HOW SUSTAINABLE IS CONCRETE?

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Abstract

An analysis was carried out to determine whether concrete is a sustainable housing material. Sustainability generally means having no net negative impact on the environment, and this analysis compared the environmental impact of producing concrete and steel. To make this comparison, we first designed a simple reinforced concrete beam and a steel I-beam with the same moment capacity, and we then estimated the environmental impact of the production of these two beams using a commercial computer program designed for this purpose. The estimation showed that the concrete beam required much less energy and had a lower net environmental impact than the steel beam.

1. Introduction

Some time ago we wrote a proposal to study the use of cementitious materials in residential construction. In that proposal we argued that concrete is a sustainable material for housing. However, we knew very little then about how to compute the environmental impact of a construction material. The proposal was not funded, but it piqued our interest in how such a computation can be made. Since that time several computer programs for such computation have become commercially available, and we recently purchased such a program, ATHENA[1] to use in a course on sustainable housing for civil engineering students. The purpose of this paper is to describe the computation of environmental impact. As an illustration, we use ATHENA to compare the environmental impact of ordinary concrete with that of concrete containing fly ash, and to compare the environmental impact of concrete with the impact of steel. Through this computation we hope to answer the question posed in our earlier proposal – whether concrete causes less environmental damage than steel and therefore whether our claim that concrete is a sustainable material for housing was legitimate.

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[1] ATHENA™ is a registered trademark of the ATHENA Sustainable Materials Institute, Merrickville, Ontario, Canada.

2. Sustainability

As used in everyday speech, sustain means to support or to keep a process going,[2] and the goal of sustainability is that life on the planet can be sustained for the foreseeable future. There are three components of sustainability: environment, economy, and society. To meet its goal, sustainable development must provide that these three components remain healthy and balanced. Furthermore, it must do so simultaneously and throughout the entire planet, both now and in the future. At the moment, the environment is probably the most important component, and an engineer or architect uses sustainability to mean having no net negative impact on the environment. Thus the term sustainable has come to be synonymous with environmentally sound or friendly and "green."

The environmental component has our attention now because deterioration of our environment is driving the current worldwide focus on sustainable development. We could cite countless examples of environmental deterioration, and all are important. Probably the most troubling for the long-term health of the planet and for the goal of sustainability are the climate changes resulting from the thinning of the ozone layer and the progressive decline in biodiversity resulting from loss of habitat. Both of these changes are a direct result of human development.

The economic component is given less attention in the developed countries of the world, but is equally essential to the goal of sustainable development. There is poverty throughout the planet, and the global inequities in consumption of resources are staggering. Economic sustainability and environmental sustainability are closely linked. Much environmental degradation occurs when people are struggling to obtain the resources essential for life (food, water, shelter, etc.), and it is inevitable that the basic economic struggle may take precedence over environmental sustainability. Conversely, environmental deterioration exacerbates economic inequity, for example diseases associated with lack of clean water are a significant cause of poverty.

The social component is also given less attention at the moment but will hopefully be brought into balance in the ensuing decades. The goal of sustainable development clearly requires stable social structures. Only with broad social commitment implemented by governmental policies can we progress towards sustainable

[2] This is the definition given in the Random House College Dictionary published in 1973, the edition on my (LS) bookshelf. Interestingly, this dictionary does not separately define sustainability. The latter term has found its way into common speech only more recently, with the more widespread interest in environmental impact during the last two decades of the 20th century.

development. War, probably inevitable in the absence of stable social structures, causes both economic disparity and environmental deterioration.[3]

Despite the critical importance of all three components (environmental, economic, and social) in sustainable development, this paper focuses only on the environmental impact of construction materials. Even that is a very broad issue. In the manufacture and use of construction materials, the critical elements of environmental impact are the utilization of resources, the embodied energy, and the generation of waste materials. These are the issues that engineers and architects must consider when planning and building a structure, and these are the issues we address here. That is not to say that economic and social issues are less important, merely that they are outside our purview.

3. Sustainability of Construction Materials

In order to estimate the environmental impact of a construction material, it is necessary to consider all stages in the life of the material (Fig. 1).

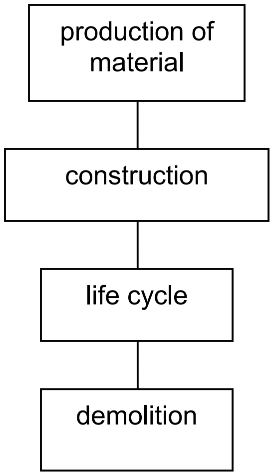

Fig. 1: Stages considered when estimating environmental impact

Each construction material is manufactured from some combination of raw materials, with some expenditure of energy, and with associated wastes. Therefore manufacture is an essential element in computing the environmental impact, and manufacture is probably the element most widely cited when considering the environmental impact of construction materials. Are the raw materials renewable? Are they scarce? Are they important to the global environment? How much energy is required in the manufacture? How much waste is produced during the manufacture? What impact do these wastes have on the environment? These questions are very important and

[3] Because one of us (LS) grew up in the shadow of the major world wars of the last century, we recognize the horrendous negative impact of war on human development. We recognize as well that war is not prevented by stable social structures, but we hope, and history teaches us, that such social structures make war less likely.

this phase probably receives the most attention, both from the general public and from the government.

