Concrete Materials and Sustainable Development in the United States

By

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The Challenge

Sustainable Development has become a household word, standing for a set of self-evident principles that are hard to argue with. Probably the first person who formulated the term was Hans Carl von Carlowitz (1645 – 1714), a forester in Saxony, Germany[1], who called for sparing use of trees to give the forest a chance to regenerate and sustain itself. As logical as this principle appears to be, it has often been violated with at times catastrophic consequences. In 1992, McDonough and Braungart formulated the most comprehensive set of requirements in their “Hannover Principles: Design for Sustainability”[2]. Whether familiar with these basic principles or not, most of us must intuitively agree, because deep down we are all concerned about the world we will be leaving behind for future generations, that is, our children and their children. The old political conflict between supporters of “development” and those who wish to preserve the environment obscures the fact that sustainability and development are not mutually exclusive. Rather, we are called upon to find a proper balance between economic development and environmental preservation, i.e., to improve the living standard and quality of life, without adversely affecting our environment.

It is the purpose of this article to discuss some aspects of the concrete industry (particularly in the United States), because it has a much larger impact on sustainability than many of us may realize. It may be appropriate to start out by stressing the fact that concrete is by far the most important, the most versatile, and the most widely used building material worldwide. It has achieved this predominance because of a number of decisive advantages. As a result of that popularity, the concrete industry has an enormous impact on the environment[3,4]:

1. Worldwide, over ten billion tons of concrete are being produced each year. In the United States, the annual production of over 500 million tons implies about two tons for each man, woman and child. Such volumes require vast amounts of natural resources for aggregate and cement production.
2. In addition, it has been estimated that the production of one ton of Portland cement causes the release of one ton of CO_2 into the atmosphere. CO_2 is known to be a greenhouse gas that contributes to global warming, and the cement industry alone generates about 7% of it.
3. The production of Portland cement is also very energy-intensive. Although the North American plants have improved their energy-efficiency considerably in recent decades to the point where this is now comparable to that of plants in Japan and

Germany, it is technically next to impossible to increase that energy-efficiency much further below the current requirement of about 4 GJ per ton.

4. The demolition and disposal of concrete structures, pavements, etc., constitutes another environmental burden. Construction debris contributes a large fraction of our solid waste disposal problem, and concrete constitutes the largest single component.
5. Finally, the water requirements are enormous and particularly burdensome in those regions of the earth that are not blessed with an abundance of fresh water. The concrete industry uses about one billion cubic meter of water each year worldwide, and this does not even include wash water and curing water.

These points and these numbers seem to indicate that the concrete industry has become a victim of its own success and therefore is now faced with tremendous challenges. But the situation is not as bad as it might seem, because properly produced concrete is inherently an environmentally friendly material, as can be demonstrated readily with a life-cycle analysis[5]. The challenges derive primarily from the fact that Portland cement is not environmentally friendly. One could therefore reduce this problem to the simple requirement of using as much concrete with as little Portland cement as possible.

Tools and Strategies

There are a number of ways how the concrete industry can increase its compliance with the demands of sustainable development:

1. Increased use of supplementary cementitious material. Since the production of Portland cement is so energy intensive and responsible for CO_2 generation, the substitution of other materials, especially those that are byproducts of industrial processes, such as fly ash and slag, is bound to have a major positive impact.
2. Increased reliance on recycled materials. Since aggregate constitutes the bulk of concrete, an effective recycling strategy will lessen the demand for virgin materials.
3. Improved durability. By doubling the service life of our structures, we can cut in half the amount of material needed for their replacement.
4. Improved mechanical properties. An increase in mechanical strength and similar properties leads to a reduction of materials needed. For example, doubling the concrete strength for strength-controlled members cuts the required amount of material in half.
5. Reuse of wash water. The recycling of wash water is readily achieved in practice and already required by law in some countries.

There are large differences between the degrees to which different countries have already implemented these strategies. In particular, there is a noticeable difference between the United States and many European countries. Whereas most Americans have been raised on the principles of conspicuous consumption, with often wasteful use of their vast natural resources and little priority given to recycling, their higher population densities and the devastations of two world wars have taught Europeans to make more sparing use of their resources. But the self-evident principles of sustainable development are now being accepted also by a growing part of the American public, and a very vocal environmental movement is seeing to it that this trend continues. As a result, Americans are increasingly willing to contribute their share to the preservation of their environment, which includes a reasoned approach towards sustainable development. Much of what follows is generally well known and already implemented in many European countries and Japan, but not in the United States, where the construction industry in general and the concrete industry in particular are not known as exemplary role models for sustainable development. A systematic adoption of the strategies outlined above will go a long way towards improving the industry's record.

