

Essentials of Civil Engineering Materials

First Edition

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Introduction to Engineering Materials

I. Why Do Civil Engineers Need to Study Materials?

The simple answer to the aforementioned question is that civil engineers *build* things—and building anything requires *materials*. Everything—built or natural—is made up of materials of some kind. Try to envision a bridge built *without* materials. That doesn't even make sense! Clearly, materials are important.

Answered another way, if we as civil engineers are to be *trusted* to build things, we want to reliably predict how the materials in those things (whether a building, a bridge, or a roadway) behave under the conditions for which they were designed. However, we, as good practicing engineers, want to *smartly* choose the materials we use, which requires some basic knowledge of the *science* of materials. Clearly, all disciplines of engineering, from civil to mechanical to electrical, need a working knowledge of materials. There is also an underlying motivation (but not necessarily a requirement) to select the *best* quality and type of materials for a given project's specifications, not simply materials that “just work.”

The highly interdisciplinary field of **materials science** involves the discovery and design of *new* materials, as well as the increased understanding and characterization of *all* materials. Critical to societal needs, materials science can be viewed as a direct complement to technological progress—aside from the Romans' use of concrete, classes of materials have been used to classify stages of civilizations, ranging from the Stone Age to the Bronze Age, and the current Silicon Age (or perhaps Semiconductor Age). Many of the most pressing scientific challenges humans currently face are due to the *limitations* of the materials that are available and, as a result, breakthroughs in materials science are likely to have a significant effect on the future of technology. What are some limitations of current materials? Think about it.

At the same time, there is also a trend to explore and exploit smaller and smaller material scales as modern scientists use nanotechnologies to enable analysis and design at the molecular level (i.e., from the “bottom up”). In nanoscience, researchers use the latest methods in applied physics and chemistry to quantify the relationship between

a material's atomic and molecular structure and the emergent engineering properties. No longer is knowledge of macroscale properties sufficient—one must also be familiar with atomistic and molecular features (e.g., a basic knowledge of chemistry and physics). This has led to advances in metal processing—for example, manipulating the molecular structure to produce higher-strength steels for construction.

Civil engineering, in particular, is the engineering discipline that deals with the design, construction, and maintenance of the physical and naturally built environment, including works such as roads, bridges, canals, dams, and buildings. As a result, our concern, from a materials perspective, is the *building materials* of those works, such as concrete, steel, and aggregates. That being said, from a civil engineering perspective, there seems to be an overreliance on well-used and well-trusted materials, such as steel and concrete. These materials have formed the basis of urban infrastructure for over one hundred years, and engineers in particular like things that “just work.” But just as cutting-edge plastics and alloys have replaced less-advanced materials in commercial goods, there is an increasing push to replace steel and concrete with high-performance “designer” materials that are stronger, tougher, cheaper, greener, and more efficient. Perhaps the next super-material for construction is in the near future.

II. Basic Requirements of Engineering Materials

While today's civil engineers need not be material specialists, a basic understanding of a material's *selection* and subsequent *performance* are essential to design, construction, and sustainment. For example, proper materials selection is an essential link between design and structural mechanics. In structural mechanics, we analyze loads, internal stresses, and deformation of members, and in design, we select the member materials and the ultimate shape of a structure to carry those loads.

When considering if a material is suitable for engineering purposes (whether civil, mechanical, electrical, etc.), several requirements are to be met. Engineering materials *must* be as follows:

1. **Understood:** How the material behaves when put to use must be known. From experience, you probably wouldn't build a road out of cotton balls. Without knowing the technical properties, you know that a stronger material is required. Before materials were rigorously characterized and categorized, tradesmen knew how certain materials performed by experience. We must understand material behaviors, such as the strength when subjected to load, if it stretches like a rubber band or if it is stiff like a rock, if it weakens when heated or if it gets brittle when cold.

2. **Reliable:** The material must have consistent properties and be durable enough to last the intended lifetime of its application. For example, it would be difficult to construct a house made of wood if the strength was unpredictable. Likewise, consideration must be taken if the materials degrade and/or corrode and lose strength.
3. **Workable:** The material must be easily shaped, handled, fastened, connected, and so on to enable construction of various components and structures. One of the reasons steel is so desirable as a construction material is its ability to be formed into different structural shapes and easily connected (via bolts or welds). Likewise, concrete can be cast into many different forms. A material like diamond, for example, is extremely strong, but would be almost impossible to form into anything other than small stones. Some metals, such as titanium alloys, are known as difficult-to-machine materials—many machine shops avoid titanium because of its reputation as a tool killer that is unreasonably expensive to machine.

If the material is well understood, reliable, and workable, we *can* build something from it. Moreover, we can likely predict how the final product will behave. However, those are not the only requirements we impose on our material selection. Good engineers strive to impose **efficiency** in their designs. Efficiency can mean a lot of things, but usually there is a balance of strength (to carry a load) as well as self-weight (which adds to a load) and geometric constraints. The ancient Egyptians, for example, were able to build the pyramids out of stone, but the base of the pyramids had to be extremely large compared to their height in order to carry the weight. The material (relatively weak limestone) is not very efficient to construct large buildings—but it served well at the time because the Egyptian craftsmen understood the properties of limestone, and it was workable. Modern buildings clearly do not use limestone. Efficiency can also imply durability (long lasting), ease of construction (connections), meeting time constraints (curing times), and, of perhaps most importance, cost.

Related to cost (supply and demand), the final general requirement engineers must consider for material selection is **availability**. Sometimes the best material for the job is simply not convenient (or too costly) to acquire—thus, consideration must be made for alternatives that are easily attained. For example, while steel is relatively easy to acquire in urban areas, more rural areas may benefit from cast-in-place concrete. Globalization of materials supply has somewhat alleviated this problem. Availability is one of the reasons steel is so predominant as a construction material. Steel is produced by iron ore,¹ which

¹ There is more discussion in **chapter 5** on the chemical composition of steel.

happens to be one of the most available raw resources. Around 98 percent of the mined iron ore is used to make steel. In terms of importance to the global economy, only oil is comparable to iron ore for substances we mine from the ground. Estimates put available and accessible iron ore deposits on the order of 20 billion metric ton. If we preferred to build structures out of platinum, for example, there is only approximately 50,000 metric tons on the entire planet—about one-tenth the weight of the Burj Khalifa.

