REINFORCED CONCRETE AS A CONSTRUCTION MATERIAL

HOW DOES IT COMPARE TO WOOD, STEEL?

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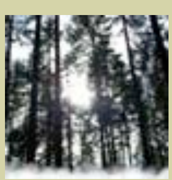
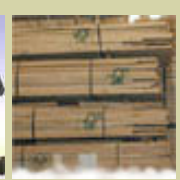
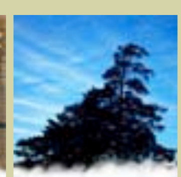
    

Reinforced Concrete as a Construction Material

How Does It Compare to Wood, Steel?

Introduction

The possibilities of concrete construction have captured the imagination of an increasing portion of the residential construction and home-buying public in recent years. With interest driven primarily by devastating impacts of hurricanes in the southeastern U.S., and forest fires in California, the use of concrete for residential construction of above-grade walls has grown substantially in the United States over the past fifteen years.

The overall market share of concrete construction in new single-family detached housing, in the form of concrete block, cast-in-place systems, pre-cast concrete, or insulated concrete forms (ICF), rose every year from 1993 through 2005, increasing from less than 0.1 percent of the market in 1993 to 17.9 percent in 2005 – spectacular growth by any measure.

However, recent steep declines in home building activity in the two largest concrete construction markets – Florida and California – and rising raw material costs relative to competing materials have led to a drop in the overall concrete home market share. From the 17.9 percent of above-grade walls attained in 2005, market share declined to 14.4 percent in 2007. Insulated concrete form (ICF) construction has also seen market fluctuation, from a 0.7 percent market share in 1997, ICF construction grew to 4.7 percent in 2006, and then declined slightly in 2007 to 4.5 percent of the residential market (ICF Builder 2008). Even with these adjustments, concrete construction in the residential market remains quite substantial compared to a decade ago.

Today, concrete construction of residential homes is being promoted as environmentally advantageous to alternative forms of construction. Claimed advantages of concrete include an ability to recycle and to incorporate recycled content, high durability, and superior energy efficiency of some concrete construction systems. This article examines the science behind these and other claims.

Environmental Impacts of Concrete Construction

A life cycle inventory systematically examines measurable quantities of all inputs (all raw materials, air, water, energy) and outputs (products, co-products, emissions, effluents, and solid wastes) over a defined sequence of manufacturing steps. When life cycle methodology is applied to the evaluation of a building, a series of life cycle inventories are conducted. Information is collected for each of the materials to be used in construction, including data for materials transportation and all activities involved with construction. Assessments are sometimes extended to consider impacts subsequent to construction: heating and cooling, maintenance, and building deconstruction.

Over the past several decades numerous life-cycle based studies of the environmental impacts of concrete construction have been conducted. Differences in impact in comparison to construction using alternative materials are often substantial, and consistently point to life cycle impacts of concrete construction that are higher than for comparable wood-framed structures, but lower than for structures framed in steel. These life cycle impact differences primarily relate to raw material extraction and production of construction materials.

When otherwise equivalent buildings (equal size, configuration, thermal envelope insulation values, and orientation on site) are constructed of different materials, there is little to no difference in the quantity of energy required to heat and cool such buildings once the construction process has been completed. What this means is that the environmental implications of building materials selection are immediate, with the initial advantage of one building material over another persisting throughout the life of the structure. However, the relative *magnitude* of difference tends to narrow with each year of building operation. An hypothetical example of two buildings, one of which requires one-half the energy to construct as the other, illustrates this point (Table 1); note that the large (100 percent) difference in energy consumption at the point of construction between buildings A and B becomes progressively smaller with progressive heating/cooling seasons even though energy consumption for building operation remains the same.

