Concrete and Sustainable Development

by Vesa Penttala

The first signs of global warming caused by the greenhouse effect are now apparent. In the near future, a new evaluation of building materials in light of their ability to fulfill the requirements of sustainable development will be required. In this paper, the energy consumption and greenhouse gas emissions of concrete in residential buildings will be examined, taking into consideration production and operational phases, as well as traffic-induced energy consumption and emissions in residential areas. The massiveness of concrete buildings causes significant energy and emission savings compared to buildings comprised of lighter materials. This improves the ecological balance of concrete and lifts it to the group of building materials which burden the environment least.

Keywords: by-products; concrete; carbonation; cement production; durability life; emissions; energy absorption; energy consumption; environmental effects; heating energy; life cycles; service life; sustainable development; recycling; wastes.

The annual global production of concrete is about 5 billion tons. Mankind consumes only water in larger quantities. The production of brick structures is only about one-tenth of the amount of concrete by weight and wooden structures are built less than 5 percent of the annual concrete production in the world measured by weight basis. Concrete has an exceptionally important role in such densely populated developing countries as India and China. Because of the large production amount it is important to define concrete’s impact on global ecology.

ENVIRONMENTAL THREATS

The greatest threats that endanger the prevailing future on earth are population growth; global temperature rise, i.e., the greenhouse effect; impurities in the air, seas, lakes, and soil; and the limited supply of available fresh water resources. These features are somewhat interrelated, but in Western Europe and North America some progress has been achieved in diminishing atmospheric and watercourse pollution.

The worst pollutants are such synthetic industrial by-products as PCB and CFC1-aerosol gases, which destroy the ozone layer in the stratosphere. According to international treaties, the production of CFC1 gases has been banned. Due to strict legislation the quality of water sources has improved remarkably over the last 15 years, particularly in the Nordic countries. Similarly, the emission of sulfur into the atmosphere has diminished in those countries where cleaning facilities have been installed for exhaust gases of electricity and heat power stations using fossil energy sources. This has also decreased the amount of acid rain and thus diminished the acidity in soil and water sources.

It has proven difficult to restrict the gas emissions of carbon and nitrogen oxides, which are vital for life on earth. Carbon dioxide is essential in the photosynthesis of plants. The level of CO₂ in air has increased during the last 200 years due to the effects of industrial revolution. These CO₂ emissions are increasing primarily due to traffic emissions and other uses of fossil fuels. According to the curve presented in Fig. 1, the gradient of the CO₂-emission curve has slowly but steadily increased. Carbon dioxide, methane, nitrogen oxides, CFC1 gases and water vapor belong to the group of so-called greenhouse gases that are responsible for the global temperature increase. The greenhouse gases allow high-frequency heat waves from the sun to penetrate the atmosphere and heat the surface of earth, but they do not allow the low-frequency heat radiation from earth’s surface to escape back into space. The increased quantity of greenhouse gases in the atmosphere increases the earth’s surface temperature. A simple additional law does not apply in this phenomenon—the effect of an increase in greenhouse gases is nonlinear in respect to the temperature rise. A small increase in the amount of greenhouse gas causes an enhanced response in the global temperature rise because more water vapor evaporates into the atmosphere due to the higher temperature; thus, the warming effect in exaggerated.
About 85 percent of the oxides of nitrogen in the atmosphere are caused by traffic emissions and energy production. NO\textsubscript{x} gases also lower the pH values of water sources and soils as a result of acid rain.

**RESEARCH SIGNIFICANCE**

The first effects of global warming caused by the greenhouse gases are only now becoming apparent; by 2010 they will most likely exert a drastic effect on public opinion and eventually on legislation. This author’s opinion is that not only building processes will be evaluated according to sustainable development, but the discharges and effects from maintenance and heating or cooling will also be taken into consideration in the life-span analysis of buildings.

Currently cement-based materials are more widely used than any other building material in the world. Possible carbon-dioxide taxation based on unreasonable pretenses could have a drastic effect on concrete consumption. A CO\textsubscript{2} tax would not take into account the beneficial effects of concrete carbonation, which would be unfair since during its life span concrete acts as a CO\textsubscript{2}-sink.

