

Materials for Sustainable Sites

A Complete Guide to the Evaluation, Selection, and Use of Sustainable Construction Materials

by Meg Calkins





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Preface

- nvironmental and human health impacts of materials are a hidden cost of our built environment. Impacts during manufacture, transport, installation, use, and disposal of construction materials can be significant, yet often invisible. A broad and complex web of environmental and human health impacts occurs for each of the materials and products used in any built landscape, a web that extends far beyond any project site. Construction materials and products can be manufactured hundreds, even thousands, of miles from a project site, affecting ecosystems at the extraction and manufacturing locations, but unseen from the project location. Likewise, extraction of raw materials for these products can occur far from the point of manufacture, affecting that local environment. Transportation throughout all phases consumes fuel and contributes pollutants to the atmosphere. Disposal of manufacturing waste and used construction materials will affect still another environment. These impacts are "invisible" because they are likely remote from the site under construction and the designer's locale. For example, the impact of destroying a wetland on the site can be clearly demonstrated and understood, but it is difficult to see the effects of global warming resulting from the release of CO₂ during concrete manufacture, or the destruction of a rainforest halfway around the world from bauxite mining for aluminum.

Despite the fact that we can't see their impacts, materials used in construction of the built environment are damaging the world's ecosystems at an alarming rate. Most materials are made from nonrenewable resources, and their extraction disrupts habitats; impacts soil, air, and water; and affects human health either directly or indirectly through environmental damage.

These high costs have contributed to an increased interest in green design, and the rapid adoption of the U.S. Green Building Council's LEED[™] system; however, material selection and specification remains a challenging, sometimes even contentious issue. Many designers experience difficulty understanding the full extent of environmental and human health impacts of building materials as they are not easily quantified. Complete and accurate information is elusive. Life-cycle assessment (LCA), a thorough accounting of environmental and human health impacts of a material, is the best tool for truly evaluating materials. Yet LCAs for materials and products used in site construction are limited, and wide variations between proprietary products, manufacturing methods and study boundaries can make comparisons difficult.

And the right answer may not always lie in a new, green material, but instead in a conventional, tried-andtrue material used in green ways. This book is written with the assumption that conventional materials may eventually be replaced by greener alternatives, but for the time being, designers must take steps to specify conventional materials in such a way as to minimize their environmental and human health impacts. For example, in the future there may be a material that performs better than asphalt, costs less, is widely accepted by the road building industry, and is better for the environment and human health, but in the meantime designers can take steps to specify asphalt in such a way that the impacts are minimized by incorporating recycled aggregates such as tires, glass, and reclaimed asphalt; cooling the mix; and making it porous.

This book provides detailed and current information on construction materials for sustainable sites. The first four chapters of the book discuss general environmental and human health impacts of the materials and products industry; provide tools, techniques, ideologies, and resources for evaluating, sourcing, and specifying sustainable site materials. The second part of the book devotes a chapter each to nine basic types of site construction materials—both conventional and emerging green materials. These are concrete, earthen materials, brick masonry, asphalt, aggregates and stone, wood, metals, plastics, and nonliving biobased materials. Each chapter discusses environmental and human health impacts of the material at all phases of its life cycle, and presents detailed strategies to minimize these impacts.

It is important to note that this book does not provide definitive answers for "right" and "wrong" materials and products. It is an impossible task to determine what is right or wrong for every situation—climate, application, site conditions, aesthetic, and performance requirements—across the board. Requirements vary. No one aesthetic will work everywhere so nor should one for "green" materials. Nor should this ever be the goal. The FSC-certified wood harvested from local forests may be the right material for a camp on Bainbridge Island, Washington, but it is not right for an intensively used public plaza 3,000 miles away in New York City.

This book will equip the reader with knowledge and skills for "life-cycle thinking"—techniques to evaluate and minimize the environmental and human health impacts of materials and products for a particular climate, application, and location. This book is not a substitute for true LCA techniques, and where they are available they should be the primary method of evaluation. This book emphasizes the following four major principles:

- Choose materials and products that use resources efficiently. Reduce, reuse, and recycle materials in order to reduce resource consumption and habitat destruction and ecosystem disruption that result from extracting and harvesting the resources. Use of durable, reusable, recyclable, and renewable materials can support this principle as can reducing the amount of material used
- Choose materials and products that minimize embodied energy and embodied carbon. Use of local, low embodied energy materials can support this principle. Materials that are manufactured with nonfossil fuel-based renewable energy sources can also contribute.
- Avoid materials and products that can harm human or environmental health at any phase of their life cycle. Materials or by-products from materials that hold potential to emit toxins, pollutants, and heavy metals to air, water, or soil where they can impact ecological and human health should be avoided.
- Choose materials that assist with sustainable site design strategies. Some materials may not be "green" themselves, but if they are used to construct a sustainable site design feature, they may be.

Acknowledgments

he seeds of inspiration for this book were planted by many mentors, colleagues, and friends. Several years ago, Linda Jewell inspired my interest in construction materials—both their aesthetic possibilities and their environmental impacts. This led to one of the book's major undercurrents—that "green" materials can and should be aesthetically pleasing; this will hasten their adoption. Linda, a very supportive mentor over the years, introduced me to Bill Thompson, editor of *Landscape Architecture* magazine—a major forum for the preliminary material of this book. Bill allowed me wide rein to explore many topics related to materials and sustainability while asking valuable questions about some of my conclusions.

With training in both architecture and landscape architecture, one of my main career goals has been to strengthen connections between the two professions in areas of green building. This book is an attempt to create common ground between site and building in the area of green building materials. As such, the book is inspired by others exploring these issues in both professions: Alex Wilson and all the writers of *Environmental Building News*, Tom Lent, Bill Walsh, Charles Kibert, Kim Sorvig, Bruce Ferguson, Daniel Winterbottom, and my knowledgeable inspiring colleagues on the Sustainable Sites Initiative (SSI) Materials Technical Subcommittee.

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This book is dedicated to my children, Annie and Jack. My concern for the future of their earth is the impetus for this book. I am particularly grateful for the support of my family during the germination and growth of this book. My parents, lifelong learners themselves, fostered in me a love of inquiry that sustained the creation of this book. More practically, my parents lent endless moral support and childcare and my children provided much needed comic relief and great artwork at the end of a long day. I thank George Elvin for his calm encouragement, steady belief in my abilities, good humor, and his willingness to go beyond his share of the parenting during the many deadlines.

chapter



Materials for Sustainable Sites Defined

Since the mid-nineteenth century when Olmsted excavated stone from the meadows of Central Park to build the park's bridges, walls, and stairs, the construction materials industry has undergone major changes. There has been a shift away from localized use of materials to centralized large-scale production and global distribution; from minimally processed materials to highly processed ones; and from simple materials to engineered composites, mixed materials assemblies, and liberal use of chemical additives to impart a wide array of properties.

Materials of site construction have evolved in response to many twentieth-century trends: the shift from skilled craftsmen to cheap labor in construction, increasingly nationalized standards that do not specifically address regional materials or conditions, centralized production of building materials and products, cheap and abundant resources where "real" costs of ecosystem destruction and pollution are not factored in, increasing use of composite materials, and huge growth in the global materials industry.

The result has been a consumptive and sometimes wasteful materials industry with use of a limited palette of nationally standardized site construction materials (e.g., concrete, asphalt, pressure-treated lumber, powdercoated steel). Local, low embodied energy structures, such as earthen construction in the Southwest or dry stone construction in New England, have decreased in use as labor costs are high, workers skilled in these techniques are increasingly scarce, and national building codes hamper their use.

Abundant resources, inexpensive labor, and minimal environmental regulations in developing countries have shifted production of many building materials overseas. This has further reduced designers' capacity to understand the impacts of construction material production, or even to know where they come from. Aggregate may come by train from a quarry 200 miles from the site, while the aluminum for the handrails may have visited three continents before it arrived at the site. This means that today, a far greater portion of the impacts of building materials are those related to energy consumption incurred in trucking, shipping, and train transport. These are not insignificant, given the weight of many site construction materials.

Site construction materials of the twenty-first century must respond to an entirely different set of forces global climate change, air pollution, rising fuel costs, ecological destruction, and loss of biodiversity. These forces are shaping the site and building construction industry through the rapidly growing sustainable development movement. And they will necessitate significant changes in the materials industry. These changes may involve closedloop material manufacturing systems that eliminate waste; use of renewable energy sources for manufacturing, processing, finishing, and transport activities; "mining" of construction demolition sites for "raw materials"; substantial reductions of pollution from material manufacture, use, and disposal; an emphasis on minimally processed local or regional materials; and greater reuse of site structures in place or on-site.

To address the goal of sustainable development, the construction material production and construction industries must shift their use of resources and fuels from nonrenewables to renewables, from waste production to reuse and recycling, from an emphasis on first costs to life-cycle costs and full-cost accounting, where all costs such as waste, emissions, and pollution are factored into the price of materials (Kibert et al. 2002).

