Concrete

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This article is about the construction material. For other uses, see Concrete (disambiguation).

Not to be confused with cement or mortar (masonry).

Exterior of the Roman Pantheon, finished 128 AD, still the largest unreinforced solid concrete dome.[1]

Interior of the Pantheon dome, seen from beneath. The concrete for the coffered dome was laid on moulds, probably mounted on temporary scaffolding.

*Opus caementicium*exposed in a characteristic Roman arch. In contrast to modern concrete structures, the concrete used in Roman buildings was usually covered with brick or stone.

Concrete is a composite material composed of coarse aggregate bonded together with a fluid cement which hardens over time. Most concretes used are lime-based concretes such as Portland cement concrete or concretes made with otherhydraulic cements, such as ciment fondu. However, road surfaces are also a type of concrete, asphalt concrete, where the cement material is bitumen, and polymer concretes are sometimes used where the cementing material is a polymer.

In Portland cement concrete (and other hydraulic cement concretes), when the aggregate is mixed together with the dry cement and water, they form a fluid mass that is easily molded into shape. The cement reacts chemically with the water and other ingredients to form a hard matrix which binds all the materials together into a durable stone-like material that has many uses.[2] Often, additives (such as pozzolans or superplasticizers) are included in the mixture to improve the physical properties of the wet mix or the finished material. Most concrete is poured with reinforcing materials (such as rebar) embedded to provide tensile strength, yielding reinforced concrete.

Famous concrete structures include the Hoover Dam, the Panama Canal and the Roman Pantheon. The earliest large-scale users of concrete technology were the ancient Romans, and concrete was widely used in the Roman Empire. TheColosseum in Rome was built largely of concrete, and the concrete dome of the Pantheon is the world's largest unreinforced concrete dome.[3] Today, large concrete structures (for example, dams and multi-storey car parks) are usually made with reinforced concrete.

After the Roman Empire collapsed, use of concrete became rare until the technology was redeveloped in the mid-18th century. Today, concrete is the most widely used man-made material (measured by tonnage).

Contents

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History[edit]

The word concrete comes from the Latin word "*concretus*" (meaning compact or condensed),[4] the perfect passive participle of "*concrescere*", from "*con*-" (together) and "*crescere*" (to grow).

Prehistory[edit]

Perhaps the earliest known occurrence of cement was twelve million years ago. A deposit of cement was formed after an occurrence of oil shale located adjacent to a bed of limestone burned due to natural causes. These ancient deposits were investigated in the 1960s and 1970s.[5]

On a human timescale, small usages of concrete go back for thousands of years. Concrete-like materials were used since 6500BC by the Nabataea traders or Bedouins who occupied and controlled a series of oases and developed a small empire in the regions of southern Syria and northern Jordan. They discovered the advantages of hydraulic lime, with some self-cementing properties, by 700 BC. They built kilns to supply mortar for the construction of rubble-wall houses, concrete floors, and underground waterproof cisterns. The cisterns were kept secret and were one of the reasons the Nabataea were able to thrive in the desert.[6] Some of these structures survive to this day.[6]

Classical era[edit]

In both Roman and Egyptian times it was re-discovered that adding volcanic ash to the mix allowed it to set underwater. Similarly, the Romans knew that addinghorse hair made concrete less liable to crack while it hardened, and adding blood made it more frost-resistant.[7] Crystallization of strätlingite and the introduction of pyro-clastic clays creates further fracture resistance.[8]

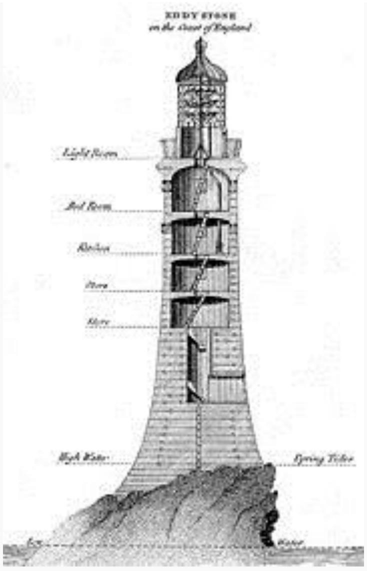
German archaeologist Heinrich Schliemann found concrete floors, which were made of lime and pebbles, in the royal palace of Tiryns, Greece, which dates roughly to 1400-1200 BC.[9][10] Lime mortars were used in Greece, Crete, and Cyprus in 800 BC. The Assyrian Jerwan Aqueduct (688 BC) made use of waterproof concrete.[11] Concrete was used for construction in many ancient structures.[12]