Similarly, such positive effects as reductions in heating or cooling energy consumption, due to the massiveness of concrete structures as compared to buildings erected from lighter materials, should be taken into consideration. Changes in taxation or other building restrictions could change the perceived benefits of different building materials. The construction industry and research community have long undermined environmental issues in marketing, product development, and in the overall information disseminated to the public. This could prove harmful if environmental directives will be drawn based on irrational principles.

**SUSTAINABLE DEVELOPMENT**

The basic principle of sustainable development is the accommodation of mankind’s economic and other functions to the resources and endurance of nature. The core of sustainable development can be summarized in single a sentence:

*The production processes of all products must be closed and recyclable so that no waste materials are produced. As a consequence, a community must responsibly dispose of its waste products. Additionally, production processes must be energy-saving and should not generate poisonous or other harmful by-products in the production or in the use of products. Although recycling of concrete will be discussed in this paper the main emphasis is on the energy-saving aspects of concrete buildings.*

Usually the adaptation of a community to the principles of sustainable development leads to a need for a remarkable increase in the lifespan and quality of different products, which usually will minimize the ecological burden. This is due to the effect of substantial production and renovation costs as compared to maintenance costs. The application of the principle of sustainable development emphasizes the abilities of the product to fulfill the functional requirements, otherwise the service life will be unnecessarily shortened.

**ECOLOGY OF CONCRETE**

The basic ingredients of concrete—cement, aggregates and water—are natural materials and do not cause environmental risks. The durability properties of adequately produced concrete are generally good; thus they do not need to be improved by other poisonous substances as are sometimes used to increase the long-term lifespan of some of the competing building materials. Admixture ingredients in concrete generally comprise only a tiny percentage of total concrete weight, they often consist of various polymers, tensides, and/or formaldehydes, which are by-products of other fields of industry. Only a very small portion of concrete admixtures are poisonous in their dosage state, and even then only mildly so. Even these mildly poisonous admixtures are bound into hydration products, become harmless, and disintegrate from them only in fire temperatures exceeding 600 deg C.

**Production energy and emissions**

The major part of energy consumption in concrete production is caused by cement manufacturing, wherein carbonates and other minerals are heated to about 1400 deg C and thereafter ground to pulverized dimensions. The efficiency of ce-

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**Fig. 1**—The rise in atmospheric carbon dioxide concentration at Mauna Loa observatory in Hawaii. Fluctuations reflect seasonal variation where the summertime low values are caused by uptake of CO\textsubscript{2} by plants.

**Fig. 2**—The different age definitions in a life span analysis of a product.
ment production has improved remarkably—between 1960 to 1989, required heating energy has been nearly cut by half. Currently, part of the coal used in cement burning can be replaced with car tires or wastes from the paint industry. A portion of portland cement can be replaced with other hydraulic binders, including ground blast-furnace slag, fly ash, and condensed silica fume, some of which are by-products of steel manufacturing and commercial energy production. When blast-furnace slag and fly ash are used, heating energy is obtained for free—a cost that does not burden nature.

The results in Fig. 3 are primarily drawn from Connaughton's and Marsh's investigations. Energy consumption in concrete production has been calculated for a concrete which consists of 15 percent portland cement with no other hydraulic binders; the energy expended by transport and site functions has been evaluated as 0.4 GJ/t (1.0 GJ/m³). This results in a production energy of 1.4 GJ/t (3.4 GJ/m³) for normal concrete. Brick structures consume 2 GJ/t (3.6 GJ/m³) energy and the energy consumption of timber structures varies from 1 to 5.3 GJ/t (0.5 to 2.6 GJ/m³), depending on the surface treatment and drying measures.

Kreijger has compared the costs, strengths, production energy amounts and SO₂-emissions of different building materials. The large amount of energy consumed in the manufacture of reinforcement does increase the production energy of reinforced concrete structures. However, the cost/strength ratio of reinforced concrete beams is still advantageous, even though energy consumption of timber is rated lower in this report.