And this shift has already begun. The first decade of the twenty-first century has seen the start of what will be significant changes to the construction materials industry:

- Global warming is well acknowledged by global decision makers and treaties such as the Kyoto Protocol for greenhouse gas reduction.
- Policies for waste reduction and reuse in the European Union and to a lesser degree in the United States are fostering growth in salvage, recycling, and industrial materials exchange industries.
- In the EU, policies are increasing the responsibility of producers to reduce and recycle packaging, increase the recycled content of their products, recycle more of their waste, and even take back and recycle components of their own products.
- Industrial designers and product manufacturers are looking to natural systems for closed-loop design, new material compositions, and green chemistry to reduce waste and pollution of their product production.
- Standards and criteria for reducing the environmental and human health impacts of materials and products are being developed and increasingly used by product specifiers to make decisions. The LEED system, Cradle to Cradle Certification, Greenguard, EPA Comprehensive Procurement Guidelines, Green Globes, and others offer criteria and standards for material or product selection.

Life-cycle assessment (LCA) studies are increasingly available, yet still limited, for construction materials and products. In the United States, BEES and the Athena Environmental Impact Estimator interpret and weigh LCA results for building assemblies and some site construction materials.

Yet while progress is being made, selection of materials and products with the least environmental and human health impacts remains a challenging, confusing, and sometimes even contentious issue. The appropriate materials for sustainable sites will vary by impact priorities, regional issues, project budgets, and performance requirements. Some will emphasize materials that conserve resources by being reused without remanufacturing, by being extremely durable, or by closing material loops with high recycled content and manufacturer take-back programs. Others place great emphasis on low toxicity of products and emissions throughout their life cycle, while others may regard low ecological impacts or conservation of water as the highest priority. With this wide variety of priorities comes an even wider variety of "right answers." Portland cement concrete may appear to be a "green" material for those with durability or regionally produced materials as a priority, whereas it might be rejected by those who are concerned about the global warming impacts of material manufacture or high embodied energy materials. Composite lumber (a mix of recycled plastic and wood fibers) seems like a good alternative to wood lumber for those concerned with the ecological impacts of clearcutting forestry practices, but it may be rejected for its mixed material composition by those concerned with the closed-loop recyclability of materials.

In addition to varying priorities and goals in green material selection, there are shades of green. For instance, the ideal green material might be a natural, renewable, local and indigenous, nontoxic, low embodied energy material such as willow cuttings for slope stabilization or rammed earth for a retaining wall; however, these materials may not be feasible in all situations. They may not be able to perform to current construction standards, construction workers may not be skilled in techniques to build structures with these materials, or they may not be appropriate for the scale of construction or performance requirements. Claims of green abound as product manufacturers capitalize on the rapidly growing "green" segment of the construction materials industry. Yet it can be difficult for designers to cut through the hype and determine just how green the product is, let alone compare it with six or seven alternatives. Evaluating multiple products for a given use can be like comparing apples and oranges. One product may pose global warming impacts while another may involve a known human carcinogen; a third product may require large amounts of fossil fuel–powered energy to produce, but it may be more durable with the potential to last twice as long as the first two alternatives.

True life-cycle assessment (LCA), an accounting of all inputs and outputs through a product's life cycle, can potentially offer some answers for sustainable site material selection. But it is outside the time and skill constraints of most designers. And while LCA information is becoming available for a wide variety of products through Athena or BEES in the United States, to date these tools have focused on evaluating building assemblies and materials with only minimal analysis of site construction materials.

Materials for Sustainable Sites Defined

This section defines characteristics of materials for sustainable sites. It is important to note that all of the strategies summarized below and addressed in this book are not equal. Just diverting a waste material from the landfill is not always enough. While it is a step in the right direction, what is actually done with the diverted material will determine whether it is a large or small step. In resource conservation, as in other aspects of designing for sustainable sites, there are shades of green from light to dark. For example, chipping a reclaimed old-growth oak beam into mulch is not the highest and best use of the material. Instead, reusing it in whole form is the best use. Better yet, if the beam came from an old barn that is no longer needed, keeping the beam in place and adapting the barn structure to another use will maintain the resource in place, incurring no transportation costs and maintaining the integrity of the beam—and the old structure.

So the definition of materials for sustainable sites can vary widely, and some materials or products will be slightly green while others may be dark green. It can all be a step in the right direction, and taking the largest step possible in a given situation will help push the site construction industry incrementally toward substantial changes.

Materials and products for sustainable sites are those that minimize resource use, have low ecological impacts, pose no or low human and environmental health risks, and assist with sustainable site strategies. Within this definition, specific characteristics of materials for sustainable sites are summarized below. These attributes are also woven throughout the chapters on individual materials in this book, and are discussed there in greater detail.

Characteristics of "green materials" listed below are not in a ranked order as priorities will vary among projects. Environmental priorities as ranked by the EPA Science Advisory Board are discussed in Chapter 3 and a hierarchy of waste reduction strategies is discussed in Chapter 4.

MATERIALS OR PRODUCTS THAT REDUCE RESOURCE USE

Reducing use of virgin natural resources in the production and use of construction materials can substantially reduce their environmental impacts. Using fewer materials in construction by reducing the size of a structure or by retrofitting an existing one will not only save virgin resource use for the new product or material, but it will also reduce the "ecological rucksack" of waste, often many more times than the actual product entails, that is created through the raw material acquisition and manufacturing processes. Reusing materials or using waste as feedstock for new products will reduce virgin resource impacts as well.

Impacts associated with virgin resource use will also be reduced with reuse or recycling of resources. Habitat destruction, waste generation, energy, and air and water pollution are minimized with reduced use of virgin resources. Energy is saved in the processing and manufacture of new materials as primary processing steps are often eliminated with use of recycled materials. And, if materials are reused on-site or even in place, transportation impacts can be eliminated. Use of reclaimed, refurbished, and recycled content materials is discussed in greater detail in Chapter 4.

Use No New Materials, Don't Rebuild

While not always feasible or appropriate, this is the best way to minimize use of resources. This might mean a choice is made not to build or rebuild a structure, and a site can be used as is. Designing sites for adaptability with open plans and multiuse spaces, so the site and its structures do not require adaptation in a short period of time, can help minimize future use of resources.

Reuse Existing Structures in Place

Adapting or retrofitting existing structures without deconstruction and rebuilding can give them new life with minimal use of new materials. For example, the cracked concrete deck of an old loading dock might be stained with a natural iron oxide pigment (which is a by-product of iron ore production) to become a terrace for a new condo in the adjacent warehouse. Reuse of existing structures on-site can enhance the design of the site by referencing the identity of the previous intervention. At the start of the project, evaluate project sites and old buildings for materials to reuse. Include known subgrade structures in the evaluation as well.

Reduce Material Use

Designing smaller structures (e.g., smaller decks, thinner slabs and walls, flexible footings, cable balustrades rather than hollow steel tube rails, smaller parking lots and spaces, narrower roads) with fewer elements (e.g., excessive finishes or ornaments) and smaller members (e.g., 4×4 posts, not 6×6 unless structurally necessary) can substantially reduce use of materials. Designing structures to modular material sizes can minimize construction waste (e.g., cutoffs). For instance, wood decks should be sized based on available board lengths.

Use Durable Materials

Designing and detailing site structures with durable materials that will last the life of the site and beyond to other structures will reduce virgin resource use. Ease of repair of the structure will also extend the life. Brick or concrete bricks are durable materials and when sandset can be easily repaired, replaced, or re-leveled without removal of the entire installation. After the useful life of the paving they can be removed and reused in another installation.

Reclaim and Reuse Materials or Products in Whole Form

Deconstructing previously developed sites rather than demolishing them can allow for reclamation of materials and products that can be reused in new site structures or applications. In addition to reducing use of virgin resources and saving manufacturing energy and pollution, reuse of materials on-site can save energy and costs of transporting new materials to the site. Reduced demolition waste can save on landfill fees, which may offset the increased cost of deconstruction over demolition. A major consideration is storage of reclaimed materials during the construction process. It is important that storage facilities on or near the site maintain the integrity of the material (e.g., recovered wood should be protected from excess moisture) without negatively impacting the site itself (e.g., avoid stockpiles on tree roots). Where deconstructed materials can't be reused on-site, they can be taken to local salvage or reprocessing facilities.

Use Reclaimed Materials from Other Sources

The only major impacts of reused materials are energy consumption in transport, reworking and refinishing, and installation. Reclaimed materials can be obtained from numerous sources beyond the project site. Materials exchanges are increasing in areas of the country with higher landfill fees, and many municipalities will list recycling and salvage facilities in the region. There are many Internet materials exchange websites as well. Materials should be obtained from local sources as fuel use for transport can be considerable with heavy landscape materials.

Reprocess Existing Structures and Materials for Use On-site

Reprocessed materials are those that are broken down or size reduced from their unit or standard size. Although downcycled, reprocessing materials uses less energy and produces fewer emissions than remanufacturing for recycling. Bringing crushing or other processing equipment to the site rather than hauling the materials to a reprocessing facility can save transport fuel use and costs. Plan for processed material stockpiles during construction.

