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Sustainable Cements and Concrete for the Climate Change Era – A Review

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ABSTRACT

This paper includes a brief introduction to the ***sustainability*** crisis from climate change that has emerged as the most serious and immediate threat to life and environment on the earth. Latest data confirm that heat-trapping gases, primarily CO_2, is the major cause of the problem that must be controlled by drastic cuts in the carbon-emitting sectors of the industrialized and urbanized world. The global cement industry is also responsible for large carbon emissions attributable to portland clinker production.

At the same, with middle class population soaring in rapidly developing countries, global cement and concrete industry projects high growth rates. Earlier publications generally failed to reconcile these two contradictory demands on the concrete construction industry. This state-of-the-art review, therefore, is based on a few selected and most recent publications including latest reports by World Business Council for Sustainable Development, and Gigaton Throwdown Initiative. Brief reviews are presented of High-Volume Fly Ash Concrete Technology – a proven, low-cost, technology for reducing cement and clinker consumption, and a holistic roadmap based on this technology for developing sustainable concrete industry.

INTRODUCTION TO SUSTAINABILITY

Major forces that were responsible for economic and social transformations in society during the previous century and are continuing to shape the 21st century world are:

- Population growth
- Industrialization and urbanization
- Globalization of market economy and consumerism
- Environmental pollution

Like the consecutive links of a chain, the forces listed above are interconnected. Their combined impact has triggered another force now, namely ***climate change***, which is threatening to cause serious damage to human civilization on the earth. Global warming, unquestionably, is the most important sustainability issue today in the public mind. There is general agreement among the weather scientists that the current global warming trend began three or four decades ago. Since 1990, already in many parts of the world severe-weather events attributable to global warming have been experienced, e.g., rapid melting of glaciers and ice sheets, devastating cyclones and hurricanes, heavy rainstorms and floods, and unprecedented heat waves and droughts. Available statistics show that these severe-weather disasters have caused enormous damage to life and environment.

According to Intergovernmental Panel on Climate Change (IPCC), human activities on the planet are the primary source of large volumes of heat-trapping, ***greenhouse***, gases responsible for global warming; and that global warming is occurring now at a rate that would be catastrophic if immediate steps are not taken to cut these gases to a safe level, as discussed below. Approximately 80% of the atmospheric greenhouse gas is made up of CO_2. From a plot of the earth's average surface temperature and the atmospheric CO_2 concentration for the 1880 to 2009 period, Karl et. al. have confirmed a direct correlation between carbon dioxide concentration and global warming (Fig. 1).

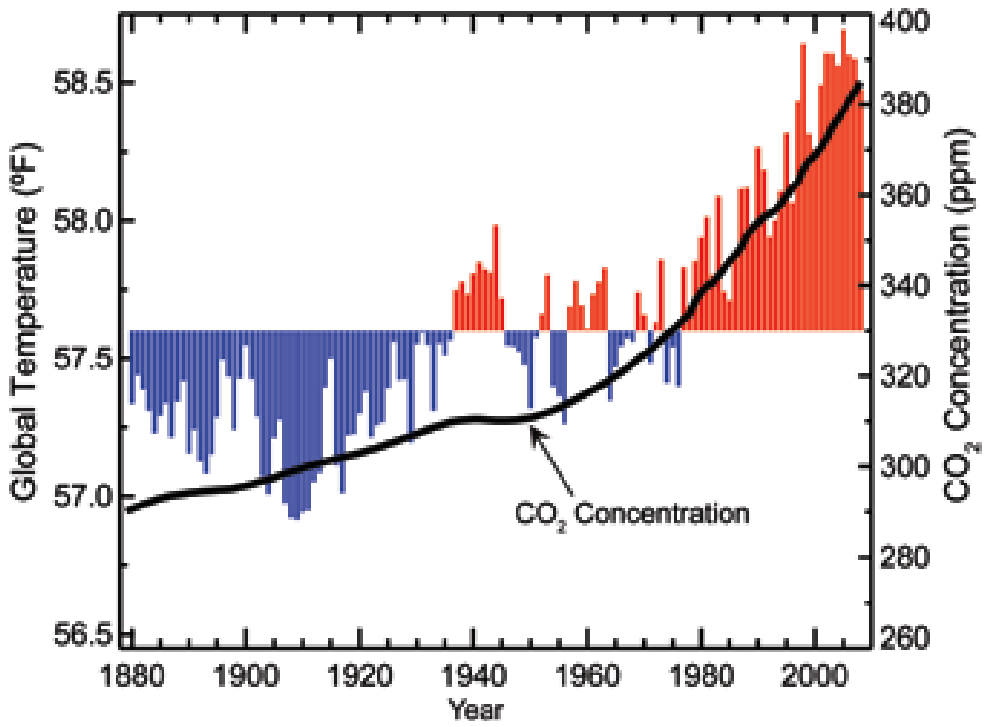

Figure. 1 CO_2 Concentration and Global Temperature
(Source: Karl, T.R. et. al., June 2009 www.globalchange.gov/usimpacts)