Because dust emissions produced in cement production have been significantly reduced in the past four decades, the most significant ecological weakness of concrete may be CO₂ emissions from the burning of cement clinker. The total carbon-dioxide emission produced during cement production is roughly the same amount by weight as the amount of clinker produced. CO₂ is liberated from burning fuel and from calcium carbonate CaCO₃ heated to 600 to 800°C.

CO₂ emission and calcium carbonate decomposition cannot be inhibited or decreased when producing portland cement. Environmentalists have proposed imposing emission taxes on those industries which are responsible for greenhouse gas emissions. However, when concrete is considered, the beneficial effects of concrete carbonation—which acts as a CO₂-sink—have been overlooked. When cement hydrates the reactants are calcium silicate hydrates (CSH), calcium aluminate and ferrite hydrates (CAH, CFH), different aluminate and ferrite phases containing sulfur (AFT and AFm), and calcium hydroxide (Ca(OH)₂). Not only calcium hydroxide and CSH-phases carbonate but all other hydration products which contain CaO in the structure are also attacked by CO₂ originating from air and partly dissolved in pore solution. As well, unhydrated cement minerals (C₃S, C₂S, C₃A, C₄AF) carbonate in the final phases of the reaction. In some of the following carbonation equations cement chemistry notations have been used; ̅ stands for O, S, C, A, K, Na, Mg, Fe, Ca, Al, Si and ̅ denotes SO₂.

\[
C_xS_yH_z + x\overline{C} \rightarrow x\overline{C} + S_yH_z - w + wH
\]

\[
C_xA_yH_z + x\overline{C} \rightarrow x\overline{C} + A_yH_z - w + wH
\]

\[
C_x(A,F)_yH_z + x\overline{C} \rightarrow x\overline{C} + (A,F)_yH_z - w + wH
\]

\[
C_x(A\overline{C})_3H_{32} \rightarrow 3\overline{C} + 3\overline{C} + 3\overline{C} + AH_{x-y} + (26-x)H
\]

\[
C_x(A\overline{C})H_{12} \rightarrow 3\overline{C} + 3\overline{C} + 3\overline{C} + AH_x + (10-x)H
\]

\[
Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O
\]

\[
2NaOH + CO_2 \rightarrow Na_2CO_3 + H_2O
\]

\[
2KOH + CO_2 \rightarrow K_2CO_3 + H_2O
\]

\[
C_3S + (3-x)\overline{C} + yH \rightarrow C_xSH_y + (3-x)\overline{C}
\]

\[
C_2S + (2-x)\overline{C} + yH \rightarrow C_xSH_y + (2-x)\overline{C}
\]

\[
C_3A + \overline{C} + CH + 11H \rightarrow C_xA(C\overline{C})H_{12}
\]

Carbonation is a complicated and time-consuming process which deteriorates the durability properties of reinforced concrete by lowering the pH of the pore solution. High alkalinity in the pore solution prevents corrosion of reinforcement in moist environments. Designers use different methods to slow down the carbonation rate and hence try to increase the life span of reinforced concrete structures situated in moist environments. However, carbonation is a natural phenomenon that

![Fig. 3—Production energy consumption of different building materials](image-url)
is part of the life cycle of concrete when it returns to its original composition of CaCO$_3$—or rather to its impure forms. Even though a normal indoor concrete structure carbonates almost completely in about 100 years, it still can perform its structural function without any danger of reinforcement corrosion. According to the preceding carbonation equations, all of the CO$_2$ that was emitted from CaCO$_3$ during the clinker burning will be consumed back to carbonation products and thus not increase greenhouse gas content in the atmosphere in the long run. Coal is the heating fuel normally used in cement manufacture, and it will cause permanent CO$_2$ emissions of about 40 percent of the amount of clinker produced. This amount is not unlike that of timber structures, which release CO$_2$ into the air by decaying or burning—and it takes about 80 years to grow a new pine or spruce tree. Of course, high-strength concrete is very much denser than normal strength concrete and the total carbonation of these concretes can take as long as 500 to 1000 years.

