

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

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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 alkalis, such as calcium hydroxide, and which combines with the lime to form a

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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

¹John 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.

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

³R. 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.

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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 Lorient (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 Chaussées, 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.

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

⁵J. L. 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.

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

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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.

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

⁸Robert 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

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

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

¹⁰Engineering 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 con-

struction 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

¹²Robert 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.

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

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

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

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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 & Dellbrück 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.

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

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

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

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

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

¹⁹Robert 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.

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

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

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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 pro-

posed 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 Michæelis, 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

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

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

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

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

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

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 Chaussées 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

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

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

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

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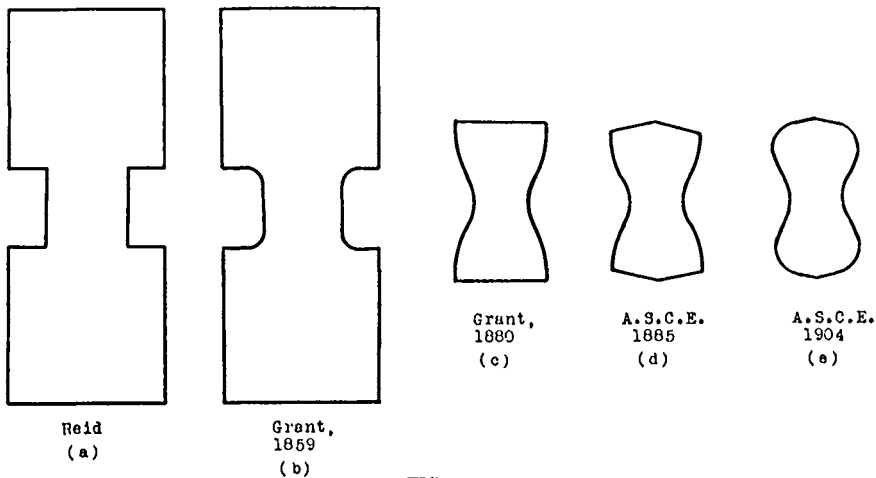


FIG. 1
Evolution of Specimen for Tensile Tests

the same as that adopted as a standard in the United States in 1885 and shown in Fig. 1(d) and the final standard adopted in 1904 as shown in Fig. 1(e).

In 1859 Grant prepared the specifications for the cement to be used in building the London sewers and the general and loose character of this specification as compared with the minute detail of those written today is apparent in the following extract:

"The whole of the cement . . . is to be Portland cement, of the very best quality, ground extremely fine, weighing not less than 110 lb to the striked bushel, and capable of maintaining a breaking weight of 400 lb on an area $1\frac{1}{2}$ inch x $1\frac{1}{2}$ inch, equal to $2\frac{1}{4}$ square inches, seven days after being made in an iron mould, of the form and dimensions shown . . . and immersed six of these days in water."³⁰

As showing the importance of the testing, and he is writing near the conclusion of the work, Grant states that they used more than 70,000 tons of cement and had made nearly 15,000 tests. This was twice the amount of cement which had ever been used in an equal period of time—six years—since it had been discovered.³¹

The requirements of these specifications were increased in various ways a number of times during the progress of the work and while the cement manufacturers complained bitterly because of the high requirements, yet they were able to produce the cement demanded of them. Since the requirements were changed during the course of the work it is not possible to make numerical comparisons between the specifications and the test results but the average tensile strength of the seven day neat briquettes, of which 11,587 tests were made, was 207 lb per sq in.

For comparison with the specifications written by Grant, those of the French engineers of the Ponts et Chaussées required for portland cement a weight of 103 lb per imperial bushel and a breaking weight of 280 lb on $2\frac{1}{4}$ square inches of neat cement at the age of 5 days. Something of the improvement in the tensile strength may be judged by the early English requirements for neat cement tested at the end of 7 days.

³⁰"Experiments on the Strength of Cement," Minutes of Proceedings of the Institution of Civil Engineers, Vol. 25 (1865-1866), p. 67.

³¹"Experiments on the Strength of Cement," Minutes of Proceedings of the Institution of Civil Engineers, Vol. 25 (1865-1866), pp. 67-68.

Date	Tensile Strength lb per sq in.	Mix	Age when tested, days	Tensile Strength (lb per sq in)
1859	178			
—	222	Neat cement	7	.250-550
1865	250	Neat cement	28	350-700
1870	350	1:3 sand mortar	7	80-125
		1:3 sand mortar	28	100-200

Though Grant made his early tests with neat cement he later stated that nothing had done as much to raise the quality of cement in Germany as the tests made with a 1:3 cement mortar briquette using a standard sand and testing at the age of 28 days.³²

The standards for cement and methods of testing were developed in the same general manner in a number of countries. In Germany the years 1878, 1887 and 1909 mark definite advances in some phase of the development of standards. The first British Standard Specification was prepared in 1904 and at about this same time other countries set up what might be called national standards.

The formulation of a standard specification in the United States came about in two steps; first a standard method of testing cement, and second, the adoption of reasonable values for the different properties determined by the standard tests. The first part of this standardization began in 1884 with a preliminary report by a committee of the American Society of Civil Engineers.³³ A year later the committee made its regular report which embodied the ideas of the earlier report, modified to some extent, and added a table of average minimum and maximum values for the tensile strength of portland cement; values which were in accord with the test results obtained from 1878 to 1884 at the Boston Main Drainage Works, by Eliot C. Clark. A part of this table is as follows:

³²"Portland Cement; Its Nature, Tests and Uses," Minutes of Proceedings of the Institution of Civil Engineers, Vol. LXII (1880), p. 99.

³³"Preliminary Report of the Committee on a Uniform System for Tests of Cement," Transactions, Am. Soc. Civ. Eng., Vol. 13 (1884), p. 53.

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In their report, (1885) the committee called attention to three briquette testing machines which were then on the market, viz., the Fairbanks, the Olsen and the Riehle. This committee was revived in 1897 and made a preliminary report in 1903 and a final report in 1912. In this latter report they reviewed and discussed very completely the various tests and methods of testing and pointed out why they had been unable to agree with the Board of Engineers of the United States Army on tests which would be acceptable for all cement users in the United States, something which was highly desirable.

The second part of this standardization, the selection of numerical values for the properties, began in 1896 when there was considerable agitation for standard specifications for cement. Since there was no generally accepted specification, each engineer wrote his own, and the resulting diversity was one of the bane of manufacturers as well as of the engineers. Lesley examined between two hundred and three hundred specifications between 1886 and 1898 and found that no two were exactly alike.³⁴

This general desire for a standard specification for cement, accelerated by the increased use of cement for reinforced concrete, found definite expression in 1902 through the cooperation of a newly formed committee of the American Society for Testing Materials, with the committees of the American Society of Civil Engineers, The American Portland Cement Manufacturers, and the American Railway Engineering and Maintenance of Way Association. In

³⁴Proceedings of Engineers Club of Philadelphia, Vol. XVI (1899), p. 145.

1904 this joint committee made a report³⁵ which was adopted by the various co-operating organizations and this was, perhaps, the first joint committee to function in the preparation of specifications, a practice which has since become very common.

The specifications adopted in 1904 were so satisfactory that they are still in force, though modified in 1908, 1909, 1916, 1920, 1926, 1930, 1937, 1938, and 1941 in a number of respects as the art has progressed and knowledge has increased. In 1921 this joint committee and one from the Board of Engineers of the United States Army agreed on a uniform specification for cement and this was the first Standard United States Specification to be adopted by the Engineering Standards Committee, a group which represents all of the engineering societies. The tensile strength requirements have been gradually increased, as the following table of values for 1:3 standard sand mortar briquettes shows.

Date of Adoption of Specification	Tensile Strength (lb. per sq in)	
	7 days	28 days
1904	150-200	200-300
1909	200	275
1917	200	300
1926	225	325
1930	275	350
1938	275	350
1941	275	350

Composition and Constitution of Portland Cement.

With increased use there came to be more and more thought and attention given to the composition of portland cement, to the compounds formed during the burning process, and to the compounds formed during the hydration of the cement in the concrete. John Grant expressed a view which was probably generally held when he said: "that while the manufacture of portland cement required care in the mixture of clay and chalk, it was not of a complex charac-

ter."³⁷ Few cement manufacturers today would be willing to admit that it is as simple as Grant thought it was.

