Concrete as a Green Building Material

C. Meyer
Columbia University, New York, NY 10027, USA

Abstract

Concrete is by far the most widely used construction material worldwide. Its huge popularity is the result of a number of well-known advantages, such as low cost, general availability, and wide applicability. But this popularity of concrete also carries with it a great environmental cost. The billions of tons of natural materials mined and processed each year, by their sheer volume, are bound to leave a substantial mark on the environment. Most damaging are the enormous amounts of energy required to produce Portland cement as well as the large quantities of CO_2 released into the atmosphere in the process.

This paper summarizes the various efforts underway to improve the environmental friendliness of concrete to make it suitable as a "Green Building" material. Foremost and most successful in this regard is the use suitable substitutes for Portland cement, especially those that are byproducts of industrial processes, like fly ash, ground granulated blast furnace slag, and silica fume. Also efforts to use suitable recycled materials as substitutes for concrete aggregate are gaining in importance, such as recycled concrete aggregate, post-consumer glass, tires, etc.

The paper discusses some of the economic drivers which determine the degree of commercial success. Simply deposing of waste materials in concrete products is unlikely to succeed except in unusual situations. But by identifying and exploiting specific properties inherent in various waste materials or byproducts, it is possible to add value to such materials and increase their chances of success in a market-driven economy of supply and demand. Also, the emergence of the Green Building movement in North America is already changing the economic landscape and the factors that influence resource utilization.

Keywords: sustainable development, green buildings, supplementary cementitious materials, recycling, recycled concrete aggregate

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Christian Meyer
Department of Civil Engineering and Engineering Mechanics
Columbia University
New York, NY 10027, USA

Email: meyer@civil.columbia.edu
Tel: 212-854-3428

1.0 Sustainable Development – The Challenge for the Concrete Industry

S*ustainable 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 general principle appears to be, it has often been violated with at times catastrophic consequences. Most of us are 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 the 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 various 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. Concrete is by far the most widely used construction material worldwide. In fact, it is more widely used than any other material, except water. Its huge popularity is the result of a number of well-known advantages, such as low cost, general availability, and adaptability to a wide spectrum of performance requirements. But this popularity of concrete also carries with it a great cost in terms of impact on the environment [2,3]:

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 over 1 trillion gallons 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 concrete is inherently an environmentally friendly material, as can be demonstrated readily with a life-cycle analysis [4]. The challenges therefore reduce primarily to reducing Portland cement's impact on the environment. In other words, we should use as much concrete, but with as little Portland cement as possible.

2.0 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 energy intensive and responsible for much of the 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 various countries have already implemented these strategies. In particular, there is a noticeable difference between the United States and many European countries in this regard. Whereas most Americans have been raised on the principles of conspicuous consumption, with often wasteful use of their vast natural resources and little emphasis on 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 active and 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 have not been 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.

Implementing effective strategies to lessen the environmental impact of the concrete industry by prudent use of those tools requires a concerted effort of the industry, starting with well-focused research and development. Even more important for success are economic incentives to convince industry leaders that increased incorporation of sustainable development principles is possible without adversely impacting the industry's profitability. On a less benign parallel track, political developments are underway or imminent which are likely to force the industry to change or lose market share. Bold initiatives are required that are not without risk, yet strict adherence to principles such as "we have always done it this way" is certainly counterproductive, because the world around us will change anyway.

A considerable body of literature exists on methods to improve the mechanical properties and durability of concrete. The emphasis here will be on how to make concrete a "green building material" by use of cement substitutes and recycled materials.

3.0 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*, a residue of coal combustion, which is an excellent cementitious material. As shown in Table 1 [4], 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. The relatively low rate of 13.5% in the US is an indication that there is a lot of room for improvement.

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. Fly ash is also widely available, namely wherever coal is being burned. Another advantage is the fact that fly ash is still less expensive than Portland cement. Maybe 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 – a major aspect of green building construction.

