A Brief History of Lime, Cement, Concrete and Reinforced Concrete

The paper was not presented at a meeting of the Society but was accepted for publication.

Jasper O. Draffin,* M.W.S.E.

Submitted October 22, 1942.

DEVELOPMENT OF LIMES AND CEMENTS

Early Materials

FROM the dawn of history to the present time men have sought for materials to cement stone and brick together in walls and foundations; to plaster and stucco walls, ceilings and other surfaces; and to waterproof buildings, conduits and a variety of other structures. The Assyrians and Babylonians in some places used bituminous materials for laying up their walls and the former people used gypsum as a plaster and as a cement. Some of the bricks found in the ruins of an old palace were stamped with the name of Nebuchadnezzar and were laid in a lime cement while in the neighboring city of Ur of the Chaldees part of the bricks in a temple were laid in a cement of lime and ashes. The Egyptians used gypsum mortars and lime mortars in building the Pyramid of Cheops and other structures. Some of the most ancient mortar yet discovered was found in Cyprus in the ruins of a Phoenician temple near Larnaca. The mortar was of lime, very dense and hard, and was almost completely carbonated. From pieces which have been found it is evident that the Greeks used lime mortar to some extent. An analysis of a piece taken from the Pnyx, or platform, from which Demosthenes and Pericles delivered many of their orations, shows that it was substantially a lime-magnesia mortar and that it was completely carbonated. Lime mortar is sometimes referred to in literature as air-mortar because it hardens in the air, that is by evaporation of the mixing water and by carbonation, the lime of the mortar and the carbon dioxide of the air forming calcium carbonate.

It seems probable that the Romans gained part of their knowledge of mortars from the Greeks since much of their knowledge of the building arts seems to have been derived from this source. The principal writers on the Roman art of handling mortar were Pliny and Vitruvius, the latter being the standard writer on the building activities of the Romans. The so-called Roman mortars have been held in high repute in modern times because of the permanence of the Roman structures in which these mortars were used. Surely the aqueducts, the Coliseum, and the ruins of the Thermae in Rome bear irrefutable evidence of the durability of the ancient mortars. The best mortar appears to have been made of lime mixed with a volcanic rock or sand called puzzolona, named after the place where it was first found—Pouzzol, near Vesuvius. This sand contains an aluminum silicate from which the silica is readily liberated by the caustic alkalies, such as calcium hydroxide, and which combines with the lime to form a

*Professor of Theoretical and Applied Mechanics, University of Illinois, Urbana, Illinois.

hard cementing material, and one which will harden under water.

There is no satisfactory evidence that the Romans had any knowledge of the reason for the superiority of the puzzolona mortar over the lime mortar but they did have considerable ability in making and using it. Where the puzzolona was not readily available they mixed the lime with powdered bricks which presumably furnished the silica in the proper form, since ordinary silicious or quartzite sands are but slightly affected by lime. The marked endurance of some of the ancient structures is partly to be attributed to this lime-silica mortar and partly to the favorable climate.

Hydraulic Lime

In the mortars of modern times the first forward step was in the manufacture and use of hydraulic limes. Here the names of Smeaton and Vicat stand out preëminently. When John Smeaton (1724-1792) was engaged to rebuild the Eddystone Lighthouse in 1756 he recognized that the ordinary lime mortar would not harden under water and would not be sufficiently durable to resist the wear from the waves of the sea. Consequently he undertook an investigation of the quality of the mortars obtained from the different kinds of limestone and found that the best mortar came from the limestones which contained the greatest percentage of clay. The results of his investigation of mortars were reported in 1791 in his account of building the lighthouse.[1]. That his studies gave satisfactory results is shown by the fact that the Eddystone Lighthouse stood for one hundred and twenty-six years before it was replaced. The studies of Smeaton gave the first real information of modern times, and probably of all times, as to the elements which increased the strength of lime mortar and permitted it to harden under water. This view of the basic character of Smeaton's work is expressed not only concisely but with poetic insight by Wilhelm Michaëlis in the preface to his book "Hydraulischen Mörtel," 1869, where (translated) he says:[2]

