CHAPTER 1 WHY MATERIALS MATTER

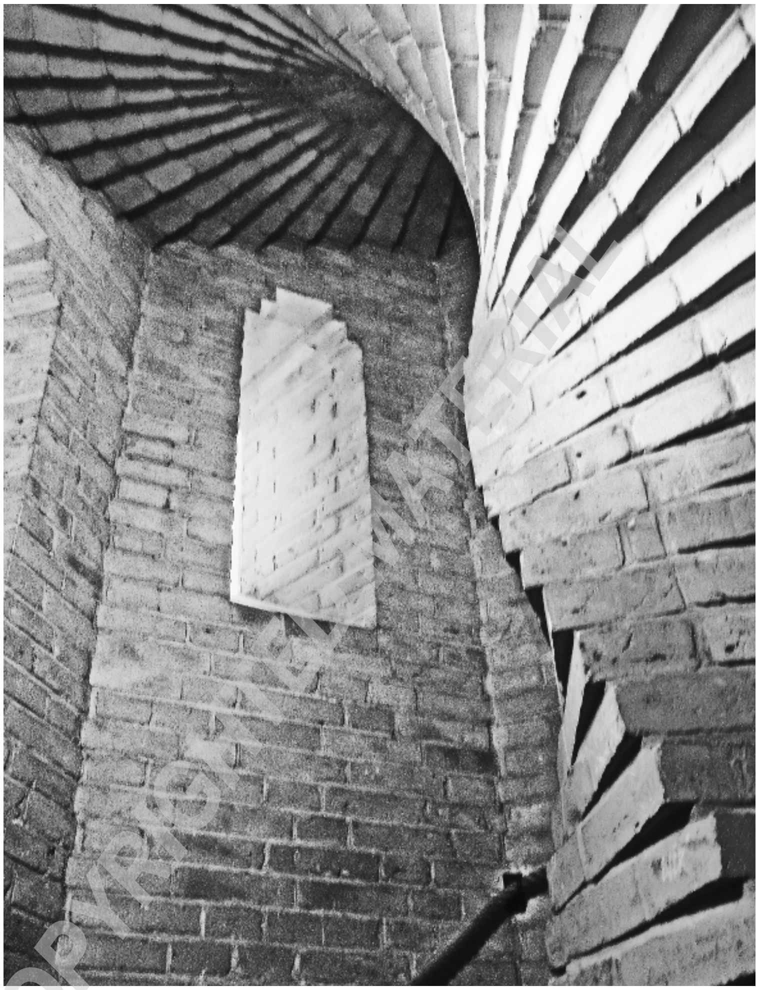


Figure 1-1 Peder Vilhelm Jensen-Klint's stairwell design of Grundtvigs Kirke in Copenhagen, Denmark (1913), intentionally uses whole brick masonry units throughout in order to draw associations between the integrity of the material and the church community. *Photography by Sarah Sokoloski.*

Specific characteristics of materials and consideration of their use in design and construction are detailed throughout this book. This chapter introduces the general issues pertinent to all materials in advance of examining their use within a specific building assembly in subsequent chapters. A holistic framework of interrelated considerations is established by examining the following topics:

- Design intentions
- Historical overview
- What it's made of and how it's made
- Environmentally sustainable design considerations
- Material properties and performance characteristics
- Applications
- Installation methods
- Maintenance requirements
- Resources and sources

DESIGN INTENTIONS

Figure 1-2 The faceted soffit is clad in polished stainless steel with a pockmarked texture. Barcelona Forum, Barcelona, Spain, designed by Herzog & de Meuron (2004). *Photography by Audrey de Filippis.*

Every material possesses an inherent poetry that is interconnected with human experience and engages both the mind and the body (see Figure 1-1). The connections that materials have with human experience can, however, be highly subjective or have broad cultural associations. Our connotation of an object made out of wood may differ greatly from that of a similar object made out of metal or glass. The generally accepted notion is perhaps that glass is sleek, metal is cold, and wood is warm. However, it is not just the material of an object that imbues it with character. Rather, our perception of an object's materiality is influenced by the distinctions of its particular color, surface texture, thermal conductivity, density, and finish. It is possible for wood to be highly figured, carved, knotty, stained, unfinished, weathered, or have either open or closed grain. Brickwork can appear rough, smooth, flat, or shiny. Glass can appear clear, translucent, opaque, textured, colored, or be laminated to other materials. Similarly, metals can range in color and surface texture, be polished or brushed, have a patina, or be rusted through. Therefore, objects made of the same material but with different finishes have their own unique character and sense of materiality.

New technologies have expanded the range of materials and finishes available. The development of new manufacturing techniques has enhanced performance characteristics and broadened the spectrum of unique aesthetic properties (see Figure 1-2). These innovations make it necessary for architects and interior designers to frequently revisit the palette of contemporary materials.

Aesthetics can significantly influence one's sense of luxury and comfort, or the lack thereof. It has been said that 75 percent of an object's monetary value lies in its visual appeal.[1] Polished marble, highly figured wood, and lustrous velvet invoke a sensorial response quite unlike that of natural concrete, unfinished knotty pine, and vinyl upholstery. To articulate the range of associations that a particular

▶**Figure 1-3** Salon Ovale, Hôtel de Soubise, Paris, France, designed by Germain Boffrand (1735–1740). *Photography by Patrick Snadon.*

▶▶**Figure 1-4** Crafted and reserved woodwork in the Ministry Workroom on the second level of the Meeting House, Shaker Village, Pleasant Hill, Kentucky (ca. 1820–1910). *Photography by William A. Yokel.*

material might invoke, we use descriptions such as elegant, casual, sleek, rustic, traditional, trendy, and so on. Just as there are no "ugly" colors, there are no "ugly" materials. Beauty, however, entails only one dimension of materiality. Environmental context and cultural bias collectively give materials their broader meaning, while interior space offers a spatial framework for daily experience (see Figures 1-3 and 1-4).

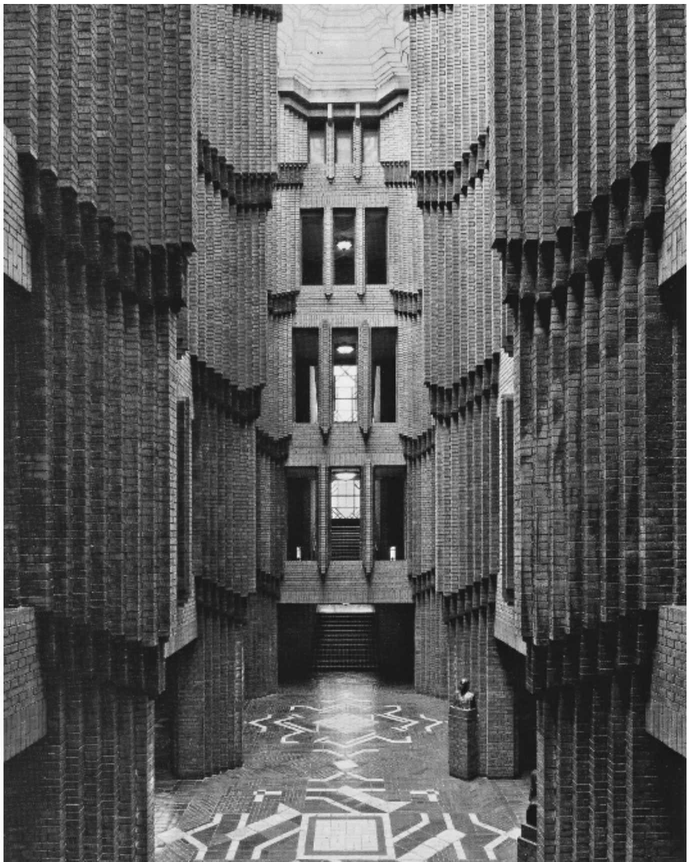
The Design Concept

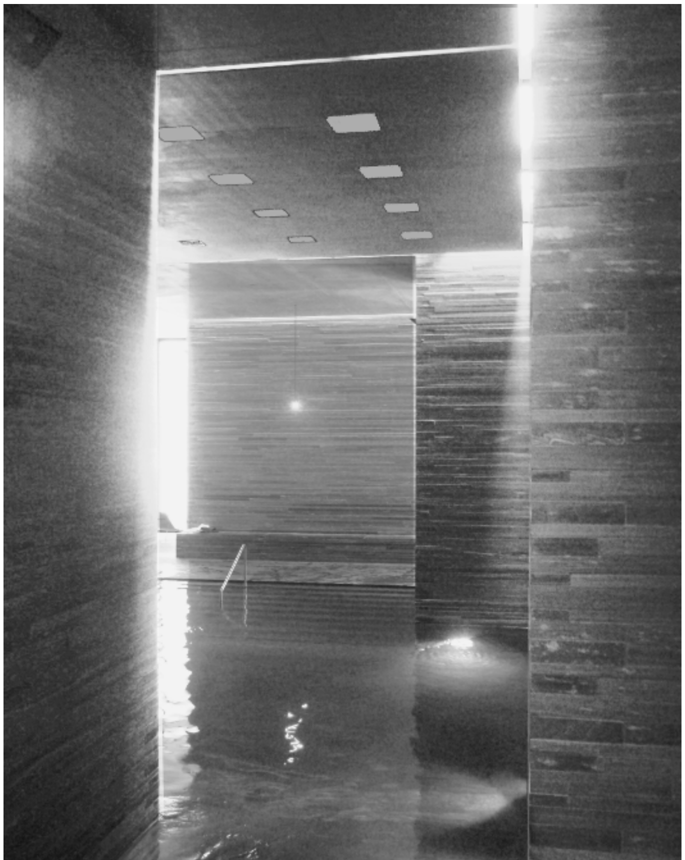
A strong design concept demands the integration of many considerations. *Intradependent* upon a working knowledge of design and construction, material selection is guided by the desire to actualize the design concept. A single material or finish can inspire a design concept or the development of a color scheme. Choosing to install hardwood flooring versus carpeting conveys a different design intention that must be considered in the early phase of the design process. Beyond the selection of materials lies an equally important consideration of use, application, and detail. The deliberative use, application, and detail of materials can reinforce design principles such as rhythm and repetition, scale and proportion, and unity and variety, thereby creating ideological links among material, spatial experience, and design intention (see Figure 1-5 and Color Plate 1).

The inherent poetry of a material can imbue a strong design concept with the powerful sense of experience and meaning. Peter Zumthor's Thermal Baths at Vals, in the canton of Graubünden, Switzerland (1996), is one example. Natural materials, including local Valser quartzite combined with elements of gently flowing water, ambient light, and the aroma of jasmine, infuse the space with a deep sense of relaxation that promotes well-being (see Figure 1-6).

◣**Figure 1-5** Peter Behrens manifests the German expressionist movement of the 1920s with his use of masonry in the administration building of the IG Farben Company, Frankfurt, Germany (1920–1925). The use of gradated color bricks, corbelled from floor to ceiling, creates a dynamic visual experience of the interior space. *Photography by Jerry Larson.*

▼**Figure 1-6** The interior spaces of the Thermal Baths at Vals, in the canton of Graubünden, Switzerland (1996), seem cavelike, with the sound of moving water, the use of dry-stacked stone walls, and the play of daylight on the water. Designed by Peter Zumthor. *Photography by James Herrmann.*





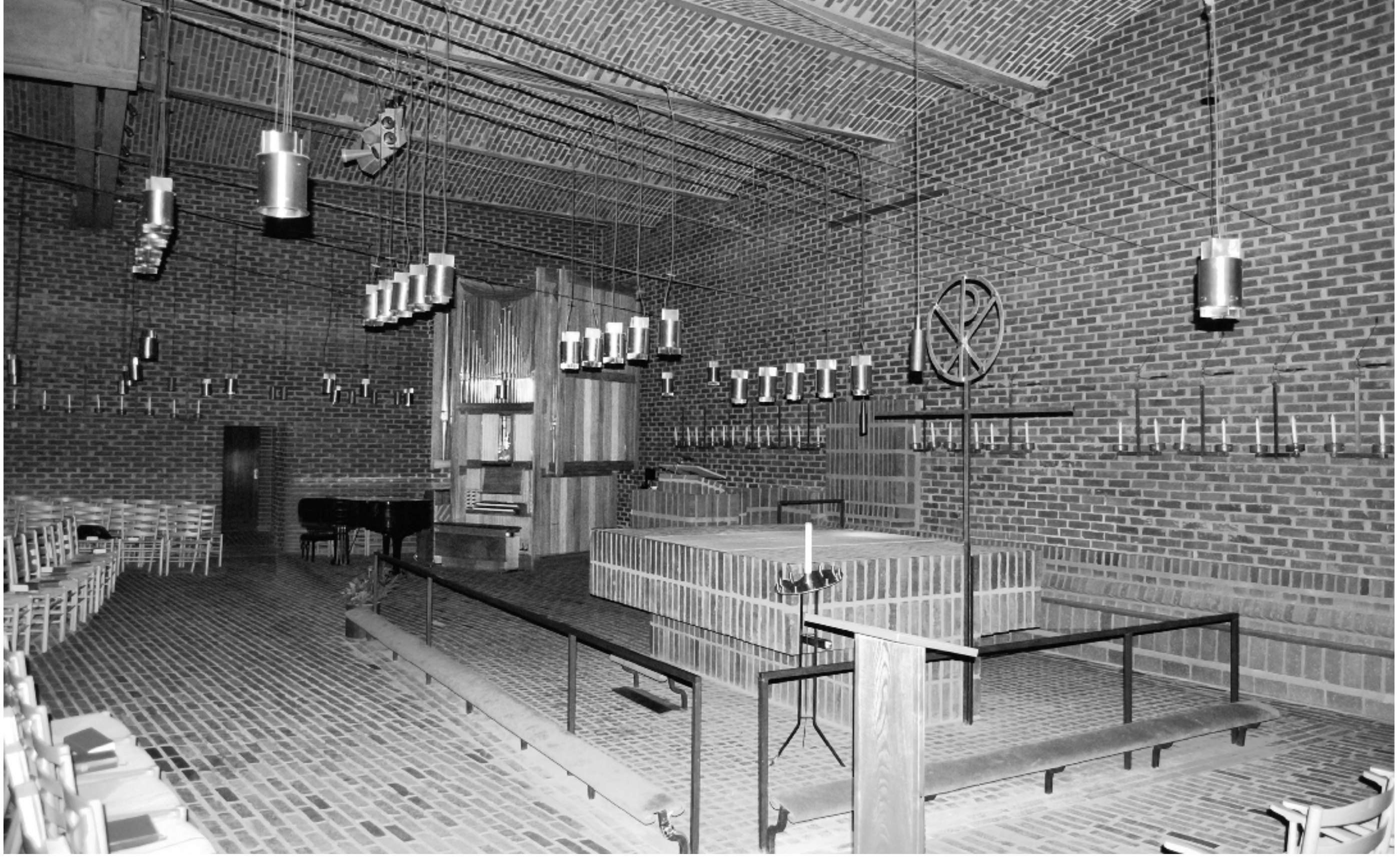


Figure 1-7 Chapel of St. Petri, Klippan, Sweden (1962–1966). Swedish architect Sigurd Lewerentz intentionally used every brick in the chapel's construction, whether it was broken or irregular. He chose not to cut any brick as a metaphor to express the intrinsic value of each person. Note the residual grout spacing. *Photography by Jerry Larson.*

St. Petri, Klippan, Sweden (1962–1966), designed by Sigurd Lewerentz, is another example of a building and its interior spaces in which the flooring, walls, and vaulted ceiling are all made with dark brick masonry, creating a quiet and somber sacred place for meditation, worship, and prayer (see Figure 1-7).

Human Factors

Human factors is an area of study that involves scientific research on the interaction between the human body and the built form (see Figure 1-8). A human factors specialist conducts user trials in order to evaluate the design of products, as well as their effect on the people who use them. The application of this combined research aims to improve the well-being and ensure the safety of the end user.

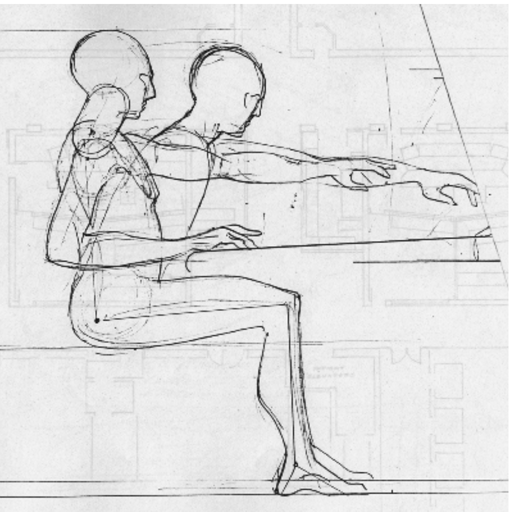


Figure 1-8 Sketch of the human figure in different postures interacting with the built form. *Drawing by Gil Born.*

Human factors encompasses specific areas of research that include:

- Accessible design
- Anthropometrics
- Ergonomics
- Human perception and behavior
- Posture
- Proxemics
- Universal design

The ADA Accessibility Guidelines for Buildings and Facilities are outlined in Title III of the Americans with Disabilities Act Accessibility Guidelines (ADAAG). These standards outline minimum dimensional requirements for pathways, ramps, slopes, and stairs regarding access and egress through a building. Although specific materials are not discussed, the measure and performance of selective elements are, and include, for example, the minimum recommended coefficient of friction for floor surfaces.

Anthropometrics is a science dealing with the measurement of the human body. It is an area of study built upon statistical research of the human body, funded in part by the U.S. military and laterally adopted in both the design and the engineering disciplines. Today, anthropometrics and medical research include statistical data on gender and ethnographic matters and serve as a foundation for ergonomics and other related fields of study.

Ergonomics is an applied science that investigates the interaction between built form and the actions the human body makes in order to perform a task. Henry Dreyfuss' *The Measure of Man* and Etienne Grandjean's *Fitting the Task to the Man* have made contributions to this area of study, which designers and researchers today continue to build upon. The principal aim of ergonomics in the area of design is to achieve a harmonizing alignment among built form, activity, and the limits of the human body.

Human behavior is inherent in the design of buildings and interior spaces. This notion is predicated upon the idea that design is deeply rooted in the human condition. While design is a part of the humanities, it is also an applied art, and as such, it is dependent upon the selection, application, and resolution of materials.

