Green engineering

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Last updated: 2008

DOI: https://doi.org/10.1036/1097-8542.YB080170 (https://doi.org/10.1036/1097-8542.YB080170)

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Green engineering is a much-needed approach to transform existing engineering disciplines and practices to those that promote sustainability. The concept of sustainability is to develop and implement technologically and economically viable products, processes, and systems that meet the needs of humanity, while protecting the environment. Green engineering is governed by the following principles:

1. Use the least amount of energy to achieve any given task.

2. Generate as much energy as possible using renewable resources.

3. Generate the least amount of pollutants and by-products during energy generation.

4. Use renewable and biodegradable materials to a maximum extent for building structures and fabricating products.

5. Reduce waste during construction and fabrication.

6. Design structures and products to maximize their life spans and minimize maintenance.

7. Design for easy deconstruction and facilitate the reuse of components and materials from obsolete structures and products in new construction and fabrication.

8. Make the least impact on the environment.

The obvious question is: Why are these principles not followed? The answer is: Because of economics, convenience, ignorance, and affluence, with economics playing the major role. For example, thermal power plants are still a more economical source for electrical energy compared to solar energy. However, the depletion of raw materials and the cost of controlling pollution and by-products are resulting in a steady increase in the cost of electricity produced by thermal power plants. This, in combination with the improved efficiency of solar cells, is making solar cells a viable alternative. Similar arguments can be made for all the other principles. Another example is the use of steel versus timber for structures.

Industrialization has created a demand for large factory and office buildings that cannot be built with timber and bricks. Even though steel consumes much more energy to produce and fabricate, it has to be used to construct tall buildings and cover long spans. In this case, the economics of doing business and crossing large rivers takes priority over the consumption of energy.

In the area of energy production, the fraction of energy produced by renewable resources is still very small. The popular sources are coal, natural gas, oil, and nuclear. Hydroelectric power plants are a long-standing renewable source. The growing sources of energy production are solar and wind. Fossil fuels generate carbon dioxide and large amounts of residues, such as fly ash and bottom ash. Nuclear power plants generate less waste, but, it is very expensive to dispose of nuclear wastes. Philosophically, most of the energy we are using came from the Sun. For example, coal, oil, oil shale, and tar sand were produced over millions of years from forest growth. If we could harness solar radiation, then most of the world's energy needs could be met. To achieve this, the efficiency of solar cells has to be increased considerably. It is estimated that the Sun provides about 120 quadrillion watts of energy daily, while worldwide consumption is about 13.5 trillion watts per year.

In the area of energy consumption, buildings and other infrastructures consume the major share. If the consumption for maintenance is included, the energy consumed by the building industry is estimated at 40%. The other major consumer is transportation. The transport of people and goods around the world is steadily increasing, and economic growth in Asia could accelerate this trend.

Buildings and infrastructures also consume the lion's share of materials. The most common construction materials are concrete, asphalt, steel, and clay. Timber is used widely in North America and in some parts of Australia. It is estimated that 12.5 billion tons of concrete are used annually and that it will be the dominant structural construction material for the near future. Portland cement, the most expensive ingredient in concrete, is produced worldwide, with the production cost ranging from (U.S.) $0.07 to $0.15 per kilogram. Almost every country in the world has the expertise for using this material, including design, fabrication, and maintenance. However, cement production results in the emission of carbon dioxide, which is a major drawback. Asphalt is a by-product of oil conversion to various fuels, and its use parallels that of oil. Timber is the only renewable structural construction material, but it is available in large quantities only in a few countries such as the United States and Canada. Steel consumes the most energy to produce but has mechanical properties that cannot be matched by any other structural material. Therefore, its use will continue at the current or slightly accelerated rate over the next few decades, especially in developing countries like China and India.

Built environment

The built environment uses the majority of the world's nonrenewable and much of its renewable material resource as well as contributes significantly to pollution, habitat destruction, and other forms of environmental damage. As the developing world's economies continue to grow, resources will be depleted even faster and exhausted sooner.

The National Science Foundation (NSF) of the United States supports research for developing building systems that are compact, minimally intrusive of the natural environment, resilient, economical, and easily recyclable, as well as systems that minimize the use of nonrenewable materials and nonrenewable energy. Specific research projects focus on developing pervious pavement that meets strength and durability requirements and is easily recyclable. Pervious concrete is an alternative paving material that is being considered as a best management practice for stormwater runoff and nonpoint source pollution control. NSF sponsored a project by the University of South Carolina for developing and implementing pervious concrete on several roads throughout South Carolina. The demonstration sites allowed researchers to gather data on the performance of this highway material.

