CHAPTER 1

Introduction to Concrete

Concrete's versatility, durability, sustainability, and economy have made it the world's most widely used construction material. About four tons of concrete are produced per person per year worldwide and about 1.7 tons per person in the United States. The term concrete refers to a mixture of aggregates, usually sand, and either gravel or crushed stone, held together by a binder of cementitious paste. The paste is typically made up of portland cement and water and may also contain supplementary cementing materials (SCMs), such as fly ash or slag cement, and chemical admixtures (Figure 1-1).

Understanding the fundamentals of concrete is necessary to produce quality concrete. This publication covers the materials used in concrete and the essentials required to design and control concrete mixtures for a wide variety of structures.

Figure 1-1. Concrete components: cement, water, coarse aggregate, fine aggregate, supplementary cementing materials, and chemical admixtures.

Figure 1-2. Ready mixed concrete is conveniently delivered to jobsites in trucks with revolving drums.

Industry Trends

The United States uses about 230 million cubic meters (300 million cubic yards) of ready mixed concrete each year (Figure 1-2). It is used in highways, streets, parking lots, parking garages, bridges, high-rise buildings, dams, homes, floors, sidewalks, driveways, and numerous other applications (Figure 1-3).

Cement Consumption

The cement industry is essential to the nation's construction industry (Figure 1-4). Few construction projects are viable without utilizing cement-based products. The United States consumed 86.5 million metric tons (95 million short tons) of portland cement in 2014. U.S. cement production is dispersed with the operation of 91 cement plants in 33 states. The top five companies collectively operate around 59% of U.S. clinker capacity (PCA 2015).


Figure 1-3. Concrete is used as a building material for many applications including high-rise (left) and pavement (right) construction.

Cement consumption varies based on the time of year and prevalent weather conditions. Nearly two-thirds of U.S. cement consumption occurs in the six month period between May and October. The seasonal nature of the industry can result in large swings in cement and clinker (unfinished raw material) inventories at cement plants over the course of a year. Cement producers will typically build up inventories during the winter and then ship them during the summer (Figure 1-5).

The majority of cement shipments are sent to ready-mixed concrete producers (Figure 1-6). The remainder are shipped to manufacturers of concrete related products, contractors, materials dealers, oil well/ mining/drilling companies, as well as government entities.

The domestic cement industry is regional in nature. The logistics of shipping cement limits distribution over long distances. As a result, customers traditionally purchase cement from local sources. About 97% of U.S. cement is shipped to customers by truck. Barge and rail account for the remaining distribution modes.

Concrete is used as a building material in the applications listed in Table 1-1. Portland cement consumption in the United States by user groups is defined in Figure 1-7. The apparent use of portland cement by market is provided for 2014 in Figure 1-8. The primary markets (Figure 1-9) are described further in the following sections.

Pavements

Concrete pavements have been a mainstay of America's infrastructure since the 1920s. The country's first concrete street (built in Bellefontaine, Ohio, in 1891), is still in service today. Concrete can be used for new pavements, reconstruction, resurfacing, restoration, or rehabilitation. Concrete pavements generally provide the longest life, least maintenance, and lowest life-cycle cost of all alternatives.

Figure 1-4. Portland cement manufacturing plant (Courtesy of GCC).

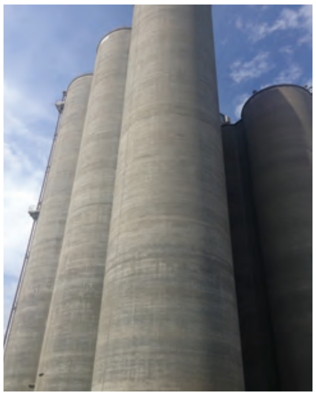


Figure 1-5. Storage silos for cement at a manufacturing plant.

Figure 1-6. The majority of cement is shipped to concrete producers in cement haulers (tankers).