When people are not standing or sleeping, it is likely that they are sitting and engaged in a number of tasks while being seated. Posture is the position of the human body when standing, walking, squatting, or sitting. It shapes and is shaped by design, as well as communicates societal and cultural norms.

Proxemics is the study of the inversely proportional distances between people as they communicate in and through space. These distances, both required and desired, affect the way people move through and interact with one another and the built environment. The anthropologist Edward T. Hall coined the term in his book *The Hidden Dimension*.

Universal design is a broad and inclusive design concept that attempts to accommodate all people, not just people with disabilities. Universal design incorporates principles of accessibility, intuitive use, and equitable use in design. The term was coined by architect Ron Mace (1941–1998) and has been widely disseminated in both academia and professional practice.

Our sensory experience of materials in the world around us is immediate and constant. We touch and experience materials on a daily basis, especially those used in interior millwork and furniture. We notice when we have to extend our effort to open a heavy door or brush against an abrasive surface. We become acutely aware of physical sensations when we touch aluminum in a cool environment or experience an unsettling electrical shock in a dry environment. The synthesis of perception includes the use and feel of a material in a given environment. Our sensory response to materials directly influences our experience and contributes to our perception of comfort or discomfort, pleasure or dissatisfaction (see Figure 1-9).

Human factors and materials research are interdependent upon the following considerations:

- Perception and behavior
- Visual characteristics
- Haptic sensation
- Health, safety, and welfare

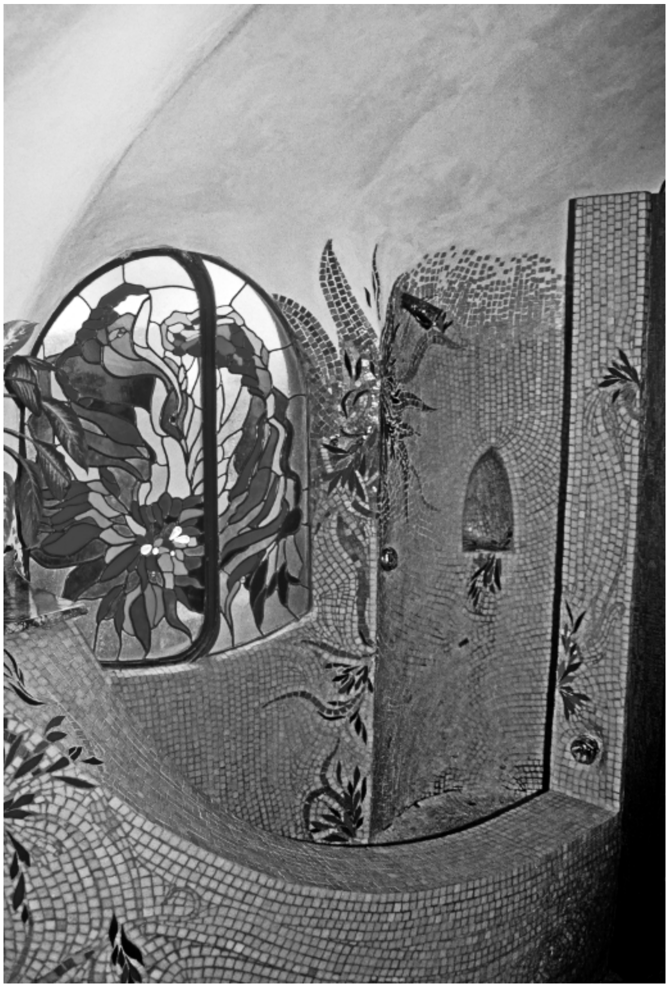


Figure 1-9 Mosaic tile shower with stained glass, inspired by nature and embellished with stone quarried from the building site. Rainbow Hill, Julian, California, designed and fabricated by James Hubbell (1991). *Photography by Jim Postell.*

Perception

Perception is an active process, which is both learned and innate. Through our senses, we develop an understanding of materials. Materials and the built environment, both directly and indirectly, stimulate the body's senses:

Visual sense	=	Sight
Tactile sense	=	Touch
Thermal sense	=	Environmental comfort
Auditory sense	=	Hearing
Olfactory sense	=	Smell

Materials are a visceral encounter as well as a visual phenomenon. Some materials contribute to our sense of pleasure and touch, such as the experience of grasping a wooden, hand-formed handrail or walking on a resilient cork floor (see Figure 1-10). Others negatively affect the experience of a space due to the concern that they might contribute to accidents. Walking on a wet, polished marble floor can lead to slips and falls, while the glare from a highly reflective floor or wall surface might create the unpleasant sensation of temporary blindness, depending on the location and source of light. In addition, many adhesives and sealers selected to enhance technical performance are known to contain carcinogens and emit harmful volatile organic compounds (VOCs).

Figure 1-10 The profile of the smooth wooden handrail complements the coarse brickwork at the First Christian Church, Columbus, Indiana, designed by Eliel Saarinen (1940–1942). *Photography by Jim Postell.*

Visual Characteristics

People rely primarily upon their sense of sight when describing materials. Generally, a material is conveyed first through optical perception, followed closely by the other senses. A key part of visual perception is the manner and effect in which light strikes a material's surface (see Figure 1-11). Visual characteristics can be described using the following specific terms:

- Color/hue: The visual property that depends on the light reflected by a surface, which is generally perceived as red, blue, green, and everything in between. The perception of color is influenced by the surface conditions of the material and the surrounding environment (see Figure 1-12 and Color Plate 10).
- Depth: The visual or perceived depth of a material's surface (see Figure 1-13).

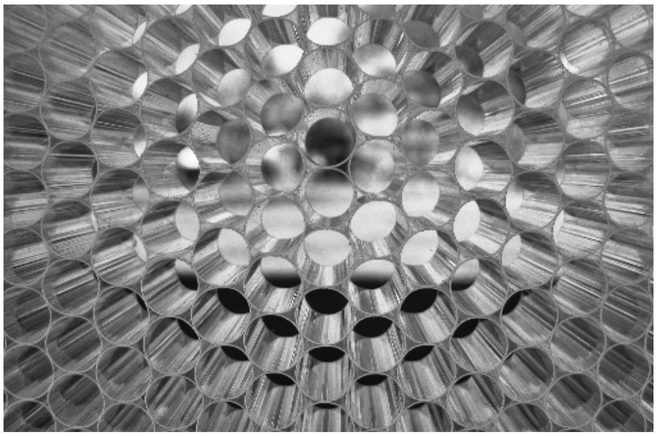


Figure 1-11 Daylight softly illuminating the concrete walls and floor in the Chapel of the Holy Cross, Turku, Finland, designed by Pekka Pitkänen (1967). *Photography by Jerry Larson.*

Figure 1-12 Daylight passes through the south-facing colored glazing into the lobby at Palais de Congrès de Montréal, Montréal, Canada. Designed in 2003 by Canadian architect, Hal Ingberg, in collaboration with Tétreault, Parent, Languedoc and Associates, Saia and Barbarese Architects, and the architects Dupuis, Dubuc and Associates (Ædifica). *Photography by Malcolm Lee.*

Figure 1-13 Close-up view of Panelite IB T04 partition at McCormick Tribune Campus Center, Illinois Institute of Technology, Chicago, Illinois, designed by Rem Koolhaas, OMA (2003). *Photography by Mandy Hamberg.*

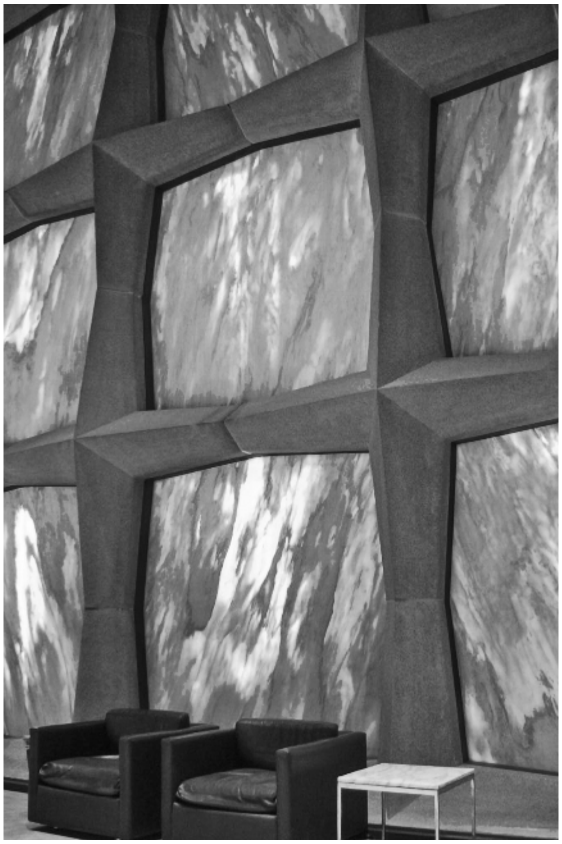


Figure 1-14 Translucent Vermont Danby marble slabs allow daylight to pass into the Beinecke Rare Book and Manuscript Library, Yale University, New Haven, Connecticut, designed by Gordon Bunshaft of SOM (1963). *Photography by Jim Postell.*

- Light transmission: The property of a material or substance to permit the passage of light, with little or none of the incident light absorbed in the process (see Figure 1-14).
- Luster: A visual quality caused by the refraction and reflection of light off a finished surface (see Figure 1-15).
- Reflection: The change in direction of a wavelength at the interface of two different media so that the wavelength returns to the medium from which it originated (see Figure 1-16).
- Shade/tone: The presence of black in a color or hue (see Figure 1-17).

Figure 1-15 Brushed stainless steel flooring panels refract light inside the CaixaForum Madrid, Madrid, Spain, designed by Herzog & de Meuron (2008). *Photography by Malcolm Lee.*

Figure 1-16 Light reflecting off polished stainless steel panels in the Experience Music Project (EMP), Seattle, Washington, designed by Frank Gehry (2000). *Photography by Yvette Njoki Waweru.*

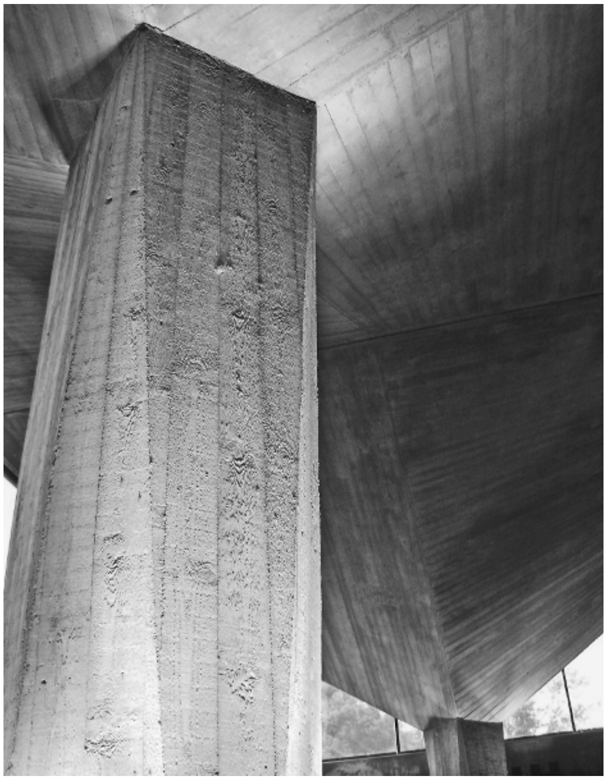


Figure 1-17 The rough texture of the funnel-shaped concrete pillars and canted ceiling in the Sibelius Museum, Turku, Finland, offers an acoustical benefit with dramatic visual presence of shade and tone. Designed by Woldemar Baeckman (1968). *Photography by Jim Postell.*

- Sheen: The appearance of gloss on a surface (see Figure 1-18).
- Texture: The tactile appearance of a surface (see Figure 1-19 and Color Plate 19).
- Tint: The presence of white in a color or hue (see Figure 1-20).
- Value: The overall degree of lightness and darkness of a hue (see Figure 1-21).

In addition to sight, people rely on a synthesis of their senses of sound, smell, and touch to inform their perception and experience of space. Thermal, visual, acoustic, and haptic sensations are experienced phenomena. Perception is an active phenomenon and is dependent on the selection, finish, and detail of materials and interior components. Human perception and behavioral response to material is critically important to consider in the broadest sense.

Figure 1-18 Light reflects off the high-gloss sheen of the hardwood maple floor in New Harmony's Atheneum, New Harmony, Indiana, designed by Richard Meier (1976). The sheen, along with the curved glass wall, alludes to the river beyond the Atheneum. *Photography by Mandy Hamberg.*

Figure 1-19 The combed surface treatment of the plaster walls and ceiling surfaces in the Chapel of St. Ignatius, Seattle, Washington, is highlighted by indirect, color-tinted daylight. Designed by Steven Holl (1999). *Photography by Michael Zaretsky.*

Figure 1-20 Various subtle hues and shades are present in the white painted surfaces and Carrara marble flooring at the Milwaukee Art Museum, Milwaukee, Wisconsin, designed by Santiago Calatrava (2001). *Photography by Sina Almassi.*

Figure 1-21 The open studio space in Crown Hall, Illinois Institute of Technology, Chicago, Illinois, foregrounds the transmission of light and shadow through the lower translucent wall panels and adjustable blinds above. Designed by Ludwig Mies van der Rohe (1950–1956). *Photography by James Eckler.*

Figure 1-22 Leather-wrapped door handle at Säynätsalo Town Hall, Säynätsalo, Finland, designed by Alvar Aalto (1949-1952). *Photography by Jim Postell.*

Haptic Sensation

Haptic sensations are physical and phenomenological experiences of touching and interacting with materials, particularly experienced through the hands and feet. Environmental conditions that influence the sense of touch include air movement, air temperature, and air humidity. Metals often feel cool to the touch, especially in temperate or thermally controlled environments. Glass can feel cool to the touch because it draws heat away from our bodies into the glass. When exposed to direct sunlight, however, glass can feel exceptionally warm. A material's thermal sense is influenced by its emissivity, conductivity, and radiant potential, all of which are influencing factors regarding the perception of touch. Emissivity is the degree of light reflectivity from the surface of a material. Highly reflective materials have a low emissivity rating (near 0). Highly absorptive or black surfaced materials have a higher emissivity rating (up to 1). A material's conductivity indicates the rate of transfer of heat energy through the material. A material's radiant potential is its capacity to release heat into the surrounding ambient environment.

Natural oils in the hands and fingers can leave marks on glass if the glass is not properly treated. Vinyl does not absorb moisture, and, as a result, condensation can form when direct contact is made with exposed skin. Plastic laminates can be abrasive over time to both clothes and skin. In response to these conditions and characteristics, designers and architects have sought to work with new materials and have used existing materials in unconventional ways. For example, hard surfaces can be treated and finished to create a range of visual and visceral effects. Granite, for example, can be hammered, flamed, honed, or polished. Polished granite feels and looks much different from flamed granite.

Glass can be annealed, cast, distressed, floated, blown, or tempered. For nearly every material, there is more than one option to consider regarding the characteristics and quality of its surface and finish. Different material finishes will result in unique sensory experiences.

Designers can appreciate the subtle, tactile distinctions between synthetic leather and genuine leather, but it is important to be aware of the variances in their versatility, application, and maintenance. A designer must ascertain when it is best to specify full-grain or split-grain leather, how best to apply it, and how leather's surface quality is maintained.

Alvar Aalto's work reveals a tradition rich in materials and architectural details intended to humanize the built form. In Aalto's Säynätsalo Town Hall in Finland, every detail is thought through, with a commitment to enrich the user's experience. For example, the door handles are made of woven leather strips through a metal form, which are tactically pleasing to grasp (see Figure 1-22).

Aalto's furniture offers a significant sensorial experience, perhaps designed in reaction to the cold tubular-steel furnishings that were beginning to emerge in Germany during the 1930s. Of particular note is Aalto's Paimio chair, designed for patients at the Paimio Sanatorium. Aalto claimed the chair's design helped the sanatorium's patients to breathe better and was fabricated in wood rather than steel because wood is perceived to be a warmer and more tactile material. It is made of laminated wood veneers, and despite its lack of upholstery, the springy seat and sufficient area for the body to move about results in comfortable sitting. Aalto's furniture designs, his innovative use of materials, and his tactile interior environments exemplify the uniquely Scandinavian concept of *hygge*, a Danish word that roughly translates to mean "cozy." Human experience and the sensation of touch are directly influenced by material properties, which inevitably will change over use and time. Architects and interior designers need to understand how materials and the processes of maintaining materials influence their properties and, in turn, influence the tactile experience of the built form.

Health, Safety, and Welfare

The specification of materials and finishes contributes to the health, safety, and welfare of their users. A material's finish can be used as a means of wayfinding to help direct people through a large space. A material change on the nosing profile of a stair assembly can create a sense of sure-

footedness when a person is descending a stair, thereby avoiding potential injury (see Figures 1-23 and 1-24).

Designers need to be aware of health, safety, and welfare issues within local, national, and international building codes, including the ADAAG, as well as practical considerations that extend beyond code compliancy. It is also important to understand why these codes are in place. Materials that are not properly fire rated for their specific application can contribute to the spread of both flame and smoke and possibly result in unnecessary injuries and damages. Excessive lateral force or concentrated live loads within buildings may contribute to the structural failure of a floor assembly, wall, or partition. Inadequate sound isolation due to a partition's or a ceiling's low Sound Transmission Class (STC) rating may contribute to the transmission of unwanted sound (i.e., noise), which can result in psychological stress or physical discomfort. The designer's challenge is to select appropriate materials while considering the limits of the human body, functional needs, and spatial ambience relative to use and experience.

▲▲ **Figure 1-23** Extended stair profiles designed by Alvar Aalto; each has a different rise/run ratio. Aalto created this folly as a lesson in stair design for the students in the Department of Architecture in Otaniemi, Espoo, Finland, located at the Aalto University School of Science and Technology (TKK) campus, which he also designed (1969). *Photography by Jerry Larson.*

▲ **Figure 1-24** Stainless steel nosing defines the edge of the carpeted spiral stair at the SAS Radisson Blu Royal Hotel, Copenhagen, Denmark, designed by Arne Jacobsen (1960). *Photography by Jim Postell.*

Indoor Air Quality

Indoor air quality is a significant health, safety, and welfare concern in the design of interior spaces. Sick building syndrome can result from the buildup of toxic vapors produced by the off-gassing of certain building materials and can be exacerbated by poor heating, ventilating, and air conditioning (HVAC) systems.

