## Concrete

A composite material that consists essentially of a binding medium, such as a mixture of portland cement and water, within which are embedded particles or fragments of aggregate, usually a combination of fine and coarse aggregate.

Concrete is by far the most versatile and most widely used construction material worldwide. It can be engineered to satisfy a wide range of performance specifications, unlike other building materials, such as natural stone or steel, which generally have to be used as they are. Because the tensile strength of concrete is much lower than its compressive strength, it is typically reinforced with steel bars, in which case it is known as reinforced concrete. *See* REINFORCED CONCRETE.

**Materials.** A composite material is made up of various constituents. The properties and characteristics of the composite are functions of the constituent materials' properties as well as the various mix proportions. Before discussing the properties of the composite, it is necessary to discuss those of the individual constituents as well as the effects of the mix proportions and methods of production. *See* COMPOSITE MATERIAL.

*Cement.* There are many different kinds of cements. In concrete, the most commonly used is portland cement, a hydraulic cement which sets and hardens by chemical reaction with water and is capable of doing so under water. Cement is the "glue" that binds the concrete ingredients together and is instrumental for the strength of the composite. Although cements and concrete have been around for thousands of years, modern portland cement was invented in 1824 by Joseph Aspdin of Leeds, England. The name derives from its resemblance of the natural building stone quarried in Portland, England. *See* CEMENT.

Portland cement is made up primarily of four mineral components (tricalcium silicate, dicalcium silicate, tricalcium aluminate, and tetracalcium aluminoferrite), each of which has its own hydration characteristics. By changing the relative proportions of these components, cement manufacturers can control the properties of the product.

The primary product of cement hydration is a complex and poorly crystalline calcium-silicate-hydroxide gel (or CSH). A secondary product of hydration is calcium hydroxide, a highly crystalline material. A category of siliceous materials known as pozzolans have little or no cementitious value, but in finely divided form and in the presence of moisture will react chemically with calcium hydroxide to form additional CSH. This secondary hydration process has a generally beneficial effect on the final concrete properties. Examples of pozzolans are fly ash, ground granulated blast-furnace slag, and microsilica or silica fume.

The American Society for Testing and Materials (ASTM) defines five types of cement, specifying for each the mineral composition and chemical and physical characteristics such as fineness. The most common cement is Type I. Type III cement is used if more rapid strength development is required. The other types are characterized by either lower heat of hydration or better sulfate resistance than that of Type I cement.

*Aggregate.* The aggregate is a granular material, such as sand, gravel, crushed stone, or iron-blast furnace slag. It is graded by passing it through a set of sieves with progressively smaller mesh sizes. All material that passes through sieve #4 [0.187 in. (4.75 mm) openings] is conventionally referred to as fine aggregate or sand, while all material that is retained on the #4 sieve is referred to as coarse aggregate, gravel, or stone. By carefully grading the material and selecting an optimal particle size distribution, a maximum packing density can be achieved, where the smaller particles fill the void spaces between the larger particles. Such dense packing minimizes the amount of cement paste needed and generally leads to improved mechanical and durability properties of the concrete.

The aggregate constitutes typically 75% of the concrete volume, or more, and therefore its properties largely determine the properties of the concrete. For the concrete to be of good quality, the aggregate has to be strong and durable and free of silts, organic matter, oils, and sugars. Otherwise, it should be washed prior to use, because any of these impurities may slow or prevent the cement from hydrating or reduce the bond between the cement paste and the aggregate particles.

*Admixtures.* While aggregate, cement, and water are the main ingredients of concrete, there are a large number of mineral and chemical admixtures that may be added to the concrete. The four most common admixtures will be discussed.

1. Air-entraining agents are chemicals that are added to concrete to improve its freeze–thaw resistance. Concrete typically contains a large number of pores of different sizes, which may be partially filled with water. If the concrete is subjected to freezing temperatures, this water expands when forming ice crystals and can easily fracture the cement matrix, causing damage that increases with each freeze–thaw cycle. If the air voids created by the air-entraining agent are of the right size and average spacing, they give the freezing water enough space to expand, thereby avoiding the damaging internal stresses.