Beyond the general requirements discussed earlier (understood, reliable, workable, efficient, available), and alongside simple function (will it work?), when selecting a material, civil engineers have other socioeconomic factors to consider:

1. The primary criterion should always be **safety**. As both the National Society of Professional Engineers and the American Society of Civil Engineers **Code of Ethics** dictate,

Engineers, in the fulfillment of their professional duties, shall hold paramount the safety, health and welfare of the public.²

Whether selecting steel for a skyscraper or a recycled glass concrete for a walkway, always know that even if safety is not specifically written in the design criteria, it is most definitely implied for all materials that are to be selected.

2. **Economics** is another important design criterion (and likely the most restrictive to any large design or build project). Every project will have a budget that limits how materials are selected. Since multiple materials may share the properties specified, it is up to the engineer to select the most appropriate material for each project's budget. However, the cost of materials has and will continue to change with time. Unforeseen events, such as a natural disaster, might result in production issues of certain materials that suddenly raise their cost or completely limit their availability. Construction issues may also play a part in material selection. Timing is critical on many projects; therefore, materials with faster delivery or curing times may trump an initial decision to choose a less costly material.
3. **Sustainability** is a more recent addition to engineering design. From one perspective, sustainability refers to the overall impact a material's use will have both on the present and future environment. We—as civil engineers—want to ensure that future generations can rely on the continued use of a material supply indefinitely. Sustainable development and engineering consists of balancing local and global

² National Society of Professional Engineers (NSPE), “Code of Ethics,” <https://www.nspe.org/resources/ethics/code-ethics>; American Society of Civil Engineers (ASCE), “Code of Ethics,” July 29, 2017, <https://www.asce.org/code-of-ethics/>.

efforts to meet basic human needs and build infrastructure without destroying or degrading the natural environment.

Regardless of the material system or intended use, these considerations are implicit for any engineering application and/or design. First and foremost, good knowledge of material *properties* is necessary to even compare materials for possible selection, which is the topic of the next section.

III. Material Properties

Material properties are the fundamental descriptors of a material. When comparing two materials (be they steel and concrete, straw and sticks, or feathers and bricks), we can list characteristics to describe how the material looks or behaves, or some features of the material that can be objectively measured, to differentiate between the two. These are the material *properties*. For engineers, there are some properties that are critical for technological applications (such as strength or thermal conductivity), but others are not as interesting (e.g., color or smell). Since they are so important, we pay special attention to the mechanical properties of materials.

Mechanical properties are design criteria that you would find in a set of specifications—they deal with the load and deformation limits of a material, such as strength, stiffness, and extensibility. Mechanical properties describe how a material should perform in the field and are key parameters for structural engineering. **Chapter 2** focuses solely on the mechanical properties of materials. To establish these properties, we measure a material's performance in the lab under a series of tests that might push, pull, twist, deform, age, or generally damage the material in an attempt to find its limits. Examples of mechanical properties include strength, formability, stiffness, toughness, and durability (see **table 1.1**).

Nonmechanical properties can be broken into four subgroups: physical properties, chemical properties, transport properties, and process properties.

- a. **Physical properties** describe how a material looks or feels with respect to the laws of physics. They include properties such as shape, molecular structure, color, opacity, roughness, and mass. These are properties that can usually be measured through nondestructive testing and/or microscopic observation.
- b. **Chemical properties** are characteristics relating to a material's atomic makeup and reaction potential; they define how a material will chemically react in the design environment. It is important to make sure that a chosen material is environmentally safe, meaning that it does not degrade or corrode because of the environment or pollute a surrounding environment.

TABLE 1.1 PROPERTY EXAMPLES

Property Type	Property Subgroup	Example(s)	
Mechanical	N/A	Strength	
		Formability	
		Stiffness	
		Toughness	
		Durability	
		Creep	
		Ductility	
		Modulus of elasticity	
		Elongation	
		Proportional limit	
Nonmechanical	Physical	Shape/geometry	
		Texture	
		Aesthetics	
		Unit weight density	
		Specific gravity	
		Permeability	
		Moisture content (MC)	
		Porosity	
		Chemical	Corrosion resistance
			Electrochemical reactivity
	Ultraviolet (UV) susceptibility		
	Flammability		
	Transport	Biodegradation	
		Electrical conductivity	
Thermal conductivity			
Process	Ion exchange		
	Gas diffusion		
	Resonance		
	Emissions		
	Acoustical masking		

- c. **Transport properties** are related to processes that move a quantity through a material, such as electric current or heat, and depend on “moving ions.” They are related to chemical properties but can be separated due to their importance.
- d. **Process properties** describe how materials or material systems physically interact with their surroundings. Vibration dynamics is an example of a process property, which is important to understanding how a material will respond in an earthquake or dampen acoustical noise in a concert hall.

Currently, the most common materials used in construction by civil engineers are steel (**chapter 5**), aggregates (**chapter 6**), concrete (**chapter 6**), asphalt (**chapter 6**), wood (**chapter 7**), soil (**not covered**), and masonry (**not covered**). While many of these materials have been around for a while (the Bedouins first used concrete in 6500 BC!) and will probably continue to be used into the future, we have seen and will see vast improvements in their performance. Additives such as fiber reinforcement and super plasticizers in concrete are just two examples of chemical and nanoscale research improving material performance.

In recent years, there has also been significant growth in the use of **high-performance materials**. Advanced polymer composites, geotextiles, lightweight metals (like aluminum or titanium), and engineered woods (glulam) are just some of examples of new materials being selected by engineers. Joining the high-performance materials revolution is also another movement—the call for **sustainable or “green” materials** (revisited in **chapter 8**). In an effort to create sustainable designs, engineers are selecting materials that will reduce energy consumption and potentially improve the environment. To achieve this, engineers could select recycled or recyclable material to minimize the energy required to manufacture a new material or select a great insulating material to minimize energy transfer from the building to the environment.

