ten large cities, an initiative that extended to 33 cities in 2008, and 84 cities as of July 2009. The expectation was a net savings of 2.4 % reduction in cement consumption, a 4.5 % savings in reduced materials loss, with the added benefit of avoiding 3.3 million cubic meters of timber use for paper bag production.

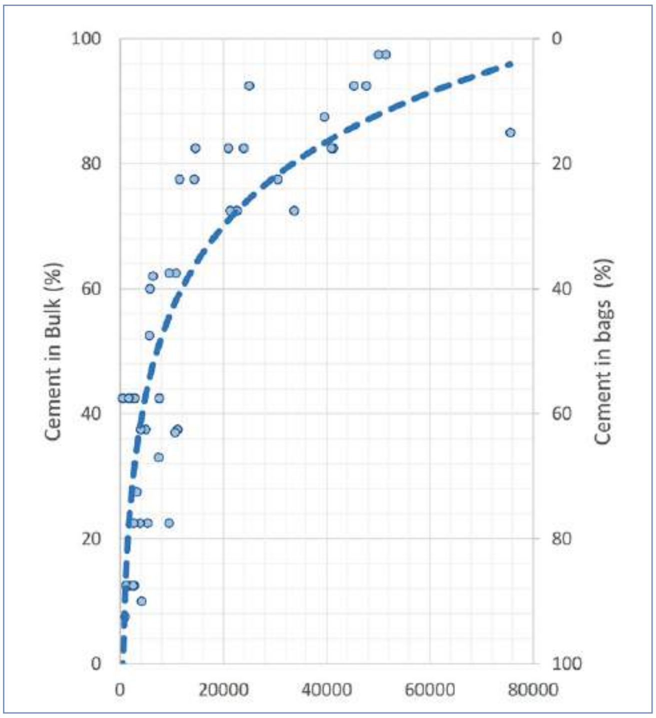
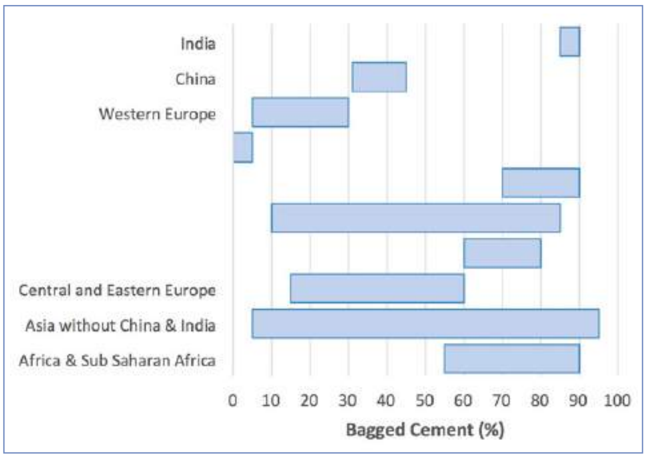


Figure 17. Range of market share of bagged cement in various regions and key countries (top) and market share of bulk versus GDP (bottom). Bagged cement market share are from LafargeHolcim Corporate Strategy Estimates as of Q1 2016. GDP are from World Bank [13]. Data covers countries responsible for about 90% of total cement production.



Industrialisation is only feasible in medium to large cities, where consumption rates are higher and transportation distances are more favourable between producers and consumers. However, according to UN [53, 54] the pace of urbanisation, particularly in Africa and Asia, is accelerating. In 2014, 54% of the population was situated in urban areas; this figure will increase to 66% by 2050. About half the total urban population lives in cities larger than 500,000 inhabitants and one-eighth in cities larger than 10 million.

Chemical admixtures

Chemical admixtures are products that used in small amounts are capable of improving cement-based materials performance. From the preceding sections, it is clear that dispersants (plasticisers and superplasticisers) are critical for improving the efficiency of cement use. The white paper by Cheung et al discusses in detail the role of admixtures in a more sustainable cement value chain.

Reduced CO_2 emissions can be achieved with four types of admixtures:

1. Dispersant-based water reducers (plasticisers and superplasticisers) reduce the amount of water needed to make concrete that can be easily placed, and so reduce the amount of cement clinker needed for a given strength and durability. This technology also enables higher filler contents and additions such as calcined clays, which can be used to increase the eco efficiency of concrete in many applications. A case study in the white paper by Cheung et al, illustrates how the use of admixtures with proper mix designs and use of SCMs can even lead to CO_2 savings at equal load carrying capacity of 67%.
2. Air entraining agents (chemicals capable of incorporating fine air bubbles in mortars or concretes during mixing) improve rheology and resistance to frost action. In mortar and concrete components where the main requirement is volume filling rather than strength, these agents are an effective tool for increased materials efficiency and saving materials, including cement.
3. Accelerators (chemicals capable of accelerating cement clinker hydration) enable faster strength development. They allow concretes with higher proportions of slower-strength developing SCM's to reach adequate early strength required for construction by accelerating the clinker phase hydration.
4. Chemicals that address major concrete durability issues, including freeze thaw protection through air entrainment, reinforcement corrosion protection through corrosion inhibitors, cracking reduction through shrinkage reducing admixtures, etc. While these may not reduce initial environmental load, prolonging service life in critical structures will reduce environmental impact.

The performance of cement dispersants has improved substantially in recent years, but there may still be compatibility problems with individual cements and SCMs, particularly in hot climates. Advances in recent years in the understanding cement-SCM-admixture compatibility issues have generated practical solutions. Along with more rapid laboratory- and field-based detection tools, the use of admixtures can clearly be better adapted to developing countries, where admixture usage is currently limited. These obstacles can be overcome with easy-to-use diagnostic tools and disseminating educational material.

Recycling cement-based waste

Significant efforts have been made in recent years to recycle concrete and other cement-based waste, particularly by producing recycled aggregates. This is motivated

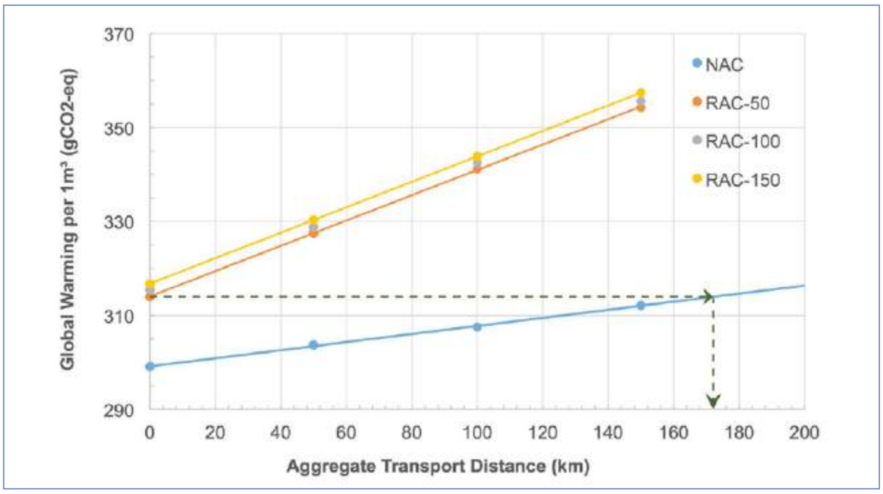


Figure 18. The effect of transportation distance on associated CO_2 emissions of concretes produced with recycled aggregates and natural aggregates. The substantial difference results from tested recycled aggregates requiring much higher cement content to reach the necessary design strength [47].

by the need to reduce construction and demolition waste (CDW) going to land fill, and also by the increasing scarcity of viable sources of virgin aggregates situated in proximity to metropolitan areas. Recycling concrete and mortar yields meaningful environmental benefits, from these perspectives. However, recycling does not contribute significantly to reducing CO_2 emissions in the cement-based materials sector. Naturally occurring virgin aggregates have a CO_2 footprint two orders of magnitude lower than cement [55]. This makes their share of the CO_2 footprint very low — typically less than 10%, even taking into account long-distance transport via roads. Processing recycled aggregates is generally a bit more energy intensive than processing virgin materials, because recycling requires decontaminating demolition waste and may generate substantial quantities of fines, which typically have no commercial value [56]. Transport and waste disposal are decisive elements in the environmental impact equation — but generally speaking, if aggregates can be recycled close to usage sites, there will be a small net reduction in their associated CO_2 emissions due to reduced transportation.

