

Sustainable Architecture Module:

Qualities, Use, and Examples of Sustainable Building Materials

Written by

Jong-Jin Kim, Assistant Professor of Architecture,
and Brenda Rigdon, Project Intern;

Edited by

Jonathan Graves, Project Intern;

College of Architecture and Urban Planning
The University of Michigan

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430 E. University Ave., Ann Arbor, MI 48109-1115
734.764.1412 • fax: 734.647.5841 • nppc@umich.edu
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Introduction

Careful selection of environmentally sustainable building materials is the easiest way for architects to begin incorporating sustainable design principles in buildings. Traditionally, price has been the foremost consideration when comparing similar materials or materials designated for the same function. However, the “off-the-shelf” price of a building component represents only the manufacturing and transportation costs, not social or environmental costs.

Life Cycle Design

A “cradle-to-grave” analysis of building products, from the gathering of raw materials to their ultimate disposal, provides a better understanding of the long-term costs of materials. These costs are paid not only by the client, but also by the owner, the occupants, and the environment.

The principles of Life Cycle Design provide important guidelines for the selection of building materials. Each step of the manufacturing process, from gathering raw materials, manufacturing, distribution, and installation, to ultimate reuse or disposal, is examined for its environmental impact.

A material’s life cycle can be organized into three phases: Pre-Building; Building; and Post-Building. These stages parallel the life cycle phases of the building itself (see this compendium’s “Sustainable Building Design” module). The evaluation of building materials’ environmental impact at each stage allows for a cost-benefit analysis over the lifetime of a building, rather than simply an accounting of initial construction costs.

Three Phases of Building Materials

These three life-cycle phases relate to the flow of materials through the life of the building (see **Figure 1**).

Pre-Building Phase

The **Pre-Building Phase** describes the production and delivery process of a material up to, but not including, the point of installation. This includes discovering raw materials in nature as well as extracting, manufacturing, packaging, and

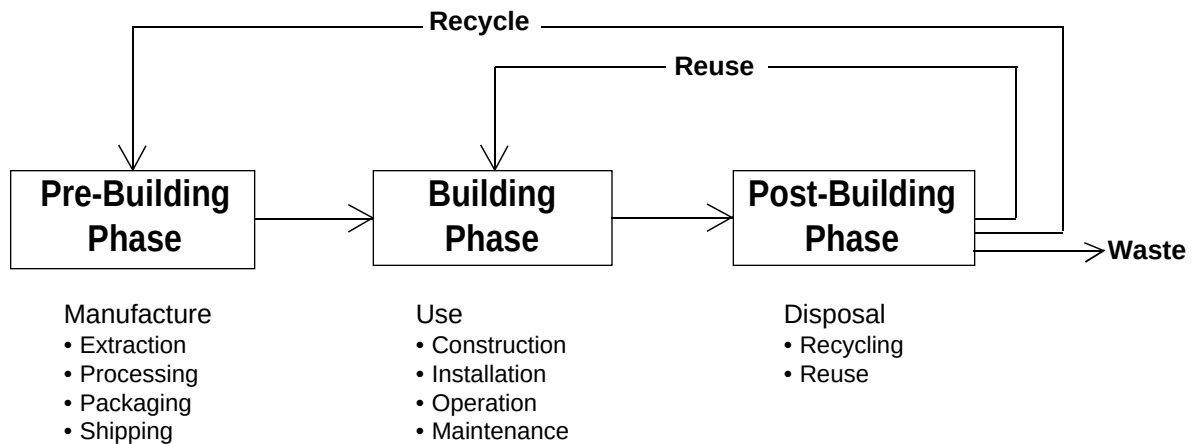


Figure 1: Three phases of the building material life cycle.

transportation to a building site. This phase has the most potential for causing environmental damage. Understanding the environmental impacts in the pre-building phase will lead to the wise selection of building materials. Raw material procurement methods, the manufacturing process itself, and the distance from the manufacturing location to the building site all have environmental consequences. An awareness of the origins of building materials is crucial to an understanding of their collective environmental impact when expressed in the form of a building.

The basic ingredients for building products, whether for concrete walls or roofing membranes, are obtained by mining or harvesting natural resources. The extraction of raw materials, whether from renewable or finite sources, is in itself a source of severe ecological damage. The results of clear-cutting forests and strip-mining once-pristine landscapes have been well documented.

Mining refers to the extraction, often with great difficulty, of metals and stone from the earth's crust. These materials exist in finite quantities, and are not considered renewable. The refining of metals often requires a large volume of rock to yield a relatively small quantity of ore, which further reduces to an even smaller quantity of finished product. Each step in the refining process produces a large amount of toxic waste.

In theory, harvestable materials like wood are renewable resources and thus can be obtained with less devastation to

their ecosystems. In reality, a material is only considered a renewable or sustainable resource if it can be grown at a rate that meets or exceeds the rate of human consumption. Hardwoods, for example, can take up to 80 years to mature.

The ecological damage related to the gathering of natural resources and their conversion into building materials includes loss of wildlife habitat, erosion, and water and air pollution.

Loss of habitat: Habitat refers to the natural environment in which a species is found; usually, these areas are undeveloped. Cutting forests for lumber or removing vegetation for mining destroys the habitats of animal and plant species. A microclimate may be immediately and severely altered by the removal of a single tree that protectively shaded the plants below.

As wilderness declines, competition for food, water, and breeding territory increases. Some species, like Michigan's Kirtland's Warbler, are so highly specialized that they can only thrive in a specific, rare ecology. Damage to these special ecosystems leads to extinction. A record number of species disappear every year due to loss of habitat. All consequences of this loss are yet unknown, but many biologists believe that such a severe reduction in diversity threatens the long-term adaptability, and thus survival, of plants, animals, and humans.

Plants return moisture to the air through respiration, filter water and air pollutants, and generate the oxygen necessary for people and animals to survive. Tropical rainforests are a main route for the movement of water from the ground into the atmosphere: trees, like people, expel moisture as part of their respiration cycle. A decrease in the amount of atmospheric water may lead to a decrease in worldwide rainfall, resulting in drought and famine.

Tropical rainforests support a vast range of plants and animals. As part of the photosynthesis process, they also absorb carbon dioxide from the atmosphere. The widespread destruction of rainforests to make way for mining and farming operations has been linked to increased levels of carbon dioxide in the atmosphere, which in turn has been linked to global warming.

Erosion: The removal of trees and groundcover also leaves areas vulnerable to erosion. The erosion of topsoil and runoff into streams and rivers has become a major environmental concern. Active surface mining accounts for the erosion of 48,000 tons of topsoil, per square mile mined, per year.¹ In addition to depleting the area of fertile soil, the particulate matter suspended in water reduces the amount of sunlight that penetrates to plants below the surface. The resulting plant die-off triggers a reaction that moves up the food chain. As plants die, the amount of oxygen available to other life-forms decreases. Eventually, a stream or lake can become clogged with decaying plants and animals, and can no longer be used as a drinking source by wildlife or humans.

Water Pollution: Waste and toxic by-products of mining and harvesting operations are also carried into the water. Like soil erosion, they can increase the turbidity, or opacity, of the water, blocking sunlight. Many of these byproducts are acidic and thus contribute to the acidification of ground water, harming plant and wildlife. Oil and gasoline from engines and toxic metals leftover from mining may also leech into the groundwater, causing contamination of drinking supplies.

Air Pollution: Mining and harvesting operations contribute to air pollution because their machinery burns fossil fuels and their processes stir up particulate matter. Combustion engines emit several toxic gases:

- carbon monoxide, which is poisonous to most life
- carbon dioxide, known as a “greenhouse gas”; has been linked to global warming
- sulfur dioxide and nitrous oxide, which contribute to “acid rain”: precipitation acidified by atmospheric gases, that can damage buildings or kill plants and wildlife. In the United States, the Northeast has been particularly hard hit by acid rain. Forests and lakes have “died” as a result of increasing acidity in the water and soil.

¹ American Institute of Architects, *Environmental Resource Guide* (Washington: 1992).

Building Phase

The **Building Phase** refers to a building material's useful life. This phase begins at the point of the material's assembly into a structure, includes the maintenance and repair of the material, and extends throughout the life of the material within or as part of the building.

Construction: The material waste generated on a building construction site can be considerable. The selection of building materials for reduced construction waste, and waste that can be recycled, is critical in this phase of the building life cycle.

Use/Maintenance: Long-term exposure to certain building materials may be hazardous to the health of a building's occupants. Even with a growing awareness of the environmental health issues concerning exposure to certain products, there is little emphasis in practice or schools on choosing materials based on their potential for outgassing hazardous chemicals, requiring frequent maintenance with such chemicals, or requiring frequent replacements that perpetuate the exposure cycle.

Post-Building Phase

The **Post-Building Phase** refers to the building materials when their usefulness in a building has expired. At this point, a material may be reused in its entirety, have its components recycled back into other products, or be discarded.

From the perspective of the designer, perhaps the least considered and least understood phase of the building life cycle occurs when the building or material's useful life has been exhausted. The demolition of buildings and disposal of the resulting waste has a high environmental cost. Degradable materials may produce toxic waste, alone or in combination with other materials. Inert materials consume increasingly scarce landfill space. The adaptive reuse of an existing structure conserves the energy that went into its materials and construction. The energy embodied in the construction of the building itself and the production of these materials will be wasted if these "resources" are not properly utilized.

