

Reducing the Environmental Impact of Concrete

Concrete can be durable and environmentally friendly.

BY P. KUMAR MEHTA

Before discussing the environmental impact of concrete, it is helpful to have a general understanding of how current environmental problems relate to technology choices. Let us assume that environmental damage (D) is a function of three interlinked factors that are expressed mathematically as follows:

$$D = f(P \times I \times W)$$

where P stands for population, I is an index of industrial and urban growth, and W an indicator of the degree to which a culture promotes wasteful consumption of natural resources. The exponential and unsustainable forecast of CO_2 emissions during the 21st century (Fig. 1) is based on an estimate of population increase from 6 to 9 billion, a corresponding growth in industrial development and urbanization that would

result in three-fourths of the earth's inhabitants living in urban communities, and *assuming little or no change in today's wasteful consumption pattern of natural resources*. As (W) has a multiplier effect on the environmental damage, we can control the degree of damage by controlling this factor. To do this, we have to examine our current economic models and technological choices that promote wasteful consumption of natural and manufactured materials.

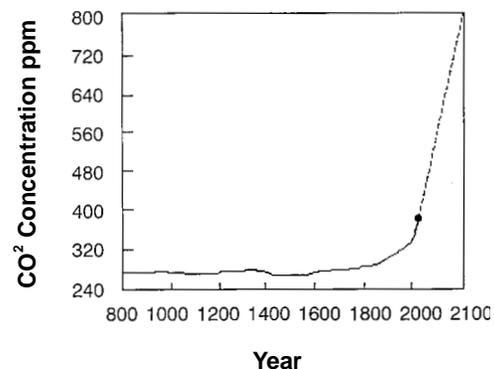


Fig. 1: Historical and future atmospheric CO_2 concentrations

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In a thought-provoking book, Hawken et al.¹ state that only 6% of the global flow of materials, some 500 billion tons a year, actually ends up in the desired products while most of the virgin materials are returned to the environment as harmful solid, liquid, and gaseous wastes. Obviously, a serious drawback of the modern economic model and technology is that the methods used for industrial development during the past 200 years did not take a holistic or a long-term view of the impact of unwanted by-products of the industry. Thus, while it should have been apparent from common sense, we are learning now from hard experience that, *in a finite world the model of unlimited growth, unrestricted use of natural resources, and uncontrolled pollution of the environment is ultimately a recipe for planetary self-destruction.*

The authors predict a new industrial revolution based on a very different mind-set than that of conventional capitalism. A fundamental assumption of the new capitalism that they call “natural capitalism,” is that *the environment is not a minor factor of production but rather an envelope containing, provisioning, and sustaining the entire economy.* Radical increases in resource productivity or materials efficiency would be the key features of “natural capitalism” in redesigning commerce to achieve a sustainable economy. During the past two centuries of the Industrial Revolution, the emphasis was on labor productivity because the global stock of natural materials was abundant and the environment was healthy. Now that people are the abundant and renewable resource but the environment needs healing, radical increases in resource productivity will have to become the cornerstone of successful business. Using materials more efficiently has three significant benefits: it slows down resource depletion at the input end of the value chain; it lowers pollution at the output end; and it provides a sound basis for increase in the worldwide employment.

Hawken and co-authors credit the movement toward resource productivity to the Factor Ten Club. This club consists of a group of scientists, economists, and business people who, in the fall of 1994, called for a leap in resource productivity to reverse the ecological and social impact of wasteful use of energy and materials. The declaration of the Factor Ten Club began with the words: “Within one generation, nations can achieve a ten-fold increase in the efficiency with which they use energy, natural resources and other materials.” In the ensuing years, Factor Ten (meaning a 90% reduction in energy and materials intensity) and Factor Four (meaning a 75% reduction) have entered the vocabulary of government planners, academics, and business people throughout the world. This approach has been endorsed by the European Union as *the new paradigm for sustainable development.* Hawken and his co-authors suggest that minimization of materials use, maximization of product durability, and reduction of maintenance cost will not only increase customer satisfaction and product value

but also profitability of the business enterprise. When both producers and consumers have acquired an interest in improving the resource productivity, this, in turn, will protect the world’s ecosystems.

