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Embodied Energy and Carbon Footprint of Concrete Compared to Other Construction Materials

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The main objective of infrastructure design codes is to protect the public's welfare, health, and safety, none of which appear directly related to the current sustainability movement that has focused on protecting the natural environment, conserving resources, and minimizing the toxicity of construction materials and processes. Some United States jurisdictions have adopted language related to sustainability based on the United States Green Building Council to curtail adverse effects of global climate change, minimize environmental impact of new construction of built assets (i.e., buildings and infrastructure), and in some cases, improve air quality in the community. The focus of this paper is to compare the embodied energy and carbon footprint of various construction materials: concrete, steel, timber, masonry, and fiber reinforced composites. To properly compare these materials from a sustainability standpoint, we propose an index that characterizes material ecological properties by dividing strength and stiffness by embodied energy. The index is similar to the structural specific properties index used to characterize the mechanical properties of materials (i.e., strength and stiffness divided by density). Using this ecological index, concrete and steel appear to be the most sustainable materials. As a result of their higher strength and stiffness, concrete and steel require less embodied energy to satisfy specific structural demands.

Keywords: *embodied energy, carbon footprint, LEED, specific embodied energy*

Introduction

From conventional to high-performance composite materials, construction materials have been developed and modified over the past century. With the increased use of contemporary materials, such as concrete, steel, timber, masonry, and fiber reinforced composite, steps are currently being taken to reduce their pollution impact and to promote their sustainability. Driven in part by governmental policies to increase awareness of the effects of greenhouse gases and to utilize limited natural resources more efficiently, sustainability has become an important aspect in infrastructure design. Many of the innovations in sustainability have been spearheaded by professional organizations, such as the American Society of Civil Engineers (ASCE), the American Institute of Steel Construction (AISC), the American Concrete Institute (ACI), the American Forest & Paper Association (AF &PA), the U.S. Green Building Council (USGBC), etc. These organizations' primary sustainability goals are to reduce the carbon footprint of structures, curtail

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any negative environmental effects caused by construction, improve indoor environmental quality, and assuage adverse social and economic impact.

The main approach for attaining such goals is by working with engineers and architects to implement changes that reflect sustainability methods in design and construction of built assets – buildings and infrastructure. To assess the degree of achievement, professional organizations have developed a sustainability certification for existing and new structures. Certifications rate their overall impact on the environment, society, and the economy. The USGBC leads the way via their Leadership in Energy and Environmental Design (LEED) certification program which serves to standardize the overall sustainability of buildings using a point system in LEED v4.1 (current version as of 2021).

The LEED certification program has created standards for the design and development of new construction of various types of buildings. LEED awards points based on the following eight parameters: Location and Transportation (16 points), Sustainable Sites (10 points), Water Efficiency (11 points), Energy and Atmosphere (33 points), Materials and Resources (13 points), Indoor Environmental Quality (16 points), Innovation (6 points), and Regional Priority (4 points). The standard point values are assigned to new construction but can change depending on building type. Classification is assigned as Certified (40 to 49 points), Silver (50 to 59 points), Gold (60 to 79 points), or Platinum (80 points and above).

Of the eight areas that LEED addresses, Materials and Resources as well as Innovation are directly related to sustainable materials. Indoor Environmental Quality is indirectly related to sustainable materials, as three of its 16 points assess Low-Emitting Materials. Energy and Atmosphere should also be considered in evaluating the sustainability of materials since upfront carbon emissions generated in the mining, harvesting, processing, transportation, and installation of construction materials can constitute a larger portion of a new building's embodied energy compared to all other stages in its life cycle (WGBC 2019).

Building sustainable infrastructure has been more expensive and less profitable for developers, but recent advances in materials, processes, and equipment have made the cost of building 'green' competitive. For a typical building, the structural system usually accounts for 10 to 20% of the construction costs (Kneer and Maclise 2008). The increased cost associated with achieving the lowest LEED certification is approximately 4%. Higher certification levels have increased cost premiums; for example, gold certification can cost up to 10%, while Platinum up to 12.5% (WorldBGC 2019). More importantly, the life cycle cost, including energy consumption of the building, can be lower compared to the costs of conventional construction (WorldBGC 2019).