The IPCC data on historical and projected atmospheric concentration of CO_2 for the period 800–1200 in Fig. 2. shows that before the industrial revolution the CO_2 concentration remained nearly constant at about 280 ppm (parts per million). However, by 1950 it rose to about 315 ppm, and thereafter began a sharp climb in response to escalating rates of fossil fuels consumption to meet the energy and resource needs of the rapidly growing economies of the world. The atmospheric CO_2 concentration today is 385 ppm, and is rising at an approximate rate of 2 ppm every year. According to IPCC if necessary actions are not taken to cut back the carbon emissions, in about 30 years from now the CO_2 concentration will reach 450 ppm – the danger point above which the ***irreversible*** climate change will occur. Since it is assumed that the era of climate change began in 1990, IPCC recommends that atmospheric CO_2 concentration must be reduced to the 1990 level or less in the next 20-30 years and, therefore, major CO_2-emitting industries must take decisive measures for achieving drastic cuts in CO_2 emissions within this period.

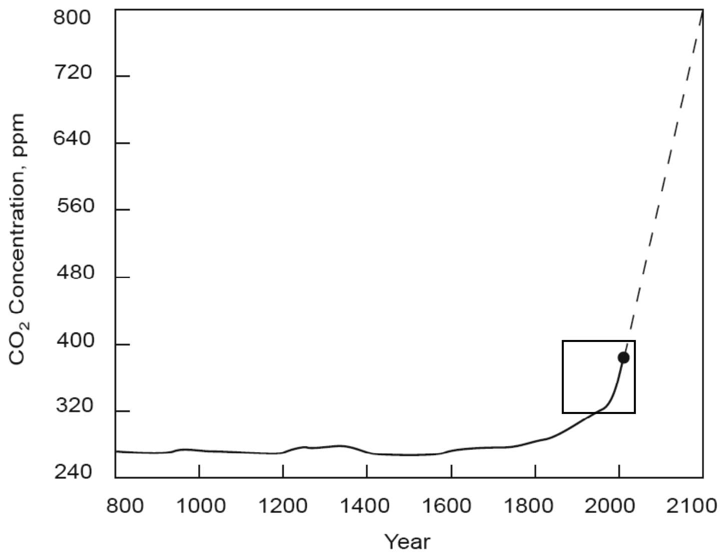

Figure. 2 Historical and Projected Atmospheric CO_2, ppm
(Source: IPCC, Cambridge University Press, 2007)

INDUSTRIAL SOURCES OF CARBON EMISSIONS

As a result of globalization of the American model of market economy, during the last 20-30 years, countries with large populations, such as China and India have achieved fast economic growth by rapid industrialization without paying attention to the environmental impact of huge volumes of solid, liquid, and gaseous waste products including CO_2 gas. Major industrial sources of CO_2 emissions in the world are power generation plants, transportation sector, oil refineries, and steel and cement manufacturing industries.

The rapidly developing economies have been successful in moving a large number of the poor to middle class in a short span of time. This has caused a growth of the population sector which is a large consumer of energy and resources. Friedman reported that, in the last 30 years, 300 million people in China have escaped rural poverty and joined the urban middle class. As a result, the scale and scope of urbanization in China is mind-boggling. More than 40% of the 1.3 billion Chinese now live in towns and large cities, and by 2020 the urban population is expected to swell to 60% – adding hundreds of satellite cities and a sky-rocketing demand for energy and energy-intensive structural materials (e.g., cement and steel) for the construction of new buildings, factories, roads, and highways. China today accounts for 50% of the world's cement production (approx. 2800 MT/year), and 40% of the world's steel production (approx. 1300 MT/year).