Some of the changes which have taken place in the composition of cement are shown in Table II (see page 30). The individual analyses of natural cement, of which the averages are given in the table, show a relatively large variation while those of portland cement show a relatively small variation. However, all of the analyses show that in the portland cements the silica, lime and alumina constitute about 90 per cent of the total. These then appear to be the most important compounds as was pointed out by Vicat and others. Two facts are outstanding in this table; first, the small amount of lime in the American natural cements as compared with the European cements and, second, the distinctly higher percentage of lime in the later portland cements over those made in the earlier period. The importance of this high lime content in the portland cements will be pointed out later.

The first man to make real progress on the determination of the compounds formed in portland cement during the burning was Henri Le Chatelier (1850-1936) of France. His most important work in this field was published in 1887 and translated into English in 1905.³⁸ Le Chatelier realized that the ordinary chemical analysis did not give complete information about the compounds present and so he supplemented chemical methods with microscopic ones using the polarizing microscope, which had already rendered good service in mineralogy. By chemical and microscopic means he concluded that the principal constituents of portland cement were tri-calcium aluminate ($(\text{CaO})_3\text{Al}_2\text{O}_3$), tri-calcium silicate ($(\text{CaO})_3\text{SiO}_2$), and di-calcium silicate ($(\text{CaO})_2\text{SiO}_2$), and verified his conclusion by the synthetic preparation of these compounds.

³⁷"Experiments on the Strength of Cement," Minutes of Proceedings of the Institution of Civil Engineers, Vol. 25 (1865-1866), p. 68.

³⁸Henri Le Chatelier, Translated by J. L. Mack, "Experimental Researches on the Constitution of Hydraulic Mortars."

³⁵"Report of Committee C on Standard Specifications for Cement," Proceedings American Society for Testing Materials, Vol. 5 (1905), pp. 74-78.

The next man to report significant data was A. E. Tornebohn who in 1897 reported that he had found microscopically, and separated by specific gravity methods, four crystalline substances in portland cement clinker. He named these substances alite, belite, celite, and felite. While later experimenters were able to identify the substances named and described by Tornebohn, there is no general agreement as to their composition.

As early as 1867 Wilhelm Michaëlis of Germany began work on the constitution of cements but his views of this phase of cements were not published until 1906. Just before this, in 1904, Clifford Richardson (1856-1932), in United States, expressed views somewhat like those of Michaëlis. Both held that the constituents of portland cement clinker were not chemical compounds but solid solutions of lime, silicates, and aluminates which were soluble in each other in varying degrees.

The status of the constitution of portland cement clinker was in a state of uncertainty with the various theories just mentioned, and many others which have not been mentioned, until about 1906 when Day, Shepherd and Wright of the Geophysical Laboratory of the Carnegie Institution at Washington published a report of their work on the "Lime-Silica Series of Minerals." This was followed by other reports and finally in 1915, G. A. Rankin, with the cooperation of Fred E. Wright, completed the series of papers by a report on the ternary system lime-silica-alumina.³⁰ They carried on their experiments by fusing lime, alumina and silica in various proportions after which they quenched the product to a glass and examined it with a microscope. They plotted the data thus obtained on a diagram having three coordinate axes and were able to determine the range of composition within which certain compounds and no others would be found. Then by the aid of "Gibb's Phase Rule" they interpreted the meaning of their observations.

³⁰G. A. Rankin, "The Ternary System CaO-Al₂O₃-SiO₂," The American Journal of Science, Vol. XXXIX (Jan., 1915).

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The papers of Rankin and his associates were epoch making in their contribution to the underlying basic knowledge of portland cement. Other experimenters corroborated the findings of Rankin and it came to be generally agreed that for a mixture which contains only lime, alumina and silica in the proportions usually found in portland cement and which is reduced to a perfectly burned clinker, i.e., the temperature is such that a condition of equilibrium is established, three components and only three, will be formed and that these will be tri-calcium aluminate, tri-calcium silicate, and di-calcium silicate. However, in practice a complete state of equilibrium is seldom reached and then small amounts of lime and of five-three calcium aluminate (CaO)₅(Al₂O₃)₃ may form.

Not all investigators agreed with the workers of the Geophysical Laboratory and particularly the German workers E. Janecke in 1912 and Walter Dyckerhoff in 1924 questioned the existence of tri-calcium silicate; Janecke maintained that what was called tri-calcium silicate was really a calcium-alumina silicate (CaO·Al₂O₃)₃(SiO₂)₂; Dyckerhoff claimed that tri-calcium silicate did not form until higher temperatures than those used in the manufacture of portland cement were reached and that the active hydraulic agent was a solid solution of lime in di-calcium silicate.

This was the state of our knowledge in 1924 and before going further it will be necessary to refer briefly to the formation and work of the "Portland Cement Association." This organization began in 1902 with an informal gathering of representatives of cement mills to discuss business matters of common interest and especially the problem of the return of cement sacks. This informal gathering led to the formation of the "Association of Portland Cement Manufacturers" of which the activities increased rapidly. In 1904 the name was changed to "Association of American Portland Cement Manufacturers" and in 1916 to "Portland Cement Association." Since the organization included the manufacturers of North and South America,

but principally those in the United States, it became a powerful factor in promoting the use of and knowledge about portland cement. In 1914 they introduced the slogan "Concrete for Permanence" and in 1913-1916 research laboratories were established. Thus the Portland Cement Association gradually came to be interested in the technical as well as in the business aspect of cement.

In 1924 a cooperative agreement was made between the Portland Cement Association and the National Bureau of Standards for the investigation of the constitution of portland cement. Professor R. H. Bogue of Lafayette College, a recognized authority on colloid chemistry, was placed in direct charge of the work and associated with him has been a notable corps of workers, L. T. Brownmiller, Wm. Lerch, W. C. Hanson, and F. W. Ashton. He has directed the research in a way that has produced basic scientific data which have been reported in a series of "Fellowship Papers" of the two cooperating groups. One of the early and important tasks which this cooperative group performed was to bring together into a compact and condensed form a summary of all the previous work on the constitution of portland cement.⁴⁰

This work is being carried out in the Clay and Silicate Products Division of the National Bureau of Standards, of which Mr. P. H. Bates is the Chief.

The discrepancy previously mentioned between the American and the German workers over the constituent called tri-calcium silicate continued to exist until 1927. Then Dyckerhoff came to Washington and worked with the other investigators at the Bureau of Standards and the result of this collaborated study was a paper in which they stated that the constituent in question is a tri-calcium

silicate and not a solid solution or a ternary compound.⁴¹ It is of interest that these investigations used all of the more modern methods, chemical analysis, X-ray analysis, microscopic examination, and high-temperature apparatus; surely a pronounced change since the time of Vicat when chemical analysis alone was available. The final conclusion then is that portland cement consists principally of tri-calcium aluminate, tri-calcium silicate, di-calcium silicate and tetra-calcium alumina ferrite together with small amounts of calcium sulfo-aluminate and other compounds the influence of which is not fully understood.

Hydration of Portland Cement.

The final phase of the problem remains to be discussed. Cement must be mixed with water before it will act as a binding material and the character of the reaction which takes place after its mixture with water has received considerable attention. Vicat concluded that the lime combined with the water and that there was an affinity between lime and silica but he did not believe that there was a chemical combination between lime and silica.⁴² Various theories were advanced by different investigators but Le Chatelier in 1887 was the first to present a reasonable picture of what happened. He has been the foremost discoverer in the realm of portland cement. He expressed the view that when a portland cement compound, say tri-calcium silicate, is brought into contact with water that a part of it dissolves. This dissolved salt then breaks down or is combined with more water to form a higher hydrate which, as it continues to form, supersaturates the solution, with respect to the higher hydrate, and is precipitated out in the form of small elongated crystals.⁴³ Le Chatelier believed that the strength of the mortar was intimately related to the elongated

⁴⁰R. H. Bogue, "A Digest of the Literature on the Constitution of Portland Cement Clinker," Paper 3, Portland Cement Association Fellowship at the Bureau of Standards, Washington, D. C. (1927).