Table 1
Relative Differences in Energy Consumption for Two Functionally_Equivalent Buildings Constructed of Different Materials

		Building A	Building B	% Difference
1	Units of energy consumed in extraction of raw materials, production of bldg. products, and building construction.	500	1,000	100
2	Units of energy consumed in heating and cooling the structure over a 20-year period.	500	500	
3	Units of energy consumed in construction of building *and* heating and cooling over a 20-year period. (line 1 + line 2)	1,000	1,500	50
4	Units of energy consumed in heating and cooling the structure over a 40-year period.	1,000	1,000	
5	Units of energy consumed in construction of building *and* heating and cooling over a 40-year period. (line 1 + line 4)	1,500	2,000	33
6	Units of energy consumed in heating and cooling the structure over a 60-year period.	1,500	1,500	
7	Units of energy consumed in construction of building *and* heating and cooling over a 60-year period. (line 1 + line 6)	2,000	2,500	25

Environmental Impacts of Cement and Concrete Production

Cement is the active ingredient of concrete that binds sand, gravel, and other aggregate material together to form the finished product. Although made of natural ingredients such as limestone (calcium carbonate), the environmental impact of cement production is relatively high due to the quantity of energy needed to reduce calcium carbonate to lime (or calcium oxide) in a cement kiln where temperatures above 2,700 F are maintained, and the substantial release of CO_2 inherent in the process.

Chemically, reduction of limestone looks like this:

$$\underset{\text{limestone}}{CaCO_3} \xrightarrow[\Delta]{} \underset{\text{lime}}{CaO} + \underset{\text{carbon dioxide}}{CO_2}$$

Thus, in addition to the mining activity needed to obtain limestone, sand, and gravel (and sometimes clay and other ingredients), cement production includes significant environmental impacts from combustion of coal or natural gas and associated emissions to air, as well as direct release of carbon dioxide in production of lime. In general, the production of a ton of cement results, in the release of about a ton of carbon dioxide. Cement comprises about 12 to 15 percent of the weight of dry concrete.

Of the three primary structural materials used in construction, lumber requires by far the lowest energy input in the manufacturing phase, followed by 100 percent recycled steel, concrete, and virgin steel. As a result, there are large differences in net emissions of carbon associated with production of basic construction materials (Table 2).

Table 2
Net Carbon Emissions in Producing a Ton of: [1/] [2/]

Material	Net Carbon Emissions (kg C/metric ton)
Softwood lumber	33
Recycled steel (100% from scrap)	220
Concrete	265
Concrete block[3/]	291
Steel (virgin)	694

[1/] Values are based on life cycle assessment and include gathering and processing of raw materials, primary and secondary processing, and transportation.

[2/] Source: USEPA (2006).

[3/] Based on the EPA concrete value and information about energy requirements in block-making.

Environmental Impacts of Concrete and Other Types of Buildings

A number of studies of concrete construction are outlined below. These studies encompass construction of a wide range of buildings, from large commercial structures, to multi-story apartment buildings, to single family homes. Studies examining only the impacts linked to materials production and building construction are presented first, with studies examining the full life cycle of structures presented thereafter.

Analysis of a Large Office Building

This analysis included a comparison of various methods of constructing 3-story office buildings. Life cycle assessment methods were used to examine total energy use and CO_2 emissions associated with wood, steel, and concrete construction (Forintek Canada 1997); raw material extraction, manufacturing, all transportation, and building construction were included in the assessment. The concrete structure required more total energy than wood, but less total energy than steel construction. As all three of the structures were designed with concrete foundations, the only part of the structures in which different structural materials were used was the above-grade portion, and thus it is here that meaningful comparison can be made. As shown in Table 3, concrete construction required 72 percent more energy than wood construction, but 29 percent less energy than steel construction. CO_2 emissions, however, were significantly higher for the concrete structure than for any other type of construction.

Table 3
Total and Above Grade Energy Use and CO_2 Emissions Resulting From Construction of Three-Story Office Buildings of Concrete, Wood, and Steel

Construction	Total Energy Use*	Above Grade Energy Use*	CO_2 Emissions**
Concrete	5.50	3.70	132
Wood	3.80	2.15	73
Steel	7.35	5.20	105

Source: Forintek Canada, 1997.
* GJ x 10^3
** kg x 10^3

Analysis of a Multi-Story Apartment Building

A life cycle assessment focused on energy and greenhouse gas emissions associated with construction of a four-story apartment building in Växjo, Sweden examined concrete and wood alternatives. The building contained 16 apartments, comprising 12,800 usable square feet (1,189 m^2) in total (Figure 1).