> "A century has elapsed since the famous Smeaton completed the building of the Edystone Lighthouse. Not only for seafaring but for all humanity this lighthouse stands as a true signal of blessed work, a light in a dark night. From a scientific point of view it illuminated the darkness of nearly 2000 years.
>
> The errors which came to us from the Romans, and which were shared even by the excellent Belidor, were dispersed.
>
> The Edystone Lighthouse is the foundation upon which our knowledge of hydraulic mortars has been built and it is the chief pillar of modern construction. Smeaton freed us from the shackles of tradition by showing us that the purest and hardest limestone is not the best, at least for hydraulic purposes, and that the source of the hydraulicity of lime mortar must be sought in the argillaceous admixtures."

But others besides Smeaton were thinking about this subject. In 1780 T. Bergman (1735-1784), a Swedish chemist, analyzed a limestone which gave hydraulic lime and found that it contained manganese and he concluded that it was this element which gave hydraulic properties to lime. In spite of much evidence to the contrary Bergman's view continued to be held by many men, though a number of dissenting opinions were expressed, notably in 1806 by Vitalis (?-1832) and in 1813 by Collet-Descotels (1773-1815), a Professor of Chemistry at the School of Mines in France. The latter expresses the view that it is essential that the limestone contains a large quantity of silicious material in fine grains if the lime is to be of the best quality.[3]

[1]John Smeaton, "A Narrative of the Building and a Description of the Construction of the Edystone Lighthouse with Stone." (1791) Chap. IV. Experiments on Water Cements, pp. 102-123.

[2]Wilhelm Michaëlis, "Die Hydraulischen Mörtel Insbesondere Der Portland-Cement" (1869).

[3]R. H. Bogue, "A Digest of the Literature on the Constitution of Portland Cement," Portland Cement Association Fellowship at the National Bureau of Standards, Washington, D. C. Paper No. 3, p. 4.

It would not be just to omit the names of many men who worked to advance our knowledge of limes and cements even though their work cannot be discussed in detail. Some worked on the chemical side, some on the construction of kilns, and some on the use of lime but all added their contributions to the general store of knowledge. In France we find Loriot (1716-1782), Faujas de Saint-Fond (1741-1819), Guyton de Morveau (1737-1816), General C. L. Treussart (1779-1834), Berthier, and Chaptal (1756-1852)—in Switzerland, Saussure (1740-1799)—in England, Bry Higgins who wrote in 1780—in Germany, Gersdorf (1744-1807), and J. N. Fuchs (1774-1856)—in Russia, Colonel Raucourt de Charleville, a Frenchman. These and many others carried on experiments and proposed theories to explain the action of hydraulic limes. In 1810 the Dutch Society of Sciences proposed for discussion the question as to why the lime made from limestone was better than that made from shells, and the means which might be used to improve that obtained from shells. J. F. John (1782-1847), a Professor of Chemistry in Berlin, concluded that it was the presence of clay, silica and iron oxide which improved the lime from limestone. For his answer Professor John was given a medal by the Society in 1819.[4]

Though the men just named contributed in various ways to the theory and art of limes and cements, the next man after Smeaton to markedly extend our knowledge of mortars was the eminent French engineer of the Ponts et Chausseës, J. L. Vicat (1786-1861), who in 1812 began an investigation of the various limestones of France and their suitability for lime.

This was an extensive piece of work and the first results of it were published in 1818; these results were later extended and incorporated into a book in 1828; this book in turn was translated into English in 1837 by Captain J. T. Smith. The work of Vicat was thorough and laid groundwork for future studies in this field. He invented the Vicat needle, so widely used today, for determining the time required for lime and cement to set. His conclusions concerning the effect of the composition of the raw material were to the effect that the limestones which furnished hydraulic limes contained silica, alumina, manganese, magnesia and iron to the extent of from one-fifth to one-quarter of the total. He was not able to state the proportions which were necessary but was emphatic in stating that no perfectly hydraulic mortar exists without silica and that all lime worthy of the name contains a certain amount of clay, made up of silica and alumina.[5] Here then is the fundamental statement by Vicat, confirming that of Smeaton, that a lime or cement with hydraulic properties must contain lime, silica, and alumina.