IV. Illustrating Physical Properties: Mass, Density, and Weight

Civil engineers like to describe a material with respect to its physical structure and the nature of its matter. Of particular importance is the degree of packing of the material; there are three general ways of measuring this. The first, **density** (ρ), is defined as the mass per unit volume and is given by the following equation:

$$\rho = \frac{\text{mass}}{\text{volume}} = \frac{m}{V}.$$

The second, **unit weight** (γ), is defined as the weight of a material per unit volume, or

$$\gamma = \frac{\text{weight}}{\text{volume}} = \frac{W}{V}.$$

The equations for density and unit weight are related to each other through **gravity** (g). The major determining factor when using either measurement is the system of units with which you are working (metric or imperial). The following equation shows the relationship:

$$\text{weight} = \text{mass} \times \text{gravity},$$

or simply,

$$W = mg.$$

From the definition of unit weight, we can easily derive a relation between unit weight and density, where

$$\gamma = \frac{W}{V} = \frac{mg}{V} = \left(\frac{m}{V} \right) g = \rho g.$$

Thus,

$$\gamma = \rho g.$$

The third most common way of describing a material is to designate its specific gravity. **Specific gravity** (G) is defined as the ratio of a material's mass for a given volume to an equivalent volume of water, both at the same given temperature, T° , or

$$G = \frac{\text{density of material @ } T^\circ}{\text{density of water @ } T^\circ} = \frac{\rho_{\text{material}}}{\rho_{\text{water}}}.$$

Since specific gravity is a ratio measurement, we could interchangeably say that

$$G = \frac{\text{unit weight of material @ } T^\circ}{\text{unit weight of water @ } T^\circ} = \frac{\gamma_{\text{material}}}{\gamma_{\text{water}}},$$

as

$$G = \frac{\rho_{\text{material}}}{\rho_{\text{water}}} = \frac{\rho_{\text{material}}}{\rho_{\text{water}}} \left(\frac{g}{g} \right) = \frac{\gamma_{\text{material}}}{\gamma_{\text{water}}}.$$

As a result, G is unitless and is constant regardless of using metric or imperial units.

With such relations, we can begin to define material properties and objectively compare them. For example, aluminum has a specific gravity of 2.7, while steel has a specific gravity of 7.8. *Does that mean that those materials will sink or float in water? What is the specific gravity of water?*

Working out the mass and/or weight of a material is relatively easy (only requiring a set of scales). However, such properties related to mass do not tell us if the material is suitable for a *particular function*. Is a dense material strong or weak? We don't know! To answer such questions, we need to assess properties, such as **strength** and **stiffness**. How does one go about measuring strength? Today, with various testing equipment and machines, such tests seem obvious. But this was not always the case. The logical step was applying the **scientific method** to materials testing, which we will briefly discuss to help understand how material properties are determined.

V. The Scientific Method

The so-called scientific method is a formal description of scientific inquiry that has characterized natural science since the seventeenth century. In effect, if you have a question that necessitates a scientific answer or explanation, certain steps *must* be followed to be accepted by the scientific community. There are many ways to describe the scientific method (which we discuss in more detail next), but the key components are (1) a well-defined question or **hypothesis**, (2) an **experiment** to test the hypothesis, and (3) results to support the hypothesis. This may seem obvious, but it was not always the *status quo*. To illustrate, we can consider the famous case of Galileo's so-called Leaning Tower of Pisa experiment:

In 1589, the Italian scientist Galileo Galilei is said to have dropped two spheres of different masses from the Leaning Tower of Pisa to demonstrate that their time of descent was *independent* of their mass. Via this method, he supposedly discovered that the objects fell with the same acceleration (Earth's acceleration owing to gravity, g), proving his prediction (or **hypothesis**) true, while at the same time disproving the long-believed theory of gravity proposed by Aristotle (which states that objects fall at a speed relative to their mass—i.e., heavier objects were thought to fall faster). Now, the idea that heavier objects fall faster may make sense if you compare something like a balloon and a brick.³ However, no one *actually tested* this fact to make sure it was universally true. Galileo did with a simple experiment.⁴

If you remember equations of motion from physics, you know that an object that starts from rest with a constant **acceleration**, a , will cover a **distance**, x , over a **time**, t :

$$t = \sqrt{\frac{2x}{a}}.$$

3 The balloon may fall slower because of the air resistance or *drag*, but that has nothing to do with its *mass*.

4 While this story is commonly retold as historical fact, there is no account by Galileo himself of such an experiment, and it is accepted by most historians that it was only a *thought experiment* that did not actually take place—a *Gedankenerfahrung*.

It is clear from the math that *mass does not influence the time!* These equations are supported by the results of Galileo’s experiment—we trust them because of the scientific method. They are physically testable!

The scientific method provides information to support a claim or hypothesis. From a philosophical sense, there are no definitive answers. This is, however, an important concept in materials science, because it effectively means all our *testing provides approximate answers.*

Wait, what does this mean?

If we test steel and get a strength of 30,000 psi, we typically report that “steel has a strength of 30,000 psi.” However, what is unwritten is that “the particular steel specimens we have tested have an average strength of 30,000 psi within a range of precision limited by our testing equipment.” The more *support* for the number (30,000 psi), the more confidence you can have in the property. More support comes from repeated testing (ideally using different methods and from independent groups). However, you can never know 100 percent that the *next* steel specimen will have the same strength—which is why engineers always apply conservative safety factors to material properties.