2. Water-reducing admixtures, also known as superplasticizers, are chemicals that lower the viscosity of concrete in its liquid state, typically by creating electrostatic surface charges on the cement and very fine aggregate particles. This causes the particles to repel each other, thereby increasing the mix flowability, which allows the use of less water in the mix design and results in increased strength and durability of the concrete. *See* FLOW OF SOLIDS.

3. Retarding admixtures delay the setting time, which may be necessary in situations where delays in the placement of concrete can be expected. Accelerators shorten the period needed to initiate cement hydration—for example, in emergency repair

situations that call for the very rapid development of strength or rigidity.

4. Color pigments in powder or liquid form may be added to the concrete mix to produce colored concrete. These are usually used with white portland cement to attain their full coloring potential. *See* PIGMENT (MATERIAL).

*Reinforcing steels.* Because of concrete's relatively low tensile strength, it is typically reinforced with steel bars (**Fig. 1**). These bars are produced in standard sizes. In the United States, the identification number of a reinforcing bar refers to the nominal diameter expressed in eighths of an inch. For example, a number 6 bar has a diameter of $^6/_8 = 0.75$ inch. The available bar sizes range in general from 2 to 18. Reinforcing steel usually has a nominal yield strength of 60,000 lb/in.$^2$ (414 MPa). To improve the bond strength between the bars and the concrete, the bars are fabricated with surface deformations or ribs. The relatively high cost of steel mandates its sparing use. This means that the concrete is usually assigned the task of resisting compressive forces, while the steel carries primarily the tensile forces. The alkalinity of the cement paste generally provides sufficient protection of the steel against corrosion. However, corrosion protection is often breached, for example, in highway bridge decks with continuous pore structure or traffic-induced cracks that permit the deicing chemicals used in winter to penetrate the protective concrete cover. Additional protective measures may be necessary, such as using epoxy coatings on the bars, noncorrosive steels, or nonmetallic reinforcement (for example, fiber-reinforced polymers). *See* CORROSION.

Other important concrete terminology can be defined. A mixture of cement and water is called cement paste. Cement paste plus fine aggregate is called mortar or concrete matrix. Mortar plus coarse aggregate constitutes concrete. Concrete reinforced with steel or other high-strength material is known as reinforced concrete. *See* MORTAR.

**Fig. 1. Workers placing and vibrating concrete on a bridge deck including epoxy-coated reinforcing steel. (*Portland Cement Association*)**

**Production of concrete.** The properties of the end product depend not only on the various constituent materials listed above but also on the way they are proportioned and mixed, as well as on the methods of placing and curing the composite.

*Mix design.* It is not possible to predict the strength and other concrete properties solely based on the properties and proportions of the mix components. Therefore, mixes are designed on an empirical basis, often with the help of trial mixes. The objective of the mix design is to assure that the product has specified properties in both the fresh and hardened state. The most important mix design variable is the weight ratio between water and cement, referred to as the w/c ratio. There is a theoretical minimum amount of water needed for the cement to completely hydrate, which can be determined using the equations of hydration chemistry. Any excess water creates pores which, together with any air-filled pores, do not contribute to the material strength. The result is a drastic decrease in strength as a function of increasing the w/c ratio. On the other hand, too low w/c ratios cause poor workability of the concrete. For practical reasons, the w/c ratio typically varies between 0.4 and 0.6. The other important mix design variables are the cement-to-aggregate ratio and the fine-to-coarse aggregate ratio. Also, the maximum aggregate size is of importance. And since cement is the most expensive bulk ingredient, the mix design will generally aim at the least amount of cement necessary to achieve the design objectives.