Natural Cement

It should be remembered that the preceding conclusions and generalizations refer to a product burned at a temperature only high enough to drive off the carbonic acid and used as a lime without grinding; the limestone was calcined but not fused and the product was not a natural cement. The first natural cement of which we have a clear record was that manufactured in England by James Parker who took out a patent in 1796 for a natural cement which came later to be called "Roman Cement." This he prepared by calcining nodules found in gravel deposits, nodules which he had found gave a cement with hydraulic properties. Because of the higher content of clay he burned them at a higher temperature than that used in burning lime but not high enough to vitrify them. After burning, the product was reduced to a powder. If any of the material became fused it was picked out and thrown away as being worthless. At about the same time (1796) a French military engineer, Lesage, produced a cement similar to that of Parker's from pebbles found at Boulogne-sur-Mer in France.

[4] Dr. Ing. Riepert (Herausgegeben von), "Die Deutsche Zement Industrie," S. 49.

[5] L. J. Vicat, Translated by J. T. Smith, "A Practical and Scientific Treatise on Calcareous Mortars and Cements, Artificial and Natural" (1837), pp. 10-11.

In 1822 James Frost obtained in England a patent for an artificial cement, which he termed "British Cement," in which the raw material was calcined until all the carbonic acid was expelled, after which the material was ground. This cement of Frost's, like those of Parker and Lesage, was a quick-setting cement. These natural cements had a good reputation in England and in America, in fact they commanded a higher price than the early portland cements. Vicat discusses them by stating that where the clay exceeds 27 to 30 per cent of the limestone it is difficult to calcine it into lime but that it will furnish a natural cement which acts somewhat as plaster of Paris. He says that this cement is used in England, France and Russia, but that its use will become less as the hydraulic limes become better known.[6] When we remember that the burning temperatures for natural cement were as yet a matter of the purest guesswork, that they were not adequately controlled, and that grinding machinery was still extremely crude, this adverse conclusion of Vicat is not a strange one. Surely if he could have foreseen the rise and fall of the use of natural cement, the rise of portland cement and the relatively insignificant production of hydraulic lime, he would have been surprised.

While the manufacture of natural cement started in England at the beginning of the nineteenth century it soon spread into Belgium and Germany. At this time also the industrial and transportation developments in the United States were just beginning. The Erie Canal had been begun in 1817 and before this numerous other canals in the East Atlantic region were in operation or under construction. These canals, with other public and private works, created a need for cement. The first natural cement made in this country was from a natural cement rock discovered in 1818 near Chittenango, Madison County, N. Y., by Canvass White, an engineer on the Erie Canal.

[6]L. J. Vicat, Translated by J. T. Smith, "A Practical and Scientific Treatise on Calcereous Mortars and Cements, Artificial and Natural" (1837), pp. 111-112.

In 1828 a cement works was established at Rosendale, Ulster County, N. Y., the product of which was first used in the construction of the Delaware and Hudson Canal, then being built through the town of Rosendale. Other cement works followed at this place.[6a] In 1829 a cement rock was discovered near Louisville, Ky., during the construction of the Louisville and Portland Canal and other discoveries were made as follows: in 1836 at Round Top near Hancock, Md., during the building of the Chesapeake and Ohio Canal; in 1838 at Utica, Ill., near the Illinois and Michigan Canal; in 1848 at Balcony Falls, Va., near the James River Canal; and in 1850 at Siegfried, Pa., near the Lehigh Coal and Navigation Co. Canal.[7]

The localities in which these discoveries were made soon grew into great manufacturing centers of natural cement. The three most important regions were the Hudson River district, New York, generally called the Rosendale district; the Louisville, Ky., district and the Lehigh Valley, Pa., district. These cement regions were situated on or near navigable waterways, and consequently they were able to command the relatively cheap water rates of that time. They built up a very flourishing industry which, however, declined as portland cement came into greater use. The Rosendale district, discovered in 1828 and furnishing cement used for the Delaware and Hudson Canal, was the most important one. Lesley says that in 1898 the Rosendale district furnished 41.9 per cent of the natural cement produced in this country.[8] The great development in this district was due to the proximity of the projects requiring cement, the fine transportation facilities afforded by the railroads and the Hudson River, and also the superior quality of the cement.