A more problematic issue for recycled aggregates is that depending on their quality and substitution levels, these materials may increase cement demand for a given strength, in turn negatively affecting the overall CO_2 footprint of the concrete [55]. At present, most techniques that improve aggregate quality by removing cement paste also tend to have a high CO_2 footprint [56]. Figure 18 shows how recycled aggregate needs to be sourced much closer to the site of use to compensate for this effect.

Recycling also results in a high amount of CaO rich fines, most of which are non-carbonated. With informed planning and management, these fines may be recycled as raw materials for clinker production, thus reducing chemically related CO_2 emissions for clinker [57]. Another useful by-product from aggregate recycling with potential market value is good quality recycled sand [58].

11. Soil Concrete

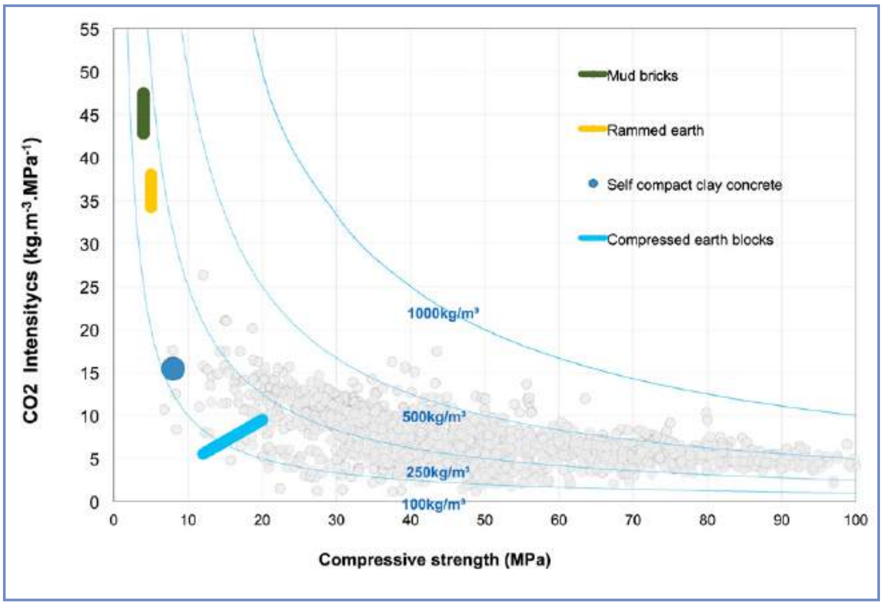
Raw (crude, unbaked) earth (subsoil) is a traditional building material used in a wide range of construction techniques. These are presented in more detail in the white paper by van Damme and Houben. Stabilised soils remain in significant use for dwelling construction all over the world. Without industrial additives, it is a material with a remarkably low environmental impact. A recent trend has been to "stabilise" the raw earth with lime, plaster of Paris, Portland cement (PC), or supplementary cementitious materials (SCMs). This had led to the now widespread incorporation, mainly for compressed earth blocks and in rammed earth,of typically between 5 and 10% PC by weight. This approach is generally used to minimise the high maintenance involved with pure soil materials, particularly in regions with heavy rainfall.

In comparison with concrete, soil stabilisation can be an extremely inefficient way to use large volumes of Portland cement. Figure 19 shows the CO_2 intensity of such cement-stabilised soil-based materials compared to conventional concrete discussed in Section 10 (Figure 14). The data points for stabilised earth follow the exponential curve for concrete. Compressed earth bricks (CEB) behave like a concrete with moderately poor environmental and mechanical performances. They are usually structurally solid masses, while concrete and ceramic blocks tend to be hollow. In environmental terms, self-compacting clay concrete (SCCC) is nearly the worst formulation (in environmental terms), even neglecting the impact of the superplasticiser. Rammed earth (RE) and mud bricks (B) have extremely poor environmental performance, with CO_2 intensity indices 20–25 times larger than the asymptotic value of high performance concretes. Stabilised soil technology seems to offer only moderate mechanical improvement at a high environmental cost, which can only be positively offset under specific conditions where the service life is greatly extended, or as a building material of last resort.

Van Damme concludes: Stabilisation of soil concrete with OPC is not advisable. It provides only very moderate benefits while employing large binder volumes. One acceptable use could be compressed blocks, but their strength is still at least three times smaller than the same amount of OPC would offer for good concrete formulation. He points out that unstabilised soil construction can have good durability and low maintenance if two cardinal rules are followed — "good boots", meaning a water tight foundation, and a "good hat", meaning a roof to keep rain off the walls.

Stabilised soil supplemented with cement or lime is also used for road subbase. Around 5% of cement worldwide is used for road construction, about 20% of which is for stabilising the subbase, amounting to about 40 Mt in 2015. Therefore, even is if some reduction in the CO_2 emissions are possible, it will not contribute significantly to overall CO_2 reductions in the sector.

Figure 19. CO_2 intensity index of mud bricks (B), compressed earth blocks (CEB), and rammed earth (RE) stabilised with 5–10% OPC, in comparison with data for PC concretes. Also included is the index of self-compacted clay concrete (SCCC) stabilised by 5% CSA cement. Note that the carbon footprint of the superplasticiser (~40% of that of cement) has not been taken into account (adapted from Fig. 5 of (Damineli et al. (2010))).



12. Structures

As discussed in the introduction, this report focusses on technologies at the materials level. Nevertheless, it should be mentioned that there is also considerable potential for saving cement at the design level. Not least, it is undoubtedly true that many structures use concrete of a higher strength than needed for the design, which amounts to a waste of materials.

This is not an easy topic, since most of the discussion on sustainable cement-based materials is focussed on solutions to minimise cement CO_2 footprint by the use of SCMs, etc., and strategies to increase service life, especially of steel reinforced concrete structures. However, design decisions, at both architectural and structural design levels, control the amount of materials, particularly steel and cement, and therefore, have a direct influence on the minimisation of the environmental impact and particularly the efficiency of cement use. Designers decide aspects such as the thickness of a wall, of a concrete block component or the number and size of reinforced concrete columns and beams in a building.

There is no international, universally recognised benchmark for the CO_2 footprint or concrete consumption for buildings or other structures allowing producers, consumers and researchers to make informed decisions. A unique global initiative in a closely related field is the Common Carbon Metric for measuring Energy Use & reporting Greenhouse Gas Emissions from building operations protocol, developed by UNEP-SBCI, but it is focused on building use phase [59].

