Tools for Reducing Carbon Emissions Due to Cement Consumption

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Several recent books have concluded that global warming is a very serious environmental issue [1, 2, 3, 4, 5]. A number of reports published in 2007 by the United Nations Intergovernmental Panel on Climate Change (IPCC) have also drawn public attention to global warming. The IPCC contends that global warming, attributable to the build-up of greenhouse gases from human-made sources, is occurring at an unacceptable rate. Further, the IPCC warns that catastrophic changes to the environment may result unless immediate steps are taken to reduce the atmospheric concentration of carbon dioxide (CO_2) and other greenhouse gases.

It is well known that carbon dioxide makes up approximately 77% of anthropogenic greenhouse gases. The current atmospheric concentration of CO_2 is about 385 ppm (parts per million), and it is rising annually at the rate of two to three ppm. Well-known NASA scientists, James Hansen and his colleagues, recently published *Target Atmospheric CO_2: Where Should Humanity Aim?* where they concluded that "paleoclimate evidence and ongoing global changes imply that today's CO_2, about 385 ppm, is already too high to maintain the climate to which humanity, wildlife, and the rest of the biosphere are adapted". They strongly suggest that the preservation of civilization, as it has developed, requires that CO_2 be reduced to at most 350 ppm [6]. Others warn against crossing the threshold of irreversible climate change predicted to occur at around 450 ppm. According to the IPCC 4th Assessment Report [7], the worst effects of global warming may be avoided if annual CO_2 emissions are reduced to the 1990 level within 20 years. To achieve such a drastic cut in carbon emissions worldwide, all major emitters, such as power plants, oil refineries, transportation industry sources and manufacturers of industrial materials and consumer products, are contemplating what actions to take by the year 2010.

Concrete has become a popular construction material worldwide. With annual consumption approaching 20,000 million metric tonnes (mmt), concrete is the most voluminous manufactured product in the world, (note: 1 metric tonne equals 1.102 U.S. tons). The carbon emissions associated with concrete use are mostly attributable to cement production. Globally, the concrete industry consumed nearly 2,300 mmt of cement in 2005. According to a comprehensive report by Mehta and Walters [8], on average, modern cements contain 84% portland clinker; the manufacturing process releases 0.9 tonnes of CO_2 per tonne of clinker. Thus, direct CO_2 emissions from clinker producing kilns are 1,740 mmt/year (2,300x0.84x0.9). Due to the rise in cement consumption between the years 1990 and 2005, the carbon footprint of the cement industry has almost doubled.

The last several decades have seen an unusually high demand for cement and concrete. Fifty years ago, the world's concrete consumption was 1 tonne per capita; today, it is 3 tonnes per capita. Global growth in concrete consumption is due in part to the rapid industrialization of developing countries such as China and India; in the developed world, demand is driven by the need to replace, repair and retrofit existing structures. If the current rate of cement consumption is not reduced, the significance of cement as a contributor to global warming will increase. Achieving major cuts in the world's cement consumption and, at the same time, meeting the future concrete requirements of both developing and developed countries is a formidable challenge. All stakeholders in the concrete construction industry – designers, builders, cement and concrete producers – must join hands to confront and reduce the carbon emissions attributable to cement consumption. *Figure 1* shows a new low-carbon approach for the retrofit of a major historic structure that utilizes high volume fly ash concrete.

The movement to construct sustainable buildings is already underway. For example, the LEED (Leadership in Energy and Environmental Design) rating system developed by the U.S. Green Building Council has become a useful tool for the conservation of energy and water in new buildings [9]. A similar rating system could be adopted for the specific purpose of cutting the CO_2 emissions attributable to materials used for new projects. As an interim solution, LEED recognizes the value of reducing the cement content of concrete: an "Innovation in Design" credit is awarded to projects that demonstrate a "minimum 40% reduction in CO_2 by weight for all cast-in-place concrete" as compared with standard baseline mixes [10] .

Minimizing the consumption of concrete through innovative architecture and structural design is one way to save

Utah State Capitol – Seismic Retrofit:

- 4,500 m^3 (5,886 yd^3) of high volume fly ash concrete
- 0.44 clinker factor
- 900 tonne CO_2 reduction
- 34 MPa (4,931 psi) 28-day field strength
- w/cm = 0.38

Figure 1: Utah State Capitol Building, seismic retrofit 2006 using high volume fly ash concrete for foundations, beams and shear walls, courtesy Mason Walters & Forell/Elsesser Engineers, Inc.

