Concrete is a ubiquitous building material that a mixture of a cementing component, such as Portland cement, fly ash, slag, or silica fume; a mineral aggregate of different fineness such as sand or gravel as filler, and water. The mixture is initially viscous, however, water causes the cement to harden through an exothermic reaction called \textit{hydration} – not the same as \textit{drying by evaporation}. This is also called the curing process, ultimately causing the mixture to harden around aggregates. \textit{Portland cement} is made by burning a mixture of clay and limestone at very high temperatures in a rotary kiln. It is very commonly used. \textit{Fly ash} is a pre-consumer recycled waste of coal-burning process; less common, the manufacturing process unknowns can cause quality variations and unpredictability. Ancient Romans made concrete with Pozzolana cement as a binder, and pumice or brick rubble as aggregate fillers, as early as the 3rd century. Written in the 1st century BC, Vitruvius talks about concrete and mixture proportions in his treatise.
Fig.06/01 The dome of Pantheon showcases the capabilities of concrete as a construction material.

Fig.06/02 Portland cement factory. The long tube diagonally running left to right is the kiln.

on architecture. Roman concrete is also known by the name Opus Caementicium. **Reinforced concrete**, a composite material involving a steel rebar lattice embedded in a concrete matrix, is the most common application in construction and featured in virtually all modern construction projects.

The high temperatures, approximately 2700°F, required to manufacture cement cause **substantial environmental impact**. Furthermore, approximately one-third of the mass of ingredients is released as CO₂ in the kiln, giving cement a huge carbon footprint as well, accounting for almost 8% of total man-made CO₂ production per year. The limestone and aggregate used to produce concrete needs to be quarried in large quantities. **Quarrying rock** removes vegetation and soil, generates dust and noise creating considerable environmental impact, resulting in holes and pits that can speed up erosion. Since concrete is such a common material in construction, it makes up for a large percentage of construction waste. Even though rebars can be fully recycled, only a small percentage of concrete is generally recycled as filler. **Uncured cement** is a known irritant; due to high alkalinity it is corrosive to human tissue. However, after curing it is chemically inert and non-toxic.

**On grade** refers to the ground level of the building; **below grade** refers to any level below the ground level. Concrete is highly susceptible to moisture absorption and transfer, if the material is in contact with a source of moisture, such as soil, it needs to be carefully insulated, especially if situated below grade. The typical concrete is hydrophilic, meaning it will readily suck any moisture present in the environment. Even slight insulation failures would result in carbonation as well as rebar corrosion over time; causing a reduction in concrete’s strength, inducing cracking and spalling. **Efflorescence** refers to the white-colored salt streaks and spots on the

**Vid.06/01** Video on the cement manufacturing process.

**Vid.06/02** Video on concrete, cement, and mortar.
Concrete can and should be tested for the presence of moisture before any finish application; there are multiple convenient tests available such as on-site humidity probes, calcium chloride test, and digital moisture meters.

There are two common methods for concrete subfloor preparation. Screed is a method of topping a horizontal concrete application with a finer coat and leveling the surface either with a flat board or a mechanical tool. This thin top layer features either very fine or no aggregate for a smooth result, as opposed to the thicker base layer, which features larger aggregate size and the outcome is coarse but much stronger. Floating screed is laid on top of a layer of insulation and does not directly bond to the floor slab underneath. Even though expensive, it mechanically separates two layers and minimizes cracking. Self-leveling concrete is another method of achieving a smooth, level finish; this application features a polymer-based additive in the concrete mix and it is less viscous and runnier than the typical screed concrete. The mix is lightly spread with a flexible blade smoother while the application slowly levels itself out. Self-leveling concrete is relatively expensive, however, it can be applied as a thinner layer.

Concrete aggregate is fairly brittle when cured and it is subject to dimensional change with shifting moisture and heat conditions. Before the concrete is poured resilient expansion joints are placed 10’ to 15’ apart, around 20 to 30 times the thickness of the slab. It is also possible to saw-cut joints, which should be...
Expansion joints are crucial for protecting the integrity of the concrete for extended periods. Otherwise, concrete will crack while curing due to contraction.