Environmental impact of concrete

The world’s yearly cement production of 1.6 billion tons accounts for about 7% of the global loading of carbon dioxide into the atmosphere. Portland cement, the principal hydraulic cement in use today, is not only one of the most energy-intensive materials of construction but also is responsible for a large amount of greenhouse gases. Producing a ton of portland cement requires about 4 GJ energy, and portland cement clinker manufacture releases approximately 1 ton of carbon dioxide into the atmosphere.^{2,3} Furthermore, mining large quantities of raw materials such as limestone and clay, and fuel such as coal, often results in extensive deforestation and top-soil loss.

Ordinary concrete typically contains about 12% cement and 80% aggregate by mass. This means that globally, for concrete making, we are consuming sand, gravel, and crushed rock at the rate of 10 to 11 billion tons every year. The mining, processing, and transport operations involving such large quantities of aggregate consume considerable amounts of energy, and adversely affect the ecology of forested areas and riverbeds. The concrete industry also uses large amounts of fresh water; the mixing water requirement alone is approximately 1 trillion L every year. Reliable estimates aren’t available, but large quantities of fresh water are being used as wash-water by the ready-mixed concrete industry and for curing concrete.

Besides the three primary components, that is, cement, aggregates, and water, numerous chemical and mineral admixtures are incorporated into concrete mixtures. They too represent huge inputs of energy and materials into the final product. What about batching, mixing, transport, placement, consolidation, and finishing of concrete? All these operations are energy-intensive. Fossil fuels are the primary source of energy today, and the public is seriously debating the environmental costs associated with the use of fossil fuels.

Finally, the lack of durable materials also has serious environmental consequences. Increasing the service life of products is a long-term and easy solution for preserving the earth’s natural resources. Concrete structures are generally designed for a service life of 50 years, but experience shows that in urban and coastal environments many structures begin to deteriorate in 20 to 30 years or even less time.⁴ In the April 1998 issue of *ASCE News*, the American Society of Civil Engineers gave the nation’s infrastructure an average grade of D and estimated that it would take \$1.3 trillion to fix the problems. The cost to repair or replace several hundred thousand concrete bridge decks alone would be \$80 billion, whereas the present annual federal funding for this purpose is about \$5

to \$6 billion. Considering the funding constraints, Freyermuth⁵ has suggested that in the future structures be designed and built for a minimum service life of 100 to 120 years, and major bridges in urban environments should have at least 150 years of useful life. The trend toward designing infrastructure based on life-cycle cost will not only maximize the return on the available capital but also on the available natural resources.

The need for reducing the environmental impact of concrete is recognized in a recent report of the Strategic Development Council. An abbreviated version of the report, "Vision 2030: A Vision for the U.S. Concrete Industry," was published in *Concrete International*, March, 2001. According to this report, *concrete technologists are faced with the challenge of leading future development in a way that protects environmental quality while projecting concrete as a construction material of choice. Public concern will be responsibly addressed regarding climate change resulting from the increased concentration of global warming gases.*

Suggestions for reducing environmental impact

The environmental impact of the concrete industry can be reduced through resource productivity by conserving materials and energy for concrete-making and by improving the durability of concrete products. The task is most challenging but can be accomplished if pursued diligently.

To examine how the concrete industry will have to restructure when the business paradigm shifts its emphasis from a culture of acceleration to a culture of resource productivity, I have subdivided the environmental impacts of modern concrete construction practice into several categories that are discussed separately as follows.

Cement conservation

Cement conservation is the first step in reducing the energy consumption and greenhouse-gas emissions. Resource productivity consideration will require us to minimize portland cement use while meeting the future demands for more concrete. This must be the top priority for a viable concrete industry. Except for blended portland cements containing mineral additions, no other hydraulic cements seem to satisfy the setting, hardening, and durability characteristics of portland cement-based products. Although there is steady growth in the use of portland cement blends containing cementitious or pozzolanic by-products, such as ground granulated blast-furnace slag and fly ash, vast quantities of these by-products still end up either in low-value applications such as landfills and road subbases, or are simply disposed by ponding and stockpiling. The world cement consumption rate is expected to reach about 2 billion tons by the year 2010, and there are adequate supplies of pozzolanic and cementitious by-products that can be used as cement substitutes, thus eliminating the need for the production of more portland cement clinker.

Interestingly, as will be discussed below, portland cement blends containing 50% or more granulated blast-furnace slag or fly ash can yield much more durable concrete products than neat portland cement, and this would also contribute to natural resource conservation. The slower setting and hardening rate of concrete containing a high-volume of a mineral admixture can be compensated for, to some extent, by reducing the water-cementitious materials ratio with the help of a superplasticizer.² Nevertheless, for most structural applications, somewhat slower construction schedules ought to be acceptable when resource maximization, not labor productivity, becomes the most important industry goal.