The Romans used concrete extensively from 300 BC to 476 AD, a span of more than seven hundred years.[5] During the Roman Empire, Roman concrete (or *opus caementicium*) was made from quicklime, pozzolana and an aggregate of pumice. Its widespread use in many Roman structures, a key event in the history of architecture termed the Roman Architectural Revolution, freed Roman construction from the restrictions of stone and brick material and allowed for revolutionary new designs in terms of both structural complexity and dimension.[13]

Concrete, as the Romans knew it, was a new and revolutionary material. Laid in the shape of arches, vaults and domes, it quickly hardened into a rigid mass, free from many of the internal thrusts and strains that troubled the builders of similar structures in stone or brick.[14]

Modern tests show that *opus caementicium* had as much compressive strength as modern Portland-cement concrete (ca. 200 kilograms per square centimetre (20 MPa; 2,800 psi)).[15] However, due to the absence of reinforcement, its tensile strength was far lower than modern reinforced concrete, and its mode of application was also different:[16]

Modern structural concrete differs from Roman concrete in two important details. First, its mix consistency is fluid and homogeneous, allowing it to be poured into forms rather than requiring hand-layering together with the placement of aggregate, which, in Roman practice, often consisted of rubble. Second, integral reinforcing steel gives modern concrete assemblies great strength in tension, whereas Roman concrete could depend only upon the strength of the concrete bonding to resist tension.[17]



Smeaton's Tower

The widespread use of concrete in many Roman structures ensured that many survive to the present day. The Baths of Caracallain Rome are just one example. Many Roman aqueducts and bridges such as the magnificent Pont du Gard have masonry cladding on a concrete core, as does the dome of the Pantheon.

Middle Ages[edit]

After the Roman Empire, the use of burned lime and pozzolana was greatly reduced until the technique was all but forgotten between 500 and the 14th century. From the 14th century to the mid-18th century, the use of cement gradually returned. The*Canal du Midi* was built using concrete in 1670,[18] and there are concrete structures in Finland that date from the 16th century.[*citation needed*]

Industrial era[edit]

Perhaps the greatest driver behind the modern usage of concrete was Smeaton's Tower, the third Eddystone Lighthouse in Devon, England. To create this structure, between 1756 and 1759, British engineer John Smeaton pioneered the use of hydraulic lime in concrete, using pebbles and powdered brick as aggregate.[19]

A method for producing Portland cement was patented by Joseph Aspdin on 1824.[20]

Reinforced concrete was invented in 1849 by Joseph Monier.[21] In 1889 the first concrete reinforced bridge was built, and the first large concrete dams were built in 1936, Hoover Dam and Grand Coulee Dam.[22]

Composition of concrete[edit]

There are many types of concrete available, created by varying the proportions of the main ingredients below. In this way or by substitution for the cementitious and aggregate phases, the finished product can be tailored to its application with varying strength, density, or chemical and thermal resistance properties.

Aggregate consists of large chunks of material in a concrete mix, generally a coarse gravel or crushed rocks such as limestone, or granite, along with finer materials such as sand.

Cement, most commonly Portland cement, is associated with the general term "concrete." A range of materials can be used as the cement in concrete. One of the most familiar of these alternative cements is asphalt concrete. Other cementitious materials such as fly ash and slag cement, are sometimes added as mineral admixtures (see below) - either pre-blended with the cement or directly as a concrete component - and become a part of the binder for the aggregate.

To produce concrete from most cements (excluding asphalt), water is mixed with the dry powder and aggregate, which produces a semi-liquid that workers can shape, typically by pouring it into a form. The concrete solidifies and hardens through a chemical process called hydration. The water reacts with the cement, which bonds the other components together, creating a robust stone-like material.

Chemical admixtures are added to achieve varied properties. These ingredients may accelerate or slow down the rate at which the concrete hardens, and impart many other useful properties including increased tensile strength, entrainment of air, and/or water resistance.

Reinforcement is often included in concrete. Concrete can be formulated with high compressive strength, but always has lower tensile strength. For this reason it is usually reinforced with materials that are strong in tension, often steel.

Mineral admixtures are becoming more popular in recent decades. The use of recycled materials as concrete ingredients has been gaining popularity because of increasingly stringent environmental legislation, and the discovery that such materials often have complementary and valuable properties. The most conspicuous of these are fly ash, a by-product of coal-fired power plants, ground granulated blast furnace slag, and silica fume, a byproduct of industrial electric arc furnaces. The use of these materials in concrete reduces the amount of resources required, as the mineral admixtures act as a partial cement replacement. This displaces some cement production, an energetically expensive and environmentally problematic process, while reducing the amount of industrial waste that must be disposed of. Mineral admixtures can be pre-blended with the cement during its production for sale and use as a blended cement, or mixed directly with other components when the concrete is produced.