Table 1-1. Markets and Applications for Concrete as a Building Material

Bridges
Buildings
Masonry
Parking Lots
Pavements
Residential
Transit and Rail
Soil Cement and Roller-Compacted Concrete
Waste Remediation
Water Resources

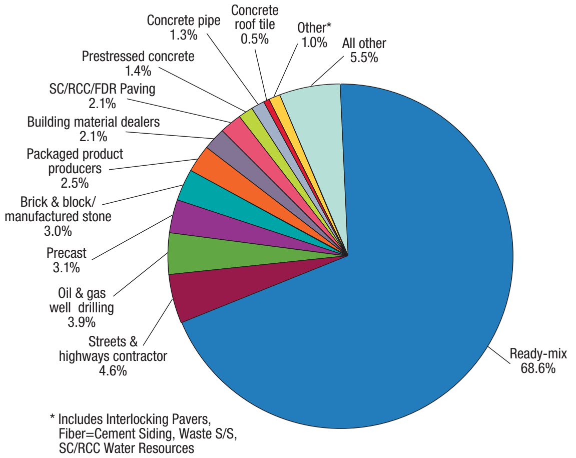


Figure 1-7. Portland cement consumption in U.S. by user groups (PCA 2015).

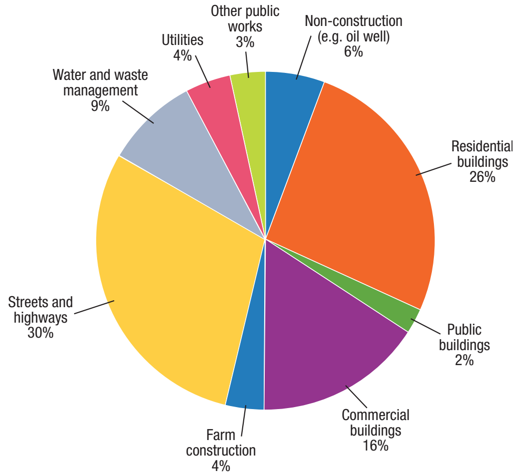


Figure 1-8. Apparent use of portland cement by market (PCA 2015).

A variety of cement-based products can be used in pavement applications including soil-cement, roller-compacted concrete, cast-in place slabs, pervious concrete, and whitetopping. They all contain the three same basic components of portland cement, soils/aggregates, and water.

While concrete pavements are best known as the riding surface for interstate highways, concrete is also a durable, economical and sustainable solution for rural roadways, residential and city streets, intersections, airstrips, intermodal facilities, military bases, parking lots and much more.

Bridges

More than 70% of the bridges throughout the U.S. are constructed of concrete. These bridges perform year-round in a wide variety of climates and geographic locations. With long life and low maintenance, concrete consistently outperforms other materials as a choice for bridge construction. A popular method to accelerate bridge construction is to use prefabricated systems and elements. These are fabricated off-site or adjacent to the actual bridge site ahead of time, and then moved into place as needed, resulting in a shorter duration for construction. These systems are constructed with concrete – reinforced, pretensioned, or post-tensioned (or a combination thereof). Engineered to meet specific needs, high-performance concrete (HPC) is often used for bridge applications including: high-durability mixtures, high-strength mixtures, self-consolidating concrete, and ultra-high performance concrete.

Figure 1-9. Concrete's primary markets include: pavements, bridges, and high-rise and low-rise buildings.

Buildings

Reinforced concrete construction for high-rise buildings provides inherent stiffness, mass, and ductility. Occupants of concrete towers are less likely to perceive building motions than occupants of comparable tall buildings with non-concrete structural systems. A major economic consideration in high-rise construction is reducing the floor to floor height. Using a reinforced concrete flat plate system, the floor to floor height can be minimized while still providing high floor to ceiling heights. As a result, concrete has become the material of choice for many tall, slender towers.

The first reinforced concrete high-rise was the 16-story Ingalls Building, completed in Cincinnati in 1903. Greater building height became possible as concrete strength increased. In the 1950s, 34 MPa (5000 psi) was considered high strength; by 1990, two high-rise buildings were constructed in Seattle using concrete with strengths of up to 131 MPa (19,000 psi). Ultra-high-strength concrete is now manufactured with strengths in excess of 150 MPa (21,750 psi).

Slightly more than half of all low-rise buildings in the United States are constructed from concrete. Designers select concrete for one-, two-, and three-story stores, restaurants, schools, hospitals, commercial warehouses, terminals, and industrial buildings because of its durability, excellent acoustic properties, inherent fire resistance, and ease of construction. In addition, concrete is often the most economical choice: load-bearing concrete exterior walls serve not only to enclose the buildings and keep out the elements, but they also carry roof, wind, and seismic loads, eliminating the need to erect separate systems. Four concrete construction methods are commonly used to create load-bearing walls for low-rise construction: tilt-up, precast, concrete masonry, and cast-in-place.