Use Reprocessed Materials from Other Sites

Material reprocessing facilities are growing in number as landfill costs increase. Crushed concrete, tires, asphalt, glass, and other materials can be obtained from reprocessing facilities for use as aggregates or concrete or asphalt ingredients. Care should be taken to minimize haul distances.

Specify Materials and Products with Reuse Potential and Design for Disassembly (DfD)

Materials that are installed in such a way that they can be easily removed at the end of the life of the landscape and reused elsewhere may not be green themselves, but the way that they are assembled is. For example, masonry installations where no mortar is used, such as interlocking retaining wall units, allow for easy disassembly and reuse of the materials. Also, use of metal fasteners rather than welding, where applicable, facilitates removal of reusable parts.

Specify Recycled-content Materials and Products

Recycled-content materials or products are manufactured using reclaimed materials, scrap, or waste as the feedstock. Some energy is used and emissions and waste result from manufacturing of the new product; however, it is often less than with use of virgin feedstocks. Use of recycled materials will also divert waste from landfills or incinerators. Post-consumer recycled content is preferable to pre-consumer as it is more likely to have been diverted from landfills. Pre-consumer recvcled content often can be reused in other industrial processes. With the exception of metals and some plastics, most recycled-content products are downcycled from their original use (e.g., wood joists chipped for mulch). An overemphasis on recycled-content materials can result in greater environmental impacts for a given structure. For example, use of steel with a relatively high recycled content may be chosen over wood that has no recycled content, yet even the recycled steel can result in greater energy use, emissions, and waste than a comparable wood member.

Use Materials and Products with Recycling Potential

In an effort to close materials loops, thinking ahead to the end of a structure's useful life and the recyclability of materials used to build it is an important step in resource minimization. Simple materials such as concrete, asphalt, wood, and polyethylene plastics (e.g., HDPE, PE, LDPE) are easily reprocessed and recycled. Composite materials such as mixed plastic and wood fiber composite lumber or coated metals have no or limited recycling potential. PVC, a common site construction material for pipes, fences, and decking, is technically recyclable, but many plastics recycling facilities consider it a contaminant to other plastics recycling and will not take it.

Specify Materials and Products Made from Renewable Resources

Materials and products made from renewable resources offer the opportunity for closed-loop material systems. A number of site construction products are made from renewable, biobased resources; however, some will decompose and biodegrade if not preserved in some way. Wood is the most common site construction material that is renewable. It is considered to be a "long-cycle" renewable material as the average regrowth time from trees used for lumber is 25 years for softwoods. Rapidly renewable materials are primarily plants that are harvested in cycles shorter than ten years. Coir and jute are used for geotextiles; succulents are used as stabilizers for loose aggregate paving; and plant oils are used in form-release agents. Bamboo and willow can be used in landscape structures, and fiber from processed crops is used in engineered wood products. Living materials (e.g., slope stabilization with plants, willow wattles, willow fences and domes) are renewable in place. Recycling of renewable materials can often be accomplished by composting or aerobic/anaerobic digestion, using minimal energy and chemicals.

Specify Materials or Products from Manufacturers with Product Take-back Programs

Product or packaging take-back programs are a new trend in manufacturing, particularly in EU legislation and incentive programs. In many EU countries, some manufacturers are required to take back and reuse or recycle the packing for their products. This has resulted in more efficient packaging methods and greater use of recyclable packaging materials. Some manufacturers offer take-back programs for their product as well. Construction material take-back programs are starting to be seen among carpeting and flooring manufacturers.

MATERIALS OR PRODUCTS THAT MINIMIZE ENVIRONMENTAL IMPACTS

Materials and products can cause negative impacts to ecosystems and the environment during all phases of their life cycle. In the materials acquisition phase, mining and harvesting practices can impact habitats and removal of vegetation increases runoff, loss of topsoil, and sedimentation of waterways. Waste piles from mining can leach heavy metals into the soil and ground and surface waters. Emissions and waste from manufacturing can impact air, water, and soil both near and far from the facility. Transport of materials and products between all life-cycle phases uses nonrenewable fuel and releases emissions. Construction and maintenance of materials and products can involve solvents, adhesives, sealers, and finishes that off-gas VOCs or release toxic chemicals to the environment. Dust from unstabilized roads can impact air quality and adjacent vegetation and crops. And disposal of materials and products after their use can fill landfills, impact soil and water around poorly managed landfills, and impact air quality if incinerated.

Use Sustainably Harvested or Mined Materials

Some manufacturers take steps to eliminate or mitigate air, water, and soil pollution from their raw material acquisition processes. While mining operations are largely unregulated, some companies make efforts to protect or remediate negative effects from their mining activities. Growth and harvesting of renewable materials can have environmental impacts from fertilizer and pesticide use, impacting soil health and resulting in eutrophication of nearby water bodies. Attention should be paid to farming and harvesting practices of renewable materials.

Use Certified Wood

As it is renewable and has relatively low embodied energy, wood can be considered a green material if it comes from well-managed forests and is harvested sustainably. Environmentally responsible forest management includes practices that protect the functional integrity and diversity of tree stands, minimize clearcutting, protect old-growth forests, and minimize wasteful harvesting and milling techniques (Forest Stewardship Council [FSC]). The Forest Stewardship Council (FSC) has developed standards for third-party certification of sustainably harvested wood. Certification of lumber should be made by an FSC-certified independent party. Chapter 10 discusses other forest certification organizations.

Use Minimally Processed Materials

Materials and products that are minimally processed (e.g., uncut stone, earth materials, wood, bamboo) often pose fewer ecological impacts. Reduced manufacturing and processing can conserve energy use and potentially harmful emissions and wastes. Minimally processed materials are usually associated with fewer hidden wastes.

Specify Low Embodied Energy Materials

Products that are minimally processed, such as stone and wood, usually have lower embodied energy than highly processed materials such as plastics and metals. Embodied energy is the total energy required to produce and install a material or product during all stages of the life cycle. Evaluating the embodied energy of materials can be a useful baseline for comparing two different materials; however, this type of analysis does not take into account other factors of production such as pollutants and toxins released, resources used, or habitats disturbed. If a product is complex (made from more than one material, such as a steel and wood bench), the embodied energy of the bench would include the energy inputs from both the wood and steel components plus the energy inputs to assemble and finish them.

Specify Materials Produced with Energy from Renewable Sources

Materials and products produced using renewable energy sources (e.g., solar, wind, hydroelectric, biofuels, geothermal) can have reduced environmental impacts. Combustion of fossil fuels, the primary energy source in a high percentage of manufacturing activities, releases greenhouse gases and air pollutants contributing to global climate change, acid rain, and human respiratory health problems. Any comparison of embodied energy of materials should include an examination of energy sources as a product with relatively high embodied energy may be considered lower impact if it is produced with energy from renewable sources. Aluminum requires around eight times as much energy to produce as a comparable amount of steel, yet its primary energy source is renewable hydroelectric power, whereas the primary fuel energy source of steel is coal.

Use Local Materials

Transport of building materials, especially heavy or bulky ones, not only requires a tremendous amount of fuel energy, but also contributes to air and water pollution. Using regionally extracted and manufactured materials can help lessen the environmental impact of a material, by reducing environmental impacts of transport. Transportation costs may also be reduced; at the same time the local economy is supported. Availability of regionally manufactured materials depends on the project location. Ideally, heavy materials such as aggregate, concrete, and brick should be procured within 100 miles, medium-weight materials within 500 miles and lightweight materials within 1000 miles of the project site (Living Building Challenge). Distances between raw material extraction locations and manufacturing/processing facilities should be included in these calculations. Researching regionally available materials and products during the schematic design phase can facilitate use of local materials. Creating databases of regional materials and products can save time on future projects within the same region.

Specify Low-polluting Materials

Some raw material extraction, manufacturing, or disposal processes for construction materials produce waste, by-products, and emissions that can contribute harmful pollutants and particulates to air, water, and soil. Some manufacturers minimize pollution from their processes through equipment or process improvement or state-of-the-art pollution controls. Materials with relatively high-polluting processes are metals mining, primary metal production, metal finishing, cement production, and PVC production and disposal.

Specify Low-water Use and Low–water-polluting Materials

Some materials and products require large amounts of water during processing, manufacturing, or construc-

tion. The used water is often contaminated with heavy metals, hazardous chemicals, or particulates and sediments, and is a disposal risk if not treated and remediated. Material manufacturing processes that use large amounts of water or can result in water pollution are metal mining and primary processing, PVC production, stone working, brick making, and lumber processing. Disposal of some materials, such as PVC pipes, can affect groundwater quality. Some manufacturers recycle wastewater back into manufacturing processes. Some employ chemical and heavy metal removal techniques to safely dispose of potential pollutants.

MATERIALS OR PRODUCTS THAT POSE NO OR LOW HUMAN HEALTH RISKS

Low-emitting Materials and Products

Many adhesives, sealers, finishes, and coatings contain volatile organic compounds (VOCs) and other harmful chemical ingredients that can off-gas in use, leading to air pollution, or leach into soil and groundwater in disposal. Construction workers and end users exposed to these chemicals can be adversely affected in many ways. Products containing synthetic chemicals should be carefully examined for harmful effects. Many synthetic chemicals are not biodegradable or easily broken down. The National Research Council estimated that over 65,000 synthetic chemical compounds introduced and in use since 1950 have not been tested on humans (IN-FORM 1995). Nontoxic, organic, or natural alternative products are increasingly available.

