Sustainable development and physical infrastructure materials

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Physical infrastructure, including buildings, roads, pipelines, bridges, power lines, communications networks, canals, and waterways, make up a substantial fraction of worldwide material usage and flows. Consequently, the overall mass of materials and the associated environmental impacts must be addressed to achieve sustainable development of infrastructure. This article surveys the magnitude of material use for infrastructure, including trends in the use per person, environmental impacts of the production and use of infrastructure materials, variations in the longevity of physical infrastructure, and changes in the recycling of infrastructure materials.

Introduction

Physical infrastructure provides the foundation for human society and economic activity and represents the greatest use of raw and processed materials by weight. This article discusses some of the largest infrastructure applications of materials, such as buildings and transportation, and the trends in material use for current and emerging applications. These topics have profound implications for sustainable development. In addition to the sheer mass of material resources required, infrastructure construction and operation require vast energy inputs and generate substantial flows of wastes and pollution. To plot a more sustainable course for infrastructure, society must become more diligent in the selection and use of materials. This includes considering the lifetimes of structures with the goal of minimizing the embodied energy as amortized over their time in use, so that the best long-term solution is achieved through a combination of reduced energy requirements and avoided pollution and waste.

Concrete, sand, and other natural minerals make up the greatest tonnage for infrastructure applications. Next are metals, primarily steel, but increasingly aluminum for some weight-sensitive applications. The third most widely used material grouping is biomass. These materials, primarily wood, had declined from their original dominance of infrastructure, but are now becoming increasingly interesting as renewable building materials. The next three sections of this article describe the magnitudes and trends in use of these three material classifications. The article then considers the environmental impacts of infrastructure material production and use and discusses various factors that affect this impact, namely, the longevity of infrastructure, the recycling of construction materials, and the use of waste streams as a source of materials for infrastructure.

Natural minerals used for physical infrastructure

Even though physical infrastructure is a worldwide social need, data on materials used in infrastructure are often inconsistent, incomplete, and uncertain.[1] Nevertheless, international efforts have been made to compile consistent data on overall material flows within each country, from which reliable infrastructure-related data can be extracted. **Figure 1**a shows the magnitudes of construction minerals extracted worldwide for the period 1980–2007.[2] Construction minerals include asphalt, clay (for bricks), rock (for concrete and structures), limestone, sand, slate, and gravel.[3] Extraction has been steadily increasing over time as worldwide population has grown and economies have made additional infrastructure investments. By 2007, total worldwide extraction was about 20 billion tonnes per year.

From a material-flow standpoint, the increase in extraction is particularly notable for Asia, which has extracted the greatest