The Beginning of an Industry

The oldest concrete discovered dates from around 7000 BC. It was found in 1985 when a concrete floor was uncovered during the construction of a road at Yiftah El in Galilee, Israel. It consisted of a lime concrete, made from burning limestone to produce quicklime, which when mixed with water and stone, hardened to form concrete (Brown 1996 and Auburn 2000).

A cementing material was used between the stone blocks in the construction of the Great Pyramid at Giza in ancient Egypt around 2500 BC. Some reports say it was a lime mortar while others say the cementing material was made from burnt gypsum. By 500 BC, the art of making lime-based mortar arrived in ancient Greece. The Greeks used lime-based materials as a binder between stone and brick and as a rendering material over porous limestones commonly used in the construction of their temples and palaces.

Natural pozzolans have been used for centuries. The term "pozzolan" comes from a volcanic ash mined at Pozzuoli, a village near Naples, Italy, following the 79 AD eruption of Mount Vesuvius. Sometime during the second century BC the Romans quarried a volcanic ash near Pozzuoli. Believing that the material was sand, they mixed it with lime and found the mixture to be much stronger than previously produced. This discovery was to have a significant effect on construction. The material was not sand, but a fine volcanic ash containing silica and alumina. When combined chemically with lime, this material produced what became known as pozzolanic cement. However, the use of volcanic ash and calcined clay dates back to 2000 BC and earlier in other cultures. Many of the Roman, Greek, Indian, and Egyptian pozzolan concrete structures can still be seen today. The longevity of these structures attests to the durability of these materials.

Examples of early Roman concrete have been found dating back to 300 BC. The very word concrete is derived from the Latin word "concretus" meaning grown together or compounded. The Romans perfected the use of pozzolan as a cementing material. This material was used by builders of the famous Roman walls, aqueducts, and other historic structures including the Theatre at Pompeii, Pantheon, and Colliseum in Rome (Figure 1-10). Building practices were much less refined in the Middle Ages and the quality of cementing materials deteriorated.

Figure 1-10. Coliseum in Rome, completed in 80 AD, was constructed of concrete. Much of it still stands today (Courtesy of J. Catella).

The practice of burning lime and the use of pozzolan was lost until the 1300s. In the 18th century, John Smeaton concentrated his work to determine why some limes possess hydraulic properties while others (those made from essentially pure limestones) did not. He discovered that an impure, soft limestone containing clay minerals made the best hydraulic cement. This hydraulic cement, combined with a pozzolan imported from Italy, was used in the reconstruction of the Eddystone Lighthouse in the English Channel, southwest of Plymouth, England (Figure 1-11).

The project took three years to complete and began operation in 1759. It was recognized as a turning point in the development of the cement industry. A number of discoveries followed as efforts within a growing natural cement industry were now directed to the production of a consistent quality material. Natural cement was manufactured in Rosendale, New York, in the early 1800s (White 1820). One of the first uses of natural cement was to build the Erie Canal in 1818 (Snell and Snell 2000).

The development of portland cement was the result of persistent investigation by science and industry to produce a superior quality natural cement. The invention of portland cement is generally credited to Joseph Aspdin, an English mason. In 1824, he obtained a patent for a product which he named portland cement. When set, Aspdin's product resembled the color of the natural limestone quarried on the Isle of Portland in the English Channel (Aspdin 1824). The name has endured and is now used throughout the world, with many manufacturers adding their own trade or brand names.

1750 1810 1820 1840 1860 1870 1885 1890

1759 J. Smeaton began construction of the Eddystone Lighthouse built with hydraulic lime

1818 Natural cement is used to build the Erie Canal

1824 Joseph Aspdin is granted a patent for hydraulic cement and names it after a premier quality limestone quarried from the Isle of Portland in the English Channel

1845 I. C. Johnson of White and Sons, Swanscombe, England, produces a portland cement with improved properties

1868 Portland cement is first imported to the United States

1871 Portland cement is first produced in the United States in Coplay, Pennsylvania

1885 Ransome invented the rotary kiln

1890 Navarro introduced rotary kiln to U.S.
1897 Feret develops a relationship between strength and the volume of cement, water and air in concrete

Figure 1-13. Timeline of concrete milestones.

concrete makes good HISTORY

1900

1902 The Association of American Portland Cement Manufacturers is founded

1904 The American Society of Testing and Materials publishes ASTM C-1 *Standard Specification for Natural and Portland Cement*