Some of the most important changes related to sustainable construction have been spurred by government agencies through the adoption of LEED certification for public projects; for example, requiring all public governmental buildings to be LEED certified. To further increase public sector investment in the development of LEED certified structures, incentives have been offered, such as grants, tax credits, and low interest loans. Incentives for private development include higher rents, sale prices, and occupancy rates for LEED office spaces (Miller et al. 2008). Each incentive confers lower investment risks and higher profits. In fact, the potential lower life cycle cost is the primary reason many private and public entities are specifying LEED certified structures. Life cycle cost analyses support the return on investment, not just the initial cost.

Pollution Impact of Infrastructure Materials

As noted, two sustainability areas, Energy and Atmosphere as well as Indoor Environmental Quality, indirectly relate to sustainable materials. These areas are primarily concerned with control of pollutants and their effects on public health and the environment. Of particular importance is curtailing CO_2 emissions to reduce the adverse effects of climate change. Table 1 lists CO_2 emissions per ton generated in the production of various materials; the most widely used of which is concrete. Most of the embodied CO_2 in concrete comes from cement, which produces nearly as much CO_2 as the material itself. Thirty-five percent is generated by using fossil fuels during the heating of limestone and clay, while the remaining 65% is released in the calcination process when calcium carbonate ($CaCO_3$) from limestone is converted to calcium oxide (CaO):

$$CaCO_3 + \text{Heat} \rightarrow CaO + CO_2$$

It is estimated that between 33% and 57% of CO_2 produced during cement production can be reabsorbed into concrete surfaces during a 100-year product life cycle through a reverse carbonation process (Pade and Guimaraes 2007). This is usually not accounted in the total CO_2 reported.

Table 1. *Net CO_2 Emissions in Producing Various Materials*

Material	**Net CO_2 Emissions (kg CO_2/kg)** [a]
Aggregate	0.005
Framing lumber	0.033 [b]
Brick	0.25
Concrete blocks	0.29
Recycled steel (100% from scrap)	0.30
Concrete	0.95[c]
Cement	1.0
Steel (virgin)	1.30
Glass fiber reinforced plastic (GFRP)	18.8
Carbon fiber reinforced plastic (CFRP)	35

[a] Values are from various sources (primarily form Crawford et al. 2019 and Ashby 2009) and are based on gathering and processing of raw materials, primary and secondary processing, and transportation.

[b] This value depends on where the lumber is harvested and can be as high as 0.38; Also, carbon stored within wood will eventually be emitted back to the atmosphere at the end of the useful life of the wood product. Near-term net CO_2 emissions, including CO_2 storage within material, can be considered negative, – 0.46 kg CO_2/kg).

[c] This value is estimated by the Portland Cement Association estimates; also see Figure 1.

Global cement production contributes approximately eight percent of total CO_2 produced each year. However, it is difficult to establish a definitive value since different countries report different figures. Even in the United States, the Environmental Protection Agency (EPA) reports that different states, in some cases, fabrication plants, report different values (U.S. EPA 2009). This is expected given that equipment, local regulations, and methodology used to quantify CO_2 emissions differ from plant to plant. Therefore, any reported values should be used only as average estimates.

Though only approximately 25% of a building's environmental impact is attributed to its materials (WGBC 2019), this total environmental impact happens immediately, while the environmental impact of operations occurs over the life of buildings. Therefore, considering the conclusions of the Intergovernmental Panel on Climate Change report (IPCC 2018) regarding the catastrophic changes to the environment if drastic steps are not taken immediately to reduce CO_2 levels in the atmosphere, the initial global warming effect from materials should be expected to be much more severe than those from operations.

Current laws have incentivized limiting the amount of pollution produced in the manufacturing of infrastructure construction materials. Companies producing these materials have opted to reduce energy consumption and recycle to comply with current environmental protection laws and decrease processing costs. Limitations of air emissions and waste from manufacturing have both contributed to environmental improvements in these industries.