The scientific method is commonly based on empirical or measurable evidence subject to specific principles of reasoning, typically accomplished in a stepwise manner. Laboratory exercises typically follow such a procedure. However, the steps are frequently modified to suit the needs of the problem, so there is no “definitive guide to the scientific method.” With that being said, one *interpretation* of the steps in the scientific method consists of the following:

1. **Ask a question:** What is the basic problem you are solving? Or, from a material perspective, what property, characteristic, or behavior are you investigating?
2. **Do background research:** Has anyone tackled this problem before? Or something similar? What is already known?
3. **Formulate a hypothesis:** How do you think the experiment will result and why? Make a prediction. Don’t worry if you are right or wrong; that’s what the test is for!
4. **Design an experiment:** Develop a procedure to test your hypothesis or determine a material property (see the discussion on experimental design in the next section).
5. **Perform the experiment and collect data:** Gather and record all relevant data, measurements, and observations.
6. **Interpret data:** Analyze data to aid in theoretical descriptions.
7. **Draw conclusions:** Was your hypothesis correct? Did you determine a material property or behavior? Are the conclusions adequately supported independently by the results?

8. **Refine the procedure** (optional): If the hypothesis failed or the experiment was insufficient, revise and repeat steps three to seven.
9. **Communicate the results:** Summarize findings to add to “science.”

The final step (**communication**) is critical, because a single test/result does not prove anything. Results are validated and vindicated when other scientists repeat experiments and come up with the same (or supporting) results. A history of evidence and validations shows that the original statements were correct and accurate. It is a simple idea and the basis of all science—*validation through replication*. Statements must be confirmed with as much evidence as possible. In fact, failure to repeat results has led to a so-called replication crisis in academia. This **replication crisis** refers to alarming (and growing) evidence scientists have found that indicates that the results of many scientific experiments are difficult or impossible to replicate on subsequent investigation, either by independent researchers or even by the original researchers themselves. Since the **reproducibility** of experiments is an essential part of the scientific method, this phenomenon potentially has grave consequences for many fields of science in which significant theories are grounded on experimental work that has now been found to be resistant to replication. Luckily, the crisis is more prevalent in the fields of biology and medicine, not materials science or engineering.⁵

Perhaps the most critical step in the scientific method (and for replication) is prudent and careful consideration of experimental design. How you *attain* data is almost as important as the data itself! As such, **experimental design** is the next topic of discussion.

VI. Experimental Design

Experimental design consists of the design of a procedure or task to describe or explain some variation of information/data. Planning an experiment properly is very important in order to ensure that the *right type of data* and a *sufficient sample size* are available to answer the research questions of interest as clearly and efficiently as possible. There are many interpretations of experimental designs, but for our purposes, we consider material testing a primary goal.

From a material characterization perspective, experimental design effectively means the design of a test procedure to determine a material property or behavior. Double-blind placebo studies are not what we are interested in. If we want to know the strength of steel, for example, we need to test it until it breaks. Seems simple enough at first glance.

More formally, the key concepts of experimental investigations are (in the context of steel testing) (a) **manipulation** of a desired independent variable (e.g., increase load on steel

⁵ It turns out that it is relatively easy to break things consistently!

specimen); (b) **control** of other variables, except the dependent variable constant (e.g., constant specimen geometry); and (c) **observation** of the independent variable on other dependent variables (e.g., measure change in length with respect to the change of load). Specific questions that the experiment is intended to answer must be clearly identified before carrying out the experiment. If our goal is testing the strength of steel (defining the output), for effective experimental design, we need to ask a set of simple questions:

1. What will our test specimens look like in terms of geometry?
2. How many specimens will be needed?
3. Will they all be tested to failure?
4. How is failure defined or observed?
5. What equipment will we be using?
6. What kind of load will be applied (stretching, squeezing, twisting)?
7. How will we gather the data? What data?

Those initial questions will be a good start and may result in a simple test for the strength of steel (sticking to our initial example). In effect, we are defining the **controlled experimental variables**.

Things will get complicated as you delve a little deeper into the test details and other questions emerge. Such questions include the following: Do I have enough specimens to be statistically relevant? Do I need control specimens? Does geometry matter? Does loading rate matter (e.g., how fast you test a specimen)? Does the temperature matter? Humidity? Frequency of data collection? Precision of the measurement? Unfortunately, some of these questions *cannot* be answered until you perform some **trial experiments**. One should also attempt to identify known or expected sources of **variability** in the experimental units since one of the main aims of a designed experiment is to reduce the effect of these sources of **uncertainty**.

A well-designed experiment is logical, delivers the predicted data and/or results, and can be easily replicated if the procedure is followed under the same conditions at a different time.

In theory, one can design multiple tests and attempt to characterize many different materials. However, if we design a specific test, and you design a specific test, will we get the same results? Unless we collaborated with each other, it is likely (a) our tests may be completely different, requiring different equipment, specimens, and so on, and (b) the results may slightly differ because of slight variations in the test procedure. If they differ, whose results should be trusted? Whose experimental procedure was “better”?

This becomes an issue for commonly used (and thus frequently tested) materials. Common ground is needed between testing parties. Rather than “reinventing the wheel” every time a material property needed to be assessed, a more consistent method is required.

Luckily, many engineers in the past have determined what properties are necessary for particular functions and developed the “best” ways to test for these properties.⁶ These methods became so-called standards (i.e., a set of guidelines judged to be suitable to assess materials). To make things more consistent for design and to ensure public safety, a formal system of **material standards** enables property selection based on known values grounded on prior accepted tests. Such standards also dictate extremely specific procedures for measuring the properties of materials, thereby allowing comparison of results from any source as long as the specific procedure is followed.

VII. Material Standards

Material standards are generally accepted and theoretically sound rules to determine the quality, performance, and proper use of a material. Material standards are usually determined by external agencies instead of individual manufacturers. Every standard usually focuses on a specific, measurable concept and is clearly written to ensure consistency and to avoid conflict within a family of standards. Well-written standards (usually those with the broadest marketplace acceptance) help industry by improving products, expanding markets, and lowering risk. Standards can be used by individuals, companies, and even government agencies, which all reference them for guidance. In fact, enactment of the **1996 National Technology Transfer and Advancement Act** (Public Law 104-113) required government agencies to use privately developed standards when at all possible! This law has proven beneficial for two reasons: it has ensured the use of high-quality, market-relevant standards and has also saved taxpayers millions of dollars by eliminating duplicative standards development efforts.