In the processes of fabrication and construction, materials are often bonded or laminated, surfaces are primed and painted, and edges are seamed and sealed. The adhesives, binders, paints, sealants, solvents, thinners, and varnishes used in these processes can release a substantial amount of volatile organic compounds (VOCs) into the atmosphere.

VOCs are naturally or synthetically derived, carbon-based organic chemicals emitted as gases into the air by the process of evaporation. Gases, such as methane (a greenhouse gas), can be naturally produced by biological decay of organic matter, including the burning of wood and wood-based materials. Formaldehyde, the second most common VOC, is produced as the solvent in adhesives, paints, and varnishes evaporates. Maintaining a moderate temperature can affect VOC emissions because relatively hot and humid conditions allow for more vaporization of formaldehyde from wood-based material. Many cleaning products and wood-finishing preservatives are sources of VOCs. Determined levels of mold, bacteria, and secondhand smoke can affect the health and well-being of building inhabitants.

When released in enclosed interior spaces, VOCs can cause health effects, such as:

- Allergic sensitization or asthmatic symptoms
- Eye, nose, and throat irritation
- Headaches
- Loss of coordination
- Nausea
- The exacerbation of lung, heart, and other existing health problems when combined with nitrogen oxide to form ground-level ozone

VOCs can penetrate the fibers of absorptive materials such as carpeting, ceiling tiles, drapery, and upholstered furnishings in which they can remain embedded for weeks, months, and even years. Therefore, whenever possible, these materials should be installed after the installation of materials finished with polyurethane, catalyzed lacquer varnishes, or solvent-based adhesives. An effective way to reduce VOCs is through forced ventilation for a period of time using fresh outside air and a filter with a minimum efficiency reporting value (MERV) of 12. Another, preventative approach is to keep interiors properly ventilated and in good repair. Replacing water-stained ceiling tiles and carpeting can prevent the growth of mildew and mold spores. Using materials made with bio-based adhesives and water-based solvents will dramatically reduce the amount of airborne particulates and contaminating VOCs. Other preventative measures include the implementation of green cleaning policies and proper maintenance of HVAC systems.

The indoor air quality (IAQ) and the environmental air quality (EAQ) are relative measures, quantified in parts per million (ppm), to help determine the quality of indoor air. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) defines acceptable indoor air quality as "air in which there are no known contaminants at harmful concentrations as determined by cognizant authorities and with which 80% or more people exposed do not express dissatisfaction."[2] The U.S. Environmental Protection Agency (EPA) studies of human exposure to air pollutants indicate that indoor air levels of many pollutants may be 2 to 5 times higher and, in some situations, nearly 100 times higher than outdoor levels. The high levels of indoor air pollutants relative to outside air is a concern that needs to be addressed by designers, especially because it is estimated that people spend as much as 90 percent of their time indoors. At this time, the EPA only regulates VOCs in the air, water, and land, but no standards have been established for nonindustrial indoor air. The Occupational Safety and Health Administration (OSHA), however, has issued a permissible exposure limit (PEL) for formaldehyde (a known carcinogen). What complicates the issue even further is that the definition of VOCs varies across agencies and countries. Products labeled "low VOC" or "zero VOC" can be a false claim attributed to the fact that a particular compound was exempt from the EPA's definition. Visit www.epa.gov//iaq/voc.html for more information.

Material Safety Data Sheets

In an effort to manage product stewardship and workplace safety, manufacturers of building materials and components are required to supply Material Safety Data Sheets (MSDS). These forms, published by the American National Standards Institute (ANSI), are a widely used system for cataloging information pertaining to the use of chemicals. MSDS are intended to provide procedures for the safe use and management of potential hazards associated with a specific material in an occupational setting. They record a material's physical data (melting point, flash point, etc.) and outline the risks to human health and the environment. The sections below outline considerations covered in standard (MSDS) forms:

- Substance identity and company contact information
- Chemical composition and data on components
- Hazards identification
- First-aid measures
- Firefighting measures
- Accidental-release measures
- Handling and storage
- Exposure controls and personal protection
- Physical and chemical properties
- Stability and reactivity
- Toxicological information
- Ecological information
- Disposal considerations
- Transport information
- Regulations

HISTORICAL OVERVIEW

The discovery, extraction, manufacturing, installation, maintenance, and reuse of materials are important to understand within a chronological and geographical context. Reflecting upon the history of various material processes can inspire designers to consider materials in innovative ways or to create new ones. Knowing when and where a specific material or fabrication technology was first used can foster connections among materials, fabrication, users, and place. This can provide a better understanding of social and cultural connotations inherent in the use of specific materials.

Initially, human beings began exploring and developing natural materials that were on hand and abundantly available to construct dwellings that provided shelter from the elements. Availability and functionality influence the selection and use of materials, as do a host of other issues such as climate, site, design intention, and workability. Materials provide thermal insulation and wind resistance when applied correctly. They also provide meaning, utility, and structural integrity to the built form. By providing an array of visual and visceral stimuli, as well as acoustic and olfactory sensation, materials help to shape, and, in turn, are shaped by, cultural, environmental, and technological factors. As a result, the historic development of building materials parallels the chronology of how societies have thought about design, building, and technology. As settled societies developed throughout the world, so too did the notions of place and place attachment, through which materiality has contributed substantially to the geographic and cultural identity of place (see Figures 1-25 and 1-26, and Color Plate 28).

Formulating cultural associations among materials, fabrication techniques, use, place, and time exemplifies the German concept of *zeitgeist*, translated to mean "in the spirit of the age," as studied by theorists and historians. This concept tempers how one might consider materials and their role in design and construction, especially in the context of place and time. It emphasizes the communication of societal and cultural meanings and weaves together use, intention, and material technology.

Currently, the science of material technology is under pressure to address urgent issues concerning the environment. In this age of technological advancement and globalization, architects and interior designers are fortunate to have a wide variety of materials from which to choose. This abundance of choice is an opportunity to exercise our highest conscious intention concerning ecological responsibility. Mainly, designers consider the aesthetics of a material, its poetic quality, and its intended meaning, yet now, more than ever before, designers must balance their desire for aesthetics with issues pertaining to performance, installation, maintenance, and life-cycle costing. The growing popularity

▲**Figure 1-25** The Old Church at Petäjävesi, Finland, built of local timber in an architectural tradition unique to eastern Scandinavia (1763). *Photography by Per Jansen.*

▼**Figure 1-26** Thirteenth-century Konark Sun Temple, Konark, India. The temple takes the form of the chariot of Surya (Arka) and is exquisitely carved in red sandstone in the tradition unique to the region of Orissa, India (1236–1264). *Photography by John Arend.*

Figure 1-27 Close-up detail of local materials used at the Hubbell residence, Santa Ysabel, California. The hand-formed clay tiles, shells, and broken-glass mosaic are embedded into concrete. *Photography by Peter Hilligoss.*

of Leadership in Energy and Environmental Design (LEED)–rated new construction and commercial interiors suggests that, in some ways, we have come full circle and ought to reconsider local materials and sustainability as a paramount concern.

The crafted interior spaces of James Hubbell (an artist living and working in Southern California) invoke a sense of place and time through the use of local and natural materials (see Figure 1-27).

Some artists, designers, and architects use new materials in traditional ways, while others seek unique ways of using conventional materials (see Figure 1-28 and Color Plate 8). In either scenario, materials can be a significant determinant of form. At the cutting edge of many contemporary interiors are the working prototypes made from new polymers, new alloys, aerogels, new wood products, smart materials, biodegradables, and rapidly renewable materials (see Figures 1-29 and 1-30).

Before exploring some of the newer materials available and used today, consider the chronology of material discoveries and technological inventions that have occurred during the past 7000 years. It is illuminating to review how the evolution of materials and methods of fabrication have influenced the design and construction of buildings and interior spaces.

Figure 1-28 Cast-in-place concrete partitions, metal handrails, and wood ceiling, all conventional materials, used in unique ways. Simmons Hall, Massachusetts Institute of Technology, Cambridge, Massachusetts, designed by Steven Holl (1999–2002). *Photography by David M. O'Connell.*

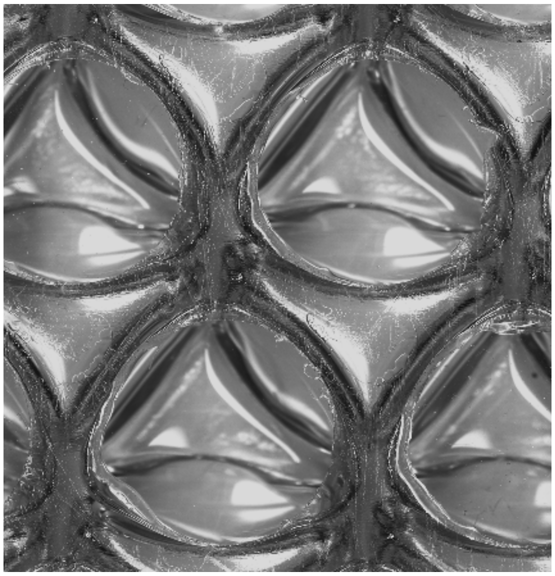
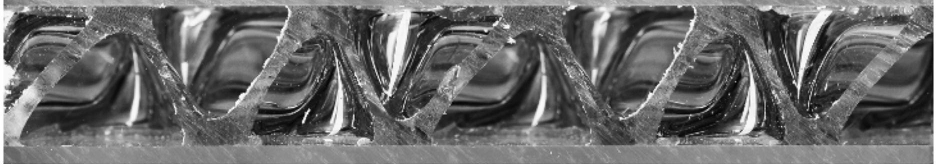


Figure 1-29 Bencore Starlight composite panel with external layers in acrylic (available in various colors). *Photography by Jim Postell.*

Figure 1-30 Bencore Starlight sectional-cut view of the composite plastic resin panel showing inner-patented, microcellular, translucent styrene acrylonitrile (SAN) core bonded with external layers in acrylic (available in various colors). *Material scan by Jim Postell.*



Chronology and Technological Development

5300 ABD	Sun-dried mud bricks were made in Mesopotamia.
5000	Urushiol-based lacquers were used in China to produce hard, durable finishes.
4000	Copper was used by the Egyptians for cutting implements and the edges of tools.
4000	Updraft kilns were used to make kiln-dried ceramic tiles throughout the Middle East and the Mediterranean.
3000	Bronze (an alloy of copper and tin, in the ratio of nine parts copper to one part tin) was used by the Egyptians for temple doors, offering tables, and small items.
2600	Glass (i.e., enamel) was used by the Egyptians for nontransparent glass beads.
2300	The Bronze Age began in Britain.
1550	The Hittites developed a crude form of iron extracted from iron ore.
1300	The Iron Age began in the Near East.
500	Brass, an alloy of copper and zinc, was widely used by the Romans.
200	The Romans used cement, made of calcium carbonate and limestone.
50 BD	The Romans used lead plumbing in Bath, England.
105	The Chinese court official Ts’ai Lun invented papermaking from textile waste using rags. Later, Chinese papermakers developed sized, coated, and dried paper.
700	Porcelain was first used by the Chinese.
1784	Edmund Cartwright invented the first mechanized loom in order to speed textile production.
1791	Samuel Peal patented the waterproofing of fabrics with a rubber solution.
1805	Luigi Brugnatelli invented modern electroplating.
1824	Joseph Aspdin invented portland cement by heating finely ground limestone and clay, then grinding the mixture to a powder.
1829	Michael Faraday established a formula for natural rubber known as C_5H_8.
1834	Justus von Liebig developed melamine (a heat-resistant polymer).
1840	Richard Prosser and Herbert Minton shared the patent for a hand-operated flywheel press that could compact clay dust between metal dies and press up to 3000 ceramic tiles per day.
1843	Charles Goodyear and Thomas Hancock individually applied for rubber vulcanization patents.
1856	Henry Bessemer developed the Bessemer converter to produce steel.
1868	The reisssue of a patent by John K. Mayo that described a cross-laminated sheet product as a precursor to plywood.
1870	Benjamin Chew Tilghman patented the sandblasting process.
1873	Glass fibers, woven into cloth (the precursor to fiberglass), were manufactured by Jules de Brunfaut.
1894	Augustine Sackett patented the manufacturing process for Sackett Board, a gypsum plaster sheet product similar to contemporary wallboard but with open edges and smaller dimensions.
1905	Three-ply veneer assembly, sheet material manufactured out of built-up layers of wood veneers, were first produced by the Portland Manufacturing Company.
1907	Leo Hendrik Baekeland created Bakelite, the first totally synthetic thermosetting plastic, derived from the reaction of phenol-formaldehyde, which sets solid when heated.
1909	Leo Hendrik Baekeland received a “heat and pressure” patent for phenolic resins.

1912 Daniel J. O'Conor and Herbert A. Faber invented Formica.

1912 Russian scientist Ivan Ostromislensky patented the use of plasticizers and developed synthetic rubber.

1913 Stainless steel was rediscovered by Harry Brearley in Sheffield, England.

1916 Felt-facing gypsum sheets were produced in 4-foot widths by Harry Brearley in Sheffield, England. Gypsum wallboard was manufactured in large quantity by the United States Gypsum Company.

1920 Quick-drying, solvent-based lacquers containing nitrocellulose were developed in the early 1920s by scientists working at DuPont in the United States.

1922 Hermann Staudinger synthesized rubber.

1926 A more flexible and easier way to process PVC was discovered by Waldo Semon at BF-Goodrich while seeking to find an adhesive that would bond rubber to metal.

1928 First commercial applications of urea-formaldehyde and PVC.

1930 Neoprene and polystyrene were invented.

1935 Wallace Carothers invented nylon 6.6, as an engineered substitute for silk.[3] It is strong, resists water and mildew, and is a malleable thermoplastic.

1936 A forerunner of Plexiglas (polyvinyl methacrylate) was created by pressing two sheets of polymethyl acrylate between two sheets of glass.

1936 Use of oil-based polyurethane, an important polymer used to finish and protect wood floors.

1938 Paul Schlack developed nylon 6 at IG Farben, and it was given the trade name Perlon.

1953 Karl Zeigler developed a means to produce a high-density polyethylene, which was made into dishes and soft plastic components.

1959 British glassmakers Pilkington Brothers patented the float glass process.

1960 Medium-density fiberboard (MDF) was developed in the United States. This synthetic, wood-based composite board consists of fine fibers of timber mixed with urea-formaldehyde resin and additives to form a material that is then subjected to heat and pressure to create rigid boards and panels.

1964 The first use of COR-TEN for architectural applications was the John Deere World Headquarters, Moline, Illinois, designed by Eero Saarinen.

1964 British engineer Leslie Phillips created carbon fiber by stretching the synthetic fibers, then heating them to blackness. This resulted in fibers twice as strong as steel.

1971 Kevlar, a fiber five times stronger than steel, was invented.

1975 Howard Fromson invented and patented continuously anodizing aluminum.

1977 Hideki Shirakawa, Alan MacDiarmid, and Alan Heeger discovered electrically conducting organic polymers, which were developed into light-emitting diodes (LEDs).

1990 Two new biodegradable plastics, Novon and Biopol, were developed.

1992 The U.S. Energy Policy Act mandated minimum energy efficiency standards for commercial buildings using research and standards developed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE).

1993 The first international conference on "green goods" was held at The Hague, Netherlands.

2008 Universal Fibers used the physical purification process to recycle nylon 6.6 fiber back into face fiber.

WHAT IT'S MADE OF AND HOW IT'S MADE

By examining what a material is made of and how it is made, a comprehensive understanding begins to emerge of the relationship among the aspects of health, safety, welfare, and sustainability. Other results of this inquiry reveal performance expectations, cultural associations, the development of new materials, and material-making technologies.

Identifying a material's chemical components can shed light on toxicity issues that could compromise the health, safety, and welfare of the people who manufacture them, as well as those who inhabit the interior spaces they are built with. For example, the discovery that exposure to the airborne fibrous mineral, asbestos, causes cancer led to the end of its use in vinyl asbestos tile (VAT). In the 1980s, talc was substituted for asbestos, thereby creating vinyl composition tile (VCT).

The use of vinyl has recently come into question because it emits dioxin when combusted. In response, PVC-free products are beginning to emerge in the marketplace. Public awareness, advocacy, and especially legal action concerning these discoveries contribute to the sustained demand for and development of safe material solutions. Prior to specifying a material, a designer is advised to review the MSDS, which contains data regarding potential hazards, including chemical components, melting point, flash point, and reactivity.

Most materials require some degree of milling, curing, or surface finishing. Knowing if a material is first a liquid, cast into a mold, extruded, and how it cures can provide insight into a material's properties and performance characteristics. These variables can affect the application and method of assembly.

Handmade glazed ceramic tiles, for example, are hand pressed into a mold, glazed, baked, and cooled. Prior to baking, the clay has a high moisture content. Once fired, ceramic tiles tend to become somewhat dimensionally irregular. This lack of consistent uniformity affects the installation because a wider grout joint is required to make up for the difference in the tile's edging. Machine-made tiles have cleaner edges and less warping and variation from handling. Mechanized production methods contribute to maintaining a consistent moisture content ratio. A material's chemical composition will also affect its dimensional stability. Different polymers expand and contract at different rates. An element made from polypropylene will vary in dimension from an element made from acrylonitrile butadiene styrene (ABS) plastic when manufactured using the same mold. If the size differential is not considered prior to the method of manufacture and assembly, the component's design and performance can be affected.

Cast glass rarely produces a dimensionally precise result due to the movement differential caused by the cooling process. Similarly, tempered glass has a tendency to distort during the cooling process, especially when its proportions extend beyond basic rectangular shapes. An example of this point can be seen in the difficulty of specifying and detailing the manufacture of long, thin-shaped, tempered glass pieces because the final dimensions may vary due to the tempering process.

Illuminating a material's components, as well as its total manufacturing process, can reveal issues pertaining to sustainability. One begins to understand how the amount of resources and embodied energy used in production and transportation can define a material's true shade of green. For example, producing aluminum consumes a significant amount of energy and water in treating bauxite (the ore from which aluminum is made). Manufacturing techniques, although they are more difficult to ascertain than MSDS, can be detrimental to the environment. For instance, the plating of selective metals such as bronze, steel, and nickel emits dangerous gases into the atmosphere, and the current processing of aluminum creates a heavy metal by-product that can potentially contaminate our water and food supplies. These examples make it clear that sustainability and issues of health, safety, and welfare go hand in hand with technological advancement. As cleaner energy sources are developed and regulations impose stricter criteria on manufacturing plants, we look forward to facilities that yield less pollution and use fewer resources.

