exhibiting little or no degradation in performance up to about 200°F (93°C).

Conclusions

Many opportunities are available for materials advances to reduce the energy use and atmospheric emissions associated with the building sector. The energy and cost performance of walls, roofs, windows, mechanical systems, and on-site renewable electrical and thermal systems can all be improved through advances in materials. Specifically, materials that improve the performance of thermal insulation, thermal storage, vapor retarders, weather barriers, glazings, solar thermal collectors, and photovoltaic generators could all have a profound impact on the overall energy efficiency and sustainability of buildings. Buildings have a relatively long lifecycle compared to automobiles and most manufactured products, so materials for buildings must be highly durable, nontoxic, aesthetically pleasing, and comfortable and safe for human interactions. Materials that reduce energy use in both new construction and retrofitting and refurbishment projects are needed. A challenge for building scientists and materials scientists is the difficulty of assigning a quantitative energy savings value to any given materials improvement. The elements of a building are highly interactive in their energy performance and also dependent on the surrounding climate, building type, and usage patterns in the building. Building scientists at the National Renewable Energy Laboratory have begun to develop sophisticated computer tools to address this issue, and those tools will improve as computer power increases. Because buildings are so numerous, even relatively small energy reductions on an individual-building basis can have a large impact globally.

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Environmental Performance Enters Construction Materials

Peter Bonfield (Building Research Establishment, UK)

Drivers for Change

The environmental sustainability of materials used in construction applications is driving a requirement for the quantification of performance attributes of such materials. For example, the European Union (EU) Energy Performance in Buildings Directive[1] will give commercial buildings an energy rating when rented or sold. The Code for Sustainable Homes launched by the U.K. Government's Department for Communities and Local Government (CLG) in January 2007 sets out the requirement for all new homes to be carbon-neutral by 2016. In addition, homes in the United Kingdom will need to significantly reduce water consumption from today's average 160 liters (l) per person per day to less than 80 l per person per day. Similarly stringent targets are required for waste, materials, and other factors. Such environmental and energy standards are complementing characteristics such as strength, stiffness, durability, impact, cost, and expected life with factors such as "environmental profile," "ecopoints" (a single unit measurement of environmental impact arising from a product throughout its lifecycle that is used in the United Kingdom), "carbon footprint" (amount of CO_2 produced for the lifecycle of the item), "recycled content," and "chain of custody" (a legal term that refers to the ability to guarantee the identity and integrity of a specimen from collection through to reporting of test results).

Companies are gradually being pulled into requiring demonstrations of environmental sustainability, through regulations, customer's demands, or a general desire to make a positive contribution to protecting the planet.

This is placing new challenges on materials scientists and technologists. One of the challenges is to translate the previously rather ethereal concept of sustainability into an objective,

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quantifiable performance measure that is as robust as bending strength, for example. Significant progress is being made in this respect. A number of calculation methodologies and new standards are now available that allow objective environmental sustainability measures to be calculated. For example, BRE's Environmental Profiles methodology[2] allows the environmental impacts of producing construction materials to be determined. This methodology takes input and output data from product manufacture and calculates environmental impacts across 12 key impact categories, including such factors as climate change, ozone depletion, mineral extraction, eutrophication, and human toxicity. (Eutrophication is the process by which a body of water becomes rich in dissolved nutrients from fertilizers or sewage, thereby encouraging the growth and decomposition of oxygen-depleting plant life and resulting in harm to other organisms.) The Environmental Profiles methodology is a lifecycle analysis approach that measures and evaluates the environmental burdens associated with a product system, such as insulation board or carpet, or an activity, such as production of a ton of material, by describing and assessing the energy and materials used and released to the environment over the lifecycle.

This means that many manufacturers, materials scientists, and technologists are now engaged in a new area of environmental performance assessment that sits alongside more traditional elements of property evaluation.

Product Selection

The lifecycle information calculation by the Environmental Profiles methodology has been further processed into a simple-to-use guide[3] that gives best to worst ratings (ranked from A to G, respectively) of the environmental impacts of typical building elements. A building element can be a roof, wall, floor, window, or cladding construction, for example; the environmental impacts are derived by summing the environmental impacts of the relative amounts of each of the materials used in the element's construction. Such an approach allows objective comparisons of different element constructions to be compared on a like-for-like basis.

Design

Environmental design standards, such as the BRE Environmental Assessment Method (BREEAM)[4] and the Code for Sustainable Homes,[5] bring a common approach to enabling environmentally sustainable designs to be used in the construction of new homes, schools, offices, sporting venues, and hospitals. The standards work on a credit system whereby increasingly better levels of environmental performance are rewarded by higher levels of credits. Credits are awarded in the following categories: energy, water, transport, pollution, materials, land use and ecology, and health and well being.

In materials, credits are awarded for using low-environmental-impact building materials and elements and for responsible sourcing. The public and private sectors have widely adopted these standards.

Perhaps one of the most significant needs for new research and product solutions comes from design. Very few materials are used on their own in buildings; rather, they are nearly always part of a construction that involves a range of materials working together to deliver the required performance outcomes. As discussed earlier, the performance requirements for products used in buildings have changed, and they continue to change markedly, driven primarily by environmental sustainability considerations. Therefore, developing design solutions that allow the whole building to perform better is required. Thermal efficiency of wall elements is one example. Another is how the products interface to deliver higher levels of air-tightness (and, with it, less heat loss). A holistic and integrated approach is required to enable building design to be optimized from a sustainable performance prospective.

Innovation

The drivers and methodologies just described require innovation in the composition and functionality of materials and products used in construction. Examples include improving process efficiency; fostering reduction, recycling, and substitution; employing natural materials; and developing better phase change materials.