In the United States, there are over 400 industry-driven standards development organizations, while most other countries use a government-based approach. This is not to say that there are not government-based standards agencies in the United States. Examples of government standards range from local (e.g., town building codes) all the way to the federal level (e.g., **National Institute of Standards and Technology (NIST)**, to name one). The largest private standards organization in the United States is **ASTM International** (formerly known as the American Society for Testing and Materials). There are five main standard types recognized by ASTM International, including the following:

1. **Product specification standards**—which govern how things are called for in a procurement document

⁶ What makes them the “best”? Think about it.

2. **Manufacturing practice standards**—which govern protocols that do not produce a test result
3. **Test method standards**—which govern lab and field tests that produce a specific result
4. **Standardized terminology standards**—which set official definitions
5. **Operational and purchasing guide standards**—which give informational descriptions of options

To ensure that buyers know that they are purchasing an item that has met a particular standard, many items are stamped with their relevant standard number. **Figure 1.1** is an example of a pipe in the Hurtig Building at Northeastern University (Boston, Massachusetts) that displays an ASTM stamp. Manufacturers of products following any of the internationally recognized standards are more likely to be used, as they are more likely to be called for in a contract. This is in part because of a large movement by international trade organizations, such as the World Trade Organization, to encourage the use of standards to support fair trade practices. (Fair trade is defined herein as a trading condition that is sustainable both environmentally and economically.) Standards help ensure that when a material is specified in a contract, all parties involved benefit from uniformity and transparency.

As another example, **figure 1.2** shows a standard sieve, which is used for the Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates (ASTM C136/C136M-14). The test is used to determine the particle size distribution of a particular aggregate of interest.

You may think that all sieves are alike—just grab one from a sandbox or a baker’s kitchen! This, however, is a recipe for disaster (or at least inadmissible testing)! Precision sieves

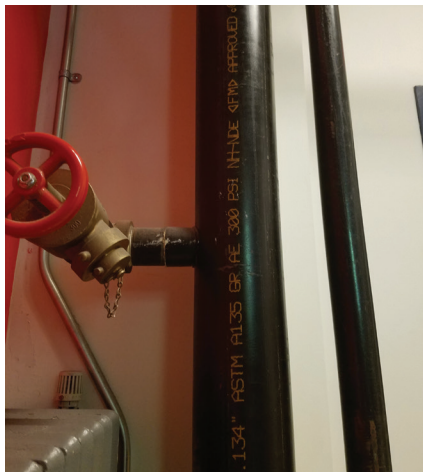


FIGURE 1.1 Example of ASTM labeled pipe.



FIGURE 1.2 Sieve.

with standardized materials are an essential part of the sieve analysis, and an incorrectly fabricated mesh or ill-advised material can result in bad and/or useless test results. ASTM designation E11-17 states,

The sieve cloth used in test sieves shall meet the requirements of Table 1 and shall be designated Specification E11 Sieve Cloth. The number of inspected apertures shall be in accordance with Table 1 (Column 7). Sieve cloth conforming to this specification shall be woven from stainless steel, brass, or bronze. Sieve cloth with openings greater than or equal to 75 micrometers shall be woven using a plain weave. For sieve cloth with openings equal to or less than 71 micrometers the sieve cloth may be supplied using a twill weave. The sieve cloth shall not be coated or plated.⁷

When a difference exists between the tool and the test specification, there is a lot of space for variance in your results. Simply put, if you do not use the “standard” sieve, you did not complete the “standard” test, and you may have just as well not tested at all.

One *negative* aspect of standards is that *meeting them* is frequently a significant expense. For example, the sieve depicted in **figure 1.2**, while appearing equivalent to a baking gadget or kid’s toy, cost more than \$50 to purchase. While meeting standards adds value to a material or product, it is not free to subject materials to testing. Moreover, the testing equipment itself is often highly specialized (as it must meet the minimum requisite measurement precision). Likely, materials and products are sent to third parties who specialize in testing procedures. This ultimately increases the cost of the material. Guaranteed quality and performance costs money. It is one (of many) **economic factors** that must be considered in **material selection** for engineering design and application.

VIII. Economic Factors

There are many factors involved in the **economics of materials selection**.⁸ Not only must we consider how much a material costs at the time of construction, but also what the costs of the material will be over its *lifetime*. Life-cycle costs

The following link will take you to the ASTM page for the standard sieve test. Please note that you must have a university library with a subscription in order to access.

https://compass.astm.org/EDIT/html_annot.cgi?C136+14#s00013



As you can see, the details are quite specific for every aspect of this test right down to the test scale tolerances and where the mesh midpoints are measured! This ensures true uniformity for anyone performing the test in the United States or abroad and results in product reliability.

⁷ ASTM, *Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates, C136/C136M-14* (West Conshohocken, PA: Author, 2014).

⁸ A fancy expression for the cost of materials. Money is the bottom line!

are becoming increasingly important to owners and affect the selection of materials. This is due to smarter financial planning by many owners and can also be accredited to growing environmental and social movements.

The process of accounting for costs over a material's lifetime is known as **life-cycle cost analysis (LCCA)**. LCCA includes the following: (a) raw material acquisition and material manufacturing processes, (b) transportation expenditures from every phase of the material's life, (c) the installation and use in a structure (including ongoing maintenance), and (d) end-of-life disposal via recycling or being placed in a landfill.

There are many "hidden costs" associated with every material. Here, our discussion just scratches the surface with the most apparent costs in a material's "life." The **environmental cost** of extracting many raw materials is very high, with pollution a major weighing factor. Moreover, **raw materials** from oil to iron to wood can vary in availability because of political issues or global climate change. **Figure 1.3** depicts a graph with the pricing of crude oil (which relates to **transportation costs**), with some major international events highlighted. The international conflicts affected the availability and cost of crude oil, which in turn increased the costs of many raw materials.

Once a material is selected (made either from raw or recycled components), **manufacturing costs** must also be considered. The typical construction site does not possess the ability to turn raw limestone and shale into future concrete and must rely on manufacturing plants to provide a finished product at reasonable prices. Should **market demand** for the

Figure omitted due to licensing restrictions.