*Construction practice.* The material obtained immediately upon mixing of the various concrete ingredients is called fresh concrete, while hardened concrete results when the cement hydration process has advanced sufficiently to give the material mechanical strength. Concrete that is batched and mixed in a plant and then transported by truck in its fresh, or plastic, state to the construction site for final placement is called ready-mixed concrete. If the resulting structure or highway pavement, for example, remains in place after placement, the concrete is referred to as cast-in-place concrete, whether mixed on-site or off-site. Precast concrete refers to any structure or component that is produced at one site, typically in a precasting plant, and then transported in its hardened state to its final destination. The controlled environment of a precasting plant generally permits higher quality control of the product than is possible with cast-in-place concrete produced at a construction site. *See* CONSTRUCTION METHODS; PAVEMENT.

Code-writing organizations, such as the American Society for Testing and Materials, the American Concrete Institute (ACI), and the American Association of State Highway and Transportation Officials (AASHTO), have published detailed specifications and recommendations for measuring, mixing, transporting, placing, curing, and testing concrete. A proper mix design assures that the concrete mix is well proportioned. The mixing time should be sufficient to assure a uniform mixture. When placing the concrete, care should be taken to avoid segregation. For example, if dropped too far, the heavy or big aggregate particles can settle and lighter mix components, such as water, tend to rise. The concrete is conveyed from the mixing truck to its final destination in dump buckets by cableways or cranes or by pumping through pipelines. In modern high-rise building construction, concrete has been pumped as high as a thousand feet (330 m).

During placement, large amounts of air are entrapped in the mix, which lowers the strength of the hardened concrete. Much of the air is removed by compaction, which is achieved by either immersing high-frequency vibrators into the fresh concrete or attaching them to the outside faces of the formwork (Fig. 1). Care must be taken to avoid excessive vibration; otherwise the heavy aggregate particles settle down and the light mixing water rises to the surface.

For underwater construction, the concrete is placed in a large metal tube, called a tremie, with a hopper at the top and a valve arrangement at the submerged end. For so-called shotcrete applications such as tunnel linings and swimming pools, the concrete mixture is blown under high pressure through a nozzle directly into place to form the desired surface.

Before the concrete sets and hardens, it is relatively easy to give its exposed surfaces the desired finish. Surfaces cast against forms can be given various textures by using form liners or treating the surfaces after forms are removed. Hardened surfaces can be textured by grinding, chipping, bush-hammering, or sandblasting.

*Curing.* Once the concrete has been placed and compacted, it is critical that none of the mixing water needed for cement hydration is lost. This is the objective of curing. For example, in hot or dry weather large exposed surfaces will lose water by evaporation. This can be avoided by covering such surfaces with sheets of plastic or canvas or by periodically spraying them with water. In precast concrete plants, concrete elements are often steam-cured, because the simultaneous application of hot steam and pressure accelerates the hydration process, which permits high turnover rates for the formwork installations.

*Quality control.* To assure that the finished material has the specified properties, quality assurance and quality control procedures need to be implemented. From a public safety viewpoint, strength is the most important property. To assure adequate strength, such as determining the time of safe formwork removal, concrete batches are sampled by casting test cylinders at the same time and place as the structure being built. These cylinders are then tested by accredited laboratories to determine their strength. If the in-situ strength of existing structures needs to be evaluated, concrete cores may be drilled from selected parts of the structure and tested in the laboratory. There are also nondestructive test methods available to determine various properties of hardened concrete.

**Fig. 2. Concrete slump test with a slump of 1.5 in., typical for pavement work. (*Portland Cement Association*)**

**Properties of fresh concrete.** The most important property of fresh concrete is its workability or flowability, because this determines the ease with which it can be placed. It is determined using a slump test, in which a standard truncated metal cone form is filled with fresh concrete (**Fig. 2**). The mold is then lifted vertically, and the resulting loss in height of the concrete cone, or the slump value, is indicative of the concrete's workability. For very liquid mixes, the flow test is performed, which is similar to the slump test, except that the mean diameter of the cake formed by the fresh concrete (or mortar) is measured.