Besides being commonly used as a structural element and flooring substrate, concrete is also regularly specified as a finish in commercial as well as residential settings. **Polished concrete**, involves sanding the screed or self-leveling concrete overlay with abraders of incrementally higher grit. Before polishing, concrete needs to be fully cured. This happens typically 10 days after application but in some conditions, up to 28 days are needed. Polished concrete finish has high mechanical and chemical resistance and appropriate for environments with high traffic loads, including forklift traffic. The gloss level can be adjusted; high gloss providing around 0.50 slip resistance and low gloss around 0.60. It is possible to apply polymer coating for higher slip resistance. It is an inert finish that does not degrade and can last many years. **Cement can be mixed with pigments and textured through stamps for various decorative effects, which are called cement overlays.**

Concrete is a viscous material, before it is cured and needs to be poured in a watertight mold, which is commonly referred to as **concrete formwork**. In order to prevent sticking and ensure separation while removing a release agent, also known as a parting compound, should be applied inside the formwork. After 2 to 4 days the formwork is removed to let the concrete continue curing. It is possible to use various **admixtures to enhance or modify concrete’s properties**. The setting rate can be slowed or curing time can be reduced, possible rebar corrosion can be inhibited, or with plasticizers, concrete can be molded without vibration or compaction, ensuring homogeneous dispersion. **Board-formed concrete**
Video on creating board-formed concrete mock-ups.

refers to the process of pouring concrete into a wooden formwork to achieve a characteristic linear look, with the imprint of wood grain. **Wall ties** hold the formwork together, when removed leave characteristic circular markings on the concrete surface. With Glass Fiber Reinforced Concrete sculptural forms can be achieved; it is widely used for DIY furniture. Concrete, can be **precast** to avoid curing times, cracking, or inconsistencies. These can be structural elements, or they can be countertops, furniture, fixtures, or tiles. **Pre-stressed concrete** is great for structural use; the purpose being increasing tensile strength and structural stability.

**Terrazzo** is a cementitious material that substitutes typical gravel aggregate with chips of marble, quartz, granite, glass or any other suitable material of varying sizes. Typically the material receives a polished finish. Cement can be substituted with polymer resin. Terrazzo can be applied either as cast-in-place or sold as precast panels that can be cut into any required shape. Terrazzo tiles are also available in the market. **Cast-in-place** or poured terrazzo is set with brass, aluminum, zinc, or vinyl divider strips, which also function as expansion joints.

Polymer-based terrazzo can be as thin as 1/4” applied directly over the prepared subfloor, a moisture membrane or crack suppression membrane may be required. Monolithic terrazzo is applied at 1/2” thickness, directly over the prepared concrete subfloor. Bonded terrazzo is also 1/2” thick, however, sits on a 3/4” to 1-1/4” mortar underbed. Unlike monolithic terrazzo, bonded terrazzo does not require meticulous subfloor preparation. Lastly, sand cushion terrazzo features a wire reinforcement, sheet insulation, as well as a thick sand layer under the mortar underbed, totaling at 3” application thickness. The mechanical separation from the subfloor ensures that building settling or deflection of structural elements won’t fracture the brittle terrazzo application.

Terrazzo is a very durable and long-lasting material, can be easily maintained and repaired. It is a popular material for countertops, stairs, outdoor

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*Fig.06/09 Four different terrazzo aggregates: (a) broken glass bottles, (b) unfinished pebble, (c) varying aggregate sizes, (d) large marble pieces.*
furniture, etc. The substituted aggregate chips are waste or leftovers from other processes, rendering terrazzo an upcycled and relatively environmentally friendly product. Cementitious finishes such as polished concrete and terrazzo are stain-resistant, as long as spills are cleaned and dried quickly. Highly acidic or alkaline cleaners can damage concrete and terrazzo, nevertheless, diluted hydrogen peroxide or ammonia can still be utilized.

BRICK

Masonry is a method of building with natural or manufactured units of stone, brick, or concrete that are usually bonded together with mortar, a relatively fine cementitious paste. Masonry elements are often manufactured in standardized modular units. Brick is a common masonry unit manufactured out of clay and hardened through firing in a kiln or sun-drying. The standard brick size is 2-1/4” by 3-5/8” by 8” and weighs around 5 pounds. There are many shapes and sizes of brick available such as solid, frogged, cellular, or perforated; some are for decorative purposes others solve unique masonry problems, such as cornering at a specific angle.

First examples dating back to 7000BCE, bricks have been a staple building material across many geographies with many local interpretations and unique designs. Mud bricks were one of the first building materials, molded by hand and dried in the sun. Brick veneer, also known as thin brick was introduced after the Second World War. It is available in 5/8” thick “flat back” units and 3/4” thick with back geometry. This enabled lightweight decorative applications on wall substrates that appeared like load-bearing masonry walls. Frank Lloyd Wright used the material and exploited the effect in many of his projects.

