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Energy
Materials
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Cement and Concrete: Environmental Considerations

From EBN Volume 2, No. 2 -- March/April 1993

Contents:

Cement and concrete are key components of both commercial and residential construction in North America. The cement and concrete industries are huge. There are approximately 210 cement plants in the U.S. and 4,000 to 5,000 ready mix plants (where cement is mixed with aggregate and water to produce concrete). The Portland Cement Association estimates that U.S. cement consumption has averaged between 75 and 90 million tons per year during the last decade, and projects that consumption will exceed 100 million tons per year by 1997. Worldwide, cement production totaled 1.25 billion tons in 1991, according to the U.S. Bureau of Mines.

What does this mean in terms of the environment? Are these products good or bad? As builders and designers, should we be looking for alternatives or embracing concrete over competing materials? As with most building issues, the answers are not clear-cut. Concrete and other cementitious materials have both environmental advantages and disadvantages. This article takes a look at how these materials are made, then reviews a number of environmental considerations relating to their production, use, and eventual disposal.

Cement and Concrete Production

Cement is the key ingredient in concrete products. Comprising roughly 12% of the average residential-grade ready mix concrete, cement is the binding agent that holds sand and other aggregates together in a hard, stone-like mass. Portland cement accounts for about 95% of the cement produced in North America. It was patented in England by Joseph Aspdin in 1824 and named after a quarried stone it resembled from the Isle of Portland.

Cement production requires a source of calcium (usually limestone) and a source of silicon (such as clay or sand). Small amounts of bauxite and iron ore are added to provide specific properties. These raw materials are finely ground and mixed, then fed into a rotary cement kiln, which is the largest piece of moving industrial equipment in the world. The kiln is a long, sloping cylinder with zones that get progressively hotter up to about 2700°F (1480°C). The kiln rotates slowly to mix the contents moving through it. In the kiln, the raw materials undergo complex chemical and physical changes required to make them able to react together through hydration. The most common type of cement kiln today (accounting for 70% of plants in the U.S.) is a *dry process* kiln, in which the ingredients are mixed dry. Many older kilns use the *wet process*.

The first important reaction to occur is the *calcining* of limestone (calcium carbonate) into lime (calcium oxide) and carbon dioxide, which occurs in the lower-temperature portions of the kiln--up to about 1650°F (900°C). The second reaction is the bonding of calcium oxide and silicates to form dicalcium and tricalcium silicates. Small amounts of tricalcium aluminate and tetracalcium aluminoferrite are also formed. The relative proportions of these four principal compounds determine the key properties of the resultant portland cement and the type classification (Type I, Type II, etc.). These reactions occur at very high temperatures with the ingredients in molten form. As the new compounds cool, they solidify into solid pellet form called *clinker*. The clinker is then ground to a fine powder, a small amount of gypsum is added, and the finished cement is bagged or shipped bulk to ready mix concrete plants.

Concrete is produced by mixing cement with fine aggregate (sand), coarse aggregate (gravel or crushed stone), water, and--often--small amounts of various chemicals called *admixtures* that control such properties as setting time and plasticity. The process of hardening or setting is actually a chemical reaction called *hydration*. When water is added to the cement, it forms a slurry or gel that coats the surfaces of the aggregate and fills the voids to form the solid concrete. The properties of concrete are determined by the type of cement used, the additives, and the overall proportions of cement, aggregate, and water.

Raw Material Use

The raw materials used in cement production are widely available in great quantities. Limestone, marl, and chalk are the most common sources of calcium in cement (converted into lime through calcination). Common sources of silicon include clay, sand, and shale. Certain waste products, such as fly ash, can also be used as a silicon source. The iron and aluminum can be provided as iron ore and bauxite, but recycled metals can also be used. Finally, about 5% of cement by weight is gypsum, a common calcium- and sulfur-based mineral. It takes 3,200 to 3,500 pounds of raw materials to produce one ton (2,000 lbs.) of finished cement, according to the Environmental Research Group at the University of British Colombia (UBC).

