Material Selection for Building Design

Dr John Straube, P.Eng.
Associate Professor, Faculty of Engineering University of Waterloo
& Principal, RDH Building Science

The use of materials is fundamental to the practice of architecture, engineering, and of course to building design. The physical components of civil engineering and building systems are built from materials, whether they are cladding, beams, roofing, pipe, wires, backfill, or roads. In the selection and design of building enclosures, understanding materials takes on a special significance because, unlike a bridge or a pipe, the environmental conditions that a material is exposed to varies significantly with the design and with the layers of an assembly.

From the perspective of performance, the job of the designer is to select materials and arrange them in such a manner as to fulfill the function of that component for its desired service life. Durability can be defined as the ability of a material, component, or system to perform its intended function for the specified or expected service life without unplanned repair and maintenance. It can be said that there are no non-durable materials, only materials used in a non-durable manner – selecting the correct material in the correct arrangement will result in desired performance and durability. For example, although paper is highly susceptible to water, locating paper-faced gypsum on the interior face of an office's exterior wall is acceptable because that wall can be designed to ensure no water is exposed to the paper. Using paper-faced gypsum in a shower stall or directly behind cladding would be a bad design choice and would result in poor durability.

To make the appropriate choice and optimal use of materials, designers and specifiers require some understanding of materials, their properties, and behaviour. What follows is a very broad and general introduction that is intended to organize ones thinking about materials.

Material Classifications

Classifications of matter, based on their properties or their structure, are used to group the many millions of material variations into manageable classes.

The most common classes of engineering materials are metals, minerals, polymers, and composites.

Minerals or Ceramics are compounds formed from the combination of metallic and non-metallic elements. Common ceramic materials include glass, cement, and clay, all critically important materials for the building industry. Ceramics tend to be non-reactive, hard, moderately to very strong, stiff, and brittle. Processed mineral-based materials, such as gravel and stone, are widely used. Glasses are often sufficiently important that they may get their own category.

Metals are mixtures (alloys) of metallic elements, often in crystalline form. They have free electrons that can move readily through the crystals. This explains the thermal and electrical conductivity of metals, as well as their relatively high degree of reactivity (which explains corrosion, or reaction with oxygen). Metals are strong due to their bonding, and ductile due to their structure: these are ideal properties for many structural applications. Different types of metals may be alloyed to create phases within the solid body, or unique metallic compounds that have special properties.

Polymers are molecules based on carbon, hydrogen and other non-metallic elements. They are characterized by the large size of their molecules, and tend to have low density, low stiffness and strength, and sensitivity to temperature. A polymer may be composed of ten to tens of thousands of molecules in chains of repeating mer units. For example, polyethylene is a polymer made from chains of ethylene CH_2-CH_2-and so on. Most polymers are called "organic" (and are often based on hydrocarbons) to reflect the fact that their chemistry is carbon based. Silicone is the only practically important inorganic polymer (they act in many ways like carbon-based polymers, but the bonds are stronger) but replacing hydrogen with fluorine results in some important changes. Important sub-classifications of polymers include elastomers, thermosets, thermoplastics.
Natural polymers (usually carbohydrates), in the form of wood, natural fibres (e.g., cotton), bone, leather etc. tend to be very complex and have traditionally been very important, often being awarded their own category: plant- and animal-based materials.

Composites or hybrids are materials made of more than one material type. These are increasingly important, as they allow materials engineers to design specific properties that take optimal advantage of different materials. Examples include reinforced concrete (steel and concrete), fiberglass (glass fibres in a polyester resin matrix), and wood-fibre reinforced cement. Concrete is a mixture of different ceramic elements and steel is a mixture of carbon and iron, but are considered but are not considered composites because the mixture is occurring at the molecular level. Glass-fiber reinforced cement composites are on the other hand considered a composite because the combination occurs at a macro level.