The general use common brick, also known as burnt clay brick, is not treated for color or texture. It has a reddish-brown color with a porous but flat facing. Common brick is often used for non-structural masonry work. There are many other versions available, one being the engineering brick which is used for demanding applications where strength, durability, moisture, and frost resistance are required. Face brick, is manufactured to be visually exposed and it can feature various colors ranging from creamy whites/light tans to dark browns/blues and finishes such as smooth, sand-faced, glazed, or distressed. Concrete brick is not the same as cinder block, features two hollowed-out gaps and an aesthetic finish; more appropriate for interior applications. Due to its porosity. Concrete masonry unit (CMU) is highly versatile, more strong and durable than concrete brick, and commonly used as a construction material for load-bearing
Compressed earth block (CEB) is manufactured by compacting damp soil under high pressure into the shape of a brick. It is an environmentally friendly manufacturing method, however, the unit output is fairly low and the end product has fairly low abrasion and moisture resistance. Rammed earth involves the same technique, the resulting product is large blocks or entire floors and walls.

Clay bricks have lower embodied energy per weight than concrete, glass, steel, or aluminum. Brick is a brittle material and there’s always some broken ones in every transported batch, but the small size and modular nature of bricks allow construction waste to be reduced through careful design and detailing. Also, its modular nature enables expressivity and creative visual statements. Even though they are not as durable as new bricks, reclaimed or antique bricks can be used for their distinctive character. They are slightly more expensive and significant visual variability should be expected.

Brick can be bonded in many different ways; every single one providing different structural properties as well as visual character. Certain bonding methods are associated with different cultures, regions, or eras. Stretcher is the long side of the brick, and the bond featuring bricks laid in stretcher courses with only their long sides showing is called the stretcher bond or a running bond. Each course is staggered to the half-length of the brick face. Similarly, header is the short side of the brick and only the short side is seen in the header bond. English bond is a very strong bricklaying method featuring one stretcher course and one header course in alternation. Common bond, or American bond involves a header course between three to five stretcher courses. Flemish bond, involves courses made up of a stretcher and a header in alternation. These are staggered so that the center of the header in one course meets the center of the stretcher on the course above and below. Stack bond is somewhat weak and can only be used for decorative purposes, features completely aligned stretcher faces with no staggering.
Brick’s texture and profile as well as the depth of mortar lines enhance the effect of light and shadow. **Mortar lines** can be shaped to influence water-shedding behavior besides the aesthetics; they can be concave, flush, angled, recessed, or extruded. Brick walls can be painted for decorative purposes, which can be removed through pressure washing.

Fig.06/13 A selection of important brick bonding techniques.

Fig.06/14 Brick can be painted over to achieve a more contemporary feel.
STONE

Rock is a naturally occurring mineral aggregate. When rock is removed from its bed for various purposes, it is referred to as stone. Stone can be directly used without any processing, or it can be cut, shaped, and, dressed to create dimensional stone. Besides wood and mud, stone was one of the first construction materials used by man. First stone constructions were not made out of quarried stone, but contained undressed stone, boulders, and rubble. One of the earliest examples, Skara Brae is a cluster of eight stone houses in a Neolithic village located in Scotland. The Great Pyramid of Giza, built 4600 years ago, is the biggest stone monument today, a testament to the material’s strength and durability. Furthermore, natural stone is also highly desirable when aesthetics is a concern, owing to their rich and complex color and texture features. For instance, pietra dura, a technique for producing natural stone inlays was used extensively in Taj Mahal (1653) showcasing ornamental mastery.

Natural stone is extracted through quarrying, which involves cutting and removing large blocks of stone from the earth. With the diamond wire technology operations sped up and rapidly expanded to previously hard to quarry areas. Diamond wire technology replaced the feather and wedge technique, which involves inserting metal tools called feathers into periodically drilled holes on a line on the stone and pushing wedges into the feathers, to force the stone to split. This technique is time-consuming, expensive, and the results could be unpredictable as the stone is essentially split instead of cut.

Depending on how difficult it is to remove natural stone from its bed, its embodied energy can be higher or lower. However, this is only true for locally sourced stone, as imported stone requires very heavy material to be transported from thousands of miles away, as some desirable colors and textures can only be quarried in specific locations over the world. For instance, Lava Jewel is quarried in India, or Blue Bahia is quarried in Brazil. Quarrying has a significant negative environmental impact. Besides scar-ring an established landscape possibly causing erosion and destruction of habitat, deeper quar ries may affect groundwater flow patterns and quality.
The Rock of Ages granite quarry is located in Vermont. It is the largest deep-hole quarrying operation in the world, measuring at 600 feet.