Use of Cement Substitutes

A primary goal is a reduction in the use of Portland cement, which is easily achieved by partially replacing it with various cementitious materials, preferably those that are byproducts of industrial processes. The best known of such materials is *fly ash*, the residual of coal combustion, which is an excellent cementitious material. As shown in Table 1, the utilization rates vary greatly from country to country, from as low as 3.5% for India to as high as 93.7% for Hong Kong – presumably because Hong Kong receives its coal from a single source of high-quality material. The relatively low rate of 13.5% in the US is an indication that there is a lot of room for improvement.

Table 1 Coal-Ash Production and Utilization (1995)[4]

Country	Million Tons Produced	Million Tons Utilized	%
China	91.1	13.8	15.1
Denmark	1.3	0.4	30.8
Hong Kong	0.63	0.59	93.7
India	57.0	2.0	3.5
Japan	4.7	2.8	59.6
Russia	62.0	4.3	6.9
USA	60.0	8.1	13.5

The use of fly ash has a number of advantages. It is theoretically possible to replace 100% of Portland cement by fly ash, but replacement levels above 80% generally require a chemical activator. We have found that the optimum replacement level is around 30%. Moreover, fly ash can improve certain properties of concrete, such as durability. Because it generates less heat of hydration, it is particularly well suited for mass concrete applications. Most important, as a byproduct of coal combustion fly ash would be a waste product to be disposed of at great cost, if we don't make good use of it. By utilizing its cementitious properties, we are adding value to it, we "beneficiate" it. Also, fly ash is widely available and has a cost advantage over Portland cement.

There are also some disadvantages. First, there is the relatively slow rate of strength development. But this is irrelevant for applications where high early strength is not required. More significant is the wide variability of its chemical composition and quality, which is the main reason for the low utilization rates. It may be rejected for as trivial a reason as its color: One concrete block manufacturer we have worked with discontinued the use of fly ash, because he could not control the color of his product. Customers generally prefer a uniform color.

Ground granulated blast furnace slag (GGBFS) is another excellent cementitious material. It also is the byproduct of an industrial process, in this case the steel making industry. Here the optimum cement replacement level is somewhere between 70 and 80%. Like fly ash, also GGBFS can improve many mechanical and durability properties of concrete and it generates less heat of hydration. In many cases, a blend of Portland cement, fly ash, and GGBFS has been used successfully. Yet, slag is not as widely available as fly ash. The US steel industry is only a faint image of what it was only a few decades ago, and as a result, the slag marketed in some East Coast states is being imported from Italy. Because of its excellent attributes, the cost of slag is comparable to that of Portland cement, so that there is no advantage in this respect.

Perhaps the greatest success story in beneficiating an industrial byproduct is that of *condensed silica fume*, a byproduct of the semiconductor industry. This siliceous material improves both strength and durability of concrete to such an extent that modern high-performance concrete mix designs as a rule call for the addition of silica fume. Even though the material is difficult to handle because of its extreme fineness, its benefits are so obvious that its cost exceeds that of cement considerably. In fact, it is now available not only as an industrial byproduct, but also produced specifically for the concrete industry.

Several researchers have confirmed that finely ground glass powder has cementitious properties[7,12] and therefore can be used as replacement of a major portion of Portland cement. Similarly, other byproducts such as rice husk ash have been identified as suitable cement substitutes.

Most metropolitan areas in the United States are facing major solid waste disposal problems. This is particularly true for New York City, which probably generates more solid waste than any other city in the world, including those that are much bigger. One of the means to dispose of it is to burn it in so-called waste-to-energy facilities. However, the disposal of the ash is problematic because the fly ash in particular may contain unacceptable levels of contaminants. This problem can be circumvented by mixing the fly ash and bottom ash such that the toxicity level of the blend is below the acceptable limit. Even then, the wholesale disposal of such ash in landfills is not exactly an environmentally friendly solution, especially since the ash has also cementitious properties. Moreover, it has been shown that it is possible to encapsulate the heavy metals in the ash and render the organic contaminants harmless such that they cannot leach out. However, before such technologies are applied in actual practice, additional research is needed. In particular, the questions of public acceptance need to be addressed.