The Building and Construction Authority in Singapore edited a guide to promote the optimum use of concrete [60] , within the scope of their BCA Green Mark building rating system. The guide presents a benchmark of the concrete usage index (CUI), which measures the amount of concrete (m^3) used for each unit of floor area (m^3) of the building, usually limited to the superstructure (excluding the foundation), with values ranging from 0.35 m^3/m^2 to 0.7 m^3/m^2. For 2–3 storey buildings the CUI is much lower, varying from 0.2–0.3 m^3/m^2 (Figure 19). The guide also includes examples of technologies that help to save concrete, including pre-stressed slabs, lightweight partition walls, hollowed slabs, composite steel-concrete systems and high-strength concrete. A study conducted by the Lawrence Berkeley Laboratory [61] on concrete buildings in China estimates CUI between 0.53 – 0.61 m^3/m^2 in 2008, which is expected to growth due to the increase in storey numbers to between 0.62–0.70 m^3/m^2 in 2030, with an average steel consumption varying between 81–96 kg/m^3 of concrete. In a pioneer study, Warszawski [62] made an estimate of cement consumption for the future in Israel, giving results varying from 0.39–0.69m^3/m^2 of concrete. Data from high-rise buildings in the Middle East shows results varying between 0.4–0.7 m^3/m^2 for buildings between 20–40 floors, but reaching a maximum of 0.9 for a building with 85 floors [63]. These values are remarkably coherent. On the other hand, data from 93 buildings in Brazil shows much lower CUI, varying from 0.16–0.3 m^3/m^2 for 4–30 storey buildings and 0.07–0.11 for 1–3 storey residential buildings. In all cases scatter is important, and reflects design decisions such as percentage of steel reinforcement, which has a high CO_2 footprint, differences in loads, concrete strength especially for columns, typical spams of beams and slabs, the eventual need for earthquake-resistant designs, which is not the case for Brazil. Optimisation of the design of buildings in terms of environmental impacts is a complex task, because in includes multiple functions, including fire resistance, acoustics performance as well as seamless integration with multiple materials, especially the reinforced concrete and will require significant research and development effort.

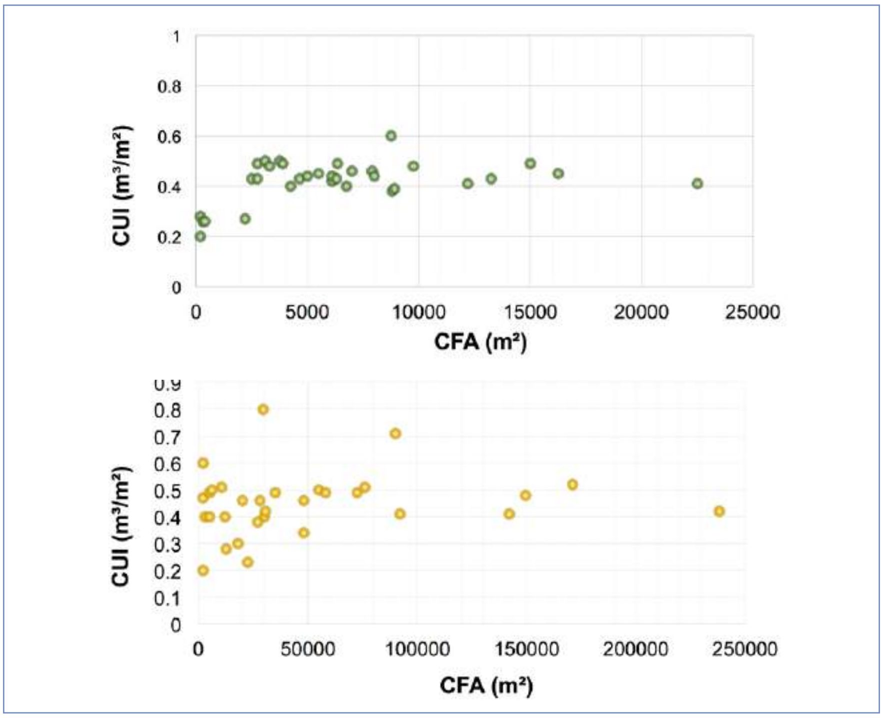


Figure 20. Example of Concrete Usage Index for buildings from Singapore. Residential buildings represented in the top chart segment, commercial buildings in the bottom [52].

In the literature higher strength concrete is often promoted as a tool to reduce environmental impact, because it is has a lower binder intensity and CO_2 intensity (see Figure 14), is capable of carrying more load per unit of area, therefore reducing the amount of cement and aggregates needed and increasing the liveable space of the building [64] and have higher durability. However, the actual benefits seem to be smaller than estimated by simple reduction in materials demands and cement use efficiency. Nevertheless, literature shows estimated CO_2 mitigation as high as 20% for construction of a bridge in France (up to 50% if the uncertain use phase is excluded) [65], with values for buildings varying between 4.1 [66] to and 16.5% [64] for the construction of buildings. In conclusion, benefits seems be limited for situations where the increase in strength induces a significant volume reduction, compensating the increased cement amount per cubic meter allows a significant increase of service life of the structure [65]. Therefore explains why the amount of concretes with strength above the class 35–45 MPa represents less than 15% of the European market [67].

Concepts such as topology optimisation, where the design seeks for the shape that reduces the amount of material have been explored for buildings [68] and certainly can be applied for small components — such as concrete blocks to bridge beams. Functionally grading the properties of cementitious materials can allow localised reduction of cement. This concept has been demonstrated for fibercement [69], but can also be applied to concrete components. The combination of such concepts with digital production methods certainly has a potential for mitigation.

It is clear that structural design represents an area where considerable savings in CO_2 are possible, but this will require substantial investment in research and development as well as in education to raise the awareness of engineers to the possibilities.

Improving Durability

Cement based materials are typically expected to have a service life of at least several decades. Fifty years is standard, although often the expectation is for much longer. Durability is not an intrinsic property, it depends on the interaction between cement-based materials and their usage environment. There is ample scientific and technical expertise available to understand degradation, but predicting service life in real environments where many factors interact is complex.

The overwhelming majority of problems of concrete durability — probably about 90% — are related steel reinforcement corrosion, which is related mostly to chloride ingress, and less commonly to carbonation. It is important to realise that only a very small proportion of cement use is at risk, because only about 25% of cement use is in reinforced concrete (Section 5 Figure 8). Only a fraction of this is exposed to conditions posing durability risks. In these applications, longer lasting concrete would certainly reduce environmental impact. However, in terms of total cement consumption, the amount of extra cement consumed related to repairing degraded structures is rather small.

Every effort should be made to design and build costly infrastructure, such as bridges, to last as long as possible. However, the using the same concrete for all applications would be an unduly conservative approach that would also be very wasteful from the standpoint of resources and CO_2 emissions.

13. Standardisation

Standardisation can be a major barrier to the introduction of new solutions. It is a consensus-based process, with serious economic implications for numerous businesses. Standards are further complicated by the fact that they operate on (at least) three levels — the cement level, the concrete and at the construction level — often with a lack of communication between these levels.

The majority of standards worldwide are prescriptive; they dictate the composition of the materials that can be used. Two sets of standards dominate — the European EN standards and those originating from ASTM, based in North America. Many Latin American, African and Asian countries follow one or the other of these standards to varying degrees. The other large cement consuming countries of China, Japan, India, and Russia have their own standards, nevertheless inspired by EN or ASTM approaches. Some approaches, such as limestone use and even the use of slag and fly ash, can face local resistance resulting from poor commercial or technical understanding.