⁴¹W. C. Hansen, W. Dyckerhoff, F. W. Ashton and R. H. Bogue, "Studies on the System Lime-Alumina-Silica. The Composition $8\text{CaO} + \text{Al}_2\text{O}_3 + 2\text{SiO}_2$," Paper No. 6, Portland Cement Association Fellowship at the National Bureau of Standards, Washington, D. C. (1927).

⁴²J. L. Vicat, Translated by J. T. Smith, "A Practical and Scientific Treatise on Calcareous Mortar and Cements, Artificial and Natural" (1837), p. 126.

⁴³Henri Le Chatelier, Translated by J. L. Mack, "Experimental Researches on the Constitution of Hydraulic Mortars" (1905), pp. 84-85.

form of crystal and the manner in which they were distributed."

The crystallization hypothesis of Le Chatelier formed the basis of most theories of hardening until Wm. Michaëlis presented his colloidal hypothesis in 1906. According to this theory, the hydrated silicates are present in the form of colloidal precipitates rather than in the form of crystals. It was the question of crystals as opposed to colloidal cementing material. But later work by many men including important work at the Bureau of Standards by P. H. Bates, A. A. Kline, and A. J. Phillips, has brought the divergent views closer together and the general agreement is in favor of Le Chatelier's crystallization theory, modified in some respects. Probably the most recent concise summary of the present state of knowledge is that presented by Bogue, who says in part:

"(1) The aluminates are first to hydrate, forming amorphous hydrated tricalcium aluminate. Crystals of calcium sulfo-aluminate are formed with the calcium sulphate. Most of the free lime is rapidly hydrated.

(2) Hydration of tricalcium silicate begins within 24 hours. This is responsible for the strength between 1 and 28 days. The amorphous aluminate begins to crystallize and tends to cause retrogression of strength.

(3) Dicalcium silicate hydrates slowly, and is responsible for increasing strength after 28 days."⁴⁵

High Early-Strength Cements.

The quality of portland cement has been improved markedly since the beginning of its manufacture. This is borne out by the increase in tensile strength requirements specified by the American Society for Testing Materials for tensile strength at 28 days. This

change has come about by the natural improvement in the art and science of manufacture and also partly by the competition forced on the makers of standard portland cement by the development of high early-strength cements.

Eckel says^{46a} that high early-strength portland cement was first developed in Austria in 1912-1913 and soon after that in Switzerland; that it was used during the World War I for military purposes, and that it has been in commercial use since 1918. One writer says that, "The greatest advance . . . has been during the past few years in the introduction of rapid-hardening portland cement, a super-fine portland cement first produced in Great Britain,"^{46b} while another states that it was first introduced in England in about 1924.^{46c} The first American high early-strength portland cement apparently appeared about 1927 though it does not seem to have been given much publicity at the time, particularly in the technical literature.

The high early strength of portland cement is due to (1) increased lime so as to have as much tri-calcium silicate and as little di-calcium silicate as possible, (2) better control of burning and of cooling the clinker, and (3) finer grinding.

Attention was earlier called to the increase in lime content as shown in the two columns giving the composition of portland cement in Table II; the cements of the earlier period would have very little tri-calcium silicate. This point is stressed strongly in the advertising of one brand of cement in which they claim that a second burning and regrinding of the cement produces a larger proportion of tri-calcium silicate.

Standard specifications for high early-strength portland cement were adopted by the American Society for Testing Materials in 1936 and these were revised in 1938 and 1939. These specifica-

⁴⁵Henri Le Chatelier, Translated by J. L. Mack, "Experimental Researches on the Constitution of Hydraulic Mortars" (1905), p. 109.

⁴⁶R. H. Bogue, "A Digest of the Literature on the Nature of the Setting and Hardening Processes in Portland Cement," Paper No. 17, Portland Cement Association Fellowship at the Bureau of Standards, Washington, D. C. (1938), p. 37.

^{46a}E. C. Eckel, "Cements, Limes and Plasters," 3rd Ed. (1928), p. 668.

^{46b}A. C. Davis, "Portland Cement" (1934), p. 19.

^{46c}"Progress Universal in British Cement Industry in 1927," A. C. Blackall, "Concrete" (Mill Section), March, 1928, p. 110.

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Chemical Components	Limestone for Hydraulic Limes	Average of 50 analyses of Natural Cement, United States	Average of 18 analyses of Natural Cement, France and Germany	Average of 4 European Portland Cements, (1849-1873)	Average of 7 American Portland Cements, (1900-1920)
CaO	80	39.85	55.54	54.20	62.01
SiO ₂	10	26.40	23.63	20.79	21.47
Al ₂ O ₃	--	8.22	9.23	7.79	7.27
Fe ₂ O ₃	10	3.16	4.57	8.46	3.26
MgO	--	13.68	4.12	1.21	1.82
Values in percentages					
* From Vicat's Treatise on Mortars and Cements					
Other values from Eckel's "Cement, Limes and Plasters," 3rd Ed. (1928)					

TABLE II
Chemical Composition of Cements

tions were discontinued in 1941 at which time a specification was adopted which covered a variety of cements for different purposes.^{40c}

About 1925 a new, quick-hardening cement, distinctly different from portland cement, began to make its appearance in commercial quantities. The average composition of ten brands of this type, including American and European, is approximately as follows:^{40d}

Chemical Compound	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO
Percentage	8	42	11	38	1

These high-alumina cements, while not quick-setting, attain a strength in 24 hours comparable with that attained in 28 days by ordinary portland cement. The results of tests as given in a circular issued by one of the manufacturers shows how it compares with ordinary portland cement and with high early-strength portland cement (See Table III). It will be seen that about 83 per cent of the 28-day strength is reached in 24 hours.

This high early strength is a valuable property where time is the most im-

portant consideration, such as repairs in heavy-traffic streets, although such cements cost more than standard portland cement. The competition of the high early-strength cements with the standard portland cements caused the manufacturers of standard portlands to consider how to improve their product. This was accomplished by going part way toward the high early-strength procedure and used sufficient lime to increase the amount of tri-calcium silicate and decrease the amount of di-calcium silicate and by finer grinding. These measures have resulted in a considerable increase in the strength of the standard portland cement.

Low Heat Cement

In all high early-strength cements as well as in the standard portland cements the amount of heat evolved is large and in mass concrete this sometimes involves serious problems. The evolution of heat is sometimes an advantage, as where concrete is to be placed in cold weather. But where large masses of concrete must be placed rapidly and where the heat is dissipated slowly the problem assumes large proportions, as for example, in the case of the Boulder, Grand Coulee, Bonneville, Norris, Fort Peck and other large dams. In Boulder Dam, 571 miles of piping were installed in the interior of the mass of the dam for the circula-

^{40d}E. C. Eckel, "Cements, Limes and Plasters," 3rd Ed. (1928), p. 655.

^{40e}Specifications for Portland Cement (C150-41), 1941 Supplement to American Society for Testing Materials Standards, Part II, pp. 1-4.

Age of Cement	High-Alumina Cement	High Early-Strength Portland, ASTM 1941 Specifications*	Portland, ASTM Specifications
1 day	464	275	---
3 days	---	375	150
7 days	537	---	275
28 days	561	---	---
1 year	628	---	---
Values are in lb per sq in			
* 1:3 sand mortar briquettes			

TABLE III
Tensile Strength of Cement Mortars

tion of cooling water from a refrigerating system.⁴⁷

It was at first assumed that the tri-calcium aluminate was responsible for most of the heat⁴⁸ but more extensive studies at the Riverside Cement Co., Riverside, Calif.,⁴⁹ and at the Bureau of Standards⁵⁰ showed the relative values to be about as follows:

	Calories per gram
Tri-calcium aluminate..	207
Tri-calcium silicate	120
Beta di-calcium silicate..	62
Tetra-calcium aluminoferrite	100

The increased building of large dams and the knowledge of the heat production of the constituents of cement led to the designing of low-heat and medium-heat (modified) cements which have been used in the Morris, Boulder,

Bonneville, Norris, Grand Coulee and Tygart dams.⁵¹

Such modifications from the standard portland cement are called "special cements" and there are a number of them in use. That this important problem is not yet completely solved is indicated by the statement by Lerch that, "... there are a number of variables which affect the heat of hydration of portland cement . . . it seems desirable that when cement is to meet a specific heat of hydration requirement, dependence should not be placed upon estimates from composition and fineness but the heat of hydration should be actually determined."⁵²

Probably the first actual use of a cement which specified a definite limitation on the heat generated was used in the Pine Canyon dam on the San Gabriel River for the water department of Pasadena, Calif. In this cement, which is one of three alternate types, it was specified that the cumulative heat should not exceed 77 calories per gram of cement at the age of 7 days nor 90 calories at the age of 28 days.⁵³

⁴⁷Byram W. Steel, "Cooling Boulder Dam Water," *Engineering News-Record*, Oct. 11, 1934, pp. 451-455.