The construction process also involves some expenditure of energy and produces some waste. There are several important questions. How much of each manufactured material is used? Can materials be used that have less environmental impact? How much energy is used? How much waste is produced? What is the impact of the waste on the environment? Some of these questions can only be answered for a specific structure. Increasing attention is being given to the construction phase as part of global and regional efforts to make development more sustainable.

The lifetime of the structure has a direct impact on sustainability. When the structure deteriorates, it must be destructed and rebuilt. The lifetime is directly controlled by the durability of the construction materials. It is further influenced by the adaptability of the design to repair and renovation, and repair and renovation themselves have environmental impacts. Finally, the lifetime of a structure is influenced by cultural and market forces. When a structure no longer serves an important function (not necessarily the function for which it was constructed), it is likely to be destructed. And if it is not aesthetically pleasing, it may be destructed. So materials and design considerations directly affect the lifetime of a structure and the lifetime must be considered when computing environmental impact.

During its life, the structure uses considerable energy. Energy use during the life of a structure is a key element in computing its environmental impact and is also a factor widely recognized for its importance. Each material makes a contribution to the thermal insulation, thereby affecting energy use. Of course, energy use is strongly affected by the mechanical systems used to heat and cool the structure. Energy use is thus directly affected by both design and materials.

The final stage in the life of a structure is its demolition. How much of the structure can be reused? How much of the materials can be recycled? What is the environmental impact of the waste produced during the demolition? What materials must be disposed of? What is the environmental impact of the disposed materials? In the USA, there is little consideration of the demolition stage during design and construction. However, the impact of demolition must be considered when computing the environmental impact of a structure.

4. Sustainability of Concrete

Concrete is manufactured from aggregates (rock and sand), hydraulic cement, and water. It usually contains a small amount of some chemical admixture, and (at least in the USA) it often contains a mineral admixture replacing some portion of the cement. A typical concrete formulation contains a large amount of coarse and fine aggregate, a moderate amount of cement and water, and a small amount of admixture. Most of these constituents are themselves manufactured products, byproducts, or materials extracted by mining. In order to assess the environmental impact of concrete manufacture, it is necessary to consider the impact of each separate constituent.

The aggregates are usually obtained by mining. The coarse and fine aggregates are usually mined separately. Occasionally aggregate is obtained as a by-product of some other process (e.g., slag or recycled concrete). Aggregates may be crushed and may be washed. They are usually separated into various size fractions and reconstituted so as to satisfy the grading requirements. They may need to be dried. A modest amount of energy is involved in all these processes. The principal wastes are dust and water, neither of which is especially damaging to the environment. The dust may be used in some other process or may be disposed in a landfill.

The hydraulic cement may be straight portland cement or a mixture of portland cement and some proportion of a supplemental cementing material such as fly ash or slag. Portland cement is usually manufactured by heating a mixture of limestone and shale in a kiln to a high temperature (approximately 1500°C), then intergrinding the resulting clinker with gypsum to form a fine powder. Thus it is not surprising that the portland cement has a rather high embodied energy. The reaction between limestone and shale to produce clinker produces CO_2. Furthermore, the fuel used in the kiln and the electricity in the grinding mills themselves produces some amount of gaseous waste, principally CO_2 and CO. These gases are non toxic and are released to the atmosphere, where they contribute to global warming. Supplemental cementing materials, as noted above, may also be used as mineral admixtures in concrete. These are byproducts of other manufacturing processes and as such are taken to have minimal embodied energy.

The water in concrete is normally ordinary tap water with no further processing. Thus it has very little embodied energy and no waste. It is only an environmental issue in locations where the water is already not sufficient for basic needs.

Concrete is usually manufactured by combining and mixing these constituents in large batches in a ready-mixed concrete plant and hauling the mixture to the construction site in a truck. These processes (moving materials, mixing them, and hauling the concrete) require modest amounts of energy and produce small amounts of waste. Dust, unused concrete, and wash water contaminated with concrete are the principal waste, and the latter two wastes may be at least partially reclaimed and reused.

Concrete used in structural applications normally includes some amount of reinforcing steel, and in some applications this steel is prestressed. Prestressed concrete is often precast. Precast concrete is manufactured at a plant and heated to accelerate the early hydration reactions and allow rapid removal from formwork.