[6a]Uriah Cummings, "American Cements" (1898), p. 19.

[7]Richard K. Meade, "Portland Cement" (1906), pp. 4-5.

[8]Robert W. Lesley, "History of the Portland Cement Industry in the United States" (1924), p. 33.

The industrial importance of a supply of cement that was reasonably near to the place where it was to be used can be seen when it is recalled that the freight rate in 1833 between Baltimore and Washington, in wagons over the turnpike, was about 25 cents per ton mile, and that the Baltimore and Ohio Railroad in that year adopted a freight rate of 4 cents per ton mile.[9] Since the average receipts per ton mile for the railroads of the United States for the past twenty-five years is probably less than one cent per ton mile, the effect of the cost of transportation on the production of cement in the early days is easy to understand.

Natural cements are usually burned in vertical kilns which are 25 to 40 feet high and 10 feet in diameter. The burned material or clinker is broken into small pieces and pulverized by means of some kind of grinding apparatus. Mill stones were formerly used but these have been superseded by grinding mills which are less expensive and which grind much finer. Since natural cement is prepared directly from the rock it is to be expected that there will be considerable variation in the quality of the cement, and that differences will tend to be regional according to the composition of the rock from which the cement is made. But in spite of these variations this cement has served very well, especially where it was used in sea water where in some cases it surpasses portland cement in durability. It is quick-setting, is relatively weak and is low in cost of manufacture. But it may acquire high strength in time as is shown by some tests which P. H. Bates reports:

Two pieces of natural cement mortar taken from a building foundation were tested at the age of 35 years and gave an average strength of 11,300 lb. per sq. in. and six other pieces, made from a different cement than the 35-year specimens, tested at the age of 50 years gave an average compressive strength of 4,680 lb. per sq. in.[10]

Years	Natural Cement	Portland Cement
	(Barrels)	(Barrels)
1818-1829	25 000	-------
1830-1839	100 000	-------
1840-1849	425 000	-------
1850-1859	1 100 000	-------
1860-1869	1 642 000	-------
1870-1879	2 200 000	8 200
1880-1889	4 346 000	147 000
1890-1899	8 070 000	1 728 000
1900-1909	5 050 000	33 383 000
1910-1919	757 000	83 995 000
1920-1929	1 520 000	143 224 000
1930	1 792 000	161 197 000
1931	1 227 000	125 100 000
1933	432 000	63 473 000
1935	1 006 000	76 742 000
1936	1 819 000	112 650 000
1940	2 535 000	130 217 000

TABLE I

Average Yearly Production of Cement in the United States

The production of natural cement reached a high point between 1890 and 1900, but twenty years later it was a negligible quantity in the total production of hydraulic cements, though it later assumed a slightly more important role. The growth and decline of the natural cement industry in the United States is shown in Table I which is compiled mainly from the "Mineral Resources" of the United States Bureau of Mines; from Cummings "American Cements," and from Lesley's "History of the Portland Cement Industry in the United States." The figures are averages of the mill shipments for the periods stated and are given in round numbers.

Portland Cement

On December 15, 1824, Joseph Aspdin (1779-1855), a bricklayer in England, took out a patent for the manufacture of a new and improved cement which he

[9]Edward Hungerford, "The Story of the Baltimore and Ohio Railroad," Vol. I (1928), p. 162.

[10]Engineering News-Record (Jan. 21, 1932), p. 96.

called portland cement because it resembled in color the stone which came from the Isle of Portland.