Some building materials may be chosen because of their adaptability to new uses. Steel stud framing, for example, is easily reused in interior wall framing if the building occupants' needs should change and interior partitions need to be redesigned (modular office systems are also popular for this reason). Ceiling and floor systems that provide easy access to electrical and mechanical systems make adapting buildings for new uses quick and cost-effective.

Features of Sustainable Building Materials

We identified three groups of criteria, based on the material life cycle, that can be used in evaluating the environmental sustainability of building materials. The presence of one or more of these features in building materials make it environmentally sustainable.

Pollution Prevention Measures in Manufacturing

Pollution prevention measures taken during the manufacturing process can contribute significantly to environmental sustainability. Identical building materials may be produced by several manufacturers using various processes. Some manufacturers are more conscientious than others about where their raw materials come from and how they are gathered. While all industries are bound to some extent by government regulations on pollution, some individual companies go far beyond legal requirements in ensuring that their processes pollute as little as possible. These companies are constantly studying and revising how they produce goods to both improve efficiency and reduce the amount of waste and pollutants that leave the factory. In effect, they perform their own life cycle analysis of internal processes.

Selecting materials manufactured by environmentally responsible companies encourages their efforts at pollution prevention. Although these products may have an initially higher “off-the-shelf” price, choosing products that generate higher levels of pollution exploits the environment.

The “law of supply and demand” also works in reverse: reduced demand for a product results in lower production. Lowered production means less waste discharged and less energy consumed during manufacturing, as well as a lower volume of raw materials that must be gathered. Packaging

that is environmentally sound can be a pollution prevention feature, as the way in which a product is packaged and shipped affects the total amount of waste it generates.

Water is used in large quantities in many manufacturing processes, especially in the production of paper, cement, and metals. This wastewater is often released directly into streams and can contain toxic substances. Dye used for coloring paper and carpet fiber are examples of environmental contaminants that escape freely into the waste stream.

By becoming aware of which manufacturers use environmentally sustainable manufacturing methods, specifying their products, and avoiding goods produced through highly polluting methods, architects can encourage the marketing of sustainable building materials.

Waste Reduction Measures in Manufacturing

The *waste reduction* feature indicates that the manufacturer has taken steps to make the production process more efficient, by reducing the amount of scrap material that results. This scrap may come from the various molding, trimming, and finishing processes, or from defective and damaged products. Products with this feature may incorporate scrap materials or removed them for recycling elsewhere. Some industries can power their operations by using waste products generated on-site or by other industries. These options reduce the waste that goes into landfills.

Reducing waste in the manufacturing process increases the resource efficiency of building materials. Oriented strand board and other wood composite materials are made almost entirely from the waste produced during the process of milling trees into dimensional lumber. Kilns used to dry wood can be powered by burning sawdust generated on-site, reducing both the waste that leaves the mill (to be disposed of in landfills) and the need for refined fossil fuels. Concrete can incorporate fly ash from smelting operations. Brick, once fired, is inert, not reacting with the environment. The firing process can be used to encapsulate low-level toxic waste into the brick, reducing the dangers of landfill disposal. Water used for cooling equipment or mixing can be filtered and reused rather than discharged into the waste stream.

Recycled Content

A product featuring *recycled content* has been partially or entirely produced from post-industrial or post-consumer waste. The incorporation of waste materials from industrial processes or households into usable building products reduces the waste stream and the demand on virgin natural resources.

By recycling materials, the embodied energy they contain is preserved. The energy used in the recycling process for most materials is far less than the energy used in the original manufacturing. Aluminum, for example, can be recycled for 10–20% of the energy required to transform raw ore into finished goods.² Key building materials that have potential for recycling include glass, plastics, metals, concrete or brick, and wood. These generally make up the bulk of a building's fabric. The manufacturing process for all of these materials can easily incorporate waste products. Glass, plastics, and metal can be reformed through heat. Concrete or brick can be ground up and used as aggregate in new masonry. Lumber can be resawn for use as dimensional lumber, or chipped for use in composite materials such as strand board.

Embodied Energy of Common Building Materials

All figures are for MJ/kg

Material	Virgin	Recycled
Aluminium	196	27
Polyethylene	98	56
PVC	65	29
Steel	40	18

Figure 2: Table comparing embodied energy content of common building materials from primary vs. secondary sources. [Values are from J. L. Sullivan and J. Hu, "Life Cycle Energy Analysis for Automobiles," SAE Paper No. 951829, SAE Total Life Cycle Analysis Conference, Vienna, Austria; October 16, 1995 (Warrendale, Pa.: Society of Automotive Engineers).]

Embodied Energy Reduction

The *embodied energy* of a material refers to the total energy required to produce that material, including the collection of raw materials (see **Figure 2**). This includes the energy of the fuel used to power the harvesting or mining equipment, the processing equipment, and the transportation devices that move raw material to a processing facility. This energy typically comes from the burning of fossil fuels, which are a limited, non-renewable resource. The combustion of fossil fuels also has severe environmental consequences, from localized smog to acid rain. The greater a material's embodied energy, the greater the amount of energy required to produce it, implying more severe ecological consequences. For example, the processing of wood (harvested in a sustainable fashion) involves far less energy and releases less pollution than the processing of iron, which must be extracted from mined ores.

² American Institute of Architects, *Environmental Resource Guide* (Washington: 1992).

A revision of a manufacturing process that saves energy will reduce the embodied energy of the material. Conventional materials with a high embodied energy can often be replaced by a material with low embodied energy, while using conventional design and construction techniques.

Use of Natural Materials

Natural materials are generally lower in embodied energy and toxicity than man-made materials. They require less processing and are less damaging to the environment. Many, like wood, are theoretically renewable. When natural materials are incorporated into building products, the products become more sustainable.

Reduction of Construction Waste

Minimal construction waste during installation reduces the need for landfill space and also provides cost savings. Concrete, for example, has traditionally been pre-mixed with water and delivered to the site. An excess of material is often ordered, to prevent pouring delays should a new shipment be needed. This excess is usually disposed of in a landfill or on-site. In contrast, concrete mixed on-site, as needed, eliminates waste, and offers better quality control.

Designing floor intervals to coincide with the standard lengths of lumber or steel framing members also reduces waste. Taking advantage of the standard sizes of building materials in the design phase reduces waste produced by trimming materials to fit, as well as the labor cost for installation.

Local Materials

Using locally produced building materials shortens transport distances, thus reducing air pollution produced by vehicles. Often, local materials are better suited to climatic conditions, and these purchases support area economies. It is not always possible to use locally available materials, but if materials must be imported they should be used selectively and in as small a volume as possible. For instance, the decorative use of marble quarried halfway around the world is not a sustainable choice. Steel, when required for structural strength and durability, is a justifiable use of a material that is generally manufactured some distance from the building site.

Energy Efficiency

Energy efficiency is an important feature in making a building material environmentally sustainable. The ultimate goal in using energy-efficient materials is to reduce the amount of generated energy that must be brought to a building site. The long-term energy costs of operating a building are heavily dependent on the materials used in its construction.

Depending on type, the energy-efficiency of building materials can be measured using factors such as R-value, shading coefficient, luminous efficiency, or fuel efficiency. Preferred materials slow the transfer of heat through a building's skin, reducing the need for heating or cooling. Quantitative measurements of a building material's efficiency are available to help in the comparison of building materials and determining appropriateness for certain installations.

- *R-Value*: Building envelopes are generally rated by their insulating value, known as the R-value. Materials with higher R-values are better insulators; materials with lower R-values must be used in thicker layers to achieve the same insulation value. R-values can be measured for individual materials (e.g., insulation, siding, wood paneling, brick) or calculated for composite structural elements (e.g., roofing, walls, floors, windows). Many types of insulation materials are available, from organic cellulose made from recycled paper to petrochemical-derived foams.
- *Shading Coefficient*: Although daylighting is the cheapest and most pleasant form of illumination, the accompanying heat gain from direct solar radiation is not always welcome, particularly in hot climates. The shading coefficient (SC) is a ratio of the solar heat gain of a building's particular fenestration to that of a standard sheet of double-strength glass of the same area. This allows a comparison of the sun-blocking effectiveness of various glass types, shading devices, and glazing patterns. Shading devices can be designed to block solar heat gain at certain times of the day or year: overhangs are often used to block high summer sun but admit direct light during the winter. Certain types of glass or applied films allow selective transmission of the visible radiation (light) while preventing or reducing the transmission of infrared radiation (heat).

- *System Efficiency:* Electrical and mechanical systems are responsible for more than 50% of a building's annual energy costs.³ Heating, ventilation, and air-conditioning (HVAC) systems should be selected for the greatest efficiency at the most commonly experienced temperatures. A system that offers peak efficiency at an outdoor temperature experienced by the building's climate only 5% of the time will not necessarily be the best choice. Regular maintenance programs are also necessary to keep equipment operating at peak efficiency.

Water Treatment/Conservation

Products with the *water treatment/conservation* feature either increase the quality of water or reduce the amount of water used on a site. Generally, this involves reducing the amount of water that must be treated by municipal septic systems, with the accompanying chemical and energy costs. This can be accomplished in two ways: by physically restricting the amount of water that can pass through a fixture (showerhead, faucet, toilet) or by recycling water that has already entered the site. For instance, graywater from cooking or hand-washing may be channeled to flush toilets; captured rainwater may be used for irrigation.