1904 Portland cement from throughout the U.S. is featured at the World's Fair in St. Louis as the magic powder that will revolutionize the century

1905 National Association of Cement Users (NACU) holds its first convention in Indianapolis

1908 Thomas Edison invents cast-in-place concrete housing system

1910

1913 NACU changes its name to the American Concrete Institute

1916 Portland Cement Association is founded in Chicago; previously called the Association of American Portland Cement Manufacturers

1916 PCA publishes *Proportioning Concrete Mixtures and Mixing and Placing Concrete*

1918 Abrams (Lewis Institute—now IIT) publishes the relationship between water to cement ratio and strength of concrete (LS001)

1920

1921 PCA starts long term field and lab study on concrete's resistance to sulfate soils

1925 Abrams publishes *Studies of Bond Between Concrete and Steel* (LS017)

1925 PCA Research lab moved to 33 West Grand Avenue

1926 PCA Fellowship at National Bureau of Standards

1930

1930 National Ready Mixed Concrete Association is founded

1931-1936 Hoover Dam construction

1938 Powers (PCA) discovers that air entrainment gives frost resistance to concrete

1940

1941 A long-term field study of cement performance on concrete using 27 cements of various properties is established (RX026)

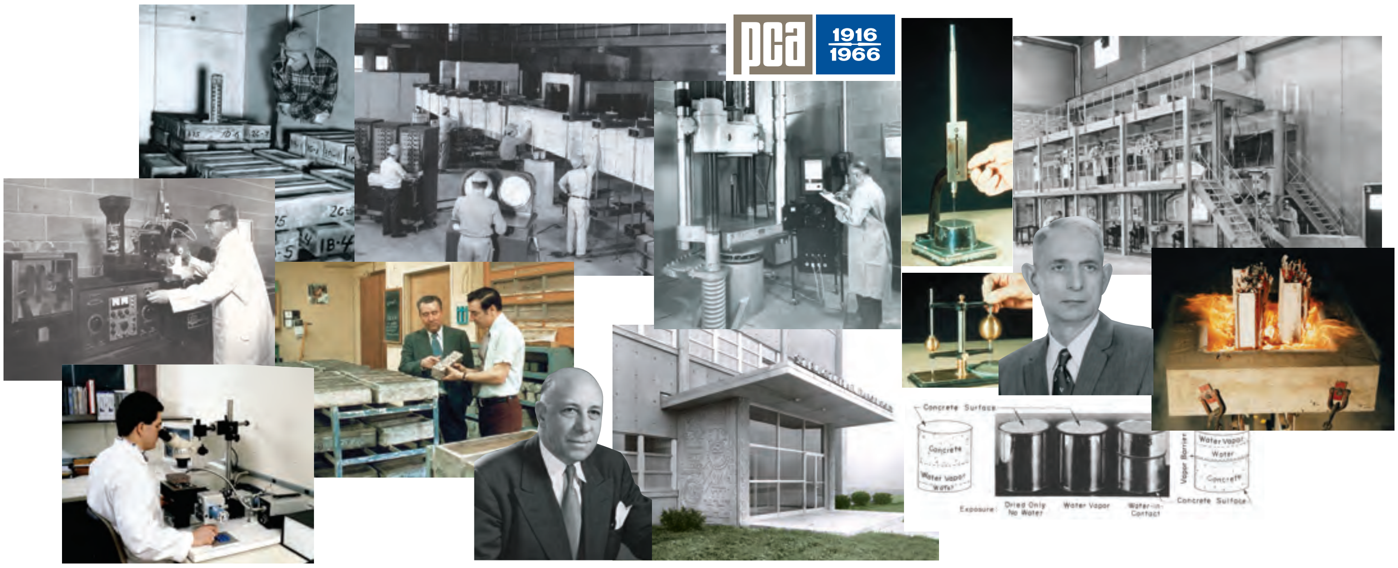
1946 The Influence of gypsum on the hydration and properties of portland cement paste (RX012)