Increased efficiency in cement use requires market segmentation and flexibility to exploit local opportunities for raw materials, both for clinker and for supplementary materials like fillers. This will allow products optimised for specific applications, rather than the conventional approach of one-type-fits all. This can only be achieved with performance standards specifying properties that must be met, such as strength, elastic modulus, and durability.

Performance Standards for mechanical properties are relatively easy to implement based on measurements at relatively short ages, such as 28 days. There is much greater difficulty ensuring durability over the service life of a structure. To be practical performance tests need to give results in a relatively short time — a few months at most — to reliably predict performance in the field over many decades. Considerable advances have been made in understanding fundamentals of the predominant degradation mechanisms, but the simultaneous action of various mechanisms remains less well established [70]. Applying fundamental knowledge gained from short term laboratory testing to long term durability performance is challenging, because of the broad range of environments in which cement-based materials are used.

Developing a robust scientific understanding and pilot applications in representative conditions could help accelerate the development of performance standards, especially if the process involves cement producers, governmental clients and regulators and large building contractors. Technical approval schemes, where available, can facilitate pilot applications. This will require international collaboration at a scale not yet seen in the field.

There is also the significant issue of cement versus concrete standards. Cement standards are far easier to enforce because cements are generally manufactured by large and easily identifiable companies. It is well known that concrete performance, especially durability, depends on good quality control in the field, for example to ensure the use of the correct water to cement ratio and avoid cracking. To be truly successful, the performance standards approach will have to be applied to concretes and other cement-based end products rather than just to cements. This objective will be difficult, especially in developing economies, although this is also where the greatest ecological returns can be realised. We have shown in this report that there are very significant ecological returns from minimising clinker use in concrete. These can also be associated with a reduced unit cost on the assumption that Portland cement clinker is replaced by less expensive fillers. But such benefits can only accrue if the importance of good concrete mix design and quality control is understood by end users.

Changing our approach to standardisation will therefore also require a major educational initiative to ensure that the engineers responsible for designing and executing concrete works fully understand the relevant issues.

14. Estimating the Mitigation Potential

This study has considered CO_2 mitigation material-based technologies for the cement-based materials industry, which were not quantified by means of the Cement Technology Roadmap 2009 [1]. The full methodology is detailed in the white paper by Miller et al. The mitigation potential of each technology is uncertain, due to uncertainty on CO_2 and energy footprints, and future market share, which ultimately depends on investments in industrial facilities. Actual CO_2 emission and production costs will also be influenced by the R&D investments in each technology, both by industry and public agencies. Consequently, the mitigation potential presented for each technology simply represents a desirable possible outcome.

Emission factors

Emissions factors for several alternative materials were based on life cycle assessment (LCA) methodology. Production was considered at regional levels and global emissions factors were estimated by means of weighted averages. The Getting the Numbers Right (GNR) database [12] reports kiln use by region as well as kiln efficiency. Fuel mixes were estimated based on data from GNR and the International Energy Agency (IEA) [71]; CO_2 emissions from fuel were calculated based on values reported by the Intergovernmental Panel on Climate Change [72]. Raw material derived emissions ("chemical" CO_2 from the breakdown of limestone) were considered to be 0.507 kg CO_2/kg of clinker [73]. For models of Ordinary Portland Cement (OPC), the use of clinker was modeled with additional processing and the inclusion of 5% gypsum by mass. Beyond OPC, the production and consumption of supplementary cementitious minerals — blast furnace slag, fly ash, natural pozzolans, and filler — in cement or as cementitious replacement were considered. Carbon dioxide emissions factors for such materials were based on calculations by Gursel and Horvath [74], and on consumption data from the GNR database [12]. For the LCAs conducted, regional electricity mixes based on calculations by Miller et al [75] were used for additional processing of clinker and for processing of other cementitious products. The ranges of values of the emissions factors for the production of calcined clay were taken from various sources [76, 77]. Carbon dioxide emissions associated with the production of limestone filler were based on methods developed by Gursel and Horvath [74] and were adapted to account for regional electricity mixes.

The mitigation potential of Alkali activated materials (AAMs) based on blast furnace slag and fly ash reduces between 40 and 80% of the emissions corresponding to Portland cement [78]. CO_2 emissions associated with alkali activators, varied from 0.9 t/t — assumed to be possible with new technology routes — to 1.8 t/t (dry basis), being the lowest emission factor presented by [78]. Table 2 contains the emissions factors based on regional hydraulic cement production values.

Table 2. Emission factors considered in the estimate of mitigation potential (kg of CO2 per kg of material produced).

Clinker+ gypsum	Calcined Clay	Limestone Filler	Sodium silicate	RBPC	BYF	CCSC
0,86	0.2–0.35	0.008	0.90– 1.8	0.79	0.62–0.66	0.54

IEA ETP 2016 [11] low demand, 2˚C scenario was considered as a reference for our alternative scenario. For the year 2050 this scenario foresees a production of cement of 4556 Mt. To meet the 18% target for overall CO_2 reduction of about 900Mt, it is assumed 347Mt of reduction in CO_2 emissions will come from the solutions (alternative fuels and raw materials, energy efficiency and conventional SCMs, including 10% of limestone filler as discussed in Section 3) and the remaining 552 Mt from capture and storage of CO_2. Different technologies may have inherently different efficiencies for the various typical cement applications, due to differences on mechanical strength and even densities. Despite this being an important factor, it was not considered in the model.

Limits for market share gain

It is estimated that blast furnace slag and fly ash will be around 16% of the cement production in 2050 [16]. Nearly all of this production has already considered to be used for clinker substitution in the IEA mitigation scenario. Therefore, the use of AAMs or any other technology based in such raw materials is, limited. Furthermore, if these materials are diverted from use in Portland cement clinker based blends, the mitigation potential already assumed will be decreased. The possible use of remaining fly ash in some regions is considered, but in most of cases it will require thermal curing. Since thermal curing was not considered in the model, the mitigation potential of this option is overestimated. Calcined clay based AAMs can be scaled up, but this will require investments to increase the production of sodium silicate. To supply 15% — 7.5% of AAM fly ash and 7.5% for calcined clay — of the cement market of 2050 about 250Mt of sodium silicate would be needed, an increase by a factor of 42 in comparison with current annual production. However, there are extensive reserves of soda ash and silica that are needed to develop the product [79].

For BYF (belite ye'elimite ferrite) clinkers, the critical materials are bauxite and other high-alumina minerals from which the fraction of Al_2O_3 is 16.4% [80]. Al_2O_3 content in bauxite is circa 40% [81], and bauxite resources are estimated to be 55 to 75 billion tonnes [82]. Today's 91% of the bauxite production is concentrated in 15 countries, mostly Australia, China, Brazil and Malaysia and India; the price of exports to USA ports is USD $30–46 [82]. If all of today's bauxite extraction were diverted to BYF cement, it will be possible to produce around 650 Mt of cement. Competition with aluminum for bauxite and regional material availability are limitation factors.

Carbonation-hardening CCSC and MOMS require special industrial facilities to carbonate cement in a controlled environment. Therefore, they have a potential to capture a share of the smaller industrial components market. Because there are no published studies on future market share of industrialised cement-based components their share was estimated up to a maximum of 15% in 2050.

On the other hand, filler from limestone and other minerals, and calcined clay plus limestone filler are not limited by the resources available, which are very large in comparison to cement demand. However, they are limited by the maximum fraction of clinker substitution. Clinker substitution by filler or calcined clay and filler modelling will be developed as an additional to the 10% already consider in the reference mitigation scenario.