Water Conservation issues address efficient use of water as well as an overall reduction in the volume consumed. Water-saving showerheads and toilets are now widely used in residences as well as commercial buildings. Even in the Great Lakes region, with its abundant freshwater, conservation becomes an issue as municipal water treatment plants and septic systems are strained by urban sprawl. With the exception of buildings utilizing well-water and septic systems, all water that comes into or leaves a building must be treated.

Vacuum-assisted or composting toilets use very little water and therefore produce less waste. The advantages of composting toilets are that no waste enters the already overburdened waste stream, and the resulting compost can be used as fertilizer. The potential to separate the wastewater stream into "graywater" (dirty from washing or cooking but not containing human or animal waste) and "blackwater" (sewage

³ Paul Graham McHenry, Jr., *Adobe and Rammed Earth Buildings: Design and Construction* (New York: John Wiley, 1984).

containing biological waste or factory effluent) can be incorporated into plumbing and fixture design. Restrooms in Japan commonly direct water from the sink drain to the toilet tank, where it is used to flush toilets. The use of indigenous plants that are drought-tolerant reduces the need for irrigation, as important a consideration for the homeowner in Detroit as in Phoenix.

Rainwater collected from roofs or paved parking lots can be used for flushing toilets and landscape irrigation. The building itself can be designed to act as a collector of rainwater, to be stored in a cistern for later use. For health reasons, current building codes prohibit the use of this gathered water for human consumption, but it is possible that future water purification devices will make on-site water safe to drink—at a lower cost than current municipal water treatment.

Use of Non-Toxic or Less-Toxic Materials

Non- or less-toxic materials are less hazardous to construction workers and a building's occupants. Many materials adversely affect indoor air quality and expose occupants to health hazards. Some building materials, such as adhesives, emit dangerous fumes for only a short time during and after installation; others can contribute to air quality problems throughout a building's life.

Air Quality and Reduced Toxicity: The rush to make buildings airtight in the wake of the 1970s oil crises created a new health problem: "sick building syndrome." This occurs when natural or artificial ventilation is inadequate to remove odors and chemicals emitted by certain building materials. These substances may be hazardous, even carcinogenic. The resins in plywood, particleboard, and the chemicals used in foam insulation have been implicated in sick building syndrome. Formaldehyde, benzene, ammonia, and other hazardous or cancer-causing chemicals are present in many building materials, furnishings, and cleaning solutions.

Previously, the infiltration rate of outside air through the gaps and cracks in a building's envelope compensated for contamination of the inside air by human respiration, bacteria or molds, and material emissions. The problem of indoor air contamination is magnified by the increasing airtightness of buildings. Super-insulating buildings in attempts to conserve

energy has caused reduced air infiltration, meaning occupants are exposed to higher concentrations of toxins for longer time periods. The health effects of these toxins must be considered when selecting materials and calculating air exchange rates. By selecting materials with lower or nonexistent levels of these materials, environmental health problems can be avoided and the need for expensive air scrubbers reduced.

Material toxicity is of increasing concern with the growing number of building products containing petroleum distillates. These chemicals, known as volatile organic compounds (VOCs) can continue to be emitted into the air long after the materials containing them are installed. The severity of this process, called “outgassing,” is dependent on the chemicals involved, rate emission, concentration in the air, and length of exposure. Many adhesives, paints, sealants, cleaners, and other common products contain VOCs. Often, the substances are only exposed for a short time during and after installation; the outgassing diminishes drastically or completely once the offending materials have cured or been covered by other building materials. Therefore, higher air cycling rates are recommended during installation of these materials and for several months following building occupation.

Renewable Energy Systems

Building sites are surrounded by natural energy in the forms of wind, solar radiation, and geothermal heat. Renewable energy systems can be used to supplement or eliminate traditional heating, cooling, and electrical systems through the utilization of this natural energy. Components that encourage daylighting, passive and active solar heating, and on-site power generation are included in this category. Solar power can be utilized in many forms, both for heating and production of electricity. In many parts of the country, windpower is a feasible way to generate electricity and pump water. Active solar or geothermal heat requires outside electricity for pumps but still saves energy in comparison to the operation costs of traditional mechanical systems.

Longer Life

Materials with a longer life relative to other materials designed for the same purpose need to be replaced less often. This reduces the natural resources required for manufacturing and the amount of money spent on installation and the associated labor. Durable materials that require less frequent replacement will require fewer raw materials and will produce less landfill waste over the building's lifetime.

Durability: The durability of materials is an important factor in analyzing a building's life-cycle costs. Materials that last longer will, over a building's useful life, be more cost-effective than materials that need to be replaced more often. By looking at durability issues, the selection of initially expensive materials like slate or tile can often be justified by their longer lifespans.

Low Maintenance: Maintenance consumes a significant portion of a building's operating budget: over the building's lifetime, maintenance can easily exceed the original construction costs. This includes the cost of labor, cleaning/polishing materials, equipment, and the replacement of items valued at less than \$5,000.⁴ Less frequent cleaning of materials reduces the exposure of the building occupants and janitorial staff to cleaning chemicals—this is especially important for surfaces or systems that must be cleaned with petroleum-based solvents.

Reusability

Reusability is a function of the age and durability of a material. Very durable materials may have many useful years of service left when the building in which they are installed is decommissioned, and may be easily extracted and reinstalled in a new site. Windows and doors, plumbing fixtures, and even brick can be successfully reused. Timber from old barns has become fashionable as a reclaimed material for new construction. The historic preservation movement in this country has spawned an entire industry devoted to salvaging architectural elements of buildings scheduled for demolition. These materials are used in the renovation of old buildings as well as in new construction. In many cases, the quality of materials and craftsmanship displayed by these pieces could not be reproduced today.

⁴ Alphonse J. Dell'Isola and Stephen J. Kirk, *Life Cycle Costing for Design Professionals* (New York: McGraw-Hill, 1981).

Recyclability

Recyclability measures a material's capacity to be used as a resource in the creation of new products. Steel is the most commonly recycled building material, in large part because it can be easily separated from construction debris by magnets.

Many building materials that cannot be reused in their entirety can be broken down into recyclable components. Often, it is the difficulty of separating rubble from demolition that prevents more materials from being recycled. Once separated, glass is very easy to recycle: post-consumer glass is commonly used as a raw material in making window glass, ceramic tile, and brick. Concrete, unlike steel and glass, cannot be re-formed once set, but it can be ground up and used as aggregate in new concrete or as road bedding. Currently, very little concrete and glass from site demolition is recycled because of the difficulty in separating these materials from construction debris.

Plastics alone are easy to recycle but are often integrated into other components which makes separation difficult or impossible. Plastic laminates are generally adhered to plywood or particleboard, making these wood products also hard to recycle. Some foam insulation can be reformed, but the majority cannot. Foam insulation can, like glass, be used as filler in concrete and roadbeds.

Biodegradability

The biodegradability of a material refers to its potential to naturally decompose when discarded. Organic materials can return to the earth rapidly, while others, like steel, take a long time. An important consideration is whether the material in question will produce hazardous materials as it decomposes, either alone or in combination with other substances.

Materials

Key Building Materials and Sources

Limestone

Limestone is perhaps the most prevalent building material obtained through mining. It is used as a cladding material and plays an important role in the production of a wide range of building products. Concrete and plaster are obvious examples of products that rely on limestone; less obvious is the use of limestone in steel and glass production.

An abundant natural resource, limestone is found throughout the world. In the U.S., the states of Pennsylvania, Illinois, Florida, and Ohio are the largest producers.⁵ The mining of this sedimentary rock generally takes place in open-pit quarries. Pit-mining requires the use of heavy equipment to move the topsoil, vegetation, and overlaying rock (collectively referred to as “overburden”). Large blocks of stone are removed from the rock bed by controlled drilling and explosions. These blocks may be cut into smaller units for use as structural masonry or veneer material. Most limestone is crushed at the quarry, then converted to lime, by burning, at another location.

The burning of limestone creates sulfide emissions, a major contributor to acid rain. Limestone (primarily calcium carbonate) is converted to quicklime (calcium oxide) through prolonged exposure to high heat. This removes water and carbon from the stone and releases carbon dioxide into the atmosphere. The quicklime is then crushed and screened. Before it can be used in plaster or cement, it must be mixed with water and then dried. The hydrated lime then becomes an ingredient in concrete, plaster, and mortar.

Steel

Steel requires the mining of iron ore, coal, limestone, magnesium, and other trace elements. To produce steel, iron must first be refined from raw ore. The iron ore, together with limestone and coke (heat-distilled coal) are loaded into a blast furnace. Hot air and flames are used to melt the materials

⁵ American Institute of Architects, *Environmental Resource Guide* (Washington: 1992).

into pig iron, with the impurities (slag) floating to the top of the molten metal. Steel is produced by controlling the amount of carbon in iron through further smelting. Limestone and magnesium are added to remove oxygen and make the steel stronger. A maximum carbon content of 2% is desired. Other metals are also commonly added at this stage, to produce various steel alloys. These metals include magnesium, chromium, and nickel, which are relatively rare and difficult to extract from the earth's crust. The molten steel is either molded directly into usable shapes or milled.