Aggregate conservation

In North America, Europe, and Japan, about two-thirds of the construction and demolition waste consists of masonry and old concrete rubble. This presents a great opportunity for the concrete industry to improve its resource productivity by using *coarse aggregate* derived from construction and demolition wastes. In many parts of the world, dredged sands and mining wastes can be processed for use as *fine aggregate*. Recycling these wastes in spite of some processing cost is becoming economical, particularly in countries where land is scarce and waste disposal costs are very high. In addition, virgin aggregate deposits have already been depleted in many areas, and hauling aggregates over long distances can be much more expensive than using a free or a low-cost source of local recycled aggregate. Recycled concrete, in some cases, is being used as a roadfill, which is better than landfill but it is "down-cycling" in the sense that virgin aggregate continues to be used for making new concrete.

Lauritzen⁶ has estimated annual worldwide generation of concrete and masonry rubble at roughly 1 billion tonnes. At present, only small quantities of aggregate derived from recycled concrete and masonry are being used. Due to environmental considerations and the high cost of waste disposal, however, most countries in Europe have established short-term goals aimed at recycling 50 to 90% of the available construction and demolition waste.

Recycled-concrete aggregate, particularly the recycled-masonry aggregate, has a higher porosity than natural aggregate. Therefore, with a given workability, the water requirement for making fresh concrete tends to be high and mechanical properties of hardened concrete are adversely affected. The problem can be resolved by using blends of recycled and natural aggregate or by using water-reducing admixtures and fly ash in concrete.⁷

Water conservation

So far, fresh water is abundantly available almost everywhere, and is being freely used for all purposes by the concrete industry. In fact, construction practice codes routinely recommend the use of potable water for concrete mixing and curing. But now, the situation has changed.

Hawken et al.¹ report that fresh, clean water is getting more and more scarce every day. Although there is a lot of water on earth, less than 3% is fresh and most of that is either locked up in fast-melting glaciers and ice caps, or is too deep in the earth to retrieve. In recent press reports, the Indian government expressed deep concern over a future water shortage in the country because, due to global warming, the Himalayan glaciers, which are the primary source of water for Indian rivers, have receded by 30 m (100 ft) during the past 2 years alone.

Due to growing agricultural, urban, and industrial needs, water tables in every continent are falling. Increasing pollution of the water in our rivers, lakes, and streams compounds the problem. Hawken¹ and co-authors suggest that with water, as with energy, the only practical, large-scale solution is to use what resources we have far more efficiently. Regrettably, we're making the same mistake with water as with energy. We're depleting nonrenewable water resources rapidly and seeking yet more water.

As one of the largest industrial consumers of fresh water, it's imperative for the concrete industry to use water more efficiently. In addition to approximately 100 L/m³ (20 gal./yd³) wash-water used by the ready-mixed concrete trucks, we're using too much water for concrete mixing. I believe that the yearly global mixing water requirement of 1 trillion L can be cut in half by better aggregate grading and by greatly expanding the use of mineral admixtures and superplasticizers. Moreover, why should the industry use municipal, drinking water for mixing concrete? Most recycled industrial waters or even brackish natural waters are suitable for making concrete, unless proven otherwise by testing. This is even more true for wash-water and curing water. Significant reductions in wash-water are reported when the fresh, returned concrete is retarded and reused. Similarly, large savings in curing water can be realized by the application of textile composites that have a water-absorbent fabric on the interior and an impermeable membrane on the exterior.

Concrete durability

In addition to the steps outlined above, improving concrete durability presents a long-range solution and a major breakthrough for improving the resource productivity of the concrete industry. For example, the resource productivity of the concrete industry will jump by a factor of 10 if most structural concrete elements are built to last for 500 years instead of 50.

Why do modern reinforced concrete structures sometimes begin to deteriorate in 20 years or less, whereas there are buildings and seawalls made of unreinforced Roman concrete that continue to be in good condition after almost 2000 years? Primarily because our portland-cement concrete mixtures are highly crack-prone and therefore become permeable

during service. The embedded steel reinforcement in permeable concrete corrodes easily, causing progressive deterioration of the structure. Today's construction practice, driven by a culture of ever-accelerating construction speeds, uses concrete containing a relatively large amount of high-early strength portland cement. As a result, the extensibility or crack-resistance of modern concretes is poor because of the high-tensile stress induced by too much thermal contraction and drying shrinkage, and too little creep relaxation.