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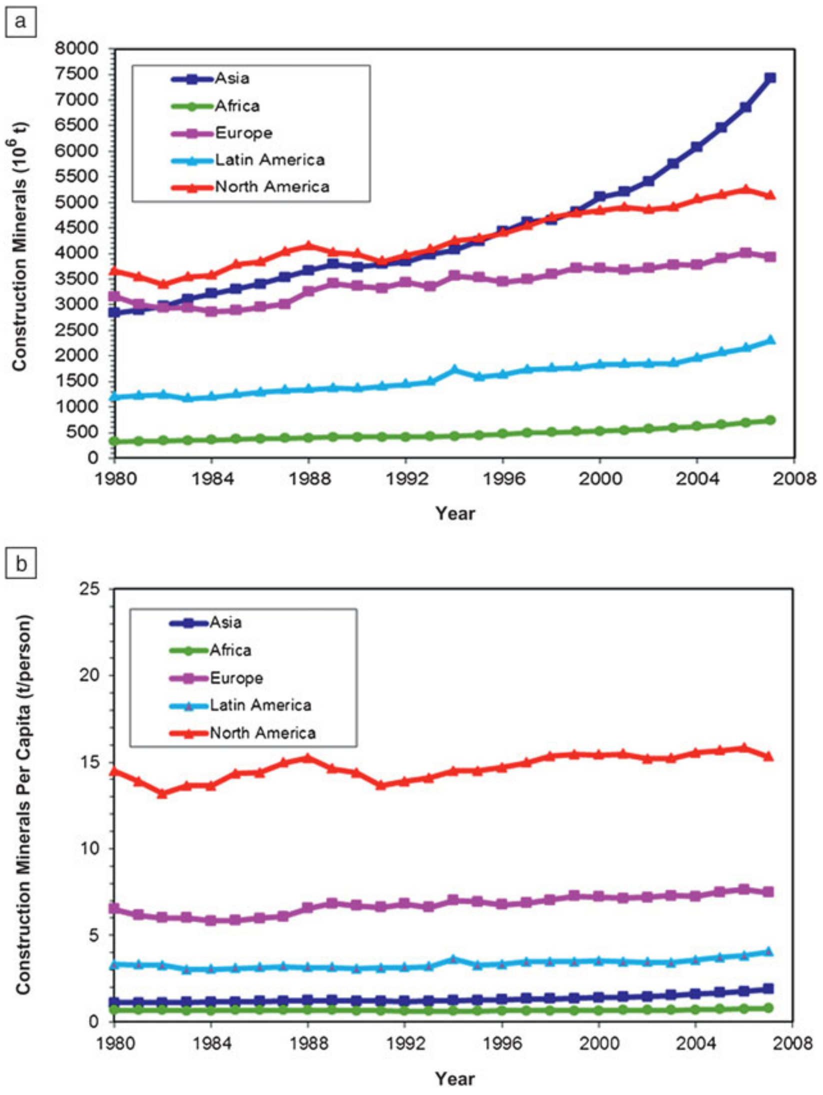

Figure 1. Annual extraction of construction minerals for five global regions, 1980–2007: (a) total and (b) per capita. Authors' summation of data from Reference 2.

amount each year since 2000. The accelerating extraction of raw materials in this region could result from increases in the number of local construction projects and perhaps in exported construction goods. Over the same time period, extraction in Europe and North America rose more slowly, matching upturns and downturns in their economies, whereas other regions of the world showed steady increases.

The implication of these trends is that material flows are primarily related to economic growth, which depends in turn on population growth, affluence, and degree of technological development, although affluence and development overlap to some extent. These dependencies are reflected in the accepted IPAT model, wherein the impact on sustainability (I) is expressed as a product of population (P), affluence (A), and technology (T).[4]

To compensate for population differences, Figure 1b shows the same data as Figure 1a, expressed on a per capita basis. North America stands out for using the largest amounts of construction minerals, reflecting its higher level of development and economic activity. This would suggest that, of the three factors influencing the magnitude of material used for construction, affluence of the population is the strongest contributing factor. Note that, for most regions, the use of construction minerals per person has been relatively constant over the time period represented in the figure.

Metals used for physical infrastructure

Although construction minerals represent the largest portion of materials used for physical infrastructure, metals are another widely used class. Metallic construction materials primarily consist of steel for buildings and reinforcement for concrete. In 2009, the total global "apparent" steel use (excluding changes in stock levels) was just over 1.4 billion tonnes,[5] and of this amount, more than 500 million tonnes was likely consumed by the construction industry.[6] Although this seems like a large amount, note that it is dwarfed by the 20-billion-tonne flow of construction minerals, as shown in **Figure 2**. Also note that, for both steel and construction minerals, significant fractions are recycled from past uses rather than being newly extracted. Whereas recycled metals are included as a separate category in Figure 2, recycled construction minerals are not; thus, even the large flow of extracted minerals (crushed stone, sand, and gravel) shown in Figure 2 underestimates their total use for physical infrastructure.

Whereas metals offer advantages as construction materials by virtue of their improved strength and mechanical performance, they suffer in terms of sustainability from high embodied energies needed for extraction and refinement and often have limited lifetimes as a result of environmental degradation. On the other hand, once extracted, metals perform at a high strength-to-weight ratio, meaning that, compared to other materials, equal performance can be obtained at reduced cross-sectional area (or mass) or improved performance can be expected from equivalent structures. Also, being malleable, metals allow for shape changes in beams, columns, and ties that can be used to further reduce the mass of material required for a desired performance. Perhaps the greatest sustainability advantage of metals, however, lies with the simplicity of recycling them, as discussed in more detail later in this article.