Friedman has also pointed out that buildings in the developed countries consume almost 40% of the national energy and, therefore, are the largest consumer of energy. More over, approximately 80% of the electric power in China is generated by burning coal, and the country is poised to add the equivalent of two 500 MW coal-fired plants every week for the next 20 years. Four years ago, China surpassed the U.S. as the largest CO_2 emitter in the world and, today, the carbon footprint of the country is considerably larger than the U.S.

CEMENT AND CONCRETE INDUSTRY SUSTAINABILITY

It is well known that among the primary materials for making concrete, CO_2 emissions are attributable to portland clinker production from cement kilns. According to rough estimates, on the worldwide average, cements today contain approx. 5% gypsum, 12% complementary cementing materials (pozzolans, blast-furnace slag, and limestone), and 83% portland clinker. Due to increasing replacement of clinker by complementary cementing materials, the clinker factor (clinker/cement) of cement is gradually decreasing. Also, on the average, CO_2 emissions from the clinker manufacturing process amount to 0.53 kg/kg clinker from raw materials decomposition, and 0.37 kg/kg clinker from fuel combustion, i.e. a total of 0.9 T CO_2/T clinker. According to Cembureau 2007 statistics, global concrete industry is consuming cement at the rate of 2770 MT/year. Therefore, as shown below, the carbon footprint of the global cement and concrete industry is significant.

With soaring middle class population in rapidly developing countries, industry projections show continued growth in the global cement and concrete consumption in the foreseeable future. However, in the era of climate change, drastic reduction in the production and use of carbon-intensive materials is also urgently needed. Apparently, these two contradictory demands of society cannot be easily reconciled, but they have to be addressed without delay. Based on a few selected and most recent publications on a wide variety of pathways available for achieving cement and concrete sustainability, a brief state-of-the-art report is presented next.

WORLD BUSINESS COUNCIL FOR SUSTAINABLE DEVELOPMENT

Damtoft and Herfort of Aalberg Portland Group, Denmark, and three researchers from Lafarge Cement, France, co-authored a comprehensive paper based on Cement Sustainability Initiative reports sponsored by WBCSD. The reports are endorsed by a consortium of 16 cement companies of the world. The authors concluded that the global cement industry is contributing positively to the climate change problem by exploiting the thermal mass of conventional concrete to save energy for heating and cooling residential and office buildings, CO_2 reduction from increased use of biofuels in cement kilns, clinker replacement in cement by optimum use of supplementary (or complementary) cementitious materials, and exploiting the potential of concrete demolition waste to absorb CO_2. The four distinct carbon-reduction levers that are available to the cement industry are:

1. Thermal and Electrical efficiency of cement plants.
2. Alternative fuel use for making clinker.
3. Clinker substitution by supplementary or complementary cementing materials.
4. Carbon capture and storage (CCS).

All of these four technologies need to be applied to achieve desirable targets of CO_2 reduction. The cement industry has been able to reduce thermal energy from 3605 to 3382 MJ/T clinker during the 16-year period, from 1990 to 2006 (approx. 6%). To meet the construction industry demands for high-early strength fine-ground cements and environmental regulations for dust emission limits, electric energy requirement has increased with a corresponding reduction in electrical efficiency. Electric energy efficiency is also reduced when slags and fly ash are interground with clinker to reduce the carbon emissions associated with clinker production.

Further, according to the report, fuel-related carbon emissions are about 40% of the total CO_2 emissions and, therefore, the use of mixed-fuels instead of coal can be 20-25% less carbon-intensive. In European cement plants, alternative fuels contribute nearly 20% of the energy (15% from recycled fossil fuels and 5% from biomass). In Australia, Japan, North and South American countries, on the average, 10-11% thermal energy contribution comes from the use of alternative fuels. However, in the opinion of this author, most of the global cement and clinker production comes from China and India, where fossil fuel substitution by alternative fuel use in 2006 was only 4%. Therefore, the overall global impact on carbon emissions from the use of alternative fuels technology would be limited.

According to the IEA-WBCSD report, in regard to clinker substitution by complementary cementing materials (such as coal fly ash, granulated blast-furnace slag, ground limestone, and natural pozzolans) except limestone, the use of CCM in EU countries will remain limited due to lack of local availability and high prices. This author, however, believes that the impact of clinker-replacement technology on global carbon emissions attributable to cement and concrete industry of the world will be high because huge quantities of CCM are available in the world's largest cement-producing countries, namely China, India, U.S.A, and Japan. In the case of CCS technology, according to the IEA-WBCSD report, this is a new technology, which has not yet been proven at industrial scale in cement plants. Feasibility of this technology can be evaluated only when the full chain of field experience, including infrastructure for CO_2 transport and storage, and access to storage sites becomes available.