⁴⁸A. A. Klein and A. J. Phillips, "Hydration of Portland Cement," *Technologic Paper No. 43*, United States Bureau of Standards, p. 47.

⁴⁹H. Woods, H. R. Starke and H. H. Steinhour, "The Heat Evolved by Cement During Hardening" and "Effect of Cement Composition on Mortar Strength," *Engineering News-Record*, Oct. 6, 1932, pp. 404-407; Oct. 13, 1932, pp. 435-437; and Apr. 6, 1933, pp. 431-433.

⁵⁰Wm. Lerch and R. H. Bogue, "The Heat of Hydration of Portland Cement Pastes," *Paper No. 26*, Portland Cement Association Fellowship, National Bureau of Standards, Washington, D. C. March, 1943

⁵¹J. L. Savage, "Special Cements for Mass Concrete," Bureau of Reclamation. Prepared for the Second Congress of the International Commission on Large Dams, World Power Conference (1936), pp. 10-11.

⁵²Wm. Lerch, "Effect of Glass Content Upon the Heat of Hydration of Portland Cement," *Paper No. 36*, Portland Association Fellowship at the National Bureau of Standards, Washington, D. C. (1938), p. 239.

⁵³*Engineering News-Record*, Oct. 6, 1932, pp. 410-411.

DEVELOPMENT OF PROPORTIONING AND PLACEMENT OF CONCRETE

Aggregate and Its Proportioning

At different times a variety of methods have been used to proportion the aggregates in concrete. The first of these was that of arbitrarily selected volumes, as for instance a "1:2:4 mix," meaning; one part of cement, two parts of sand, and four parts of stone. We cannot be certain of the beginnings of this method but it was used by Smeaton in 1756 in giving proportions for the mortars to be used in building the Eddystone Lighthouse. He specified, for example, for a particular mortar, two bushels of lime powder, one bushel of puzzolona, and one bushel of common sand.⁶⁴ The theory of this method is that the sand will fill the voids in the stone and the cement fill the voids in the sand. However, this ideal is not carried out exactly in practice since if the voids are filled with a 1:2:4 mix they will not be filled with a 1:3:6 mix and there will be an excess of cement with a 1:1:2 mix.

Probably the first comprehensive study of proportioning was made by René Feret, Chief of the Laboratory of Ponts et Chaussées in France. In 1892 he reported on a study of the density of mortars and in 1897 again reported on the relation between the strength and density of mortars.⁶⁵ He devised an ingenious method of representing his results, using a three coordinate diagram. This diagram proved to be a most useful way of representing and studying the different properties of concrete materials. Feret concluded that with the same cement, the same sand, and the same age and curing conditions, the compressive strength of any series of plastic mortars is solely a function of the ratio of the volume of cement to the volume of the water and air voids, and that the

strength varies with the square of this ratio.

The next to make a detailed study of proportioning was William B. Fuller (1862-1923) who began his work in 1901 for the East Jersey Water Company and continued it, together with Sanford E. Thompson, (1867-) in 1903-1904 for the Aqueduct Commission of New York. As a result of these studies Fuller gives a number of laws of proportioning of which the more important ones state that: With a given percentage of cement, and a given sand and stone, the strongest and densest concrete will be attained when the sand, cement and water are sufficient to just fill the voids in the stone: and (2) where the aggregate has been graded so as to give, after the addition of water and cement, a mixture of greatest density, the concrete will have a greater strength than where the same amount of cement is used without this grading.⁶⁶ Fuller maintains that for practical work the method of proportioning by the measurement by voids is misleading and is no better than the arbitrary selected volume method. His main contention is that the voids, as measured by the amount of water required to fill them, do not represent the amount of cement which will be required to fill them since the sand grains wedge the stones apart and some of the sand and cement grains are too large to enter the voids.⁶⁷ It would seem that he did not give enough attention to the possibilities in better methods of voids measurement.

Fuller and Thompson advocated making a sieve analysis of the sand and stone and proportioning by means of this. They suggested a series of ten sieves for stone and ten for sand as giving the proper data for plotting a mechanical analysis curve. The total percentage of the ma-

⁶⁴John Smeaton, "A Narrative of the Building and a Description of the Construction of the Eddystone Lighthouse with Stone" (1791), p. 122.

⁶⁵R. Feret, "Études sur la constitution intime des Mortiers hydrauliques," *Bulletin de la Société d'Encouragement pour l'Industrie Nationale*, Vol. 96 (1897), pp. 1591-1625.

⁶⁶F. W. Taylor and S. E. Thompson, "A Treatise on Concrete: Plain and Reinforced" (1912), p. 205.

⁶⁷F. W. Taylor and S. E. Thompson, "A Treatise on Concrete: Plain and Reinforced" (1912), pp. 189-191.

terial retained on each sieve is plotted as ordinates and the diameter of the particles as abscissa; the shape of such a curve for maximum density of the aggregate is a combination of an ellipse and a straight line. Having the sieve analysis of the available sand and stone it is relatively easy to find the combination which will approximate this ideal curve and thus give the maximum density of the mixture and therefore the maximum strength. They developed this scheme very fully and it gave good results. A modification of this method is to make a series of trial batches of different proportions and note the volume of each; the one having the least volume will have the greatest density of those tried though not necessarily the greatest density of which that aggregate is capable. Most of these schemes for obtaining increased strength by proportioning, it will be noted, are based on the fairly well accepted conclusion that the greatest density gives the greatest strength.

Something of a new note was injected into the study of proportioning in 1918 when L. N. Edwards of the Department of Works, Toronto, Ontario, presented what he called the "surface-area" method of proportioning, in which the surface area of the aggregate was computed from a sieve analysis. This was not a really new idea because, as he says, the thought had been advanced as early as 1893.⁵⁸ Edwards sums up his views by stating that the proposed method assumes that the physical properties of the concrete depend upon the relation of the volume of the cement to the surface area of the aggregate. The strength of the mortar depends upon the bond between the particles and the bond depends upon the amount of cement in relation to the surface area of the aggregate.⁶⁰ He also points out most emphatically that an excess of water is very injurious to the strength of the concrete. While the sur-

face area idea seems to be satisfactory from a theoretical point of view, it has never come into extensive use as a practical method of designing concrete mixtures.

Shortly before Edwards published his "surface-area" method, Duff A. Abrams, who was carrying on studies for the Portland Cement Association, had published a short article in the *Engineering News-Record* of May 2, 1918, on a new method of proportioning which he was proposing. This was followed in December by a paper before the Annual Meeting of the Portland Cement Association, which was reprinted in 1919 as a pamphlet, giving a more complete exposition of the method. The proposed method called for the determination of the "fineness-modulus" of the aggregate and laid the main emphasis upon the amount of mixing water in relation to the cement. This new term "fineness-modulus" was used to designate "the effective size and grading of an aggregate" and was obtained from a sieve analysis of the aggregate. A series of nine sieves, beginning with 100-mesh, is used, the clear opening of each being just double that of the preceding one; the fineness modulus is the sum of the percentages retained on each sieve divided by 100. Abrams claimed, quite in opposition to current views, that the strongest concrete was not that with the greatest density but that more coarse material was required.⁶⁰ He then carried the previous qualitative knowledge of the effect of too much water into a quantitative stage and introduced the idea that the quantity of water is more important than the grading of the aggregate. He maintained that, while the grading of the aggregate affected the amount of water required, the strength depended only upon the relation between the water and the cement.⁶¹

⁵⁸A. H. Heath, "A Manual of Lime and Cement" (1893).

⁶⁰L. N. Edwards, "Proportioning the Materials of Mortars and Concretes by Surface Area of Aggregates," *Proceedings American Society for Testing Materials*, Vol. XVIII, Part II, pp. 236-237.

⁶⁰"Design of Concrete Mixtures," Bulletin No. 1, Structural Materials Research Laboratory, Lewis Institute, Chicago (1918), p. 2.