1947 Pressure and volumetric methods to determine air content of fresh concrete (RX019)

1948 PCA Research and Development Laboratories builds a central research laboratory in Skokie, Illinois

1948 Studies of the physical properties of hardened portland cement paste (RX022)

1949 Air requirements of frost resistant concrete (RX033)



1950

1960

1970

1951 New York test road demonstrates the importance of air entrainment (RX038)
1951 Linear traverse technique for measuring air in hardened concrete (RX035)
1952 Effect of air on durability of concrete made with various sizes of aggregate (RX040)
1955 Concrete stress distribution in ultimate strength design (DX006)
1955 Permeability of portland cement paste (RX053)
1955 Observations of alkali aggregate reactivity (RX054)
1956 ACI Committee 318 accepts ultimate strength design as an alternate to straight line theory
1956 Pore structure of hardened concrete (RX073)
1956 Effect of various deicers on salt scaling of concrete (RX083)
1957 Plastic shrinkage and shrinkage cracking (RX081)
1957 Curing requirements for scale resistant concrete (RX082)
1957 The PCA Structural Laboratory is built with high strength steel using cast-in-place, precast, and tilt-up concrete and includes a test floor capable of resisting over 4.5 million kg (10 million pounds) to handle full sized elements
1958 The PCA Fire Research Laboratory is built to study the fire resistant properties of concrete
1958 Carbonation of hydrated portland cement (RX087)
1958 Physical structure and engineering properties of concrete (RX090)
1958 Setting of portland cement (RX098)
1959 Criteria for ultimate strength design is developed (DX031)

1960 Concrete mix water purity (RX119)
1960 Chemistry of hydration of portland cement (RX153)
1962 Tobermorite gel—the heart of concrete (RX138)
1963 Optimum steam curing of precast concrete (DX062)
1965 Brewer establishes moisture migration of concrete slabs on ground (DX089)
1965 Fatigue of reinforcing bars is evaluated (DX093)
1966 Seismic properties of reinforced concrete (DX107)
1967 Properties of portland blast-furnace slag cement (RX218)
1968 Shear and moment transfer between concrete slabs and columns (DX129)

1971 to 1973 Fire tests on concrete floors and beams is conducted (RD004 to RD009, RD016)
1977 Stress-strain relationship of high strength concrete (RD051)
1979 Effects of high-range water reducers on concrete (RD061)

1980 1990 2000 2010

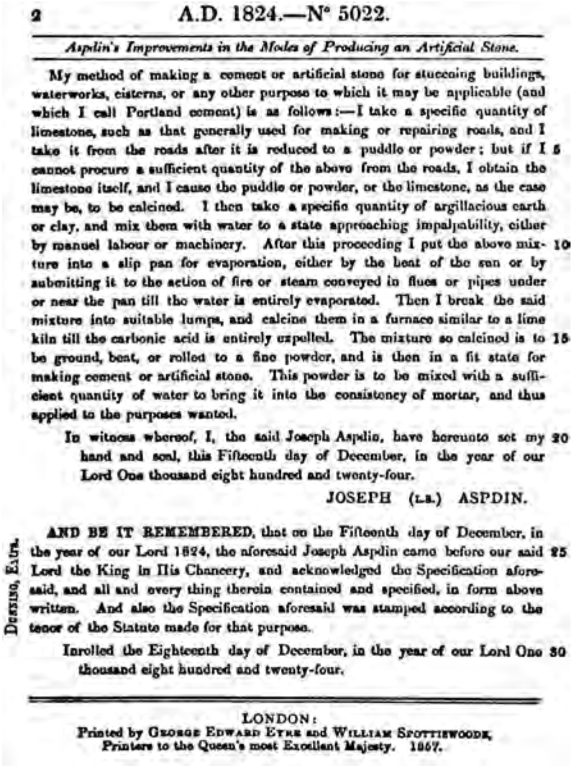
1981 Whiting developed rapid chloride permeability test (RD81/191)
1983 Effect of fly ash on air void stability (RD085)
1985 Effect of fly ash on the properties of concrete (RD089 and RD090)
1986 Effect of vibration on the air void system and durability of concrete (RD092)
1988 Flexural and shear behavior of concrete beams during fire (RD091)
1989 Influence of design and materials on the corrosion resistance of steel in concrete (RD098)

1992 Long term performance of field concrete (RD102)
1992 Fire resistance and fire rating for concrete columns (RD101)
1992 Optimization of sulfate form and content (RD105)
1992 Effects of conventional and high range water reducers on concrete properties (RD107)
1994 Engineering properties of commercially available high strength concrete (RD104)
1995 Optimizing surface texture of concrete pavements (RD111)
1996 The influence of casting and curing temperatures on fresh and hardened concrete (RD113)
1996 Use of limestone in portland cement (RP118)