The culmination of all of these factors can inspire a designer to think outside the box and consider using materials in innovative ways. The history of technological development illustrates how new methodologies, sometimes used in the fabrication of one material, can lead to the development and use of another. Plastic laminate, for example, was initially developed for use as an insulating material in the production of electrical components.

Marc Swackhamer and Blair Satterfield's research in the area of digitally fabricated modular wall systems is an example of how the use of new materials and digital fabrication technologies can help designers rethink traditional building components and, in turn, inspire a new aesthetic. Their research has resulted in several working prototypes, two of which are titled *Drape Wall* and *Cloak Wall.* These prototypes have been displayed at the Weisman Art Museum (St. Paul) and the Goldstein Museum of Design (Minneapolis). Their collaborative practice called HouMinn (pronounced "human") reflects a long-term commitment to the study of materials. Their experimentation with innovative fabrication processes has contributed to the technological development in both material science and the craft of making things.

The way we fabricate materials has come a long way since the Industrial Revolution. The development of synthetic material technologies that began in the 20th century has ushered in a new age of high-performance composite materials. Kevlar, designed by Stephanie Kwolek for DuPont in the mid-1960s, was developed based on the principles of radical polymerization that first led to the invention of nylon. This highly durable synthetic fiber can be spun into fabric, which can be used as such or melded to other materials for reinforcement. Kevlar fabric was used in the sinuous design of the 60,000-square-foot retractable roof of Montreal's Olympic Stadium. However, due to engineering and design flaws, the Kevlar roof was removed.

The cost of researching a new material for an architectural application can be problematic. Most clients are reluctant to be the first to use cutting-edge materials because they lack the security of the tried and true, and typically a design firm cannot afford to assume the liability of specifying a material that may not perform as expected. Yet, architects and designers yearn for the opportunity to create something unique. In the renovation of Alice Tully Hall at New York's Lincoln Center for the Performing Arts, the New York–based architectural firm Diller Scoffidio & Renfro (DS&R) welcomed the challenge to forge something new. The "blushing walls," as they have been poetically referred to, were the result of a one-year research and development (R&D) plan. The molded acoustic panels, which wrap the interior of the concert hall, are engineered out of the veneer cut from one large trunk of African moabi (see Figure 1-31 and Color Plate 31).

The upper part is laminated to MDF and the lower part to a resin panel that allows the built-in light source to radiate softly through the veneer. Other acoustical equipment is hidden within this seamless translucent sheathing located 18 inches from the building's exterior. Lincoln Center funded the R&D on a fixed budget that was to coincide with the end of the project's design development phase. The R&D included the resolution of all of the necessary acoustical, technical, and code compliance issues; prototyping; and a proof-of-concept mock-up. After working with many different vendors, DS&R ultimately partnered with 3-Form to manufacture this multifaceted wall assembly. Manufacturers might partially

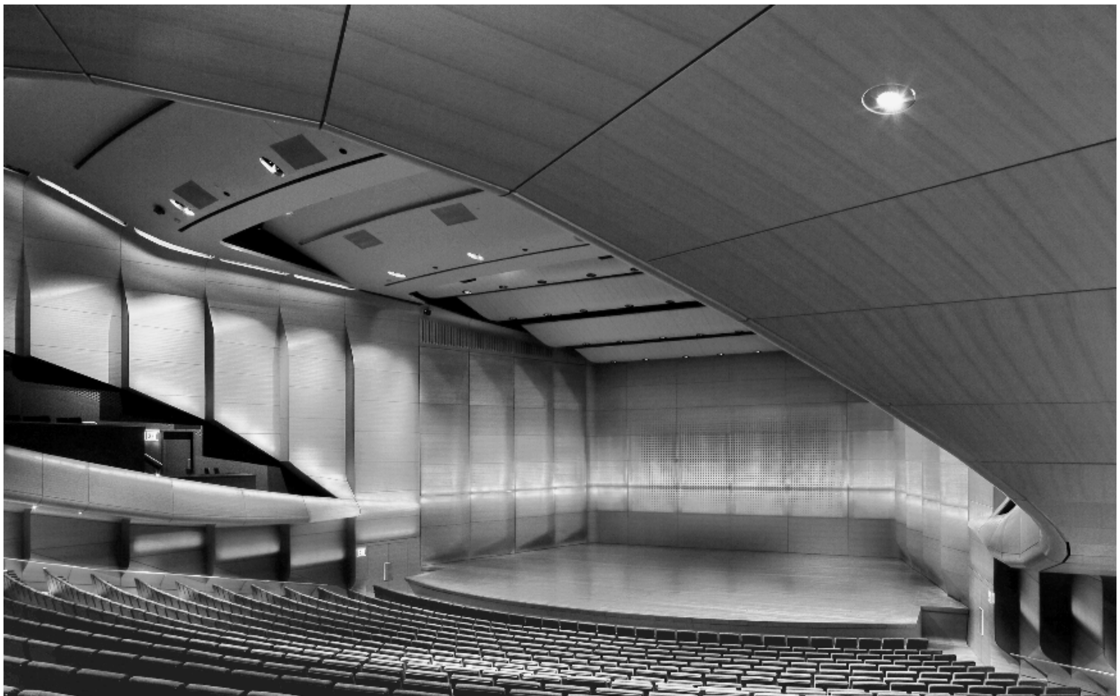


Figure 1-31 Molded acoustical panels at the Alice Tully Hall, Lincoln Center for the Performing Arts, New York (2003–2009). *Photography by Iwan Baan.*

fund the research in anticipation of a large project but, typically, clients contribute to the R&D of a new material application when both design and performance requirements are unique.

The result of analyzing what materials are made of and how they are made contributes to an understanding of the development of new materials and technologies. Today, material scientists are creating a sense of growing anticipation with their pioneering work in the emerging fields of quantum mechanics and superconductivity. Recent advancements in nanotechnology reveal how various quantum mechanical methods can be used to modify the molecular structure of matter. In controlled environments, a quantum mechanic is able to isolate molecules that are between 1 and 100 nanometers in size and is able to build arrangements of atoms different from their natural order.[4] Subsequently, the rearrangement of atoms can enhance a material's physical properties and even alter its characteristics. For example, an opaque substance such as copper can become transparent.

These complex cutting-edge technologies are spawning a new generation of highly durable, lightweight materials made of carbon, glass fibers, and self-healing plastics that can be used in applications never before imagined. Carbon nanotubes, for example, offer great promise because they are the strongest known fiber (and 10,000 times thinner than a human hair), yet research has only begun regarding the potential issues of their toxicity. Glass fiber and self-healing plastic materials are still in the developmental stage.

The availability of raw materials and the various processes required to mill them affect the overall cost. Whether extensive or modest, manufacturing expenses can range significantly depending on the amounts of energy, time, and technology used. The value of a material influences the perception of its cultural significance and, subsequently, its use in design. The history of manufacturing aluminum illustrates this point. When it was first available in the 1800s, aluminum was expensive to produce due to the high energy required in its manufacture and therefore held significant social value. As such, plans were made to use it to clad the top of the obelisk at the Washington Memorial, primarily due to its lustrous color and resistance to tarnish. After delays incurred by the Civil War, construction resumed in the 1880s. On December 6, 1884, a small cast aluminum pyramid (measuring 22.6 cm in height and 13.9 cm at its base) was installed on the memorial. This marked the time when most people learned about aluminum, creating a distinct honor and association for the material. Soon thereafter, a new invention for processing large quantities of aluminum oxide (from bauxite, a readily available ore) made aluminum much less expensive to produce. During the 1900s, it became a popular material, associated with the production of inexpensive, everyday products, such as folding aluminum chairs and aluminum cans.

Material Extraction

Accessing the organic resources of various materials involves the removal of layers of earth and core drilling. If not properly managed, these invasive processes can significantly disturb the physical and biological ecosystem. In addition, enormous amounts of water and energy are consumed in order to access and extract material.

Stone is extracted from the earth by using one of several mining techniques. Two common excavation techniques are subsurface mining and quarrying (i.e., gathering building materials through an open pit). How stone is extracted and where it comes from can influence its material properties and characteristics, impact the natural environment, and contribute to the cost and energy consumed by labor and transportation. Limestone is typically quarried in huge and exposed sedimentary layers because subsurface mining is an expensive, dangerous, and less effective method of extracting large building materials (see Figure 1-32).

Indiana Limestone is a regional limestone that is considered a freestone, meaning that it has a fine grain and no preferential direction in its grain structure. Therefore, it can be easily cut, carved, drilled, or turned on a lathe. Limestone quarried from other regions, even those in close proximity to Indiana, such as Michigan, can exhibit uniquely distinct characteristics and material properties.

Figure 1-32 Limestone quarry, foreground, indicating a significant amount of surface extraction at Carmeuse Lime & Stone, Cedarville, Michigan. *Photography by Mike Hamberg.*

The world's vast supply of bamboo is grown in tropical regions throughout the world with a significant amount harvested in China. Although bamboo is a rapidly renewable material, because it can be grown and harvested within a 10-year cycle, it is not considered completely "green" because of the fossil fuels required to transport the bamboo considerable distances for inclusion in projects located halfway across the globe. It is also considered an invasive grass species due to its rapid growth rate and can be harmful in nonnative areas when left to grow in the wild.

How forests are managed and wood is harvested will influence both the quality of the lumber and the environment. All lumber can be purchased as certified from several international organizations, but the two major organizations are the Sustainable Forestry Initiative (SFI) and the Forest Stewardship Council (FSC). Both are independent third-party organizations that certify the harvesting process and chain of custody for lumber producers. Certified lumber ensures that sustainable forestry and harvesting methods have been followed. This is particularly important when selecting and using exotic hardwoods in design.

ENVIRONMENTALLY SUSTAINABLE DESIGN CONSIDERATIONS

Green design is the application of a philosophy that addresses the global environmental crisis of climate change. It is inclusive of many disciplines that share the intention of eliminating the negative environmental impact of air and water pollution and the depletion of natural resources in the creation of physical objects, including buildings. In architecture, the scope includes site selection, scheme formation, procurement, project implementation, as well as material selection. The term *green design* is both general and inclusive. It considers distribution and packaging, biodegradability, the life cycle of materials and products, off-gassing, the toxicity in fabrication or use, and a number of other important factors, including human rights and labor standards. A material's ingredients, manufacturing methods, industry ratings, and certifications all contribute to defining the full environmental and sociopolitical impact of a product.

Raw materials are rarely found in nature and available for immediate use without requiring additional processing. They must be extracted, manufactured, and transported before being used in the fabrication or construction of projects. The technologies used in these processes must be examined holistically to determine if a material contributes to a sustainable system of production with respect for nature, or if it creates unintended consequences that are a hazard for the environment or living beings.

Architects and designers must be able to separate the important facts from the hype generated by parties with vested interests. The "Environmentally Sustainable Design Considerations" section, noted as "ESD Considerations," examines how the following questions reveal a material's comprehensive effect on the environment:

- How does the extraction of the raw material impact the environment? Is the material locally produced and/or rapidly renewable?
- How much energy is required to transport the acquired raw material to the manufacturing plant and to distribute the finished product to the end user? What kind of packaging is required?
- What are the chemical ingredients? Are they safe to manufacture, use, and dispose of?
- Are the fabrication technologies toxic to the environment or to the health of the people who make them? Are the manufacturing processes in accordance with human rights and labor laws?
- Is the material nontoxic, biodegradable, or compostable?
- Does the material off-gas and contribute to poor indoor air quality?
- Is the material made with recycled content? Is it designed to be recyclable within the current infrastructure of the local recycling stream? Are there take-back systems in place? How is it recycled, and what does it get recycled into?
- Can the material be upcycled into a new composite material or serve a new purpose after its intended use?
- What are the material's industry ratings and certifications (i.e., FSC)? Has the manufacturer substantiated the material's sustainability credentials with quantifiable life-cycle analysis data?

By examining the environmental consequences of material selection, it becomes evident that it is essential to integrate these considerations into every aspect of the design process. But perhaps the first questions designers need to ask themselves are, is new construction really necessary and can the existing construction be modified to suit the client's needs while intentionally reducing consumption and waste? Today, architects and interior designers are encouraged to use fewer resources and consider sites and existing buildings that don't require significant spatial or physical transformation. Modest spatial and physical alterations to existing buildings will likely minimize the need to use new materials. Less invasive design alterations are generally considered more sustainable. The mantra for sustainability—*reduce, reuse, recycle, and regulate*—as outlined by William McDonough and Michael Braungart in their seminal book *Cradle to Cradle: Remaking the Way We Make Things*, serves as an effective means to focus our collective attention toward the critical issues concerning the global environmental crisis.[5] McDonough and Braungart propose ways that designers can create products, interiors, and buildings in which nature and commerce might coexist.

The following concepts and ideas contribute to our understanding of sustainability in design.

Biomimicry

In the natural world, there is no waste. Every living thing is food for other living things in a perfect closed-loop system. Pollution does not exist in nature. Everything is biodegradable, powered by sunlight, and biodiversity is systemic. Animals and plants adapt to their environment in complex and fascinating ways over time. Today, it is up to designers to apply this same ingenuity and adapt to the environment in ways that respect the planet's limited resources and balanced ecosystems.

Biomimicry (a combination of the Latin words *bios*, meaning "way of living," and *mimesis*, meaning "to imitate") refers to the concept of using nature as the ideal inspiration for creating products and emulating natural methods of production. The practice of looking at nature's solutions for design inspiration has existed for centuries, although the term has only recently become widespread. The book *Biomimicry: Innovation Inspired by Nature*, written by the biologist Janine Benyus in 1997, has contributed to the growing awareness of the subject. In her book, Benyus illustrates a multitude of design inventions that were directly inspired from studying nature such as a leaf serving as inspiration for the design of a photovoltaic cell. Visit www.biomimicryguild.com for more information.

Carbon-Neutral Design

Carbon-neutral design is an important component of a sustainable design initiative that examines ways to reduce a building's or interior's carbon emissions. The issues surrounding carbon emissions are complex. Carbon is expended in the extraction of materials that we use to create products, in the transportation of these products to the site, in their construction and fabrication, in the operation of buildings, and through the people who occupy interior spaces. Carbon-neutral design attempts to reduce the carbon emissions associated with all these aspects. Further, both the nature of the work carried on within a building and the related work produced off-site contribute to whether or not a building is carbon neutral. The thoughtful location of a project or the material production site can help reduce transportation costs; therefore, carbon-neutral design considerations include neighborhood, local, and regional planning issues.

Related to the need and desire to reduce the energy consumed in the manufacturing of materials and maintenance of buildings, a letter from the Earth Institute at Columbia University indicates that research is under way to develop advanced technologies to reduce carbon emissions from coal-burning power plants. Scientists are developing methods to capture and store the carbon dioxide present in the air and inject it into marine sediments in the ocean. Certain rocks have the unusual potential to safely convert carbon dioxide emissions into common minerals like chalk and limestone.

Another interesting and recent development in carbon-neutral technology can be found in the production of precast concrete. Concrete's active ingredient, cement, is conventionally made by baking limestone and clay powders under intense heat, which is produced by the burning of fossil fuels. Making finished concrete products (mixing cement with water, sand, and gravel) generates additional emissions because heat and steam are used to accelerate the curing process. The process of making concrete accounts for more than 5 percent of human-caused, carbon dioxide emissions produced annually. A new proposed process exposes freshly mixed concrete to a stream of carbon dioxide–rich flue gas, which, in turn, accelerates the reaction between the gas and the calcium-rich minerals in cement. The technology virtually eliminates the need for additional heat or steam, saving energy and minimizing emissions. Potentially, this new technology could reduce by 20 percent all carbon dioxide emissions in the manufacturing of cement, which, if commercialized, could revolutionize concrete manufacturing and potentially produce a more durable concrete, without compromising structural integrity.[6]

Certifications

Third-party certifications serve to reassure those who specify materials that environmentally sustainable practices are being implemented and observed by their manufacturers. These watchdog organizations oversee the processing of materials to ensure that the balance and biodiversity of the ecosystems that some materials come from are maintained and protected. The standards they set help regulate a broad range of environmental benefits, including carbon-neutral design, greenhouse gas mitigation, and resource management. In addition, issues of social responsibility, child labor laws, and animal rights are taken into consideration. Selecting certified materials is an empowering act of creating positive change for the health and well-being of our planet. The following certifying organizations intend to raise public awareness of the impact of our choices:

- **The Carbon Reduction Institute's (CRI) No CO2 Certification Program:** This program offers certification that demonstrates an organization's direct and effective action against climate change.
- **Cawthron:** Offers international standards for carbon footprint measurement and offset quality.
- **The Center for Resource Solutions (CRS):** In cooperation with Green-e (an organization involved in climate change issues), has published a draft "Product Certification Standard" for carbon offsets.
- **Cradle to Cradle Certification:** A comprehensive certification program instituted in 2005 by McDonough Braungart Design Chemistry (MBDC). Its guidelines provide companies from any industry with a means to tangibly measure achievement in environmentally intelligent design. There are four levels of certification based on five criteria: Material Health, Material Reutilization, Renewable Energy Use, Water Stewardship, and Social Responsibility.
- **FloorScore:** Sponsored by the Resilient Floor Covering Institute (RFCI) and Scientific Certification Systems (SCS), FloorScore tests and certifies hard surface flooring and flooring adhesive products for compliance with rigorous indoor air quality emissions requirements.
- **Forest Stewardship Council (FSC):** FSC is an international not-for-profit organization created in 1993 to establish environmental forest management standards that include how lumber is grown, harvested, manufactured, and distributed. Its labeling system is based on the FSC Principles and Criteria. FSC is recognized under the LEED rating systems.
- **Green-e:** An independent consumer protection program that offers certification and verification for the sale of renewable energy and greenhouse gas mitigation products in the retail market.
- **Greenguard:** The Greenguard Environmental Institute, created in 2001, oversees third-party certification programs. Its mission is to establish product and building standards that aim to reduce chemical exposure and improve indoor air quality.
- **Green Seal:** An organization established in 1989 that examines the environmental impact of manufacturing processes, including facility standards and product testing methods.
- **Leadership in Energy and Environmental Design (LEED):** The not-for-profit U.S. Green Building Council (USGBC) created a comprehensive and extensive system for sustainable design practices, called Leadership in Energy and Environmental Design. LEED is an internationally recognized green building certification system, providing standards and methods to achieve environmentally green building strategies aimed at improving performance across all the metrics that matter most: energy savings, water efficiency, CO2 emissions reduction, improved indoor environmental quality, and stewardship of resources and sensitivity to their impacts.[7] Projects must meet the criteria for certification that are based on standards using a numerical point system. For any particular category of certification, a project can earn LEED certification at a base level or attain silver-, gold-, or platinum-level certification. A LEED-accredited professional is an individual who has registered and passed the LEED certification exam created by the Green Building Certification Institute (GBCI).
- **Sustainable Forestry Initiative (SFI):** An international organization created in 1996, which provides lumber producers with a standard for managing forests in a sustainable way. The organization also provides the means to track lumber and paper products from the forest to the job site, also known as chain of custody.