⁶¹"Design of Concrete Mixtures," Bulletin No. 1, Structural Materials Research Laboratory, Lewis Institute, Chicago (1918), p. 4.

Meanwhile experiments had been in progress for a number of years at the University of Illinois, and in 1923 A. N. Talbot (1857-1942) and F. E. Richart gave the results of their work. They questioned the validity of the sweeping assertions of Abrams that the strength of concrete was determined solely by the relation between the cement and the water and, while they did not minimize the effect of water, they maintained that it is the magnitude of the voids in the concrete, space occupied by water and air, after it is in place which affects the strength.⁶² Developing this idea further they state that within limits the strength of a concrete is the same as that of the mortar in it because the coarse aggregate acts only as a filler.⁶³ The term "void-cement ratio" was used to express the relation between the voids remaining in the concrete in place and the absolute volume of the cement and a simple technique was developed for determining the voids in the mortar.

Thus different workers have laid emphasis upon different elements, such as voids, density, surface area of aggregate and water content. It is apparent that some of these elements are closely related to each other, such as voids and density, and it may reduce to a question of which method is the more convenient to use in actual construction work. While each method is used by its advocates, the old method of arbitrarily selected volumes, guided by a sieve analysis of some kind, is still used a great deal except in those cases where elaborate equipment is available for proportioning.

In 1917 D. A. Abrams and O. E. Harder brought out a simple test for the presence of organic impurities in sand.⁶⁴ This test is made by soaking some of the sand in a 10 per cent solution of sodium

hydroxide. If the color of the solution after 24 hours is darker than that of a certain standard solution the sand is judged to contain too many impurities and to be unfit for making concrete. This test has proved very important where vegetable acids, injurious to concrete, particularly tannic acid, have leached into the sand or gravel banks and where their presence cannot be detected by visual inspection.

During World War I the shortage of shipping caused an effort to be made to build reinforced concrete ships. One of the by-products of the ship-building activities was the production of a light-weight aggregate of burned clay called "Haydite," developed and patented in 1918 by J. S. Hayde. It is made by burning shale in a rotary kiln to the point of incipient fusion (about 2000 degrees Fahr.). Gas is formed by the oxidation of the carbon which it contains and this gas causes the material to expand into a cellular clinker which is crushed to the desired size. Haydite gives a concrete which weighs only 95 to 100 lb per cu ft as compared with 140 to 145 lb per cu ft where stone or gravel is used. Consequently a great reduction in the weight of the structure results from this light weight concrete, especially in tall buildings and in bridge floors. Other than lightness and different sound and water absorption capacity, due to the porosity of the Haydite, the principal difference between concrete made of Haydite and of gravel is in the modulus of elasticity which is only slightly more than one-half as much in Haydite as it is in gravel concrete.⁶⁵

Effect of Water on Strength

While the importance of a proper amount of mixing water has long been recognized in a general way, until recently there has been no quantitative measure of its effect or of the amount which should be used. Vicat called attention to the views of the ancients concerning the ill effects of using too much

⁶²A. N. Talbot and F. E. Richart, "The Strength of Concrete, Its Relation to the Cement, Aggregates and Water," Bulletin No. 137, Eng. Exp. Sta., University of Illinois, p. 28.

⁶³A. N. Talbot and F. E. Richart, "The Strength of Concrete, Its Relation to the Cement, Aggregates and Water," Bulletin No. 137, Eng. Exp. Sta., University of Illinois, pp. 80-81.

⁶⁴D. A. Abrams and O. E. Harder, "Suggested Colorimetric Tests for Organic Impurities in Sand," Proceedings American Society for Testing Materials, Vol. XVII, Pt. I, p. 327.

⁶⁵F. E. Richart and V. P. Jernsen, "Tests of Plain and Reinforced Concrete Made with Haydite Aggregates," Bulletin No. 237, Eng. Exp. Sta., University of Illinois, p. 79.

water in mixing lime by saying: "The ancients insisted on the necessity of working up the mortar without any addition of water: good mortar, said they, ought to be tempered only with the sweat of the mason." But he points out that a certain amount of water is necessary to mix a dry sand and a stiff lime.⁶⁶ While there have been recessions from the general proposition that too much mixing water is harmful, in general this has been recognized by investigators though not always by builders. The action of water was evaluated by Taylor and Thompson about as follows: The effect of an excess of water on cement and aggregate is largely physical. The water forms a film and separates the grains by surface tension and thus increases the volume of the concrete. This, from the standpoint of density, decreases the strength of the concrete.⁶⁷

The investigations of Abrams, Talbot, Graf and others have shown definitely that there is a certain optimum of water depending upon the amount of cement and the gradation of the aggregate and that more water lowers the strength and decreases the durability of the concrete. In the report of Abrams, referred to previously and which covers nearly 50,000 tests, he concludes that the grading of the aggregate affects the amount of water required to produce a workable mix and that, for any given strength, the amount of cement needed is dependent upon the amount of water used in mixing. He sums it all up in the single sentence: "It is seen that for given concrete materials the strength depends upon only one factor—the ratio of water to cement."⁶⁸ He supports his conclusions by a curve, drawn from data obtained from tests in which there is a wide variation in the size and grading of aggregate,

which has the equation $S = \frac{14,000}{7^x}$

in which S is the compressive strength of concrete at 28 days and the exponent x is the ratio of the volume of the water to the volume of the cement, this ratio being called the "water-cement ratio" a term which was originated by Abrams and which has come to be widely used. He proposed a formula for computing the amount of water required in any given mix but unfortunately the formula is rather complicated and has not been used to any extent.

While Talbot and Richart, in their report published in 1923, questioned the contention of Abrams that the strength of concrete depends solely upon the relation between the water and the cement, they agreed that excess water is detrimental. They stated that the addition of 50 per cent more water than the amount required to give a normal consistency might reduce the strength to one-half of that which it would have at "basic water content," the latter term being used to designate the amount of water which gives the minimum volume of the mortar (greatest density and least voids). They further pointed out that the water-cement ratio has a variety of useful applications even though different groups of tests do not give identical results.⁶⁹

Thus, not only because of its inherent value, but because of the wide publicity given to it by the Portland Cement Association, the water-cement ratio has had a most important influence in reducing the amount of mixing water in concrete structures of importance. A recent modification of it has been proposed by Professor Inge Lyse who suggests a cement-water ratio by weight, instead of the water-cement ratio by volume, and claims that the strength of the concrete is a straight-line function of this ratio.⁷⁰ It appears that the cement-water ratio suggested by Professor Lyse had been dis-

⁶⁶L. J. Vicat, Translated by J. T. Smith, "A Practical and Scientific Treatise on Calcareous Mortars and Cement, Artificial and Natural" (1837), p. 204.

⁶⁷F. W. Taylor and S. E. Thompson, "A Treatise on Concrete: Plain and Reinforced" (1912), pp. 147, 152-153.

⁶⁸"Design of Concrete Mixtures," Bulletin No. 1, Structural Materials Research Laboratory, Lewis Institute (1918), pp. 2-4.

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⁶⁹A. N. Talbot and F. E. Richart, "The Strength of Concrete, Its Relation to the Cement, Aggregates and Water," Bulletin No. 137, Eng. Exp. Sta., University of Illinois, pp. 14, 76, 93.

⁷⁰Engineering News-Record, Nov. 5, 1931, p. 723.

cussed in Europe five or six years earlier."⁷

Practice has often lagged behind theoretical knowledge and it is one thing to know about the effect of water and quite another to be able to determine the amount of water needed and to control that amount in an easy and cheap manner. Of the many schemes proposed probably the two most used are the slump test and the flow table. Of these the slump test is the best field method and is the one which had come into common use. The apparatus consists of a steel form having the shape of a truncated cone which is filled with concrete under prescribed conditions of compacting. When the steel form is lifted off, the concrete cone "slumps" down, the amount of the slump being greater as the amount of water is increased. By specifying the maximum amount of slump allowed, the consistency of the concrete is regulated. The latest large concrete mixing units have elaborate arrangements for measuring the amount of water added and the practical problem of producing a uniform mix in production work is well on its way to a satisfactory solution. Incidentally the improved quality of the concrete which is produced is beginning to redeem somewhat the slogan "Concrete for Permanence" which had fallen into rather serious disrepute because of the number of structures which had shown lack of durability, partly because too much mixing water had been used.

