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Building Green with Concrete

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Abstract

The environmental movement toward sustainability has motivated innovative companies, researchers and industry coalitions to be more environmentally responsible and seek ways to minimize the negative environmental impacts of concrete production and find ways concrete helps building green. Although concrete has a lower total energy intensity than other generally used construction materials, cement production is a highly energy-intensive process and entails potentially significant air and water pollution. In addition, the natural aggregates have finite sources and many public concerns over environmental issues oppose the production of sand and gravel by dredging huge cavities in the traditional landscape. This article highlights several approaches to promote concrete's role in environmental friendly construction and its contribution to sustainable development. This includes use of pozzolanic materials as a replacement of Portland cement in concrete, substitution of virgin aggregate by recycled concrete aggregate, reducing embodied energy and carbon dioxide (CO_2) emission of cement production, use of pervious concrete in storm water management, reducing heat island effect, enhancing energy performance of buildings, use of concrete for CO_2 absorption, and reusable and deconstructible concrete buildings.

Keywords

Sustainable Construction, Pervious Concrete, Recycled Concrete Aggregate, Heat Island Effect, Carbonation.

1. Introduction

Every year more than one cubic meter of ready-mix concrete is produced for each person in the USA. Although concrete has a lower total energy intensity than other generally used construction materials, cement production is a highly energy-intensive process and entails potentially significant air and water pollution. The average energy needed to make a kg of cement in a US kiln is 4.88 MJ and this also produces 0.8 kg of carbon dioxide (CO_2), a main cause of global warming. In addition, the natural aggregates have finite resources and concern over environmental issues oppose the production of sand and gravel by dredging huge cavities in traditional landscape. Furthermore, the demolition of old concrete pavement and structures produce large quantities of waste that in most cases are landfilled. The environmental movement toward sustainability (leaving sufficient resources for future generations to have a quality of life similar to ours) has motivated innovative companies, researchers and industry coalitions to be more environmentally responsible and seek ways to minimize the negative environmental impacts of concrete production. In addition, the recent interest in green buildings that are designed to minimize use of resources such as energy, water, and materials while reducing impacts on human health and the environment during the building's lifecycle, has generated interests in green products. This article highlights the new approaches taken by the US cement industry in reducing embodied energy and carbon dioxide (CO_2) emission of concrete and reviews different ways concrete is currently used to help building green.

1. Reduce Embodied Energy and CO_2 Emission

The initial embodied energy of concrete is the non-renewable energy required to extract and process its raw materials (indirect energy), as well as the energy used to transport concrete to the jobsite and place it (direct energy). The recurring embodied energy of concrete can be defined as the non-renewable energy consumed to maintain and replace it, as well as recycle it or disposing of it at the end of its useful life.

The constituents of concrete are Portland cement, water, fine and coarse aggregates. Quantities of constituent materials used in an actual project will vary depending on mix designs. Table 1 shows quantities of concrete constituents along with their embodied energy for a 28 MPa compressive strength. Other materials that are sometimes added, such as chemical admixtures, are not considered.

Table 1: Embodied energy for one m^3 of a 28 MPa compressive strength concrete

Constituents	Weight kg/m^3	Energy kJ/kg	Energy MJ/m^3
Cement	320	4880	1562
Coarse aggregate	1120	82	92
Fine aggregate	760	82	62
water	160	0	0
Materials Transportation to the ready-mix plant	2200	266	585
Concrete production			247
Concrete transportation to the building site	2360	133	314
Total energy			**2862 MJ/m^3**

The following assumptions were made in calculating the embodied energy of concrete:

- Coarse and fine aggregates are produced from crushed rock using 82 kJ/kg energy (BEES 4.0, 2007)
- Freight transport energy by truck in USA is 2.655 KJ/Kg-km
- Distance for transportation of raw materials to the ready-mix plant is assumed to be 100 km.
- Distance for transportation of concrete to the building site is assumed to be 50 km.

As it is shown in Table 1 almost 55% of embodied energy of one $m^3$of a 28 MPa concrete delivered to the building site is due to its cement content. The major energy in production of Portland cement is consumed during pyro-prossessing. To reduce both energy needs and reliance on fossil fuels many cement companies have turned to energy-rich alternative fuels. Today, many plants in US meet between 20-70% of their energy requirements with alternative fuels (PCA, 2006). Many of these alternative fuels are consumer wastes or byproducts from other industries. A survey of US and Canadian Portland cement industry in 2002 showed that 15 plants used waste oil, and 40 plants in 23 states used scrap tires. Solvents, unrecyclable plastics, and other materials are used as well (PCA, 2002).