Use of Recycled Materials

Before discussing various recycled materials that may be suitable for use in concrete production, it is appropriate to briefly address the various factors that affect the *economics* of recycling.

The fundamental law of economics in a free-market economy is that the price of a service or commodity is determined by supply and demand, by competition, and the profit motive. But even in a free-market economy, government can and regularly does intervene with incentives (for example, in the form of tax write-offs) and disincentives, such as fees, penalties, or outright prohibition, if it thinks this is in the best interest of the public.

Recycling is obviously associated with a number of cost items, like collection, processing, transportation, and the required capital investments. On the other hand, solid waste that is not recycled or reused needs to be disposed of in landfills, with tipping fees as direct costs and indirect costs in the form of environmental impact and depletion of suitable landfill capacities. Another factor that affects the economics of recycling is the cost of the material to be replaced. Are we replacing sand, which is literally dirt-cheap, or marble chips, imported at high cost from Italy? Somewhat related to this issue is the value added to the material through beneficiation. At Columbia University, we have developed a keen interest in identifying special properties inherent in recycled materials. By exploiting these properties, we can add value and thereby improve the economics.

The environmental community is growing also in the United States. Almost unknown until the late 1960s, a sizeable fraction of the public now would not hesitate calling themselves environmentalists – and that implies they would be willing to pay more for a commodity that is clearly identified as “recycled” or “environmentally friendly”.

Concrete debris is probably the most important candidate for reuse in new concrete. On the one hand, vast amounts of material are needed for aggregate. On the other hand, construction debris often constitutes the largest single component of solid waste, and probably the largest fraction of this is concrete. Using such debris to produce new concrete conserves natural resources and reduces valuable landfill capacity at the same time. In Europe and Japan, such recycling is already widely practiced, whereas in the US, it is being accepted only slowly, because the economic drivers are not yet strong enough. But they are improving. The disposal of demolished concrete costs money, and those charges are likely to go up. Available sources of suitable aggregate are being depleted, such as gravel pits on Long Island, and opening up new sources of virgin material is getting increasingly difficult. Since the cost of transportation is the main contributor to the cost of bulk material like sand and gravel, it may not take much of a shift to turn the economics in favor of recycling and reuse.

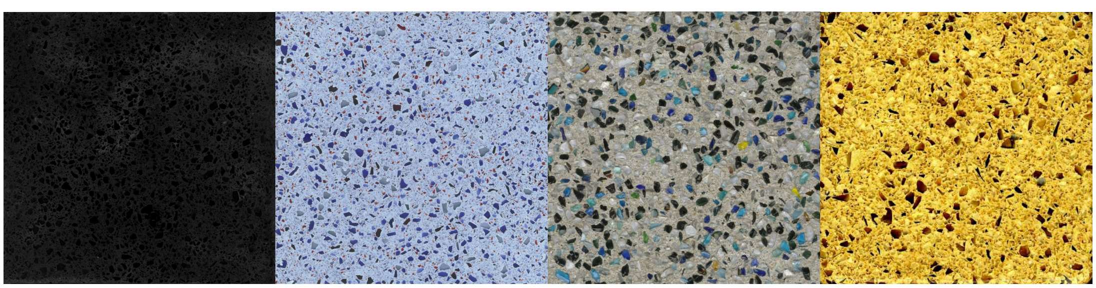
Turning recycled concrete into useful or even high-quality aggregate poses well-known technical challenges[6]. There are contaminants to be dealt with, as well as the large fluctuations in quality, the generally high porosity and grading requirements. Yet, not all applications require high-strength concrete. Recycled concrete aggregate may be quite acceptable for many applications, and for others, a blend of new and recycled aggregate may make economic and technical sense.