Mitigation potential

The mitigation potential is expressed as the fraction of market share in the year 2050, forecast to be 4,566 Mt [11]. Therefore, we are not addressing the time scale of the introduction of each technology, which will not be the same for all technologies and will clearly impact, the mitigation that can be realised in practice.

The mitigation potential *Mp* (tCO_2) of a technology is a function of the specific mitigation potential, *smp* ($kgCO_2/t$) multiplied by the amount of cement produced.

$$smp = C_t - C_c$$

Where C_t is the CO_2 footprint of the technology; C_c is the CO_2 footprint of the cement it displaces from the market, in our case, Portland cement with 10% of filler and 4% of gypsum. However, when the CO_2 mitigation of the technology diverts SCMs originally used in the production of Portland cement, such as slag and fly-ash, unless the new technology increases the SCMs' use efficiency there is no net benefit.

For the technologies based on clinker substitution, namely (a) the combination of calcined clay and limestone filler and (b) fillers, the market share is limited by the maximum amount of clinker that can be substituted without, affecting strength and durability. Fly ash and granulated blast furnace slag are the major SCMs and are available to the production of approximately 740 Mt. These two SCMs groups plus the 5% of gypsum result in an average of 70% clinker fraction in the low demand scenario.

It is possible to introduce 10% of filler in all cements produced, because at this low rate of substitution, the dilution effect can be easily compensated for by grinding. Assuming a minimum average clinker factor of 50%, it is possible to estimate that the sources or slag and fly ash available would allow combinations with, on average, 40% of fly ash and/or slag plus 10% of filler to supply 40% of the cement market**, all with 50% of clinker fraction. Without additional sources of SCMs, the remaining 60% of the cement market would have only 10% of filler. Further CO_2 mitigation could then come from the use of other SCMs, limestone and calcined clays or fillers. The engineered filler combined with dispersant is certainly more challenging to deploy.

Figure 21(a) shows the mitigation potential of a combination of 25–35% of calcined clay, 15% of limestone filler with minimum 50% clinker content. Figure 21(b) presents the mitigation potential of engineered filler combined with dispersant. These two technologies, which are based on minerals and production processes that the cement industry are familiar with, may reach the potential ascribed to CCS in the IEA ETP 2016 2DS scenario.

** 0.16/0.4

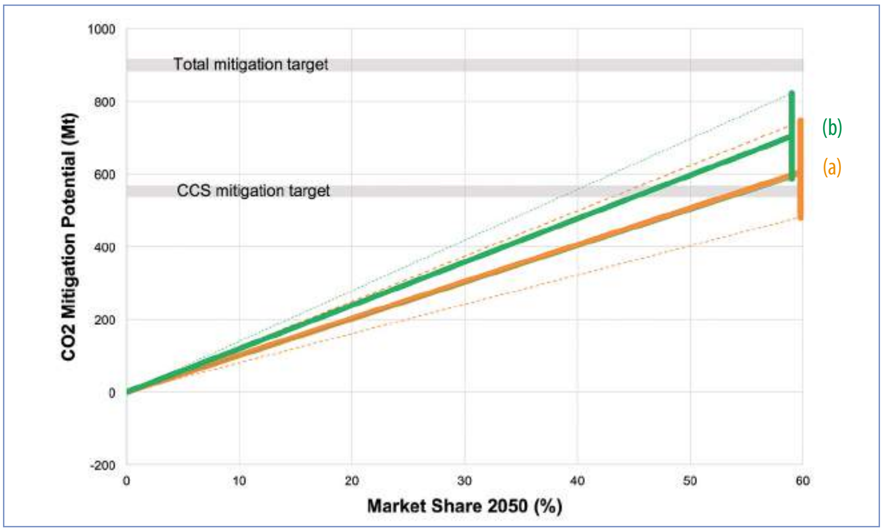


Figure 21. Mitigation potential as a function of the market share for the 2050 low demand scenario of (a) a combination of 25–35% calcined clay plus 15% of limestone filler; (b) filler substitution, varying between 25–35%. Horizontal lines present as reference the mitigation targets from the 2DS scenario for CCS and in total.

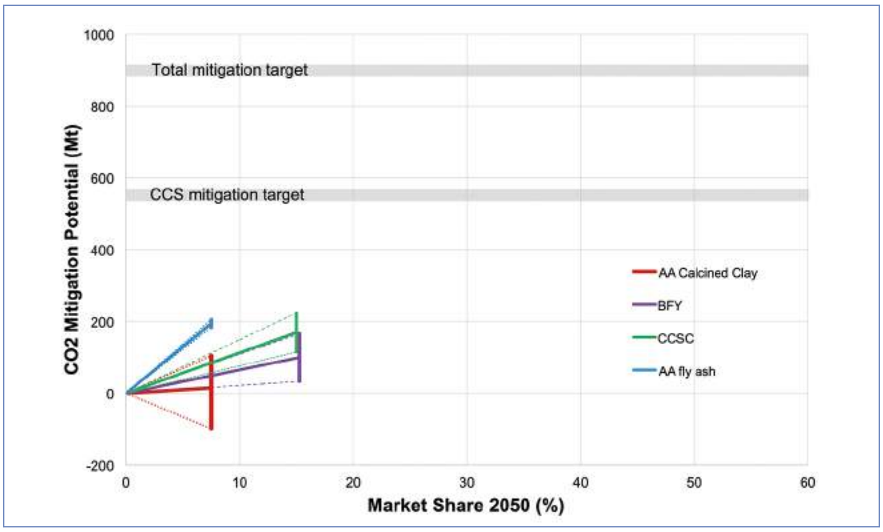


Figure 22. Rough estimative of mitigation potential for new cement technologies as a function of the market share for the 2050 LD scenario. These technologies are at earlier-stage development and so there is greater uncertainty. Horizontal grey line represents the mitigation target from the 2DS scenario for CCS. Dotted line represents uncertainty on the estimative.

In the high demand scenario, the cement production will be 30% higher — around 6 Gt. Calcined clay and fillers can cope with this increased demand, even if slag and blast furnace slag production remains constant.

Figure 22 summarises the results for the new cements. The CCSC market is limited to the production of industrial components because carbonation hardening requires dedicated industrial facilities. Since the material will be carbonated, protection of steel may be a problem in some environments. To capture uncertainty, the emission factors were varied 15% below and above the nominal CO_2 footprint. BYF is also not fully developed, and its CO_2 footprint and cost are subject to changes. Market penetration of this cement will depend on availability and costs of aluminum-rich minerals in various regions.

Alkali activated cements are not new. Sodium silicate-based technology more than 60 years old, with very limited market applications. The calcined clay AAM footprint will be affected by the amount of activator (Na_2O. $xSiO_2$, where x ~1.7) today, this varies between 25 and 55% (dry basis) of the total cement. A formulation with 55% of sodium silicate with 1.1tCO_2/t (dry-basis) will result in no improvement in comparison with Portland cement with 10% of limestone filler. FA activated AAM can be an option in some regions, but the total amount of fly ash produced is already diminishing. It will be feasible in some locations were sodium silicate is available at competitive

cost and fly ash of acceptable quality is available. Further in many practical situations it will require thermal curing of the concrete, which limits the market to precast industry. Finally, mitigation potential is overestimated because the CO_2 from thermal curing was not included in the model.

Belite rich Portland cements have small or zero mitigation potential when compared with Portland cement with 10% of limestone filler and are not considered further.