Specify Materials or Products That Avoid Toxic Chemicals or By-products

Materials can contain or emit known toxins during life-cycle phases of manufacture, use, or disposal. Persistent bioaccumulative toxins (PBTs), known and suspected carcinogens, teratogens, and products with hazardous chemicals should be avoided. For example, dioxin, a known carcinogen, is released during the manufacture and incineration of polyvinylchloride (PVC) products such as rigid pipe, plastic fencing and railings, drip irrigation tubing, garden hoses, and lawn edging. The EPA's Toxic Release Inventory (TRI) maintains manufacturer's self-reported data on their toxic releases by compound.

MATERIALS OR PRODUCTS THAT ASSIST WITH SUSTAINABLE SITE DESIGN STRATEGIES

Some site structures may be constructed from materials that are not in and of themselves green, but the way in which they are used contributes to the sustainable function of the site. For instance, use of highly reflective white portland cement concrete, not considered a "green" material because of its relatively high embodied energy, will aid in reducing the urban heat island effect over the life of a pavement, potentially saving energy to cool adjacent buildings. Over the long life of a site, the impacts from manufacture of the material may be minimized with the benefits it can provide for the site's environment.

Products That Promote a Site's Hydrologic Health

Design of sites to respect natural drainage patterns, minimize impermeable surfaces, maximize storm water infiltration, and improve storm water quality can protect the hydrologic health of a site and a region. While polyethylene filter fabric would not be considered a green material, it can go a long way toward ensuring the appropriate function of storm water structures such as bioswales or rain gardens. Green roof products can also promote hydrologic health.

Materials and Products That Sequester Carbon

Lumber, engineered wood products, and many biobased products sequester carbon until they decay; then it is released. New technologies are in development that capture carbon, reducing CO_2 from other sources such as carbon-sequestering concrete.

Products That Reduce the Urban Heat Island Effect

Heat island effects result from solar energy retention on constructed surfaces in urban areas, elevating the temperature differential between urban and rural environments. Streets, sidewalks, parking lots, and roofs are the primary contributors to the heat island effect. Use of highly reflective paving materials or open grid pavement structures with vegetation in the cells can reduce the heat island effect. Pervious pavements will cool pavement by allowing air and water to circulate through them.

Products That Reduce Energy Consumption of Site Operation

Products such as solar lights, high-efficiency lights, Energy Star pumps, and irrigation controllers will reduce a site's energy consumption over the life of the site.

Products That Reduce Water Consumption of Site Operation

Products that use water efficiently, such as drip irrigation, irrigation sensors and timers, and rainwater collection barrels, will reduce the site's water consumption.

MATERIALS OR PRODUCTS FROM COMPANIES WITH SUSTAINABLE SOCIAL, ENVIRONMENTAL, AND CORPORATE PRACTICES

Social, environmental, and corporate practices of a product manufacturer or distributor can impact the sustainability of a product. Products should be sourced from companies that take responsibility for the environmental and human health impacts of their operations; protect the health, safety, and well-being of their employees; provide fair compensation and equal opportunity for all workers; protect consumer health and safety; and contribute positively to community health and well-being (Pharos Project). Ask manufacturers for corporate ethics statements, fair labor statements, and the location (if applicable, country) of raw material acquisition and production.

The Contents and Structure of This Book

Materials for Sustainable Sites is intended to fill a critically important gap in the literature on sustainable site design. This book aims to be a comprehensive resource that clarifies the environmental and human health impacts of site construction materials and products and, maybe more importantly, provides designers, specifiers, and educators specific and detailed strategies to reduce these impacts. This book does not contain definitive answers for the "best" and "worst" site construction materials to use. This is an impossible goal given the wide range of performance expectations, site conditions, project constraints, and client priorities within which construction materials must be evaluated.

Table 1–1 Materials for Sustainable Sites Defined

Materials or products that minimize resource use:

Products that use less material Reused material and products Reprocessed materials Post-consumer recycled-content materials Pre-consumer recycled-content materials Products made from agricultural waste Materials or products with reuse potential Materials or products with recycling potential Renewable materials Rapidly renewable materials Durable materials Materials or products from manufacturers with product take-back programs

Materials or products with low environmental impacts:

Sustainably harvested or mined materials

- Minimally processed materials
- Low-polluting materials in extraction, manufacture, use, or disposal
- Low water use materials in extraction, manufacture, use, or disposal
- Low energy use materials in extraction, manufacture, use, or disposal

Materials made with energy from renewable sources (e.g., wind, solar)

Local materials

Materials or products posing no or low human and environmental health risks:

Low-emitting materials and products

Materials or products that avoid toxic chemicals or by-products in their entire life cycle

Materials or products that assist with sustainable site design strategies:

Products that promote a site's hydrological health by reducing storm water runoff quantities and improving hydrologic qualities

Products that reduce the urban heat island effect Products that reduce energy consumption of site operation Products that reduce water consumption of site operation

Materials or products from companies with sustainable social, environmental, and corporate practices

This book takes the approach that no effort to reduce environmental and human health impacts is too small, even though larger steps may be preferable. There are many shades of green in construction materials, from use of a small amount of recycled content in a standard material such as concrete to use of on-site earth materials to construct site pavements and walls.

Changes can occur incrementally through small steps or may be achieved more drastically through larger steps. Therefore, this book presents a range of options for "greening" the standard materials of site construction in addition to offering information on alternative "dark green" materials such as earthen materials, bamboo, or high-volume fly ash concrete. The aim is to encourage both small and large efforts to minimize the environmental and human health impacts of construction materials. Nearly any material can be "greened" and a small step in the right direction is better than no step if the big step is not acceptable. Many small steps can add up to big impacts, and small steps over and over can result in a changed material industryan industry that closes material loops; eliminates toxins and toxic wastes; and uses durable, local materials.

For example, if at first concrete is specified with 30% fly ash substituted for portland cement, and it performs well, then for the next project it is 40% fly ash with 10% recycled concrete for aggregate, progress has been made. Then as the clients, contractors, and structural engineers grow more familiar with these alternatives and 60% Class C fly ash, 40% recycled concrete for coarse aggregate, or 40% spent foundry sand for fine aggregate are specified to achieve a more durable concrete wall, substantial changes with far-reaching positive impacts will have been accomplished.

This incremental approach to change is the basic premise of this book. Radical change, if it can be accomplished, can be a good thing, but the reality is that the small steps of incremental change may be a much more realistic approach within the mainstream construction industry.

This book devotes one chapter each to the basic materials of site construction: concrete, asphalt, aggregates and stone, brick masonry, earthen materials, lumber and wood products, metals, plastics, and biobased materials. Each chapter discusses basic attributes of the material, and environmental and human health impacts during all phases of its life cycle. Then it provides detailed discussion of strategies and technologies to reduce these impacts, and current standards, resources, and items for consideration during specification of these materials and products.

This book is intended for all professionals who design, specify, educate, or regulate sustainable sites. Professionals and educators in landscape architecture, architecture, civil engineering, urban design, and construction management will find valuable information to assist them in material and product selection and evaluation.

And, while this book addresses site construction materials, there is a substantial overlap with many architectural building materials such as concrete, brick, lumber and wood products, metals, plastics, aggregates and stone, earthen materials, and biobased materials. They are used differently in buildings than in site applications, but their life-cycle impacts and some strategies for reducing the impacts are similar. Therefore, this book can be of value to architects as they make decisions about building construction materials as well.

This chapter, Chapter 1, "Materials for Sustainable Sites Defined," has identified the basic tenets of materials for sustainable sites. These have been carried into each individual material chapter and have shaped the content and issues discussed. There has been no attempt to rank the attributes here because their relative importance will vary by material and site conditions. Discussions of ranking priorities follow in subsequent chapters.

Chapter 2, "Background: Inputs, Outputs, and Impacts of Construction Materials," begins with a summary of environmental and human health impacts resulting from the production, use, and disposal of construction materials. Relationships between the impacts and materials are illustrated and the life-cycle phases of materials and products are defined. Chapter 2 reveals the sheer magnitude of resources and waste that result from material production and begins to pinpoint the major problem areas to address with material and product selection. The chapter concludes with a hopeful discussion of recent trends in industrial ecology and material manufacture, and ideologies, principles, and policies relating to the sustainable use of construction materials. Chapter 3, "Evaluating the Environmental and Human Health Impacts of Materials," takes the position that with careful attention to environmental and human health costs throughout their life cycle, one can minimize their impacts. Therefore chapter 3 discusses the practice of life-cycle assessment (LCA) and offers techniques for sustainability assessment (SA) and embodied energy and carbon analysis of building materials. Acknowledging that an LCA is outside the skills and scope of most designers, the chapter provides explanations of current LCA tools and other information sources to assist designers with material and product evaluation. Establishment of environmental and human health priorities and weightings is also discussed.