Biomass used for physical infrastructure

Another trend apparent in Figure 2 is the increasing use of agricultural and forest products. For the most part, this increase

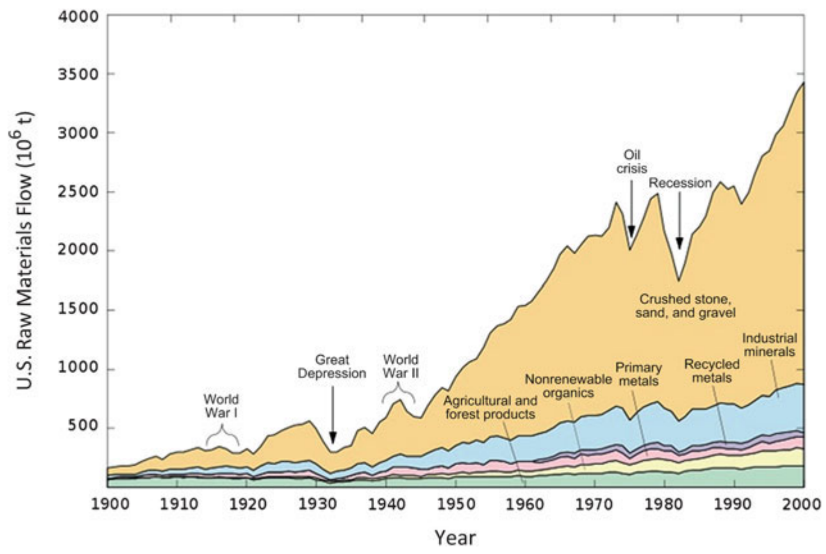

Figure 2. U.S. flow of raw materials by weight, 1900–1998.[7] Recycled construction minerals (crushed stone, sand, and gravel) are not included.

in biomass is represented by wood products. Whereas wood historically was a primary building material, it has not exhibited the significant growth trend notable for construction minerals and metals. This is not surprising, given the limitations of the resource and the mechanical challenges of modern infrastructure. The more recent growth in wood might reflect an interest in replacing conventional construction materials with biomass materials as a means of enhancing sustainability.[8] A recent report by the Consortium for Research on Renewable Industrial Materials (CORRIM) found that the inherent low embodied energy, carbon sequestration ability, and renewability of wood make it the material of choice for construction in many locations. For example, wood framing was found to use 17% less energy than steel for a house in Minnesota and 16% less energy than concrete for a house in Atlanta, GA, and to reduce the overall global warming potential in both cases.[9]

Table I. Sector outputs and total supply-chain energy and water inputs and greenhouse-gas emissions for selected U.S. construction sectors.[12,13]

Construction sector	2002 output (billion $US)	Energy input (MJ/US$)	Water input (l/US$)	Greenhouse-gas emissions (kg of CO_2e/US$)
Commercial and health care structures	129	8	18.9	0.6
Permanent residential structures	305	9	30.2	0.7
Manufacturing structures	23	6	15.1	0.4
Heavy construction[a]	292	8	22.7	0.6

[a] Heavy construction consists primarily of construction for large-scale infrastructure, such as bridges, manufacturing facilities, and large civil construction projects.

Indirect applications of biomass in infrastructure are also possible. Specifically, biomass cellulose structures offer renewable sources for polymeric precursors of lightweight plastics and for fiber structures used in composite materials. Although such applications are still in their infancy, organically derived polymers and fillers of natural materials such as bamboo and hemp fibers could be viable substitutes for petrochemically derived polymers and composites used in certain construction applications.

Environmental impacts of infrastructure material production and use

As expected for a large, material-intensive industry, construction of physical infrastructure has numerous environmental impacts.[10,11] As an example, **Table I** lists energy and water inputs and greenhouse-gas (GHG) emissions for several U.S. construction sectors. These impacts were estimated for the entire supply chain of construction production, so they include emissions for materials production, as well as emissions from construction equipment. The overall environmental impact of a sector can be assessed by multiplying the sector output by the emissions or resource use per dollar of output.