Aluminium

Aluminum, derived from bauxite ore, requires a large amount of raw material to produce a small amount of final product. Up to six pounds of ore may be required to yield one pound of aluminum. Bauxite is generally strip-mined in tropical rainforests, a process that requires removing vegetation and topsoil from large areas of land. When mining is completed, the soil is replaced. The land may then be allowed to return to rainforest, but is more likely to be used as farmland.

Aluminum manufacturing is a large consumer of electricity, which in turn comes from burning fossil fuels. The refined bauxite is mixed with caustic soda and heated in a kiln, to create aluminum oxide. This white powder, in turn, must undergo an electrolytic reaction, where direct electrical current is used to separate out the oxides and smelt the material into aluminum. The material must be heated to almost 3000°F for this process to occur. The processing of bauxite into aluminum results in large quantities of waste (called "mud") that contain traces of heavy metals and other hazardous substances. A by-product of the smelting process (called "potliner") contains fluoride and chlorine and must be disposed of as hazardous waste. Approximately 0.02 pounds of potliner are produced for every pound of aluminum.

Because aluminum has such a high embodied energy content (103,500 Btus at point of use), it is best applied where its light weight, corrosion resistance, and low maintenance can be used an advantage. Recycling aluminum requires only about 20% of the energy of refining bauxite into usable metal. Although the recycling of aluminum beverage containers is common, only about 15% of the aluminum used in construction is ever recovered.⁶

Bricks and Tile

Clay and adobe soil must also be mined. They are usually found in shallow surface deposits, and manufacturing is often done nearby, reducing extraction and transportation costs. With the exception of adobe, bricks and tiles must be fired to be useful building materials. The firing process exposes the formed clay to high, prolonged heat, producing a hard, water-proof, permanent brick or tile. The firing process can take hours or even days and requires a large amount of energy. Glazed bricks and tiles are fired twice: first to make the shape permanent and then to melt and adhere the glazed finish, which usually contains glass. The end product has much embodied energy but is also very long-lasting. Even without firing, properly maintained adobe bricks can last 350 years or more.

Petrochemicals

The building industry is highly dependent on materials derived from petroleum and natural gas. These are used in a wide range of products including plastics, adhesives for plywood and particleboard, laminated countertops, insulation, carpeting, and paints. Drilling for oil and gas is both hazardous and expensive. Heavy machinery is required, and contamination of the groundwater and soil is common.

Wood

Wood is the harvested material most commonly used in buildings and building products. Dimensional lumber is used in framing the majority of residential buildings and many commercial structures. Wood products such as plywood, particleboard, and paper are used extensively throughout the construction industry. Until recent years, the most common method of harvesting wood was clear-cutting, a process wherein all vegetation within a given area is removed for processing. Now, where clear-cutting takes place, lumber companies are required to replant the area.

Some lumber is now being produced on tree farms (“plantations”). However, replanting alone does not replace the natural biological diversity that existed before harvesting. Monoculture (same-species) plantings are particularly vulnerable to disease and insects. More companies now practice “selective cutting”: choosing only those trees large

enough or valuable enough to remove and leaving the surrounding vegetation intact.

Sustainable forestry practices include a professionally administered forestry management plan in which timber growth equals or exceeds harvesting rates in both quantity and quality. In addition, rivers and streams are protected from degradation, damage to the forest during harvesting is minimized, and biodiversity and fair compensation to local populations is emphasized.

Selecting Sustainable Building Materials

Criteria

An informal survey of building materials manufacturers conducted by the University of Michigan revealed environmentally sustainable replacements for use in every building system. Products selected from this survey illustrate the wide variety of available materials that are designed and manufactured with environmental considerations. The selection criteria include sustainability in regard to a wide range of environmental issues: raw material extraction and harvesting, manufacturing processes, construction techniques, and disposal of demolition waste.

Green Features		
Manufacturing Process (MP)	Building Operations (BO)	Waste Mgmt. (WM)
Waste Reduction (WR)	Energy Efficiency (EE)	Biodegradable (B)
Pollution Prevention (P2)	Water Treatment & Conservation (WTC)	Recyclable (R)
Recycled (RC)	Nontoxic (NT)	Reusable (RU)
Embodied Energy Reduction (EER)	Renewable Energy Source (RES)	Others (O)
Natural Materials (NM)	Longer Life (LL)	

Figure 3: Key to the green features of sustainable building materials.

Figure 3 is a chart of the criteria, grouped by the affected building life-cycle phase. This chart helps compare the sustainable qualities of different materials used for the same purpose. The presence of one or more of these "green features" in a building material can assist in determining its relative sustainability.

Pre-Building Phase: Manufacture

Waste Reduction

The *waste reduction* feature indicates that the manufacturer has taken steps to make the production process more efficient, by reducing the amount of scrap material that results. This scrap may come from the various molding, trimming, and finishing processes, or from defective and damaged products. For products with this feature, scrap materials can be reincorporated into the product or removed for recycling elsewhere. Some industries can power their operations by using waste products generated on-site or by other industries. These options reduce the waste that goes into landfills.

Pollution Prevention

The *pollution prevention* feature indicates that the manufacturer has reduced the air, water, and soil pollution associated with the manufacturing process, implying measures that exceed the legislative minimums required of manufacturers. These reductions may be achieved through on-site waste processing, reduced emissions, or the recycling of water used in the manufacturing process. Environmentally sound packaging is another pollution prevention feature, as the way in which a product is packaged and shipped affects the total amount of waste generated by the product.

Recycled Content

A product featuring *recycled content* has been produced partially or entirely of post-industrial or post-consumer waste. The incorporation of waste materials from industrial processes or households into usable building products reduces the waste stream and the demand on virgin natural resources.

Embodied Energy Reduction

The *embodied energy* of a material refers to the total energy required to produce that material, including the collection of raw materials. Any revision to a manufacturing process that saves energy reduces the embodied energy of the material. A

conventional material with a high embodied-energy content can often be replaced with a low-embodied-energy material, while still using conventional design and construction techniques.

Use of Natural Materials

Natural materials are generally lower in embodied energy and toxicity than man-made materials. They require less processing and are less damaging to the environment. Many, like wood, are theoretically renewable. When low-embodied-energy natural materials are incorporated into building products, the products become more sustainable.

Building Phase: Use

Reduction in Construction Waste

Many building materials come in standard sizes, based on the 4' x 8' module defined by a sheet of plywood. Designing a building with these standard sizes in mind can greatly reduce the waste material created during the installation process. Efficient use of materials is a fundamental principle of sustainability. Materials that are easily installed with common tools also reduce overall waste from trimming and fitting.

Energy Efficiency

Energy efficiency is an important feature in making a building material environmentally sustainable. Depending on type, the energy efficiency of building materials can be measured with factors such as R-value, shading coefficient, luminous efficiency, or fuel efficiency. The ultimate goal in using energy-efficient materials is to reduce the amount of artificially generated power that must be brought to a building site.

Water Treatment/Conservation

Products with the *water treatment/conservation* feature either increase the quality of water or reduce the amount of water used on a site. Generally, this involves reducing the amount of water that must be treated by municipal septic systems, with the accompanying chemical and energy costs. This can be accomplished in two ways: by physically restricting the amount of water that can pass through a fixture (showerhead, faucet, toilet), or by recycling water that has already entered the site. Graywater from cooking or hand-washing may be channeled to flush toilets. Captured rainwater can be used for irrigation.

Use of Non-Toxic or Less-Toxic Materials

Non- or less-toxic materials are less hazardous to construction workers and building occupants. Many materials adversely affect indoor air quality and expose occupants to health hazards. Some materials, like adhesives, emit dangerous fumes for only a short time during and after installation; others can reduce air quality throughout a building's life.

Renewable Energy Systems

Renewable energy systems replace traditional building systems that are dependent on the off-site production of electricity and fuel. Solar, wind, and geothermal energy utilize the natural resources already present on a site. Components that encourage daylighting, passive solar heating, and on-site power generation are included in this category.

Longer Life

Materials with a *longer life* relative to other materials designed for the same purpose need to be replaced less often. This reduces the natural resources required for manufacturing and the amount of money spent on installation and the associated labor. Durable materials that require less maintenance produce less landfill waste over the building's lifetime.

Post-Building Phase: Disposal

Reusability

Reusability is a function of the age and durability of a material. Very durable materials may outlast the building itself, and can be reused at a new site. These materials may have many useful years of service left when the building in which they are installed is decommissioned, and may be easily extracted and reinstalled at a new site.

Recyclability

Recyclability measures a material's capacity to be used as a resource in the creation of new products. Steel is the most commonly recycled building material, in large part because it can be easily separated from construction debris with magnets. Glass can theoretically be recycled, but is difficult to handle and separate at a demolition site.

Biodegradability

The *biodegradability* of a material refers to its potential to naturally decompose when discarded. Organic materials can return to the earth rapidly, while others, like steel, take a long time. An important consideration is whether the material in question will produce hazardous materials as it decomposes, either alone or in combination with other substances.

Examples

Site and Landscaping

Recycled plastic has been developed into a wide range of landscaping products. Plastic lumber is widely used in outdoor furniture and decking. This lumber is made by shredding and reforming post-consumer plastic containers such as pop bottles and milk jugs. Some brands incorporate waste or recycled wood as well. Plastic lumber has advantages over wood in that it is impervious to moisture and will not warp, rot, or check. It is available as dimensional stock, or in a wide variety of manufactured garden furniture and accessories. Traffic stops and bumpers are also being made from recycled plastic, replacing concrete and asphalt.