His patent read in part as follows:

"My method of making a cement or artificial stone . . . 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 has been 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 argillaceous earth or clay and mix them with water to a state approaching impalpability, either by labour or machinery. After this proceeding I put the above mixture into a slip pan for evaporation, . . . until 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 until 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."[11]

His son, William, claimed that this cement was manufactured as early as 1811. Aspdin shrouded the manufacture in mystery, sprinkling some secret compound over each batch of raw material. Certainly he originated the name portland cement, but it is more than an open question whether he should be called the inventor of the substance portland cement.

He is sometimes conceded to have demonstrated the necessity of using high temperatures,[12] though his patent gives no suggestion of it. Probably he made but little cement himself but he promoted the idea and his son William Aspdin (1816-1864), with others, carried on its manufacture at Rotherhithe on the banks of the Thames. Sir M. I. Brunel used portland cement from the Aspdin works at Wakefield in the construction of the Thames tunnel in 1828 and that was probably the first time it was used for engineering construction purposes.[13] Meanwhile, another firm, Messrs. White, were at work at Swanscombe and their manager, Isaac Charles Johnson (1811-1911), became one of the prominent men in the new field, and a successful manufacturer of portland cement. In a letter written in 1909, Mr. Mr. Johnson claimed to be the inventor of portland cement.

Though he did not manufacture any cement or present any theories, Sir Charles W. Pasley (1780-1861) was an important investigator in the field of cements and limes, beginning his work in 1826. His labors did much to contribute to the knowledge of the subject, though rather indirectly so far as practical results were concerned. If Pasley had not been so thoroughly imbued with the current idea that the temperature of burning must be kept below that which would produce vitrification, his studies might have yielded greater results, because he threw away all particles which approached vitrification. It is of interest, as showing the slowness with which such knowledge spread at that time, to note that Pasley did not know of Aspdin's work, though they labored within a few miles of each other, until he saw the Aspdin cement at the Exposition in London in 1851.

Following Aspdin's discovery or invention of the use of high temperatures—if that much may be conceded to him—and its practical development in different plants, portland cement began to be manufactured in earnest in Europe about 1850. Though Brunckhorst and Westphalen are suggested as the first to begin the manufacture of portland cement in Germany, having done so in 1850,[14] the first commercial portland cement plant in Germany is said to have been built

[11] A. C. Davis, "A Hundred Years of Portland Cement" (1924), p. 1.

[12] Robert W. Lesley in "History of the Portland Cement Industry in the United States," p. 35, quotes from "Portland Cement, Its Manufacture and Use," by Henry Reid (1877), on this point.

[13] G. R. Redgrave and Charles Spackman, "Calcareous Cements: Their Nature, Manufacture and Uses" (1924), p. 41.

[14] F. Quietmeyer, "Zur Geschichte der Erfindung des Portlandzementes" (1911), pp. 147-148.

in 1855 at Züllchow near Stettin, and was operated under a patent granted Oct. 23, 1852, to Hermann Bleibtreu (1824-1871), who built a small plant there in 1852.[15] This first plant was the genesis of the present Lossius & Dellbruck plant. In Belgium the manufacture of portland cement was begun by Edward Fewer, a son-in-law of Joseph Aspdin.[16] The first portland cement works in France were erected in 1840 at Boulogne-sur-Mer.

The first really extensive use of portland cement was in the construction of the sewerage system of London in 1859-1867. The satisfaction which it gave there increased its popularity to a marked degree and considerable quantities were exported. Incidentally the high quality of cement which the London engineers insisted upon receiving did much to stimulate improvement of the cement and to enhance its reputation. According to Lesley there is a record of 500 barrels of portland cement sent to New York from London in 1871 and importations continued to increase from 92,000 barrels in 1878 to nearly 3,000,000 barrels in 1896 after which the quantity imported began to decrease due to domestic manufacture.

The manufacture of portland cement in the United States began in the seventies at a number of places. The first successful plant was the one at Coplay, Pa., established by David O. Saylor, Adam Woolever, and Esias Rehrig. The first cement was shipped from this plant in 1871.[17] All of these three men were vigorous and aggressive. Saylor who had been connected previously with the manufacture of natural cement took out a patent in 1871 for making portland cement. He encountered many difficulties but overcame them by his energy and common sense, and his cement was used in the construction of the Eads Jetties. Others who were pioneer manufacturers were Thomas Millen (1832-1907) at South Bend, Ind., who began manufacturing in about 1871, and John K. Shinn at Wampum, Pa., who began in about 1875.