The construction sectors listed in Table I all have similar overall energy and water requirements and GHG emissions per dollar of output. However, when disaggregated, different activities within the construction industry have differing resource requirements and pollution emissions because of their different construction inputs. Suppliers of materials to the construction industry, such as cement manufacturers and iron and steel mills, have significantly higher energy and water requirements and GHG emissions per dollar of output than biomass providers or the construction industry in general, as reported in **Table II**. Although much of this greater impact can be associated with the processing required for these construction materials, for metals, some can be attributed to the global sourcing and long-distance transport of these commodities. For biomass (wood), supply is generally more local, and wood construction products generally require minimal shaping.

To reduce the environmental impact of heavy-construction activities, there is a need for improved supply-chain management. In **Table III**, the CO_2 contributions are given, first for the total of all U.S. sectors and then for the 12 highest-contributing sectors. Direct emissions originating on-site from heavy construction activities have the largest individual contribution (largely fuel combustion to power equipment); however, the total of all contributions from the supply-chain sectors actually exceeds this value. Of these, it

Table II. Energy and water requirements and greenhouse-gas emissions for seven common material inputs to infrastructure.[13]

Material	Energy required (MJ/US$)	Water required (l/US$)	Greenhouse-gas emissions (t of CO_2e/US$)
Aluminum	49	158.8	3340
Brick	31	52.9	2010
Iron and steel	43	79.4	3660
Paint	17	529.2	1070
Plastic pipe	24	71.8	1420
Ready-mix concrete	24	68.0	2740
Wood	14	41.6	522

can be seen that cement, steel, and lime products alone contribute nearly one-half of the total emissions (in CO_2 equivalents) of the supply-chain contributions.

To help manage supply-chain impacts, environmental life-cycle assessment is increasingly being applied to construction materials for physical infrastructure. Examples include buildings,[14,15] transportation infrastructure,[16] and cement.[17,18] In addition to the classic difficulties with life-cycle assessments, such as data uncertainty and ambiguity in choosing what to include within the boundaries of the analysis, these studies have been hampered by the heterogeneity of facility designs and construction practices, as well as the inherent variability in construction materials themselves. For example, concrete can have a variety of different material compositions.

Several strategies to improve the sustainability of physical infrastructure emerge from this literature on life-cycle assessment:

- substituting materials with lower environmental impacts, such as concrete for steel in bridges;[19]
- making construction processes more efficient, such as using energy-efficient construction equipment;[20]
- reducing the size of facilities, either in space requirements or in materials requirements for structures; and
- making facilities more energy-efficient, with the requirement that additional capital and energy expenditures for efficiency result in overall life-cycle savings.[21]

Design and longevity of infrastructure

Thus far, this article has considered the use of materials for physical infrastructure and the associated environmental impacts on an annual basis. However, infrastructure is usually intended to be in use for many years. Indeed, one strategy to reduce infrastructure material use for sustainability is to keep facilities in service longer. Some well-designed and -maintained infrastructure can last for decades, whereas other infrastructure systems rapidly become obsolete, as a result of design decisions; maintenance practices; or changes in circumstances, regulations, or technology. A typical expected lifetime range for infrastructure systems such as roads and bridges is 20–60 years,[22] but longer lifetimes are certainly possible.

Table III. Greenhouse-gas emissions for US$1 million in 2002 output for all U.S. sectors and for the top 12 contributing sectors in U.S. heavy construction.[13]

Sector	Contributions to greenhouse-gas emissions (t of CO_2e)					
	Total	From fossil fuels	From processes	From methane	From N_2O	From halogenated gases
Total for all U.S. sectors	**612**	**488**	**71.2**	**38.3**	**9.68**	**4.83**
Heavy construction direct emissions	200	200	0	0	0	0
Power generation and supply	110	109	0	0	1	1
Cement manufacturing	60	25	35	0	0	0
Oil and gas extraction	38	11	7	21	0	0
Iron and steel mills	33	13	21	0	0	0
Petroleum refineries	29	29	0	0	0	0
Truck transportation	19	19	0	0	0	0
Fertilizer manufacturing	9	2	3	0	4	0
Lime and gypsum product manufacturing	7	2	4	0	0	0
Pipeline transportation	7	3	0	4	0	0
Waste management and remediation services	6	0	0	6	0	0
Coal mining	5	1	0	5	0	0