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

Fly ash also has some disadvantages. First, there is the relatively slow rate of strength development. But this is irrelevant in 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 had to discontinue the use of fly ash, because he could not control the color of his product. Customers generally prefer a consistently 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 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. For many applications it is now recommended to use a blend of Portland cement, fly ash, and GGBFS. 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 (submicron) fineness, its benefits are so obvious that its cost considerably exceeds that of cement. In fact, it is now available not only as a byproduct of the semiconductor industry, but also produced specifically for the concrete industry.

Most major 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 technologies to dispose of it is to burn it in so-called waste-to-energy facilities. However, the disposal of the *solid waste incinerator ash* is problematic because the fly ash in particular contains unacceptable levels of contaminants. This problem can be circumvented by mixing the fly ash and bottom ash such that the level of contamination of the blend stays below the acceptable limit. Even then, the wholesale disposal of such ash in landfills is not exactly an environmentally friendly solution, especially since it is possible to encapsulate the heavy metals in the ash and render the organic contaminants harmless such that they cannot leach out. Moreover, the ash has also cementitious properties. However, before such technologies can be applied in actual practice, additional research is needed. In particular, the question of public acceptance needs to be addressed.

4.0 Economics of Recycling

Before discussing various other recycled materials that may be suitable for use in concrete production, it is appropriate to briefly address the question of economics, which is affected by a number of important factors.

One of the fundamental laws of economics is that in a free-market economy the price of a service or commodity is determined by supply and demand. But even in such 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.

The so-called environmental community is growing. Almost unknown in the United States until the late 1960s, a growing fraction of the public would not hesitate calling themselves environmentalists – and that implies a certain willingness to pay more for a commodity that is clearly identified as environmentally friendly or to contain recycled materials.

Recycling is associated with a number of cost items, like collection, separation, 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 direct costs in the form of tipping fees and indirect costs in the form of environmental impact and depletion of suitable landfill capacities.

An intriguing factor that affects the economics of recycling is the cost of competing materials or materials to be replaced. For example, there is a large cost difference between replacing sand, which is literally dirt-cheap, and marble chips, imported at high cost from Italy. This issue is related to 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 optimize the value of a material and thereby improve its economics.

The last and definitely not the least important economic drivers in a free-market economy are competition and the profit motive. As more recyclers enter the market, competition will bring down the cost of the recycled materials.

5.0 Use of Recycled Materials

Concrete debris is probably the most important candidate for reuse as aggregate 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 [5,6], 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 involves costs, which are likely to go up. Available sources of suitable virgin aggregate are being depleted, such as gravel pits on Long Island, and opening new sources of virgin material is getting increasingly difficult because of environmental concerns. Since the cost of transportation is the main component of 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 [5]. There are contaminants to be dealt with, high porosity, grading requirements, as well as the large fluctuations in quality. Not all applications require high-strength concrete, though. Recycled concrete aggregate is likely to be quite adequate for some projects, while for others, a blend of new and recycled aggregate may make most 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 this perception will change. The open issues are not of a technical nature. The only technical problem, namely the alkali-silica reaction (or ASR) problem can be solved. Likewise, all other potential technical problems can be taken care of. Moreover, 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 waste glass. The consequences on the market price are already apparent, because a new secondary market was created for the glass, and the cost of color-separated clean glass cullet has risen appreciably in recent years. Instead of filling up scarce landfill space with increasing tipping fees, we have demonstrated that tiles, panels, table tops, etc. with stunning effects can be produced commercially using post-consumer 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 will 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 natural sand and gravel, because he does not believe customers are willing to pay that much more for a paving stone, just because it contains recycled glass.

Value-added products do not pose such problems. On the contrary, they are already being produced commercially, even though manufacturers are paying hundreds of dollars per ton for the glass, while most municipalities are paying recyclers to take it away. Those producers are in the fortunate position where they can afford such prices, because the special aggregates replaced by the glass are also costly and the profit margins are high.