In cement manufacturing CO_2 is emitted from 1) the calcination process of limestone and 2) from combustion of fuels in the kiln. Source 1 is fairly constant around 0.50 kg CO_2 per kg of cement. Source 2 varies with plant efficiency: efficient precalciner plant 0.24 kg CO_2 per kg cement, low-efficiency wet process as high as 0.65, and typical modern practices averaging around 0.30. Therefore, typical total CO_2 emission is around 0.80 kg CO_2 per kg finished cement (Hanle, et al, 2004).

In 2000, the US cement industry started measuring carbon dioxide (CO_2) emissions, and by the year 2020, the industry plans to voluntarily reduce CO_2 emissions by 10 percent below the 1990 baseline (PCA, 2006). This goal will be achieved by upgrading plants with state-of-the-art equipment, reducing energy of production, a shift to low carbon fuels, application of waste fuels, increased use of additives in cement making, and removal of alternative cements and CO_2 from flue gases in clinker kilns.

The major waste material from cement manufacturing is cement kiln dust (CKD). An industry average of 38.6 kg of CKD is generated per metric ton of cement. Of this, 30.7 kg is landfilled and 7.9 kg is reused on-site or sold for a variety of beneficial uses (PCA, 2006).

2. Use of Recycled Concrete Aggregate

As concern and awareness for the environment increases, political and ecological entities are rightly protesting against the methods used to extract the sand and gravel from the earth. Both dredging and mining scar the earth's surface for life, and even though the vast pits and craters that are generated are sometimes transformed into green areas for society, this is no excuse to destroy the traditional landscape. Furthermore, disposal problems have risen from excessive volume of construction and demolition waste evolving into a drastic escalation of tipping fees for dumping refuse at a site.

There is an acceptable solution to these problems. If old demolished concrete was crushed to acceptable sizes, removing impurities such as steel ties, PVC pipes, and rebar along the way, it could easily be utilized for road base material or in Portland Cement Concrete (PCC) pavement (Chini et al., 2001a). Numerous other possibilities exist for the use of reclaimed PCC such as for pipe bedding, drain fields, parking lots, highway shoulders, etc. Regardless of its use, by not throwing away demolished concrete at a landfill location, the amount of natural raw materials produced yearly could decline vastly.

Total building related and infrastructural C&D waste concrete generated annually in US is estimated to be about 182 MMT (Sandler, 2003). It is estimated that about 50 percent (91 MMT) of waste concrete is recycled annually into usable aggregates. This is roughly 5 percent of 1.8 billion metric tons total aggregates market. The rest is supplied by virgin aggregates from natural sources. An estimated 68 per cent of aggregate recycled from concrete is used as road base and the remainder is used for new concrete (6 percent), asphalt hot mixes (9 percent), and low value products like general fill (Deal, 1997). The low usage rate of recycled concrete aggregate (RCA) in new concrete and asphalt hot mixes (15 percent) compared to the higher usage rates in lower valued products is related to real and perceived quality issues. Many State agencies have allowed use of RCA mostly as road base materials and not for high-quality uses such as road surfacing.

The future of recycled aggregates will be driven by higher landfill costs, greater product acceptance, government recycling mandates, and a large stock of existing roads and buildings to be demolished. Favorable in-service experience with recycled aggregates and development of specifications and guidelines for their use are necessary for recycled aggregate acceptance. A sustainable recycling aggregate industry requires sufficient raw materials, favorable transportation distances, product acceptance and limited landfill space.

3. Use of Supplementary Cementitious Materials

Consuming less cement in production of concrete is the first step in reducing the energy consumption and greenhouse-gas emissions. There are adequate supplies of solid industrial by-products such as fly ash, slag, and silica fume with cementitious and/or pozzolanic properties that can be used as cement substitutes, thus eliminating the need for the production of more portland cement clinker. In addition, portland cement blends containing 50% or more granulated blastfurnace slag or fly ash can yield much more durable concrete products than the pure portland cement.