FIGURE 1.3 Crude oil prices (U.S. dollars/barrel), 1968–2016.

finished materials be high, manufacturers can take advantage of supply-and-demand economics and adjust their pricing. It should come as no surprise that manufacturing costs for many construction materials may fluctuate into the future as developing nations such as China, India, and various African countries begin developing their infrastructure systems (see **figure 1.4**). It is at this intersection of interests that new construction products may find themselves at the forefront of industries struggling to keep up with demand.

In selecting materials, you must also consider the **transportation costs** of getting the material to your site. Whether it is transportation from a different coast or a different continent, your material needs to arrive at your site on time. Timely delivery requires knowledge of the manufacturing and shipping schedules of a material—called the **lead time**. The cost to transport materials expediently may make a cheaper material less economical when rush transportation costs are considered. **Rush costs** are higher not only because they take advantage of need, but also because they cannot take advantage of economies of scale; a single item must bear the totality of the transportation cost. Also included in transportation costs are **road access costs**. Large and/or heavy items, such as precast concrete and irregularly long steel beams, may require special oversize-load permitting and police details to deliver them to your site by truck.

The next costs to consider in material selection are **placing costs**. **Skilled labor** must be available to place the material. For example, specially trained laborers are required for working with steel and constructing tall structures in large cities. If a plan called for a large steel structure in a smaller town, not only could the number of laborers available to work be inadequate, but also those available may not have experience working on tall steel structures. The solution would be to hire skilled labor from a nearby region and put them up in hotels—thus significantly raising your placing costs. Other placing costs might include seasonal weather considerations. For example, significant effort must go into ensuring a proper cure when placing concrete in a New England winter. Heaters and blankets may be employed, leading to raised placing costs.

Figure omitted due to licensing restrictions.

FIGURE 1.4 Construction of a new highway in Accra, Ghana, in 2010. Photo credit: Adrian Brügger.

Once your structure is in place, your client may want to know about the remaining life-cycle costs, including the maintenance and end-of-life costs. **Maintenance costs** for materials might include patching for concrete, structural weld inspections for steel, and termite inspections for wood; maintenance costs may also take into account time to replace a given material. **End-of-life costs** look at the cost to remove a material from a site. These costs can range from landfill costs to recycling costs, depending on the material selection. Many designs currently lean toward the selection of materials that can be used in endless cycles of building, thus lending themselves to construction that touts environmental responsibility in material selection and sustainability; what does sustainability entail?

IX. Materials and Sustainability

A good synopsis of sustainability is “don’t do today what will damage tomorrow.” In this text, **sustainability** will be framed using the American Society of Civil Engineers (ASCE) designation:

ASCE defines sustainability as a set of environmental, economic, and social conditions—the “Triple Bottom Line”—in which all of society has the capacity and opportunity to maintain and improve its quality of life indefinitely, without degrading the quantity, quality or the availability of natural, economic, and social resources.⁹

Sustainability and related concepts and practices make sense from current ethical perspectives and social pressures. Surprisingly, this was not always the case.

Historical Perspective

For centuries, sustainable elements have been included in construction (usually by serendipitous coincidence and lack of options, rather than any intent or sense of responsibility). Historical examples of sustainable elements include the use of local and renewable materials, passive solar heating, and the use of landscaping for temperature control. It is only in the last 200-plus years that design and material selection have changed so rapidly because of accelerated material design and discovery, alongside manufacturing innovations. With global trade, we have been able to obtain inexpensive materials from across the world. However, as materials are brought from all the corners of the globe for economic benefit, they bring with them environmental detriment in the form of pollutants created by their extraction, transportation, and processing. One common measure of this environmental detriment is an object’s **carbon footprint**.

A material’s carbon footprint is best described as the **greenhouse gases** (GHG) expended to acquire, process, transport, and finish a particular material. One example of a finished material with a large carbon footprint (and thus not a very sustainable one) could be a road

⁹ American Society of Civil Engineers (ASCE), “Sustainability,” <https://www.asce.org/sustainability/>.

in Kansas made with bitumen from Venezuela and aggregate from Canada. While the initial costs may have been low for this hypothetical road, the environmental and whole life-cycle costs may tell a different story.

While local, minimally processed materials may have been the only options in the past, the age of fossil fuels has enabled the selection of cheaper and better-performing materials. However, cost and performance are only part of the picture, which needs to include environmental factors in order to create a full picture of a material's life cycle.

Contemporary Times: Energy Efficiency and Environmental Protection

The current **environmental movement** was born out of the industrial or manufacturing revolution of the eighteenth and nineteenth centuries, for better or for worse. During the **Industrial Revolution**, technology

improved rapidly because of the use of fossil fuels, such as coal and oil. Many businesses set up shop in densely populated cities and traded goods globally as shipping became faster with fossil-fuel-burning technologies. Concurrently, standards of living improved, but human health issues related to a declining ecology also increased. More air and water pollution from fossil-fuel-burning activities led to private environmental protection societies and public land preservation acts in the early 1900s. By the 1960s, the environmental movement was a national issue in America, leading to the enactment of federal legislation protecting public health and land, and from which we still benefit today. Noteworthy legal actions included the Clean Air Act of 1963, the founding of the United States Environmental Protection Agency (EPA) in 1970, the Endangered Species Act of 1973, the Safe Drinking Water Act of 1974, and the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) of 1980 (also known as the Superfund Act). These new laws reflected the

MODEL OF A GREAT SUSTAINABLE BUILDING

The Colosseum in Rome is a great example of a building with sustainable materials. The main structural pillars and external walls (still standing today, as shown in **figure 1.5**) were made from limestone from Tivoli, only 20 kilometers away. At the end of the structure's useful life, stone from the façade was recycled to make the steps of the city's churches, including those of St. Peter's Church, and 300 tons of metal clamps (used to hold the decorative stones) were recycled to make weapons in the Middle Ages. The evidence of this building's continued existence almost 2,000 years later, and its ability to be re-used over the years, certainly speaks to the sustainability of its construction!



FIGURE 1.5 Colosseum in Rome.

reality that industrial and technological “progress” came at an environmental price and that our air, water and land was in need of protection.