A short while after casting, the concrete stiffens and loses its plasticity. The time of setting can be determined by repeatedly dropping a calibrated needle into the fresh concrete and measuring the time when the needle no longer sinks in.

**Properties of hardened concrete.** By far, the most important property of hardened concrete is its compressive strength. Since this strength continues to increase with continuing cement hydration, it is a function of age which is the time after casting. In the United States, the strength is determined 28 days after casting by loading standardized test cylinders up to failure. In Europe, test cubes are often used. Most commercially produced concrete has compressive strengths between 3000 and 6000 lb/in.$^2$ (20 and 40 MPa). If loaded in tension, the material fails at a stress much lower than that, typically of the order of 10% of the compressive strength. Because of this low (and unreliable) tensile strength, concrete is usually reinforced with steel bars. *See* STRESS AND STRAIN.

During hydration and especially if allowed to dry after hardening, the concrete volume decreases by a small amount because of shrinkage. If this shrinkage is restrained somehow, it can lead to cracking. Shrinkage deformations caused by drying can be reversed only partially upon wetting. A concrete member or structure subjected to external load will undergo deformations which, up to a point, are proportional to the amount of applied load. If these loads remain in place for an appreciable time (months or years), these deformations will increase due to a material property called creep. Even for regular concrete mixes, creep deformations can be two or three times as high as the initial elastic deformations, especially if the concrete is loaded at a very young age. When designing concrete structures, such creep and shrinkage deformations must be accounted for. *See* CREEP (MATERIALS); ELASTICITY.

**Durability.** Durability is the ability of a material (or structure) to maintain its various properties throughout its design or service life. Some concrete structures built by the Romans served for over 2000 years. A material that loses its strength in time, for whatever reason, cannot be considered durable.

There can be numerous causes for loss of durability or deterioration of concrete structures. The most common one is an excessive amount of cracking or pore structure. Most concrete structures contain numerous cracks. But as long as these remain small (of the order of 0.25 mm or less), they are generally invisible to the naked eye, and the concrete remains basically impermeable to salts and other aggressive agents, so that it can continue to protect the reinforcing steel against corrosion. Larger cracks provide easy access for such agents to the steel, thereby promoting corrosion. Since the steel corrosion products occupy a larger volume than sound steel, they produce internal pressure during expansion and can spall off the protective concrete cover, the loss of which may render the structure unsafe to resist loads.

The concrete itself may deteriorate or weather, especially if subjected to many cycles of freezing and thawing, during which the pressure created by the freezing water progressively increases the extent of internal cracking. In addition, carbon in the atmosphere can react chemically with the cement hydration products. This process is known as carbonation. It lowers the pH of the concrete matrix to the point where it can no longer protect the steel against corrosion.

Most types of aggregate used for concrete production are inert; that is, they do not react chemically with the cement or hydration products. However, there are various aggregate types, including those containing amorphous silica such as common glass, which react chemically with the alkali in the cement. In the presence of moisture, the alkali–aggregate reaction products can swell and cause considerable damage. The deterioration of numerous major structures and highway pavements has been attributed to such reactions, especially alkali–silica reaction, often after years of seemingly satisfactory service. Other common causes of chemical attack are sulfates found in soils, chlorides in seawater, acid rain, and other industrial pollutants. Generally, structures built with well-designed concrete mixes, having low porosity or high density and minimal cracking, are likely to resist most causes of chemical attack, although for service in particularly aggressive environments special countermeasures may have to be taken.

Under repeated load applications, structures can experience fatigue failure, as each successive load cycle increases the degree of cracking and material deterioration to the point where the material itself may gradually lose its strength or the increased extent of cracking is the source of loss of durability.