Fly ash is a by product of coal fired electric generating plants and is used to partially replace Portland cement (by up to 60% by mass). In addition to economic and ecological benefits, the use of fly ash in concrete improves its workability and reduces heat of hydration. Although there is a steady growth in the use of fly ash in concrete, only less than 35% of the fly ash collected is being used in the cement and concrete industries (US Concrete, 2009). Vast quantities of fly ash and other by-products still end up either in low-value applications such as landfills and road subbases, or are simply disposed by ponding and stockpiling.

Ground granulated blast-furnace slag is a by product of steel production. It is highly cementitious in nature and, ground to cement fineness, hydrates like portland cement. Substitution of ground granulated blast furnace slag for up to 70 percent of the portland cement in a mix has been used.

Silica fume is a by-product of the production of silicon and ferrosilicon alloys. It has a particle size 100 times smaller than fly ash and therefore a much faster pozzolanic reaction. Silica fume is used to increase strength and durability of concrete, but generally requires the use of superplasticizers for workability.

4. Reuse of Wash Water/Aggregate Claimers

Another environmental issue that the concrete industry is attempting to solve is disposal of the waste water generated from the Ready-Mix Concrete (RMC) operations. The waste water is usually generated from truck wash systems, washing of central mixing plant, and storm-water runoff from the ready-mix plant. The quantity of waste water generated from truck wash alone is estimated to range between 3000 to 5000 gallons per day per single ready-mix plant. In the U.S., the amount of wash water generated is approximated at 1,240 million gallons annually. According to the Water Quality Act, truck wash water is a hazardous substance (it contains caustic soda and potash) and its disposal is regulated by the Environmental Protection Agency (EPA). In addition, a high pH makes truck wash water hazardous under the EPA definition of corrosivity.

The current practices for the disposal of concrete wash water include dumping at a landfill, dumping in a concrete recycling plant, or dumping into a concrete wash water pit at the ready-mix plant. The availability of landfill sites for the disposal of truck wash water has been drastically reduced over the past twenty years. In response to this reduction, most ready-mix batch plants have developed a variety of operational configurations to manage their own wash water. The alternatives include settling ponds, storm water detention/retention facilities and water reuse systems. As efficient as wash systems at batch plants may be, they still can not accommodate the amount of waste water flow needed.

One alternative to disposal of concrete wash water in the usual way is the use of chemical stabilizing systems (Chini et al., 2002). The use of these admixtures circumvents the necessity to remove any wash water from concrete truck drums, and allows wash water to be reused for mixing more concrete. Concrete treated with the stabilizing/activating admixtures behaves just like ordinary concrete. These stabilizing systems have additional advantage in that not only waste water is recycled but all the returned concrete is recycled.

A more promising method of disposal of waste water is to recycle (Chini, 2001b). The reclaimed waste water from the reclamation systems can be used as batch water for fresh concrete. Reclaimed concrete waste water has been used in the past for washout purposes or producing fresh concrete. The main concern with the practice has been the lack of knowledge of what effects the impurities in the waste water have on the properties of concrete. The research and the experience of the RMC industry with the use of concrete waste water indicate that its effects on concrete quality are neither significant nor important. This finding indicates that the problem of disposing waste water from RMC operations in an environmentally acceptable manner can be eased by re-using the waste water as concrete mixing water.

5. Sustainable Uses

Concrete is durable, light in color, can be pervious, has high density and thermal mass, absorbs CO_2, and does not pollute its final environments. As a result, it can provide solutions for the built environment that help achieve sustainable development.

5.1 Durability

Concrete durability has been defined by the American Concrete Institute as its resistance to weathering action, chemical attack, abrasion and other degradation processes. As a highly durable construction material with low maintenance requirements, well-designed concrete structures can be expected to exceed their minimum service life. This is especially critical in the infrastructure system because it allows valuable resources be spent on improving the infrastructure system, instead of on replacing or maintaining a deteriorating system.

Concrete's durability also allows repeated use of the building's structural framework for redesign and refurbishment after the initial use of the space has passed. This means that a concrete building will come to the end of its life when no further use can be found for it, not when the concrete has failed.

Ability of concrete to resist extreme weather events such as hurricane and flooding reduces destruction and prevents waste generation. Concrete's water resistance minimizes time required for drying, cleaning, and repair of damaged buildings and makes quick re-occupancy possible.