Placing Concrete

Contrasted with the danger of too much mixing water is the necessity for keeping the newly poured concrete damp for a number of days after it is made in order to provide sufficient water for the continued hydration of the cement. Various coverings have been used to accomplish this, such as straw, manure, canvas, earth, and finally, a delinquent salt, calcium chloride, which absorbs water from the air and keeps the surface of the concrete moist. The latter ma-

terial has found its most extensive use in the curing of concrete pavements on highways. It was first used in 1921 in Illinois for surface curing and in Pennsylvania where it was incorporated in the mix. The recognition of the necessity for keeping concrete wet is merely an extension of the early observation that mortar was stronger where it had been used in a damp place.

Placing concrete in water has always given a great deal of trouble. This was early recognized by Vicat who points out that "beton" which is placed under water should never be shoveled into the water but should be lowered to the bottom and deposited there. He recommends a box of the type proposed by the noted engineer and constructor B. F. de Belidor (1697-1761) which was suspended a little above the center of gravity and emptied itself by turning over when it reached the bottom of the water.¹² The modern method is to deposit concrete under water by means of a "tremie" or tube which places the concrete without allowing the water to pass through it and remove the cement. The concrete flows from the end of the tube into its place while the tube is always nearly full of concrete. Vicat also called attention to the danger, when placing concrete in water in a coffer-dam, of the formation of layers of "pulp" or laitance, "a very serious evil." Thus, some of the precautions which are recognized today as being necessary have been known and practiced since the beginning of the modern development of concrete.

One other item may be mentioned; that is, the change in the methods of mixing and placing concrete. In the early days the concrete was mixed by hand or by a simple batch mixer and it was transported to the forms by wheelbarrows and later, on large jobs, by small dump cars running on a track. However this mode of handling has been largely superseded by modern methods, except for small jobs, and today a great deal of attention is given to the design

⁷Engineering News-Record, June 23, 1932, p. 897.

¹²L. J. Vicat, Translated by J. T. Smith, "A Practical and Scientific Treatise on Calcareous Mortars and Cement, Artificial and Natural" (1837), pp. 76-77.

of the concreting plant. Two common types of concrete plant have been evolved, the spouting type and the aerial-tramway bucket type. In the first method inclined metal spouts, usually semi-circular in shape extend from a high tower, where the concrete is mixed or to which it is hoisted, to the place where the concrete is deposited in the form. The concrete must have a consistency such that it will flow down the inclined spout and this constitutes one of the dangers of the method. The spouting method is especially useful in the construction of buildings. A variation of this is where the concrete is carried by belt conveyor from the mixing plant to the place of deposit. For example, the belt conveyor type of plant was used to manufacture and place 188,000 cu yds of concrete in Vermunt Dam on the River Ill in western Austria.⁷³

Closely allied with improved methods of transporting concrete are the methods of tamping. Vibration has come to be a recognized means of producing a dense concrete filling all parts of the form. The vibrators are operated electrically and may be used against the form or inserted into the concrete mass. A much smaller amount of water may be used, than where hand tamping is used, and yet excellent results are secured.

Another recent development is that of ready mixed concrete. A central plant, permanently established, mixes concrete and sells it. This is economical because it makes unnecessary the duplication of equipment which follows where each small contractor operates his own mixing plant and at the same time it insures a good quality of concrete for small jobs.

The site is high in the Alps and the aggregate was brought to the storage bins by an aerial tramway 3 1/3 miles long. The aggregate was proportioned by automatic weighing devices and brought to the charging hoppers by conveyor belts while the cement was brought by screw conveyors. The speed of the conveyors was so regulated that the amounts desired could be obtained within 1 per cent plus or minus. The different parts of the operation were under the control of the mixer operators through a system of electric switches and signal lamps. More than two miles of conveyor belts carried the concrete from the mixers to the three distributing towers from which it was distributed to the proper place in the dam by spouting. The mix was unusual in that it was so dry that there was no slump. This was done in order to reduce the amount of cement used, to lessen the pressure on the forms and allow them to be removed earlier than otherwise would be the case, and to reduce the frost hazard which was great in that altitude.

The aerial tramway bucket plant has been successfully used on some of the large dams such as the Boulder, Grand Coulee and TVA dams. Buckets containing from 5 to 10 cubic yards of concrete are filled at the mixing plant and carried by cable way to the proper location, lowered into place and the contents discharged by opening the bottom; drier mixtures can be handled by this method than by the spouting method.

Another modern method of placing concrete is by pumping, a method which has been used successfully on Dam No. 5, Mississippi River.⁷⁴

DEVELOPMENT OF REINFORCED CONCRETE

Early Uses of Reinforced Concrete.

In spite of its value as a foundation material, concrete would never have attained the great popularity which it has if it had been used solely for this purpose. By referring to Table I it will be seen that the production of portland

cement was nearly twenty times as great during the decade 1900-1909 as it was during the preceding one. Even though this was the period during which the Panama Canal was built, which used an enormous amount of cement, a considerable influence in the increased use of cement was the growth in the use of reinforced concrete.

⁷³Engineering News-Record, Aug. 4, 1932, p. 126.

⁷⁴Civil Engineering, Aug., 1934, pp. 398-402.

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The first attempt, of which we have a clear record, to use tensile reinforcement in concrete or masonry construction was in the building of an experimental arch of brick and cement in 1832 by Sir Marc Isambard Brunel (1769-1849) while he was building the tunnel under the Thames River at London. He used strips of hoop iron and of wood for reinforcement and made what were probably the first tests of bond strength by pulling iron hoops and wood strips out of mortar made of two parts of cement and one part of sand. For the iron hoops the bond stress developed was 16-25 lb per sq in of surface.⁷⁶ Other experiments soon after this time show that the idea of using steel or iron to withstand tension in concrete was not the product of a single mind but was rather the product of the period; it was the beginning of the period marked by the use of wrought iron and cast iron as structural materials.

While Lambot in France built a small rowboat of reinforced concrete in 1850 which was exhibited at the Paris Exposition in 1875⁷⁸ and Francois Coignet is said to have taken out a patent in England in 1855 for an arrangement of steel in concrete, the invention of reinforced concrete is usually attributed to a Parisian gardener Joseph Monier (1832-1906), who made garden pots and tubs of concrete and reinforced them with a mesh of iron wire. He first patented his scheme July 16, 1867⁷⁷ and exhibited his product at the Paris Exposition in 1867 along with some work of Francois Coignet in which the latter had applied the principles of reinforced concrete to the construction of beams and arches. A Mr. Scott received a patent in England in 1867 for a type of construction which would eliminate the joist in floor construction. His patent claims that by fastening wrought iron rods into the walls, the tie rods and hoop-iron to-

gether with the concrete, take the tensile stress and the concrete takes the compressive stress.⁷⁹ Again, in 1869, Coignet devised a type of construction on which a patent was granted claimed to strengthen the concrete by a metallic framework.⁸⁰

Early Developments in America

In America the first reinforced concrete construction of which there is definite record is that of a house in Port Chester, N. Y., which was built in 1875 by W. E. Ward on the basis of experiments made in 1871 and 1872. The interior and exterior walls, towers, beams, floors and roofs were made of concrete, the bottom of the beams being reinforced with light I-beams. He describes the construction of the floor as follows:

"a thin course of the *béton* was first put on, and evenly tamped down to about an inch in thickness, over the whole space intended to be covered. Then the rods of iron, five-sixteenths of an inch in diameter, were placed both longitudinally and laterally, at a uniform distance of eight inches apart over the whole surface. Then, on this, a final layer of two inches in thickness was carefully tamped down."⁸¹

The principal American patent in the beginning of reinforced concrete was granted to Thaddeus Hyatt (1816-1901) in 1878. This pioneer inventor outlines the principles by stating specifically that the steel must be able to resist sufficient tensile stress to balance the compressive stresses in the concrete. He bent up some of the bars to resist shear, advocated deformed bars, and proposed to construct concrete columns with longitudinal steel or with horizontal circumferential hoops or both.⁸²

⁷⁶E. L. Ransome and A. Saurbrey, "Reinforced Concrete Buildings" (1912), p. 22.