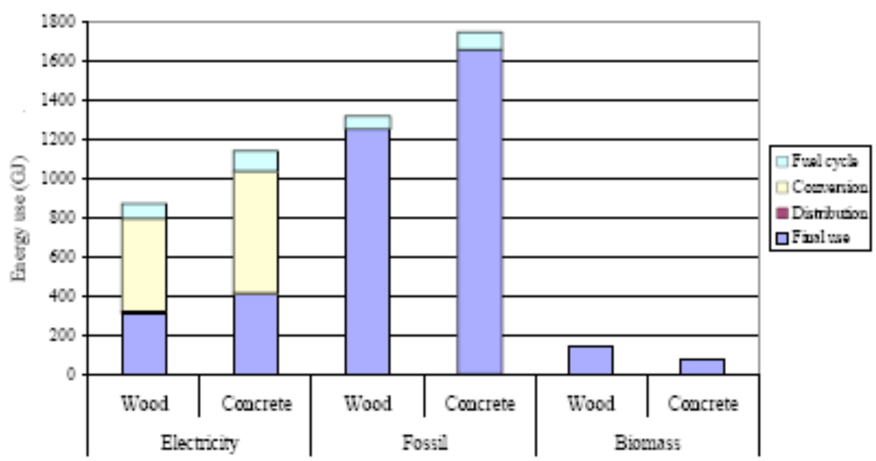
This study was conducted by analyzing the actual construction of a wood frame building, and then designing and analyzing (but not constructing) the same structure from reinforced concrete. Included in the analysis were raw material extraction, manufacturing, all transportation, and building construction activity.

Figure 1
Building Types Considered in Life Cycle Assessment of Reinforced Concrete vs. Wood Construction

Source: Börjesson and Gustavsson (2000).

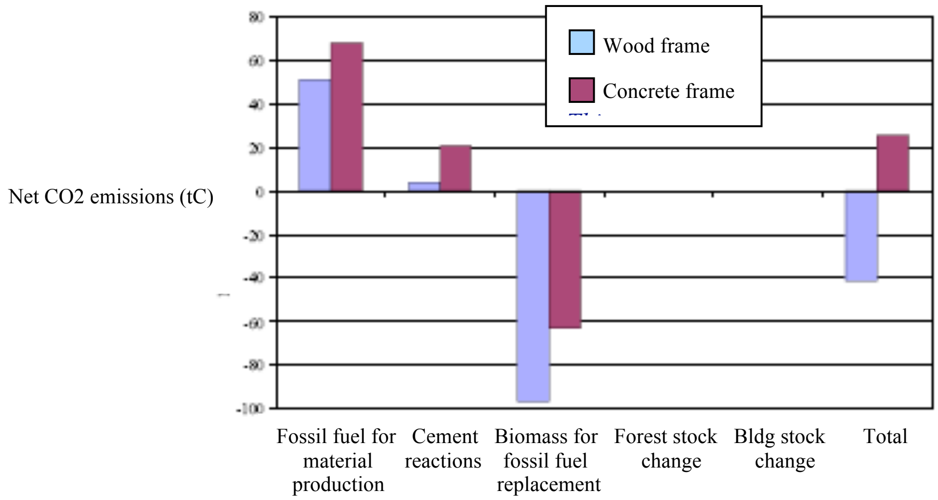
Findings revealed significantly higher energy consumption associated with concrete construction than with wood construction, both in the form of electricity and fossil fuels (Figure 2), as well as a large difference in CO_2 emissions (Figure 3).

Figure 2
Primary Energy Use for Production of Materials Used in Reinforced Concrete and Wood-Frame Construction of a Four-Story Apartment Building



Source: Börjesson and Gustavsson (2000).