By recycling plastic, a major contributor to landfill waste is put to a new use and raw materials are conserved. Water conservation also results, because recycling plastic requires less water than processing new plastic, wood, or concrete. When used in soil erosion control products, recycled plastic also prevents topsoil loss and the resulting consequences of increased water turbidity. The recycled plastic products can themselves be recycled when their useful life has ended. Because the material is inert, it will not degrade into toxic substances if discarded in landfills.

Landscape pavers made from recycled plastic can be used in place of bricks. Pavers are produced in a range of colors and styles, and can be used to replicate any traditional brick pattern. An open-grid rigid plastic mat has also been introduced (see **Figure 5**). Unlike paving, this product allows grass to grow in the open areas of the grid and permits water to drain through it. It is ideal for use in playgrounds and provides a rigid surface for wheelchair access onto lawns.

MP	BO	WM
WR		
	WTC	R
RC	NT	RU
EER		
	LL	

Figure 4: Green features of plastic lumber and pavers.

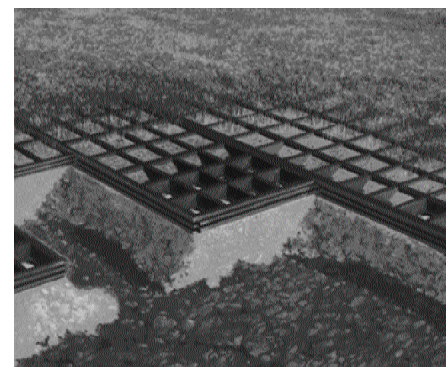


Figure 5: Porous pavement system made from recycled plastic. Excellent for providing wheelchair access to parks and playgrounds.

MP	BO	WM
WR		
		R
RC		
EER		O
	LL	

Figure 6: Green features of recycled asphalt.

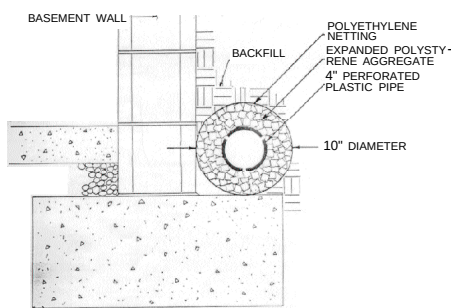


Figure 7: Prefabricated drainage system, using EPS chips instead of gravel.

MP	BO	WM
WR	EE	
	LL	

Figure 8: Green features of insulated foundations.

Conventional paving materials like asphalt are also beginning to incorporate recycled materials. Old asphalt is ground up, reheated, and used to repave surfaces—this is now standard in highway and street construction. Recycled rubber from tires, ground glass, and plastic is being used in the asphalt mix, significantly reducing waste. These materials also provide greater durability than traditional paving methods, meaning longer life and less frequent repaving. This reduces the materials and energy used over the lifetime of a project.

A new type of drainage system replaces gravel, which must be quarried, with pieces of polystyrene, which would otherwise be dumped into landfills. The polystyrene can simply be used in place of gravel, and is inert in the environment. One prefabricated system combines perforated drainage pipe surrounded by plastic chips, held in place with plastic netting (see **Figure 7**). The light weight and prefabrication save time and labor during construction. The needs for gravel trucks is eliminated, cutting down on air pollution. Either type of product can be used around foundations, in drainage fields, parking lots, and anywhere traditional site drains are used.

Foundations

Poured-in-place concrete and concrete block foundations have long been a staple in the construction industry. They provide thermal mass insulation and have a long life. Significant improvements have been made that reduce the installation waste produced on-site and increase the insulation value of these foundation systems. These systems are collectively known as super-insulated foundations.

Two of the major drawbacks of poured-in-place concrete are the time and materials required to erect formwork. Generally, plywood and dimensional lumber are used to construct the forms, then discarded after the concrete has set. This essentially wastes the energy involved in producing the wood and plywood, which can be high given the drying of wood and the petroleum used to make the binding resins. Furthermore, because of the resins, the plywood is difficult to recycle and usually ends up in a landfill. Permanent formwork has been developed using rigid plastic foam (see **Figure 9**). The foam sheets or blocks are used to contain the concrete during pouring, and improve compressive strength by retaining the heat produced as the concrete sets, resulting in a 25% stronger wall with an insulation value equivalent to R22–R24.

The holes in concrete block, designed to reduce weight and make handling easier, are a potential insulation site. Loose-fill insulation is often used to fill the holes as the wall is constructed. A new technique customizes the block's hollows and uses tight-fitting, rigid foam inserts (see **Figure 10**). These inserts come into contact at the ends of the block, providing a continuous thermal shield throughout the length of the wall.

In both styles of super-insulated foundations, the insulation value of the foam becomes integrated into the total R-value of the finished foundation. This is especially useful in residential construction, where basements are often converted to habitable space. The foam production process does not use fluorocarbons and generates only pentane. This is generally burned off and not released into the atmosphere.

Structural Framing

As the price of virgin wood rises and the quality declines, steel framing is becoming an economical alternative to wood stud framing in residential construction. It has been long favored in commercial construction for its ease of assembly and uniform quality. Until recently, the price of steel studs and the customized nature of home design made its use impractical. However, because steel is stronger, fewer members are needed to support the same load. Although steel has a very high embodied energy content, it can easily be reused and recycled. One major drawback to the use of steel in exterior walls is its conductive nature: more insulation is needed to provide the same R-value as a traditional wood stud wall.

Joist and truss systems, using fabricated lumber or a combination of dimensional lumber and steel, are also moving from commercial to residential construction. Open-web joists and trusses (see **Figure 12**) are more economical than traditional 2x12 wood members, and the manufacturing system ensures even quality. Wood, a natural product, is subject to a wide range of variables that can affect its structural strength. In these systems, less lumber, especially 2x4 material, is used overall, and metal webs can be made of recycled steel. Improved sound ratings are also a benefit of these systems.

Lumber recovered from demolition is being used in renovations and new construction, for both environmental and aesthetic reasons. Timber-framed structures are often dependent upon recycled wood due to the difficulty in obtaining large logs.

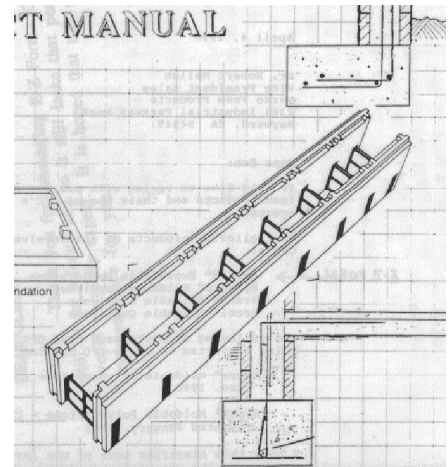


Figure 9: Permanent formwork for poured concrete walls made from rigid plastic foam.



Figure 10: Concrete blocks with foam inserts.

MP	BO	WM
		B
		R
RC	NT	RU
NM	LL	

Figure 11: Green features of steel framing.

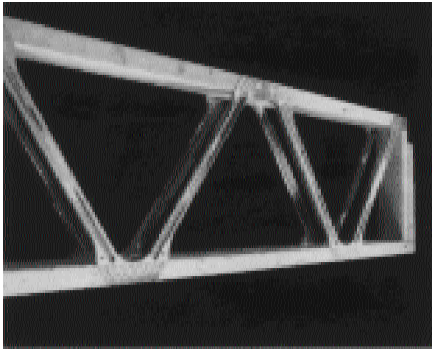


Figure 12: Wood and steel open-web joist.

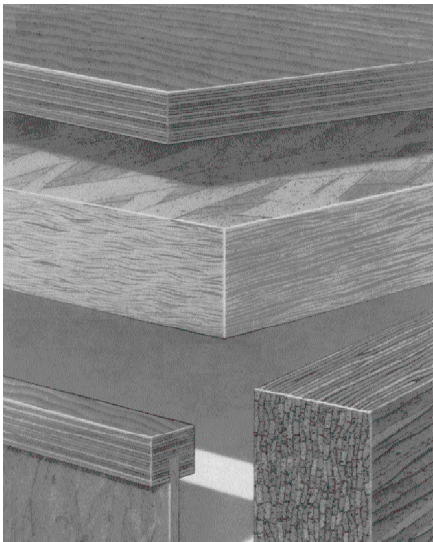


Figure 13: Composite lumber made from waste wood.

MP	BO	WM
WR	EE	B
P2	WTC	
RC	NT	
EER	RES	
NM	LL	

Figure 14: Green features of straw-based sheathing.

Timbers, flooring, trim, and paneling are salvaged from the demolition of old houses and barns, then cleaned up and resawn if necessary. The resulting product reduces landfill waste and is nontoxic, recyclable, and of better quality than commercially available virgin lumber today.

Building Envelopes

Plywood and oriented strand board are the conventional sheathing materials used to enclose buildings once the frame is in place. Both materials are wood-based: plywood consists of large sheets of veneer sandwiched together, while strand board incorporates waste wood particles (see **Figure 13**). The resins used to bind the wood fibers together are petroleum by-products. Volatile, sometimes hazardous, chemicals evaporate from the boards over the life of the product, contributing to indoor and outdoor air pollution. Therefore, these materials are best used where they will be covered or sealed in by other building products, such as siding and drywall.