MOMS theoretically provides the possibility of making concretes with a significantly negative carbon footprint, especially if carbonation hardening is used. However, reaching this goal will require the development of an energy-efficient industrial manufacturing process for MOMS. Magnesium silicate rock seems to be concentrated in some areas. This is a potentially promising approach in theory, but with current knowledge it is not possible to estimate its mitigation potential.

None of the new cement technologies are fully developed, but this is also the case for CCS and CCU. At this stage of knowledge, BYF and CCSC seem to be the most promising technologies from a CO_2 mitigation perspective. The mitigation potential from alkali activated materials (AAMs) is conditional on the availability in the world market of sodium silicate with much lower CO_2 footprint than that currently produced, and formulations with low amounts of sodium silicate, preferably with no need for thermal curing. AAMs produced with GBFS and FA will be more effective when they use materials that are not in demand for use in conventional Portland cement clinker blends.

It worth mentioning that the mitigation potential of this technologies may be enhanced by the partial replacement of the binder by engineered fillers and adequate dispersants.

Cement use industrialisation

The market share of bagged cement, a proxy for non-industrial, inefficient use of cement, in developing countries is between 50 and 90% (the latter value is for India), which demonstrates the mitigation potential of measures that promote industrialisation. For example, the potential for CO_2 reduction from the reduction of binder content from industrialisation of concrete can be estimated to be around 20–30%. The reduction of materials wastage rate due to industrialisation will add to this mitigation.

Moreover, industrialisation can facilitate an increase in the substitution rate of binder by filler and allow further mitigation by the increase of aggregates packing, reducing the demand for cement paste. These benefits have been proved effective for concrete, but can also be extended to mortar and other cement-based industrial products.

Aspects regarding more efficient design of structures, new concepts and digital production must be systematically explored and solutions developed and transferred to the various markets, which will require well-coordinated standardisation efforts.

The WWF-Lafarge report [14], estimates that increasing use efficiency can avoid 15% of cement consumption, which represents about 530Mt of CO_2 emissions on the low demand scenario, 96% of the CCS targeted. This will require investment in industrial facilities and measures to make industrial products competitive in the highly informal markets of developing world. Efficiency gains have much broader environmental and social effects than CO_2 mitigation and, therefore, must be pursued.

Final remarks

Our scenario shows that a combination of technologies have a potential to reduce CO_2 emissions beyond the current target for CCS, at a much lower cost and environmental risks.

Two clinker substitution technologies, calcined clay plus limestone and engineered filler combined with dispersant, make much higher levels of clinker substitution possible than previously expected. The sources of raw materials are almost unlimited and available virtually everywhere. The limits of adoption are related to minimum clinker imposed by the technical performance in different applications and environments. These technologies require modest adaptations in the existing production lines, are expected to have small or no effect on costs. They can be deployed rapidly because they require only modest capital investments on plants and allow the clinker fraction to be reduced progressively as R&D advances and the industry gains experience. Combined with cement use efficiency gains they may be able to meet mitigation targets allocated to CCS.

The potential of new cement technologies is encouraging. They are expected to cost more than current cement but much less than CCS. Clinkers with ye'elimite as the most reactive phase (BYF: Belite-Ye'elimite-Ferrite and Calcium Sulfoaluminate Cements) can be produced in conventional cement kilns but require aluminum rich minerals, sulphates and carbonates. CCSC uses widely available not so pure limestone and silica, processed in conventional cement kilns. They require curing in a CO_2, rich environment capturing back the process CO_2. Therefore, their market is limited to industrialised concrete plants, particularly for thin or porous sections, without steel reinforcement. MOMS is a promising approach in terms of CO_2 reduction but the technology is not yet developed.

Alkali activated materials produced with fly ash and blast furnace slag have low CO_2 footprint, but their mitigation potential is dubious since they will mostly divert slag and fly ash from Portland cement. AAMs produced with calcined clay are a scalable technology. However, they can only contribute to global CO_2 reduction if the CO_2 footprint of sodium silicate can be at least halved. Scaling up the use of geopolymers is also dependent on significant investments to increase sodium silicate production.

An increase of cement use efficiency can be achieved by promoting more industrial use of cement such as ready-mix concrete, dry-mix mortars and precast components. Industrialisation can accelerate the introduction of higher amount of fillers in replacement of binders. Use efficiency should work with both conventional or new cement technologies. New design and processing methods can also offer mitigation opportunities for both concrete structures and components.

Clinker-substitution based technologies seems to be more attractive for regions where the cement industry is expanding, because they allow mitigation meanwhile preserving investments. In regions in which existing kiln facilities are capable of supplying the future demand for cement, with an already highly industrialised market, new cement technologies that use existing conventional kilns as well as CCS may be more attractive.

It is possible to achieve the 2°C mitigation target without CCS, if the emerging technologies presented are further developed and adopted at industrial scale. Investment on R&D is therefore a priority.

15. Research Needs

This working group's primary objective has been to review technologies proposed for CO_2 reduction in the cement and concrete sector to identify promising areas where research efforts should be encouraged, and also where the investment of research funding is unlikely to be worthwhile for technologies with very low potential. This is important because many research journal submissions reveal that researchers are often repeating work and obtaining results that are already well known — this is a waste of money and human creativity.

A considerable amount of research will still be needed to meet the challenge of lowering CO_2 emissions in the sector. Regrettably, the sector's existing level of research funding is extremely low. For example, LafargeHolcim, the world's largest cement company, is believed to spend less than 0.2% of its turnover on true R&D — and this percentage is probably at the high end for the industry as a whole. Moreover, the actual proportion of industry research spending is always small relative to development part. The concrete and construction industries invest even less on anything that might be called R&D. Much University research is financed by national funding bodies, who often have little understanding of what is realistic in real-world applications. This encourages academic researchers to focus more on scientifically fashionable topics (e.g. "nanotechnology"). Although this work may result in more prestigious publications, it does not contribute in ways that might be of greater use to society as a whole — for example, developing and advancing the necessary methodologies for improving performance standards for cement-based materials.

It is imperative that better research links be built between academia and industry. A pioneering example in this area is the Nanocem Industrial-Academic partnership based in Europe (www.nanocem.org). Launched more than 12 years ago, it brings together the world's leading construction materials and construction chemical producers with the leading European academic research groups. Because the consortium is pre-competitive, it focuses on fundamental scientific questions underlying the behaviour of cement and concrete, which are important to facilitate downstream developments in the field. The network funds "core projects", which aim to fill gaps in existing research. The interaction between industrial and academic researchers has an impact which goes beyond these directly funded projects — enabling the academic groups to secure other funding sources for high quality research relevant to applications.

This report identifies the two key areas with the greatest potential for reducing the cement and concrete materials sector's CO_2 emissions over the next 2–3 decades:

1. Extending the use of supplementary cementitious materials (SCMs) in cement to further reduce clinker content, chiefly by developing technology for the combined addition of calcined clay and limestone.
2. Reducing concrete's clinker content by improving mix designs that allow for increased filler content, which can be added either via the cement or directly during concrete mixing.

In both of these cases the main research needs include:

1. Mastering the workability of fresh concrete through control of particle packing and the use of appropriate dispersants. The issues of robustness

relative to variations in cement composition and to concrete placing temperatures need to be resolved in a predictable way.