Figure 3
Carbon Balance for Reinforced Concrete vs. Wood-Frame Construction of a Four-Story Apartment Building

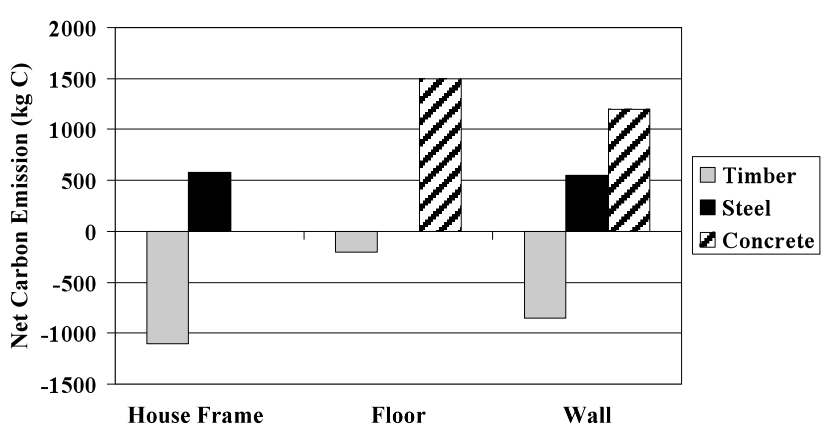


Source: Börjesson and Gustavsson (2000).

Analysis of Single-Family Residential Structures – Uniformly Similar Results

A study conducted by the Department of Civil Engineering at the University of Christchurch, New Zealand examined life cycle impacts of the use of concrete, wood, and steel for various components of a single-family residential structure. Energy use and carbon emissions from raw material extraction through building construction were the focus of the study which considered alternative house frame, flooring, and wall systems (Figure 4).

Figure 4
Carbon Dioxide Emissions of Various Components of a Typical House



Source: Honey and Buchanan, Department of Civil Engineering, University of Canterbury, Christchurch, NZ, 1992.

Taking into account the fact that wood is about one-half by weight carbon, the analysis showed concrete construction to result in greater net carbon emissions than either wood or steel in both floor and wall systems. The net *negative* carbon emissions for wood shown in both Figures 3 and 4 reflect the fact that carbon stored within wood is greater than total net carbon emissions associated with harvesting and processing of wood.

Another study, this conducted by the Consortium for Research on Renewable Industrial Materials (CORRIM) examined concrete block and wood-frame construction options for a typical home built in the Atlanta metropolitan area (Lippke et al. 2004, Perez-Garcia et al. 2005). The 2,135 square foot (198 m^2) house was a concrete block slab-on-grade design, with material differences only in the exterior walls (Figure 5, Table 4).

Figure 5
Atlanta House Design Analyzed for Concrete Block vs. Wood Construction

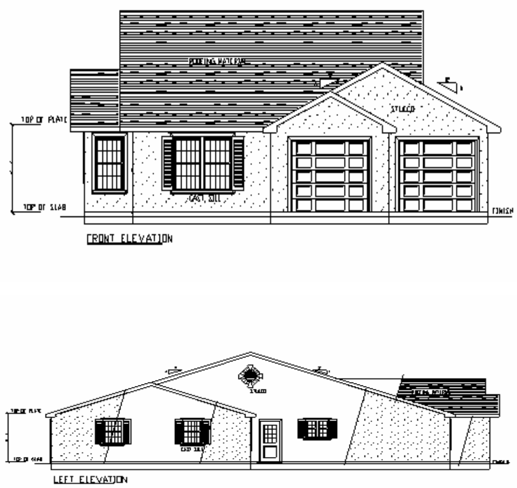


Table 4
Design Differences for Atlanta House, Concrete Block vs. Wood Construction

Wood Frame	2153 sq.ft. 1 story	Concrete Frame
	On-Slab	
2x4 studs @ 16" plywood sheathing	Exterior Walls	concrete blocks
2x4 studs @ 16"	Interior Walls no sheathing	2x4 studs @ 16"
	Roof all wood	
	Floor slab	
	Extraction (primary materials)	
11,498 kg of Wood 8,388 kg of Limestone		8,397 kg of Wood 14,487 kg of Limestone

A life cycle comparison of the two designs from material extraction through building construction shows concrete construction to result in significantly higher consumption of energy, emissions of greenhouses gases (indicated by global warming potential – GWP), emissions to air, and generation of solid wastes than wood construction (Table 5). A comparison of above grade portions of the structure only (which factors out the common slab foundation but which retains common elements in the interior walls and roof systems) shows a greater difference, with impacts 38 to 164 percent greater for concrete construction than for wood (Table 6). However, the most meaningful comparison is one in which only the different elements are compared – in this case the exterior walls (Table 7). The embodied energy difference in this instance is 149 percent, meaning that the materials for the concrete design require 2.49 times more energy to extract, convert to product, and incorporate into the finished structure than the wood design.