Other Classifications

Another useful classifications of materials is **inorganic** and **organic**. Organic materials contain carbon, and are often created by or from life forms on Earth. For example, wood, bone, and cotton are all organic carbon-based materials. Oil and natural gas, which are forms of carbon created and stored below the earth for the last

100 to 400 million years, are liquid and gaseous carbon compounds that joined with hydrogen to form hydrocarbons[1]. These compounds are used for man-made organic materials such as most modern polymer plastics. In the past, and increasingly again today, natural renewable sources of carbon, predominately carbohydrate[2] were used to produce natural-sourced plastics such as Celluloid, gutta-percha, Bakelite and Cellophane.

Plant or mineral is another traditional distinction between materials. Minerals are defined as substances that 1. occur naturally, 2. made of substances that were never alive (i.e., hence coal is not a mineral), 3. has an invariant chemical make-up (hence sand is not a mineral, but quartz is), and 4. the atoms are arranged in a regular crystalline pattern (the calcium in milk is not a mineral, since it is in solution, but is a mineral if it forms solid crystalline deposits).

Other classifications of convenience, such as semi-conductors, advanced materials, biomaterials, natural material, etc are made but these are usually not rigorously defined from a scientific point of view, or very useful for guiding building material selection.

Durability for Building Applications

To predict durability, and thereby produce designs with the desired durability, requires an understanding of the most common material deterioration mechanisms. There are three powerful environmental agents of deterioration: 1. heat, 2. ultra-violet radiation (UV), and 3. moisture. Oxygen, is a fourth common and important agent, as it allows oxidation, but usually only in the presence of some of the other agents.

The general classes of materials described earlier have rather specific and common possible failure mechanisms that can guide material selection.

Minerals / ceramics and **metals** are immune to breakdown from UV exposure or high heat—if a material is expected to be exposed to high levels of UV for a long time (e.g. cladding in the Middle East, roofing), materials from these two categories should be selected. Concrete masonry, cement, stucco, and mortar are typically considered durable materials in wet environments, and can tolerate high temperature and low temperatures with no ill effects. However, two common deterioration mechanisms attack these materials: freeze-thaw action and salt expansion

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[1] A hydrocarbon is an organic molecule consisting entirely of hydrogen and carbon.

[2] A carbohydrate is commonly defined as a large biological molecule, or macromolecule, consisting of carbon (C), hydrogen (H), and oxygen (O) atoms, usually with a hydrogen:oxygen atom ratio of 2:1 (as it is in water) giving rise to the hydrate label; the empirical formula is $C_x(H_2O)_n$.

(subfluorescence). Both require significant exposure to moisture (the material must be saturated).

Polymers, including natural polymers, are susceptible to UV degradation, especially the hydrogen-carbon bond: the energy level and wavelength of UV can penetrate the surface and cause the long polymer chains to be broken (weakening the material) and then cross-link (laterally connecting the shortened chains together), causing brittleness. Sunburn, greying of wood, and brittle and weak plastic lawn furniture are all common experiences. Some polymers are much less susceptible to UV (those that replace carbon with silicone and fluorine are almost immune), but most use additives of some form to absorb, block or reflect UV.

Oxidation attacks polymers as well. Typically this requires the presence of UV radiation (termed photo-oxidation) and moisture can also enhance this mechanism.

If the temperatures are high or low for long enough polymers will often degrade. At high temperatures oxidation (polymer chains are split and oxygen atoms are inserted) accelerates, softening or flow begins (e.g. asphalt), and off gassing (volatile organic compounds are released) increases. Some polymers are much more resistant than others. Wood has good performance up to about 80°C whereas polymers without hydrogen-carbon bonds can perform well at elevated temperatures: silicone up to 200°C, fluropolymers like Teflon/PTFE (150°C) and NOMEX fabrics (250°C).

Low temperatures often result in a significant increase of stiffness and reduction in ductility: plastics become brittle when it is very cold. Temperatures of -20 to -40°C can cause some plastics to shatter with even a small impact. At low temperature brittleness can be a problem as polymer chains become rigid and interlock. High-performance polymers like Teflon and NOMEX fabric can remain flexible down to below -80°C, as can many silicones.