Chapter 4, "Resource Reuse: Designing with and Specifying Reclaimed, Reprocessed, and Recycledcontent Materials," addresses one of the most critical and far-reaching principles of materials for sustainable sites—the reuse and recycling of materials and products. The importance of this activity is manifest not only in the conservation of natural resource use, but also in the related reductions of habitat destruction of energy use for primary processing of raw materials, waste, and pollution. The chapter discusses priorities and a hierarchy for reduction of resource use from reusing existing structures in place to recycling down to energy recovery. The chapter provides techniques of design for disassembly and deconstruction so that our existing built environment can be "mined" for resources after its useful life.

Chapter 5 leads the individual materials chapters with the most commonly used construction material in the world: concrete. The many advantages of concrete are weighed against the severe energy consumption and pollution resulting from cement manufacture. The main focus of the chapter is on use of pozzolanic and cementitious substitutes for portland cement, followed by a discussion of recycled materials that can be substituted for natural aggregates in a concrete mix. Considerations for the specification of porous concrete are provided.

Chapter 6 reintroduces earthen building materials for consideration in the modern site construction material palette. The chapter defines and discusses specification considerations for rammed earth, compressed earth blocks, adobe, sprayed earth, cob, rammed earth tires, earthbag, and soil cement construction methods. It discusses soils, soil testing and amendments, and stabilizing additives and finishes to allow use of relatively low-impact earthen structures in any climate.

Chapter 7 discusses methods to balance the environmental impacts of brick production by maximizing longevity of the brick product. Clay bricks are known for their durability and when used appropriately can be used over and over again in many different structures, often outlasting the life of a landscape and giving new life to another. Strategies to minimize quantities of bricks used through perforated walls and single-wythe serpentine walls or pier and panel walls are discussed, along with techniques for reducing a wall's structural materials and footings.

Chapter 8 addresses the most ubiquitous paving material, asphalt concrete pavement, and provides many techniques to minimize its environmental impacts, from cooling the mix to recycling asphalt in place to making asphalt porous, supporting sustainable storm water strategies and reducing the pavement's contribution to the urban heat island effect. The chapter concludes that there is much that can be done to reduce the environmental and human health impacts of asphalt pavements.

Chapter 9 provides strategies for efficient use of stone and aggregates with both natural and recycled materials. While aggregate and stone are relatively lowimpact materials to produce compared with cement or metals, the sheer volume of aggregate used in construction poses resource consumption and habitat destruction impacts. Use of a wide variety of recycled materials for aggregates in base materials and as block materials in surface pavement and walls is discussed along with techniques to reduce material use with gravel pavements, dry stack walls, gabions, and gravelbased wall foundations. Sustainable site strategies are supported with discussions of porous gravel pavements and structural soils.

Chapter 10 explores the often controversial topic of wood use for sustainable sites and concludes that wood offers the potential to be an extremely sustainable and renewable construction material if it is grown and harvested sustainably or reclaimed from other structures, naturally decay resistant, or treated with one of the newer low-toxicity treatments, finished with a renewable low-VOC finish, and detailed to conserve wood resources. The value of efficient wood use and potential impacts of engineered wood products are discussed along with the role that forests and even harvested wood play in carbon sequestration. Emphasis throughout the chapter is on detailing wood structures to last long enough to ensure that the equivalent tree can be grown to replace the lumber used, making wood a truly renewable material.

Chapter 11 addresses metals, the group of materials with the largest environmental and human health impacts of any site construction material. The chapter begins with an extensive explanation of the impacts that metals pose, primarily in the mining and primary processing phases, and to a lesser degree in the finishing phase. Strategies for metal product specification focus on ensuring a long use life for metal products by inhibiting corrosion in an attempt to offset the huge environmental impacts of their manufacture. Benefits and drawbacks of metal recycling are discussed along with the wide variety of available metal finishes.

The wide range of plastics used in site construction materials is the topic of chapter 12. While all are petroleum-based products, impacts from plastics manufacture, use, and disposal vary widely. HDPE plastic is a relatively benign plastic with the ability to be easily recycled into new plastic products—many of which are used in site construction. At the other end of the impact spectrum is polyvinyl chloride (PVC), the most commonly used plastic in construction, which poses severe impacts in manufacture and disposal and is virtually unrecyclable. The chapter discusses the oftencontested impacts of PVC and provides alternative materials to consider.

Chapter 13 discusses the expanding range of nonliving, biobased materials for site construction. Shortcycle materials grown on a ten-year or shorter rotation—such as fiber crops, bamboo, agricultural residues, and plant seed oils—are discussed along with impacts of their growth and processing. Some biobased site construction materials discussed are coir and jute erosion control products; straw mulch and straw bale; cellulose fiber mulch; compost; bamboo products; and plant-based soil stabilizers, form-release agents, finishes, and sealants.

REFERENCES

Cascadia Chapter, U.S. Green Building Council. Living Building Challenge (LBC). http://www.cascadiagbc.org/lbc (accessed April 6, 2008).

Forest Stewardship Council (FSC). http://www.fsc.org.

Healthy Building Network. Pharos Project. Institute for Local Self-Reliance. www.pharosproject.net (accessed April 6, 2008).

- INFORM, Inc. 1995. Toxics Watch 1995. New York: INFORM, Inc.
- Kibert, C. J., J. Sendzimir, and B. Guy, eds. 2002. *Construction Ecology: Nature as the Basis for Green Building*. London: Routledge.

chapter



Background: Inputs, Outputs, and Impacts of Construction Materials

he typical site construction product is composed of a variety of constituents, each with its own complex web of inputs, outputs, and impacts that led to their existence. This broad web can extend hundreds of miles, across the country, or even around the world—and is largely invisible to those who specify the product. Impacts-both to the environment and to human health-begin during the raw material extraction phase with destruction of ecosystems and habitats to extract mostly nonrenewable materials from the earth. They continue in processing, manufacturing, and fabricating phases, using energy and producing emissions, effluents, and waste. Transport impacts of materials between phases are often significant because many site construction materials are bulky and heavy. Compared with the average consumer product, the use phase of site materials is relatively long, yet maintenance activities can pose risks to the environment and to human health. After the useful life of the material, disposal will pose another set of impacts, yet a recent increase in recycling and reuse of materials such as asphalt and concrete has substantially reduced disposal to landfills.

The inputs (resources, energy, and water) and outputs (emissions, effluents, and solid waste) that occur during the phases of a product's life cycle result in a variety of impacts that affect the health of our ecosystems, our planet, and ourselves. The burning of fossil fuels and even some material processing activities contribute greenhouse gases to the atmosphere and acid deposition on water and land. Extensive quantities of water are consumed to produce some products and wastewater effluents from their processing can carry pollutants, acids, and heavy metals into the environment. Some air and water emissions contain biological toxins, carcinogens, or mutagens that find their way into the human body, potentially producing a range of negative health effects. And the amount of waste that results from each phase places a burden on the adjacent ecosystem, sometimes through pollution, other times just through sheer volume.

But changes in the ways that products are made and specified are starting to occur—changes that pay more attention to these impacts and attempt to reduce them. Growing recognition of the immensity of the above impacts, coupled with rising fuel costs, is leading to practices, sometimes policies, of pollution prevention, waste reduction, and energy conservation in the manufacturing industry. Some new ideologies of product manufacture draw inspiration from nature's closed-loop processes, in which waste from one process is "food" for another. Others acknowledge the health risks of hazardous chemical use and are attempting to reduce their use.

This chapter begins by summarizing environmental and human health issues related to construction materials and their production. Typical phases of the life cycle of a material or product are discussed along with general impacts of inputs and outputs of construction materials and products. Trends in industrial ecology and material manufacture conclude the chapter along with ideologies, principles, and policies relating to the sustainable use of construction materials.

Major Environmental and Human Health Concerns Resulting from Construction Materials and Products

In material and product production, interaction with the environment occurs in two distinct ways. The earth is the *source* of all material resources and a *sink* for emissions, effluents, and solid wastes. It is in both of these ways that the use of materials impacts the environment. Overuse at sources depletes both the quantity and quality of available resources. And extraction of resources degrades ecosystems at the source location. Overuse of sinks from overgeneration, and careless disposal of emissions and waste, impact the balance of natural processes and ecosystems.

Construction materials are a major market segment, with 24% of Total Domestic Output (by weight) of all materials manufactured for construction-related activities (World Resources Institute [WRI] 2000). The environmental and human health concerns discussed in this section have been identified as partially resulting from overuse of sources and sinks. Table 2–1 lists these concerns and their linkages to manufacturing processes. The table and information presented in this chapter demonstrate that many environmental problems are partially related to material manufacture, use, and disposal. It is important to note that the severity of impacts among materials and products varies widely. Discussion of severity of risks and priorities for reducing the impacts summarized below is included in chapter 3, "Evaluating the Environmental and Human Health Impacts of Materials."

GLOBAL CLIMATE CHANGE

Global climate change is defined as long-term fluctuations in temperature, precipitation, wind, and all other aspects of the earth's climate. Climate change holds potential to impact many aspects of life on the planet with rising sea levels, melting glaciers, more violent storms, loss of biodiversity, reduced food supplies, and displaced populations. Global warming, one type of global climate change, is the increase in average temperature of the earth's near-surface air and oceans. Global warming occurs when energy from the earth is reradiated as heat and is absorbed and trapped by greenhouse gases in the atmosphere. This greenhouse effect reduces heat loss to space, resulting in warmer temperatures on Earth.