Table 5
Environmental Impact Comparison – Wood to Concrete: Total Structure

Atlanta House	Concrete Const.	Wood Frame	Difference	Concrete environmental impact vs. wood
Embodied energy (GJ)	461	398	63	+16%
GWP (CO_2 kg)	28,004	21,367	6,637	+31%
Air emission index	6,007	4,893	1,060	+23%
Water emission index	7	7	0	0%
Solid waste (total kg)	11,269	7,442	3,827	+51%

Source: Lippke et al. (2004)

Table 6
Energy Efficiency Comparison Wood to Concrete: Above Grade Only

Atlanta House	Concrete Const.	Wood Frame	Difference	Concrete environmental impact vs. wood
Embodied energy (GJ)	231	168	63	+38%
GWP (CO_2 kg)	14,982	8,345	6,637	+80%
Air emission index	3,373	2,313	1,114	+46%
Water emission index	2	2	0	0%
Solid waste (total kg)	6,152	2,325	3,827	+164%

Source: Lippke et al. (2004)

Table 7
Energy Efficiency Comparison Wood to Concrete: Exterior Walls Only

	Concrete block wall (MJ/ft^2)	Lumber-framed wall (MJ/ft^2)
Structural[a]	75.89	6.27
Insulation[b]	8.51	8.51
Cladding[c]	8.09	22.31
Total	92.49	37.09

[a] Includes studs and plywood sheathing for the Lumber wall design and concrete blocks and studs (used in a furred-out wood-studs wall) for the Concrete wall design.
[b] Includes fiberglass and six mil polyethylene vapor barrier for both warm climate designs.
[c] Includes interior and exterior wall coverings. Exterior wall coverings are vinyl (Lumber wall design) and stucco (Concrete wall design). Interior wall coverings gypsum for both warm climate designs.
[d] Includes subtotals from Structural, Insulation, and Cladding categories.

Source: Edmonds and Lippke (2004)

Essentially identical results to those reported above have been obtained by many other research groups around the world who have studied these issues. For instance:

- A U.S. study of various wall configurations, including wood 2 by 4 construction, steel stud construction, autoclaved cellular concrete, and EPS insulating concrete form found that wall systems made of concrete had poorer energy performance when considered both at the point of completion of building construction and over the long term. The study evaluated wall systems with equivalent R-values used in cold climate regions of the United States and Canada, and included an evaluation of energy required for wall construction and for subsequent building operation over the long term (Pierquet et al. 1998).
- A life-cycle assessment (Damberger 1995, as reported by Scharai-Rad and Welling 2002) of single-family houses in Germany found concrete block construction to require 1.58x the energy overall and 2.85x the energy for the above-grade portion of structures. When considered over an 80-year life cycle overall energy requirements for the concrete structure (considering total energy needed for construction and building operation) were found to be 21 percent greater than for a functionally equivalent wood structure; global warming potential was similarly higher for the concrete structure.
- A New Zealand Study of various types of buildings, including hotels, office buildings, industrial structures, and residential homes consistently found lower energy requirements for concrete construction than for steel construction, but significantly higher energy consumption with concrete construction than wood construction. Carbon emissions associated with production of building materials and building construction were found to be similar for concrete and steel construction, with both about 50 percent higher than for wood construction (Buchanan and Levine 1999).
- A Swedish study of concrete-framed and wood-framed buildings (Gustavsson and Sathre 2006; Gustavsson et al. 2006) found higher energy and CO_2 balances for concrete-framed structures (with differences in the range 30 to 130 kg C per m^2 of floor area) and concluded that reducing the proportion of concrete building materials relative to wood building materials would be an effective means of reducing fossil fuel use and CO_2 emissions.