**Thermal and other properties.** The heavy weight of concrete [its specific gravity is typically 2.4 g/cm$^3$ (145 lb/ft$^3$)] is the source of large thermal mass. For this reason, massive concrete walls and roof and floor slabs are well suited for storing thermal energy. Because of this heat capacity of concrete, together with its reasonably low thermal conductivity, concrete structures can moderate extreme temperature cycles and increase the comfort of occupants. Well-designed concrete mixes are impermeable to liquids and therefore suitable for storage tanks without the need for impermeable membranes or liners. Although steel reinforcing bars conduct electricity and influence magnetic fields, the concrete itself does neither. *See* CONCRETE SLAB; FLOOR CONSTRUCTION; ROOF CONSTRUCTION.

**Special concretes and recent developments.** Concrete is an engineered material, with a variety of specialty products designed for specific applications. Some important ones are described below.

*Lightweight concrete.* Although the heavy weight or large mass of typical concrete members is often an advantage, there are situations where this is not the case. For example, because of the large stresses caused by their own heavy weight, floor slabs are often made lighter by using special lightweight aggregate. To further reduce weight, special chemical admixtures are added, which produce large porosity. Such high porosity (in either the matrix or the aggregate particles themselves) improves the thermal resistance of the concrete as well as sound insulation, especially for higher frequencies. However, because weight density correlates strongly with strength, ultralightweight concretes [1.1 g/cm$^3$ (70 lb/ft$^3$) and less] are used only for thermal or sound insulation purposes and are unsuitable for structural applications.

*Heavyweight concrete.* When particularly high weight densities are needed, such as for shielding in nuclear reactor facilities, special heavyweight aggregate is used, including barite, limonite, magnetite, scrap metal, and steel shot for fine aggregate. Weight densities can be achieved that are twice that of normal-weight concrete.

*Architectural concrete.* Concrete surfaces that remain exposed may call for special finishes or textures according to the architect's desires. Textures are most readily obtained by inserting special form liners before casting the concrete. Sometimes the negative imprint of roughly sawn timber is considered attractive and left without further treatment.

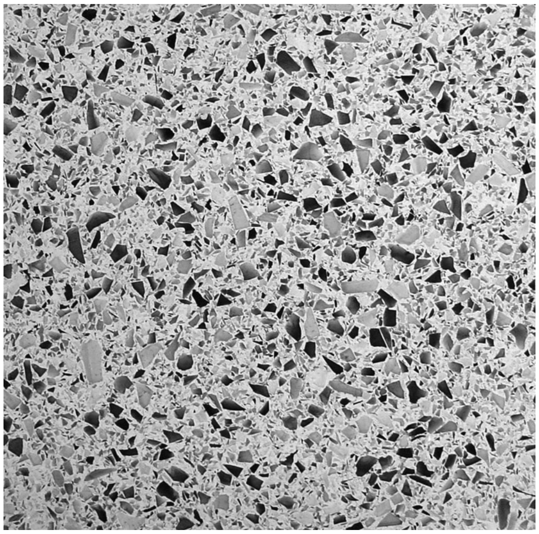

**Fig. 3. Glass concrete tile. (*C. Meyer*)**

Other surface textures are obtained by sandblasting, bush-hammering, and similar treatments. Ordinary portland cement gives concrete the typical gray color. By adding color pigments to the mix, a large variety of colors can be produced, especially in combination with white portland cement. Concrete mixed with specialty aggregate, such as marble, and ground smooth is known as terrazzo concrete, which is very popular for decorative surfaces on floors and walls. Recently, crushed postconsumer glass has been used as aggregate for decorative applications because of the esthetic possibilities, provided suitable countermeasures against alkali–silica reaction are taken (**Fig. 3**).

*Fiber-reinforced concrete.* The concrete matrix can be reinforced with short, randomly distributed fibers. Fibers may be metallic (primarily steel), synthetic (such as polypropylene, nylon, polyethylene, polyvinyl alcohol, and alkali-resistant glass), or natural (such as sisal, coconut, and rice husk). Such fibers are typically used in addition to conventional steel reinforcement, but in some applications as its replacement. For example, precast glass-fiber-reinforced building façade elements are widely used in the United States. By being uniformly distributed and randomly oriented, the fibers give the concrete matrix tensile strength, ductility, and energy absorption capacities that it otherwise would not have. In particular, when these fibers are engineered to optimize the fracture energy, so-called high-performance fiber-reinforced concrete is obtained, which has remarkable deformational characteristics and extraordinary resistance to blast and impact loads. In the concrete industry, it is very common to add small amounts of polypropylene fibers to reduce the extent of shrinkage cracking.