Roman cement, typically a mixture of hydrated lime and volcanic ash, produced a homogeneous hydration product that set and hardened slowly but was thermodynamically more stable than the hydration product of modern portland cement.⁸ Also, Roman concretes were made with far less water and, compared to today's concrete, were less crack-prone and thus highly durable. Clearly, if durability and sustainability are important goals, current construction practice and the codes of recommended practice must undergo a paradigm shift to achieve crack-free concrete structures in preference to high speeds of construction.⁹ In fact, technology is available in the form of somewhat slower-hardening blended portland cements containing 50 to 60% fly ash or granulated blast-furnace slag. Malhotra,¹⁰ and Langley and Leaman¹¹ have described mixture proportions, properties, and applications of high-volume fly-ash superplasticized concrete mixtures. As shown below, if the mixing water content and the total cementitious materials in concrete are further reduced with the help of a superplasticizer, it is possible to eliminate all or most of the shrinkage and cracking, and produce a highly durable concrete.

Mehta and Langley¹² described the construction of a large, crack-free, monolith concrete foundation, designed to endure at least 1000 years. Briefly, for a stone temple that is under construction in Kauai, an island in the Pacific Ocean about 4000 km (2400 mi) to the west of the U.S. mainland, the owner wanted a crack-free foundation composed of two parallel, independent, unreinforced, monolith concrete slabs, each 36 x 17 x 0.61 m (117 x 56 x 2 ft). To produce essentially a concrete that would be free from significant shrinkage stresses, it was necessary to control thermal and drying shrinkage by radically reducing the content of both portland cement and water in the concrete mixture.

Table 1 shows the mixture proportions used to make concrete having 5 ± 1 in. (125 ± 25 mm) specified slump and 20 MPa (3000 psi) compressive strength at 90 days with only 13 C (7 F) adiabatic temperature rise in each slab. When inspected last, almost 2 years after construction, careful examination of the exposed surfaces of concrete showed no evidence of any cracking. Microstructural investigation of the concrete cored from a test slab confirmed that, unlike conventional

portland cement concrete, the hydration product of the high-volume fly ash system was much more homogeneous and well-bonded with aggregate, which is a prerequisite for crack resistance and long-term durability (Fig. 2(a) and 2(b)). If built with conventional reinforced concrete, this foundation would have used about 230 tons (210 tonnes) of portland cement and 75 tons (68 tonnes) of steel reinforcement. Instead, by using only 80 tons (73 tonnes) of cement and no steel, the project reduced environmental carbon dioxide by 225 tons (204 tonnes). This amount may be insignificant, but it sets a trend that is worthy of emulation by the concrete construction industry if the goal is to build durable and sustainable structures in the future.

TABLE 1:
Mixture proportions for a crack-resistant,
high-volume fly ash concrete

Type I portland cement	Class F fly ash	Water	Crushed calcareous sand	Crushed basalt rock (25mm max size)	Super-plasticizer
106 kg/m ³ (180 lb/yd ³)	142 kg/m ³ (240 lb/yd ³)	100 kg/m ³ (170 lb/yd ³)	944 kg/m ³ (1600 lb/yd ³)	1120 kg/m ³ (1900 lb/yd ³)	3.5 L/m ³ (90 oz/yd ³)

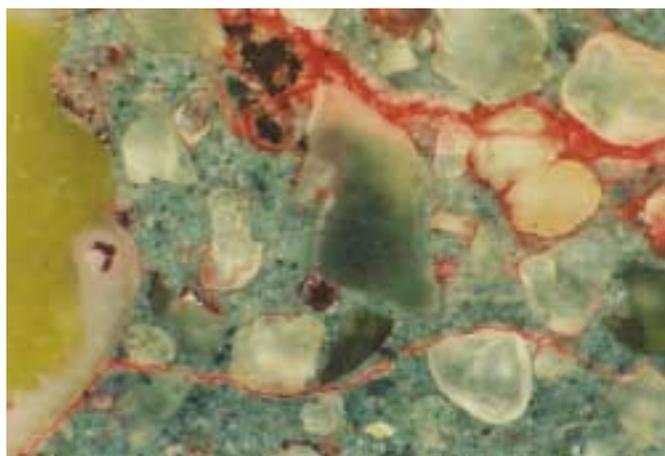


Fig. 2 (a):
Photomicrograph of a thin section of ordinary portland-cement concrete showing how the interfacial aggregate-paste microcracks join and permit penetration of fluid from the outside. The path of fluid flow is traced with the help of a red fluorescent dye. (courtesy: H. Hornain)