The environmental impact of using concrete at a construction site is basically similar to the impact of manufacturing concrete in a ready-mixed concrete plant. The concrete is moved to its desired location, consolidated into the formwork, and finished. After the concrete has set and gained some strength, the formwork is typically removed. These are all low-energy operations. Waste includes unused concrete, contaminated wash water, and used formwork. Formwork may be wood, which must be disposed in a landfill, but sometimes it is steel and can be reused.

The impact of concrete on sustainability during the lifetime of the structure is primarily a function of its role in energy transmittance (i.e., its insulating properties) and its role in energy storage. Concrete is not an especially good heat conductor, not as good as steel, for example. It is also not an especially good insulator, not as good as wood, for example. A very high porosity is necessary to provide good insulating properties, and concrete has less porosity than wood. On the other hand, concrete provides a large thermal mass so it can store energy and release it later.

At the end of its service life, a concrete structure must be demolished and disposed. The demolition process is done by brute force -- depending on the size of the structure, it may involve controlled blasting or some type of hammer. These processes use modest amounts of energy. Concrete is sometimes recycled, most commonly used as rock in a pavement sub base, but it is not commonly recycled in the USA. The waste produced by demolition of a concrete structure includes dust, powder, and fragments of concrete. These are typically land filled.

5. Computation of Environmental Impact

As noted previously, we used ATHENA™ to compute the environmental impact associated with concrete and other construction materials. Using an extensive database, this program makes quite straightforward computations to estimate the environmental impact of a building. Various aspects of the building design are input, including the specific construction materials. Any or all of the following are estimated: energy consumption, solid waste, air pollution, water pollution, global warming, or resource use.

The database used in ATHENA is critical to the validity of the computations. Reports that include the data and describe how the data were obtained are included as part of the program.

To answer the question raised in the introduction, whether concrete is a sustainable material, we compared the environmental impact of concrete with that of steel. We first estimated the energy produced during manufacture of concrete and steel. Because it is more realistic to compare energy for a structural element designed for a specific load, we then designed a simple structure to compare reinforced concrete and steel.

The ATHENA database, used in all our calculations, is from Canada, a country similar to the USA in cost and availability of materials but somewhat lower than the USA in average temperature. The cement energy calculation used data from cement plants on the west coast of Canada. The concrete computation was made both with ordinary concrete and with concrete containing fly ash, for which most of the energy is attributed to the production of power, not to the production of the material. The computation assumed normal Canadian industrial practice throughout. This included the fuel for cement and concrete manufacture and for vehicles used to transport materials. The steel results are sensitive to the type of furnace, and data were intermediate between a basic oxygen furnace and an electric arc furnace. Results are also sensitive to the use of scrap steel, and a reasonable (Canadian national average) value was used for scrap steel. The computation includes energy from sources such as coal, coke, electricity, and natural gas.

The mix proportions used for concrete, given in Table 1, were designed for 30 MPa compressive strength at 28 days.

Table 1: Concrete mix proportions

Constituent	Amount (kg/m^3 concrete)
Coarse aggregate	1092
Fine aggregate	722
Portland cement	350
Water	160

To compare the environmental impact of concrete and steel, we designed two beams with the same moment capacity, one using reinforced concrete and the other using steel. For concrete, we started with the dimensions and computed the moment. The beam (Fig. 2) is 0.30 m long, 0.15 m wide, and 0.29 m deep, with 2 bars of reinforcing steel, 30 mm in diameter and located 25 mm up from the bottom surface. The compressive strength of the concrete was assumed to be 30 MPa and the tensile strength of the reinforcing steel was assumed to be 415 MPa. We used the concrete mix in Table 1 but with 10% of the cement replaced by fly ash. The moment capacity of this concrete beam is 0.10 MN.m. The mass of concrete in this beam is 31.5 kg and the mass of reinforcing steel is 3.5 kg. For steel, we selected a steel I-beam of the same length to support the same moment (0.10 MN.m). This beam (Fig. 2) is 0.30 m long, 0.10 m wide, and 0.30 m deep. The tensile strength (i.e., yield stress) of the steel was assumed to be 250 MPa. The mass of steel in this beam is 10.0 kg.

6. Results

The energy consumed in the production of portland cement, shown in Table 2, was estimated to be 4.88 MJ/kg. The major energy, as expected, is consumed during pyroprocessing. A similar energy value, 5.5 GJ/kg (5.6 GJ/long ton), was reported for portland cement production in the USA in 1997; and this report noted that energy consumption in portland cement production in the USA has decreased 30% from 1970 to 1997 [1].