Downcycling

The term *downcycling* was first coined by Reiner Pilz and Thornton Kay in 1993. It refers to a material that has either been recycled into a material of lower grade, as in the case of some plastics, or the reuse of a product that has diminished performance characteristics for an alternate purpose, such as the reuse of batteries for lower-power appliances. In most situations, recycling is downcycling. The term *recycling* implies reuse with no loss of material purity. With each step of downcycling, a material loses its quality. For example, when plastic waste, other than that found in soda and water bottles, is recycled, it is mixed with different polymers to produce a hybrid plastic of lower quality, which is then molded into something relatively inexpensive.[8] Downcycling also describes the reuse of a material that has outlived its peak performance to serve another intended purpose (e.g., the reuse of old bath towels or cloth diapers to clean hand tools or to apply a finish to wooden furniture).

Embodied Energy

The embodied energy of a material or product is the total energy consumed during its life cycle. The embodied energy required to extract, process, manufacture, and transport a material or component to a factory or the project site deserves careful consideration.

Although it is difficult to quantify, embodied energy units are generally measured in megajoules of energy needed to produce a kilogram of a product or material. This, in turn, is converted into the tonnage of carbon dioxide created by the energy required to make a kilogram of the product.[9]

Wood and wood-based products have, in general, a significantly lower embodied energy than most plastics, concrete, and metals. Aluminum, because of the processes required in its production, has an exceptionally high embodied energy.

Life-Cycle Assessment

Life-cycle assessment (LCA) is a broad valuation given to the environmental impact caused by the use of a material or product. The impetus is to develop and use highly durable, long-lasting materials that minimize the need for frequent replacement. The intention is to use fewer natural resources and reduce the amount of waste that ends up in landfills. Other considerations of life-cycle assessment include the cost of using and maintaining materials over time.

A holistic life-cycle assessment of a material encompasses and considers the extraction of raw materials, manufacturing processes, use, disposal, all transportation required of a material, how long it lasts, and what happens when the material is no longer usable. Data are collected regarding both environmental and technical considerations for all phases and processes of the material or product. The summation of all data is organized into tables, and the result can provide a means of interpolated measure, useful in determining the inputs and outputs from all aspects of the product and assessing its impact upon the environment.

Local Materials

Using locally available materials contributes to the reduction in fossil fuels necessary for their transportation. It is also important to produce cleaner-burning fuel alternatives that do not contribute to the emission of greenhouse gases. Projects may earn points under LEED when the extraction, manufacture, and assembly of materials occur within 500 miles of the project site. The intent of crediting points to projects that use materials extracted and manufactured regionally is to support regional economies and minimize the environmental impacts resulting from transportation.

Natural and Synthetic Materials and Components

Natural *organic* materials and components are carbon based and of biological origin. Organic materials burn and naturally decompose over time without contaminating the food chain. Wood is a natural organic material. (Bamboo, cork, sisal, and wool are natural organic components that require some

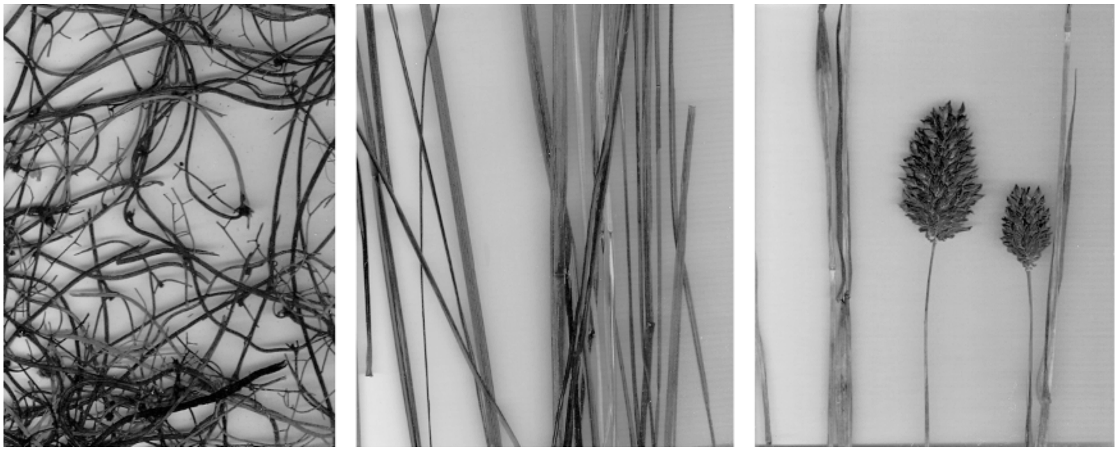


Figure 1-33 Veritas natural grasses (Napa, Savannah, and Lucille) laminated in polyethylene terephthalate glycol (PETG) resin sheets. *Material scan by Nancy Gesimondo.*

assembly before they can be used as an interior finishing material.) Natural *inorganic* materials and components are inert and naturally formed by the earth instead of by carbon-based plants or animals. Stone is a natural inorganic material. (Metal and sand are natural inorganic components.)

Synthetic materials and components are made by humans. They are often created by a chemical synthesis with the intention to imitate or improve the properties and performance characteristics of natural organic materials. However, synthetic materials can also be classified as either organic or inorganic depending on the origin of their components. Ceramic tile, cork, and linoleum are all considered synthetic organic materials, because although their primary components are derived from biological origins, they are not found in nature ready for use. Nylon and wool carpet are also considered synthetic organic materials because both are composed of carbon-based organic components.

Composite materials and composite assemblies such as concrete, glass, and terrazzo are made of natural inorganic *components* (i.e., lime, silica, and crushed stone), but classified as synthetic inorganic *materials* because they are manufactured. Stainless steel and aluminum are alloyed metals that are categorized as synthetic inorganic materials for the same reason. Plastic laminate is considered a synthetic inorganic material because the resins used in its manufacturing are synthetic and thereby override the organic categorization of the layered kraft paper. Fiberglass is another synthetic inorganic material because of the silica content in the glass mesh. With few exceptions, synthetic materials are nearly always homogeneous due to the industrial processes of their manufacturing. Synthetic composite materials can also combine natural organic materials, preserving them in time like fossils (see Figure 1-33).

When we consider materials that are a hybrid of either category, it becomes apparent that there are many shades of "green." Natural organic and inorganic materials could potentially deplete limited natural resources, and both synthetic organic and synthetic inorganic materials are responsible for emitting harmful toxins into the environment. As a general rule, however, natural materials are considered "greener" than synthetic materials because they require less energy to produce, emit fewer chemicals during manufacturing, and can potentially renew their supply naturally.

Rapidly Renewable Materials

Rapidly renewable materials are raw materials that take 10 years or less to grow and harvest in an ongoing and sustainable manner.[10] These materials are considered to be an agricultural product (including fiber and livestock). Using rapidly renewable materials in construction can help to reduce the depletion of limited natural materials and long-cycle renewable materials. Rapidly renewable materials include:

- Bamboo core plywood and flooring
- Cotton batt insulation
- Cork flooring

- Linoleum flooring
- Straw bale and straw board
- Wheat board
- Wool carpets

Reclaimed/Repurposed Materials

Examples of reclaimed materials include brick, millwork, lumber, appliances, and hardware. Reclaimed materials can also be repurposed to serve a new function. Specifying reclaimed materials offers several environmental benefits. Old gymnasium maple floors can complement contemporary loft-style residential spaces. Bookshelves once used in a retail environment can function as residential furniture. Doors can serve as work surfaces; stone trim from a wall can be used in casework or freestanding case goods in a new space. Using reclaimed materials brings a unique character and cultural value to new construction and furniture while making societal links to the community's past.

The downside in specifying reclaimed materials lies in their limited availability and the difficulty in predetermining their condition. These challenges make it difficult to assume either a qualitative or a quantitative assessment for their potential reuse. Generally, reclaiming and repurposing are core elements of sustainability, which are more the responsibility of the user, as no standards or certified dealers currently exist.

Recycled Materials

Recycled materials comprise a larger category of materials that have been collected, reprocessed, reused, and thereby diverted from becoming solid waste in a landfill. Using recycled materials makes a deliberate contribution to the reduction in resource depletion. Recycled materials are classified as either *preconsumer* or *postconsumer* recycled materials.

Preconsumer recycled materials have various percentages of industrial by-products in their manufacturing. These products can be referred to as *postindustrial products.* An example of a preconsumer recycled material is fly ash, the fine powder produced as a by-product of burning coal for the production of electricity. These micrometer-sized elements consist primarily of silica, alumina, and iron. When mixed with lime and water, the fly ash forms a cementitious compound with properties similar to that of portland cement. Fly ash can be used to replace a portion of the cement in concrete, providing a denser, tighter, and smoother surface with less bleeding. Fly ash concrete offers improved strength, textural consistency, and sharper detail over conventional concrete, without requiring any manufacture or cluttering of landfills.

Although preconsumer recycled products use by-product material from industrial manufacturing processes (such as PVC scrap from PVC pipe manufacturing to make roof shingles), preconsumer recycled materials generally do not include scrap from manufacturing processes that would normally have gone back into the manufacturing of the same products. Examples of these products include MDF and wood composite boards, such as particleboard.

Postconsumer recycled materials are generally preferable to preconsumer recycled materials because postconsumer recycled materials contribute significantly to diverting waste from landfills. Postconsumer recycled materials use waste that has been used and disposed of by consumers such as newspapers and cans, which then serve as the raw materials for other products. Examples of postconsumer recycled materials include carpets made from plastic milk containers, rubber flooring products made from recycled automobile tires, and interior components made from recycled plastic waste.

Although postconsumer recycled materials are a significant green-material category, the percentage of recycled postconsumer content and concern for potential off-gassing need to be reviewed on an individual basis. Remember, greenhouse emissions can come from repurposing processes.

Building products made with recycled content are less harmful to the environment. Many products and materials available today embody a substantial percentage of recycled content. Examples of materials with mostly recycled content include, but are not limited to:

- Acoustic ceiling tiles
- Carpet
- Composite boards
- Composite floor tiles
- Concrete
- Glass
- Gypsum
- Insulation
- Masonry
- Metals
- Terrazzo

The amount of postconsumer recycled content in steel products ranges from 20 to 25 percent. Some materials, such as Homasote and oriented strand board (OSB), are manufactured out of 100 percent postconsumer recycled materials (see Figure 1-34).

Homasote is the proprietary name of a fiberboard product made entirely of recycled newspapers, manufactured in 48 by 96 inch (122 by 244 cm) sheets, and produced in and distributed from Trenton, New Jersey. Homasote is valued for its acoustical and insulating properties and is a durable product. OSB is a composite board formed by layering strands of reconstituted wood in specific orientations and forming these stands into sheets measuring 48 by 96 inches (122 by 244 cm). The strength of these materials is quite low, however, due to their manufacturing. Furthermore, they contain high levels of formaldehyde.

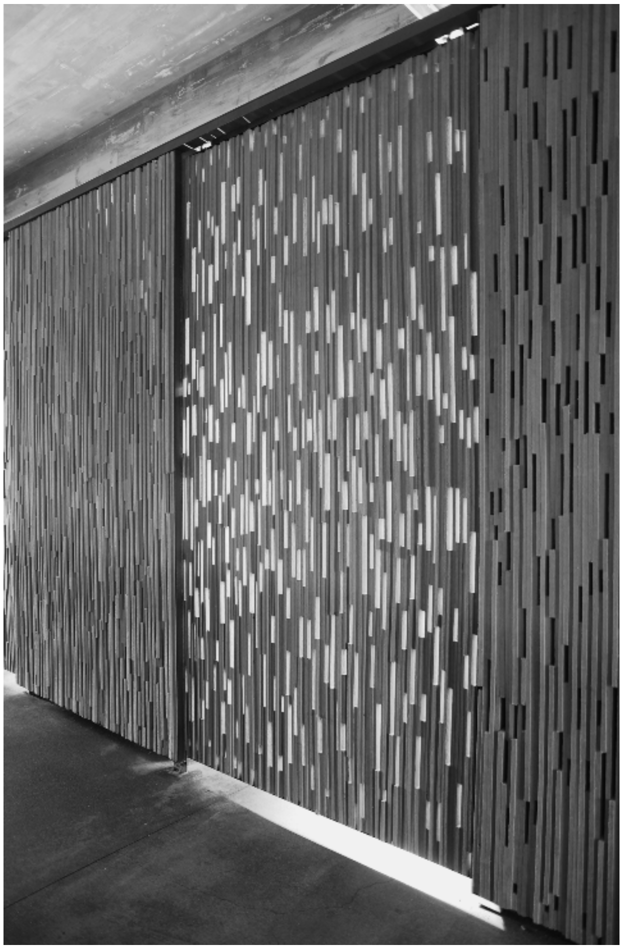


Figure 1-34 Laminated strips of Homasote are used to make perforated sliding partitions for Lightborne, Cincinnati, Ohio, designed by Terry Boling (1997). *Photography by Terry Boling.*

Today, manufacturers are responding to the consumer's desire to use more ecologically sensitive products and capitalizing on the cost effectiveness of incorporating recycled materials into new products with market appeal. The amount of recycled material content is highlighted and often compared in product specification literature. Ecologically conscious manufacturers are directing architects and designers to online resources for product literature in an effort to reduce the use of paper used for cut sheets. Some companies will pay the return shipping costs for product binders so that they can be reused. Most major manufacturers provide free shipping for sample reclamation, which can reduce the amount of waste that might otherwise end up in a landfill. Design firms can assist in this effort by collecting and separating unwanted samples to return to individual manufacturers for redistribution. An architecture or interior design firm can donate unwanted samples to organizations such as SpecSimple, which redirect them to design schools or other not-for-profit institutions that will use them as art materials. Visit www.specsimple.com for more information on its Save A Sample! program.

Upcycling

Upcycling is the other half of the recycling process, which aims to reduce the consumption of natural resources and divert used products from a landfill. However, rather than using energy to pulverize used materials into ingredients for new materials of possibly lesser quality, used materials are creatively reused in their natural form for useful, high-quality products. Upcycling is popular because of its economic advantage, especially in developing countries, where the purchase of raw materials is cost prohibitive.

Volatile Organic Compounds

The sources of VOCs emitted from material fabrication and installation processes, and their effect on indoor air quality, are outlined in the "Health, Safety, and Welfare" section at the beginning of this chapter. In this section, we focus on the hazardous effects of VOC emissions on the environment. Materials precipitate VOC emissions in two ways. One result is from the chemical composition of the material, but the most significant consequence is from the amount of energy expended by the milling processes.

However, the use of chemicals and industrial processes are not the only sources of VOCs. The metabolic systems designed by Mother Nature herself, including water vaporization and the decay of organic matter, are responsible for producing greenhouse gases. Since the Industrial Revolution, there has been an increase in the burning of fossil fuels and forest clearing, which has disrupted the ecosystem's natural balance. Most researchers believe that CO_2 (carbon dioxide), which is emitted from the burning of fossil fuels, is the largest contributor to the greenhouse effect. Deforestation is the second largest contributor to the rise in greenhouse gases because the leaves of the plants and trees are no longer there to filter and purify the air. The accumulation of VOCs in the atmosphere blankets the earth with greenhouse gases that absorb and emit infrared radiation. These trapped gases reradiate the absorbed heat back down to the earth, causing an increase in temperature, which leads to melting of the polar ice caps, glacial retreat, and a rise in sea levels worldwide. Ground-level ozone (also known as smog) forms when hydrocarbons and nitrogen oxide react with sunlight. In addition to causing many cardiopulmonary problems in humans, air pollution from ground-level ozone has been linked to the reduction in agricultural production because of its interference with photosynthesis. The reduction in the ozone layer raises concerns for the ecosystem as a whole and marine life in particular. Ocean oxygen depletion results as larger amounts of CO_2 are dissolved in the oceans.

Main greenhouse gases include:

- Water vapor
- Carbon dioxide
- Methane
- Formaldehyde
- Nitrous oxide
- Chlorofluorocarbons
- Sulfur hexafluoride
- Hydrofluorocarbons
- Perfluorocarbons
- Nitrogen trifluoride

Natural sources of VOCs include:

- Wetlands
- Ruminant livestock such as cows, pigs, goats, sheep, bison, etc.
- Rice agriculture
- Burning biomass

Artificial sources of VOCs include:

- Burning gasoline and automobile exhaust
- Upstream oil and gas production
- Burning biomass such as wood
- Evaporation of liquid fuels and solvents
- Production of building materials and furniture
- Office equipment such as photocopy machines
- Landfills

At this time, there is tremendous opportunity for the development of renewable energy sources. One of the most promising solutions for reducing the emission of landfill gas is the use of anaerobic methane digesters that capture and convert methane into biogas. Converting greenhouse gases such as methane and carbon dioxide into renewable fuel has been proven to reduce millions of metric tons of greenhouse gases.

In an effort to address issues of climate change, the EPA has issued regulatory actions under the Clean Air Act. Visit www.epa.gov/climatechange/initiatives/index.html for information on proposed greenhouse gas permitting requirements on large industrial facilities, waste recovery registration, renewable fuel standards, and geological sequestration of carbon dioxide.