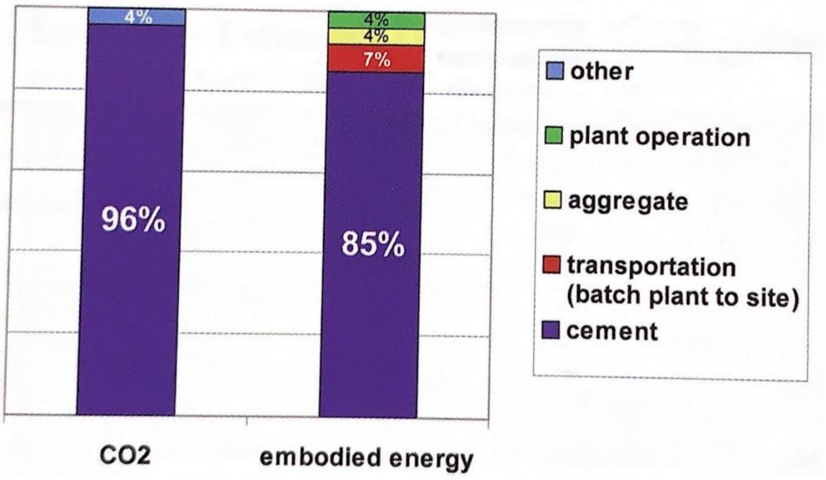
Another way in which infrastructure construction has impacted the environment is through building demolition, with solid waste from demolition increasing approximately 20% from 1996 to 2003 (U.S. EPA 2009). The average percentage breakdown of solid waste by materials is as follows: 40 – 50% concrete and mixed rubble, 20 – 30% wood, 5 – 15% drywall, 1 – 10% asphalt roofing, 1 – 5% metals, 1 – 5% bricks, and 1 – 5% plastics (U.S. EPA 2009). As resources that go into the built environment become scarce, it is anticipated that most of these materials will be reused or recycled. In some cases, existing buildings can be reused, either the entire building or parts of it. These options should be considered in every project to decrease the use of raw materials in new construction. There are several established programs that address the reuse and recycle of materials: building deconstruction, construction materials salvage, and reuse of reclaimed materials in new site and building projects. Use of recycled materials decreases extraction of raw materials and reduces the embodied energy of a construction project. Recycling and reusing materials can also result in additional revenue and decreased costs in construction. Recycling is promoted by state and local municipalities through increased fees in landfill use and waste reduction laws.

Embodied Energy in Infrastructure Materials

Life cycle energy, or embodied energy, of a building can be divided into two categories: material and operating. Material embodied energy, the focus of this paper, can be defined as the sum of all the energy sequestered to produced, transport, and install a built asset. In some instances, it may include final demolition and disposal. Operational embodied energy is defined as the sum of all energy used in a building's operation during its life and includes heating, ventilation, and air conditioning (HVAC), water heating, lighting, and other equipment. The term CO_2

emissions, or embodied greenhouse gases, can be defined as the sum of all the greenhouse gases released from material extraction, transport, material manufacturing, building construction, disposal, and other related activities. Embodied energy is measured as energy per unit mass (joules/kilogram, J/kg) or energy per unit volume (joules/meter cubed, J/m^3), while CO_2 emissions is measured in mass of CO_2 per unit mass of product (kilogram of CO_2/kilogram, kg CO_2/kg). Although a building's embodied environmental impact can be expressed in terms of embodied energy or CO_2 emissions, it is more common to use an embodied energy measurement. There is a slight difference between CO_2 emissions and embodied energy as shown in Figure 1. While CO_2 emissions include all carbon released to the atmosphere in the production of the materials, embodied energy is the amount of energy consumed by all the processes used to manufacture the material.

Figure 1. *Total CO_2 and Embodied Energy in Various Materials in Concrete (Schokker 2012)*

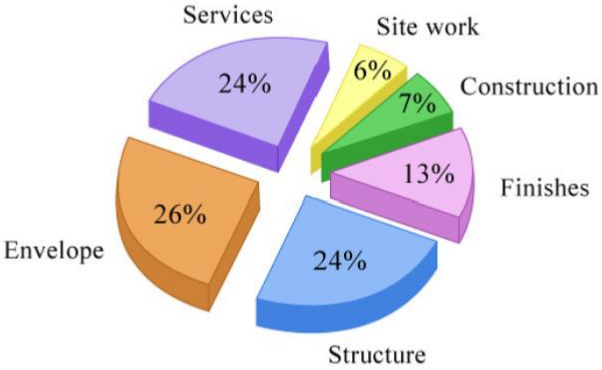


At first glance, structural engineers appear to have little to contribute to sustainability; however, Hays and Cocke (2009) make a compelling case to the contrary. It is argued that existing buildings can be repurposed to reduce embodied energy in construction materials as the greenest building is one that is already built. They present an embodied energy analysis of an adaptive reuse of a 1950's, two-story concrete warehouse. To construct a new building and replace the 4,645 square-meter space, it would require over 116 gigajoules (GJ) worth of energy: 59.6-GJ in the existing building, 0.818-GJ to demolish the building, and 59.6-GJ to construct the replacement building. A new high-efficiency building could not save this amount of energy over a fifty-year service life (Hays and Cocke 2009). Adams et al. (2010) present a breakdown of the initial total embodied energy per square meter in a typical building (4.82 gigajoules per square meter – GJ/m^2), with approximately a quarter of the embodied energy used in the structure (see Figure 2). These two examples illustrate how structural engineers can make substantial contributions to sustainability by retrofitting and repurposing existing buildings, and in cases where that is not possible, using structural materials with lower embodied energy content.