The water, sand, and gravel or crushed stone used in concrete production in addition to cement are also abundant (typical proportions of a residential concrete mix are shown in Table 1). With all of these raw materials, the distance and quality of the sources have a big impact on transportation energy use, water use for washing, and dust generation. Some aggregates that have been used in concrete production have turned out to be sources of radon gas. The worst problems were when uranium mine tailings were used as concrete aggregate, but some natural stone also emits radon. If concerned, you might want to have the aggregate tested for radon.

Table 1: Typical Concrete Mix

Component	Percent by weight
Portland cement	12%
Sand	34%
Crushed stone	48%
Water	6%

Source: Based on figures provided by the Ready Mix Concrete Association, personal communication.

The use of fly ash from coal-fired power plants is beneficial in two ways: it can help with our solid waste problems, and it reduces overall energy use. While fly ash is sometimes used as a source of silica in cement production, a more common use is in concrete mixture as a substitute for some of the cement. Fly ash, or *pozzolan*, can readily be substituted for 15% to 35% of the cement in concrete mixes, according to the U.S. EPA. For some applications fly ash content can be up to 70%. Of the 51 million tons of fly ash produced in 1991, 7.7 million tons were used in cement and concrete products, according to figures from the American Coal Ash Association. Thus, fly ash today accounts for about 9% of the cement mix in concrete.

Fly ash reacts with any free lime left after the hydration to form calcium silicate hydrate, which is similar to the tricalcium and dicalcium silicates formed in cement curing. Through this process, fly ash increases concrete strength, improves sulfate resistance, decreases permeability, reduces the water ratio required, and improves the pumpability and workability of the concrete. Western coal-fired power plants produce better fly ash for concrete than eastern plants, because of lower sulfur and lower carbon content in the ash. (Ash from incinerators cannot be used.)

There are at least a dozen companies providing fly ash to concrete producers. Talk to your concrete supplier and find out if they are willing to add fly ash to the mix. (If your local plant doesn't know where to get the fly ash, a list of companies is available from EBN.) Portland cement with fly ash added is sometimes identified with the letter *P* after the type number (Type IP). The EPA requires fly ash content in concrete used in buildings that receive federal funding (for information call the EPA Procurement Guidelines Hotline at 703/941-4452). Fly ash is widely used in Europe as a major ingredient in autoclaved cellular concrete (ACC); in the U.S., North American Cellular Concrete is developing this technology (see EBN, Volume 1, No. 2 -- September/October 1992).

Other industrial waste products, including blast furnace slag, cinders, and mill scale are sometimes substituted for some of the aggregate in concrete mixes. Even recycled concrete can be crushed into aggregate that can be reused in the concrete mix--though the irregular surface of aggregate so produced is less effective than sand or crushed stone because it takes more cement slurry to fill all the nooks and crannies. In fact, using crushed concrete as an aggregate might be counterproductive by requiring extra cement--by far the most energy-intensive component of concrete.

Energy

Energy consumption is the biggest environmental concern with cement and concrete production. Cement production is one of the most energy intensive of all industrial manufacturing processes. Including direct fuel use for mining and transporting raw materials, cement production takes about six million Btus for every ton of cement (Table 2). The average fuel mix for cement production in the United States is shown in Table 3. The industry's heavy reliance on coal leads to especially high emission levels of CO_2, nitrous oxide, and sulphur, among other pollutants. A sizeable portion of the electricity used is also generated from coal.

Table 2
Embodied Energy for Cement and Concrete Production

	% by weight	Btus per ton		Btus/yard concrete	Energy %
		Materials	Hauling		
Cement	12%	5,792,000	504,000	1,574,000	94%
Sand	34%	5,000	37,000	29,000	1.7%
Crushed Stone	48%	46,670	53,000	100,000	5.9%
Water	6%	0	0	0	0%
Concrete	100%	817,600		1,700,000	100%

Notes:

Calculations of energy requirements for cement production based on figures supplied by the Portland Cement Association, 1990 data. Aggregate and hauling energy requirements based on data supplied by PCA and based on the following assumptions:

- Cement hauled 50 miles to ready-mix plant
- Aggregate hauled 10 miles to plant
- Concrete mix hauled 5 miles to building site
- Concrete mix: 500 lbs. cement, 1,400 lbs. sand, 2,000 lbs. crushed stone, 260 lbs. water per yard.

