Construction Materials: From Innovation to Conservation

Karen Scrivener and Henri Van Damme,
Guest Editors

Abstract

This article serves to introduce the May 2004 issue of *MRS Bulletin* on Construction Materials: From Innovation to Conservation. By volume, building materials are by far the most widely used type of materials. The most common construction materials—concrete and wood—are paradigms of complex and hierarchical materials, with a microstructure extending quasi-continuously down to the nanoscale. In the past, most improvements have been obtained by modifying the microstructure at the largest scales, for instance, by reducing the macroporosity. Recent advances in our understanding of the interactions and microstructure development show that the major levers for improvement from now on will rely on surface and colloid science and the science of complex materials, often at the nanoscale. This can lead to remarkable properties, such as self-compaction and ultrahigh strength, and even new functionality, such as self-cleaning through photocatalysis. Construction materials face a wide range of challenges today, many of which are linked to the need for more sustainable development: reducing the consumption of raw materials, reducing the energy used in processing, and increasing service life. In many parts of the world, there is also an increasing need to repair, rehabilitate, and conserve old buildings. The articles in this issue touch on these challenges as well as the advances being made in construction materials through materials research.

Keywords: *cement, cohesion, concrete, construction materials, flow modeling, granular materials, photocatalysis, raw earth, self-cleaning materials, rheology, wood.*

By volume, construction materials are by far the most widely used type of materials. Buildings, bridges, roads, dams, and other parts of our infrastructure can be made of concrete, wood, earth, glass, steel, or a variety of other materials, ranging from low-tech to advanced. At first glance, these materials have little in common, except their final use. Glass is a transparent, amorphous, and brittle dielectric material, while steel is a polycrystalline metallic conductor. Concrete is composed of aggregates (essentially, crushed rock or gravel) bound together with cement, while wood is a natural polymeric multiscale organic composite (an unsurpassed example for the present biomimetic approach in materials science).

Yet, a closer look shows that from a materials science perspective, two unifying themes emerge in this heterogeneous landscape. The first covers glass, steel, and cement, all of which require a knowledge of high-temperature phase equilibria and microstructure formation. Understanding these materials also draws on knowledge from the geological sciences.

A second point of commonality brings concrete, earth, and wood together. All three are porous materials, with a broad range of microstructural length scales. All three bear a special relationship with water and swell or shrink depending on moisture conditions. All three benefit from current research and development in the fields of granular and soft matter, porous media, and foam physics. However, they have still a long way to go before their complexity can be molded into a conceptual framework as elegant as that of metals or polymers, for instance. In spite of and because of that, it is this area of materials for construction that we choose to explore in this issue of *MRS Bulletin*.

Construction materials provide the essential fabric for modern civilization; they must be cheap and readily available. This is one of the primary reasons for the overwhelming dominance of concrete as a construction material. Nearly ten times more concrete is used in construction annually—around one cubic meter per person—than all other materials combined. These large volumes are essentially determined by the human scale of construction.

The five major elements that make up the cement portion of concrete—O, Si, Ca, Al, and Fe—are the five most abundant in the Earth's crust, together constituting over 91% of the crust (Table I).[1] The other factor in the success of concrete as a building material is the astounding ability of cement to transform from a fine powder to a rigid solid of almost any form with the simple addition of water at ambient temperatures and with minimal change in dimension. For these reasons, the use of concrete has transformed the built environment over the last century.

Despite its omnipresence in construction, the application of concrete is largely based on empirical knowledge acquired through macroscopic testing, and the depth of our understanding of the chemical and physical processes that deliver the performance of concrete on a macroscopic scale is quite limited. Concrete is, in fact, an extremely complex material,[2] comprising tens of chemical species reacting to form hierarchical structures ranging from nanometers to meters, undergoing change from the moment it is mixed with water, and continuing to mature and alter over centuries. The lack of understanding of concrete is a major obstacle to improvement and innovation in the use of this material. Four of the articles that follow in this issue show how new approaches based on materials science are starting to emerge and have a significant impact on applications. It is interesting to note that many of the authors of these articles work for industrial companies.