Concrete

Production of cement, the main ingredient in concrete, nearly doubled between 1990 and 2005, (Mehta and Meryman 2009). Annual cement consumption rates have continued to increase, resulting in double the consumption of cement in the past fifteen years. This also means that pollution levels from cement production have doubled over the past fifteen years. It is estimated that global cement consumption will increase by as much as 23% by 2050 (WGBC 2019).

Figure 2. *Breakdown of Embodied Energy of a Typical Building (Adams et al. 2010)*



Cement producers are under increased pressure from governments and consumers to reduce CO_2 emissions as most of the concrete total CO_2 comes from cement as shown in Figure 1. Reduction in cement content in concrete can be accomplished by modifying a concrete mix design to replace the higher CO_2 cement with Supplementary Cementing Materials (SCMs), such as finely ground limestone, recycled fly ash (i.e., a pozzolanic byproduct of coal-fired electricity generation), and blast-furnace slag (i.e., a pozzolanic byproduct of steel blast furnaces).

The benefits of using SCMs, particularly the pozzolanic byproducts, are twofold: the materials are diverted from the landfills and the cement's environmental impact is reduced because of its replacement with a carbon-neutral byproduct. This is a common practice in Europe where Portland-slag cements contain over 50% ground granulated-blast-furnace slag (Mehta and Meryman 2009). The Portland Cement Association (PCA) and the American Concrete Institute (ACI) have developed recommendations for limestone, fly ash, and slag cement replacement by weight (Table 2). According to PCA, fly ash and slag are optimal substitutes for raw cement because their use results in no degradation to the mechanical properties of concrete. This is particularly important since cement, on average, accounts for as much as 85% of the energy needed to produce concrete (Figure 1), but only makes up a small percentage of the mix, approximately 15%. Using these by-products and reusing some hardened concrete as aggregate can result in a material that is 50 to 60% recycled and much more energy efficient.

Table 2. *Recommendations for Supplementary Cementing Materials (SCMs)*

Product	PCA/ACI Recommended Replacement by Weight	Comments
Fly Ash Class C	15% – 40%	High calcium content This has pozzolanic and cementitious properties
Fly Ash Class F	15% – 25%	Low calcium content Pozzolanic, but little cementitious properties Primarily replaces fine aggregate
Slag	30% – 40%	Used in general concrete construction
Limestone	5% – 15%	5% can replaced clinker 5% to 15% used in blended cement
Silica Fume	Up to 30%	Used to make high-strength concrete

In normal concrete, a large portion of cement never hydrates because rapid reaction inhibits uniform cement distribution throughout the concrete material. This issue is more critical for early strength concrete since it cannot reach its full potential compressive strength at the specified age. Aiming to minimize the un-hydrated cement and produce a high-performance material, PCA has developed several admixtures to promote cement hydration and obtain a higher compressive strength sooner. High performance concrete also requires optimized aggregate gradations to produce a more impermeable hardened concrete that can prevent corrosive chemicals from reaching the steel reinforcement. This results in increased material durability. Thus, mix designs optimized for early strength and rapid construction can increase the concrete durability and lessen its environmental impact. Also, higher strength concrete results in smaller components for a given target capacity.

Until recently, the main impediment to reducing cement content in concrete was conventional industry standards. Such standards had institutionalized cement intensive mix designs that exhibited poor long-term performance and as a result, unnecessary adverse environmental impacts. However, since the concrete industry is organized around consensus standards and most professionals now recognize the importance of sustainability, sustainable practices are slowly being incorporated into the concrete industry. In fact, fly ash and slag American Standard for Testing and Materials (ASTM) standards (ASTM C618 and ASTM C989, respectively) have been developed as a testament to the concrete industry's commitment to sustainability. The steps being taken by the cement industry to reduce its carbon-footprint, particularly the use of SCMs, will result in concretes with lower embodied energy, lower carbon emissions, and lower environmental impact from the extraction and processing of virgin materials, and an increased diversion of by-product materials from landfills, all of which will result in a more cost-effective, durable concrete material with a much longer service life.