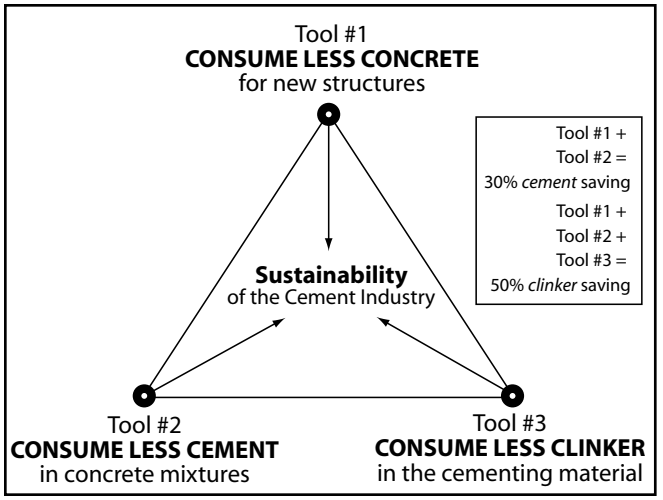

Figure 2: Tools for reducing the cement industry's carbon emissions to the 1990 level in next 20 years.

cement. Another is to reduce the cement content of concrete mixtures as described below. Furthermore, because the cement industry's CO_2 emissions come mostly from the clinker manufacturing process, considerable savings in clinker can be realized from the production and use of blended cements. These blends should contain much larger proportions of *complementary cementing materials* – such as the carbon neutral waste-products fly ash and slag – than are typically used today. The composition, properties, and field applications of concrete made with blended portland cements containing 50% or more coal fly ash (by mass) are reported in several publications [8, 11, 12]. Experience with field structures shows that, compared to conventional concrete, high-volume fly ash concretes are somewhat slower in the development of strength up to 28 days but much higher in ultimate strength. However, as explained later, they are far more durable because they are less vulnerable to cracking.

In this article, practical tools to reduce the cement industry's carbon emissions are brought to the attention of structural engineers. A roadmap presents how the application of these tools would enhance the sustainability of the global cement industry by reducing its carbon footprint by half in the next twenty years.

Structural Engineers' Tools For Reducing CO_2 Emissions

Imagine a triangle with a sustainable cement industry at the center. The three corners of the triangle represent the three tools of sustainability. To reach the center, we will have to proceed inward from each of the three corners (*Figure 2*). Now, let us examine how the simultaneous use of the three tools can result in major reductions in cement consumption and carbon emissions:

Tool 1. Consume Less Concrete for New Structures:

- **Develop innovative architectural concepts and structural designs to minimize consumption of concrete.** Experience shows that early involvement and collaboration of the structural engineer with the architect can result in reducing the project footprint and the volume of construction materials needed. For example, in 2005, the replacement of the old de Young Museum complex in San Francisco, California, reduced the building footprint by 37% while doubling the exhibition space [13].
- **Use highly durable concrete mixtures for foundations and other massive members of buildings and infrastructure elements such as bridge decks and piers, tunnels, and pavements.** Studies of the microstructure and properties of concrete show that using blended portland cements containing a high volume of complementary cementing materials can radically enhance a structure's service life. Using these materials would reduce concrete consumption in the future by extending the life of the original structure. Therefore, this is an important strategy for making the concrete construction industry more sustainable in the long term.
- **For pre-fabricated buildings, use pre-cast columns and beams specially detailed for easy assembly, disassembly, and reassembly.**

Tool 2. Consume Less Cement for Making Concrete Mixtures

- **Instead of specifying a 28-day strength requirement, for many applications specifying a 56-day strength for structural elements can result in significant cement savings.** A large volume of concrete is consumed by structural elements that are seldom subjected to significant loads in the first 2 to 3 months after installation (e.g., foundations, piers, columns, beams, and shear walls). Note that, unlike conventional portland cement concrete mixtures, the high-volume fly ash concrete mixtures gain 50% to 80% of their ultimate strength between 28 days and one year. *Figure 3* shows a new construction project that tailors high-volume fly ash mix designs and strength gain criteria for distinct building