MATERIAL PROPERTIES AND PERFORMANCE CHARACTERISTICS

We gain insight on how a material can be expected to perform through an understanding of its many inherent properties. Considering a material's attributes along with the environmental and structural conditions of the space in which it will be installed allows one to better understand how the selection of materials is integral to the design process. By highlighting all of a material's properties and performance characteristics, a designer might be inspired to use a conventional or highly unconventional material in an application previously unimagined.

What material properties should architects and interior designers consider in the design process? Some important technical and material matters arise when the following questions are raised:

- How much do materials expand or contract when exposed to environmental changes in humidity or temperature? This can help establish an index to quantify a material's stability and its structural qualities.
- How well do materials wear and age?
- What environmental conditions or structural characteristics would influence the decision to use a specific type of material?
- Might a material's ability to absorb odor, moisture, and grease influence the designer's decision to use it in a specific area (i.e., kitchen or food prep areas)?
- Might a material's "warmth" or "comfort" guide its use in a specific application?

Performance is perhaps the most critical measure to quantify when making decisions regarding the selection of a material and its detail resolution. It is one thing to understand that vinyl flooring is resilient, but how resilient is vinyl relative to linoleum, cork, or rubber flooring? Further, how might the subfloor and floor assembly influence the performance of resilient materials? Selecting and composing materials that work together is an applied art as well as an applied science. As an applied art, material selection and composition can contribute to or take away from a project's success. One can select the highest-quality hard maple strip flooring for a gym floor, but its resiliency will depend on its integration with the subfloor's engineering.

As an applied science, designers depend on their working knowledge and technical understanding of materials. An example of this can be seen in a steel-reinforced concrete floor (see Figure 1-35).

The specific pH of the concrete helps prevent the steel rebar from corroding. When concrete carbonates to the pH level of the steel reinforcing and becomes a less alkaline environment, rapid corrosion begins. The rate of corrosion due to carbonated concrete cover is, however, slower than chlorine-induced corrosion. The tensile strength of steel prevents the reinforced concrete from deflecting. The two materials complement one another. Reinforced concrete optimizes the material properties of both concrete and steel. Together, they are capable of accomplishing greater performance than either

Figure 1-35 Steel and concrete have almost identical thermal rates of expansion. The steel helps the concrete resist tensile forces, and the concrete prevents the steel from rusting due to its alkaline environment. *Photography by Jerry Larson.*

material could achieve independently. Reinforced concrete serves to underscore the potential opportunity of optimizing material properties systematically, although in doing this, new challenges arise, such as bond strength and concrete spall. The introduction of glass fibers to reinforce poured-in-place concrete is another example where mixing different materials together can create significantly new properties and material characteristics. Architects and interior designers depend on their knowledge of the physical sciences in order to determine how material properties may contribute to the performance of buildings and interior spaces.

Materials respond to environmental changes in different ways. Over a period of time, full-spectrum daylight will darken most species of wood. Wood expands and contracts differently with environmental changes in the relative humidity. Metals expand and contract when the temperature changes. Most metals develop a protective patina when exposed to air and moisture, while others, such as unprotected steel, will rust. Leather is affected by temperature and moisture changes. Thermoplastics react to temperature changes and ultraviolet (UV) radiation (full-spectrum light) more than thermosetting plastics. Acrylonitrile butadiene styrene (ABS) is a thermoplastic that is particularly sensitive to fading and becomes brittle when exposed to daylight, while polypropylene plastic is less reactive to daylight, making it more suitable for exterior applications. Concrete never completely cures, and glass is always slumping. All materials undergo some degree of creep when subjected to a uniform load or applied force.

When we consider material properties and performance characteristics within the broader view of architecture and interior design, it becomes clear, especially in technical terms, that materials matter for many reasons. Their beauty can be integrated with performance, purpose, and use. The comparative interior spaces of Carlo Scarpa and JKMM are well known and respected for their poetic use of materials that perfectly suit the performance requirements (see Figures 1-36 and 1-37, and Color Plate 7).

Whether quantitative through numeric measure, or qualitative as perceived through the senses, performance is a relative measure. How well materials perform is influenced by many considerations, grounded by technical properties and physical characteristics. As a matter of introduction, consider the following technical properties and physical characteristics of materials:

- Absorption coefficient
- Acoustics
- Aging and weathering
- Cellular structure
- Compressive and tensile strength
- Density
- Dimensional movement (creep, deflection, expandability, shrinkage, swelling)
- Ductility
- Durability
- Elasticity

Figure 1-36 Lye-finished spruce wood used throughout the interior of Viikin Kirkko, Helsinki, Finland, is environmentally safe and produces a light protective finish. Designed by JKMM Architects (2005). *Photography by Jim Postell.*

Figure 1-37 Olivetti showroom, Venice, Italy, designed by Carlo Scarpa (1957). Scarpa used concrete to create an interior landscape rich in detail and level changes, to accommodate the periodic flooding that occurs in Venice. *Photography by Paul Fatkins.*

- Emissivity
- Flame and smoke rating (Class A, B, or C)
- Moisture resistance
- Stability
- Surface attributes
- Thermal conductivity
- Thermal transmittance
- Workability and joinery

Absorption Coefficient

A material's absorptive quality is dependent on its ability to absorb moisture, oils, and odors. Fabric and unfinished wood will absorb all three. Ring-porous/semiring-porous, open-grain woods such as mahogany take stains and finishes better than diffuse-porous, closed-grain woods such as hard maple or Brazilian cherry. Different woods can receive a deep-looking finish (see Figure 1-38), but the application process necessary to achieve a desirable finish may vary among species.

Some woods, such as teak, have a relatively high oil content and are best finished using shellac. Shellac will adhere better to teak than lacquer or polyurethane because

Figure 1-38 Applying varnish to unfinished walnut and beech draws out the wood's grain and enhances the color. *Photography by Peter Hilligoss.*

shellac is exceptionally sticky. Other wood species, such as Gabon or Madagascar ebony, are remarkably dense and have difficulty absorbing oil finishes. Cork is soft to the touch, will stain when unfinished, is never absorptive, and makes an excellent resilient floor covering. In terms of ceramic tiles, unglazed quarry tiles are often specified in restaurant kitchens because of their ability to absorb grease and oils. Applying a sealer to quarry tiles would eradicate this inherently unique material characteristic.

Granite, a material commonly used for kitchen countertops, will not absorb moisture or odors. Although granite is remarkably dense, the use of impregnating sealers is suggested because bacteria can grow within the tiny pores on its surface. Calcium carbonate–based marble and limestone will absorb moisture and oils. Metals are generally considered nonabsorptive materials, although they are affected by atmospheric conditions and air quality (i.e., air pollution and acid rain). Oils and acids will affect or stain most metals, including stainless steel, over time. Metals can be lacquered to preserve their appearance, but lacquer finishes applied to metal surfaces do not last and eventually their surfaces will oxidize. Powder coating is an effective alternative finish for metals located within interior environments when nonabsorption is desired.

Acoustics

The finish and detail of materials influences how a space will function acoustically. Understanding the influence that materials have on building acoustics is difficult to quantify, however, because their use, application, and detail are as important to consider as their selection.

As an applied science, acoustics demands a working knowledge of physics and human anatomy as well as an understanding of various building technologies. It also requires the understanding of key concepts such as *sound diffusion*, *attenuation*, *sound absorption*, and *sound transmission.* Diffusion of sound occurs when it originates from a single source and spreads out from one location into several surrounding areas. As sound waves bounce and reflect throughout space, they gradually become weaker. This is known as sound attenuation. Eventually, sound waves are absorbed into the various surfaces and materials of interior space. Sound that is not absorbed is transmitted through materials into surrounding spaces. These are generally the lower-frequency wavelengths, which, if left unaccounted for, can contribute to noise pollution.

Technical terms used to quantify and measure acoustics include:

- **Amplitude:** The magnitude of pressure variation within sound waves.
- **Frequency:** The number of completed cycles (pressure fronts) that pass through a point in space per second (measured in hertz [Hz]). Sounds perceived as high notes have high frequencies, and low notes have low frequencies.
- **Phase:** The portion of the cycle through which the sound wave has progressed.
- **Wavelength:** The distance of a sound wave from peak to peak. Wavelength is measured in feet and inches. There is a direct relationship between frequency and wavelength based on the speed of sound.
- **Velocity:** Depends on the medium in which sound travels and the temperature of the medium. In air, at normal room temperature, this is about 1130 feet/second.

The human ear is sensitive to a large range of sound power, from a barely audible 10^{-16} watts/cm^2 to a painful 10^{-3} watts/cm^2. Sound is measured in decibels (dB). The decibel is commonly used in acoustics to quantify sound levels relative to a 0 dB reference. The reference level is typically set at the threshold of perception of an average human, and there are common comparisons used to illustrate different levels of sound pressure. As with other decibel figures, the ratio expressed is normally a power ratio (rather than a pressure ratio).[11]

140 dB	Jet plane takeoff		10^{-3} watts/cm^2
130 dB	Gunfire	Threshold of pain	10^{-4} watts/cm^2
120 dB	Hard rock band	Deafening	10^{-5} watts/cm^2
90 dB	Loud street noise, kitchen blender	Very loud	10^{-7} watts/cm^2
80 dB	Noisy office, average factory	Difficult to use phone	10^{-8} watts/cm^2
70 dB	Average radio	Loud	10^{-9} watts/cm^2
60 dB	Average office	Usual background	10^{-10} watts/cm^2
50 dB	Average conversation	Moderate	10^{-11} watts/cm^2
40 dB	Private office	Noticeably quiet	10^{-12} watts/cm^2
30 dB	Quiet conversation	Faint	10^{-13} watts/cm^2
20 dB	Whisper		10^{-14} watts/cm^2
0 dB	Threshold of hearing		10^{-16} watts/cm^2

Most adults can hear sound frequencies between 20 and 16,000 Hz. People are most sensitive to frequencies between 3000 to 4000 Hz. Speech is composed of sounds ranging from 150 to 5000 Hz.

- The human ear is less sensitive to low frequencies than to middle and high frequencies.
- It takes at least a 3 dB change to make a perceived change to the level of sound.
- Sounds above 85 dB can cause hearing loss.

Wallace Clement Sabine developed the first equation for reverberation time, which has since been named after him and is still used today. Reverberation is the prolongation of sound as it repeatedly bounces off reflective surfaces. Reverberation time is defined as the length of time required for sound to decay 60 dB from its initial level. The recommended time for offices is typically 0.3 seconds, while an auditorium is 1.8 seconds.

Sabine's formula is:

$$RT(60) = 0.05V/\Sigma(S) \times a$$

where:

RT(60) = reverberation time (sec)
V = room volume (ft^3)
S = surface area (ft^2)
a = absorption coefficient of material(s) at given frequency
ΣS = summation of S for all room surfaces.

A *sabin* is the absorption value of 1 square foot of material with a perfect absorption rating of 1.0.

Consider the following general concepts relative to materials and acoustics:

- Avoid hard and flat reflective surfaces on the walls, floor, and ceiling.
- The average absorption coefficient of a room should be at least 0.2.
- An average absorption coefficient above 0.5 usually is not desired. A lower value is suitable for large rooms; larger values are suitable for smaller or noisy rooms.
- Each doubling of the amount of absorption in a room results in a noise reduction of only 3 dB, which is hardly noticeable. To make a noticeable difference, the total absorption must be increased by at least three times to reduce the noise by 5 dB (which is noticeable).
- For sound absorption, ceiling treatment is most effective for large rooms, and wall treatment is effective for small rooms.

- Good acoustics for piano or organ music is different from good acoustics for voice. As a rule, voice prefers a low reflectivity, and organ music prefers a higher reflectivity rating.
- Consider absorptive material in ducts as well as the velocity of air movement due to the size of ducts (excessively small ducts may be noisy; excessively large ducts may not produce sufficient airflow).
- Consider a double structured wall, resilient flooring, or soundboard over gypsum board and lay-in insulation in the ceiling areas.
- Avoid room shapes that focus sound (i.e., barrel-vaulted hallways and circular rooms).
- Minimize shared wall areas between two rooms where a reduction in sound transmission is desired.
- Caulk and seal all partitions, edges, joints, and seams. A hairline crack can decrease a partition's transmission loss by about 6 dB.
- Consider mounting mechanical equipment on resilient pads.
- Plumbing pipes should not be rigidly attached to studs.
- Connections between vibrating equipment and ducts attached should not be rigid.

For Speech Privacy

- The ceiling's exposed material must be highly absorptive.
- There must be space dividers to help reduce the transmission of sound between adjacent spaces.
- Floors, windows, and furniture must be designed or arranged to minimize sound reflections. A window, for example, can reflect unwanted sound around a partial-height partition.

As an applied art, acoustical design requires intuitive judgment, an ear for sound quality, and a working knowledge of material finishes and details. Consider the interior spaces designed by the architect Alvar Aalto (see Figure 1-39), particularly the wall and ceiling surfaces in which acoustics was considered in both the purpose and the aesthetics of the space. Cafés and restaurants, in particular, are difficult spaces to design acoustically because all of the surfaces must be resistant to staining and need to be cleaned frequently.

Aalto was able to incorporate his understanding of spatial sound and reverberation with his ability to compose space and form with the selection of these sound-absorbing perforated wood details.

The lobby and upper-level spaces of the Seattle Public Library, designed in 2003 by OMA, are spatially striking (see Figure 1-40).

The building and its public interior spaces serve as a showcase for new information and are intended as places for repose. Nonetheless, the acoustics throughout many of the public areas is quite loud. The "living room" lobby is located under a 50-foot-high structural steel and glass skin. This element, along with the building's central and angular atrium, open circulation, and interconnected spaces, contribute to the interior's lively acoustics. In fairness to both the design of the building and to the designers, the interior spaces and deliberate use of materials mirror the building's successful social interactivity, which, in turn, results in the transmission of sound that accommodates the social activity. By ignoring traditional library acoustics, another idea that embraces the urbane has, perhaps, been created.

Floor, wall, and ceiling assemblies can receive a numeric value that quantifies their ability to reduce the transmission of sound, articulated in increments of 5 points. The numeric value is known as an assembly's Sound Transmission Class (STC). The value is dependent on the material used in a particular assembly as well as the composition and detail of its parts. The higher the STC rating, the better the sound reduction capability of the wall, partition, or ceiling assembly becomes. Relatively low STC ratings are in the numeric range of 25 to 30 points, and relatively high STC ratings are in the range of 60 to 65 points.

In conclusion, several factors involving the selection and use of materials can influence the acoustical characteristics of interior space. These include the activities within the space. Consider how use and the expectations of use can influence the acoustics of interior space. In addition, consider the sources

Figure 1-39 The spacing of birch wood slats of the interior millwork helps to improve the acoustics in the dining area of Baker House, Massachusetts Institute of Technology, Cambridge, Massachusetts, designed by Alvar Aalto (1947–1948). *Photography by Ben Meyer.*

Figure 1-40 In the lobby of the Seattle Public Library, Seattle, Washington, over half of the glass and aluminum curtain walls is triple-pane glazing with an expanded aluminum metal mesh sandwiched between the outer panes. Designed by Rem Koolhaas of OMA (2004). *Photography by Michael Zaretsky.*

of sound and noise (unwanted sound). Collectively, acoustics depends on many factors, including: the source of the sound and its transmission through material, the sound-absorbing and -reflecting qualities of interior surfaces, and the reverberation time of sound in space.

Aging and Weathering

Climatic and environmental conditions of humidity, moisture, air pollution, wind, and solar exposure all have a significant influence upon materials. Aging processes are evident in a material's decay, illustrating the temporal quality of all things physical. Copper, wood, leather, and concrete all will develop a patina over time.

Patina is a term used to describe a surface condition produced by a material's exposure to natural elements such as moisture, air, and sunlight, as well as by age, wear, or rubbing. Ultraviolet radiation breaks down the natural pigment in wood, causing lumber to turn silver over time. The span of a beam or the horizontal members of a bookshelf will always experience some degree of creep. Creep is the deformation of a material or assembly over time, when subjected to a constant load or uniformly applied force.

Aspects of aging and weathering are vital considerations with regard to the specification of materials. As materials wear with use and weather over time, their properties will change. The surface and finish of a wood or marble floor needs to be routinely maintained. Changes due to both use and time can make material selection and specification a challenge. Would the natural patina and oxidation of copper or select hardwoods influence their use in design? Would heavy traffic in a lobby or hallway limit the option to specify an engineered wood floor? Is it sensible to specify a tufted wool carpet in an entrance area or would nylon carpet tiles be a better choice? How might considerations of use and maintenance influence the specification of color and weave in carpet? These considerations can directly influence the selection and specification of materials, which, in turn, influence the assembly and detail of larger interior components.

Imperfections caused by age, use, and weather can hold value. Wood will eventually develop a silver gray patina, copper panels oxidize over time, and stone steps can become gently worn over years of use. Age and weathering, depending on the context, can be considered an asset.

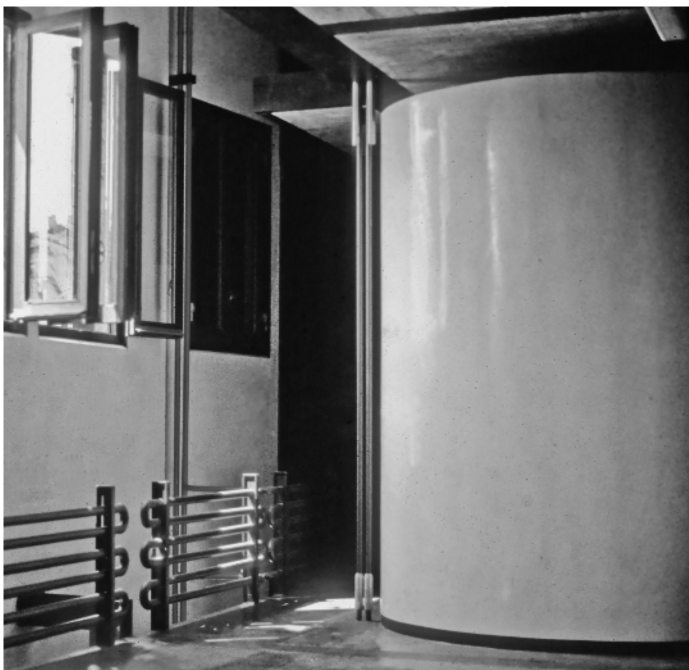
To illustrate this concept, we can consider the work of three 20th-century architects, Frank Lloyd Wright, Carlo Scarpa, and Alvar Aalto, who were each conscious of the potential benefit that time has on materials and buildings. Frank Lloyd Wright wrote about nature and said, "Nature, by invitation, would become the ornament of the building." He further explained: "ornament is to architecture what efflorescence of a tree or plant is to its structure. Of the thing, not on it."[12] Extending beyond the inspiration of nature into built form, the consideration of water, icicles, and trees was a conscious aspect in his architecture. Perhaps the greatest example of nature and building coexisting in harmony is Fallingwater, designed in 1938, at Mill Run, Pennsylvania (see Figure 1-41 and Color Plate 25).