GIGATON THROWDOWN INITIATIVE

Gigaton Throwdown Initiative is a consortium of corporations and several universities in North America. A recently published report by the Gigaton Throwdown Initiative includes data on energy, carbon emissions, and climate change solutions associated with construction materials. According to this report, multiple gigaton-scale pathways exist in the construction materials sector for reduction of carbon emissions associated with the production of materials. In the case of concrete industry, the production of portland clinker in concrete kilns is recognized as the root cause of high CO_2 emissions associated with this industry, and production of low-carbon cements is cited as the biggest single opportunity for CO_2 reduction. The report contains a questionable conclusion:

> The cement industry is responsible for an estimated 5% of global CO_2 emissions or 2.1 gigatons CO_2/year. ***With worldwide cement production (and thus carbon emissions) projected to almost double by 2020,*** l***ow-carbon cement mixes currently under development*** could cut the CO_2 emissions associated with cement production, approximately in half and avoid more than one gigaton/year by 2020. This strategy requires high adoption levels (of the technology) to achieve one gigaton target.

In the opinion of this author, the worldwide projection of cement production in the next 10 years is too optimistic. Also, among the new low-carbon cements technologies, one technology is well known and can be adopted immediately worldwide to replace portland cement as the commonly used material in concrete construction. This low-cost, low-carbon cement technology is fully developed and field-tested since 1980, with concrete structures built in Canada, U.S.A., India, and China. Known as High-Volume Fly Ash (HVFA) concrete technology, it is briefly described next.

HIGH-VOLUME FLY ASH CONCRETE TECHNOLOGY

According to Malhotra and Mehta, the following characteristics define the HVFA concrete mixtures:

- Minimum 50% coal fly ash by mass of the cementitious material (cm).
- A low water content limited to a max. 130 kg/m^3 (w/cm usually below 0.4).
- Total cementitious material 300 to 400 kg/m^3 (portland cement content usually below 200 kg/m^3).
- Freshly produced HVFA concrete mixtures possess excellent workability, and are easy to pump and consolidate. When specified slump value is higher than 150 mm, generally a superplasticizer has to be used. This is also the case when w/cm less than 0.35 is required to obtain high-early and high ultimate strength.
- Due to low heat of hydration, and low drying shrinkage, hardened HVFA concrete is resistant to cracking. Also, it shows excellent resistance to alkali-aggregrate reaction, sulfate attack, and penetration of chloride ions (ASTM 1202 Test shows <1000 coulombs with 90-day moist-cured specimens).

Due to the direct link between durability and resource productivity of materials, the use of HVFA concrete technology would obviously enhance the position of concrete as a sustainable structural material, with a much longer service life than conventional portland-cement concrete. In the short-term, as discussed next by a holistic roadmap for concrete industry sustainability, the worldwide adoption of this technology during the next 20 years has the potential of avoiding annually more than one gigaton CO_2 emissions.

What about the availability of fly ash? According to Malhotra, in 2004, over 900 million tonnes of coal ash were available in the world. On the average, about 70% of the coal ash consists of fly ash, therefore, the global supply of fly ash was more than 600 MT. Assuming a significant increase in the use of coal for power production in China and India since 2004, the global availability of fly ash today should be close to 800 MT/year. Additionally, it is estimated that a total of 200 MT/year granulated slag, natural pozzolans and limestone are available for use as complementary cementing materials for producing low-carbon cements of the future. Composite cements with a clinker factor of 0.5 or less, and containing a combination of complementary cementing materials, are being increasingly produced in many countries of the world. Where fly ash is not available, high-volume granulated blast-furnace slag, or some natural pozzolans can be successfully used to make low-carbon cementitious materials. Laboratory studies by Ural et. al. have shown that a local pozzolanic material in Turkey produced high-volume natural pozzolan cements which were successfully used to make structural concrete.

SUSTAINABILITY OF THE CONCRETE INDUSTRY – A ROADMAP

To prevent atmospheric concentration of CO_2 from crossing the point of irreversible climate change, IPCC recommends that the total carbon emission rates of major carbon-emitting sources of the global economy must be brought back to the 1990 level or less in 20-30 years. Because nearly 90% of carbon emissions in the concrete industry are attributed to portland clinker production from cement kilns, the roadmaps developed by the cement industry alone are not holistic enough to meet the IPCC target. For example, by using the levers in the IEA-WBCSD cement roadmap, the amount of avoidable carbon emission will be less than the additional CO_2 produced by 5% annual growth rate projected for the global cement and concrete industry in the foreseeable future.