**Life span analysis**

The comparisons presented in the previous part of this article are imperfect. The focus must be on a complete group of structures, preferably an entire residential area. The examination should include the total energy consumption of the area and not merely production energy. Energy consumption and emissions of the operational, service phases, and the effects of traffic should be taken into consideration.

Harmaajärvi has compared four typical Finnish residential areas from the viewpoint of sustainable development. Residential area 1 is a compactly built small housing area equipped with a district heating system. Residential area 2 is a spacially built small housing area equipped with individual heating systems. The small houses of these first two residential areas are built from wood and the apartment houses of residential areas 3 and 4 from reinforced concrete. Residential area 3 is a spacially built apartment housing area where there are also some small houses. Half of the houses in this area are served by a district heating system. Residential area 4 is a compactly built apartment housing area equipped with a district heating system. The distance between the residential areas and the down town centers have been assumed 10 km for the small housing areas and 5 km for the apartment housing areas.

The original life span in Harmaajärvi’s study was planned to be 40 years, but the report contained data from which the effects of a 100-year life span could be estimated. A 100-year life span is taken as the basis for this paper even though the renovation costs during the life span have not been included in the analysis. Figure 4 presents the total energy consumption of the residential areas during a life span of 100 years. The energy consumption in the production phase...
Fig. 6—Carbon dioxide emissions of the Finnish residential areas during the 100 year life span. Residential areas 1 and 2 are comprised of wooden residential houses and residential areas 3 and 4 are made of reinforced concrete apartment houses. The emissions of vehicular traffic transportation are included into the total carbon dioxide emissions.

Fig. 7—Sulfur dioxide emissions of the Finnish residential areas during the 100 year life span. Residential areas 1 and 2 are comprised of wooden residential houses and residential areas 3 and 4 are made of reinforced concrete apartment houses. The emissions of vehicular traffic transportation are included into the total sulfur dioxide emissions.

Fig. 8—NO\textsubscript{x} emissions of the Finnish residential areas during the 100 year life span. Residential areas 1 and 2 are comprised of wooden residential houses and residential areas 3 and 4 are made of reinforced concrete apartment houses. The emissions of vehicular traffic transportation are included into the total NO\textsubscript{x} emissions.

Fig. 9—Heating energy, ventilation, and indoor temperatures in small houses produced from light and massive materials on two days in succession in March. The legend of the solid and dashed lines refers to the indoor temperatures on the lower portion of the figure.

Fig. 10—Consumption of heating energy in small houses as a function of structural mass\textsuperscript{14}

Fig. 11—Consumption of heating energy in apartment houses as a function of structural mass\textsuperscript{14}
prises of only 6 to 8 percent of the total energy consumption. About 60 percent of the energy consumption in the operational phase is caused by heating the dwellings. The material composition of the four residential areas is presented in Fig. 5. Even though Areas 1 and 2 are small housing areas where the principal load bearing material is wood, concrete materials have also been used in these residential areas in much larger amounts than wood materials. The label “Other stone materials” includes the soil transports during the building phase and therefore the amount of brick structures and insulation materials cannot be estimated.

From the results presented in Fig. 4 it can be calculated that only 5.9 to 8.1 percent of the total energy consumption was used in the production phase of the different residential areas. In the small houses, which were wooden structures, the production energy amount of wood was only 0.03 percent of the total energy consumption in the life span of the residential area. In these small housing areas 1 and 2 the production of concrete structures used 0.06 percent of the total energy consumption even though the concrete amount that was consumed in these housing areas was over three times the volume of wood. In reality, production energy has a very small effect on the total energy consumption of a residential area. Even a 0.7 percent saving in heating energy corresponds to the entire production energy of the wooden structures in the small housing areas. It is an exaggeration to advertise ecological materials when the window sizes and geographical direction of the buildings have a multifold effect on the energy consumption of the building area. The air permeability of the facade structure material and the ability to reserve energy in massive structures have a much larger influence on the energy consumption than the differences in production energies of the different competing materials.