The vast majority of the energy consumed in cement production is used for operating the rotary cement kilns. Newer dry-process kilns are more energy efficient than older wet-process kilns, because energy is not required for driving off moisture. In a modern dry-process kiln, a pre-heater is often used to heat the ingredients using waste heat from the exhaust gases of the kiln burners. A dry-process kiln so adapted can use up to 50% less energy than a wet-process kiln, according to UBC researchers. Some other dry-process kilns use a separate combustion vessel in which the calcining process begins before the ingredients move into the rotary kiln--a technique that can have even higher overall efficiency than a kiln with pre-heater.

In the United States, producing the roughly 80 million tons of cement used in 1992 required about .5 quadrillion Btus or quads (1 quad = 10^{15} Btus). This is roughly .6% of total U.S. energy use, a remarkable amount given the fact that in dollar value, cement represents only about .06% of the gross national product. Thus, cement production is approximately ten times as energy intensive as our economy in general. In some Third World countries, cement production accounts for as much as two-thirds of total energy use, according to the Worldwatch Institute.

While cement manufacturing is extremely energy intensive, the very high temperatures used in a cement kiln have at least one advantage: the potential for burning hazardous waste as a fuel. Waste fuels that can be used in cement kilns include used motor oil, spent solvents, printing inks, paint residues, cleaning fluids, and scrap tires. These can be burned relatively safely because the extremely high temperatures result in very complete combustion with very low pollution emissions. (Municipal solid waste incinerators operate at considerably lower temperatures.) Indeed, for some chemicals thermal destruction in a cement kiln is the safest method of disposal. A single cement kiln can burn more than a million tires a year, according to the Portland Cement Association. Pound for pound, these tires have a higher fuel content than coal, and iron from the steel belts can be used as an ingredient in the cement manufacturing. Waste fuels comprise a significant (and growing) part of the energy mix for cement plants (see Table 3), and the Canadian Portland Cement Association estimates that waste fuel could eventually supply up to 50% of the energy.

Table 3: Fuel Use for Cement Production

Fuel	Thousand Btus per ton of cement	Percent
Petroleum products (diesel, gasoline, LPG)	63.	1.1
Natural gas	476.	8.2
Coal & coke	3,524.	60.8
Waste fuel[1]	286.	4.9
Electricity[2]	1,443.	24.9
Total	**5,792.**	**100.**

Sources:

- Waste fuel includes used motor oil, waste solvents, scrap tires, etc.
- Electricity figure includes primary energy used to generate the electricity.
  Source: Portland Cement Association, *U.S. Cement Industry Fact Sheet*, page 15. 1990 data.

Energy use for concrete production looks considerably better than it does for cement. That's because the other components of concrete--sand, crushed stone, and water--are much less energy intensive. Including energy for hauling, sand and crushed stone have embodied energy values of about

40,000 and 100,000 Btus per ton, respectively. The cement, representing about 12% of concrete, accounts for 92% of the embodied energy, with sand representing a little under 2% and crushed stone just under 6% (see Table 2).

Use of fly ash in concrete already saves about 44 trillion Btus (.04 quads) of energy annually in the U.S. Increasing the rate of fly ash substitution from 9% to 25% would save an additional 75 trillion Btus.

CO2 Emissions

There are two very different sources of carbon dioxide emissions during cement production. Combustion of fossil fuels to operate the rotary kiln is the largest source: approximately $^{3}/4$ tons of CO_2 per ton of cement. But the chemical process of calcining limestone into lime in the cement kiln also produces CO_2: $CaCO_3$ ' CaO + CO_2limestone ' lime + carbon dioxide This chemical process is responsible for roughly 1/2 ton of COCO_2 per ton of cement, according to researchers at Oak Ridge National Laboratory. Combining these two sources, for every ton of cement produced, 1.25 tons of CO_2 is released into the atmosphere (Table 4). In the United States, cement production accounts for approximately 100 million tons of CO_2 emissions, or just under 2% of our total human-generated CO_2. Worldwide, cement production now accounts for more than 1.6 billion tons of CO_2--over 8% of total CO_2 emissions from all human activities.