5.2 Heat Island Effects

In cities and urban areas, where more buildings and pavements have taken the place of trees and vegetation, the temperature is 2 to 4°C warmer than the surround area due to the heat island effects. Trees and vegetation give off water that evaporates and cools their surfaces and surrounding air. This rise of temperature in hot days increases the peak energy consumption due to higher air conditioning load and increases the probability of smog and pollution.

The ratio of the amount of solar radiation reflected from a surface to the total amount reaching the surface is called solar reflectance. The U.S. Green Building Council uses an index called the solar reflective index (SRI) to estimate how hot a surface will get when exposed to full sun. SRI of a surface is a function of its solar reflectance and emmisivity. For opaque non-metallic construction materials such as concrete, wood and asphalt SRI of a surface is mainly a function of its solar reflectance. Table 2 exhibits solar reflectance and SRI of some common construction materials used on roads, parking lots, driveways and sidewalks (PCA, 2008). Using materials with higher SRI will reduce the heat island effect, consequently saving energy by reducing demand for air conditioning, and improve air quality. The table shows that solar reflectance for new concrete is 0.35 to 0.45 compared to 0.05 for new asphalt. As a result paving areas covered with concrete will minimize the urban heat island effect.

Another benefit of using concrete pavements is that its higher surface reflectivity reduces need for street lighting. It is estimated that electricity savings of about 30% could be achieved due to better light reflection on the brighter concrete surface (CCANZ, 2007). In addition, higher surface reflectivity reduces number of accidents and its associated loss of life and injury.

Table 2. Solar reflectance and Solar Reflective Index (SRI) of select material surfaces

Material surface	Solar Reflectance	SRI
Black acrylic paint	0.05	0
New asphalt	0.05	0
Aged asphalt	0.1	6
New concrete (ordinary)	0.35 to 0.45	38 to 52
Aged concrete	0.2 to 0.3	19 to 32
White acrylic paint	0.8	100

5.3 Pervious Concrete

Concern has been growing in recent years toward reducing pollution levels in streams, rivers, lakes, and the environment. Storm-water has a significant effect on pollution level because it contains pesticides from agricultural land, bacteria from livestock wastes, and fuels and oils from vehicles. Runoff from developed real estates has the potential to pollute surface and groundwater supplies. Excessive storm-water also reduces groundwater recharge and therefore diminishes aquifer supplies. Pervious concrete pavement reduces the impact of development by reducing runoff rates and protecting water supplies.

Pervious concrete has been defined by American Concrete Institute as a zero slump, open-graded concrete with little or no fine aggregate. A pervious concrete pavement has a hard surface with connected pores ranging in size from 2 to 8 mm that allow water to pass through easily. The drainage rate of pervious concrete pavement will vary with aggregate size and density of the mixture, and varies from 81 to 730 L/min/m2 (ACI, 2006). This allows rainwater to drain through the paved surface in a controlled way into the ground before being released into sewers or waterways. The use of pervious concrete is a simple and effective means of reducing the amount of storm-water and reduces the necessity for other more expensive storm-water management systems. It contributes toward sustainability, both environmentally and economically.

5.4 High Density and Thermal Mass

Thermal mass is the ability of a material to absorb heat energy. A large thermal mass within the insulated portion of a building is effective in improving building comfort in any place that experiences outside daily temperature fluctuations -- both in winter as well as in summer. By absorbing heat when the surroundings are hotter than the mass and giving heat back when surroundings are cooler, thermal mass can play an important role in reducing energy use of the building's heating and cooling systems.

Concrete is an ideal material for thermal mass because it has a high specific heat capacity and high density. A lot of heat energy is required to change the temperature of a high density material like concrete. For example, the heat energy required to raise concrete's temperature one Celsius degree is 880 joules per kilogram. Concrete's thermal mass helps maintain a minimum indoor temperature of 9ºC, a level below which there is an increased risk of dust mites and allergens. Concrete walls also tend to remain at a more stable temperature, reducing condensation and thereby minimizing mold and mildew.

5.5 CO_2 Absorption

The carbonation of concrete is a chemical process where atmospheric CO_2 reacts with CaO in the concrete to form calcium carbonate (CaCO3). This counters the CO_2 emissions resulting from the calcination of limestone during original manufacture of cement. In other words, while CO_2 is released to the atmosphere through calcination of limestone in the manufacturing process, CO_2 is re-absorbed again during the life cycle of concrete. The carbonation process is relatively slow process and depends on the diffusion rate of CO_2 into the concrete. Surfaces in direct contact with carbon dioxide and water carbonate rapidly, while the interior of concrete carbonates at a slower rate.