Alternatives to wood-based sheathing and toxic resins are being developed from agricultural waste products. Straw paneling, assembled with water-based adhesives and fiberglass tape, is available for use as exterior sheathing. Like the wood in strand board, the straw is shredded and compressed to form a lightweight, monolithic panel that can be assembled into roof and walls with specially developed latex adhesives and coatings. This replaces conventional materials such as wood, steel, and cement. This product turns agriculture waste that is usually burned (contributing to air pollution) into a valuable commodity and preserves other natural resources. The product is nontoxic, biodegradable, energy efficient, and long-lived.

Wood, aluminum, or vinyl siding is generally installed over sheathing to protect it from the weather. All three materials have disadvantages: wood is difficult to maintain and increasingly scarce; aluminum and vinyl both have high embodied energy and are generally unsuccessful in imitating the aesthetic qualities of wood. However, both can be composed primarily of recycled materials. Alternative siding materials are also available, ranging from other products that are imitations of wood to advanced stucco materials.

Fiber-chemical siding and shingles imitate the look of wood without the maintenance, and without the high embodied energy content of aluminum or vinyl. Formed of fiberglass or

plastic resins, they are nontoxic, noncombustible, lightweight, and moisture resistant.

Enhanced stucco materials do not hold water. Their greater flexibility in comparison to traditional stucco prevents cracking, providing a longer life. The material is easily applied by spraying or troweling. A polymer sealant in the mix allows the walls to breathe, and the color, which is incorporated into the mix, won't fade. The product is available in a variety of textures and custom color and can be applied over many substrates. A mesh of wire or fiberglass is attached to the substrate, then covered with the stucco material. Rigid foam insulation systems may also be installed, then covered with stucco. This system is quicker and easier to install than traditional stucco, which requires many coats and is subject to cracking. Supplementing the coating with rigid polystyrene foam can yield an insulation value of R-21 without increasing wall stud depth.

Structural Envelopes

Structural envelopes combine the two-step process of framing and infill. The most common example is true masonry construction, where stone, brick, or concrete masonry units (CMUs) provide the structural strength of the building, and are not used as veneers or infill between wood or metal framing members. Stone, which must be quarried, is expensive and difficult to transport, so it is almost never used in solid masonry today. Brick and CMUs are still used structurally, generally in residential or light commercial applications.

Although clay for brick must be quarried, clay is abundant and can be easily obtained from surface deposits. Bricks are commonly manufactured and sold near the quarry site, reducing transportation costs and air pollution. The firing process imparts a high embodied energy content. Most brick is colored with organic pigments, but some glazing materials and pigments can be hazardous to the environment. CMUs do not require firing but are often kiln-dried. The burning of limestone to produce the lime used in cement and mortar also consumes a great deal of energy. However, bricks and CMUs are long-lasting materials, have a thermal mass insulation value, and are inert if discarded in a landfill. They can also incorporate industrial waste products such as fly ash, glass, plastics, even hazardous waste.

MP	BO	WM
	NT	
	LL	

Figure 15: Green features of fiber-chemical siding.

MP	BO	WM
	EE	
RC	NT	RU
		O
NM	LL	

Figure 16: Green features of bricks and CMUs.

Traditionally thought of as building types limited to the southwest U.S. and other arid regions, adobe and rammed-earth construction is undergoing a renaissance. Globally, 40 percent of the world’s population is housed in earthen shelters. Materials can be obtained locally, even on the building site itself. They are nontoxic, biodegradable, and can incorporate waste from manufacturing or installation. Plastic binders in the earth-mix and improved stucco systems have increased the water resistance of these structures, allowing earth construction to spread beyond arid regions to the damp climates. Adobe and rammed-earth are nonpolluting, nontoxic, recyclable, highly energy-efficient, and, when properly constructed, long-lived: some structures found today are 350 years old.



Figure 17: Structural building panels.

Super-insulated stress-skin panels (see **Figure 17**) are giant sandwiches of rigid insulation encased in plywood or strand board. Some brands of panels are load-bearing and can be used in the structural system. Standard sizes are four feet wide with various lengths up to 24 feet. The panels connect easily, often with a tongue-and-groove feature. Because the wall is uniform, insulation is more complete. Built-in channels carry electrical and plumbing conduits.

The use of these panels offers significant waste reduction, time and labor savings, and long life. The foam core can be made with recycled expanded polystyrene, and the wood used in the plywood or strand board comes from renewable crop lumber and mill waste. Because there is no airflow through the panels, windy days have less of an effect on the heating and cooling costs. Energy savings of 40–60% over 2x6 stud constructions are common. Because many of the materials used in the stress skin panels are recycled, far less energy is required to produce the panels than other building materials.

MP	BO	WM
WR	EE	
P2		R
RC	NT	
		O

Figure 18: Green features of recycled polystyrene.

Insulation

Thorough insulation is one of the best ways to reduce energy consumption and building operating costs. Insulation also offers acoustic benefits. In contemporary construction, the familiar fiberglass insulation has been supplemented by hi-tech polymers and old-fashioned cotton.

Rigid foam insulation applied in panels in new construction can offer a very high R-value per inch of thickness. The energy saved by installing these materials far exceeds the

energy consumed in production. The R-value is not affected by moisture, and the plastic foam is not edible by insects.

Because of the high embodied energy content of plastics and the potential hazards of volatile chemicals outgassing from them, a return to organic insulation has begun. Several brands of insulation currently on the market are made from recycled newspapers (see **Figure 19**) or recycled textiles. They are available in batting, loose-fill, or spray-on applications.

A spray-applied thermal and acoustic insulation made from recycled paper fibers, with an acrylic-based adhesive, offers an R-value of 4.54 per square inch. Using 100% post-consumer paper conserves trees, water, and landfill space. The acrylic binder is non-toxic and keeps the insulation in place, preventing eventual settling that would reduce R-values. The spray-on application also allows the insulation to easily fill in around pipes and electrical outlets, unlike batting. Flame retardants and insecticides are added to the fibers in the manufacturing process.

Cotton insulation is made from recycled textile fabrics that normally end up in a landfill. R-values are available from R-11 (3.5" thick) to R-38 (12" thick). The process used to recycle the cotton uses very little energy, is nontoxic, and can incorporate waste materials. No air pollutants or harmful emissions result from the production process. As with cellulose insulation, flame retardants and insecticides are added to the fibers in the manufacturing process.

Glazing

Windows and skylights allow daylight to reach the interiors of buildings, reducing the need for artificial light. Operable units assist in ventilation and cooling, reducing or eliminating the need for mechanical equipment. However, windows are the weakest point in the building envelope in terms of energy loss, and much research has gone into developing more efficient window systems. Improved glazing techniques offer low-emissivity glass and inert gas-filled air spaces between panes. The window sash and frame have also been improved with added insulation and seals.

Heat gain through direct solar radiation is the easiest to prevent, by providing shading devices and using low-emissivity (low-E) glass. Low-E glass acts as a radiation mirror, reflecting

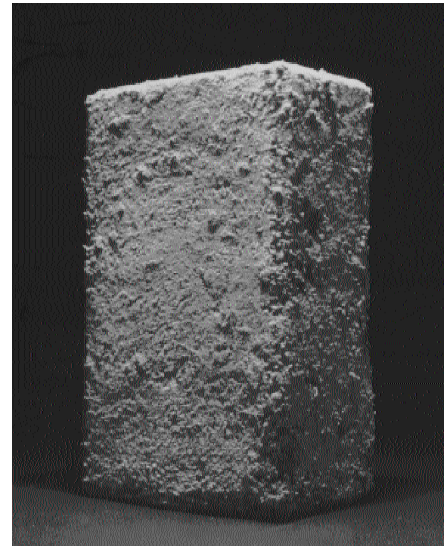


Figure 19: Insulation made from recycled newspapers.

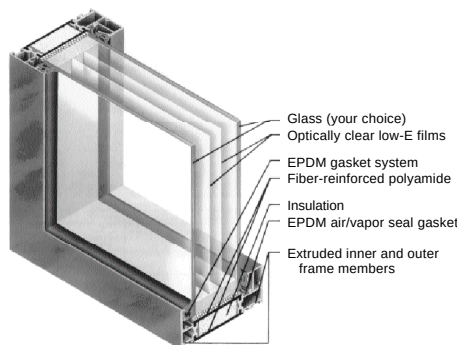


Figure 20: Double-paned glass with films forming additional airspaces and UV protection.

infrared (heat) rays back to the source. This prevents solar heat gain in the summer and retains heat within the building during the winter.

Heat loss or gain through windows also occurs due to conduction. Double- and triple- paned glass use an airspace between panes to block the transfer of heat (see **Figure 20**). By filling the air space with an inert gas such as argon, the conductivity is further reduced. The airspace can also be used to hold low-E films or integrated shading devices. Glazing is available with a solar control film encapsulated within the glass layers. The film divides the airspace, creating two airspaces and further reducing conductivity. The transparent film allows daylight to enter the room but blocks ultraviolet radiation (UV). UV is responsible for fading and deterioration of textiles and is a primary cause of skin cancer. The film reduces heat gain and saves energy during cooling seasons while it maximizes daylighting. Nontoxic materials are used to avoid pollution during manufacturing, and the film harmlessly biodegrades when exposed to the environment.