Steel

Steel has become a highly recycled material. By taking large amounts of scrap steel to manufacture new steel, it is the most recycled material today. Steel recycling and new processing methods have decreased its impact on the environment by as much as 75% over the past 75 years. In fact, at the end of a building's life, over 98% of all steel is recycled and reconstituted into new steel products (AISC 2011). Not only is steel 100% recyclable, but it can be multi-cycled without degradation to its mechanical properties, making it truly a cradle-to-cradle material unlike other materials that can only be recycled into a lower quality product or downcycled (AISC 2011). Furthermore, processing innovations have allowed the steel industry to produce steel that is 40% stronger than steel from half a century ago. Most steel today is produced by electric-arc furnace, which can use electricity produced from renewable sources, such as solar and wind. This will eventually permit the steel industry to attain its goal of producing steel that has no carbon footprint (i.e., zero-carbon steel).

Due to its cradle-to-cradle property, the energy consumption during steel production has decreased by as much as 75% over the past 75 years (AISC 2011). The most drastic change came in the 70's and 80's when the industry began using recycled steel and switching from coal burning furnaces to electricity. Over the past half century, various developments in the production of new steel have led to tremendous progress towards some of the most important goals of sustainability (e.g., promoting energy efficiency, reducing the use of virgin materials, minimizing site disturbance, and providing a healthier living environment). Considering its high strength-to-weight ratio, the carbon footprint from steel is relatively small, as little as 300-kg of CO_2 are produced to manufacture a ton of steel (Table 1).

Several advances in recent years have contributed to the reduction in the volume of steel used in any given project, particularly the development of high strength steel that has 40% higher strength (36 ksi to 50 ksi). This increase in strength results in smaller elements that in turn, results in smaller supporting superstructure and foundation components. Also, since steel has a high strength-to-weight ratio, it can carry large loads with a smaller structural system which reduces the impact of a building on the site by requiring less widespread site development.

The use of recycled steel also increases the volume of materials diverted from the landfills and repurposed. Byproduct materials that would typically result from extracting raw material from the ground are diverted from the landfills since virgin steel is replaced by recycled steel. Minimal steel waste is generated at fabrication facilities or construction sites as most waste generated is recycled. Additionally, when considering that steel buildings require minimal ongoing maintenance, have long lives, and are recyclable at the end of their life, the resulting environmental impact of steel is minimal. Furthermore, steel from deconstruction is made easier and faster because of the use of steel bolts to fasten steel systems. Figure 3 shows repurposed structural steel sections being used as shoring to support the construction of a concrete bridge.

Figure 3. *Repurposed Steel*

Other innovations in the design of steel buildings that can have a significant impact on their sustainability include:

- The use of a design-build approach which entails reducing the delivery schedule of a project by overlapping the design and construction phases. This compressed schedule also lessens the adverse effects of construction on the site.
- The use of Building Information Modeling (BIM) allows the designer to create 3-D computer models of all building systems to determine their interactions and conduct conflict resolutions before construction even begins. BIM can be used to optimize the integration of mechanical systems within the floor beams leading to lower floor-to-floor heights and resulting in less building volume to be heated or cooled. This lowers the building's energy consumption.
- Continuous improvement in water resource management in the production of steel has resulted in a 95% water recycling rate; currently, less than 70 gallons of water are consumed per ton of steel produced (AISC 2011).
- With concern for indoor environmental quality, steel framing systems can be used to span large indoor areas to improve occupant comfort. Such systems can also span large wall openings for windows to allow natural lighting which can result in a reduction in electrical consumption and further reductions in CO_2 emissions.

Initiatives in place reduce steel's carbon-footprint, particularly with high-strength steel, new innovative design techniques, and recycling and reusing steel. This results in increased diversion of byproduct materials from landfills and more importantly, buildings with a lower embodied energy, lower CO_2 emissions, and lower environmental impact from the extraction and processing of virgin materials. The steps already taken and future developments will make steel a more sustainable and cost-effective material.

Timber

Timber construction has had the most significant impact on the environment, both positive and negative. Until third-party certified sustainably harvested wood became available, timber production resulted in soil erosion, pollutant runoff, increased CO_2 levels, and habitat loss. Timber that comes from certified forests has been managed to maximize timber yield, promote healthy ecosystems for wildlife habitat, and minimize erosion to protect waterways (DeStefano 2009). The certification programs best recognized in North America are the Forest Stewardship Council (FSC), the Sustainable Forestry Initiative (SFI), and the Program for the Endorsement of Forest Certification (PEFC).