Another of the early men was Robert W. Leslie (1853-1935) who organized the cement selling firm of Lesley & Trinkle, Philadelphia, in 1874 and sold 10,000 barrels the second day of business and while still working for the Philadelphia Public Ledger. Leslie tells some interesting tales of the endeavors of certain firms to sell cement shipped to them; they knew little of its properties, but found some contractors who were willing to take a chance on it. From the selling end this firm gradually went into manufacturing at Egypt, Pa. Mr. Leslie was one of the most prominent of the early men in the development of the portland cement industry in the United States and he did much to promote the development of standard specifications. In another section of the country one other manufactory will be mentioned, that of the Alamo Portland and Roman Cement Company at St. Antonio, Texas, founded by William Loyd and W. R. Freeman in 1880.

The growth of these various small cement manufactories is shown by the fact that in 1878 there were 28,000 barrels of portland cement manufactured in the United States as compared with 92,000 barrels imported, while in 1896 there were 1,543,023 barrels manufactured as compared with 2,989,597 barrels imported.[18]

The first establishment of portland cement as a structural material brought about an unfortunate promotional phase during the first decade of the present century. It is astonishing to read of the gullibility of the investors, especially where technical matters were involved. Leslie gives an interesting account of some of the schemes used to lure investors into taking stock in the enterprise.[19]

[15]Dr. Ing. F. von Emperger (Herausgegeben von), "Handbuch für Eisenbetonbau," Erster Band (1908), S. 2.

[16]Robert W. Lesley, "History of the Portland Cement Industry in the United States" (1924), p. 38.

[17]Robert W. Lesley, "History of the Portland Cement Industry in the United States" (1924), p. 18.

[18]Uriah Cummings, "American Cements" (1898), p. 289.

[19]Robert W. Lesley, "History of the Portland Cement Industry in the United States" (1924), Chap. XII.

The early manufacturers had a difficult time meeting foreign competition because engineers, being naturally conservative, preferred the cement which had a reputation to that which was unknown. But gradually the domestic cement came to have a reputation of its own and was recognized as a superior product.

The first and by far the most important improvement in the manufacture of portland cement came in the kiln. In the beginning, the portland cement kilns were of the vertical type, following European practice, and each kiln would produce about 200 barrels every 10 days. In 1886 Jose F. de Navarro (1823-1909), a man of large business interests, introduced an inclined rotary kiln 24 feet long and 12 feet in diameter. This one did not prove to be a success and in 1889 he erected another one built under the patents of Frederick Ransome (1818-1893) of England, a man who was interested in the manufacture of artificial stone and cement. At first this also did not work well but after many changes and much experimentation it was satisfactory. The work of the de Navarro group in the introduction of the rotary kiln was most important.

The first successful rotary kiln in the United States was about 25 feet long and 5 feet in diameter and from this size the kilns increased up to those which were 60 to 80 feet long and 5 to 6 feet in diameter and which burned 160 to 300 barrels of cement per day. Then came those built under the Thomas A. Edison patents of 1909; they started with kilns 150 feet long and 7 to 8 feet in diameter and went up to kilns 260 feet long, which burned 1000 barrels of cement per day. A kiln installed in 1930 at the plant of the Wolverine Portland Cement Co., Quincy, Mich., is 305 feet long and 10 feet in diameter. It replaced seven 120-foot kilns.[20]

One of the early troubles in the attempted use of the rotary kiln was the "balling up" of the raw material due to the attempt to burn it in small lumps as was done in the vertical kilns. This difficulty was remedied by fine grinding of the raw material and since about 1900 nearly all cement plants have used the rotary kilns. One of the advantages of the rotary kiln is the ease with which powdered coal may be used as fuel, a development which was due to E. H. Hurry and H. J. Seaman who secured patents on the process in 1898.