Table 4: CO2 Emissions from Cement and Concrete Production

	lbs CO2 per ton of cement	**lbs CO2 per cu. yd. of concrete**	**Percent of total CO2**
CO2 emissions from energy use	1,410	381	60
CO2 emissions from calcining of limestone	997	250	40
Total CO2 emissions	2,410	631	100

Notes:

- Calculations of energy requirements for cement and concrete as in Table 2.
- CO2 emissions from different fuels from ACEEE *Consumer Guide to Home Energy Savings*, 1991.
- Estimates of emissions from calcining limestone from *CO2 Release from Cement Production 1950-1985*, by Richard Griffin, Institute for Energy Analysis, Oak Ridge Assoc. Universities, 8/87.

The most significant way to reduce CO_2 emissions is improving the energy efficiency of the cement kiln operation. Indeed, dramatic reductions in energy use have been realized in recent decades, as discussed above. Switching to lower-CO_2 fuels such as natural gas and agricultural waste (peanut hulls, etc.) can also reduce emissions. Another strategy, which addresses the CO_2 emissions from calcining limestone, is to use waste lime from other industries in the kiln. Substitution of fly ash for some of the cement in concrete can have a very large effect.

Other Air Emissions

Besides CO_2, both cement and concrete production generate considerable quantities of air-pollutant emissions. Dust is usually the most visible of these pollutants. The U.S. EPA (cited by UBC researchers) estimates total particulate (dust) emissions of 360 pounds per ton of cement produced, the majority of which is from the cement kiln. Other sources of dust from cement production are handling raw materials, grinding cement clinker, and packaging or loading finished cement, which is ground to a very fine powder--particles as small as $^{1}/25,000$ of an inch.

The best way to deal with the dust generated in cement manufacturing would be to collect it and put it back into the process. This is done to some extent, using mechanical collectors, electric precipitators, and fabric filters (baghouses). But recycling the dust is difficult, according to UBC researchers; it first has to be treated to reduce its alkalinity. Some cement kiln dust is used for agricultural soil treatments, and the rest (of that collected) is often landfilled on site. There was investigation into the possibility of using cement kiln dust for treatment of acidified lakes in eastern Canada, but rather than simply buffering the low pH of the water, the dust chemically created a potentially harmful salt.

In addition to dust produced in cement manufacturing, dust is also generated in concrete production and transport. Common sources are sand and aggregate mining, material transfer, storage (wind erosion from piles), mixer loading, and concrete delivery (dust from unpaved roads). Dust emissions can be controlled through water sprays, enclosures, hoods, curtains, and covered chutes.

Other air pollution emissions from cement and concrete production result from fossil fuel burning for process and transportation uses. Air pollutants commonly emitted from cement manufacturing plants include sulfur dioxide (SO_2) and nitrous oxides (NO_x). SO_2 emissions (and to a lesser extent SO_3, sulfuric acid, and hydrogen sulfide) result from sulfur content of both the raw materials and the fuel (especially coal). Strategies to reduce sulfur emissions include use of low-sulfur raw materials, burning low-sulfur coal or other fuels, and collecting the sulfur emissions through state-of-the-art pollution control equipment. Interestingly, lime in the cement kiln acts as a scrubber and absorbs some sulfur.

Nitrous oxide emissions are influenced by fuel type and combustion conditions (including flame temperature, burner type, and material/exhaust gas retention in the burning zone of the kiln). Strategies to reduce nitrogen emissions include altering the burner design, modifying kiln and pre-calciner operation, using alternate fuels, and adding ammonia or urea to the process. The cement industry claims to have reduced overall pollution emissions by 90% in the last 20 years.

Water Pollution

Another environmental issue with cement and concrete production is water pollution. The concern is the greatest at the concrete production phase. "Wash-out water with high pH is the number one environmental issue for the ready mix concrete industry," according to Richard Morris of the National Ready Mix Concrete Association. Water use varies greatly at different plants, but Environment Canada estimates water use at batching plants at about 500 gallons per truck per day, and the alkalinity levels of washwater can be as high as pH 12. Highly alkaline water is toxic to fish and other aquatic life. Environment Canada has found that rainbow trout exposed to portland cement concentrations of 300, 500, and 1,000 milligrams/liter have 50% mortality times (the time required for 50% of the population in test samples to be killed) of 68, 45, and 29 minutes, respectively.