Note that as a result of rapid growth of the concrete industry, since 1990 the carbon emissions from the world's cement industry have almost doubled. Apparently, in order to reduce the carbon footprint of concrete as a primary structural material, we must use a holistic roadmap that not only would reduce the carbon emissions from cement, but also restrain the future growth of both the concrete and the cement industries. To meet the future needs of the global construction industry, needed resources, such as cement and concrete, must come from savings that could be achieved by more efficient utilization of materials rather than by increasing their production. Taking this approach, a roadmap developed by the author is discussed next.

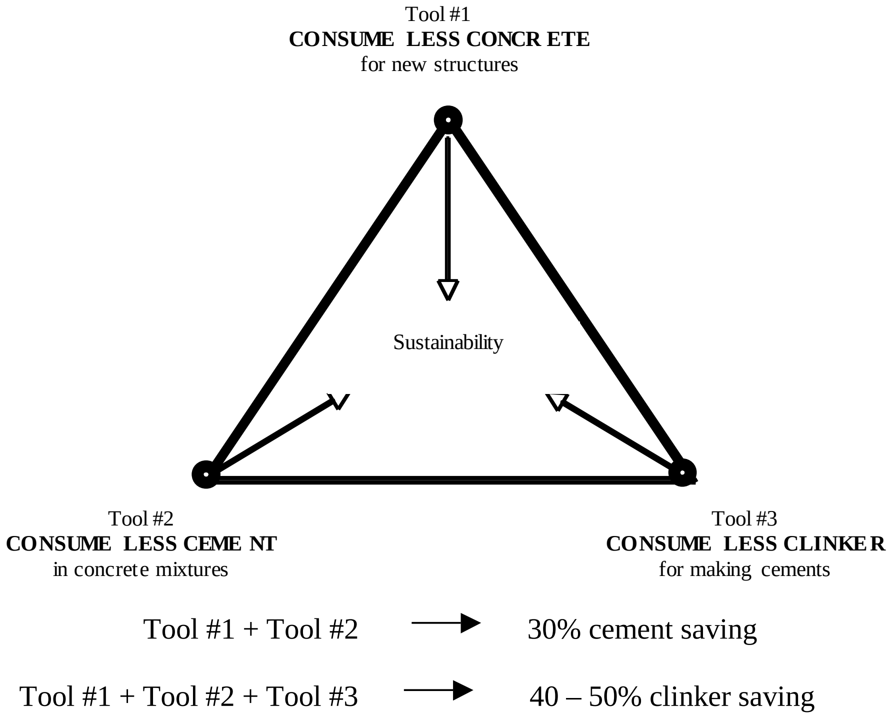

Figure 3. Tools for Reducing the Cement Industry's Carbon Emissions to the 1990 Level in Next 20 Years

The three tools needed for a sustainable cement industry are represented by the three corners of a triangle in Fig 3. In order to reach sustainability it is at once clear that we must travel from the corners to the middle of the triangle. Thus, the ***combined use of following three tools*** would enable the global cement and concrete industry to become sustainable in 20 years provided we undertake the journey without delay:

- ***Tool #1 – Consume less concrete***. Urban planners and architects should use innovative concepts to minimize the materials' footprints of projects. Similarly, structural designers should consider reducing the thickness of foundations and other massive structural elements to the minimum safe level.
- ***Tool #2 – Consume Less Cement in Concrete***. Large cement savings can be achieved if the specification writers specify 56 or 90-day strength requirement (instead of 28-day) for foundations and piers that consume huge quantities of concrete. Similarly, to improve the consistency of fresh concrete, instead of more cement and more mixing water, mix designers should use better aggregate grading and more efficient plasticizing admixtures.

- ***Tool #3 – Consume Less Clinker for Cements***. As discussed before, in blended cements 50-60% portland cement can be replaced with one or more complementary cementing materials, which can be interground with clinker or ground separately and blended subsequently in cement mills. When blended cements are not available, portland cement can be replaced during batching at concrete mixing plants.