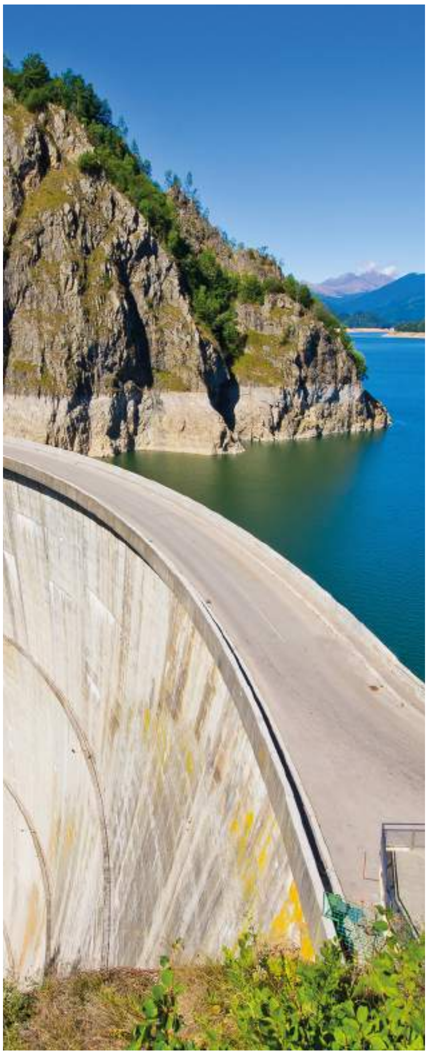
2. Developing cost-effective methods for producing the necessary particle size distributions for efficient multi-component binders.

3. Establishing performance-based approaches between the service life and the embodied CO_2 of the final products, allowing for specific applications and use-environments. This would entail developing or adapting service life prediction test methods for new systems that may differ from current conventions, as well as supporting research to extend those service lives if needed.

It will be necessary to develop generic approaches based on understanding the characteristics and interactions of raw materials, their hydration and microstructural development, which can be adapted to a wide variety of real raw materials without the need for extensive local empirical testing. This will necessitate the development, validation and use of improved and advanced modelling tools to expand information and design heuristics for broader usability, based on data generated for a subset of all possible material compositions and combinations.

New advanced models to design large structures and simple components are also of interest, particularly those associated to concepts such as topology optimization and functionally graded materials, which can be associated to digital production

Additionally, there is potentially still value in supporting some carefully targeted research on other binders that could have a significant longer-term impact:



BYF clinkers: While there is as yet no cost-effective alternative to Portland cement clinker in the current economic environment, the most feasible alternative class of hydraulic clinkers is belite-ye'elimite-ferrite (BYF) clinkers, which have already been shown to offer, on an industrial scale, substantial CO_2 reductions relative to Portland cement clinker, but which suffer from higher raw materials costs. Further R&D in this area directed at improving the performance/cost ratio seems justifiable on the grounds that BYF may allow us to progress further in terms of CO_2 reduction than Portland cement clinker-based approaches alone, and at a cost that remains well below that of CCS.

Technologies for alkali-activated binders that do not require the use of blast-furnace slags: Alkali-activated binders are compromised by the fact that most current practical technology depends on the supply of granulated blast-furnace slag, (GBFS), a low-CO_2 industrial by-product that is in limited supply and faces strong demand from other more conventional applications, especially as an SCM for use in PCC-based cements designed for special exposure applications. The use of alkali-activation to valorise certain under-utilised coal and agricultural ash resources, as well as non-ferrous slags and other industrial by-products, has in recent years become a prolific field of research, although generating little generically-transferable information to provide broader understanding of underlying factors. This raises opportunities for useful and high-impact research. New alkali-activated binder technologies that do not require GBFS-for instance materials obtained by efficient calcination of clays which would otherwise be of limited value due to low purity or high iron content-are valued for research and for commercialisation if they can be shown to have true industrial potential for replacing significant amounts of Portland cement clinker in concretes while retaining a lower net carbon footprint. The durability performance of AAMs in the field also requires significant further investigative research.

Clinkers made using globally abundant ultramafic rocks instead of limestone as the main raw material: In theory this approach has the advantage over all limestone-based technologies in that it could be truly carbon-negative. No feasible energy-efficient industrial manufacturing process has yet been invented, although some progress has been reported recently. To date, very little research has been done in this area, so we believe it merits further research effort to determine whether or not it is truly feasible, because the potential CO_2 payoff could be large. These clinkers would have an even greater impact if used in applications where they can be hardened by carbonation rather than by hydration.

Specific areas where we believe further fundamental research to be a poor investment with respect to environmental benefits include:

- Using Portland cement clinker or lime to stabilise rammed earth construction products. This emits more CO_2 and gives worse properties than conventional concretes.
- The use of self-compacting soil concretes, which have a high demand for expensive admixtures but add little value to more conventional soil-based construction technologies.
- Using 3D printing for general cement-based construction applications. It is a useful technique for highly specialised applications, but seems unlikely to have much value in reducing global CO_2 emissions.

16. Education and Sustainable Construction

Civil engineering and architecture curricula were defined in simpler times, when concrete was made from simple "pure" Portland cement, aggregates and water. Most civil engineers would spend their working time doing structural design and complex calculations without the aid of computers. Design requirements were primarily concerned with structural safety. The number of materials and components incorporated in a building or a bridge were limited. Teaching materials is often just a question of explaining a few standards. The education of civil engineers continues to focus on developing the skills needed for structural design.

In the last 30–40 years the engineering process has changed dramatically. Nowadays, structural design is handled with sophisticated computer models. Productivity in the field is much higher and a smaller proportion of engineers are involved in this very specialised field. Minimising environmental impact over the construction life cycle is now an implicit part of the process. New materials and industrialised components are coming to the market at a rapid speed. Variability will increase faster because minimal environmental impact will require locally optimised solutions. Construction requirements have become much more complex, specifying very abstract performance requirements reaching as far out as the end of service life. Ethics, social equity, and users' wellbeing are now part of doing business day-to-day. Current training curricula are not sufficient to equip industry professionals to navigate the unknown future, delivering the high-quality eco-efficient built environment that society demands. Educating civil engineers and architects has to envision a better common future for humanity. This issue is discussed in detail in the white paper of Schmidt et al.

The materials dimension of construction is now much more important, because construction uses more than 50% of the materials extracted from nature. Cement based materials alone account for more than one third of raw materials and 5–10% of the anthropogenic CO_2. Scientific understanding — of materials in general and cement-based materials in particular — has advanced significantly, encompassing solutions to simultaneously improve the built environment while reducing construction's environmental impact. This knowledge is not yet reflected in education curricula.

Deploying the technologies described in this report will require professionals capable of understanding not only the environmental aspects faced, but also the fundamentals of the material problem. The education of civil engineers and architects regarding building and cementitious materials needs to change.

Instead of focusing on teaching standard solutions for standard problems, university curricula need to teach materials fundamentals to prepare future professionals to face future problems and create corresponding solutions. This shift will require a change of in the technical background of university professors and easier access to better educational materials.

In short, most construction occurring in the near future will be the responsibility of professionals that have been educated to solve problems of the past. Current professionals will be in charge of developing new technologies and updating today's construction standards, which may facilitate the introduction of new, more eco-efficient technologies. A robust continuing education program must be designed targeting practitioners in the field. The engagement of professional associations and cement industries of different countries is essential. Governments in particular could facilitate the transition to more eco-efficient construction technologies by simply educating their staff in more advanced concepts, which in turn would enable public procurement to accelerate the advances.