At the batch plant, washwater from equipment cleaning is often discharged into settling ponds where the solids can settle out. Most plants are required to have process water discharge permits from state, federal, or provincial environmental agencies to dispose of wastewater from these settling ponds. As long as the pH of this wastewater is lower than 12.5, it is not considered a hazardous material by U.S. law. Some returned concrete also gets put into settling ponds to wash off and recover the aggregate. On the positive side, many newer ready mix plants have greatly reduced water use in recent years because of both wastewater disposal issues and drought conditions in some parts of the country. "More companies are going to completely closed-loop systems," according to Terek Kahn of the National Ready Mix Concrete

Association.

Despite the apparent significance of the wastewater concern, the National Ready Mix Concrete Association to date has not developed standards for member companies on wastewater treatment, including rinsing of trucks and chutes at the building site. John Mullarchy of the association says that procedures are developed on a company-by-company basis. In many areas, environmental regulations dictate procedures relative to wastewater treatment. In more urban areas, the on-site rinse water (for chutes) often has to be collected and treated or disposed of at the plant.

Solid Waste

While the cement and concrete industries can help reduce some of our solid waste problems (burning hazardous waste as cement kiln fuel and using fly ash in concrete mixtures, for example), one cannot overlook the fact that concrete is the largest and most visible component of construction and demolition (C&D) waste. According to estimates presented in the AIA *Environmental Resource Guide*, concrete accounts for up to 67% by weight of C&D waste (53% by volume), with only 5% currently recycled. Of the concrete that is recycled, most is used as a highway substrate or as clean fill around buildings. As more landfills close, including specialized C&D facilities, concrete disposal costs will increase and more concrete demolition debris will be reprocessed into roadbed aggregate and other such uses.

Concrete waste is also created in new construction. Partial truckloads of concrete have long been a disposal problem. Ready mix plants have come up with many innovative solutions through the years to avoid creating waste--such as using return loads to produce concrete retaining wall blocks or highway dividers, or washing the unset concrete to recover the coarse aggregate for reuse. But recently, there have been some dramatic advances in concrete technology that are greatly reducing this waste. Concrete *admixtures* are available that retard the setting of concrete so effectively that a partial load can be brought back to the ready mix plant and held overnight or even over a weekend--then *reactivated* for use.

When it is possible to use pre-cast concrete components instead of poured concrete, doing so may offer advantages in terms of waste generation. Material quantities can be estimated more precisely and excess material can be utilized. Plus, by carefully controlling conditions during manufacture of pre-cast concrete products, higher strengths can be achieved using less material. The Superior Wall foundation system, for example, uses only about a third as much concrete as the typical poured concrete wall it replaces. Waste water run-off can also be more carefully controlled at centralized pre-cast concrete facilities than on jobsites.

Another interesting trend that relates to waste minimization is the idea of producing *reuseable* concrete masonry units. The National Concrete Masonry Association has been working on interlocking blocks called *Formwall(TM)*, designed specifically so that they can be reused. While these blocks are not yet on the market, this type of thinking is a big step forward.

Health Concerns

Working with wet concrete requires a number of precautions, primarily to protect your skin from the high alkalinity. Rubber gloves and boots are typically all that is required to provide protection. *Cement dermatitis*, though relatively uncommon, occasionally occurs among workers in the concrete industry who fail to wear the proper protective clothing.

Once it has hardened, concrete is generally very safe. Traditionally, it has been one of the most inert of our building materials and, thus, very appropriate for chemically sensitive individuals. As concrete production has become higher-tech, however, that is changing. A number of chemicals are now commonly added to concrete to control setting time, plasticity, pumpability, water content, freeze-thaw resistance, strength, and color. Most concrete retarders are relatively innocuous sucrose- (sugar-) based chemicals, added in proportions of .03% to .15%. Workability agents or superplasticizers can include such chemicals as sulfonated melamine-formaldehyde and sulphon-ated napthalene formaldehyde condensates. Air-entraining admixtures function by incorporating air into the concrete to provide resistance to damage from freeze-thaw cycles and to improve workability. These are usually added to the cement and identified with the letter *A* after the type (Type IA). These materials can include various types of inorganic salts (salts of wood resins and salts of sulphonated lignin, for example), along with more questionable chemicals such as alkyl benzene sulphonates and methyl-ester-derived cocamide diethanolamine. Fungicides, germicides, and insecticides are also added to some concrete.