The Intergovernmental Panel on Climate Change (IPCC) concludes, "Most of the observed increase in globally averaged temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations," which leads to warming of the surface and lower atmosphere by increasing the greenhouse effect (IPCC 2007b). Greenhouse gases (GHG) include carbon dioxide (CO_2) , methane, nitrous oxide, ozone, sulfur hexafluoride, hydrofluorocarbons, perfluorocarbons, and chlorofluorocarbons. In addition, there are several gases that do not have a direct global warming effect but indirectly impact solar radiation absorption by influencing the formation of greenhouse gases, including ground-level and stratospheric ozone. They are carbon monoxide (CO), oxides of nitrogen (NO_x), and non-CH₄ volatile organic compounds (NMVOCs). The IPCC predicts that a rise in mean global temperatures of between 2 and 11 degrees Celsius could be expected by the end of the twenty-first century (IPCC 2007b).

The global carbon cycle, made up of large carbon flows and reservoirs, involves billions of tons of carbon in the form of CO_2 . CO_2 is absorbed by sinks (e.g.,

Environmental Concerns	Connections to Construction Materials
Global climate change	Greenhouse gas (GHG) emissions from energy use, non-fossil fuel emissions from material manufacture (eg. cement production, iron and steel processing), transportation of materials, landfill gases
Fossil fuel depletion	Electricity and direct fossil fuel usage (e.g., power and heating requirements), feedstock for plastics, asphalt cement, and sealants, solvents, adhesives
Stratospheric ozone depletion	Emissions of CFCs, HCFCs, halons, nitrous oxides (e.g., cooling requirements, cleaning methods, use of fluorine compounds, aluminum production, steel production)
Air pollution	Fossil fuel combustion, mining, material processing, manufacturing processes, transport, construction and demolition
Smog	Fossil fuel combustion, mining, material processing, manufacturing processes, transport, construction and demolition
Acidification	Sulfur and $\mbox{NO}_{\rm x}$ emissions from fossil fuel combustion, smelting, acid leaching, acid mine drainage and cleaning
Eutrophication	Manufacturing effluents, nutrients from nonpoint source runoff, fertilizers, waste disposal
Deforestation, desertification, and soil erosion	Commercial forestry and agriculture, resource extraction, mining, dredging
Habitat alteration	Land appropriated for mining, excavating, and harvesting materials. Growing of biomaterials, manufacturing, waste disposal
Loss of biodiversity	Resource extraction, water usage, acid deposition, thermal pollution
Water resource depletion	Water usage and effluent discharges of processing and manufacturing
Ecological toxicity	Solid waste and emissions from mining and manufacturing, use, maintenance and disposal of construction materials

Table 2–1 Environmental Concerns and Connections to Construction Materials

Sources: Ayers 2002; Azapagic et al. 2004; Graedel and Allenby 1996; Gutowski 2004; UNEP 1999

oceans and living biomass) and emitted to the atmosphere by sources in natural processes such as decomposition of plant or animal matter. In equilibrium, carbon fluxes are somewhat balanced; however, since the Industrial Revolution, global atmospheric concentrations of CO_2 have risen around 35% (IPCC 2001). This rise is due largely to the combustion of fossil fuels.

In the United States in 2005, fossil fuel combustion accounted for 94% of CO_2 emissions, with the remainder from sources such as chemical conversions (e.g., cement, iron, and steel production), forestry, and land clearing for development. Globally, the United States contributed 22% of CO_2 emissions in 2004 (IPCC 2007b) while the U.S. population is just 4.5% of the worldwide population.

Three-quarters of anthropogenic greenhouse gas emissions are generated from fossil fuel combustion to

power vehicles and power generation plants, and as raw material for production of synthetic polymers (IPCC 2007a). Other major greenhouse gas releases result from the conversion of limestone into lime for cement manufacture, from animal agriculture, and from deforestation. Table 2–3 contains greenhouse gas contributions of major industrial sectors involved in material production related to construction materials.

Greenhouse gas emissions are often directly related to the embodied energy of a construction material, as for most materials the emissions stem from the fossil fuel combustion required in their production. For instance, steel requires a relatively high amount of energy to produce—energy derived primarily from coal combustion processes, so the greenhouse gas emissions are directly related. Aluminum and concrete are the two main construction material exceptions to this, for

 Table 2–2
 Global Warming Potentials (GWPs) and

 Atmospheric Lifetimes (Years) of GHG^a

Gas	Atmospheric Lifetime In Years	GWP ^b
CO ₂	50-200	1
CH ₄	12 ± 3	21
N ₂ O	120	310
HFC-23	264	11,700
CF ₄	50,000	6,500
C_2F_6	10,000	9,200
C_2F_{10}	2,600	7,000
C_6F_{14}	3,200	7,400
SF ₆	3,200	23,900

^a100-year time horizon

 $^b The \ GWP \ of \ CH_4$ includes the direct effects and those indirect effects due to the production of tropospheric ozone and stratospheric water vapor. The indirect effect due to the production of CO_2 is not included.

Source: U.S. EPA 2007c

different reasons. Because the energy requirements to produce aluminum are so great, hydroelectric power is the primary power source (55%). While hydroelectric power poses other environmental concerns, CO₂ release

is relatively low compared to coal combustion or even natural gas; therefore, pound for pound steel has a lower embodied energy than aluminum, but higher GHG emissions. Greenhouse gas emissions for concrete are about twice the embodied energy, as almost equal amounts of CO_2 are released in the conversion of limestone to lime as in the fossil fuel combustion to heat the limestone.

FOSSIL FUEL DEPLETION

Fossil fuels, the primary source of energy for the industrialized world, are being extracted at a rate thousands of times faster than the time taken for them to renew. They are considered to be nonrenewable resources because they take millions of years to renew. As fuel reserves decrease, it is expected that extraction and refinement costs will increase. Fossil fuels are used throughout a product's life cycle to power vehicles (used in extraction, transportation, construction, and maintenance); to produce steam or heat for industrial processes; for electricity; to power machinery; and as raw material for production of plastics, other synthetic polymers (e.g., fibers), and solvents. Besides the impacts associated with extraction and combustion of fossil

Table 2-3 Greenhouse Gas Emissions by Industrial Sector in the United States

Industry	1990 Tg CO ₂ Eq	2005 Tg CO ₂ Eq	Percent Change
Fuel-related GHG emissions from industrial processes	1,539.8	1,575.2	2.3
Nonfuel GHG from industrial processes:			
Iron and steel production	86.2	46.2	-46.4
Cement manufacture	33.3	45.9	37.8
Lime manufacture	11.3	13.7	21.2
Aluminum production	25.3	8.7	-65.6
Limestone and dolomite use	5.5	7.4	34.5
Titanium dioxide production	1.3	1.9	46.2
Ferroalloy production	2.2	1.4	-36.4
Zinc production	0.9	0.5	-44.4
Petrochemical production	2.3	4.0	74.0
Total GHG emissions from all sources	4,724.1	5,751.2	21.7

Source: U.S. EPA 2007c.

fuels, there are no direct environmental impacts of depletion per se.

There is widespread disagreement about the finite nature of fossil fuels, and if and when they will be depleted. Some scientists warn that the effects of current levels of fossil fuel combustion will wreak havoc on climate and the environment before fossil fuel supplies are depleted.

Political concerns over ownership of fossil fuel reserves and concerns about the environmental and human health impacts of combustion have led to increased policy interest in renewable energy sources such as biofuels, geothermal, wind, and solar power in some countries. In the industrial sector, as costs of fossil fuels and purchased electricity increase, some manufacturers are looking to alternative energy sources such as wind power, hydroelectric power, landfill methane capture, or energy recovery from incineration of waste.

STRATOSPHERIC OZONE DEPLETION

The naturally occurring ozone layer of the stratosphere is a critical barrier that prevents harmful shortwave ultraviolet radiation from reaching the earth. Humancaused emissions of ozone-depleting substances, such as chlorofluorocarbons (CFCs; used as a propellant in manufacturing and a refrigerant) and halons (used in fire suppression systems), can cause a thinning of the ozone layer, resulting in more shortwave radiation on Earth. This has a number of potentially negative consequences, such as impacts on plants and agriculture, and increases in cancer and cataracts in people. Additional effects on climate and the functioning of different ecosystems may exist, although the nature of these effects is less clear.

In 1987, over 190 countries, including the United States, signed the Montreal Protocol calling for elimination of CFCs and other stratospheric ozone-depleting substances (ODSs). Since that time, the production of ODSs has been in the process of being phased out. Use of substitutes for CFCs and HCFCs such as hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs) has grown; while they do not contribute to ozone depletion, they are powerful greenhouse gases with high global warming potential (GWP) and long atmospheric lifetimes.