While human health concerns led to the environmental movement, among the most powerful catalysts in bringing sustainable energy practices to the public’s attention were the Arab oil embargoes of 1973 and 1979. During this time, the price of oil skyrocketed, affecting nearly all aspects of the global economy. The tangible effect on people’s wallets finally motivated political action. In response to the economic upheaval created by the embargoes, an **energy efficiency movement** arose. Several energy efficiency measures were passed by Congress, including a change in fuel economy standards from 13.5 miles per gallon (mpg) to 27 mpg and the enactment of the maximum speed limit law, which forced vehicles to travel at a maximally efficient speed.

Taking cues from the environmental and energy efficiency movements, the contemporary **sustainable building movement** arose from the need for more energy-efficient and environmentally friendly building practices. These practices called for design mindful of energy consumption and environmental impact for both new construction and the retrofitting of existing structures. According to the United States Environmental Protection Agency (USEPA), sustainable building is

the practice of creating structures and using processes that are environmentally responsible and resource-efficient throughout a building’s life-cycle from siting to design, construction, operation, maintenance, renovation and deconstruction. This practice expands and complements the classical building design concerns of economy, utility, durability, and comfort.¹⁰

In effect, such concerns placed civil engineering at the forefront of sustainable practices.

Driving Agents for Sustainability in Civil Engineering

As civil engineers, we are involved in the sustainable building movement through design, construction practices, and selection of sustainable materials. For example, a sustainable building could

- be designed to incorporate materials that create healthy indoor environments with minimal pollutants (e.g., reduced product emissions);
- be constructed with a waste management plan that minimizes the waste stream and maximizes material reuse; and

¹⁰ United States Environmental Protection Agency (USEPA), “Green Building,” February 20, 2016. <https://archive.epa.gov/greenbuilding/web/html/about.html>.

- employ structural and finishing materials that can be reused, contain recycled content, or are made from renewable resources.

In 1996, the ASCE code of ethics was modified to include sustainable development as part of the canon of civil engineering principles. As the leading society for the profession, ASCE has brought recognition and significance to the sustainable building movement. In changing the ASCE canon, the organization demonstrated its conviction that the principle of sustainable development was of such importance as to be before all others, as shown in **table 1.2**.

TABLE 1.2 ASCE FUNDAMENTAL CANONS¹¹

1. Engineers shall hold paramount the safety, health, and welfare of the public and shall strive to comply with the principles of sustainable development in the performance of their professional duties.
2. Engineers shall perform services only in areas of their competence.
3. Engineers shall issue public statements only in an objective and truthful manner.
4. Engineers shall act in professional matters for each employer or client as faithful agents or trustees and shall avoid conflicts of interest.
5. Engineers shall build their professional reputation on the merit of their services and shall not compete unfairly with others.
6. Engineers shall act in such a manner as to uphold and enhance the honor, integrity, and dignity of the engineering profession and shall act with zero tolerance for bribery, fraud, and corruption.
7. Engineers shall continue their professional development throughout their careers and shall provide opportunities for the professional development of those engineers under their supervision.
8. Engineers shall, in all matters related to their profession, treat all persons fairly and encourage equitable participation without regard to gender or gender identity, race, national origin, ethnicity, religion, age, sexual orientation, disability, political affiliation, or family, marital, or economic status.

One of the principal contemporary drivers of the sustainable building movement is the **US Green Building Council (USGBC)**. The USGBC is best known for its **Leadership in Energy and Environmental Design (LEED)** program, formed in 1998. This program employs third-party verification (clients must hire LEED-certified engineers or architects to prepare documentation for submission to USGBC) to certify buildings, homes, neighborhoods, and communities as sustainable. USGBC has various certification levels, depending on the degree of sustainability in a design. Some major areas that would qualify a building as sustainable are described in **table 1.3**.

¹¹ ASCE, “Code of Ethics.”

TABLE 1.3 SUSTAINABLE BUILDING CONSIDERATIONS

Area	Attained by
Reduction of GHG emissions	Selection of local and/or low CO ₂ materials (reduce embodied GHG emissions)
	Energy efficient design (reduce operational GHG emissions)
Waste-stream reduction	Construction waste-management plans
	Construction sedimentation reduction plans
Water-waste reduction	Water-use reduction inside the building
	Efficient landscape design aimed at reducing water need
	Minimization of rainwater runoff
Health and safety for occupants	Materials that reduce toxin exposure to end users
	Climate controls, ventilation, optimization of daylight exposure
Site selection	Choosing a site in a well-connected area for public transit and biking
	Designing a site to minimize environmental impact

How Significant Is a Material's Life Cycle?

The most important theme in designing sustainable buildings lies in addressing their entire life cycle. As we discussed earlier in the chapter, LCCA looks at all of the costs that are associated with an item, from beginning to end. Similarly, we can also systematically account for environmental impacts through the life cycle of a material through a **life-cycle assessment (LCA)** (further discussion in **chapter 8**). Like LCCA, a material's LCA examines environmental impacts accompanying all phases of a material's life, from cradle to grave. These phases include (a) raw material extraction; (b) transportation over all phases of the material's life; (c) the energy, chemicals, and impacts associated with manufacturing processes; (d) the installation and use of the material in a structure; and (e) material disposal via recycling or placement in a landfill.

For a building, the life cycle encompasses the idea of the building itself, as well as all of its individual material components. In conducting the LCA of a material, we must first consider how the raw material is acquired. We will consider the extraction and production of aluminum as our example. It should be noted that aluminum has relatively high chemical reactivity, which means it tends to bond with other elements to form compounds and thus is found within other elements.

The point of extraction can affect surrounding ecosystems through dispersion of emissions and wastes into air, land, and water. This phase involves many fossil-fuel-burning machines to extract the raw material, bauxite, from large open pits, as shown in **figure 1.6**.



FIGURE 1.6 Example of an open pit mine.

Once the raw material is extracted from a location, it is transported to a primary processing plant for processing and refining. This stage is the most highly toxic phase and involves massive chemical and energy inputs, as illustrated next.