Because of these chemical admixtures, today's concrete could conceivably offgas small quantities of formaldehydes and other chemicals into the indoor air. Unfortunately, it is difficult to find out from the manufacturers the actual chemicals in these admixtures. For chemically sensitive clients, it may be advisable to specify concrete with a bare minimum of admixtures, or use a sealer on the finished concrete to minimize offgassing. Asphalt-impregnated expansion joint filler, curing agents that are sometimes applied to the surface of concrete slabs to reduce water evaporation, special oils used on concrete forms, and certain sealants used for treating finished concrete slabs and walls can also cause health problems with some chemically sensitive individuals.

Finally, concrete floors and walls can cause moisture problems and lead to mold and mildew growth, which cause significant health problems in certain individuals. There are two common sources of moisture: moisture wicking through concrete from the surrounding soil; and moisture from the house that may condense on the cold surface of concrete. To eliminate the former, provide good drainage around a foundation, dampproof or waterproof the outside of the foundation walls before backfilling, provide a layer of crushed stone beneath the slab, and install a polyethylene moisture barrier under the slab (protected from the concrete with a layer of sand if possible). To reduce the likelihood of condensation on concrete surfaces, they should be insulated. In northern climates, installing a layer of rigid foam on the outside of the foundation wall and under the slab will generally keep inner surface of the concrete warm enough that condensation will not occur. With interior foundation insulation, provide a vapor barrier to keep moisture from reaching the concrete surface. In southern climates, protecting against condensation may be more difficult.

Summing Up

Cement and concrete are vital components in building construction today. Concrete has many environmental advantages, including durability, longevity, heat storage capability, and (in general) chemical inertness. For passive solar applications, concrete's ability to function as a structural element while also providing thermal mass makes it a valuable material. In many situations concrete is superior to other materials such as wood and steel. But cement production is very energy intensive--cement is among the most energy-
intensive materials used in the construction industry and a major contributor to CO_2 in the atmosphere. To minimize environmental impact, therefore, we should try to reduce the quantity of concrete used in buildings, use alternative types of concrete (with fly ash, for example), and use that concrete wisely. The accompanying checklist provides practical suggestions for accomplishing these goals.

- Alex Wilson

Using Concrete Wisely: A Checklist for Builders and Designers

- **Reduce waste.**Carefully estimate quantities of concrete required on the jobsite. For large jobs, hire an expediter, who will be on site during pours to estimate exact material requirements.
- **Consider alternative foundation systems.** Pier foundations use far less concrete than poured full-height foundation walls or slab-on-grade foundations (be sure to provide adequate insulation and air sealing details at the floor system). Building a shallow footing and frost walls with horizontal insulation, which effectively reduces the frost depth, can cut concrete use considerably in northern climates.
- **Consider pre-cast concrete systems.** The integrated footer/foundation wall/insulation system produced by Superior Walls, Inc. uses considerably less concrete than conventional poured foundation walls.
- **Specify minimal admixture use.** If your clients have chemical sensitivities, specify minimal use of chemical additives for controlling concrete properties and workability--at least until adequate studies are

done to determine whether offgassing might be a realistic concern. Sucrose-based retarders should not pose any problems.

- **Specify fly ash.** Fly ash can be added to most concrete mixtures, usually with an improvement in workability and strength. Proportions up to 15% can be achieved quite easily, and higher levels are possible. Fly ash from western sources is generally better than that from eastern sources.
- **Avoid on-site environmental damage.** On the building site, use care to avoid soil compaction and resultant damage to trees. Make provisions for concrete trucks to reach the building site with a bare minimum of repositioning and turning around. Also avoid driving over tree roots. Plan ahead with these issues in mind.
- **Control washwater run-off.** If washwater from rinsing concrete chutes and trucks is not otherwise regulated, the general contractor should plan with the concrete truck driver exactly where rinsing can be done. Avoid locations where run-off will get into topsoil or flow into surface water.
- **Use concrete waste as fill.** Whenever possible, specify crushed concrete debris as clean fill around buildings or as aggregate under parking lots and driveways.

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