The design and selection of materials for a particular structure have a significant impact on the quantity of materials used. For some infrastructure applications, steel, steel and concrete, and wood all compete for application. When multiple materials satisfy the engineering constraints, the material selected usually has the lowest cost (likely corresponding to lowest weight or volume). Unfortunately, this option is not always consistent with lower environmental impacts. Other times, when engineering constraints are severe, the selection process might require special consideration regarding material performance. In these cases, unique shape and material solutions can be used to lower the overall material usage while still providing the required performance.

For example, domed structures were first constructed from grass and clay; then wood; and eventually brick, metals, and structural concrete. Each of these innovations allowed for larger dome radii and provided structural improvements (e.g., windows) but came at the cost of increased weight and material usage. In today's large dome structures, new materials and improved designs allow for a wide array of options, including metal frames covered by fabrics and synthetics. Modern domes are essentially multiple structures or composite structures built with relatively lightweight supports and coverings. These structures and materials provide unique solutions for infrastructural designs, and a great deal of material savings and improvements in longevity can be achieved by appropriate combinations of shape and materials.

In addition to considerations given to external design and material selection, the material itself can be "designed" or engineered for performance. In fact, a widely used material for modern concrete structures is a fiber-reinforced composite of concrete and steel reinforcement bar. These composite structures take advantage of gains in performance achieved through interactions between the matrix (concrete) and the embedded fibers (steel). Whereas concrete has excellent compression properties, addition of steel to the concrete matrix greatly improves its resistance to tensile loads, thus improving its durability. The amount of steel used varies from 1% to 6% of the load-carrying cross section, depending on the application.

The combination of steel and concrete is a continuing area of research. Considerable work is currently being done to evaluate steel encased in concrete structures, concrete encased in steel forms (such as tubing or box beams), and concrete filled with steel and/or polymeric fibers. It is presumed that the performance gains achieved will result in improved shape efficiencies and an overall reduction of material required for longer-lasting structures.

Recycling of construction materials

Reuse of facility components and recycling of infrastructure materials are important strategies for reducing material demands and related environmental impacts. Indeed, of the estimated 155 million tonnes of obsolete materials generated in 2003, approximately 48% was recovered for reuse.[23] Some categories of debris have higher recycling rates. For example, reuse of cement concrete and asphalt pavement debris for 1996 in the United States are estimated to be in the range of 50% for the former and near 80% for the latter.[23] Policies increasing landfill costs and higher prices for raw materials would spur more recycling of this type.

Of all materials used in infrastructure, metals have the most recycling programs in place. The result can be seen in Figure 2, with steady or growing use of recycled metals after 1960 coming primarily from the technological changes in steel production. Still, despite the high rates of metal recycling, the flow of recycled metal is less than 10% of the overall flow of new construction materials. The greatest hurdle to increasing the recycling flow of construction materials is the cost. Construction mineral debris and metals present economical options for recycling depending on form. Davis et al. reported that, in the United Kingdom, an estimated 85% of structural steel work is recycled[22] and, in the United States, beams, girders, and other major structural components are recycled at greater than 98% (approaching their limit for recyclability).

In contrast, composite structures often pose more technical problems owing to the additional work of separating two (or more) materials. For infrastructure materials, the primary concern is with concrete–steel composite material structures, and significant improvements have been made in the recovery of steel components from such structures. There also has been steady growth in recovery of reinforcing steel, as shown in **Figure 3**. Although this trend is supported by technology changes in the steel industry, it also must reflect increased recycling efforts and increased value in recycled steel.