⁷⁸E. L. Ransome and A. Saurbrey, "Reinforced Concrete Buildings" (1912), p. 30.

⁸⁰Transactions, Amer. Soc. Mech. Eng., Vol. 4 (1883), pp. 389-393.

⁸¹"An Account of Some Experiments with Portland Cement Concrete Combined with Iron as a Building Material with Reference to Economy in Construction and for Security Against Fire in the Making of Roofs, Floors and Walking Surface." Published privately in 1877 by Thaddeus Hyatt.

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⁷⁶Richard Beamish, "Memoir of the Life of Sir Marc Isambard Brunel," pp. 285-286.

⁷⁸A picture of this boat is shown in *Handbuch für Eisenbetonbau*. Herausgegeben von P. Von Emperger, Erster Band (1908), S. 12.

⁷⁷"Beiträge zur Geschichte der Technik und Industrie," 21 Band (1931-32), S. 48.

In this paper we have a complete statement by Hyatt of the broad principles underlying the theory of the reinforcing of concrete structures. The tests on which Hyatt's conclusions were based were made for him in New York and also by the well-known Kirkaldy establishment in England. C. M. Spofford lists seven conclusions which Hyatt reached on the basis of his tests. Of these conclusions, the principal ones are: (1) that the coefficients of expansion of concrete and wrought iron are the same; (2) that the ratio of the moduli of elasticity of concrete and wrought iron is about 1 to 20; (3) that portland cement concrete is fireproof; (4) that bars are more economical than rolled beams as reinforcing; and (5) that high concrete chimneys reinforced longitudinally and with wire hoops are better than those without such reinforcement.⁸² Though he advocated the use in his patent of a deformed bar, a "metal specialty rolled for the purpose with bosses or raised portions formed upon the flat surfaces of the metal," there is no indication that he ever manufactured such bars nor did he develop his reinforced concrete patents as a commercial proposition, though his theories were used later by H. P. Jackson in construction.

Hyatt was educated as a lawyer, was an ardent advocate of the abolition of slavery and was very public spirited. But he was primarily an inventor and especially interested in fireproof construction. He invented a sidewalk grating that would transmit light to the rooms below the street and received considerable income from it. This income he used for his avocation of inventing. Had he been as much interested in the promotion of reinforced concrete as he was in its invention the story of its development in America might have been a different one. The early commercial development in America was by Ernest L. Ransome (1844-1917), Edwin Thacher (1840-1920), H. P. Jackson and G. W. Percy, all of whom were practical build-

Practical Developments of Reinforced Concrete

The patents and statements referred to above show that the ideas behind reinforced concrete were not the exclusive invention of Monier, if indeed they were his at all since his early construction dealt mainly with the building of pressure vessels in more or less direct tension; the drawings for his first German patent, granted August 4, 1881, show only tubes or containers of various sorts.⁸³ But the fact remains that the German and American rights in the Monier patents were bought in 1884 by the firms of Freitag and Heidschuch in Naustadt-on-the-Haardt and Martenstein and Josseaux in Offenbach-on-the-Main and then sold to G. A. Wayss & Co. in 1885,⁸⁴ and promoted by them under Monier's name. Therefore his name is associated prominently with the early work in buildings and bridges.

Reinforced concrete construction did not advance very fast in England but on the continent it went forward more rapidly, in Germany under the influence of Möller, in Hungary under Robert Wünsch, in France under Francois Hennibique (1842-1921), and in Austria under G. A. Wayss (1851-?), Johann Bauschinger (1834-1893), Fritz von Emperger (1862-?) and Joseph Melan (1853-?), the latter of whom used a system of structural shapes invented and patented in 1892 in Austria-Hungary and patented in the United States in 1893. Two factors helped to promote the construction in Europe—the International Exposition in Paris, 1900, and the "Recommendations" of the societies of German architects and engineers in 1904.

Reinforced concrete in the United States was promoted first on the Pacific coast where E. L. Ransome between 1874 and 1884 used old wire rope and hoop iron for reinforcement and in 1884 took out a patent for a deformed bar, the twisted square bar. Mr. Ransome says,

⁸³Beiträge zur Geschichte der Technik Industrie, 21 Band (1931-1932), S. 51.

⁸⁴Emil Mörsch, "Concrete-Steel Construction," Translated from 3rd German Edition (1908) by E. P. Goodrich, pp. 204-205.

⁸²Journal of Associated Engineering Societies, Vol. 50 (1913), pp. 213-214.

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"Up to about 1888 my work in reinforced concrete was largely confined to what we now term small and unimportant structures."⁸⁶ But in 1888 he built a floor in a building 75 feet x 400 feet in St. Helena, Calif., and then constructed the floors of the California Academy of Sciences, San Francisco; these floors being supported on cast-iron columns. Next came the two-story Leland Stanford Jr. Museum at Palo Alto, Calif., which withstood the earthquake shock of 1906 with but little damage. An addition to the Borax Works at Alameda, Calif., built in 1889 is claimed as the first "ribbed-floor" construction in America, though the "first reinforced concrete beam in combination with slabs occurred as early as 1886, in connection with the erection of the library in Amsterdam, Holland."⁸⁹ Previous to this the floor slabs were supported by iron or steel beams and columns.

The practical result of advances in the science and art of reinforced concrete construction are largely embodied in the reports of the three successive joint committees on concrete and reinforced concrete composed of representatives of the American Society of Civil Engineers, American Society for Testing Materials, Portland Cement Association, American Concrete Institute, American Railway Engineering Association, and the American Institute of Architects. These committees were organized in 1904, 1920, and 1930 and presented their final reports in 1916,⁸⁷ 1924,⁸⁸ and 1940⁸⁹ respectively.

⁸⁶E. L. Ransome and A. Saurbrey, "Reinforced Concrete Buildings" (1912), p. 4.

⁸⁷Professor Emil Mörsch, "Concrete-Steel Construction," Translated from the 3rd German Edition (1908) by E. P. Goodrich, p. 206.

⁸⁸"Final Report of Special Committee on Concrete and Reinforced Concrete," Transactions American Society of Civil Engineers, Vol. 81 (1917), pp. 1101-1205.

⁸⁹"Report of the Joint Committee on Standard Specifications for Concrete and Reinforced Concrete," Proceedings American Society Civil Engineers, Oct., 1924, pp. 1153-1285.

⁸⁹"Concrete Specifications Number," Proceedings American Society of Civil Engineers, Vol. 66 (June, 1940), No. 6, Pt. 2.

The 1916 report was limited to fundamental principles of design and gave but little attention to details. The 1924 report still placed the main emphasis on fundamental principles but, because of considerable advance in the control of the strength of concrete, higher working stresses were recommended and design details, constants, and procedures were recommended in greater detail than in the 1916 report. The 1940 report featured changes in the following items:

Light weight aggregate,
Emphasis on durability of concrete,
Introduction of alternate specifications in the proportioning of concrete by—

- (1) specification of mix by engineer, or,
- (2) production of concrete of specified quality,

Recognition of new modes of placing concrete such as the mechanical vibrator, spouting, aerial-tramway and pump placing,

Principle of continuity and elastic frame analysis in the design of reinforced concrete structures.

Another important advance in the art of reinforced concrete is that of winter construction. Twenty-five or thirty years ago there was relatively little such building during cold weather but since that time methods have been evolved of heating the concrete materials, of covering the outside of the structure with tarpaulins and of heating the inside by fires. These advances have made reinforced concrete construction in the cold weather a relatively safe procedure.

Structural Action

Though buildings were being constructed of the new material and new methods were being evolved, there was still much uncertainty as to the magnitude of the stresses in the steel and concrete. The first basic theoretical analysis of the action of reinforced concrete was published by Matthias Koenen in the "Centralblatt der Bauverwaltung" in 1886⁹⁰ and this was followed in 1887 by

⁹⁰Dr. Ing. Riepert (Herausgegeben von), "Die Deutsche Zement Industrie," S. 513.

additional material in a pamphlet edited by G. A. Wayss. This pamphlet was entitled "Das System Monier in seiner Anwendung auf das gesamte Bauwesen," and it is said to be the "first German work on reinforced concrete."¹¹ Other analyses followed in particular a report on beams in March, 1894, to the Société des Ingenieurs Civils by E. Coignet and N. de Tedesco in which they proposed a formula using a linear variation of the compressive stresses and neglecting the tensile strength of the concrete. They were the first¹² to propose these approximations which have been current assumptions for nearly fifty years.