Vinyl and aluminum windows are popular for building exteriors because they require little maintenance. Often, the window sash and frame are constructed of wood, then clad with aluminum or vinyl. The wood provides a better insulating value than vinyl or aluminum alone and adds strength to the frame. These windows are particularly desirable in residential construction, as the wood can be left exposed on the interior of the window. High-quality lumber is required, even in the areas not exposed, in order to control warping. Steel is sometimes used in the window frames for added strength. Both cladding materials, especially aluminum, have high embodied energy contents.

Fiberglass window systems offer advantages over aluminum or vinyl. Like vinyl and aluminum, they are low maintenance, but they will not warp or rot. In addition, they have a longer life and a lower embodied-energy content than vinyl or aluminum. They require no wood or steel for framing, and the frames are filled with polystyrene foam for improved insulation. Silicone, not steel, spacing bars are used between multiple panes of glass. The fiberglass sash is more receptive to the airtight sealing required when using argon gas-filled airspaces between panes. Because fiberglass, being composed chiefly of strands of glass, has a thermal expansion coefficient

similar to glass itself, the materials expand and contract at approximately the same rate: this means that there is less stress to the sealants and the material of the windows as a whole. Although there is currently no recycling process for fiberglass, there is the potential for reuse, due to the product's long lifespan.

Skylights (see **Figure 21**) and skyroofs are increasingly popular in both residential and commercial construction as a way of bringing daylight deep into the interior of a structure. New sealants and flashing techniques have reduced the leakage problems common in older installations. Operable skylights are excellent for ventilation. One disadvantage is the heat gain associated with large panes of glass, particularly on roofs where there are no overhangs to reduce direct sunlight. Many manufactured skylights therefore incorporate a shading device that is either manually or electronically controlled.

An alternative to large panes of glass is a device that can be installed in the ceiling and up through the roof. Periscope-like, it has a sunlight-gathering acrylic dome on the roof, internal reflectors, and a diffuser lens that emerges within the room. This brings the advantages of natural daylight into a space without the heat gain of traditional skylights. The size of the tube allows it to be installed between roof rafters, so no cutting and rerouting of structural members takes place. The device is designed for the do-it-yourself homeowner but has potential for use in commercial installations. A 13"-diameter tube provides a summer noon output equivalent to 600 incandescent watts of lights and illuminates up to 150 square feet.

Roofing

Properly installed roofing is vital to the structural integrity of a building. Given the large surface area of most roofs, and their exposure to the elements, the choice of roofing materials significantly affects the energy-efficiency of a building. Integrated sheathing and insulation, pre-tapered for flat roofs, can also have a significant impact on the energy efficiency of a structure (see **Figure 22**). Because roofing materials and labor are expensive, a long roof life reduces operating costs and material waste and saves energy.

The roofing material with the longest life span, slate, is also the most expensive and difficult to install. Its weight requires a reinforced roof structure, and the material is difficult to



Figure 21: Operable skylights provide daylighting and natural ventilation.

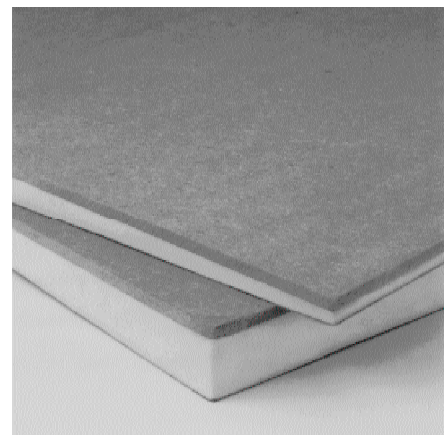


Figure 22: Integrated sheathing and insulation, pre-tapered for flat roofs.

work with, requiring skilled labor. Yet a slate roof can last hundreds of years. The aesthetic quality of slate is also popular: homeowners and businesses alike appreciate the texture and implied richness.

New imitation slate materials (see **Figure 23**) offer a longer life than asphalt or other shingles, at a fraction of the cost of real slate. The tiles are produced from 100% recycled, re-engineered materials, including rubber and cellulose. The material is cast into a variety of traditional slate patterns, using molds made from 100-year-old slate to accurately reproduced the texture and appearance. Because the material is lightweight, no structural reinforcement is needed. Waste reduction is considered during design. A small amount of waste results from installation, and all waste can be recycled into new product. The material is partially foamed, and the resulting airpockets add insulating value. The tiles can be cut with ordinary knives, making installation as easy as asphalt. The product has a 100-year life expectancy.



Figure 23: Fiber-resin composition roofing tiles cast from 100-year-old slates for an authentic look.



Figure 24: Shingles made from recycled aluminum.

Weatherproof shingles manufactured from recycled aluminum alloys combine the look of wood shakes with the durability of metal (see **Figure 24**). Unlike wood, they are also fireproof. The aluminum reflects radiant heat, reducing summertime attic heat gain by 34% in comparison to standard asphalt shingles. The 12x24" aluminum panels interlock on all sides for wind resistance and come with a 50-year transferable warranty. All production and installation scrap can be recycled, as can the product itself when its useful life has ended. Because of aluminum's light weight, the shingles can often be installed directly over an old roof, eliminating the need for stripping and disposing of old asphalt shingles.

Interior Finishes

Interior walls can be finished in a variety of ways. Generally, gypsum board or wallboard is used to enclose the wall studs; then paint, wallpaper, or other decorative treatments are applied. Largely in response to California's strict air-quality laws, which virtually prohibit traditional oil-based paint because of outgassing, there is now a wide range of paints, stains, and finishes that are non-toxic and easy to clean up. Casein paint, a technology at least 5,000 years old, is made from natural pigments, milk solids, lime, talcum, and salt. Generally sold dry, it is mixed with water as needed, reducing waste.

Sisal wall coverings offer a natural, durable, and sound-absorbent alternative to vinyl and paper wall coverings. Unlike vinyl, sisal fibers are a renewable resource; unlike paper, large amounts of water are not consumed in the manufacturing process. Sisal generally contains no toxic pigments from dying or printing and is ideal for covering rough, uneven walls.

Architectural quality wood veneer paneling is available from certified forestry sources, which employ sustainable harvesting and planting techniques. This is particularly important when choosing exotic or tropical woods for a project. Two veneer cores are available: a nontoxic, honeycombed recycled paper product; or a non-formaldehyde-based particle board. It comes in 4x8 sheets and custom dimensions, and is suitable for interior paneling and furniture. Veneer is an extremely efficient use of wood products.

Flooring

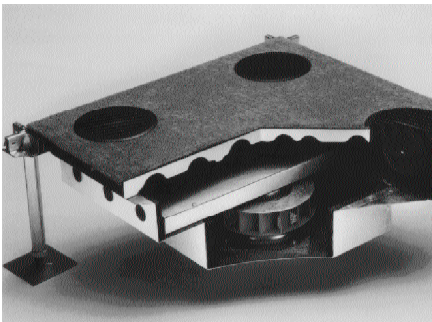
Finished flooring is available in a wide range of materials and styles. The decision about the type of flooring (e.g., carpeting versus tile) is generally determined by the program of the building. However, within each category of flooring are materials that can be judged for toxicity, embodied energy content, and other environmental factors.

Traditional wool carpeting, while non-toxic and made from a renewable resource, has not been able to compete economically with cheap petroleum products. The majority of carpeting and carpet sold today is made from petrochemicals. Not only is petroleum a dwindling natural resource, but the final products can continue to emit volatile gases long after installation, becoming a health hazard to building occupants. The health risk is compounded when petroleum-based adhesives are used to install the backing and carpet.

Natural fiber carpet cushions can be made of jute felt: recycled burlap or virgin jute fiber with some animal fibers (camel or cashmere) added for softness and resilience. Jute is a renewable crop material, with a very little energy required in the growth and manufacturing process. It biodegrades upon disposal, and can be recycled. Coatings help protect the fiber from mildew growth. The material has a higher density and longer life than comparable synthetics.



Figures 25 and 26: Access flooring allows electrical configurations to be easily modified when the building's use changes (top). Some systems have integrated ventilation modules (bottom).



Another available carpet cushion is made from recycled, ground-up tire rubber. The disposal of automotive tires in landfills creates an environmental and health hazard. By reusing the rubber from tires, landfill waste is reduced, as is the need for new petroleum products. Tires are also being used to make floor tiles and interlocking pavers. The natural resilience of rubber makes this flooring ideal for health facilities and areas where people stand a lot. The material is slip-resistant and meets American with Disabilities Act safety guidelines.

Linoleum, a product made of linseed oil, compressed cork and wood flour, resin binders, and pigments, is a low-tech and low-energy alternative to vinyl. Because linoleum is made of natural, non-toxic materials, any VOCs it emits are primarily from the oxidation of the linseed oil; these are classified as fatty acids. The raw materials of linoleum are primarily from natural, renewable resources that are cultivated without endangering the environment.

There has been renewed interest in natural cork tile flooring because of indoor air quality issues. Cork is harvested from the bark of cork trees, which shed bark naturally in a seven-year cycle. The many sustainable features of cork include shock absorption, acoustic and thermal insulation, and long life. Flooring made of cork requires sealing with wax or polyurethane. Both linoleum and cork are very long-lasting.