Process Efficiency

The need to reduce environmental profiles of construction materials is giving greater focus to methods to improve the processing efficiency of manufacturing operations. Minimization of process costs is often directly compatible with minimization of the environmental profile. One example is making the most efficient use of energy (electricity). Conserving where possible will cut energy costs and CO_2 emissions. Cutting waste will do the same, as will minimizing packaging requirements and consumables. Such synergy, however, is not always the case. The rigorous data requirements for producing an environmental profile demand that each stage of the manufacturing process be carefully analyzed and the requisite data collected. A serendipitous outcome from this analysis is that the manufacturer often obtains a more robust breakdown of the costs of operating in addition to understanding the environmental impacts of each stage, thus helping to identify areas where costs and environmental impacts can be reduced.

Reduction, Recycling, and Substitution

Materials scientists are now seeking low-environmental-impact alternatives to the raw materials used to produce construction materials as a way of improving their environmental profile. Slag-sourced cement substitutes in concrete mixes are one good example. Similarly, the use of reused or recycled materials is gaining momentum, although, for many materials, such as steel, aluminum, wood-based panel products, and concrete, such efforts have been carried out for many years. Nevertheless, the drive toward reuse and recycling and the quantities of recycled materials being used have increased. In addition, new efforts are being made to use raw materials previously viewed as waste. Unsegregated domestic waste is one example in which board materials can be made from the trash that people throw away (**Figure 1**). The compression process for the board automatically filters out detrimental materials such as glass and metal but accepts nearly everything else. Plastic products that employ plastic from previously used construction components (e.g., windows) or from domestic waste (e.g., milk bottles) are also starting to penetrate the market place.

Waste arising on construction sites is another key area that is being addressed. More offsite manufacturing, improved designs, and better tailoring of products for the buildings in which they are used are critical to address site waste, which now comprises more than 20% of all new materials used on site in the United Kingdom.

Natural Materials

Natural products (other than wood and stone) are also gradually penetrating the construction market or being rediscovered (e.g., lime mortars, rammed earth). For example, crop-based

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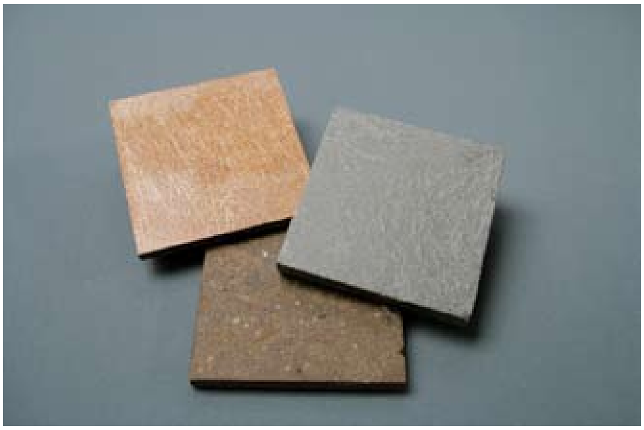

Figure 1. Domestic wasteboard made mostly of unsegregated rubbish.

building materials are being investigated and brought into the construction marketplace with renewed vigor. Hemp, straw, sisal, and jute are being used as fiber reinforcements or fillers for composite products (where limecrete, epoxy, phenolics, or formaldehyde-based binders are used) and blocks. The manufacturing of films and polymers from starch is also in development, as is the production of adhesive systems based on tannins. Whether these types of materials ever make it into the mainstream remains to be seen, but their use in more niche buildings will inevitably grow.

Phase Change Materials

The entropy changes associated with the transformation of a material from one phase to another can be exploited as a temperature-controlling mechanism in buildings. DuPont has pioneered this approach with their Energain product. The phase change material is sandwiched between two thin aluminum foils, and at around 22°C, it goes through a phase change. In doing so, the material absorbs heat from the atmosphere. In a room internally wrapped in this product, this behavior helps to mitigate heat buildup, thereby helping to keep the room cool without the need for air conditioning. The use of phase change materials is very likely to increase in construction and other applications such as transport.

Summary

It is clear that environmental sustainability is driving change throughout the construction sector in a manner that has not been seen for many decades. A key to reducing environmental impacts lies in the materials and products that are used in our buildings—in reducing their environmental impacts through manufacturing and use—and in designing them into buildings that are significantly more environmentally efficient. This endeavor provides a new sense of purpose and a new energy to materials scientists and technologists who have much to offer and much to do to enable delivery of the innovation required.

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A Super-Green Factory: The Sharp Kameyama Plant

Tetsuo Kusakabe (Sharp Corporation, Japan)

Integrating Different Types of Large-Scale Power Sources into a Distributed Power Supply System

Sharp Corporation is making a concerted effort to reduce environmental impacts to the greatest extent possible at its production facilities around the world, and it is applying its own original evaluation criteria to recognize those plants having an extremely high level of environmental performance as "Super-Green Factories."[1]

Our Kameyama plant, the first such factory to be so recognized, is an integrated, start-to-finish production facility for liquid-crystal display (LCD) televisions (TVs), from fabricating the LCD panel to assembling the finished TV set (see **Table I**). Given that large amounts of energy are consumed to operate production equipment and to power air conditioning, we focused particular attention on environmental measures intended to reduce global warming and introduced an energy supply system that combines environmental friendliness and operational stability.[2] As shown in **Figure 1**, this system is based on integrating different types of large-scale distributed power sources and consists of a gas-fired cogeneration system, a fuel cell system, and a photovoltaic power generating system. The power output of this system covers about one-third of the total electrical needs of the plant.

By situating the equipment that makes up this distributed power supply at the point where demand occurs, we are able to reduce power transmission losses compared to power supplied from distant generating stations, and we can effectively utilize the waste heat created at the time the electricity is generated, enabling the energy to be used efficiently. This approach also

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