Furthermore, wood farming mitigates the effect of clear-cutting old growth forests. These forests are harvested relatively frequently. The resulting smaller diameter trees can be used as structural wood and turned into Engineering Wood (EW) products, such as plywood, oriented-strand board panels, glued-laminated lumber, laminated and parallel strand lumber, and laminated veneer lumber. The most common binder used in EW products is phenol-formaldehyde resin which can make EW products more difficult to recycle. However, the potential adverse effects of engineered lumber are offset by the more efficient use of natural resources and potential use of recycled content.

Even though timber can be a renewable resource, only about a quarter of structural timber comes from certified, sustainably managed forests. However, significant progress has been made in recent years. In fact, because of reforestation practices, the forested area in North America is approximately the same size compared to 100 years ago. The net annual growth is three percent greater than harvests and other losses combined. On average, 98% of any given tree brought to a mill is used as timber, paper, engineered wood products, or fuel in the form of bioenergy (Ward 2010).

Timber can be considered a carbon negative material, at least in the short-term as noted in Table 1. Wood removes carbon from the atmosphere through photosynthesis (Falk 2010):

$$\text{Sunlight} + 6\,H_2O + 6CO_2 \rightarrow C_6H_{12}O_6 + 6O_2$$

namely, Energy + Water + Carbon dioxide → Glucose + Oxygen. Thus, not only can a substantial amount of CO_2 be sequestered, but oxygen can be released. For every pound of CO_2 removed from the atmosphere (i.e., sequestered through photosynthesis when a pound of timber is grown), 0.73 pounds of O_2 are released. If timber is burned or decomposes, the process is reversed, releasing the CO_2 back into the atmosphere and yielding a net carbon emission which is still the lowest CO_2 emission of all construction materials (Table 1).

Because wood requires low energy during processing and more than 60% of this energy comes from biofuel, a carbon-neutral energy source, the embodied energy in timber is much lower than other construction materials (Falk 2010). Half of the energy required to produce lumber goes into drying the wood in a kiln. Specifying green, un-dried lumber is 50% more energy efficient. Though higher than sawn lumber due to the processing involved, EW products have a relatively low embodied energy. However, EW products, such as oriented strand board and composite lumber, use wood chips manufactured from smaller trees from shorter rotation harvests. These trees sequester more CO_2 than those in longer-rotation forests (Falk 2010). This balances some of the additional embodied energy required to process EW products.

Unlike the commonplace process of recycling pre- and post-consumer steel for structural applications, timber recycling is primarily used as biofuel. Nonetheless, timber reuse from deconstruction is possible, though more complicated than for steel. Reusing post-consumer recycled timber for structural purposes requires the timber to be re-graded according to standardized grading rules, and in some cases, tested. Recycled wood can be processed into landscape mulch which is useful to retain moisture in the soil and lessen the water demands from plants.

Masonry

Masonry can be divided into categories based on application (i.e., structural and non-structural) and material (i.e., concrete, clay, and fly ash). In structural applications, masonry is used primarily as walls which can serve as combined gravity and lateral load-bearing elements. To serve this purpose, masonry walls must be reinforced with steel, though many un-reinforced clay masonry walls were built in the past and are still standing. Masonry in the form of concrete masonry units (CMU) is the most common form of masonry structural walls, while brick (clay, concrete, or fly ash) is almost exclusively used for facing buildings. Prefabricated CMU cellular elements serve as formwork for the concrete walls, eliminating the need to use timber formwork. This, however, is increasingly uncommon because the process of assembling a masonry wall is labor-intensive and more efficient methods have been developed to construct concrete walls, including site cast, tilt-up, or precast walls.

As for non-structural applications, exterior facing masonry walls can serve to provide thermal mass. This also applies to concrete walls. Depending on the thickness of the wall, this can markedly improve the thermal performance of a building. The process entails absorbing energy from the sun during the daylight hours and releasing it as radiant heat at night. This lessens the effect of temperature swings within the building envelope, and for much of the year in many parts of the world, maintains thermal comfort without the need for heating or air-conditioning.