*Textile-reinforced concrete.* Whereas in fiber-reinforced concrete the fibers are short [usually no longer than 2 in. (5 cm)] and discontinuous, textile-reinforced concrete contains continuous woven or knitted mesh or textiles. Conceptually, such reinforcement acts similarly to conventional steel reinforcing bars or welded steel wire fabrics. But these fabric materials are noncorrosive and can have mechanical properties that are superior to those of steel. The fabrics can be premanufactured in a wide variety of ways, thereby lending themselves to new applications, especially for repairing or strengthening existing concrete structures. *See* TEXTILE.

*Polymer-modified concrete.* In polymer-modified concrete, also known as latex-modified concrete, a polymer is added to improve the material's strength, imperviousness, or both. In applications such as highway bridge decks, often a layer of latex-modified concrete is placed on top of a regular reinforced concrete deck for additional protection of the steel reinforcement. In polymer concrete, the hydraulic cement is replaced by an organic polymer as the binder. *See* POLYMER; POLYMERIC COMPOSITE.

*Roller-compacted concrete.* This type of concrete is formulated with very low contents of portland cement and water and therefore is of relatively low-cost. It is often used for pavements and dams. It can be transported by dump trucks or loaders, spread with bulldozers or graders, and compacted with vibratory rollers. Because the cement content is so low, the heat of hydration does not cause the kind of problems encountered in dams built with conventional concrete.

*Ultra-high-strength concrete.* Whereas concretes with compressive strengths of 6000 to 12,000 lb/in.$^2$ (40 to 85 MPa) can now be categorized as high-strength, a new technology has been developed that results in strengths of 30,000 lb/in.$^2$ (200 MPa) and higher. The key ingredient of this ultra-high-strength concrete is a reactive powder; therefore, it is also known as reactive-powder concrete. Other characteristics of this material are low water–cement ratios, carefully selected high-strength aggregates, and small steel fibers.

*Self-leveling concrete.* The need for good workability has been mentioned. The need for highly skilled workers who can properly compact concrete at the construction site prompted researchers in Japan to optimize the mix design such that the fresh concrete can flow into place without the need for further vibration. The main challenge was to obtain a low-viscosity mix without the threat of desegregation. This innovation is particularly important in applications with dense steel reinforcement, which traditionally have caused severe difficulties of producing high-quality concrete.

*"Green" concrete.* Concrete is by far the most widely used building material. Well over 10 billion tons are produced worldwide each year, requiring enormous natural resources. Also, it has been estimated that the production of 1 ton of portland cement causes the release of 1 ton of carbon dioxide ($CO_2$) into the atmosphere, a gas that is known to contribute to global warming. Together with the large amounts of energy required to produce portland cement, the cement and concrete industry has a major impact on the environment worldwide. Efforts are underway to reduce this impact and transform the industry to

conform to the principles of sustainable development. The most significant step is the replacement of portland cement by other cementitious or pozzolanic materials, preferably materials that are by-products of industrial processes, such as fly ash (the by-product of coal-burning power plants) and granulated blast furnace slag (a by-product of the steel industry). To reduce the need for virgin aggregate, recycled concrete is the most promising approach, because construction debris, in particular demolished concrete, constitutes a major component of solid waste that fills up sparse landfill capacity. These recent developments are much more advanced in Europe and Japan than in the United States. But the "green" building movement is gaining momentum there as well, and for the concrete industry to maintain its dominant position within the construction industry, it is undertaking major efforts to make concrete a more "green" material.

Christian Meyer

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