Carlo Scarpa's work is renowned for its use of material, joinery, and workmanship. Scarpa deliberately used materials that would age and wear well over time. Stucco alla veneziana was one of his favorite wall finishes because of the lustrous patina it develops. He used it in many of his interior projects, including Banco Populare in Verona, Italy, and the Palazzo Fondazione Masieri renovation near the Grand Canal in Venice, Italy (see Figure 1-42 and Color Plate 21).

Stucco alla veneziana is a type of Venetian plaster, the details of which can be found in the section on decorative paint techniques in Chapter 3 under "Paint and Decorative Finishes."

▼**Figure 1-41** The existing slate stone on the site was used to locate the living spaces of the residence. Its rippled reflective surface recalls the stream below. Fallingwater, Mill Run, Pennsylvania, designed by Frank Lloyd Wright (1938). *Image courtesy of the Library of Congress.*

▲**Figure 1-42** Interior of Palazzo Fondazione Masieri, Venice, Italy, showing the traditional stucco alla veneziana wall finish. Designed by Carlo Scarpa (completed 1984). *Photography by Jim Postell.*



Cellular Structure

A material's cellular structure influences its technical properties, including abrasion resistance, moisture resistance, density, hardness, and its ability to absorb odors. Very often, a material's technical profile has a direct relationship to its performance. As an example, the high-density and low-moisture-absorptive quality of selective clays is a basis for determining the frost resistance in freeze/thaw-rated porcelain tiles.

Each material, whether classified as either natural or synthetic, has a unique cellular structure that contributes to its visual and visceral appeal, which, in turn, influences its inherent performance characteristics. For example, wood is not considered a homogeneous material due to its differing grain density, figure, and cellular structure within a specific tree or between different species. Therefore, the properties and workability of lumber may not be uniform. Steel, on the other hand, is a homogeneous material and its properties and workability are relatively uniform. The specific arrangement and content of a material's molecular structure will influence its properties and workability and can help to determine whether a material is porous or impervious, transparent or opaque, flammable or fire retardant. In short, a material's use and properties are directly related to its structure at a microscopic level.

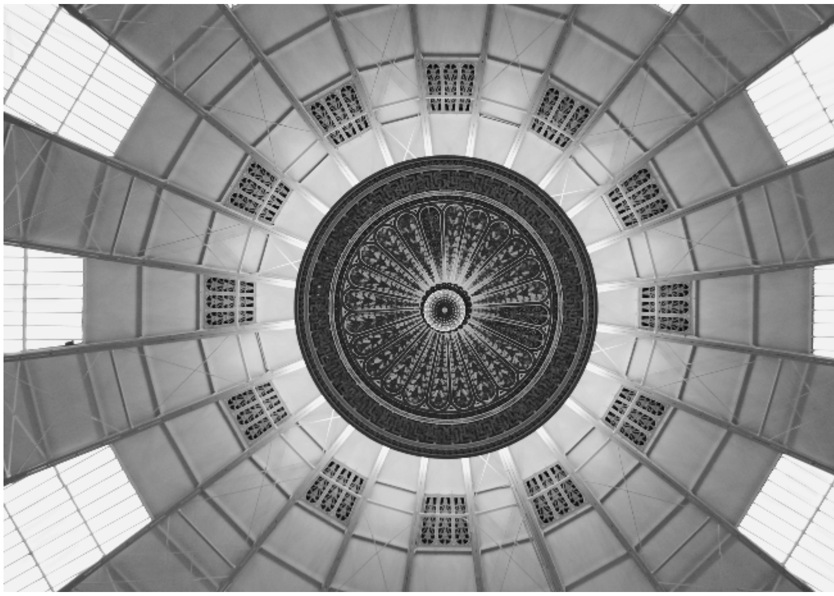


Figure 1-43 Long-span steel structural members support a 200-foot-diameter open space at the West Baden Springs Hotel, West Baden Springs, Indiana (renovated in 2006). *Photography by Sina Almassi.*

Compressive and Tensile Strength

The compressive and tensile strength of materials are both related and distinct in their performance capabilities. Compressive strength is the ability of a material to resist compressive forces (pushing), while tensile strength is the material's ability to resist tensile forces (pulling). Wood generally performs well in both compression and tension parallel to the grain, but when forces are applied at a right angle to the grain, it can split. Wood does not resist shear forces well, especially when these forces are applied along its grain. Concrete performs well in compression but poorly in tension. Steel has excellent tensile and compressive strength, making it an ideal choice for long-span structural framing. Two examples of remarkable long-span interior spaces are the West Baden Springs Hotel in Indiana and the Crystal Cathedral in Garden Grove, California.

The long-span steel framing of the West Baden Springs Hotel supported the largest free-spanning dome in the world until 1913. After falling into disrepair, due to financial issues related to the stock market crash of 1929 and its closing shortly thereafter, the hotel was renovated in 2006. Today it serves as an excellent example of long-span steel structural framing (see Figures 1-43 and 1-44).

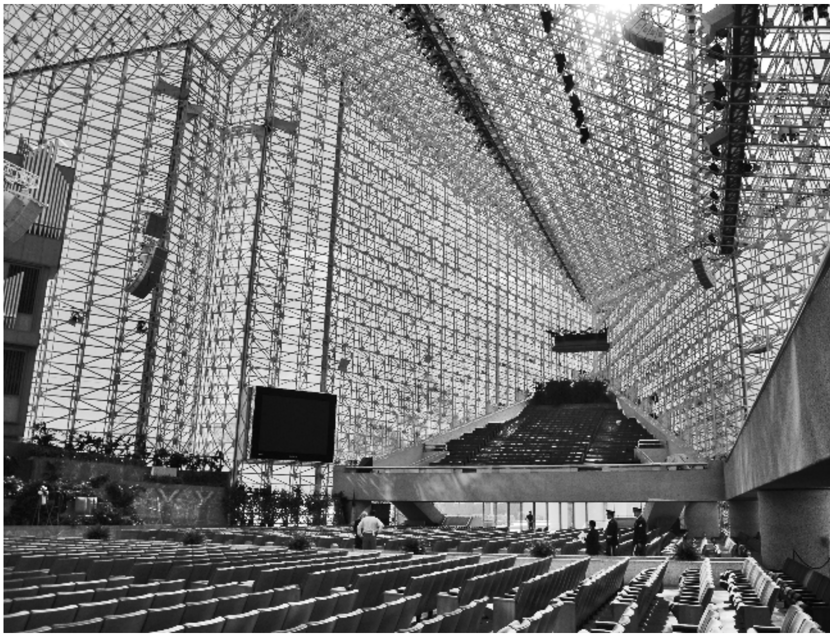


Figure 1-44 Long-span steel structural members support an open space that is 460 feet long by 200 feet wide by 128 feet high (larger than Notre Dame Cathedral in Paris). The Crystal Cathedral is located in Garden Grove, California, designed by architect Philip Johnson (1980). *Photography by Jerry Larson.*

Figure 1-45 ¾-inch ipe lumber used for outdoor decking and guardrail parapet at the Museum of Contemporary Art, Denver, Colorado, designed by David Adjaye (2009). The building is Gold LEED certified. *Photography by Malcolm Lee.*

Density

Density is the weight of a material relative to its volume or mass. For certain materials such as concrete, masonry, and stone, density classifications, such as the Mohs scale of mineral hardness, are used to define material properties, including strength. For other materials, such as wood, density classifications are far more diverse, making it difficult to generalize material properties among species. Brazilian cherry and ipe lumber (see Figure 1-45) are significantly dense tropical hardwoods that have a beautiful grain figure and make good choices for hardwood flooring. Specifically, ipe has a modulus of elasticity of 3000, making it five times stiffer than traditional pressure-treated lumber. This enables ipe decking to be ¾ inch thick, as opposed to the traditional 5⁄4-inch-thick decking lumber. In addition, due to its dense cellular structure, the wood remains stable over a long period of time.

Paper is a lightweight material made from wood pulp and is relatively warm to the touch. Although paper and cardboard are considered fragile and nonstructural materials, they can and have been used as building materials, as Shigeru Ban used in his paper tea house.

A material's density does not have to be a limiting factor in design, only another opportunity for design innovation and careful consideration.

Dimensional Movement

All wood species shrink upon drying and expand when their cells hydrate. Note, however, that wood does not begin to shrink until all free water is removed and bound-water loss begins. The moisture content of hardwood lumber must be within a range of 6 to 12 percent prior to working with it in order to meet the standards established by the National Hardwood Lumber Association (NHLA) grades. Some woods shrink and expand more than others. This is why different woods ought not to be joined along their end grain. In addition, there is a noticeable variation within any wood species between its tangential shrinkage (in the direction of the growth rings) and its radial shrinkage across the growth rings (see Figure 1-46). The internal and inconsistent stresses in lumber depend on how the log is cut at the mill. Plainsawn lumber will have a tendency to warp; therefore, stacked and stored lumber requires spacers, which provide air circulation and minimize dimensional movement (see Figure 1-47).

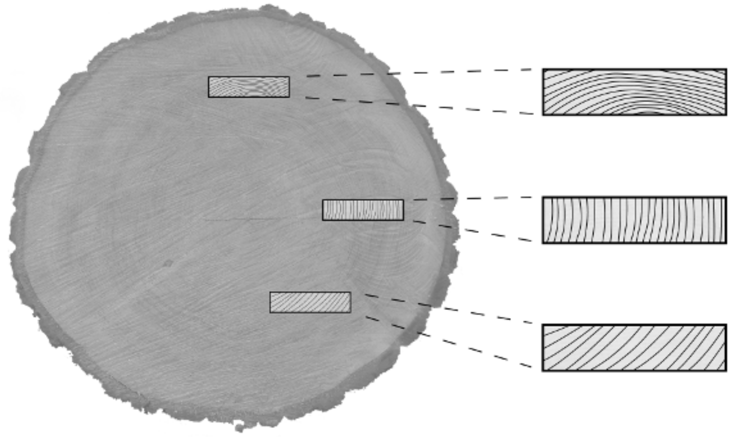


Figure 1-46 Cross section through a deciduous tree trunk indicating the growth rings, showing plainsawn, quartersawn, and rift-sawn lumber and the end grain of these boards. *Computer image by Peter Hilligoss.*

Figure 1-47 Plainsawn Brazilian mahogany boule log in storage at Rud. Rasmussen, Copenhagen, Denmark. *Photography by Jim Postell.*

It is important that designers and architects understand the degree of compatibility between materials that join or connect to one another and know what precautions must be taken to allow for the relative differential in movement by different materials. Quartersawn lumber will expand and contract similarly to plainsawn lumber, but quartersawn lumber is less prone to cupping. Plainsawn lumber has inherently greater internal forces due to its grain and the way in which the wood was cut at the mill. When freshly cut plainsawn lumber dries, it tends to move and shrink more than quartersawn lumber. Wood is not a homogeneous solid material. Although it is solid, a piece of lumber can have areas with a different grain direction or a range of cellular density, making parts of it relatively hard or soft. Because of this, the movement that results from changes in relative humidity is not equal in all directions. Shrinkage takes place in every direction of wood except along the length of the grain. As a general rule, one should avoid gluing wide and long pieces of wood cross-grain to one another and instead consider using a mortise-and-tenon (or slotted) mechanical connection to allow for expansive and contractive movement.

Ceramic and porcelain tiles are significantly distinct in how they are manufactured and in their material properties. Ceramic tiles are made from red clay and are fired in moderately hot kilns (generally at 800 degrees Fahrenheit). Porcelain tiles are made using the dust-pressed method and fired under significantly higher temperatures (up to 2200 degrees Fahrenheit). Due to the material properties of the different clays and the methods used to produce these distinctly different types of tiles, porcelain tiles shrink less than ceramic tiles when fired and are therefore more uniform in their production. This results in a more accurate final shape for porcelain tiles, enabling smaller grout spacing and larger tiles to be applied in the field (see Figure 1-48).

Figure 1-48 Because porcelain tiles are dimensionally stable, narrow grouts and relatively large tiles can be specified and installed. *Photography by Bethany Tozar of Impulse Photography.*

Most materials, except for thermosetting plastics, expand with an increase in either heat or moisture. All metals expand when heated. Wood and leather expand when moisture or humidity is increased. Thermoplastic polymers can deform when heat is applied. Fabric and rubber can deform when tensile forces are applied. To understand and use these facts is to minimize future building repair costs and design for durability.

Ductility

A material's ductility is its ability to be impacted or shaped without breaking. Copper is a ductile metal. It folds, bends, can be hammered or formed, and is easily scratched. Aluminum is far less ductile than copper and is prone to breaking under impact. Aluminum is best when forged, cast, extruded, or rolled into shape. Polypropylene is a ductile polymer and can withstand a significant impact without breaking, especially when an elastomer is added. Cork is a ductile sheet goods material and serves to make an ideal resilient floor.

Durability

Most materials are constantly in a state of flux relative to their color, dimension, surface quality, and structural performance. Applied tensile or compressive forces can influence a material's form. Sunlight, wind, and pollution are some of the exterior forces that influence the quality and integrity of a material's surface. Use, wear, and maintenance also influence the physical condition of materials over time. Together, exterior and interior forces complement one another, and the notion of durability engages both domains.

Durable materials, such as ceramics, masonry, metals, glass, and hard plastics, are generally low in VOC emissions. Thus, durable materials can positively influence the interior air quality of buildings, while enabling the building to gain LEED compliance in VOC reduction.

Figure 1-49 Hot-dipped galvanized steel panels at the State Street Village graduate residence hall, Illinois Institute of Technology, Chicago, Illinois. Building designed by Helmut Jahn (2003). *Photography by Jim Postell.*

The idea of a material's longevity, its ability to wear over time, and its structural stability are considerable attributes when it comes to the specification and use of materials in the process of designing and making buildings and interior spaces. Few materials are inherently durable at every level, but some are considerably more capable in one or more areas. Ideally, architectural materials should be able to perform for as long as possible or as long as the useful life of the building or interior space.

Specific materials within a family classification can be considered more or less durable than other materials in the same class. Thermosetting plastics are inert; once formed, they cannot be reshaped by heat. Epoxy resins fall into this category. Brass is considerably more durable than copper. Galvanized steel, which has gone through a chemical process involving zinc to eliminate corrosion, will last longer than steel when exposed to the environment (see Figure 1-49).

Once aluminum has formed a protective finish through exposure to the environment, it becomes relatively stable. Polypropylene is significantly more stable than ABS plastic. Ipe lumber is far more stable than red oak. Concrete, with fly ash added in the mix, creates a significantly stronger and more durable concrete.

Elasticity

A material's elasticity is evident as deformations produced by low stress are completely recovered once the load is removed. The ability of a material to return to its original shape can offer significant potential for wide-reaching products, which include the wooden skis made of Baltic birch in the 1940s as well as the memory foam pillows manufactured today.

The modulus of elasticity (*Young's modulus*) is a material parameter that describes the relationship between stress and strain when a solid body is subjected to external force. A material with a high modulus of elasticity is considered rigid and will resist deformation, while a material with a low modulus of elasticity will appear pliable when under stress or applied force.

Emissivity

Emissivity is a difficult concept to grasp and is often confused with the notion of heat absorption. Emissivity is the relative measure, on a scale of 0 to 1, of heat (radiation) emitted by a material's surface compared to the energy radiated by an ideal black body at the same temperature and at the same solar angle. As a general rule, the higher the coefficient of emissivity for a given material, the lower is its reflectance value. A surface that has low emissivity such as clean, untarnished galvanized steel absorbs infrared radiation. Aluminum roof coatings have intermediate emissivity levels, while glass and most material surfaces have relatively high emissivity.

A material's emissivity coefficient (ε) is measured using a determined temperature and a predetermined angle. An emissivity of 1 ($\varepsilon = 1$) is an ideal measure, which would suggest that the material completely absorbs all energy and heat. An emissivity of 0 ($\varepsilon = 0$) is similarly an ideal measure, which would suggest an absolutely perfect reflector of energy and heat. Asphalt, plaster, and roofing paper have relatively high emissivity coefficients of 0.93, 0.92, and 0.91, respectively. Aluminum foil, electroplated nickel, and polished iron have relatively low emissivity coefficients of 0.04, 0.03, and 0.02, respectively.

Fire Ratings

Flame and smoke spread ratings indicate how quickly a flame will spread along a material's surface and how much smoke is generated as it burns. A material's surface-burning characteristics rating results from the measurement of its flame spread relative to asbestos cement board (rated 0) and red oak (rated 100). Note that a surface's burning characteristics rating is not an indication of a material's fire resistance.

Materials are tested and rated for their ability to resist both flame and smoke spread when they are ignited. A number of different organizations that have developed specific tests used to measure a material's flame and smoke spread potential. Flame and smoke tests include the vertical Bunsen burner test, the American Society for Testing and Materials (ASTM) E1678 (Standard Test Method for Measuring Smoke Toxicity for Use in Fire Hazard Analysis), and the Steiner tunnel flame and smoke test, which is the current standard. The Steiner tunnel fire test was developed at Underwriters Laboratories (UL) in 1944 and has since been incorporated by many North American standards-writing organizations (e.g., ASTM E84, NFPA 255, UL 723, ULC S102) and has been widely adopted by North American building and fire code regulations. In the Steiner tunnel test, materials are suspended face-downward in a horizontal tunnel, over a fire source below. Though this is not ideal for testing flooring materials, it is nonetheless the standard interim method for determining the fire rating of floor coverings.

The National Fire Protection Association (NFPA) denotes UL Class A, Class B, and Class C classifications that define the allowable flame and smoke spread ratings of materials and finishes for various occupancies and user groups. Products manufactured outside the United States equate these classifications as Class I, Class II, and Class III, which correspond to the international rating system.