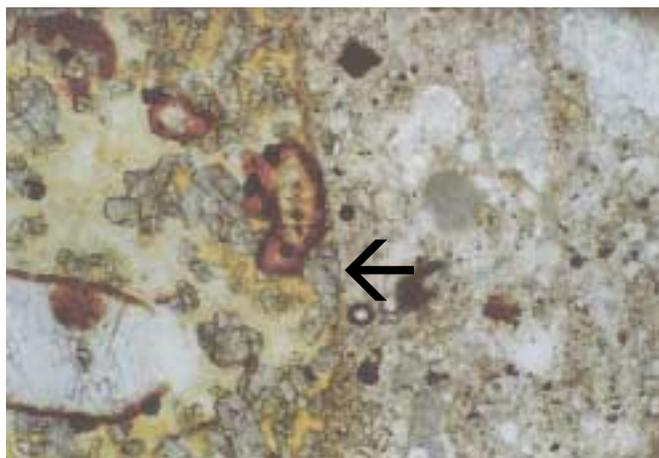


Fig. 2 (b):
Photomicrograph of a thin section from the concrete core obtained from the high-volume fly ash system used for the construction of the Iraiwan temple foundation in Kauai. A 40x magnification in plane polarized light of a coarse aggregate particle and the adjacent cement mortar shows no interfacial transition zone and no microcracks. (courtesy: J. Asselanis)

A model for the future

Ten years ago, in an article on concrete durability and resource economy, Idorn¹³ predicted that concrete of certified, long-term durability, tailored to its performance requirements, will become a basic element in the development of resource-economy policies everywhere. His prediction is coming true. The high-volume fly ash concrete system provides a model for the future for making concrete mixtures that shrink less, crack less, and would be far more durable and resource-efficient than conventional portland-cement concrete.

The ability to design and build structural members that last for 500 years or more instead of 50 will in the long run increase the concrete industry’s resource productivity by tenfold. Meanwhile, by substituting recycled materials for natural materials, as described in this article, it should be possible to substantially improve the resource productivity of the concrete industry immediately.

Unquestionably, the greatest challenge that the concrete industry faces during the 21st century is to achieve a sustainable pattern of growth. The task is formidable but the ideas and examples cited in this article show that it can be accomplished provided we make a paradigm shift from the culture of accelerating construction speeds to a culture of conservation of energy and material. Finally, I would like to close with a quote from the German poet Goethe: *“Knowing is not enough, we must practice; willingness is not enough, we must act.”*

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The environmental impact of concrete, its manufacture and applications, are complex. Some effects are harmful; others welcome. Many depend on circumstances. A major component of concrete is cement, which has its own environmental and social impacts and contributes largely to those of concrete. The cement industry is one of the main producers of carbon dioxide, a potent greenhouse gas. Concrete causes damage to the most fertile layer of the earth, the topsoil. Concrete is used to create hard surfaces. The environmental impact of concrete, its manufacture and applications, are complex. Some effects are harmful; others welcome. Many depend on circumstances. A major component of concrete is cement, which has its own environmental and social impacts and contributes largely to those of concrete. The cement industry is one of the primary producers of carbon dioxide, a potent greenhouse gas.[1] Concrete causes damage to the most fertile layer of the earth, the topsoil. Light-colored concrete can reduce the urban heat island effect, due to its higher albedo.[2] However, original vegetation results in even greater benefit. Concrete dust released by building demolition and natural disasters can be a major source of dangerous air pollution. But other environmental impacts are far less well understood. Concrete is a thirsty behemoth, sucking up almost a 10th of the world's industrial water use. This often strains supplies for drinking and irrigation, because 75% of this consumption is in drought and water-stressed regions. In cities, concrete also adds to the heat-island effect by absorbing the warmth of the sun and trapping gases from car exhausts and air-conditioner units – though it is, at least, better than darker asphalt. But there is only so much concrete you can usefully lay without ruining the environment. The ever-diminishing returns were made apparent in the 1990s, when even the most creative politicians struggled to justify the government's stimulus spending packages.