AIR POLLUTION

Air pollutants are airborne solid and liquid particles and gases that can pose risks to the environment and human health. Fugitive emissions result from many activities, including production of electricity; operation of equipment used in manufacture, transport, construction, and maintenance; manufacturing processes; and mining and crushing of materials. Air pollution from manufacturing processes related to site construction materials is discussed in greater detail later in this chapter under outputs from manufacturing.

Amendments to the Clean Air Act were passed in 1990, giving the U.S. EPA rights to restrict levels of criteria air pollutants and emissions of hazardous air pollutants from sources such as power plants and manufacturing facilities. Criteria air pollutants (CAPs) are particulate matter (both PM10 and PM2.5), ground-level ozone, carbon monoxide (CO), sulfur dioxides (SO₂), nitrogen oxides (NO_x), and lead. VOCs and ammonia are also monitored along with CAPs, as they contribute to human and environmental health risks. CAPs, particularly particulate matter and ground-level ozone, are considered by the EPA to be widespread human and environmental health threats (U.S. EPA Air and Radiation). Release of CAPs such as particulate matter, CO, lead, and ozone can contribute to asthma, or more serious respiratory illnesses such as permanent lung damage, and heart disease. SO_2 , NO_x , and ozone can contribute to acid rain and ground-level ozone, damaging trees, crops, wildlife, water bodies, and aquatic species. The EPA regulates release of CAPs by setting permissible levels for geographic areas.

Hazardous air pollutants (HAPs), also called toxic air pollutants or air toxics, are pollutants that can cause negative human or environmental health effects. They may cause cancer or other serious health effects such as reproductive effects or birth defects; damage to the immune system; or developmental, respiratory, or neurological problems in humans and other species (U.S. EPA Air and Radiation). Airborne HAPs can deposit onto soils or surface waters, where they are taken up by plants and ingested by animals, and are magnified as they move up the food chain.

Human exposure to toxic air pollutants can occur by breathing contaminated air; eating contaminated food

products such as fish from polluted waters or vegetables grown in contaminated soil; drinking water contaminated by toxic air pollutants; or touching contaminated soil, dust, or water. HAPs released into the air such as vinyl chloride (the precursor to PVC) are toxic and can cause cancer, birth defects, long-term injury to the lungs or brain, and nerve damage (U.S. EPA Air and Radiation).

SMOG

Smog is a type of air pollution, resulting when industrial and fuel emissions become trapped at ground level and are transformed after reacting with sunlight. For example, ozone is one component of smog and occurs when volatile organic compounds (VOCs) react with oxides of nitrogen (NO_x). Transport of materials and equipment used in landscape construction and maintenance contributes to smog-producing emissions. Like air pollutants and acidification compounds, smog can have negative effects on the health of people and other biotic communities.

ACIDIFICATION

Acidification occurs in surface waters and soils as acidifying gases, primarily sulfur and nitrogen compounds, either dissolve in water or adhere to solid particles. These compounds reach ecosystems primarily in the form of acid rain, through either a dry or wet deposition process. The primary sources of acid rain are emissions of sulfur dioxide and nitrogen oxide from fossil fuel combustion, although they can also result from natural processes of decaying vegetation and volcanoes. In the United States, roughly two-thirds of all SO₂ and one quarter of all NO_x emissions result from electric power generation, primarily from coal-fired power plants, while another primary source is motor vehicle fuel combustion. In material manufacture, fossil fuels are burned to produce electricity and to power equipment used in raw material extraction, manufacture, transportation, construction, and maintenance. Winds can blow these emissions from power and manufacturing plants over hundreds of miles before they are deposited (U.S. EPA Air and Radiation).

Acid rain causes acidification of rivers, streams, and oceans, lowering the pH and causing damage to fish and

other aquatic animals. This can lower the biodiversity of the water body. Soil biology is also negatively affected by acid rain with the consumption of acids by microbes killing some. Some acids in soil can mobilize toxins and leach essential nutrients and minerals.

Sulfur dioxide can interfere with photosynthesis of vegetation, slowing the growth of forests. Trees, particularly those at higher altitudes surrounded by clouds and fog that are more acidic, may be weakened and made more susceptible to other threats. Impacted soils can also contribute to vegetation impacts. Nitrogen oxides affect animals (and humans) through respiratory irritation. In addition, interaction of these compounds with other atmospheric pollutants can have toxic effects on animals and plants through formation of photochemical smog.

Acid rain also accelerates weathering of building materials such as granite, limestone, concrete, and metals. It may even cause some stainless steels to stain. This can cause premature removal and replacement of some building materials.

EUTROPHICATION

Eutrophication is the addition of nutrients, such as nitrogen and phosphorus, to soil or water resulting in overstimulation of plant growth. Eutrophication is a natural process; however, it is accelerated by human activities, causing species composition alterations and reducing ecological diversity. In water, it promotes algal blooms that can cloud the water, blocking sunlight and causing underwater grasses to die. Loss of the grasses reduces habitat and food for aquatic species, sometimes causing their death. As algae die, oxygen in water is depleted, also affecting the health of fish and aquatic species. Eutrophication impacts affect humans by affecting the taste of water (even after treatment) and by negative impacts on swimming, boating, and fishing.

Eutrophication results from the release of pollutants, such as nitrogen and phosphorus, to surface waters from fertilizers, sewage effluent, and manufacturing wastewater. Nitrogen and phosphorus are major components of synthetic fertilizers used in landscape maintenance and agriculture. Unchecked nutrients from nonpoint source pollution in stormwater runoff are also a cause of eutrophication. A 1993 survey of lakes worldwide showed that 54% of lakes in Asia are eutrophic; in Europe, 53%; in North America, 48%; in South America, 41%; and in Africa, 28% (ILEC 1993).

DEFORESTATION, DESERTIFICATION, AND SOIL EROSION

Only 36% of the world's primary forests remain as of 2005, yet forests play a key role in the health of the planet by containing half of the world's biodiversity and sequestering large quantities of carbon dioxide. Deforestation, the large-scale removal of forests, contributes to negative environmental impacts such as loss of biodiversity, global warming, soil erosion, and desertification. Deforestation is driven by factors such as poverty, economic growth, government policies, technological change, and cultural factors (Food and Agriculture Organization of the United Nations [FAO] 2005). Deforestation occurs when forested land is cleared for agriculture, mining, new construction of buildings, or roads, or when trees are harvested for fuel or lumber. For site construction materials, forest harvesting for lumber and land clearing for mining of metal ore, minerals, stone, and gravel are the primary activities that contribute to deforestation. Lumber from some forests, particularly in developing countries, holds substantial economic value and is sometimes harvested illegally. Agricultural expansion was involved in 96% of deforestation cases in a 2001 study, but it was not the sole cause, as timber harvesting and road building were often the reason for the cutting. Expansion of cattle operations in Brazil is a significant cause of deforestation in the Amazon, with a 3.2% total loss of forests between 2000 and 2005 (FAO 2005).

Nearly 37 million hectares, or just under 1% of the global forested area, was lost between 2000 and 2005. While this is about 19% less than the shrinkage rate of the 1990s, it is still substantial, with largest losses in African, South American, and Southeast Asian countries that contain valuable rain forests. Europe and China both had a net gain of forest land, with a 10% gain in China due to an aggressive reforestation program (FAO 2005).

When forests are eliminated, they no longer provide ecological services such as carbon sequestration, habitat, erosion control, and regulation of the hydrological cycle. Forests play a vital role in stabilizing the climate by sequestering atmospheric carbon. The FAO estimates that between 1990 and 2005, the carbon storage capacity of forests declined by more than 5%. When forests are cut, they can be a significant source of carbon emissions from rotting branches and debris that gives off carbon dioxide. Lumber and other wood products continue to sequester carbon until they decay. Estimates attribute 25% of human-caused carbon emissions to deforestation (FAO 2005). On a global scale, deforestation can affect the albedo, or reflectivity, of the earth, altering

Region	1990 Area (1,000 ha)	2005 Area (1,000 ha)	Change in Area (1,000 ha)	Change in Area (%)
South America	890,818	831,540	-59,278	-6.65
Africa	699,361	635,412	-63,949	-9.14
Oceania	212,514	206,254	-6,260	-2.95
Central America and Caribbean	32,989	28,385	-4,604	-13.96
North America	677,801	677,464	-337	-0.05
Europe	989,320	1,001,394	+12,073	+1.22
Asia	574,487	571,577	-2,910	-0.51
World	4,077,291	3,952,025	-125,265	-3.07

Table 2-4 Change in Extent of Forest, 1990-2005

Source: Adapted from FAO 2005, Annex 3, Table 4

surface temperatures, water evaporation, and rainfall patterns.

Deforestation causes soil erosion, resulting in topsoil loss and sedimentation of water bodies. Increased runoff volume from deforested land can carry topsoil and pollutants into surface waters, causing reduced light penetration, increased turbidity, increased biochemical oxygen demand (BOD), and deoxygenation. These stressors can result in a loss of faunal diversity and possible fish kill. The EPA has estimated that erosion from clear-cut forests can be as much as 12,000 tons per square mile per year. This is 500 times the erosion rate of undisturbed forests.