2000 National Concrete Placement Technology Center is founded
2001 Long term performance of concrete in seawater is evaluated (RD119)
2001 Frost and deicer scaling resistance of high strength concrete (RD122)
2002 40 year performance of concrete in outdoor test facility (RD124)
2002 Performance of concrete in sulfate environments (RD129)
2004 Frost durability of roller compacted concrete pavements (RD135)
2004 Translucent concrete patented
2005 Long term performance of architectural panels (RD133)
2005 Chemical path of ettringite formation in heat cured mortar and its relationship to expansion (DEF) (SN2526)
2006 Effect of minor elements on cement performance (RD130)
2007 Hydraulic design of pervious concrete (EB303)
2007 Life cycle inventory of portland cement concrete (SN3011)
2007 Diagnosis and control of alkali-aggregate reactions in concrete (IS413)
2008 Factors affecting formation of air-void clustering (SN2789a)
2009 Blast resistant design for concrete structures (EB090)
2009 MIT Concrete Sustainability Hub is founded

2010 The world's tallest building, Burj Khalifa, Dubai UAE is completed
2010 Life cycle assessment of pavements (SN3119a)
2011 Use of limestone in cements at levels up to 15% (SN3148)
2012 Life cycle evaluation of concrete buildings (SN3119)
2013 Rapid test to determine alkali-silica reactivity of aggregates using autoclaved concrete prisms (SN3235)
2014 ACI 318-14 reorganized
2014 Product category rules developed for cement
2016 Environmental product declaration developed for cement (industry average)
2016 PCA Centennial

Figure 1-11. Eddystone lighthouse constructed of natural cement by John Smeaton.



2 A.D. 1824.—N° 5022.

Aspdin's Improvements in the Modes of Producing an Artificial Stone.

My method of making a cement or artificial stone for stuccoing buildings, waterworks, cisterns, or any other purpose to which it may be applicable (and which I call Portland cement) is as follows:—I take a specific quantity of limestone, such as that generally used for making or repairing roads, and I take it from the roads after it is reduced to a puddle or powder; but if I cannot procure a sufficient quantity of the above from the roads, I obtain the limestone itself, and I cause the puddle or powder, or the limestone, as the case may be, to be calcined. I then take a specific quantity of argillacious earth or clay, and mix them with water to a state approaching impalpability, either by manuel labour or machinery. After this proceeding I put the above mixture into a slip pan for evaporation, either by the heat of the sun or by submitting it to the action of fire or steam conveyed in flues or pipes under or near the pan till the water is entirely evaporated. Then I break the said mixture into suitable lumps, and calcine them in a furnace similar to a lime kiln till the carbonic acid is entirely expelled. The mixture so calcined is to be ground, beat, or rolled to a fine powder, and is then in a fit state for making cement or artificial stone. This powder is to be mixed with a sufficient quantity of water to bring it into the consistency of mortar, and thus applied to the purposes wanted.

In witness whereof, I, the said Joseph Aspdin, have hereunto set my hand and seal, this Fifteenth day of December, in the year of our Lord One thousand eight hundred and twenty-four.

JOSEPH (L.S.) ASPDIN.

Dessing, Extr.

AND BE IT REMEMBERED, that on the Fifteenth day of December, in the year of our Lord 1824, the aforesaid Joseph Aspdin came before our said Lord the King in His Chancery, and acknowledged the Specification aforesaid, and all and every thing therein contained and specified, in form above written. And also the Specification aforesaid was stamped according to the tenor of the Statute made for that purpose.

Inrolled the Eighteenth day of December, in the year of our Lord One thousand eight hundred and twenty-four.

LONDON:
Printed by George Edward Eyre and William Spottiswoode, Printers to the Queen's most Excellent Majesty. 1857.

Figure 1-12. Aspdin's patent for portland cement.

Aspdin was the first to prescribe a formula for portland cement and the first to have his product patented (Figure 1-12). However, in 1845, I. C. Johnson, of White and Sons, Swanscombe, England, claimed to have "burned the cement raw materials with unusually strong heat until the mass was nearly vitrified," producing a portland cement as we now know it. This cement became the popular choice during the middle of the 19th century and was exported from England throughout the world. Production also began in Belgium, France, and Germany about the same time and export of these products from Europe to North America began about 1865. The first recorded shipment of portland cement to the United States was in 1868. The first portland cement manufactured in the United States was produced at a plant in Coplay, Pennsylvania, in 1871. Figure 1-13 provides a timeline of significant achievement in the concrete industry.