From a sustainability standpoint, masonry can be used in permeable pavement applications. Masonry as concrete, clay, or fly ash units can improve the storm water management of a site by providing a permeable material for storm water infiltration over a hard surface. This type of permeable pavement system can also reduce surface runoff by improving the soil percolation of a site.

The masonry industry has made great progress in reducing the embodied energy of its products, particularly that of brick. Brick continues to be one of the most popular building facing materials because of its classic beauty, high thermal and acoustic mass, and durability. The industry is expected to continue promoting practices that will reduce its carbon-footprint, such as minimizing the use of cement in CMU and replacing fired clay brick with more sustainable fly ash brick.

Advanced Composite Materials

While there has been much research and interest over the past few decades, advanced composite materials have had limited use in infrastructure applications when compared to traditional infrastructure materials. Typically, they are used as retrofit components or components targeted to address specific issues, such as corrosion in steel reinforced concrete. The main advantages of composites over their conventional counterparts are their high structural performance, high specific mechanical properties, and durability. The most common applications for composites to date include rehabilitation of structures, seismic retrofitting of columns, and bridge decks. Most of these applications of composites are intended to extend the life of structural systems well beyond their expected life, which may, in many cases, balance their adverse environmental effects.

As shown in Table 1, FRP has a very large carbon footprint. When compared to aluminum or steel parts made from average recycled content, composite parts' embodied energy is much higher. However, a study based on life-cycle analysis of structural components fabricated by Strongwell Composites indicates that the embodied energy of some composite components is lower than that of steel members made from virgin materials (Black 2010). The report suggests that this is primarily due to the composites' superior specific properties, such as high strength-to-weight and high stiffness-to-weight ratios.

One other area where composites stand to have a significant positive impact on the environment is renewable energy systems, particularly wind power. To harness the power from wind, large turbines are placed on high towers. The turbine blades must be relatively light for transportation and efficient operation which is why most turbine blades are manufactured using composites. In 2007, more than 17,000 turbines (nearly 50,000 blades) were in operation around the world for a total capacity of 94,112 megawatts. This constitutes the largest single applications of engineered composites in the world (Hollaway 2010). The Global Wind Energy Council tracks the global wind power growth and reported the 2020 wind power capacity at 743,000 megawatts, which is equivalent to a reduction in CO_2 emissions equivalent to the annual emissions produced in South America.

Comparison of the Embodied Energies in Infrastructure Materials

Table 3 shows the density, strength, stiffness, and specific properties (i.e., a ratio of the strength-to-density and stiffness-to-density) for the various materials listed in Table 1. To properly compare materials from a structural standpoint, an indexing approach is typically used that accounts for the vast differences in material strength, stiffness, and density. For example, a kilogram of steel is much stronger and stiffer than a kilogram of concrete. However, dividing by densities, material properties can more properly be compared. Inspection of Table 3 clearly indicates that FRP composites have the best performance from a structural standpoint, followed by steel and timber. Concrete has similar properties to timber based on the effective properties of the two materials. This approach is widely used in fiber reinforced composite materials when comparing their properties to those of traditional construction materials. A similar analysis can also be performed in terms of cost to identify the most economical design. The approach in this paper is applied to compare the ecological properties of various materials.

Table 3. *Comparison of Effective Structural Properties for Various Materials*

Material[a]	**Ave. Density, ρ kg/m^3**	**Strength, σ MPa**	**Stiffness, E GPa**	**Specific properties (MPa*m^3/kg)**	
				σ/ρ	**E/ρ**
Aggregate	2300	-	-	-	-
Portland Cement	1500	-	-	-	-
Concrete	2400	35	30	0.015	12.5
Steel (100% recycled)	7800	350	210	0.045	26.9
Lumber (Douglas Fir)	450	6.9	13.1	0.015	29.1
Concrete blocks	1500	13.5	3.75	0.009	2.5
Common Brick	1700	7	4	0.004	2.4
GFRP (45% Epoxy)	1800	40	870	0.022	483.3
CFRP (50% Epoxy)	1500	142	1730	0.095	1153.3

[a] Values are from various sources (primarily form Crawford, 2019 and Ashby, 2009) and are based on life cycle analyses.