Another renewable material being evaluated is recycled tires used in manufacturing sidewalk tiles. These sidewalks provide a surface that is more durable than traditional concrete sidewalks, since cracks caused by root growth do not occur because the material can flex. Compared to concrete, rubberized sidewalks provide a softer surface for running and walking.

On the larger scale of civil-built infrastructure, there is continued research on sustainable systems. For example, researchers are working on better systems for integrated water use for individual structures such as the reuse of so-called greywater in irrigation as well as rain collection and use in heating and cooling. Additional research includes developing local electrical generating systems and the means of connecting them to the larger grid.

Environmentally friendly materials

Research to develop novel bio-based products for use in various applications lies in the larger scope of renewable materials. Bio-based materials include industrial products, but not food or feed, made from renewable agricultural and forestry feed stocks, including wood, wood wastes and residues, grasses, crops, and crop by-products. Such eco-friendly biomaterials are desired for their recyclability and triggered biodegradability. Applications include natural fiber–reinforced composites, which could replace artificial fibers such as carbon and glass in various applications in the automotive industry. Researchers at Daimler-Chrysler have developed a plant-fiber-based material that has reduced the weight and cost of insulation in car door panels.

Energy devices

Another area of green engineering is the development of materials and processes that are biomimetic in nature. Researchers from the Massachusetts Institute of Technology, the U.S. Naval Research Laboratory, and the University of Tennessee have mixed biology and electronics in solar cells that use photosynthetic spinach leaf molecules or photosynthetic bacteria to convert light to electricity. Potentially, the method could be used to fabricate low-cost solar devices on plastic and other thin, flexible surfaces using inexpensive spray-on techniques.

Environmentally friendly manufacturing processes

Manufacturing and assembly processes are active areas of green engineering. The chemical process industry is developing methods for creating products necessary for daily life that do not cause collateral damage to the environment or society as a whole. Another area of interest is in disassembly of electronic components for reuse. By embedding a desired disassembly process in the products, disassembly is achieved simply.

Fundamental research needs

Research needs essentially follow the principles of green engineering. We need to generate more energy from solar and wind power, design and build structures and products to last longer, use renewable and biodegradable materials, and use less energy for maintenance of structures and transportation needs. In the case of solar power, the research needs are to increase the efficiency of energy consumption and develop new materials other than silicon for energy conversion. Developments in nanotechnology are creating new opportunities for introducing new photovoltaic materials.

In the area of structures, recent developments in self-cleaning and depolluting material combinations are opening up new research areas. By incorporating nano-sized anatase titanium dioxide (TiO_2) in concrete and surface coatings, researchers have shown that self-cleaning and depolluting surfaces can be created. This opens up avenues to use buildings to clean the air around them. Energy and resources are saved by reducing maintenance. A short review of the current state of the art and the research needs is presented in the following section.

Self-cleaning and depolluting construction systems

Photocatalysis, which is a reaction mechanism used between a semiconductor catalyst such as titanium dioxide and natural or artificial light, is the scientific basis for both self-cleaning and depollution mechanisms. The focus of most of the current work is on the use of titanium dioxide. Titanium dioxide is available in rutile and anatase forms; the anatase form is preferred for its photocatalytic activity.

Both indoor and outside air purification systems have been attempted. Most studies in Japan focus on indoor pollution. Building sizes with an airflow range of 100 to 1,500,000 m^3/h have been used in experimental studies. European studies are focusing on the outdoor environment. They are evaluating plaster, mortar, concrete, and coatings containing TiO_2. One of their recently reported activities was the use of 7000 m^2 of road surface in Milan, Italy, for evaluating photocatalytic cement, resulting in up to 60% reduction in the concentration of nitrogen oxides.

In the United States, researchers at Rutgers University are evaluating an inorganic polymer coating containing photocatalytic materials. The advantage of this system is that it can be applied to both new and old structures. The composition is compatible with common construction materials such as concrete, steel, timber, and clay bricks. **Figure 1** shows the self-cleaning properties of a coating made using nanoparticles. It is seen that the coated surface is free of mold, compared to the adjacent uncoated surface.

Fig. 1 Self-cleaning coating (on left) made of nano-particles.