Depending on a quarry’s proximity to various radioactive elements deep underground, radioactive contamination can occur. Consequently, there’s a possibility that natural stone used in interiors might emit radon, as well as beta and gamma rays, however, the radiation is fairly negligible and does not present any danger to the occupants, according to the EPA.

Petrology is the study of the composition and structure of rocks, their formation, and transformation. Stone is categorized based on how it was formed. This also determines the hardness of the material. Stones from igneous formations are harder than metamorphic formations which are harder than sedimentary formations. Igneous rocks are simply solidified molten magma. Examples include granite, andesite, basalt, pumice, etc. Sedimentary rocks consist of highly compressed deposited sediment such as limestone, sandstone, travertine, onyx, and alabaster. Metamorphic rocks are formed when the pressure and heat conditions around
existing igneous or metamorphic dramatically change and force the rock formation to transform. This last group includes marble and gneiss. **Fieldstone** is loose stone readily found on the surface of the soil, removed and used as masonry material. Fieldstones can be split to produce a flat surface. Broken off stone chunks and fragments are referred to as **rubble. Pebbles** are rounded rock fragments. **Flagstone** is flat stone slabs often used on horizontal and vertical architectural surfaces. **Stone Mosaics** are made from small pieces of colored stone arranged into decorative designs. **Tumbled stones** are broken off pieces of stone that are placed into a large spinning drum with grit and other chunks of material. **Engineered stone**, or commonly referred to as quartz, is formulated from stone aggregate and resin matrix. The constitution of this material is very strong, non-porous, and durable. Thanks to its homogeneous resin matrix, it does not require periodic sealing of the surface, unlike its natural counterparts.

The hardness of any stone is expressed by the **Mohs hardness scale**, which is a comparative abrasion resistance test for minerals. The hardness rating ranges from 0 to 10. Materials from each subsequent hardness rating can scratch the surface of materials belonging to the previous rating. A higher rating means the material is more resistant to abrasion.

Natural stones can be specified for countertops and furniture, panels and tiles are used for finishing floors, walls, and many other architectural features. Natural stone is **heavy and brittle**, consequently, breakage is a common occurrence. The designer should think about

| Tab.06/01 Hardness ratings of various natural stones in accordance with Mohs hardness scale. |
|---------------------------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| Rating | Material          | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|--------|------------------|---|---|---|---|---|---|---|---|---|---|---|---|
| 1      | Talc             |   |   |   |   |   |   |   |   |   |   |   |   |
| 2      | Gypsum           |   |   |   |   |   |   |   |   |   |   |   |   |
| 3      | Calcite          |   |   |   |   |   |   |   |   |   |   |   |   |
| 4      | Fluorite         |   |   |   |   |   |   |   |   |   |   |   |   |
| 5      | Apatite          |   |   |   |   |   |   |   |   |   |   |   |   |
| 6      | Feldspar         |   |   |   |   |   |   |   |   |   |   |   |   |
| 7      | Quartz           |   |   |   |   |   |   |   |   |   |   |   |   |
| 8      | Topaz            |   |   |   |   |   |   |   |   |   |   |   |   |
| 9      | Corundum         |   |   |   |   |   |   |   |   |   |   |   |   |
| 10     | Diamond          |   |   |   |   |   |   |   |   |   |   |   |   |

Vid.06/07 Video on rock formations.

Fig.06/20 The vein structure on onyx results in varying levels of translucency and illumination patterns.

Vid.06/08 Video on quartz manufacturing and properties.

Fig.06/20 The vein structure on onyx results in varying levels of translucency and illumination patterns.
how components will be handled and transported to the building site as well as how they will be installed. Natural stone can contain voids, fissures, separation lines that significantly affect workability. The *Marble Soundness Classification* published by the Natural Stone Institute categorizes marbles and granites into 4 groups in relation to the number of holes, voids, and fissures: “rating A” with minimal proportion of geological faults and highest quality, whereas on the other end, “rating D” with the largest proportion of geological faults. Such holes may be repaired by waxing, sticking, or filling with a polymer resin.

Stone slabs are sawn from larger blocks. Typical slab size is around 5’ by 10’, but the actual usable area depends heavily on the source block shape and it is often assumed to be approximately 45 square feet. The typical slab cuts have 2cm (3/4”) and 3cm (1-1/4”) thickness, custom thicknesses are also possible. Stone slabs can be cut in different ways to achieve different visual effects. **Vein cut** is when the slab is cut against the vein, featuring parallel lines and layers. **Cross cut** is when the slab is cut in favor of the vein, has swirly and cloudy variations.