Similar improvements have been made in the grinding apparatus for the fused clinker. The clinker was formerly ground with buhr or mill stones but by 1886-1887 the Griffin iron mill had begun to supersede the mill stones and later the tube mill charged with flint pebbles replaced the Griffin mill for fine grinding. Still later, the pebbles were supplanted by steel balls, of which a single tube may contain 65 to 95 tons.[21] Natural cement, as previously stated, is quicksetting as was the first portland cement made in the rotary kilns. This difficulty was finally overcome at the works of the de Navarro interests at Coplay, Pa., by a French chemist, P. I. Giron, who added a small amount of gypsum to the mix and thus increased the time required for setting. Gypsum has been used ever since then as a retarder in the manufacture of cement.

Portland cement is an essentially different material from natural cement. The raw materials for the former are selected and proportioned with care, all parts of the process are under definite laboratory control and temperatures of 1400-1500 degrees C. are used. With natural cement temperatures of 1100-1300 degrees C. are used and if any of the material is fused it is thrown aside as worthless, while with portland cement, incipient fusion is an essential feature of the process. Portland cement is relatively slower setting, is much stronger but the manufacturing cost is higher than for natural cement.

[20]Pit and Quarry, Dec. 17, 1930, p. 25.

[21]Concrete (Mill Section), Vol. 38 (Feb., 1931), p. 97.

In 1928 it was estimated that of the total production in the United States, 32.5 per cent went into the construction of streets and pavements, 25 per cent into buildings and 15.5 per cent into farm structures. The tabulation given across shows the relative position of the United States in the world production of hydraulic cements in 1937.[22]

Country	Barrels
United States	118,000,000
Germany	74,000,000
British Empire	67,000,000
France and Colonies	27,000,000
Belgium	18,000,000
Japan	39,000,000
Russia	32,000,000
Other Countries	116,000,000
Total	491,000,000

PHYSICAL AND CHEMICAL PROPERTIES OF CEMENT

Tests and Specifications

While the early use of cement was mainly for mortar to cement bricks and stones together in the building of bridges, piers, abutments, foundations and walls, engineers used at times a mixture which the French call "beton" and which we call concrete. Though it was recognized that the strength of mortar was influenced by a number of factors besides the cement, it was understood that the quality of the cement was important and methods were devised of testing it. While specific gravity, fineness of grinding, and chemical composition provide important information, yet, in the main, the quality of a cement has been and still is judged by three criteria, namely; its ability to harden, its soundness, and its compressive or tensile strength.

The first of these three properties has long been recognized as of prime importance and Vicat devised an apparatus to determine the amount of time required for a cement to acquire an initial set. This apparatus, "the Vicat needle," is well known and is one of our pieces of standard testing apparatus. Based on the same general idea, resistance to indentation, is the apparatus known as the "Gillmore needles," named after Major General Quincy Adams Gillmore (1825-1888) who conducted a series of investigations of cement for the engineers of the War Department of the United States. This apparatus was first proposed by M. Antoine Racourt of France,[23] and General Gillmore says that they were used in his tests and that they had been used by Gen. J. G. Totten (1788-1864) in his experiments at Fort Adams, R. I., for several years prior to 1830.

The size and weight of these needles as used today are the same as those used by Totten and Gillmore.[24] Gillmore used the two needles to determine the "hydraulic activity" (rapidity of set) and the "hydraulic power" (continued increase in hardness) of cements.

The soundness test has frequently been of the simplest kind, consisting merely of a number of pats of neat cement placed on a glass plate and allowed to harden—a test originated by Grant.[25] If the pats cracked, the cement was considered unsound but if they did not crack the cement was sound, which usually meant that it did not contain any free lime. Sometimes immersion in boiling water or in steam has been used as a test for soundness. The boiling test is attributed to William Michäelis, Sr., who proposed it about 1895.[26]

The first attempt at the determination of tensile strength was apparently made by building a cantilever beam of bricks

[22]"Cement and Concrete: A General Reference Book" (1941), Portland Cement Association.