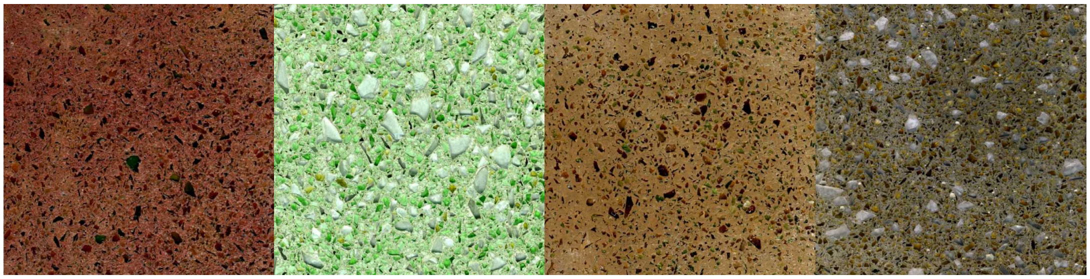
Post-consumer glass is another example of a suitable aggregate for concrete, as research at Columbia University has shown[7-9]. It costs taxpayers in New York City approximately 60 million dollars to dispose of its waste glass. Still, it is a widely held but wrong belief that throwing away old bottles is cheaper than recycling them. By having demonstrated the economic feasibility of concrete production as a viable secondary market for post-consumer glass, we hope to be able to change this perception. The open issues are not of a technical nature. The only technical problem, namely the alkali-silica reaction (or ASR) and other potential problems can be solved. By exploiting the zero water absorption of glass, its high hardness and abrasion resistance, the excellent durability and chemical resistance, and in particular the esthetic potential of colored glass, true value is added to the glass. The consequences on the market price are already apparent, because a new secondary market was created for the glass.

Making commodity products such as paving stones economically viable is a difficult proposition, because in this case, profit margins are low and the primary objective is to use as much glass as possible. For example, one paving stone manufacturer in New Jersey could single-handedly use all 200,000 tons of glass that the City of New York may collect once its restarted recycling program is again in full swing. But the manufacturer cannot afford to pay more for the glass than he is currently paying for the sand and gravel.

Value-added products do not pose such problems. On the contrary, they are already being produced commercially, even though the manufacturer is paying hundreds of dollars per ton for the glass, while most municipalities are paying recyclers to take it away. But the company is in the fortunate position to afford such prices, because the special aggregate replaced by the glass is also costly and the profit margins are high. Figure 1 gives a general impression of what esthetic effects can be achieved with glass concrete.

Fig. 1 Typical glass concrete tiles





Dredged material shall serve as the third example. The Port Authority of New York and New Jersey needs to dredge about 3 million cubic meter each year to keep shipping lanes open and also to deepen them to accommodate the larger new vessels. As long as the Port Authority was able to dump the material in the open ocean, the disposal costs were minimal. But since national legislation and international treaties are prohibiting such ocean dumping, the material has to be deposited in engineered landfills at great cost, because much of it is highly contaminated with heavy metals, dioxins, PCBs, oils, etc. It is vital for the Port Authority that the disposal costs be drastically reduced. Similar problems are faced by many other world ports.

Treatment methods are already available, which render the material suitable for concrete production, because the heavy metals can be encapsulated chemically such that they cannot leach out. But the economics of such treatment methods are complicated by numerous factors, not all of which are of a technical nature. In spite of all scientific evidence to the contrary, the public perception may reject a technically sound solution, as demonstrated, for example, by the case of the bricks manufactured with material dredged from the Port of Hamburg[10]. It is also possible to treat the material in a barge right upon dredging, thereby avoiding public opposition against construction of treatment facilities and temporary storage of the material. Preliminary studies have identified a number of potential applications of treated dredged material. For example, such material can serve as an excellent filler for concrete, which can increase the freeze-thaw durability of concrete specimens by as high a factor as 70. More research is likely to identify other uses of treated dredged material, thereby adding value to a material, which at present needs to be disposed of at high cost.

A fourth example is the material excavated from tunnels, such as for Manhattan’s Second Avenue Subway, which may very well be suitable as aggregate to produce concrete for the tunnel liner and subway stations. Relatively, only small amounts of such material will be needed. But in absolute terms, it would render unnecessary the mining of millions of tons of virgin material. The technical issues are again the least difficult ones to solve. Much more difficult are the logistics and scheduling problems, i.e. coordinating the times when the material is excavated and when the aggregate is needed. The solution of these problems requires close cooperation between owner, engineer, construction manager, contractor, and aggregate supplier and a common willingness to find an environmentally optimal solution.

We have also studied the use of recycled carpet fiber[11]. Millions of tons of old carpets need to be disposed of each year, constituting another sizeable fraction of solid waste.