Sustainable Development

Concrete is the basis of much of civilization's infrastructure and much of its physical development. Twice as much concrete is used throughout the world than all other building materials combined. It is a fundamental building material to municipal infrastructure, transportation infrastructure, office buildings, and homes. And, while cement manufacturing is resource- and energy-intensive, the characteristics of concrete make it a very low-impact construction material, from an environmental and sustainability perspective. In fact, most applications for concrete directly contribute to achieving sustainable buildings and infrastructure.

Essentials of Quality Concrete

The performance of concrete is related to workmanship, mix proportions, material characteristics, and adequacy of curing. The production of quality concrete involves a variety of materials and a number of different processes including: the production and testing of raw materials; determining the desired properties of concrete; proportioning of concrete constituents to meet the design requirements; batching, mixing, and handling to achieve consistency; proper placement, finishing, and adequate consolidation to ensure uniformity; proper maintenance of moisture and temperature conditions to promote strength gain and durability; and finally, testing for quality control and evaluation.

Many people with different skills come into contact with concrete throughout its production. Ultimately, the quality of the final product depends on their workmanship. It is essential that the workforce be adequately trained for this purpose. When these factors are not carefully controlled, they may adversely affect the performance of the fresh and hardened properties.

Suitable Materials

Concrete is basically a mixture of two components: aggregates and paste. The paste, comprised of portland cement and water, binds the aggregates (usually sand and gravel or crushed stone) into a rocklike mass as the paste hardens from the chemical reaction between cement and water (Figure 1-14). Supplementary cementitious materials and chemical admixtures may also be included in the paste.

The paste may also contain entrapped air or purposely entrained air. The paste constitutes about 25% to 40% of the total volume of concrete. Figure 1-15 shows that the absolute volume of cement is usually between 7% and 15% and the water between 14% and 21%. Air content in air-entrained concrete ranges from about 4% to 8% of the volume.

Figure 1-14. Concrete constituents include cement, water, and coarse and fine aggregates.

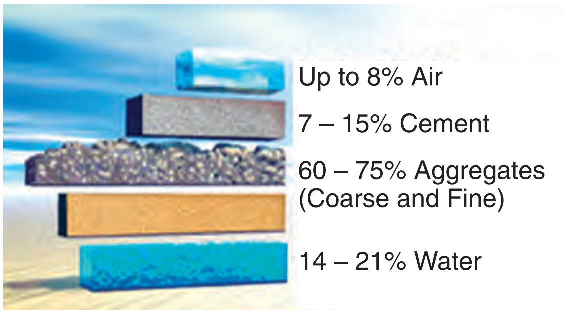


Figure 1-15. Range in proportions of materials used in concrete, by absolute volume.

Aggregates are generally divided into two groups: fine and coarse. Fine aggregates consist of natural or manufactured sand with particle sizes ranging up to 9.5 mm (3/8 in.); coarse aggregates are particles retained on the 1.18 mm (No. 16) sieve and ranging up to 150 mm (6 in.) in size. The maximum size of coarse aggregate is typically 19 mm or 25 mm (3/4 in. or 1 in.). An intermediate-sized aggregate, around 9.5 mm (3/8 in.), is sometimes added to improve the overall aggregate gradation.

Since aggregates make up about 60% to 75% of the total volume of concrete, their selection is important. Aggregates should consist of particles with adequate strength and resistance to exposure conditions and should not contain materials that will cause deterioration of the concrete. A continuous gradation of aggregate particle sizes is desirable for efficient use of the paste.

The freshly mixed (plastic) and hardened properties of concrete may be changed by adding chemical admixtures to the concrete, usually in liquid form, during batching. Chemical admixtures are commonly used to: (1) adjust setting time or hardening, (2) reduce water demand, (3) increase workability, (4) intentionally entrain air, and (5) adjust other fresh or hardened concrete properties.