Traditionally, the carbonation of concrete has been associated with negative issues such as alkalinity loss and corrosion of reinforcement. Therefore, carbonation during the service life of structural Portland cement concrete is intentionally minimized to avoid the potential for corrosion of steel reinforcing bar. The potential for CO_2 uptake at the end of a concrete product's service life is greatly enhanced when it is crushed and the absorption of CO_2 can proceed more readily due to several orders of magnitude increase in its surface area. As carbonation has the potential to reduce the net CO_2 emissions of cement-based materials, it should be considered in life cycle analyses and will also have a significant effect on the criteria for environmental labeling of cement-based materials (CCANZ, 2007).

A Canadian company named Carbon Sense Solutions based in Halifax claims that it has found a technique to accelerate precast concrete curing using CO_2 within the combustion flue gases. This technique will not only reduce greenhouse gas emissions, but will replace conventional energy-intensive steam and heat accelerated curing techniques. There is some skepticism about the ability to achieve complete carbonation that takes hundreds of years into as little as one hour during curing. In particular, some believe that as soon as cement hydration starts, the CO_2 coats everything and blocks further hydration. This does accelerate hardening, but reduces ongoing strength development and the concrete remains porous because hydration is blocked. The team at Carbon Sense Solutions appears ready to take on the challenge as it scales up production and undertakes a complete material testing program (Mehta, 2008).

5.6 Reuse and Deconstruction

The best way to preserve the embodied energy of a concrete structure is adaptive reuse. That is, the building is fit for a new use when it is no longer needed for its original use. Buildings that employ concrete frame structural systems are well suited for reuse. Deconstruction or the disassembly of the structure for the purpose of reusing its components is the next option when reuse of the whole concrete frame is not feasible. The primary intent is to divert the maximum amount of the structural components from the waste stream. Top priority is placed on the direct reuse of the components in new structures. Immediate reuse allows the materials to retain their current economic value.

There are several existing demountable building-systems in the Netherlands that at any given point in time, the structure's standard components can be dismantled and removed from the site for storage or re-erection on another site (Dorsthorst et al., 2000). These systems use standardized precast concrete structural components that are assembled without the need for poured or welded connections. A company in New Zealand named Worldwide Parking Group Ltd has developed an innovative precast concrete system for parking garages that has the potential for reuse on other sites. The company has built two car parking buildings at Auckland International airport and one in Newmarket, Auckland (CCANZ, 2007). Demountable structures will be used more often in the future as architects/engineers become more aware of precast concrete's lifecycle cost advantages. Demountable modular precast concrete components have a low cost outlay, fast assembly, minimal maintenance, and potential reuse. These are all attractive benefits in a construction environment concerned with sustainability.

5.7 Photocatalytic cement concrete

Italcemnti Group in Europe has recently developed a patented portland cement that has Photocatalytic components (Barbesta and Schaffer, 2009). Theses components use the energy from ultraviolet rays to oxidize most organic and some inorganic compounds. Concrete and plaster made with this new cement can remove pollutants from the air as its surface is kept clean when residues are washed off by rain.

Photocatalytic cement was recently used to produce two 9 m tall gateway elements at the entrances to the new I-35 W bridge in Minneapolis, MN.

6. Summary

In summary, embodied energy and CO2 emission of concrete can be reduced by using industrial by-products with cementitious and/or pozzolanic properties such as fly ash, slag, and silica fume as cement substitutes. Use of recycled aggregate and wash water in concrete production make concrete a more environmental friendly construction material by (a) conserving natural resources and (b) disposing of waste materials. Concrete's role in sustainable development will be further enhanced as material recycling becomes a more integral part of the cement and concrete industry. Design of concrete buildings for reuse and disassembly can help preserve embodied energy of concrete structural framing systems. Use of concrete's durability and thermal efficiency, and application of pervious concrete in stormwater management are becoming more commonplace and increase the contribution of concrete to sustainable construction. A technique to accelerate precast concrete curing using CO_2 within the combustion flue gases is promising and will not only reduce greenhouse gas emissions, but will replace conventional energy-intensive steam and heat accelerated curing techniques.

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