Since carpet fibers are typically made of nylon, recycled fibers have been shown to improve some mechanical properties of concrete. Other recycled materials that can be used in concrete are wood waste, rubber tires, plastics, pulp, and paper mill residuals.

Changing Political Landscape

There are signs that the public attitude towards sustainable development is changing. “Green building” design principles are finding their way into design practice, spearheaded by the architectural community. The US Green Building Council has developed a rating system for the Federal Government as a guide for green and sustainable design. This system, called “Leadership in Energy & Environmental Design” (LEED)[12], has become a standard adopted by several governmental agencies in its original form or some modified versions of it. It assigns points in five different categories:

1. Sustainable Sites, 14 possible points
2. Water Efficiency, 5 possible points
3. Energy & Atmosphere, 17 possible points
4. Materials & Resources, 13 possible points
5. Indoor Environmental Quality, 15 possible points
6. Innovation & Design Process, 5 possible points

In order to become “certified”, a project requires at least 26 out of the total of 69 points. Projects with 33 points are “Silver”-rated, those with 39 points are “Gold”-rated, and to reach the highest rating of “Platinum”, 52 points are required. Means and methods to increase the number of points for a concrete building can be found elsewhere[5]. Here it suffices to point out that under the current system, only a rather small number of points can be earned by making concrete more environmentally friendly. For example, in a mix design that contains 15% cementitious material, the replacement of 30% of Portland cement by fly ash will introduce only 4.5% recycled material. The reward in terms of LEED points in no way reflects the gain in environmental friendliness, as measured by the reduction of CO_2 generation and energy consumption. This example illustrates that the LEED rating system, as currently formulated and administered, appears to place concrete at a disadvantage. This situation can be changed only through a concerted effort of the concrete community under the stewardship of a well-respected organization such as ACI.

The LEED rating system is gaining significance because numerous governing bodies on the federal, state, and local levels have embraced the principles of sustainable development and are either requiring LEED rating for their own projects (such as the General Services Administration and the U.S. Army Corps of Engineers), or offer tax credits for projects within their jurisdictions. Developers are paying attention, especially since they are discovering that “green design” can be profitable. The completion of the Solaire in New York’s Battery Park City, the first residential green high-rise building in the US, and the Conde Nast Building at 4 Times Square, the country’s first green high-rise office building, are proof that the pairing of a progressive developer with a “green” architect can lead to a successful development of such projects.

The environmental community, with active or passive support of a large segment of society at large, is becoming increasingly aggressive in demanding that future developments adhere to the principles of sustainable development. If the concrete industry does not adjust on time to the changing political and societal climate, it could easily be losing the market share, which it had worked so hard to obtain during the last few decades. With modest investments in research and development, it should be possible to identify inherent valuable properties in other industrial byproducts and thereby beneficiating them. Yet, this will happen only if the leaders of our industry display vision and courage, which includes a willingness to take risks.

Summary and Conclusions

The principles of sustainable development are self-evident, as most of us are concerned about the world we are passing on to future generations. It requires a difficult balancing act to weigh the needs of environmental preservation against those of development to raise the living standard, as the World Summits of Rio and Kyoto have demonstrated. While the industrialized countries are called upon to reduce pollution of the environment and their share of the world’s resources, the developing countries need to avoid the mistakes of the past.

The concrete industry, due to its sheer size, has a considerable impact on the environment. Yet, concrete itself is inherently environmentally friendly, whereas Portland cement is not. Therefore one way to make the construction industry more compatible with the requirements of sustainable development would be to use as much concrete as possible, but with the least amount of Portland cement as possible. Byproducts of industrial processes excellent cementitious properties are available, such as fly ash, ground granulated blast furnace slag, and condensed silica fume. The other strategy to improve the environmental friendliness of the concrete industry is the large-scale utilization of waste products such as construction debris, post-consumer glass, dredged material, recycled carpets, tires, etc. An analysis of the economic drivers shows that modest investments in research can lead to major improvements without the need for massive governmental intervention. The key lies in the identification and exploitation of properties inherent in recyclable materials, which improve certain properties of the concrete and thereby create value through beneficiation. A good example is the glass concrete, which utilizes a number of properties inherent in soda-lime glass and in particular exploits the esthetic potential of colored glass for architectural and decorative concrete applications.

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