Many man-made plastics can be very durable if they are protected from UV radiation and maintained at close to room temperature (hence their predicted lifespan of centuries if discarded in landfills), but they must contain anti-oxidant additives to slow oxidation if exposed to high temperatures and UV-absorbing/blocking additives if exposed to UV. In all cases, high temperatures reduce stiffness and strength, and low temperatures increase stiffness and brittleness.

Natural polymers (cellulose, starch) are affected by all of the above, and can in the presence of moisture, be eaten by decay fungi[3]. This is a critical concern with paper and other processed wood products, and the eventual demise of almost all natural polymers such as wood and bamboo. However, natural polymers are usually more

[3] Even hydrocarbon-based polymers can be attacked by some fungi as well as by hydrolysis, but the process is generally very slow.

insensitive to temperature variations (the mechanical properties of wood are surprisingly stable between -40 and +60C) and hence wood is often used for its structural properties in the extremely cold liquid natural gas industry.

Metals corrode, or, technically speaking react with oxygen, via oxidation. Metallic corrosion is an electrochemical process and hence requires moisture. As sufficient oxygen is available in essentially all practical situations, it is moisture and the electrochemistry that must be managed to ensure durability. Alloys of steel (notably stainless steel) and pure aluminum for strong corrosion products that adhere to and protect the steel. This provides long life in most cases. However, mechanical abrasion and some atmospheric impurities can cause rapid corrosion of even these two relatively durable classes.

Dose-Response Influences

The intensity, duration, and frequency of exposure to a particular agent of deterioration will generally increase the rate of deterioration. A material susceptible to UV degradation can be exposed to hundreds of hours of outdoor light before deterioration is observed, but exposure to thousands of hours of bright sunshine will cause total failure. Masonry may be exposed to many hundreds of rain events, followed by freezing, with no damage, but if the masonry is saturated by long and intense exposure to rain, a single freezing event may cause a visible crack.

Hence the design of building materials, and their selection, is filled with nuance, as some materials of the same class (i.e., plastic, metals, minerals) can be much more resistant to deterioration than others: despite this, it is important to recognize that all carbon-based polymers will be damaged by UV (only the rate of damage can be slowed), all masonry can be damaged by freeze-thaw (only the degree of saturation required can be increased), and all metals will corrode (only the rate can be reduced).

Applications to Building

The designer of a building, especially of a building enclosure, has tight control of the environmental conditions that will be experienced by materials over the life of the product by selecting the materials and their relative arrangement. Whether the material that forms the layer of an air barrier, a seal between water barriers, or the head of a cladding fastener, the expected long-term performance may be judged. Small volumes of unique conditions – nanoclimates – can form and must be foreseen, for example, a pocket that traps water, a joint that allows UV penetration, etc.

Most building products are not made of a single material, but complex composites and hybrids of polymers, metals, and/or ceramics, with a vast array of additives and coatings. This allows manufacturers to supply the most economical, and resource-friendly mix of properties for a specific application but massively complicates product selection. A bituminous air-barrier may have excellent performance based on the SBS-bitumen used, but plasticizers added to enhance flexibility at low temperature may migrate out of the product over time and cause premature failure. Or the polyethylene facer used as structural reinforcement for the product may break down quickly with short UV exposure during construction, rendering the product weak.

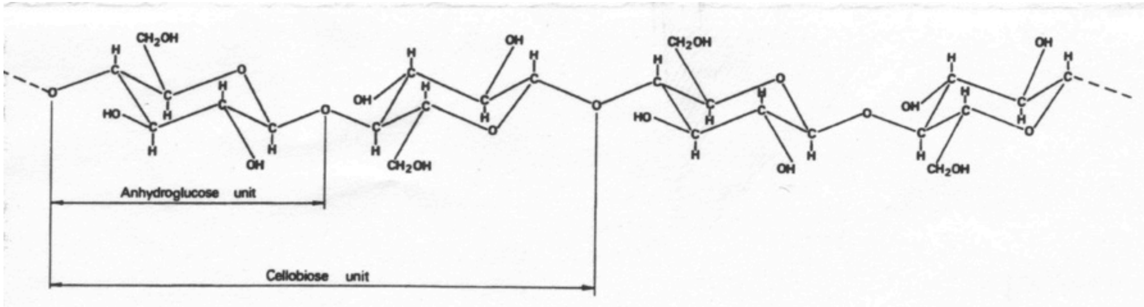
The interior layers of an enclosure or partition are usually are not exposed to water, UV, or a wide range of temperatures, and are therefore easier to specify. The primary risks tend to be from abnormal events, i.e., fire or flooding. Cladding is often one of the most critical choices in terms of material durability as it is exposed to the most challenging environmental conditions.