The situation is similar when the gas emissions are studied. The production emissions presented in Table 2 have been compared with the operational and traffic emissions during the life span of the four residential areas in Fig. 6 through 8. Carbon dioxide, sulfur dioxide, and nitrogen oxide emissions have been analyzed separately. The results show that the influence of the production stage is as small as that of the energy consumption comparison and the direct effect of the different building materials is extremely small. The influence of the different building materials on the gas emissions is much more remarkable indirectly in the way in which they effect on the heating or cooling energy consumption. It will be shown that the energy consumption, CO$_2$-, SO$_2$-, and NO$_x$-emissions are smaller when the residential area is built from massive building materials.

The effects of massiveness of structures on the heating energy consumption of residential houses was studied by Niittymäki, Salokangas, Niemi and Jäämä. They simulated the situation by a computer program for structures that were as light as possible, like wooden houses where mass of the structure was 30 kg/floor-m$^2$, or they were completely produced from concrete having a mass of 700 kg/floor-m$^2$. The studied houses were a contemporary small wooden house and a small house produced from concrete. For the apartment houses, a concrete structure was compared with a wooden apartment house where only the basement was made of concrete. Other variables in the research project were the size and geographical direction of the windows in the houses.

The computer simulations show that in the Nordic countries during late winter, spring, and fall, free radiation energy is brought into the rooms on sunny days through windows which face to the south. If the house is built from light materials the indoor temperature during the previously mentioned seasons on sunny days rises fast to an intolerable temperature level, which causes the need for ventilation through windows or by an automatic ventilation system. If people are not present in the rooms during daytime the ventilation takes place in the evening when they arrive from work. This way the free solar energy is lost. In houses built from massive and heavy materials which possess good heat capacity proper-

![Fig. 12](image-url)  
**Fig. 12**—Relative consumption of heating energy as a function of structural mass, solar environment, and window area facing to compass direction

![Fig. 13](image-url)  
**Fig. 13**—Comparison between the heating energy savings caused by the massiveness of concrete structures and the production energies of building materials
ties, the indoor temperature will not rise as high and ventilation will not be necessary. The solar energy is absorbed into the structure and it decreases the need for heating energy during the following cold night.

The heating energy savings that the massive structures accomplish are significant. According to the results presented in Fig. 10 and 11, savings in heating energy range from 14 to 10 percent when wooden and concrete houses are compared. This depends largely on the window area and into what compass direction the windows face as is shown in Fig. 12. When the findings of this research project are combined with Harmaajarvi’s results, the histograms of Fig. 13 are achieved. The heating energy savings of the massive concrete buildings are about twice the combined production energies of wood and reinforced concrete structures. Similarly, when buildings are built from massive materials like concrete or bricks, the gas emissions of CO$_2$, SO$_2$, and NO$_x$ are remarkably decreased. Therefore the use of massive building materials like concrete or brick is ecologically more advantageous compared to the situation where light materials are used.

This examination has been limited to Nordic countries; however, because cooling systems use more energy than heating facilities the use of massive materials as a cooling reservoir by which colder night temperatures can be stored and used to level off the daytime higher temperatures can be ecologically even more advantageous in hot climates.

Recycling of concrete
Recycling of concrete and other building materials during the building process of new buildings and at the end of the life cycle is usually very inadequately arranged. This is the most regrettable situation because concrete is one of the most easily recyclable building materials.

In Finland the annual recyclable concrete amount from new buildings is 42 kg/inhabitant; from renovation the yearly amount is about 10 kg/inhabitant. From demolished buildings the concrete and brick waste amount was 60 kg/inhabitant; unfortunately, the recyclable concrete waste amount cannot be estimated from the available statistical data. The total amount of both concrete and brick waste is over 110 kg/year/inhabitant, and it is mostly transported to waste dumps. However, it is certain that due to long transportation distances only a portion of the concrete waste can be recycled profitably.

The technology for concrete recycling exists and transferable crushing plants have been developed. Reinforced or tensioned concrete structures are cut to about one meter long pieces with a cutter which is mounted on a bucket loader. The reinforcement can be separated from the crushed concrete and can also be recycled. Crushed concrete is easily recycled into aggregates for new concrete. However, despite the fact that a portion of the cement in the old concrete has not hydrated, nearly as much new cement must be used as in concrete produced by natural gravel aggregates. The energy consumption is about the same as in virgin concrete production, as can be seen in Table 3. In Finland recycled concrete is mostly used as a subbase layer for road construction. Because of the unhydrated cement, the layer thicknesses can be diminished due to the better load-carrying capacity caused by the subsequent cement hydration of the crushed concrete.