Class A indicates materials that have the best flame and smoke spread rating in the industry with a numerical rating at 25 or less. A numerical rating of 25 means that the flame spread of the burning material would spread 25 percent as quickly as would a sample of burning red oak. Class B materials offer a rating between 26 and 75. Class C materials have a flame and smoke spread rating between 76 and 200. In every case, the numerical rating is a percentage of flame spread of the selected material compared to burning red oak, which is used as the testing standard in determining a material's flame spread characteristic. High flame spread ratings indicate poor resistance to flame and smoke spread. Lower numbers indicate better resistance of a material's potential not to spread flame and smoke as quickly as materials with higher flame spread ratings.

Toxic potency for most materials during combustion is relatively similar, save for a few specific anomalies. The primary toxin released when organic materials burn is carbon monoxide (CO). The higher the yield of CO, the higher is the toxicity parameter of the material. Therefore, for most materials, the toxicity of the smoke is relative to the amount of smoke produced when the material burns. PVC, however, has an exceptionally high toxic potency. PVC releases a combustion product known as hydrogen chloride (HCl), which is a significant irritant and is considered carcinogenic. When combusted, PVC releases chlorine gas when sprayed with water or foam. This airborne hydrochloric acid will burn out and destroy microcircuitry. Inhalation of fumes can cause coughing; choking; and inflammation of the nose, throat, and upper respiratory tract. In severe cases, it can cause pulmonary edema, circulatory failure, and death. Skin contact with hydrochloric acid can cause severe burns and eye damage.

Radiant flux and smoke density floor covering flame tests measure the flammability and smoke spread data that is obtained during combustion. Radiate flux (Φ) is the flow of energy per unit of time that is radiated from a source and is measured in watts. The standard test method for determining the critical radiant flux of floor covering systems using a radiant heat energy source is ASTM E648. This test method indicates the critical radiant flux for horizontally mounted floor covering systems. Since April 1999, the U.S. Federal Aviation Administration (FAA) has employed this test to examine the fire behavior of thermal acoustical insulation covering films. Remember that flammability requirements may govern actual product use. Those who specify flooring materials ought to consider floor flammability requirements in addition to reference specifications before selecting a floor covering.

The generation of smoke from a burning material is the most frequent cause of death in a fire situation. The U.S. Department of Health and Human Services has established that floor covering materials used in health care occupancies must have a smoke density of 450 or less. The smoke density rating (overall average) for maple is 365, while bamboo is 298. The test procedure is the ASTM E662 or NFPA 258 method.

Stability

Stability is a characteristic of a material to remain inert, with little or no dimensional change, even when changes occur in moisture, temperature, or applied force. Medium Density Fiberboard (MDF) is one of the most dimensionally stable wood-based composite materials available today and is often used as a substrate for wood veneers and plastic laminations. Marine-grade plywood is excellent for outdoor use or in wet conditions. It is also able to withstand submergence in boiling water for up to an hour without delaminating at the core. Granite and thermosetting plastics are stable materials, dimensionally unaffected by either moisture or temperature.

Particleboard is particularly susceptible to structural deformation when exposed to moisture. Most sheets of particleboard are made with formaldehyde, which does not prohibit moisture from causing the wood chips to expand. For this reason, particleboard should not be used in millwork unless it is adequately supported and protected from moisture. In contrast to particleboard, tungsten is a metal that requires a temperature above 1000 degrees Fahrenheit before it will deform. Tungsten is used in metal tools because it holds a sharp edge at high temperatures.

Surface Attributes

Historically, societies have placed a high value upon the surface and finish of all things made. Beyond their visual appeal, surfaces are felt; they absorb and emit odor; they need to be cleaned and maintained; and most will wear, scratch, and fade. Many common materials such as wood, stone, and natural fabrics are porous and require sealers to protect and enhance their visual appeal.

A material's unique cellular structure will influence its surface attributes. The particular arrangement of its atoms will differentiate if it is absorptive or impervious, brittle or resilient, transparent or opaque, and so on. A material with an open-cell cellular structure, such as cotton, will breathe well. A painted, open-grain wood can be susceptible to peeling when changes in humidity cause the grain to rise and expand. Resilient materials such as cork and linoleum have a unique ability to regain their original surface when weight is removed from their surfaces. Wood can warp, dent, or split. Metal can tarnish, glass can slump, and stone can wear over time (see Figures 1-50 and 1-51).

A material's finish is a visual phenomenon that is dependent on the reflection and absorption of light as well as on color and pattern. Finish can also refer to an applied treatment. Many porous materials, such as wood and stone, require the application of impregnating sealers to enhance their visual appeal and protect them from degradation. Polished stone can be slip resistant when dry but slippery when wet. Architects and interior designers must integrate a material's surface attributes with the proper finish in order to realize the material's maximum potential.

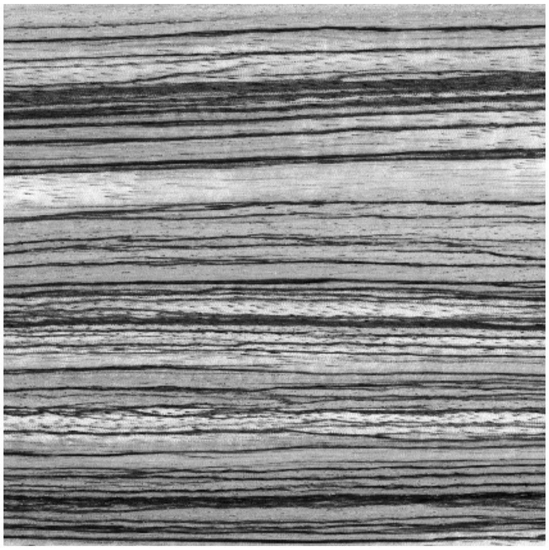


Figure 1-50 Quartersawn zebrawood. The face grain quality is a result of the long and short growing seasons and how the wood is milled. Wood is more resistant to forces applied perpendicular to the grain than those parallel with the grain. *Material scan by Jim Postell.*

Figure 1-51 Coralito marble is a calcium carbonate material, resulting from metamorphic formation under extreme heat and pressure. Its color is a result of the specific minerals in its composition. Marble is a relatively fragile stone, especially along its veins. Therefore, care must be taken in working with long, thin pieces of marble. *Image scan by Jim Postell.*

Thermal Conductivity

A material's thermal conductivity lies in its ability to transfer heat from a region of high temperature to a region of lower temperature. Conductivity is related to the density of a material. Dense materials, such as metals, tend to conduct heat away from the body, resulting in the sensation of coolness to the touch. Concrete conducts heat away from the body 10 times faster than wood, whereas steel conducts heat away 300 times faster than wood. The rate at which heat is transferred through a material is measured in British thermal units (Btu) conducted through the material in one hour.[13]

The insulating value or resistance to heat flow is important to consider when stone or tile is used as a floor covering. Stone and tile floors are perceived as cool to the touch in an ambient environment. However, they have significant capacity to store and radiate heat over an extended period of time, which can be a significant advantage, especially in conjunction with underfloor heating systems.

Consider the perceived temperature of an aluminum panel compared to a wooden panel in a similar thermal environment. Metals, glass, and ceramics are heat-conducting materials and will appear to feel cooler relative to non-heat-conducting materials such as wood, paper, and foam under similar, moderate-temperature, and atmospheric conditions.

Figure 1-52 Tabernacle at Saint Charles Borromeo, Kettering, Ohio, fabricated using tempered glass, cherry, and purpleheart woods. The tabernacle was fabricated off-site, assembled on-site in two parts, and mechanically attached to the floor with anchor bolts (1992). *Photography by Jim Postell.*

Figure 1-53 Cherry lumber with cross-grain figure. *Photography by Michael Toombs.*

Thermal Transmittance

The property of a material to conduct heat is a quantifiable measure of its thermal conductance. Thermal conductivity (*k*) is an inverse measure of the insulating value or resistance to heat flow. Thermal bridging is the result of a conductive material directly transferring heat or cold from the outside to the inside of a building. Thermal bridges penetrate or bypass the insulation system of the building envelope through bridging elements, which might include a metal fastener or a concrete beam, slab, or column. In order to avoid thermal bridging in the design phase, one must establish breaks in continuous materials and insulate between their components and assemblies.

Workability and Joinery

Building materials are generally available in predetermined or limited dimensions. Small-formatted materials are the norm, and they often are combined with other small-formatted materials to form larger components. The workability of materials and the available options in joining and jointing them all together create an important basis for aesthetic expression.

Building components such as floors, walls, and roofs are *constructed.* Interior millwork such as built-ins, casework, and handrails are *fabricated.* In order to realize these components, designers need to consider the workability and joinery of materials as well as the installation of these assemblies in a larger context (see Figure 1-52). In doing so, aspects of durability, structural integrity, aging, weathering, detailing, finish, and maintenance of materials and their surfaces need to be considered in the design process.

Workability is the quality of a material's resistance to being cut, drilled, sanded, planed, folded, or shaped. For wood, the classification applied to the resistance in cutting and the blunting effects on tools is based on the baseline standard of kiln-dried wood at 12 percent moisture content. Mahogany and walnut are relatively easy to cut and carve and are ideal choices for wood-based millwork. Woods that have changes in their grain direction are difficult to joint and plane. Cherry, despite its beautiful grain and figure, often has directional changes in its wood grain, making it difficult to work (see Figure 1-53).

Glass cannot be drilled or cut after tempering. Care should be taken, even in light etching, because these procedures can cause tempered glass to shatter into tiny pieces. Limestone is an unusual stone in that it can be easily drilled, cut, sanded, honed, and carved. Marble, however, is especially fragile along its veins and can easily fail when shear forces are applied along its veins. The workability of metal is influenced by the material's property and dependent on how it was produced, finished, and whether or not it is an alloy. Whether a metal is cast or wrought will influence its hardness, ductility, and surface characteristics. Stainless steel and copper can be welded, but it is difficult to weld copper because the heat required to weld can also melt the copper. In welding copper, low-temperature/high-voltage welds are necessary.

APPLICATIONS

Which building material or interior assembly is best suited for a given purpose? Ideally, the physical and measurable aspects of materials should align with the needs and desires of a building's occupants.

Take wood, for example, as a floor suitable material. When might one consider specifying an engineered wood floor over a hardwood floor? A ⅜-inch-thick engineered wood floor may appear beautiful and be relatively durable, but a cloudy film can result when standing water remains on the aluminum oxide finish for an extended period of time. A solid wood floor may be refinished several times over the course of its projected life but requires a minimum ¾-inch clear depth in order to install. Should the direction of the wood's grain run parallel to or perpendicular to foot traffic? Which species of wood performs better in terms of durability? What attributes should be considered when deciding upon finish? Many aspects are considered when determining a floor's surface. Some considerations have to do with activity and foot traffic. Other considerations have to do with aspects of health, safety, and welfare; wayfinding opportunities; comfort; sound control; sustainability; and aesthetics. Designers ought to consider the broadest possible inquiry relative to purpose and usability in the process of making material decisions.

Materials are used to construct or fabricate interrelated components and assemblies. It is practical to consider material options and design matters in the context of the performance of interrelated assemblies. As an example, tile, stone, or concrete would make a better choice for flooring than wood, cork, or carpet if the floor assembly were to incorporate a radiant heating system. Tile, stone, and concrete would conduct heat from the circulating warm water piping below, transmitting the heat into the interior space. While wood, cork, or carpet flooring would partially trap the heat from the circulating pipes, rendering the radiant heating system less effective. Building components and interior assemblies ought to be designed to work together.

Materials can facilitate and inspire wayfinding strategies through space. Pathways, hallways, ramps, slopes, stairs, escalators, and elevators present unique design opportunities for navigating people through space and influence how they experience built form through circulation. Inherent in the design of these specific interior components are material decisions that are best made in a holistic context and resolved in an integrated manner.

Raised access floor assemblies can incorporate mechanical and electrical systems (see Figure 1-54). Walls and partitions can promote many uses and functions. They have the capacity to control sound, create visual privacy, partition space, and influence thermal comfort. Ceilings can help to control unwanted noise and can incorporate lighting, security, and mechanical systems.

Figure 1-54 TecCrete raised access floor system with Power Base AI, manufactured by Haworth. *Photography by Jim Postell.*

INSTALLATION METHODS

Designing or selecting the appropriate installation method is contingent upon several factors. At the top of the list is the nature of the building material. Other considerations are the existing conditions and properties of the substructure, the adjoining materials and interior building components, and the building assembly. These factors must be integrated with the means and methods available to construct, fabricate, and install the building materials.

Existing Conditions

Existing conditions influence how newly constructed or fabricated components are installed. Whether a component is prefabricated and delivered to the project site or whether the installation is integrated with the on-site construction is significant and must be determined early on in the design phase.

Construction and Fabrication

Although basic installation methods for various products are outlined throughout this book, it is necessary to review and follow all of the manufacturer's recommendations in order to ensure a successful installation that meets the performance expectations and complies with warranty requirements.

Substructures and Assemblies

Substructures and related building assemblies need to be engineered for inclusion with finished materials and specified components. Before selecting a finished floor, wall, or ceiling material, it is important to verify its substructure. Is the substructure framed or solid? What is its depth and bearing capacity? What building or engineering systems are incorporated within the assembly?

MAINTENANCE REQUIREMENTS

The architect or interior designer must consider how a material will be maintained, repaired, and serviced throughout its useful life cycle and share the responsibility to instruct their clients about maintenance requirements. The upkeep of a material must be evaluated when considering a litany of factors pertaining to its integration into the building assembly. An architect or designer can determine if a material would be suitable for a particular application through the comprehensive understanding of how the necessary maintenance requirements affect the durability of the product and the cost of management over time.

Green Cleaning Policies and Products

Many cleaning agents and products used to maintain the materials and components in our living and working environments contain toxic chemicals, such as formaldehyde, harsh acids, and solvents. The U.S. Environmental Protection Agency (EPA) acknowledges that these and other harmful chemicals contribute to poor indoor air quality by emitting VOCs up to five times greater than outdoor levels. Exposure to VOCs can cause a myriad of symptoms, including eye, nose, and throat irritation; headaches; loss of coordination; nausea; or damage to the central nervous system, liver, or kidneys, which can potentially be life-threatening. Some VOCs are known to cause cancer in animals; others are known or suspected to cause cancer in humans.

The biodegradability of cleaning products is another crucial consideration for a holistic understanding of their impact. Once these chemicals are rinsed down the drain, they can do further damage to animals and plants as they make their way into lakes and streams. For example, phosphates, natural inorganic compounds found in many detergents, are a major indicator of water quality because they can upset the balance of nutrients in freshwater environments. Other toxic chemicals can be hazardous to the environment, as well as human health, if they contaminate the food chain.

An impending lawsuit brought by various environmental and health advocates may result in a mandate for manufacturers of cleaning products to disclose a full list of the chemical ingredients in all of their products. Research indicates that the ingredients to avoid are: antibacterial agents, chlorine bleach, petroleum, phosphates, and phthalates. Companies such as Arm & Hammer, Begley's Best, Clorox, Earth Friendly Products, Martha Stewart, Method, Mrs. Meyer's Clean Day, Planet People, and Seventh Generation have introduced nontoxic cleaners for the home.

There are some natural ingredients that can be used to safely clean, disinfect, and polish materials. Various combinations of these basic inexpensive items can be used to substitute for store-bought products, including drain and oven cleaners. Simple recipes can be found at many online green living magazines. Visit www.eartheasy.com/live_nontoxic_solutions.htm, www.thedailygreen.com/green-homes/latest/green-cleaning-46030, or www.co.thurston.wa.us/health/ehhm/pdf/greencleaningrecipes.pdf for more information.

- Baking soda (sodium bicarbonate) can be used as a gentle scouring powder for porcelain sinks, toilets, and tubs; countertops; ceramic tiles; grout; and stone. It can also be used to remove the paint from metal hinges and hardware when mixed with hot water and soaked for a short period of time.
- Cornmeal can be used to absorb carpet spills.
- Club soda can be used to clean some resilient flooring materials such as linoleum or vinyl, polish glass, and remove stains from fabric.
- Hydrogen peroxide (3 percent) is a disinfectant as well as a nontoxic, stain-removing alternative to bleach.
- Lemon juice is an effective grease-cutting and stain-removing agent.
- Liquid castile soap is a gentle vegetable-based all-purpose cleaner with grease-cutting and disinfecting properties.
- Pure essential oils such as eucalyptus, lavender, lemongrass, peppermint, and especially tea tree oils have antibacterial and antifungal properties that can be added to an all-purpose cleaner to create a nontoxic disinfectant as well as to provide a pleasing natural scent.
- Washing soda (sodium carbonate) can be used to clean mineral stains from metals and ceramic tiles and strip wax from wood floors. Washing soda is caustic and must be used with caution in well-ventilated areas and in small doses because it can be harmful if inhaled or swallowed.

Green Depot sells hypoallergenic commercial and industrial cleaning products, including mold remediation products that are Green Seal certified. Visit www.greendepot.com for more information. As with all products, one must read packaging labels for instructions for appropriate and responsible use. Visit the U.S. Department of Health and Human Services Web site for its household product database at www.householdproducts.nlm.nih.gov/ for more information.

Improving indoor air quality is an important health issue in both commercial and residential buildings. Existing buildings seeking LEED-EB certification must have a green cleaning policy in place. LEED points can be accumulated when cleaning products and equipment with a low environmental impact are used and properly stored in a designated and isolated location, such as a housekeeping closet.

RELATIVE MATERIAL COST

There are many considerations that influence the relative cost of a material, including:

- Availability
- Transportation
- Manufacturing
- Installation
- Maintenance
- Life cycle

Material cost is documented as a relative measure throughout this book in order to provide a basis for comparison. As a relative measure, installed material cost is presented in a range from 1 ($) to 5 ($$$$$), with 1 ($) denoting the lowest relative cost, 3 ($$$) denoting the average cost for comparable material, and 5 ($$$$$) denoting the highest relative cost for comparable material. When appropriate, life-cycle cost and maintenance cost are acknowledged in the appropriate sections of the book, but due to the time-sensitive nature of cost, supply and demand, and evolving technologies, the actual cost per square foot or meter has been intentionally omitted. Furthermore, installed pricing will vary depending on the trades and location, but wherever appropriate in Chapters 2 to 5, the relative cost for installation of specific material is included.

RESOURCES AND SOURCES

In Chapters 2 through 5, this heading serves as a compendium of the manufacturers of the materials and building components discussed, along with their contact information and details including where they are produced or their place of origin.