If a cladding material is expected to be exposed to water, oxygen, and temperatures above freezing, polymers, composites, and mineral-based materials would be preferred over metals. But if there is high UV exposure, and/or high temperatures, mineral-based materials would, as a class, have the highest durability. However, if the material sought is to be used in a freeze-thaw environment, mineral products may be susceptible to damage. Hence, a highly resistant metal alloy, such as stainless steel or zinc, or a metal protected with polymers or mineral-based coatings (i.e, paint) would be an option. Cladding at grade in a low UV environment (a cold city) might be best made of a polymer.

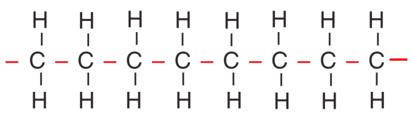
Conclusions

Understanding the fundamental characteristics of the different classes of materials can be a starting point for material selection during enclosure design. Given the wide variations between materials of the same class, and the proliferation of composite and hybrid materials, what has been presented above is just a rough guide as a starting point, but should also help guide a deeper exploration of specific materials and applications.

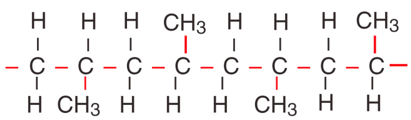
Wood, a natural polymer, exposed to weather graying



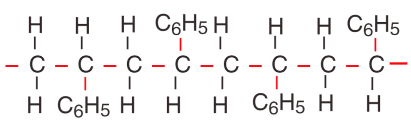
Cellulose Polymer (a carbohydrate)



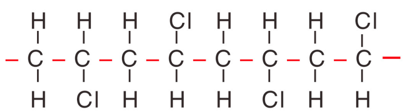
Polyethylene, **PE**



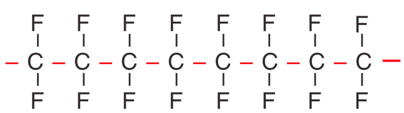
Polypropylene, **PP**



Polystyrene, **PS**



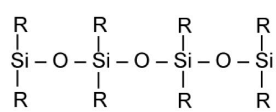
Polyvinyl chloride, **PVC**



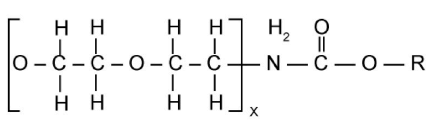
Polytetrafluoroethylene, **PTFE**

Some Common Carbon-based Polymers

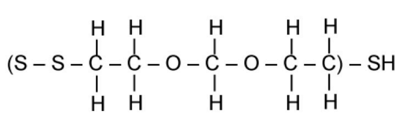
Silicone Polymer



Polyurethane Polymer



Polysulfide Polymer



Example Sealant Polymers

A rubber tire cracked (due to oxidation, UV-exposure, embrittlement) from long-term sun exposure

Bituminous Roof Membrane deterioration, for many of the same mechanisms as a tire.

Asphalt Shingle Deterioration : once the mineral protective layer washes away, the rate of deterioration of the underlying asphalt is massively accelerated.

Corrosion of galvanized steel corrosion at a steel studs exterior flange as this is where it remained moist for several years

Corrosion of galvanized steel at the weld points only.

Serious Freeze Thaw of a brick veneer because of a small lip retaining water at the base

Differential rates of stone erosion and deterioration evident because of the use of different types of stone (the building is centuries old)

Corrosion of a copper roof beginning to manifest (after 100 years)

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