Sustainable construction

Realizing the importance of green engineering, the Directorate for Engineering of NSF is requesting proposals for research in the area of resilient and sustainable infrastructures (RESIN). This area was chosen as one of the two emerging frontiers of research innovation for 2007 by the Directorate. One of the focal areas addresses green engineering directly. The solicitation states, "Sustainable technologies for the design, analysis, and construction of resilient physical infrastructure networks that can be deconstructed and reconfigured or recycled, without generating waste and which require orders of magnitude less nonrenewable resources for their function." Although the focus is on infrastructure, the principles are applicable for manufactured products as well.

One of the important aspects of sustainable construction is the use of renewable structural material, and timber is the primary and truly renewable structural material. The major concerns with using timber are related to fire resistance, low stiffness and strength, creep, and durability. Recent developments in high-strength composite materials can be used to overcome most of these deficiencies. For example, research at Rutgers University indicates that carbon fibers and inorganic polymer can be effectively used to improve mechanical properties and fire resistance. Using normal and high-modulus fibers, they improved stiffness up to 20 times and the strength up to 10 times. The fiber has a modulus of 900 GPa, which is three times higher than steel. They also showed that 3-mm-thick structural insulation is sufficient to pass the

Federal Aviation Administration's requirements for high-temperature exposure. **Figure 2** shows balsa wood with the coating after fire exposure. Experimental and analytical investigations covered the topics of beams and columns and various types of wood.

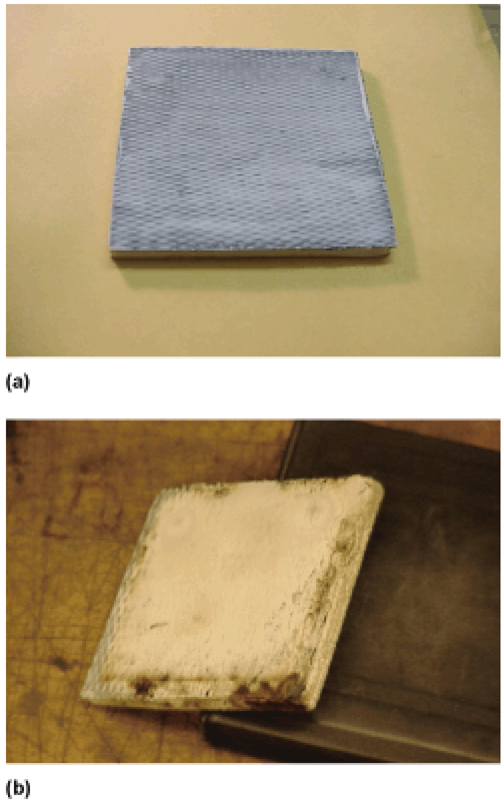

Fig. 2 Balsa wood with an inorganic polymer coating (*a*) before and (*b*) after high-temperature exposure.

Another promising area is the use of nanotechnology and ceramics to create alumina-silicate coatings for concrete structures. It is well known that ceramic surfaces can last for thousands of years. Terracotta (baked clay) soldiers (figures) have been discovered in China that are more than 2000 years old. We now have the technology and materials to create complex shapes with terracotta properties with no need for high-temperature processing.

Photovoltaic cells

The use of solar cells for energy production is increasing steadily. The most recent advances include the development of non-silicon-based solar cells, including flexible sheets and energy-producing paints. In the area of efficiency, researchers at the University of Delaware achieved 42.8% efficiency in 2007. They used a high-performance crystalline silicon solar-cell platform to achieve this efficiency at standard terrestrial conditions. The goal is to achieve 50% efficiency. These developments could lead to a net efficiency that is 30% greater than existing module efficiency and twice the efficiency of standard silicon solar-cell modules.

[The authors would like to acknowledge the contribution of Matt Carnavos, who compiled the research projects being supported by NSF.]

See also: **Biodegradation (/content/biodegradation/422025)**; **Ceramics (/content/ceramics/121000)**; **Concrete (/content/concrete/154600)**; **Conservation of resources (/content/conservation-of-resources/157900)**; **Construction engineering (/content/construction-engineering/158300)**; **Construction methods (/content/construction-methods/158500)**; **Electric power generation (/content/electric-power-generation/216600)**; **Energy sources**

(/content/energy-sources/233000); **Green chemistry (/content/green-chemistry/803120)**; **Nanoparticles (/content/nanoparticles/802960)**; **Renewable resources (/content/renewable-resources/580950)**; **Solar energy (/content/solar-energy/633300)**; **Structural materials (/content/structural-materials/662400)**

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