When a block of natural stone is cut, it generates a series of slabs with similar color and texture features. Very similar to how wood veneers are matched, in order to cover large surfaces while maintaining a coherent and pleasing visual whole, various matching techniques can be employed. **Slip matching**, or side slip, involves repeating the same pattern without changing the orientation of the tiles. A very common method, **book matching** involves reversing...
one tile to mirror the adjacent tile, resembling an open book. **Diamond matching**, or quarter match, involves 4 tiles mirrored on two axes creating an impression of a diamond shape with their linear vein structure. **Pattern matching**, or blend pattern, involves carefully aligning visual features to create a consistent and continuous visual composition.

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Even though it can create a lot of wastage, for smaller-sized pieces, such as countertops or furniture components, a specific section of the stone slab can be identified and cut based on desired vein structure.

Also referred to as **sawn finish**, stone slabs can be left unfinished after they are cut, which creates a raw, rough, and irregular look. Or, slabs can be further processed to create polished, honed, leathered, sandblasted, or flamed finishes. **Grinding, sanding, and buffing with increasingly fine grit abraders produce a high-gloss, polished surface.** Denser stones such as marble and granite can achieve a higher sheen compared to sedimentary stones such as limestone or sandstone. Polished granite is high maintenance, requires daily mopping, and regular waxing and buffing. The polish wears off with traffic exposure. Polished stone is often less expensive and readily available. It has poor slip resistance, not appropriate for exterior applications without surface treatment or walk-off mats. Moreover, the reflective polished surface can cause significant glare, especially for darker colored stones. Installation requires extra care as loose sand and grout smears are capable of scratching the polished finish. **Honing is another type of smooth, yet not glossy finish achieved through grinding and sanding, but with lesser grit abraders.** Visually, it is more understated than a polished finish, though it can hide dirt and smudges; better for low maintenance, high traffic applications; provides better slip resistance. It is possible to rebuff already polished stone to get a honed finish. **Leathering** is similar to honed granite; it has smooth appearance, but the surface is somewhat coarse and textured. This finish can hide dirt and smudges slightly better than a honed finish but cleaning and maintenance is harder. Requires additional processing therefore slightly more expensive than honing. **Flaming** is achieved by applying high-temperature, via a blowtorch, to the stone surface essentially fracturing it, creating a highly textured and almost weathered look. This finish hides imperfections and gives slip resistance, though it can affect the natural color of the stone resulting in a darker and duller appearance.

There are two common types of masonry, ashlar, and rubble. **Ashlar masonry** involves laying straight cut rectangular stones in horizontal courses, often with relatively thin layers of
mortar. The term ashlar also refers to each of the rectangular masonry units. Rubble masonry involves undressed or roughly dressed masonry units, arranged in a seemingly random pattern. Natural stone can be laid in mortar, cement- or epoxy-based adhesive, or used as a facing veneer anchored to a concrete or masonry backup wall. Natural stone is very heavy, between 6 to 10 pounds per square foot, depending on tile thickness. The substrate must be capable of supporting the weight without deflection over time. Depending on the extent of the application consultation and site visit with a structural engineer might be needed. Natural stone tiles are cut with a waterjet, ensuring minimal dimensional difference between each tile. This enables the grout lines to be very thin, down to 1/16”.

Similar to ceramic and porcelain natural stone can be installed on a substrate with a thinset and thickset method. Thinset installation requires consistent and meticulous subfloor preparation, especially important for polished finishes for consistent reflections. On the other hand, the mortar bed created with thickset installation helps accommodate for the weight and thickness variations. Stone slabs can be anchored to gypsum board, masonry, or concrete walls with wire ties or it is possible to install with an epoxy-based thinset adhesive for reliable bonding.

Even though the surface of natural stone looks tough and impenetrable, it is actually porous and it readily absorbs liquids. Invisible crevices and pores, moisture and food traces are sought-after real-estate for bacteria. Consequently, there is a need for periodical sealant application. Sealers can be topical or penetrating. Topical sealers, such as polyurethane (PU) and acrylic, tend to wear out quickly and must be stripped before reapplication. Penetrating sealers include silicone and fluoropolymers, which create a stronger bond, however, the finish appears matte, dull, or even foggy if applied improperly. Acids in common food such as dairy, carbonated drinks, alcohol, or even meat can damage the stone if not cleaned immediately, resulting in dull marks and pits. Natural stone with calcite in their composition, such as marble and travertine can stain and etch by acid exposure more readily, especially if its color is lighter.

Video on granite cutting with waterjet.