Raw aluminum + 12 kg of input materials + 290 MJ = > 15 kg CO₂ emissions + 1 kg Al

Inspecting the earlier equation, aside from the fact that 1 kilogram of aluminum (Al) results in 15 kilograms of carbon dioxide (CO₂), some questions to consider include the following: What happens to the 12 kilograms of input materials? Can it be reused? Is 290 MJ a lot of energy? What is the energy source? How is it generated? Did that produce more CO₂? More waste? Down the rabbit hole we go. Typically, the more questions asked, the worse a material becomes.

Lastly, the material is transported to another facility for manufacturing and assembly into products, such as aluminum beams. This stage of the process might involve high-temperature ovens to melt the aluminum into the desired shapes and can involve the use of oils, solvents, coatings, and other alloying metals. Surprisingly, this phase is the least

TABLE 1.4 ENVIRONMENTAL CONCERNS CONNECTED TO MATERIAL SELECTION

Concern	Materials Link
Climate change	<ul style="list-style-type: none">• Emissions from materials manufacturing• Transportation of materials• Landfill gas emissions from disposal of material
Fossil-fuel depletion	<ul style="list-style-type: none">• Creation of plastics, asphalt cement, solvents, sealants, direct/indirect use of fuels to manufacture, process, and deliver materials
Air pollution	<ul style="list-style-type: none">• Fossil-fuel combustion during materials' lifetime• Emissions from material cleaning and cooling processes
Deforestation, desertification, and soil erosion	<ul style="list-style-type: none">• Commercial forestry and agriculture• Resource extraction• Mining• Dredging
Water pollution and eutrophication	<ul style="list-style-type: none">• Mining nutrient drainage• Water use and effluent discharge from material manufacturing process• Construction site fine sediment runoff• Waste disposal
Energy waste	<ul style="list-style-type: none">• Excessive power and heating needed because of poor thermal conductivity of a selected material

polluting when compared to the primary processing. While the material is now ready for transportation to a construction site for use, our LCA does not end here. Most buildings are generally designed for 50 years of use. The final point to consider in the LCA is whether the aluminum can be easily reused or recycled at the end of its life.

Through this example, we see the environmental costs are great when we are considering using new aluminum as material. From extraction to landfill, there are many chemical and energy inputs needed to make this material. Recognizing the inputs in this complete life cycle allows us to understand the need for sustainable building practices that call for recycled materials. By employing reused and recycled materials, and eliminating the primary processing step, we can also eliminate a significant portion of the associated environmental maladies. Consider the environmental impacts and effects of materials processing outlined in **table 1.4**.

X. Concluding Remarks

In conclusion, this introductory chapter described the importance of materials in engineering as well as the requisite material knowledge to use them reliably in the built environment.

To understand materials fully, we need to determine their properties, such as density and specific gravity, which requires scientific inquiry and associated experimental design. Such explorations define the process known as the scientific method. Need for consistency led to the development of material standards, which aids in the selection of materials and regularity from application to application. Materials selection is the process of weighing many factors, from the performance desired and the restrictions of budgeting and economic factors to selecting an environmentally responsible material and weighing ecological affects (i.e., sustainability). A successful engineer must take into account all considerations to make the most apt choice of materials for design. Now, we proceed to define some key material properties and behaviors—specifically, how to describe the underlying **mechanical principles** and responses of common engineering materials.

XI. Problems

1. What are the characteristics of good engineering materials?
2. Identify a material that is NOT a good engineering material and explain why it is not a good engineering material.
3. In the context of materials, what does the term “workable” imply?
4. Describe the difference between mechanical and non-mechanical properties.
5. Match each material property to the category that best describes it.

Categories	Material Properties:
a. Mechanical	Resonance
b. Physical	Flammability
c. Chemical	Thermal conductivity
d. Transport	Corrosion resistance
e. Process	Creep
	Specific gravity
	Strength
	Ultraviolet susceptibility
	Electrical conductivity
	Shape

6. It is proposed to use piles to support docks in saltwater at a marine port facility. Name one property in each of the following categories that is important for

the pile material in this application. Identify a material that may work well in this case.

- a. Physical property
 - b. Mechanical property
 - c. Chemical property
7. A metal rod is 2 cm in diameter and 10 cm long. In the lab, the mass of the rod was measured at 84.76 g. The temperature of the rod in the lab is 20°C. Using this information, determine the following:
- a. The density of the metal.
 - b. The unit weight of the metal.
 - c. The specific gravity of the metal (the density of water at 20°C is 0.998 g/cm³).
 - d. Based on the prior results, what metal is the rod most likely made from?
8. A block of wood has a volume of 150 cm³. Its mass was measured on a balance in the lab at 135g.
- a. What is the weight of the block of wood, in Newtons?
 - b. What is the density of the wood?
 - c. What is the unit weight of the wood?
 - d. What is the specific gravity of the wood (you may assume the density of water is 1g/cm³)?
9. In a few sentences, explain what a standard is and why standards are important in engineering.
10. Look up the following ASTM standards. Give the title of each and summarize them in one or two sentences each.
- a. D2525
 - b. C134
11. Write a pseudo standard for exterior deck screws that includes at least three criteria.
12. Identify at least four different costs associated with materials that impact material selection and design.

13. Find a sustainability rating system (other than the US Green Building Council and the LEED program for certifying sustainable buildings) and report the following:
 - a. Who developed the system.
 - b. The applicability of the system (e.g., LEED is primarily for buildings)
 - c. How certification in the system is administered/evaluated

14. Many materials are manufactured from raw materials that are obtained through mining. Identify at least two environmental concerns that are directly associated with mining.

Credits

Fig. 1.3: Source: <https://www.eia.gov/outlooks/steo/realprices/>.

Fig. 1.4: Copyright © by Adrian Brügger. Reprinted with permission.

Fig. 1.5: Copyright © Diliff (CC BY-SA 2.5) at https://commons.wikimedia.org/wiki/File:Colosseum_in_Rome-April_2007-1-_copie_2B.jpg.

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