The *mix design* depends on the type of structure being built, how the concrete is mixed and delivered, and how it is placed to form the structure.

Cement[edit]

Main article: Cement

A few tons of bagged cement. This amount represents about two minutes of output from a 10,000 ton per day cement kiln.

Portland cement is the most common type of cement in general usage. It is a basic ingredient of concrete, mortar and manyplasters. English masonry worker Joseph Aspdin patented Portland cement in 1824. It was named because of the similarity of its color to Portland limestone, quarried from the English Isle of Portland and used extensively in London architecture. It consists of a mixture of calcium silicates (alite, belite), aluminates and ferrites - compounds which combine calcium, silicon, aluminium and iron in forms which will react with water. Portland cement and similar materials are made by heatinglimestone (a source of calcium) with clay and/or shale (a source of silicon, aluminium and iron) and grinding this product (called *clinker*) with a source of sulfate (most commonly gypsum).

In modern cement kilns many advanced features are used to lower the fuel consumption per ton of clinker produced. Cement kilns are extremely large, complex, and inherently dusty industrial installations, and have emissions which must be controlled. Of the various ingredients used to produce a given quantity of concrete, the cement is the most energetically expensive. Even complex and efficient kilns require 3.3 to 3.6 gigajoules of energy to produce a ton of clinker and then grind it into cement. Many kilns can be fueled with difficult-to-dispose-of wastes, the most common being used tires. The extremely high temperatures and long periods of time at those temperatures allows cement kilns to efficiently and completely burn even difficult-to-use fuels.[23]

Water[edit]

Combining water with a cementitious material forms a cement paste by the process of hydration. The cement paste glues the aggregate together, fills voids within it, and makes it flow more freely.[24]

A lower water-to-cement ratio yields a stronger, more durable concrete, whereas more water gives a freer-flowing concrete with a higher slump.[25] Impure water used to make concrete can cause problems when setting or in causing premature failure of the structure.[26]

Hydration involves many different reactions, often occurring at the same time. As the reactions proceed, the products of the cement hydration process gradually bond together the individual sand and gravel particles and other components of the concrete to form a solid mass.[27]

Reaction:[27]

> Cement chemist notation: $C_3S + H \rightarrow C\text{-}S\text{-}H + CH$
> Standard notation: $Ca_3SiO_5 + H_2O \rightarrow (CaO)\cdot(SiO_2)\cdot(H_2O)(gel) + Ca(OH)_2$
> Balanced: $2Ca_3SiO_5 + 7H_2O \rightarrow 3(CaO)\cdot 2(SiO_2)\cdot 4(H_2O)(gel) + 3Ca(OH)_2$ (approximately; the exact ratios of the CaO, SiO_2 and H_2O in C-S-H can vary)

Aggregates[edit]

Crushed stone aggregate

Main article: Construction aggregate

Fine and coarse aggregates make up the bulk of a concrete mixture. Sand, natural gravel, and crushed stone are used mainly for this purpose. Recycled aggregates (from construction, demolition, and excavation waste) are increasingly used as partial replacements for natural aggregates, while a number of manufactured aggregates, including air-cooled blast furnaceslag and bottom ash are also permitted.

The size distribution of the aggregate determines how much binder is required. Aggregate with a very even size distribution has the biggest gaps whereas adding aggregate with smaller particles tends to fill these gaps. The binder must fill the gaps between the aggregate as well as pasting the surfaces of the aggregate together, and is typically the most expensive component. Thus variation in sizes of the aggregate reduces the cost of concrete.[28] The aggregate is nearly always stronger than the binder, so its use does not negatively affect the strength of the concrete.

Redistribution of aggregates after compaction often creates inhomogeneity due to the influence of vibration. This can lead to strength gradients.[29]

Decorative stones such as quartzite, small river stones or crushed glass are sometimes added to the surface of concrete for a decorative "exposed aggregate" finish, popular among landscape designers.

In addition to being decorative, exposed aggregate may add robustness to a concrete.[30]

Reinforcement[edit]

Constructing a rebar cage. This cage will be permanently embedded in poured concrete to create a reinforced concrete structure.

Main article: Reinforced concrete

Concrete is strong in compression, as the aggregate efficiently carries the compression load. However, it is weak in tension as the cement holding the aggregate in place can crack, allowing the structure to fail. Reinforced concrete adds either steel reinforcing bars, steel fibers, glass fibers, or plastic fibers to carry tensile loads.