Table 2: Energy used in the production of portland cement

Production Step	Energy (MJ/kg cement)
Extraction of raw materials	0.044
Transportation of raw materials	0.089
Crushing and grinding of raw materials	0.386
Pyroprocessing	4.041
Grinding cement	0.188
Transportation of cement	0.133
Total	4.882

Using this value for portland cement and the mix proportions in Table 1, the energy in the production of concrete, shown in Table 3, was estimated to be 2.07 GJ/m^3 or 0.89 MJ/kg. Replacing 10% of the portland cement with fly ash reduced this to 1.94 GJ/m^3 or 0.83 MJ/kg. The major part of this energy, as expected, is associated with the portland cement.

Table 3: Energy used in the production of concrete

Constituent	Energy (MJ/kg concrete)
Coarse aggregate	0.028
Fine aggregate	0.028
Portland cement	0.735
Water	0.000
Manufacturing	0.102
Total	0.893

The total energy in the production of steel was estimated to be 23.70 GJ/kg. A reasonably similar energy value, 25.5 GJ/kg (25.9 GJ/long ton), was reported for iron and steel production in the USA in 1994 [2]. The value computed for steel is considerably higher than the value computed for concrete. We used the computed value for estimating the embodied energy in the beams, both for reinforcing steel in the concrete beam and for steel in the I-beam, although the latter would probably be hot-rolled and would therefore require some additional energy.

Using these computed energy values, the energy to produce the reinforced concrete beam shown in Fig. 2 was estimated to be 109 MJ and the energy to produce the steel I-beam shown in Fig. 2 was estimated to be 237 MJ. Thus the energy to produce a reinforced concrete beam was about half the energy to produce a similar steel I-beam.

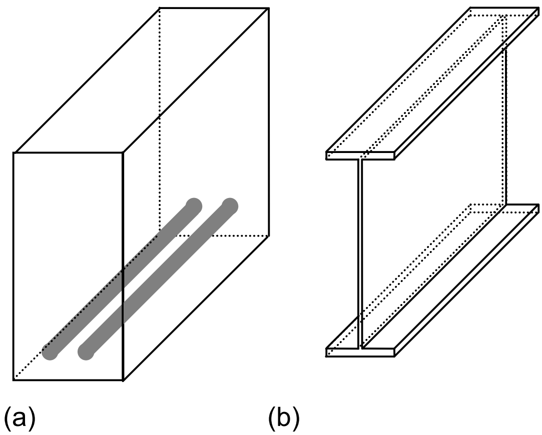

Fig. 2: Schematic of structures: (a) reinforced concrete beam and (b) steel I-beam

Other environmental parameters estimated for the two beams (reinforced concrete and steel) using ATHENA are listed in Table 4. The resource use for concrete was about double that for steel. Both produced high levels of carbon dioxide, but the amount for concrete was quite similar to the amount for steel. The water pollution index for concrete was about half that for steel. The air pollution values were similar. The solid waste values were similar. The energy consumption for concrete was about two-thirds that for steel. The energy values computed using ATHENA were different from the values we computed, in part because ATHENA included construction and demolition while we considered only the manufacture of the materials. Overall, the computation shows a smaller environmental impact for concrete than for steel.

Table 4: Environmental impacts of reinforced concrete and steel beams

Impact	Reinforced concrete	Steel
Resource use (kg)	48.85	18.69
Warming potential (kg equivalent CO_2)	9.97	8.95
Water pollution index	0.34	0.98
Air pollution index	2.01	2.46
Solid waste (kg)	1.87	1.80
Energy (MJ)	140.18	229.69

7. Discussion

Computing environmental impact is a very complex task. We chose a fairly simple problem here, comparing two structural materials. It is important to consider, as we did here, a specific structure, and we chose a fairly simple structure, a beam, so we could compare the amount of each material required for the same engineering function. It is certainly possible to estimate the environmental impact of a specific house that utilizes specific materials, but the computation becomes even more complex. In comparing the environmental impact of specific structural materials in a given structure, it is probably necessary to use a different structural design tailored for each specific material, as we did here.

The simple structure used here did not allow us to include any differences in insulating capacity of the two materials, although the program does provide that capability. Moreover, the program does not predict a life cycle to use in the calculation of environmental impact.

This computation showed that concrete has less environmental impact than steel when compared in structures designed for the same engineering function. It is much more difficult to answer the broader question of whether concrete housing is sustainable. That question requires that we weigh the environmental impact and economic cost of the structure against its social benefits. We have found no absolute criteria on which to evaluate sustainability. What we can conclude from this analysis is that concrete is more sustainable than steel in the same structure.

8. Conclusions

The environmental impact of a reinforced concrete beam and a steel I-beam designed for the same engineering function was estimated using a computer program designed for this purpose and commercially available. Based on this estimation, production of the concrete beam required much less energy and had a lower net environmental impact than production of the steel beam.

References

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