The basic variable underlying the performance of concrete is the amount of water added to it. More water increases the space between the cement grains, which must subsequently be filled with the products of the reaction between the cement grains and water (known as hydration).

Table I: Comparison of the Abundance of Principal Elements in the Earth's Crust and in Portland Cement.

Element	% in Earth's Crust	Typical % in Portland Cement
Oxygen	46.71	34
Silicon	27.69	9
Aluminum	8.07	3
Iron	5.05	3
Calcium[a]	3.65	46
Total	91.17	95

[a] Despite the low overall abundance of calcium in the Earth's crust relative to Portland cement, it is widely available in the relatively pure form of limestone.

Space not filled by the hydration products remains as porosity, which limits both the mechanical performance and durability of the concrete. Therefore, theoretically, the best properties are obtained when the amount of water is minimized. On the other hand, the minimum quantity of water is determined in practice by the need to produce a mixable fluid paste that can flow into a form. This minimum amount is determined by the size and packing of the granular materials and by the forces between them. This is covered in the first article, by Flatt et al., describing the science behind the development of organic admixtures for concrete that deflocculate the cement grains during mixing and allow much lower quantities of water to be used. Such organic admixtures have been the major factor in the development of high-strength concrete over the past few decades. High-strength concretes can be routinely produced with compressive strengths of 100 MPa or more, as compared with ~20–40 MPa for "standard" concrete.

Although the process of strength development in concrete can be described simplistically as filling the space originally occupied by water with hydration products, there must nevertheless be some cohesion between these hydration products. The origin of this cohesion is one of the basic mysteries of the science of concrete. Recent molecular simulation studies, discussed in the article by Pellenq and Van Damme, provide new insights into the possible origin of these cohesive forces.

Several recent developments—improved flow through the use of organic admixtures, optimization of particle packing, and the use of fiber reinforcing—have been brought together to produce ultrahigh-performance concretes, as described in the article by Vernet. These materials have exceptional mechanical performance, similar to steel, allowing lighter structures to be built with less material. They also have outstanding durability. In terms of architectural design, these developments will allow further progress toward more elegant concrete structures, as illustrated in Figure 1.

Nowhere are construction materials under greater attack from pollution than in big cities. Dirt deposits and biodegradation from colonization by algae, fungi, and lichens, favored by the presence of moisture, are responsible for the accelerated aging of concrete structures. Photocatalysis may well prove to be a solution for "stay-clean" buildings, as discussed in the article by Cassar. Glass coated with a thin, transparent (in the visible range) layer of titanium dioxide is self-cleaning in daylight, thanks to the strong oxidizing power of the electron holes generated by near-UV-bandgap light, which are able to decompose almost any organic compound. Concrete or cement mortar doped with TiO_2 behaves similarly, and several self-cleaning buildings have already been constructed. Furthermore, this concrete can be used to reduce environmental pollutants such as NO_x. Building facades and roads offer huge unexploited areas for this application. Preliminary tests performed on actual roads with heavy traffic show that this is not a dream.[3] Remarkably, the composite TiO_2/concrete material appears to be more effective at self-cleaning and NO_x breakdown than the photocatalyst alone.

After concrete, we chose to illustrate a recent development with wood. The use of wood in construction is substantial and its rate of consumption is probably close to the limit that sustainable forests can support. The availability of timber also imposes geographical limits on its use. Wood has excellent strength for its weight and can be easily cut; however, most of the use of timber in construction is unsophisticated and involves minimal processing. The interaction of wood with moisture, leading to dimensional change and degradation, is the main disadvantage of its use. The article by Navi and Heger describes research on novel processing techniques for wood that aim to overcome this moisture sensitivity.

Finally, we have chosen to include an article on construction with the most basic and ancient material of all: raw earth. This material, whose importance in this field is often overlooked, continues to provide a

Figure 1. Two bridges built 50 years apart, spanning the Elorn River in Brittany on the west coast of France. The lighter structure of the more recent bridge (foreground) demonstrates progress in concrete construction, compared with the older bridge (background): modern concretes are ten times stronger than those of the beginning of the 20th century.

major part of the construction needs in many developing countries. Earthen construction has evolved toward well-controlled procedures that make it, with the proper architectural design, a very flexible, cost-effective, and environmentally friendly solution in a wide range of possible applications, including in developed countries. As discussed in the article by Houben et al., the problem of conservation of our huge but fragile earthen architectural and artistic heritage, which represents at least 17% of UNESCO's "World Cultural Heritage" list, still remains. Only progress through materials science will allow us to find reliable long-term solutions.