Dredged material shall serve as the third example. The Port Authority of New York and New Jersey needs to dredge about 4 million cubic yards each year to keep shipping lanes open and also to deepen them to accommodate the larger modern vessels. As long as the Port Authority was able to dump the material in the open ocean, the disposal cost was minimal. But since national legislation and international treaties are prohibiting such ocean dumping, because much of it is highly contaminated with heavy metals, dioxins, PCBs, oils, etc., the material has to be deposited in engineered landfills at great cost. The financial viability of the Port Authority requires a drastic reduction of such disposal costs. Similar problems are faced by all major 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]. At least, public opposition to construction of treatment facilities and temporary storage of the material can be avoided by treating the material in a barge right after dredging.

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 anywhere from 10 to 70-fold. More research is likely to identify other uses of treated dredged material, thereby adding value to a material, which at present needs to 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 may render unnecessary the mining of hundreds of thousand tons of virgin material. The technical issues are again the least difficult ones to contend with. Much more important are the logistics and scheduling problems, i.e. coordinating the time 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 of all parties 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, which constitute another sizeable fraction of our solid waste. As the carpet fibers are typically made of nylon, they have been shown to improve some mechanical properties of concrete.

Other examples of materials that can be used in concrete are waste wood, rubber tires, plastics, pulp, and paper mill residuals. The challenge is to identify situations where one person's waste or byproduct becomes another person's valuable resource. It requires relatively modest investments in research and development to identify similar inherent valuable properties in other industrial byproducts and thereby beneficiating them. Yet, that will not happen unless the leaders of our industry display vision and courage, which includes a certain amount of risk taking but may also offer potentially lucrative returns. Most important of all, the environment will benefit, and our future generations will thank us for it.

6.0 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, originally 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 six 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 a 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 [4]. Several industry-wide efforts are currently underway to develop guides for the industry, to not only increase the number of LEED-points, but also to improve the environmental friendliness of concrete construction across the board. 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.

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. In New York City, the Battery Park Development Authority has developed guidelines for Green Building construction, which are among the most progressive in the country. The successful completion of the Solaire, the first residential green high-rise building in the US, has demonstrated that it is possible to develop such a building in New York City. Similarly, the Conde Nast Building at 4 Times Square, the country's first green high-rise office building, is proof that the pairing of a progressive developer with a "green" architect can lead to a successful development of such a project.

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 lose again the market share, which it had worked so hard to obtain during the last few decades.

7.0 Conclusions

The economic feasibility of recycling depends largely on the application. In general, virgin materials have a quality control advantage over recycled materials. But the economic feasibility of recycling will increase in time, as virgin materials become increasingly scarce and the disposal costs of construction debris and other waste materials keep increasing. More important, we will see a proliferation of Green Building and sustainability development principles, which will modify the economic picture in favor of the environment. We all agree that we cannot keep wasting our natural resources. Eventually they all will run out. It is basically up to governmental authorities to level the playing field by holding producers responsible for the costs associated with disposal of their products, whether these are associated with reuse, recycling, or landfilling. In many European countries, this is already the law and forces manufacturers to design their products with those disposal costs in mind. In other words: let him who pollutes pay for the cleanup.

The principles of sustainable development are self-evident. It is difficult to disagree with the goal of passing on to future generations a world no worse than the one we were given. The political differences appear when it becomes necessary to balance the needs of environmental preservation against those of development to raise the living standard. The World Summits of Rio and Kyoto were serious attempts to balance the needs of the "haves" and the "have-nots". While the developed, industrialized countries are called upon to reduce pollution of the environment and their share of the usage of the world's resources, including energy, the developing countries need to avoid the mistakes of the past. This problem is particularly acute, since cement production as well as fly ash generation in China and India are expected to increase significantly in the next few decades. Advances in concrete research have demonstrated that it is possible to coordinate these two developments, thereby minimizing the need for vast additional cement production capacity and creating that balancing act of sustainable development on a global scale. The concrete industry, which uses vast amounts of energy and natural resources and contributes to generation of CO_2, can improve its record with an increased reliance on recycled materials and in particular by replacing larges percentages of Portland cement by byproducts of industrial processes. The American concrete industry has not been a leader in this transition. But let us now all work together to keep our planet livable.

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