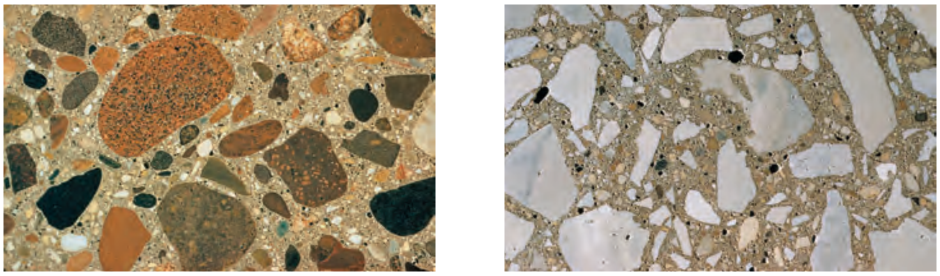


Figure 1-16. Cross section of hardened concrete made with (top) rounded siliceous gravel and (bottom) crushed limestone. Cement and water paste completely coats each aggregate particle and fills all spaces between particles.

The quality of the concrete depends upon the quality of the paste and aggregate and the bond between the two. In properly made concrete, each particle of aggregate is completely coated with paste and all of the spaces between aggregate particles are completely filled with paste, as illustrated in Figure 1-16.

Specifications for concrete materials are available from ASTM International, formerly known as American Society for Testing and Materials (ASTM) and the American Association of State Highway and Transportation Officials (AASHTO) . Material guides and standards for construction are available through the American Concrete Institute (ACI).

Water-Cementitious Materials Ratio

In 1918, Duff Abrams published data that showed that for a given set of concreting materials, the strength of the concrete depends on the relative quantity of water compared with the cement. In other words, the strength is a function of the water to cement ratio (w/c) where w represents the mass of water and c represents the mass of cement. However, in current practice, w/cm is used and cm represents the mass of cementing materials, which includes the portland cement plus any supplementary cementing materials such as fly ash, slag cement, or silica fume.

Unnecessarily high water content dilutes the cement paste (the glue of concrete) and increases the volume of the concrete produced (Figure 1-17). Some advantages of reducing water content include:

- Increased compressive and flexural strength
- Lower permeability and increased watertightness
- Increased durability and resistance to weathering
- Better bond between concrete and reinforcement
- Reduced drying shrinkage and cracking
- Less volume change from wetting and drying

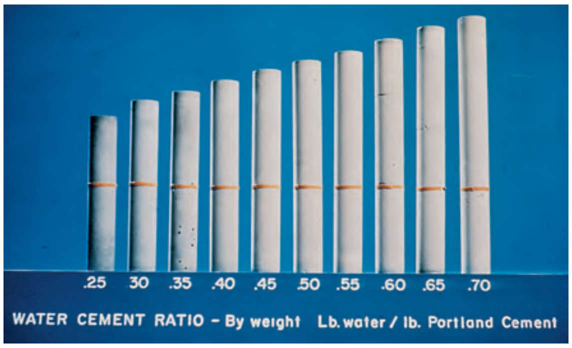


Figure 1-17. Ten cement-paste cylinders with water-cement ratios from 0.25 to 0.70. The band indicates that each cylinder contains the same amount of cement. Increased water dilutes the effect of the cement paste, increasing volume, reducing density, and lowering strength.

The less water used, the better the quality of the concrete provided the mixture can still be consolidated properly. Smaller amounts of mixing water result in stiffer mixtures; with vibration, stiffer mixtures can be easily placed. Thus, consolidation by vibration permits improvement in the quality of concrete.

Reducing the water content of concrete, and thereby reducing the w/cm, leads to increased strength and stiffness, and reduced creep. The drying shrinkage and associated risk of cracking will also be reduced. The concrete will have a lower permeability or increased water tightness that will render it more resistant to weathering and the action of aggressive chemicals. The lower water to cementitious materials ratio also improves the bond between the concrete and embedded steel reinforcement.

Design-Workmanship-Environment

Concrete structures are built to withstand a variety of loads and may be exposed to many different environments such as exposure to seawater, deicing salts, sulfate-bearing soils, abrasion and cyclic wetting and drying. The materials and proportions used to produce concrete will depend on the loads it is required to carry and the environment to which it will be exposed. Properly designed and built concrete structures are strong and durable throughout their service life.

After completion of proper proportioning, batching, mixing, placing, consolidating, finishing, and curing, concrete hardens into a strong, noncombustible, durable, abrasion resistant, and watertight building material that requires little or no maintenance. Furthermore, concrete is an excellent building material because it can be formed into a wide variety of shapes, colors, and textures for use in an unlimited number of applications.

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For more information on all aspects of cement and concrete technology, readers are encouraged to visit the website for PCA's Library: http://www.cement.org/library/catalog. The library's online catalog includes links to PDF versions of many of our research reports and other classic publications.

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