Together, the articles in this issue show a small part of the range of research currently being carried out on construction materials. We believe that it is important to pursue research based on disciplines such as materials science that seek to relate macroscopic performance to mechanisms occurring on the micro- and nanoscale. Improvements in these materials are needed to respond to the increasing demand of society and especially to the key issues of environmental impact and sustainable development. In developed countries, over half the capital investment is in buildings and infrastructure and about half of the materials extracted from the earth each year is destined for use in construction. The materials described here are all low-energy materials. Earth and wood only require energy for collection, transport, and forming. Surprisingly, despite the high-temperature firing needed to produce cement, the energy content, by weight, of concrete is today only slightly more than that of cut wood (which has to be dried), and even less than that of processed wood like plywood (Table II).

Table II: Comparative Energy Costs of Materials.

Material	Energy Cost to Manfacture/Process (MJ per metric ton)
Concrete	600–800
Wood	
Cut wood	~500
Plywood	~4000
Glass	15,700
Steel	21,000
From scrap	11,000
Aluminum	164,000
Recycled	18,000
Plastics (high-density polyethylene)	81,000

Source: Reference 5.

What are the next challenges? One of them is certainly to reduce further the carbon dioxide production involved in the use of concrete. A cement kiln generates carbon dioxide in two ways: through the combustion of fuel and by decarbonation of the most abundant raw material, limestone. However, similarly to the energy content, the carbon dioxide balance of concrete is much lower than that of pure cement. The processing of sand and other aggregates used to make concrete produces little CO_2. Furthermore, the lime (portlandite) in hardened cement reacts slowly, year after year, with atmospheric CO_2, reabsorbing some of the CO_2 produced during cement production. Everything considered, concrete is much more "eco-friendly" than is generally thought.[4] With photocatalysis, it even deserves the "green material" label. Yet, progress can still be made by increasing what may be called the mechanical yield of the hydration products, by producing more durable strength with less cement. We can also imagine the better exploitation of the other functionalities of building materials, such as heat and moisture transfer and resistance to degradation. No doubt this will require a broad materials science approach, extending from crystal growth to molecular engineering, from granular materials physics to hybrid materials chemistry, and from the physics of surface forces to the mechanics of porous media.

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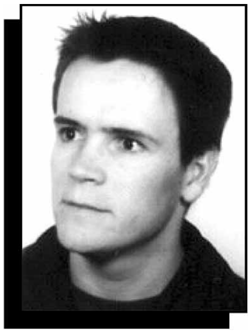
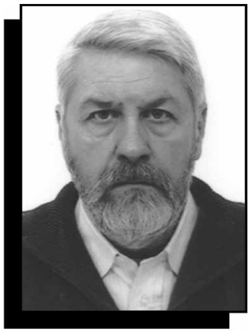


Frédéric Heger



Hugo Houben

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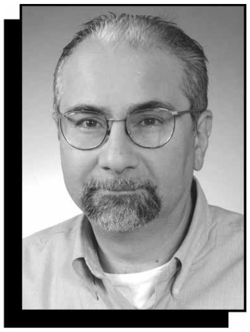

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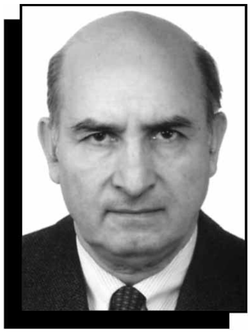

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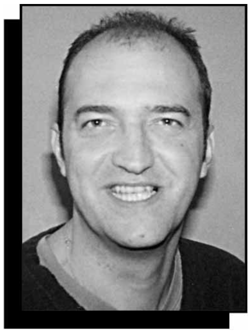

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