Many more such studies could be cited. Results are remarkably consistent across all of these studies. However, there are several recent studies that offer seemingly contrary results.

Seemingly Contrary Findings Regarding Life Cycle Impacts

The conclusions of two recently published studies by Marceau and VanGeem[1] appear, at first glance, to conflict with other studies that have compared environmental impacts of concrete construction relative to wood construction. While in all of these studies there was concurrence that the concrete construction process (including all steps from raw material extraction through completion of construction) results in the consumption of more energy and greater emission of carbon dioxide than wood construction, the opposite conclusion was reached after considering energy consumption and carbon dioxide generation though all steps of materials production, building construction, and 100 years of building operation. The following statements are excerpts from the summaries of the two reports:

- "The results show for a given climate, the life-cycle environmental impacts are similar for the wood and concrete masonry unit (CMU) houses."
- "The results show for a given climate, the life-cycle environmental impacts are greater for the wood house than for the ICF house."

Study results, in other words, show that while wood construction results initially in lower environmental impacts, cumulative environmental impacts linked to building operation over the life of a structure shift the advantage to concrete. Given that these conclusions appear to be markedly at odds with previous studies, a look at project methodology and assumptions are in order.

As shown in Table 8 (on the following page) there are many ways to configure a wall assembly and there can be wide variance in thermal performance depending upon wall design. Therefore, it is standard practice in comparative studies to design functionally equivalent structures, including equal thermal performance. Similarly colored sections of Table 8 illustrate wall sections of various construction materials designed so as to achieve thermal equivalence.

It appears that the difference in Marceau and VanGeem's findings lies in the fact that each of the concrete walls considered was designed to have higher insulating properties than the wood walls used for comparison; in three out of four the designed R-values of the wood walls are only 70 percent that of the ICF walls. With this methodology, it is not surprising that early advantages of wood construction are reversed by greater energy consumption during long-term building occupation.

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[1] Marceau, M. and VanGeem, M. 2008b. Comparison of the Life Cycle Assessments of an Insulating Concrete Form House and a Wood Frame House. Portland Cement Association Publication SN3041 (http://www.cement.org/bookstore/profile.asp?itemid=SN3041). Marceau, M. and VanGeem, M. 2008a. Comparison of the Life Cycle Assessments of a Concrete Masonry House and a Wood Frame House. Portland Cement Association Publication SN3042 (http://www.cement.org/bookstore/profile.asp?itemid=SN3042).

Table 8
R-Values of Different Wall Systems

	Wall System	R-value
1	6 in. poured or precast concrete, R-10.5 interior insulation, wood furring, and ½ in. gypsum board interior.	8.7
2	3 5/8 steel stud wall with 1 5/8 flange, 24 in. o.c., R-11 batts, beveled wood siding over ½ in. plywood sheathing, ½ in. gypsum board interior.	8.7
3	8 in. concrete block wall, cores filled with perlite or vermiculite, and R-10.5 interior insulation, wood furring, and ½ in. gypsum board interior.	11.5
4	2 x 4 wood stud wall 16 in. o.c., R-11 batts, beveled wood siding over ½ in. plywood sheathing, 5/8 in. gypsum board interior	11.5
5	12 in. concrete block wall, partial grout, cores filled with perlite or vermiculite, and R-11 interior insulation, wood furring, and ½ in. gypsum board interior.	13.4
6	3 5/8 steel stud wall with 1 5/8 flange, 12 in. o.c., R-11 batts, beveled wood siding over 5/8 in. plywood sheathing and 1 in. XPS, 5/8 in. gypsum board interior.	13.4
7	2 x 4 wood stud wall 16 in. o.c., R-15 batts, beveled wood siding over 5/8 in. plywood sheathing, ½ in. gypsum board interior.	13.4
8	12 in. concrete block wall, partial grout, cores filled with perlite or vermiculite, beveled wood siding over R-10 exterior insulation, wood furring, and ½ in. gypsum board interior.	17.9
9	2 x 6 wood stud wall 24 in o.c., R-21 batts, beveled wood siding over 5/8 in. plywood exterior sheathing, 5/8 in. gypsum board interior.	17.8
10	Insulated concrete form (ICF), with 2 in. thickness EPS on either side of 6 in. thickness of normal concrete, beveled wood siding, and ½ in. gypsum board interior.	21.5
11	3 5/8 steel stud wall with 1 5/8 flange, 12 in. o.c., R-15 batts, beveled wood siding over 2 in. extruded polystyrene rigid insulating sheathing, 5/8 in. gypsum board interior.	21.5
12	Insulated concrete form (ICF), with 2 in. thickness, XPS on either side of 7.5 in. thickness of normal concrete, beveled wood siding, and 5/8 in. gypsum board interior.	23.6
13	2 x 6 wood stud wall 24 in o.c., R-19 batts, beveled wood siding over ½ in. plywood exterior sheathing and 1½ in. EPS, ½ in. gypsum board interior.	23.6