[23]"Final Report of the Special Committee on Uniform Tests of Cement." Transactions, Am. Soc. Civ. Eng., Vol. 75 (1912), p. 666.

[24]Q. A. Gillmore, "Practical Treatise on Limes, Hydraulic Cements and Mortars," 3rd ed. (1870), p. 80.

[25]G. R. Redgrave and Charles Spackman, "Calcareous Cements; Their Nature, Manufacture and Uses" (1924), p. 270.

[26]G. R. Redgrave and Charles Spackman, "Calcareous Cements; Their Nature, Manufacture and Uses" (1924), p. 280.

and noting the length of beam which would support itself; this length was taken as a measure of the tensile strength of the mortar. The Aspdins challenged other manufacturers to use this test to compare the quality of their respective cements. Smith in his translation of Vicat's book adds in a footnote that it was not uncommon to see a beam composed of 20 to 30 bricks projecting out at right angles from a wall and estimates the "cohesive force" as "nearly 91 lb per sq in."[27] Vicat says that when the correct amount of water is used and the cement properly mixed the following tensile strengths may be attained with mixtures one year old and exposed to the weather.[28]

"Eminently hydraulic mortars, 171 lb per sq in.

Common hydraulic mortars, 142 lb per sq in.

Hydraulic limes of medium quality, 100 lb per sq in.

Rich limes, 43 lb per sq in.

Bad mortar often made by builders, 11 lb per sq in.

But the building of a cantilever beam of bricks was subject to so many variables that, considered as a test of the cement, it was extremely crude and therefore was abandoned as better methods were developed. Another early test and one used by Sir Charles Pasley was that of adhesion, consisting of cementing two bricks together, and observing how much load was required to pull them apart.

The first report on tensile and compressive tests of cement was made in 1836 by E. Panzer of Germany.[29] The tensile test piece had the form of a cylinder with the section reduced in the central part; the ends were held in clamps and pulled apart. The compressive tests were made on "slabs" or short compression blocks which were crushed by a load applied through a lever arrangement which multiplied the load 20 times. Numerous other engineers made tensile tests on briquettes of various sizes and shapes in the period 1840-1860. The modern method of making a briquette of neat cement or of mortar and breaking it to determine its tensile strength is probably due to the French engineers of the Ponts et Chausseés who began to make tests of cement in the period 1840-1850.

The first tests of cement on an extensive scale were made under the direction of John Grant (1819-1888), engineer of the Metropolitan Board of London, in his selection of cement for the sewers of London. This was the first use of cement on a large scale and its success had considerable influence in promoting its use in the United States. Because of the extensive character of the work in London, Grant began in 1858 to do some preliminary work looking toward acceptance tests of portland cement. He states that a briquette of the shape and size shown in Fig. 1(a) had been in use in France and England for a number of years and he used it in his preliminary tests. But in order to find the best shape he tested tensile briquettes of ten different shapes and sizes and adopted the one which gave the highest strength, Fig. 1(b). At first the briquettes were cast in rectangular form and notches were chipped in the sides for the testing clamps. Then they were made in a one-piece mold originated by H. Reid and had to be pressed out of the mold by a special press, a procedure which was greatly improved by the two-piece mold. The briquette in Fig. 1(b) which had a cross-section of 2.25 sq in, was used by Grant in all of his early work but in a paper presented in 1880 he states that he had then adopted the briquette shown in Fig. 1(c) which had a cross-section of 1.00 sq in and that he was pleased with it. He considered the German specimen, which had an area of only 5 sq cm (0.775 sq in) too small. It will be noted that Grant's final form is substantially

[27] J. L. Vicat, Translated by J. T. Smith, "A Practical and Scientific Treatise on Calcareous Mortars and Cements, Artificial and Natural" (1837), pp. 111-112.

[28] J. L. Vicat, Translated by J. T. Smith, "A Practical and Scientific Treatise on Calcareous Mortars and Cements, Artificial and Natural" (1837), p. 123.

[29] Dr. Ing. Riepert (Herausgegeben von), "Die Deutsche Zement Industrie," S. 277.