Mixer and truck-washing water from some ready-mix concrete plants are recycled—when the settling basins become full, the aggregate-binder waste is recycled for land fills. Washing water could also be recycled for batch water but due to economical reasons this is not common.

FUNCTIONAL PROPERTIES OF BUILDINGS
According to the previous reasoning, production energy or emissions caused by the production phase of residential buildings have a fairly insignificant effect on the ecological balance. The ecologically important and decisive factors are energy consumption and respective emissions from the operational phase in the life span of the residential area. Different building materials have a remarkably larger impact indirectly through the effects the material has on heating or cooling energy. Comparatively heavy concrete structures which also have good heat-absorption properties possess a clear advantage in this context. Therefore concrete is shown to be the best ecological alternative.

During the ecological comparison of different building materials the functional quality properties should also be considered. For example, during a life span of 100 years, buildings usually suffer several flooding accidents. If these require expensive repair work due to material vulnerability, the ecological effect of these could exceed the ecological costs of the production phase many times over. Other properties which belong to this category are fire durability and sound insulation properties. It is clear that longtime durability and periodical painting or other finishing processes have a large effect on the ecological balance of the building. The properties of building materials have an effect on insurance premiums, which are a kind of ecological index to measure the destruction risk of a building material. A building material’s ability to fulfill the functional properties of the building will be the most significant competitive factor in the future also.

CONCLUSIONS
Ecologically, concrete has many advantages. It is produced from natural materials. In its production and use no poisonous substances are emitted. The production energy consumption of concrete is quite small and its ingredients are found in abundant measure all over the world. The only eco-

Table 3—Energy consumption of virgin and recycled production of building materials in Great Britain$^5$

<table>
<thead>
<tr>
<th>Building material</th>
<th>Virgin production, GJ/t</th>
<th>Recycled production, GJ/t</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>0.5–1.5</td>
<td>0.5–1.5</td>
</tr>
<tr>
<td>Brick</td>
<td>2.5–6.1</td>
<td></td>
</tr>
<tr>
<td>Timber$^*$</td>
<td>4–5</td>
<td></td>
</tr>
<tr>
<td>Glass</td>
<td>13–25</td>
<td>10–20</td>
</tr>
<tr>
<td>Plastic</td>
<td>80–220</td>
<td>50–160</td>
</tr>
<tr>
<td>Steel</td>
<td>25–45</td>
<td>9–15</td>
</tr>
<tr>
<td>Copper</td>
<td>70–170</td>
<td>10–80</td>
</tr>
<tr>
<td>Aluminum</td>
<td>150–220</td>
<td>10–15</td>
</tr>
</tbody>
</table>

$^*$Harvested in Great Britain.
logical disadvantage of concrete is the emission of carbon di-
oxide during the burning of cement clinker. However, over
60 percent of the CO$_2$-emissions will be bound back into
crude during the carbonation process. When other poz-
zolanic or cementitious binders such as fly ash and blast fur-
nace slag which are by-products of other industries are used,
the heating energy is obtained free and no additional carbon
dioxide emissions will be caused.

In residential houses, the massiveness of concrete struc-
tures acts as a heat battery which makes it possible to store
solar energy obtained through windows during sunny days in
late winter, spring, and in the fall seasons. When the struc-
ture is built from a heavy material, the free radiation energy
does not raise the room temperature intolerably and no ven-
tilation is needed. During the following cold night the ab-
sorbed energy decreases the need of heating energy. In this
way heavier structures save heating energy and subsequently
gas emissions will be diminished compared to the situation
in which light materials have been used.

This together with the fact that concrete is one of the most
easily recyclable building materials improves the ecological
balance of concrete and lifts it to the group of building mate-
rials which burden the environment least.

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