Sources: Oregon Department of Energy. 2008; Washington State Building Code, Chapter 51-11-1005.

A critical component of life cycle assessment of comparative wall structures is to assume that walls are designed to *functional equivalence* prior to considering long-term performance. If the walls in these three most recent studies were designed with the same R-values, the differences in energy and emissions up to the point of construction would have narrowed slightly, while differences in energy consumption over the life of structures would have been eliminated or minimized – with the result that conclusions would have been in agreement with other published studies.

An important observation that is made in the two studies is that the quantity of energy used over the life of a building – for heating and cooling, lighting, and so on – is substantially greater than the quantity of energy needed to produce construction materials and to erect the building. Typically, the energy needed for production and construction is equivalent to 7-15 years of building operation. The equivalency period increases as building energy efficiency is increased (Keoleian et al. 2001); this reality points to the need for care in building design to ensure optimal performance over the life of a building.

On the one hand, energy and emissions linked to production of building materials and building construction can be dismissed as representing a relatively small proportion of life cycle impacts (only 5 to 10 percent in the two studies cited). On the other hand, seemingly small percentages can translate to very substantial differences in energy consumption and CO_2 and other emissions linked to building construction. For instance, if from this point forward every new home built in the U.S. were built of concrete rather than wood, the increase in energy consumption would be roughly equivalent to permanently operating 800,000 - 900,000 SUVs, each driving 20,000 miles per year.

Thermal Mass

It is important to remember that R-values are only one measure of a walls total energy performance, albeit the dominant one in use today. One argument in favor of the use of concrete in construction is that the thermal mass of a concrete structure aids in energy efficiency. Concrete tends to retain heat and cold, and thus serves to moderate daily temperature swings. Concrete floors and interior walls can also be used in passive solar designs. These systems usually consist of buildings with an elongated east-west axis and a thermal storage mass (i.e. concrete slab) that is exposed to solar radiation.

While research on the energy-efficiency benefits of concrete construction is not yet definitive, there is some agreement that the benefits of thermal mass may be greater (or at least more economically accessible) in hot climates and less applicable (or potentially even a disadvantage) in very cold climates. As stated by researchers at the Oak Ridge National Laboratory (Kosny et al. 2001) " . . . research demonstrates that in some U.S. locations, heating and cooling energy demands for buildings containing massive walls of relatively high R-values can be lower than those in similar buildings constructed using lightweight wall technologies." They note potential energy savings from massive wall construction (i.e. very thick interior walls) of 5-16 percent in a climate like that of Phoenix, but potential increases in energy consumption in a climate such as that of Minneapolis.

The Bottom Line

Concrete construction offers an alternative that may be attractive to building designers, builders, and home-buyers in some situations. From an environmental impact point of view, concrete construction is preferable to steel-frame construction from an energy use standpoint, but is generally disadvantageous to steel with regard to generation of CO_2 and other greenhouse gases. When concrete construction is systematically compared to wood construction, results consistently show higher energy consumption and related emissions, including carbon dioxide and other greenhouse gases, associated with concrete construction.

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