In arid and semiarid regions, removal of natural forest cover can lead to desertification by exposing soil to wind, erosion, salinization, and rapid evaporation of soil moisture—all of which alter biodiversity and habitats. Desertification is estimated to have affected over 250 million people with potential to affect over a billion, as 40% of the earth's surface is drylands susceptible to desertification (United Nations Convention to Combat Desertification [UNCCD] 2007).

HABITAT ALTERATION

Habitats are altered or destroyed when human activity results in a change in the species composition of plant and animal communities. This can occur through practices that change environmental conditions and reduce habitat, as well as through differential removal or introduction of species. Habitat alteration is a primary impact resulting from mining and harvesting of materials for the manufacture of construction materials. Habitat alteration also can occur as a result of air, water, and land releases from industrial processes that change environmental conditions, such as water quality and quantity, in naturally occurring communities. Effects of habitat alteration include changes in ecosystem function and possible reduced biodiversity.

LOSS OF BIODIVERSITY

Global climate change, the destruction of forests and habitats, and air, water, and soil pollution have all contributed to a loss of biodiversity over the past few centuries. The Millennium Ecosystem Assessment estimates that "extinction rates are [currently] around 100 times greater that rates characteristic of species in the fossil record" (World Resource Assessment 2005). Biodiversity was defined at the UN Earth Summit in 1992 as "the variability among living organisms from all sources including, inter alia, terrestrial, marine, and other aquatic organisms, and the ecological complexes of which they are part: this includes diversity within species, between species and of ecosystems" (United Nations Environment Programme [UNEP] 1999). The stability of an ecosystem is compromised as its species are made extinct and it decreases in complexity. An example of this is monoculture plantings following deforestation for lumber.

Biodiversity is critical to the health of the ecosystems that provide many services keeping humans and the environment in relative balance. The biodiversity of ecosystems plays a role in regulating the chemistry of the atmosphere and water supply, recycling nutrients, and providing fertile soils. Biodiversity controls the spread of diseases, provides food and drugs for humans, and provides resources for industrial materials such as fibers, dyes, resins, gums, adhesives, rubber, and oils.

WATER RESOURCE DEPLETION

Human activities and land uses can deplete water resources, through use rates that exceed groundwater reserves and through practices that prevent aquifer recharge. Product manufacturing activities use water, and effluent wastes that are released to water bodies reduce water resources through pollution. In addition, the use of impervious surfaces (such as concrete and asphalt) seriously reduces groundwater recharge, as do storm water management strategies that convey runoff away from the site. Water resource depletion has serious consequences, by disrupting hydrological cycles, reducing the water available to dilute pollutants, and decreasing water for human consumption and for plant and animal communities that require more abundant and constant water supplies.

ECOLOGICAL TOXICITY

Toxic materials can be released into ecosystems as byproducts of manufacturing processes and fossil fuel combustion, and from direct environmental application of toxic pesticides. Like substances that have negative effects on human health, these can also harm animals and plants, with potential impacts on ecosystem function and loss of biodiversity.

HUMAN HEALTH DAMAGE

Negative human health effects can result from exposure to toxic materials, either human-made or naturally occurring. Toxic chemicals and substances can be encountered in all phases of the life cycle of construction materials. Many of these substances result from manufacturing, using, or disposing of plastics (e.g., PVC, polystyrene, ABS), metals, metal finishes, solvents, and adhesives. The effects of these substances vary from momentary irritation (acute) to prolonged illness and disease (chronic) to death. Some compounds are carcinogens, persistent bioaccumulative toxins (PBTs), mutagens, endocrine disruptors, reproductive toxicants, teratogens, or acute or chronic toxicants.

Humans are exposed through numerous pathways to toxic substances, and because the effects are not always noticable, they are often overlooked. Some mine tailings left from extraction of raw materials can pollute habitats and watersheds, concentrating in fish and working their way up the food chain. Harmful chemicals can be released into water from processing and manufacture and find their way into the drinking water supply. Some manufacturing processes can pose a risk to worker health through exposure. And during use, materials such as asphalt sealants and CCAtreated lumber pose toxic risks to people in contact with the materials. Commonly used adhesives, finishes, sealants, and maintenance products can contain hazardous chemicals and VOCs. During landfill disposal, some materials can threaten drinking water supplies, while incineration of some materials such as PVC can release hazardous chemicals and PBTs into the air and eventually the food supply. Material safety data sheets are mandated by the Occupational Safety and Health Administration's (OSHA) hazard communication standard and are available for all materials/products that may pose risks to human health. Table 2-5 defines classifications of toxins and provides sources of information on each.

Table 2–5 Classifications and Listings of Toxic Substances

PERSISTENT BIOACCUMULATIVE TOXINS (PBTs)

PBTs such as mercury and DDT last for a long time in the environment with little change in their structure or toxic effects. This means that a persistent toxic chemical transported in the wind can be just as toxic 10,000 miles away as it was at the smokestack from which it was released. Some PBTs, such as polychlorinated biphenyls (PCBs), have been found in remote parts of the Arctic, far away from the industrial sources that produce them.

Some of the PBTs that move through the air are deposited into water bodies and concentrate up through the food chain, harming fish-eating animals and people. Small fish may consume plants that live in water contaminated by PBTs, which are absorbed into plant tissues. Larger fish eat smaller fish and as the PBTs pass up the food chain, their levels go up. So a large fish consumed by people may have PBT levels thousands of times in its tissues than those found in the contaminated water. Over 2,000 U.S. water bodies are covered by fish consumption advisories, warning people not to eat the fish because of contamination with chemicals, often PBTs. These compounds have been linked to illnesses such as cancer, birth defects, and nervous system disorders (U.S. EPA Air and Radiation).

PBTs of concern for site construction materials include dioxin emissions from PVC and cement manufacture and PVC disposal, and heavy metals such as lead, mercury, chromium, and cadmium from metal production and finishing.

U.S. EPA Priority PBTs. http://www.epa.gov/pbt/pubs/cheminfo.htm

U.S. EPA Great Lakes Pollution Prevention and Toxics Reduction, The Great Lakes Binational Toxics Strategy http://www.epa.gov/grtlakes/p2/bns.html

Washington State PBT list. http://www.ecy.wa.gov/programs/eap/pbt/pbtfaq.html

Continued

Table 2–5 Classifications and Listings of Toxic Substances (Continued)

Stockholm Convention on Persistent Organic Pollutants http://www.pops.int/ and

http://www.pops.int/documents/convtext/convtext_en.pdf

European Chemicals Bureau, European Union Status report on PBTs and vPvBs for new and existing substances. http://www.defra.gov.uk/environment/chemicals/achs/060606/achs0614d.pdf

CARCINOGENS

Carcinogens are defined as substances that cause or increase the risk of cancer. The International Agency for Research on Cancer (IARC) classifies substances as to carcinogenic risk in the following categories:

Group 1: The agent is *carcinogenic to humans*.

Group 2A: The agent is probably carcinogenic to humans.

Group 2B: The agent is *possibly carcinogenic to humans*.

Group 3: The agent is not classifiable as to its carcinogenicity to humans.

Group 4: The agent is probably not carcinogenic to humans.

Some chemicals in construction materials, or released during their processing, manufacture, or disposal, are known or suspected carcinogens. Vinyl chloride (used to produce PVC) can cause liver cancer, formaldehyde is linked to cancers of the sinuses and brain, and heavy metal fumes such as chromium, nickel, and cadmium can cause lung cancer (Healthy Building Network 2007).

International Agency for Research on Cancer (IARC), World Health Organization

http://monographs.iarc.fr/ENG/Classification/index.php. Provides monographs on substances that are or may be carcinogens.

National Toxicology Program (NTP), Department of Health and Human Services

Report on Carcinogens, 11th edition; U.S. Department of Health and Human Services, Public Health Service, National Toxicology Program. Lists both known and suspected carcinogens. http://ntp.niehs.nih.gov/

National Institute for Occupational Safety and Health, Centers for Disease Control

List of suspected carcinogens found in the workplace. http://www.cdc.gov/niosh/npotocca.html

State of California, EPA, Office of Environmental Health Hazard Assessment, Safe Drinking Water and Toxic Enforcement Act of 1986. Proposition 65, Chemicals Known to the State to Cause Cancer or Reproductive Toxicity. http://www.oehha.ca.gov/prop65/prop65_list/Newlist.html

Brookhaven National Labs, Department of Energy

Standard carcinogen list that is a compilation of listings by Occupational Safety and Health Administration (OSHA), International Agency for Research on Cancer (IARC), National Toxicology Program (NTP), and American Conference of Industrial Hygienists (ACGIH).

http://www.bnl.gov/esh/shsd/Programs/Program_Area_Chemicals_LabStd_Carcinogens.asp

REPRODUCTIVE TOXIN LISTINGS

Reproductive toxins disrupt both male and female reproductive systems. A teratogen is a substance that causes defects in development between conception and birth or a substance that causes a structural or functional birth defect (Agency for Toxic Substances and Disease Registry [ATSDR]). Lead and mercury, released from fossil fuel combustion and the processing of metals and metal finishes, are examples of reproductive toxins.