Table 1. A Roadmap for Reducing Global Cement Consumption and CO_2 Emissions from Clinker Production

	2010	**2030**
Cement Consumption (million tonnes)	2800	1960
Clinker Factor*	0.83	0.60
Clinker Requirement (million tonnes)	2300	1180
CO_2 Emission Factor**	0.9	0.8
Total CO_2 Emission (million tonnes)	2070	940

* Tonnes of clinker per tonne of cement
** Tonnes of CO_2 per tonne of clinker

Data in Table 1 confirm how, in the next 20 years, global cement consumption and CO_2 emissions from portland clinker production can be reduced to the 1990 level by the application of the three tools discussed above. The current annual rate of cement consumption in the world is 2800 MT/y. Assuming that by using Tool #3 most of the large cement producing countries in the world (e.g., China, India, U.S., EU, Russia, Japan, Australia, and Brazil) agree to meet their regional cement requirement by using more complementary cementing materials and less clinker, and additionally, achieve 30% cement savings by using Tools #1 and #2, then the annual global cement requirement in 2030 will be 1960 MT. The average clinker factor of cements today is about 0.83. A worldwide production and use of cements containing high-volume fly ash, slag, or natural pozzolans can easily lower the average clinker factor to 0.6, which means that 1180 MT clinker would be needed in 2030. By increasing the use of biomass and recycled fossil fuels, the carbon emission factor can be reduced from 0.9 to 0.8 T CO_2/T clinker. This brings down the total CO_2 emissions attributable to global cement industry to 940 MT in 2030, which was the rate of CO_2 emissions from cement kilns in 1990. The underlying concept is illustrated in Fig. 4.

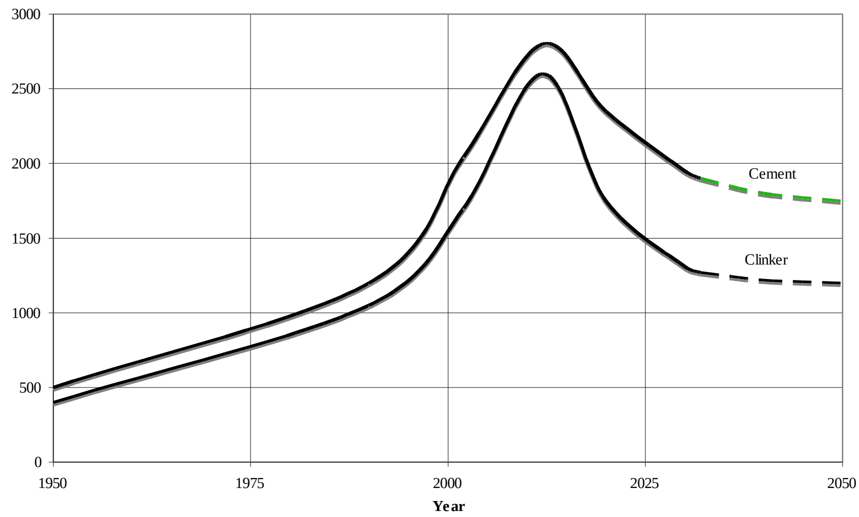

Figure 4. Predicted Cement and Clinker Requirements According to the Suggested Roadmap

CONCLUDING REMARKS

According to the Intergovt. Panel on Climate Change conclusions, recently confirmed by numerous scientific establishments including the U.S. National Oceanic and Atmospheric Administration, our window of opportunity is limited to about 30 years to avoid a catastrophic and irreversible climate change that is bound to happen unless immediate measures are taken to achieve drastic cuts in global CO_2 emissions. This warning has not been taken seriously by the developed and rapidly developing countries of the world because they are still projecting high growth rates for energy and materials-producing industries.

It is quite obvious to the author that the carbon-intensive sectors of global economy cannot achieve both the objective at the same time namely, a large reduction in CO_2 emissions, and a high growth rate of energy and materials-producing industries with available technologies that, already, are responsible for very high atmospheric concentration of CO_2. Instead, we should focus on proven technologies that will meet the basic human needs and, simultaneously, permit a sustained reduction, not growth, of the carbon-intensive industries. A roadmap presented in this article shows how this can be achieved by the global cement and concrete industry.

According to the roadmap, a 30% reduction in the global cement consumption in the next 20 years is achievable by more efficient use of concrete in structures and better methods of concrete mix-proportioning. Additionally, a large reduction in clinker consumption is achievable from a substantial use of complementary cementing materials that are available worldwide in large quantities.

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