Ceramic tile is another flooring material noted for its long life, even in high-traffic areas. It is nontoxic, stain-resistant, and inert when discarded in landfills. Glazed and unglazed tile can be made using recycled glass as filler, which allows the firing temperature to be lowered.

Plumbing

Water conservation issues and overburdened septic systems have led to a reexamination of our traditional plumbing methods. There have been three areas of focus: reducing fresh water use; recovering and reusing graywater; and reducing the amount of sewage entering the municipal waste stream.

Several recent toilet designs have emphasized low water consumption. Generally, these toilets use differential air pressure instead of water and gravity to transport sewage. Compared to a standard five-gallon toilet, a vacuum-assisted one requires

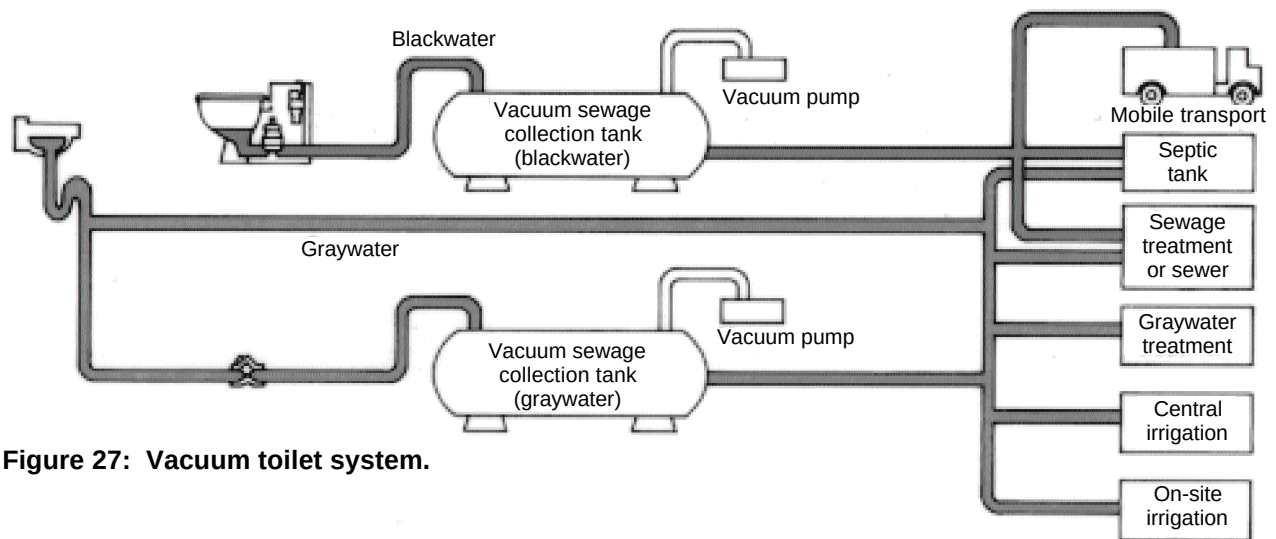


Figure 27: Vacuum toilet system.

only three pints of water. The reduced sewage means smaller pipes can be installed, reducing the cost of materials.

Vacuum-assisted toilets (see **Figure 27**) also have the advantage of being able to flush horizontally or upward, allowing maximum flexibility in the routing of pipes. Because no slope is required, as in gravity systems, floor to floor spacing can be reduced, again saving materials. Venting stacks are also eliminated. Two parts compose the system: the bowl and a vacuum tank or pump. One vacuum tank can serve several fixtures, or even several buildings. The atmospheric pressure causes the “flush” when the valve to the vacuum tank is open. Sewage can then be stored for discharge at off-peak times.

Other toilet systems route the sewage to a central holding tank, where it is composted. Consequently, there is no burden on municipal water treatment facilities. The compost can be used as lawn fertilizer; tanks incorporate odor-control devices.

Ventilation

Energy recovery ventilators are designed to bring in fresh air and exhaust stale air, while recovering up to 85% of the energy that was used to heat or cool the outgoing air. The incoming and outgoing airstreams are prevented from mixing by an energy transfer disc that moves heat from one stream to the other (see **Figure 28**). Moisture is removed and released by a silicon coating on the disk (unlike humidifiers, there is no drain pan and thus no bacterial growth). In winter, the ventilator can use electricity to pre-warm air; even without electricity, it recovers enough heat to warm incoming air up to 60% of room temperature.

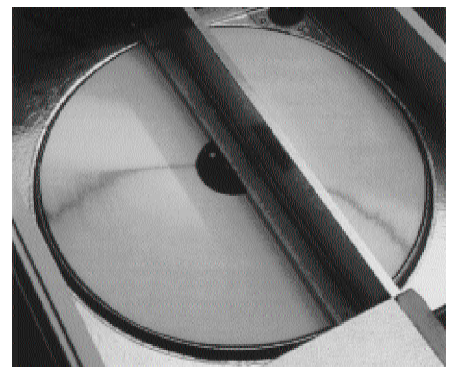


Figure 28: Heat and moisture exchange disk in a heat-recovery ventilator.

Application

Guidelines

The process of specifying environmentally friendly building products is no different than that for conventional building products: the type of materials needed must be determined, data must be gathered on comparable materials, and products must be evaluated. Environmental considerations need not be the only, or even most important, factors when selecting building materials. The key consideration is the material's appropriateness for the intended function. The longevity or insulation value of certain materials with high embodied energy content can sometimes justify the environmental costs of their manufacture. Overall, becoming more involved in materials and systems choices means the architect gains more control over the quality and sustainability of the finished building.

Determining Need

Considering materials in more general terms based on function (e.g., "flooring" over "carpeting") helps open up the possibility of alternative materials. Floor coverings are available in a wide range of materials—is carpeting necessary for the area in question, or would more durable tile be a better choice? If carpeting is deemed necessary, can wool be used instead of petrochemical-based fibers? In many cases, the performance of natural materials meets or exceeds that of synthetics, at a much lower environmental cost.

The quantity as well as type of materials to be used in construction are important. CAD systems with integrated spreadsheets make it much easier to calculate the required square footage or volume of materials. This helps the architect focus on the materials with the largest potential impact on the environment. Use environmentally friendly materials particularly when the volume of material needed is large, is exposed to air, or comes in contact with users. By using high-embodied-energy materials only where needed for their specific qualities, natural resources are preserved and pollution is reduced. Aluminum, for example, should be used only where its light weight and anti-corrosion characteristics cannot be matched by another material. Using recycled aluminum is even better.

Plywood used as sheathing is generally sealed behind drywall, where glue emissions cannot enter the breathable air. VOC-emitting materials used in interiors, like plywood for furniture, can be sealed in plastic laminate or with a painted finish, reducing or eliminating outgassing. However, this adds to the cost, and the laminate or paint can create their own outgassing problems. A better choice would be plywood made without glues that outgas.

Determining how much of a material and where will be used is the first step. The timing of the installation process is also important. Materials that are to be applied with adhesives that outgas should be installed well in advance of building occupancy, and the ventilation rate of the building should be increased for at least the first year of occupancy. Repair or replacement of such materials should be scheduled to coincide with a building's downtime (over the holidays, for example) so the impact is reduced.

Analyzing Products

The data-gathering part of the material-selection process is currently the most difficult, as sustainable building materials compose a small percentage of the market. The American Institute of Architects has published its *Environmental Resource Guide* to help architects select general types of products based on an analysis of their raw materials. Manufacturers' product data sheets are still the best source for specific brands, but it must be recognized that these are promotional materials. Product specification sheets, produced for marketing purposes, may not provide objective data, and the data may not be easily comparable with competitive products. **Architects are in a position to encourage the production of a wider variety of sustainable materials by contacting manufacturers for more specific information and refusing to specify materials made through highly polluting processes.** Insist that product data sheets list the chemicals that are used in the manufacturing process or that will be emitted by a material over time. Fire safety is also an issue, as many otherwise benign substances (like foam rubber) can become toxic when exposed to high heat or flame. Contacting manufacturers for more specific information serves two purposes: it increases the architect's knowledge base of materials, and it makes the manufacturer aware of interest in sustainable materials. Only through knowledge of the entire life cycles of otherwise comparable

building products can an intelligent, informed choice be made. By insisting that manufacturers reveal the toxicity levels and environmental impact of the manufacturing process, architects can also apply pressure on manufacturers to make their materials and manufacturing methods more sustainable.

Evaluating Performance

Some sustainable building materials rely on new technology, others reinvigorate centuries-old methods. The latter have a track record that makes performance easier to anticipate and evaluate. New technologies require testing over time. Advice from other architects and building owners who are using these new technologies can assist in determining their long-range effectiveness. Regular post-occupancy studies of buildings — conducted periodically through a building's life — are also extremely valuable in determining how well a new material functions and the ways it affects the comfort of building occupants. This information, when shared with other architects and building industry professionals, can become a powerful tool in advocating the use of sustainable materials.

References

American Institute of Architects. *Environmental Resource Guide Subscription*. Washington: American Institute of Architects, 1992.

Dell'Isola, Alphonse J. , and Stephen J. Kirk. *Life Cycle Costing for Design Professionals*. New York: McGraw-Hill, 1981.

McHenry, Paul Graham, Jr. *Adobe and Rammed Earth Buildings: Design and Construction*. New York: John Wiley, 1984.