CITRIS Building:

- 7,133 m^3 (9,330 yd^3) of high volume fly ash concrete
- 0.5 clinker factor
- Foundations and mats: 27 MPa (3,916 psi) specified for 56-day strength
- Columns, shear walls: 27 MPa (3,916 psi) specified for 28-day strength, field tests for strength at 7 and 56 days showed 20 and 40 MPa (2,900 and 5800 psi).
- 1,300 tonne CO_2 reduction
- w/cm range: 0.37 – 0.35

Figure 3: The CITRIS Building, new construction using high volume fly ash at the University of California at Berkeley, photos 2007 and 2008 (inset).

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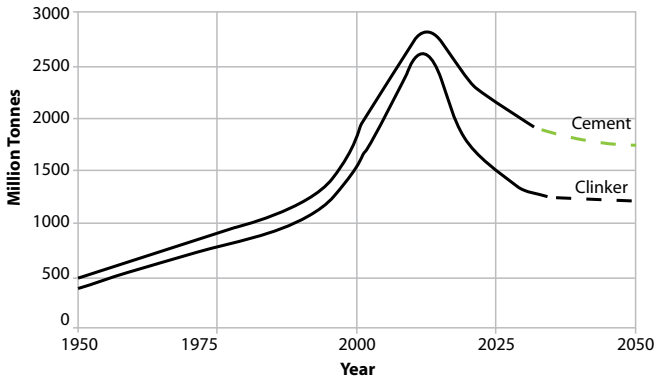

Figure 4: Historic and Projected, Annual Cement and Clinker Consumption Rates

elements. Today's building codes use the 28-day strength as the basis for design; however, more and more jurisdictions are reflecting environmental criteria in their building codes. Many states and cities now require LEED certification for all public buildings. As such, codes are being revised to accommodate these new criteria, and structural provisions are no exception. In the authors' experience on various projects, specifying 56-day strength was not a code problem. Using 56-day strength can mean the difference between 15% and 50% fly ash in the mix; therefore, the extra cement savings are indeed significant.

- **Use plasticizing chemical admixtures instead of more mixing water and cement to obtain the required consistency of fresh concrete.** A 20-25% water reduction in concrete mixtures by using superplasticizers would enable a similar reduction in cement content, without decreasing strength and durability.
- **Optimize the size and grading of aggregates to reduce the total volume of cement paste in concrete mixtures**. For example, use the largest maximum coarse aggregate size that can satisfy the project requirements.

Tool 3. Consume Less Clinker in the Cementing Material

- **Select blended portland cements and concrete mixtures that contain a high volume of one or more complementary cementing materials, such as coal fly ash, granulated blast-furnace slag, natural or calcined pozzolans, silica fume, and reactive rice-husk ash.** The microstructure and properties of concrete containing 50-60% fly ash by mass of the total cementing material are significantly different from ordinary portland cement concrete [11]. Typically, high-volume fly ash concrete shows high ultimate strength, low thermal and drying shrinkages, and high resistance to corrosion of reinforcing steel due to very low electrical conductivity. Therefore, this type of concrete is much less susceptible to cracking, which results in greatly enhanced durability. Concrete structures built with high volumes of complimentary cementing materials in the concrete should enjoy a long service life. Extending the service life of structures is an important sustainable design strategy.

A Roadmap for Reducing the Cement Industry's Impact on Climate

Climate change due to the increasing concentration of CO_2 in the atmosphere is a global phenomenon. Resolving this problem depends on the collective efforts of all sectors of the economy in every country. Carbon emissions attributable to the cement industry are very significant; worldwide the CO_2 emissions from cement manufacturing are about 2,000 mmt per year, which is 6-7% of the total global emissions from all anthropogenic sources. Presented here is a roadmap which, when pursued vigorously between 2010 to 2030, would cut the global cement industry's carbon emissions in half. For the reference year 2010 and the target year 2030, the projected rates of cement requirement, clinker requirement, and CO_2 emission attributable to clinker production are shown in *Table 1*. According to their resources and goals, each country can develop similar roadmaps for implementation. The data in *Table 1* are based on the following assumptions:

- Used together, Tools 1 and 2 would enable a 30% reduction of cement consumption. Consequently, the cement requirement is reduced from 2,800 mmt in 2010 to 1,960 mmt a year in 2030.
- The diligent use of complementary cementing materials (Tool 3) would enable a reduction in the average clinker factor (tonnes of clinker per tonne of cement) from 0.84 to 0.60. Building on the reduction above, the annual clinker requirement is further reduced from 2,300 mmt in the year 2010 to 1,180 mmt in 2030.
- The use of crop residues and industrial waste-products as alternative fuels for clinker production is expected to increase from 10% to 20%. Accordingly, the carbon emissions factor of cement kilns (tonnes of CO_2 emitted per tonne of clinker) would decrease from 0.9 to 0.8. Taking all of these reductions together, the global CO_2 emission rate is reduced from 2,070 mmt per year to the 1990 emission rate of 940 mmt per year.

The historic and projected annual cement and clinker consumption rates for the 100-year period, 1950-2050, are plotted in *Figure 4*. This illustrates how the implementation of the roadmap would influence future cement and clinker consumption rates, bringing the global concrete construction industry closer to the goal of sustainable development.

Do we have the resources and the technology to implement the roadmap proposed here immediately? Yes, we do. Large amounts of industrial by-products suitable for use as complementary cementing materials are available in most parts of the world. According to Malhotra [14], the annual global production of coal fly ash was estimated at 750 mmt a year in 2005; currently it is about 1,000 mmt, and by 2020, it is expected to be much higher. Several North American projects [8, 11, 12] have achieved significant cement savings and corresponding reductions in carbon emissions by using 50% to 65% fly ash as a cement replacement material in concrete. Similarly, for decades, portland-slag cements containing over 50% ground granulated-blast-furnace slag have been successfully used in Europe. Ternary and quaternary cement blends use three or four binder components respectively;

Table 1: Projected Rates of Cement and Clinker Consumption, and CO_2 Emission for 2010 and 2030.

Year	2010	2030
Cement requirement (mmt)	2,800	1,960
Clinker factor*	0.83	0.60
Clinker requirement (mmt)	2,300	1,180
CO_2 emission factor**	0.9	0.8
Total CO_2 emission (mmt)	2,070	940

*tonnes of clinker per tonne of cement
**tonnes of CO_2 per tonne of clinker

these types of mixes with high volumes of fly ash and/or slag, as well as small amounts of limestone or silica fume, have been successfully used in field structures.

It is clear that proven technology is already available to lower the portland-clinker factor of cements from 0.84 to 0.60 or less. Furthermore, rapid global adoption of this technology is possible because no major modifications to existing cement plants and ready-mix concrete facilities are required.

Concluding Remarks

Many years have been spent debating whether the primary cause of global warming is the exponential rise in the concentration of carbon dioxide in the atmosphere. The discussion now is how, without further delay, to mobilize society for decisive actions on slowing down and, eventually, halting the world's march toward potentially devastating and irreversible climate change. Scientists have warned that, by 2030, we must bring the atmospheric concentration of CO_2 to the 1990 level or less. This means that we have only 20 years left to accomplish this mission. We no longer have the luxury to postpone action; we cannot wait for technological solutions, such as energy supplied entirely from renewable sources and the capture and underground storage of CO_2. As global citizens and engineers, individually and collectively we have the social and professional responsibility to join the battle against anthropogenic global warming.

Concrete is a material of choice today for buildings and infrastructure throughout the world. It is a formidable task to meet the rising demand for concrete and, at the same time, reduce by half the CO_2 emissions from portland clinker production. However, the goal is achievable if we follow a roadmap and use tools like those described in this article. We have both the technology and the resources to undertake this journey. The concrete community, and especially engineers who design structures and specify the materials, are in a privileged position to lead the concrete construction industry away from unrestricted growth and toward reducing carbon emissions to levels that can support sustainable development. ▪

Global warming is a controversial issue among structural engineers and the public at large. The opinions expressed in this article are those of the authors, and do not necessarily reflect the views of NCSEA, CASE, SEI, C³ Ink, or the STRUCTURE® magazine Editorial Board. Thoughtful feedback from readers is always welcome and encouraged.

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