In developing countries, a significant part of the construction activity and the cement use is still accomplished by untrained personnel, most of whom are self-help builders. Basic training on housing essentials and how to handle construction materials and cement-based materials in particular could have tremendous potential not only for CO_2 mitigation, but also for improving their wellbeing and the quality of cities. This topic has so far been neglected by the international community, including building materials producers. This has to consider local problems and solutions; but a core set of fundamentals could be developed internationally, with new ways of getting this to the right people. In coming decades, increased cement production is projected to occur primarily in developing regions of the world. This is an opportunity to directly apply best practices and increase eco-efficiency. Swift action is required to take advantage of this chance to enhance user education and awareness that would result in more sustainable building.

The potential of digital technology — including ubiquitous mobile phones, virtual video channels, e-books and the new MOOCs — offer new opportunities for a global education platform.

The engagement of governments, NGOs, materials producers and the stakeholders in an international effort for better education in construction must be a priority.

17. Main Conclusions

There are two key areas that can deliver substantial additional reductions in global CO_2 emissions related to cement and concrete, minimising the need for costly investment in CCS over the next 20–30 years:

1. Increased use of low-CO_2 supplements (supplementary cementitious materials or SCMs) as partial replacements for Portland cement clinker.
2. More efficient use of Portland cement clinker in mortars and concretes.

We believe that Portland cement clinker based cements will dominate in the near future due to the economy of scale, level of process optimisation, availability of raw materials and market confidence in these products. In the longer term, other emerging alternative technologies could also play a role in emissions mitigation that consequently merit further investigation.

Increased use of clinker substitutes (SCMs) in Portland cement clinker based cements

Today's cements contain on average only around 20% of SCMs substituting Portland cement clinker — mainly fine limestone, granulated blast-furnace slags (GBFS) and coal fly ashes (FA). GBFS and FA sources of adequate quality are limited globally to only about 15–25% of cement consumption and are unlikely to increase. A recently developed alternative low-CO_2 SCM system uses optimised combinations of calcined clays with ground limestone. Such combinations represent a relatively inexpensive and widely available SCM source capable of replacing up to 50% of clinker while maintaining similar performance to existing cements. Additionally, a significantly-increased filler content above today's average of 6% is technically feasible by combining particle size control and dispersant admixtures, resulting in cements with low water demand. In some applications, filler contents as high as 50% in the cement can offer satisfactory performance. Increasing the average level of clinker substitution in cement to reach 40%, for instance, through the use of the above-mentioned alternatives could avoid up to 400 million tonnes of CO_2 emissions annually, which could make the need for CCS less obvious.

More efficient use of clinker in concrete and mortar

In concretes and mortars a similar magnitude of CO_2 emissions reductions of are possible:

- Optimising mix design can improve the eco-efficiency, defined in terms of CO_2 per MPa compressive strength, by a factor of 4 when comparing best practice with worst. Careful optimisation of particle packing, throughout both the coarse and fine fraction of the cementitious materials, coupled with the use of dispersants and the use of fillers can further reduce clinker contents while maintaining product performance.
- Using high strength concrete grades, where appropriate in structural applications is more efficient and can reduce overall materials consumption.
- Industrialising concrete and mortar production (i.e. ready-mix, dry-mortars) compared to poorly controlled on-site mixing, furthers substantial savings by avoiding wastage, particularly in urban areas.

New cement technologies could contribute significantly in the longer term

Non-Portland clinkers may offer promising options for the longer term, but there is as yet no cost-effective alternative to Portland cement clinker in the current economic environment. The most feasible alternative class of hydraulic clinkers is belite-ye'elimite-ferrite (BYF) clinkers, which present substantial CO_2 reductions relative to Portland cement clinker. Though this approach has higher raw materials costs than SCM and filler approaches it is still significantly less than CCS. Further R&D in this area is needed to improve the performance to cost ratio.

Among non-clinker based cements, alkali-activated binder technologies (AAM) also have the capacity to reduce global CO_2 emissions beyond what is possible with optimized use of SCMs and fillers. However, many current AAM technologies require the use of GBFS to give acceptable performance, and in many locations it is simpler to use the limited (global) supplies of GBFS as conventional SCMs. The use of alkali metal silicates as activators is also both capital- and energy-intensive, if these are produced through conventional process routes. We therefore believe that the AAM approach requires further R&D if it is to have any chance of success in global CO_2 mitigation.

Newly developed clinker technologies, in which concrete products are produced by carbonation rather than hydration, can reduce net CO_2 emissions up to 70% compared to Portland cement clinker, and are already commercially available in some locations. Unfortunately, they suffer from severe commercial limitations because they require developing a circular economy for captured CO_2, and also because they are limited to factory-made products. We therefore believe that they are unlikely to have a major global CO_2 impact as a direct alternative to Portland cement, as the facility to cast cementitious materials on-site is key to their ubiquitous use in construction.

Finally, we think that there is still some chance for a breakthrough in the area of clinkers made using globally abundant ultramafic rocks instead of limestone as the main raw material. In theory, this approach has the advantage over all limestone-based technologies in that it could be truly carbon-negative; but no feasible energy-efficient industrial manufacturing process has yet been invented, although recently some progress has been made. We consider that this area merits further research in view of its significant potential for CO_2 reduction.

Requirement for research, coordination and raising awareness

More efficient global use of all possible approaches to low-CO_2 cementitious materials, will need, amongst other things, flexible and robust performance-based standards for cement and concrete. Developing such standards will require a well-coordinated international research effort, as well as strong coordination between the industry, standard making bodies, regulators and society at large to raise awareness and create market acceptance for eco-efficient solutions.

Governmental engagement

Governmental engagement will be important to the development and implementation of a successful mitigation strategy in the cement industry. The cement value chain makes up a large proportion of all economies, including a range of stakeholders from large companies to individuals. Raising awareness in such a complex environment will require commitment from governments.

Governments also have influence on educational policies, both in undergraduate and graduate civil engineering and architecture courses, which will have to be reconfigured in ways to make it possible for the construction industry, including cement-based materials industries, to cope with the demands of sustainable development.

Research, development and innovation are strongly influenced by governments, not only through funding to academic basic research, but also by promoting alliances between academy and industry and stimulating innovation at the industrial level. Governments are also frequently in a position to influence standardization processes

Promoting the industrialization of the cement supply chain most certainly depends on actions of governments. In developing countries this will require actions to reduce the economic advantage associated with the use of aggregates from the informal market, which favours the inefficient use of cement, increasing CO2 footprint. Other options include actions to limit the use of bagged cement, as already done by China.

Finally, the mitigation potential of each technology will depend on its success in the market. Governments are among the largest consumers of cement based materials, especially when investing in infrastructure. Therefore, the use of public purchase power can be decisive in accelerating market penetration of these mitigation technologies.

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20. Glossary

AAM	alkali activated material
BAT	best available technology
BAU	business as usual
BYF	belite ye'elimite ferrite
CCS	carbon capture and storage
CCSC	carbonatable calcium silicate clinker
CCU	carbon capture and usage
CSA	calcium sulfo aluminate
CSI	Cement Sustainability Initiative (of the WBCSD)
FA	fly ash
GBFS	granulated blastfurnace slag
GNR	getting the numbers right (database of CSI)
IEA	International Energy Agency
IPCC	International Panel on Climate Change
MOMS	magnesium oxides derived from magnesium silicates
OECD	Organisation for Economic Co-operation and Development
OPC	ordinary Portland cement
PC	Portland cement
R&D	Research and Development
SCM	supplementary cementitious material
UNEP–SBCI	United Nations Environment Programme—Sustainable Buildings and Construction Initiative
WBCSD	World Business Council for Sustainable Development

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