Waste streams as a raw material source

Another potential strategy for the construction industry is to utilize waste streams from other industrial products in place of raw materials. For example, the waste streams of fly ash from coal combustion for power generation and slag from iron blast furnaces have been used to replace a portion of the cement binder in concrete.[17,25] Blast-furnace slag, in particular, is a highly desirable input for concrete providers. Granulated blast-furnace slag can be substituted 1:1 for Portland cement binder and, when used up to 50%, generally leads to a stronger

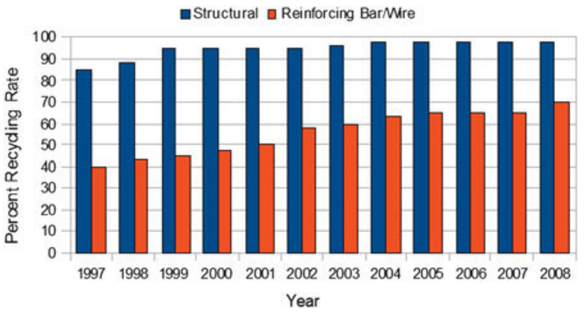

Figure 3. Recycling rates for construction steels in the United States.[24]

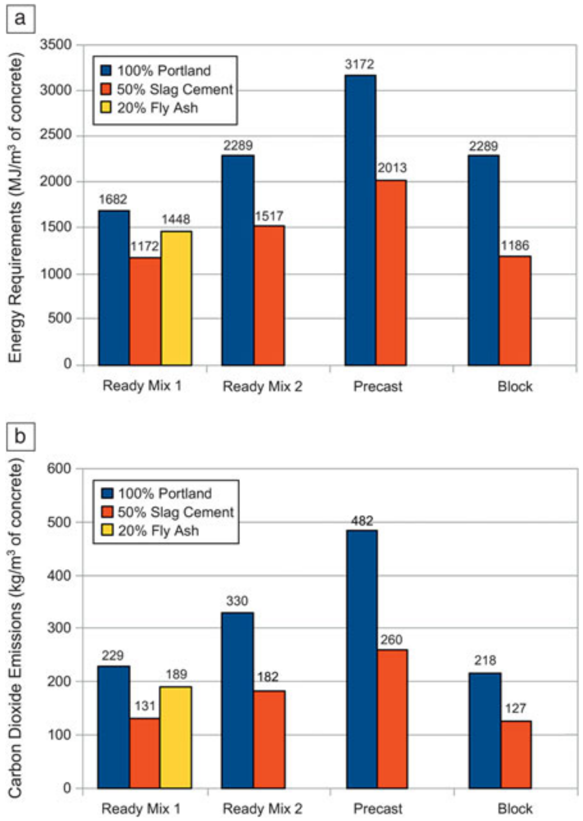

Figure 4. Reductions in (a) embodied energy and (b) greenhouse-gas emissions obtained by using slag or fly ash in place of part of the cement binder in concrete.[26] The labels represent samples of different strengths, where strength is reported in terms of the compressive stress that can be carried by the concrete at 28 days: Ready mix 1, 3000 psi (20.7 MPa); Ready mix 2, 5000 psi (34.5 MPa); and Precast, 7000 psi (51.7 MPa).

product, although final strength appears to depend on the grade (granulation size) of the slag. **Figure 4** shows the potential energy savings and reductions in GHG emissions that can be obtained through reuse of these byproducts as substitute materials in cement products.

It is not yet clear how widely the use of waste streams from other industrial processes could be applied to construction materials. The economic viability of reusing a waste stream clearly depends on the material value and processing costs. Also, legal, supply, quality, and consistency issues must all be resolved to properly leverage the advantages of byproduct reuse. However, employing waste from other processes in infrastructure reduces waste streams, capitalizes on embodied energy, and in many cases provides a superior product, making it highly attractive in efforts to achieve sustainable infrastructure.

Summary

This article draws attention to the large quantity of materials used for infrastructure construction. Clearly, this sector utilizes the largest portion of physical raw material flow, and the trend for increasing material use is growing, especially in developing economies. For the construction and material supply communities to reach a more sustainable future, strategies should include greater efforts to reduce apparent consumption of extracted raw materials and incorporate more recycled or byproduct materials. Design and construction should also strive for longer life and more efficient use and support recycling efforts, employing material selection methodologies that support all of these goals.

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