Table 4 provides a comparison of the various ecological properties of materials discussed in this paper with strength and stiffness divided by the materials' embodied energy and labeled as Specific EE. Concrete and steel are comparable in their ecological strength and stiffness, and though timber has traditionally been considered the most sustainable material, its specific EE places it third to concrete and steel. As expected, FRP composites have low specific EE values indicating their limited contribution to a sustainable build environment, which is why they are employed only in very specialized applications where they can be shown to be advantageous from an economical or sustainable standpoint. It is important to note that values in Table 4 are preliminary and should only be used as a guide. Published values for the embodied energy of materials vary widely and an effort was made here to utilize accurate values. As values for the various materials become more precise, the analysis based on effective ecological properties can be utilized as another method of comparison.

Traditionally, lightweight structural building materials have been considered to have low embodied energy compared to their heavier counterparts. However, as shown in Tables 3 and 4, this is not necessarily the case and designers should consider effective ecological strength and stiffness properties. Also, as discussed in the masonry section, there are climates with relatively large HVAC demands (i.e., significant variations in day-night temperatures) where a high level of thermal mass can offset the energy required for HVAC. Designers should balance the building energy requirements according to geography, climate, and availability of local materials, all of which should be accounted for in a life cycle analysis. Other guidelines to address sustainability during design and construction phases include:

- specifying recycled materials or materials that come from sustainably managed sources that have low embodied energy,
- reusing parts of demolished structures (deconstruction),
- using Supplementary Cementing Materials to produce “green” concrete,
- specifying locally sourced materials to reduce transportation costs and emissions,
- using durable, low maintenance materials, that can easily be refurbished or repurposed,
- specifying non-toxic material preservatives that can easily be separated and salvaged,
- using prefabricated components whenever possible,
- designing structures that can be altered and can be adapted to new uses (reuse) or loading conditions,
- specifying materials that create an efficient building envelope that can downsize or eliminate the need for HVAC
- requiring that construction site waste and demolition debris be sorted and recycled or used as biofuel, and
- specifying materials that have been produced using renewable energy sources, such as wind or solar.

Table 4. *Comparison of Effective Ecological Properties for Various Materials*

Material[a]	**Embodied Energy (EE)**		**Specific EE (MPa/MJ/kg)**	
	GJ/m^3	**MJ/kg**[a]	**σ/EE**	**E/EE**
Aggregate	0.19	0.083	-	-
Portland Cement	17.7	11.8	-	-
Concrete	2.7	1.13	31.11	26667
Steel (100% recycled)	76.4	9.8	35.71	21429
Lumber (Douglas Fir)	1	1.4	4.93	9357
Concrete blocks	0.96	2.6	5.19	1442
Common brick	11	3	2.33	1333
GFRP (45% Epoxy)	540	300	0.13	2900
CFRP (50% Epoxy)	800	533	0.27	3244

[a] Values are from various sources (primarily form Crawford, 2019 and Ashby, 2009) and are based on life cycle analyses.

Conclusions

The adverse environmental impact of new infrastructure systems can be minimized by using sustainable practices in infrastructure design. More sustainable methods in the fabrication of construction materials (e.g., concrete, steel, timber, masonry, and FRP composites) can also drastically lower the overall construction cost, particularly when direct and indirect costs over the life of the system are considered. Life Cycle Assessment is the best approach to assess sustainability

(Hsu 2010). Without incorporating sustainability in construction, the adverse environmental effects from concrete and steel consumption would have continued to increase. However, if CO_2 emissions are not reduced further, the environment will continue to suffer, threatening the long-term welfare and health of the public which are within the purview of building codes.

Carbon emissions in cement (and concrete) production is of great concern because 60% of these emissions come from the calcination process. A temporary remedy for this issue is to incorporate more Supplementary Cementing Materials like fly ash in concrete. A more permanent solution is to find alternative carbon-neutral cementitious materials and ultimately lower the overall embodied energy in concrete. There are several researchers working on such a material, dubbed "green concrete". Steel is another construction material widely used in infrastructure. Its cradle-to-cradle property allows recycling to be done without affecting its performance while at the same time, reducing manufacturing costs and the impact to the environment. The timber industry has had the greatest impact on sustainability practices because the material can be considered a renewable resource. Furthermore, the industry has embraced sustainability practices at all levels, from harvesting to construction. Masonry and composites make up a very small percentage of materials used in construction; thus, any improvement in their sustainability can be considered insignificant compared to concrete, steel, and timber.

Both the concrete and steel industries have dramatically changed over time due to institutionalized groups, such as AISC, PCA, ACI, and LEED. Their collaborations with various other groups have allowed sustainability to be more accepted worldwide. These groups have redefined the role of engineers and have changed standards that have resulted in improved environmental policies.

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