Mathematical analyses can only be as correct as the assumptions on which they are based, and in order to verify these assumptions, to discover new laws, and to determine the constants which were needed, an enormous number of tests of reinforced concrete have been made. Of the earlier experiments which were made the most influential those performed by Bauschinger, who first reported on them in 1887 with G. A. Wayss, by Bach beginning in 1895, by Considere in 1902, by Talbot in 1904 and by Withey in 1906, are in the forefront. Those named are only a few of the many outstanding investigators who have carried on this work for many years. Because of its simplicity and importance, one test will be referred to in some detail: Early tests on reinforced concrete beams indicated that the concrete on the tensile side of the beam elongated more than plain concrete would elongate without showing signs of cracking and the conclusion was drawn by some engineers that the action of concrete before and after reinforcing was entirely different. The incorrectness of this conclusion was shown at the University of Wisconsin in 1901-1902 by noting that "hair-lines" appeared on partially dried beams when they were tested. Further study showed that these were

tiny cracks and that the reinforcement distributed the cracks so much that they were not readily visible on the rough side of the beam but that where the beams were whitewashed before the test the cracks were clearly visible when they occurred. Thus a seemingly small item was really a very important one in forming correct conceptions of the structural action of reinforced concrete.

Monolithic Construction

In the beginnings of reinforced concrete, the floor, following the pattern of steel, consisted mainly of slabs supported on beams or girders and there were many schemes for arranging the reinforcement. Francois Hennibique in France used reinforced slabs as early as 1879 but he did not take out a patent until 1892. His "system" involved the pouring of slab, beams, and columns as a single structural unit and provided bars near the top of the beam over the columns to take care of the negative moment and stirrups and bent-up bars near the ends of the beam to resist shear. Hennibique's method of construction, modified in various ways, came to be largely used in the United States and the impetus which he gave to the new art was so great that he is generally regarded as the originator of monolithic construction. Up to 1910-1911 the slab, beam and girder reigned supreme but about this time the girderless floor slab, sometimes called the "Mushroom Slab" or merely "flat slab," began to be built. These slabs are poured integrally with the columns and without beams or girders, though the slab is usually thickened adjacent to the columns to provide for the large negative moments in the vicinity of the columns. Arthur R. Lord was probably the first one to use the "drop" panel or increased thickness of the slab around the column, and C. A. P. Turner added the enlarged column capital.

Flat slab construction was originated by Orlando W. Norcross in the construction of a building near Boston. Norcross was a contractor and was endeavoring to produce a cheaper structure than the ordinary slab and beam type. He applied

¹¹"Beiträge zur Geschichte der Technik und Industrie," 21 Band (1931-1932), S. 52.

¹²H. M. Westergaard, "One Hundred Fifty Years Advance in Structural Analysis," Proceedings American Society Civil Engineers (Apr., 1928), p. 1000.

for a patent on his idea Nov. 22, 1901 and it was granted to him April 29, 1902. In the Norcross patent the reinforcing was indicated as being in the bottom of the slab over the columns but in construction he placed it in the top of the slab. The Leonard Construction Company purchased the Norcross patent rights and erected a number of buildings according to this method. In 1911 C. A. P. Turner, Minneapolis, Minn., patented a similar girderless system of construction which he called the "Mushroom Slab." Turner claimed the Leonard Construction Company infringed his patents and sued the Company through the Secretary John L. Drum. Meanwhile C. M. Leonard of the Leonard Construction Company sued Turner for infringement of the Norcross patent. In the suits which ensued the Norcross patent was established as, and disclosed to be, the basic flat slab patent. In 1919 the Norcross patents expired but from 1914 until 1919, all "systems" of flat construction were licensed under the Norcross patents.

The suit was so important and the features and principles of the flat slab are so completely and succinctly described in a decree of the United States Circuit Court of Appeals, Eighth Circuit, Dec. 10, 1914, that a part of it will be quoted:

"The purpose of the invention patented to Norcross was to make in one panel or piece, extending throughout a building however large, a monolithic flooring composed of a metallic network embedded in concrete which would sustain itself and its load upon separated posts without the use of girders, floor beams, or other horizontal supports. The principle or mode of operation of the device by which this object was attained was to embed in a concrete flooring a metallic network consisting of strips of heavy wire netting which were laid lengthwise of the building, crosswise of the building and diagonally over the tops of and supported by the columns, so that a strip lengthwise, a strip crosswise, and a strip laid diagonally would lie on or under each other over the top of each

post in cobhouse fashion and leave only small triangular spaces in any rectangular space between four posts free from this metallic network."⁶³

The increased use of the flat slab construction and the lack of sufficient data for a correct mathematical analysis led to the making of a number of tests of floors in different buildings constructed in different ways. Talbot and Slater in reporting such tests point out that the methods of fabrication of a structure may affect its action, that the assumptions used in an analysis may not be correct, and that laboratory tests usually give data only on a single member and that, therefore, the finished structure may not act exactly as it is expected to do. The first of these building tests in which deformations of steel and concrete were measured was made under the direct supervision of Arthur R. Lord in Nov. 1910, on the Deere and Webber Building in Minneapolis, Minn.⁶⁴ The tests proved to be so instructive that between 1910 and 1918 the records of at least fifteen such tests are to be found in the American literature alone. They were mainly on the flat slab type of construction. Briefly the tests were made by loading the floor or a portion of it with brick, pig iron or other heavy material of which the weight might be easily determined and measuring the deformations of the steel and concrete at a large number of critical places by means of the strain gage—a portable strain-measuring instrument. The actual deformations of the steel and of the concrete were studied and from them a fairly accurate knowledge of the stress distribution was obtained. Willis A. Slater (1878-1931) was a moving spirit in this work not only in planning, directing and making the tests but in analyzing the data and interpreting the results. His untimely death removed a most zealous and competent student of reinforced concrete.

⁶³Federal Reporter, Vol. 219, p. 189.

⁶⁴Arthur N. Talbot and Willis A. Slater, "Tests of Reinforced Concrete Buildings Under Load," Bulletin No. 64, Eng. Exp. Sta., University of Illinois, pp. 5-6.

The mathematical analysis of flat slabs has been attempted many times but the results, involving as they do certain basic assumptions, have not been universally accepted. Dean H. M. Westergaard presented an analysis⁶⁶ in 1921 which was considered to be a real contribution to the subject and for this he was awarded the Wason medal of the American Concrete Institute. This analysis formed the basis for further studies by Dean Westergaard from which he proposed design formulas for slabs and beams.⁶⁹

Almost from the beginning of concrete beam and column construction the fact of continuity and of the elastic action of monolithic structures had been recognized, but the magnitude and certainty of the amount of this continuity were not known with sufficient exactness to be incorporated to any extent in specifications. To remedy this lack, extensive researches have been made on many forms of framed structures, the interaction of reinforced concrete arches with their floor systems⁶⁷—knee frames⁶⁸ being significant examples. These researches show that moments and thrusts can be calculated to a satisfactory degree of exactness in monolithic structures.

⁶⁶H. M. Westergaard and W. A. Slater, "Moments and Stresses in Slabs," Proc. American Concrete Institute, Vol. XVII (1921), pp. 415-538.

⁶⁷H. M. Westergaard, "Formulas for the Design of Rectangular Floor Slabs and Supporting Girders," Proc. American Concrete Institute (1926), p. 26.

⁶⁸Wilbur M. Wilson and Ralph W. Kluge, "Laboratory Tests of Reinforced Concrete Arch Bridges with Decks on Slender Piers," Bulletin No. 270, Engineering Experiment Station, University of Illinois.

⁶⁹F. E. Richart, T. J. Dolan and T. A. Olson, "An Investigation of Rigid Frame Bridges: Part I, Tests of Concrete Knee Frames and Bakelite Models," Bulletin No. 307, Engineering Experiment Station, University of Illinois.

W. M. Wilson, R. W. Kluge and J. V. Coombe, "An Investigation of Rigid Frame Bridges: Part II, Laboratory Tests of Concrete Rigid Frame Bridges," Bulletin No. 308, Engineering Experiment Station, University of Illinois.

March, 1943

Reinforced Concrete Columns

The first proposals to use concrete columns are due to W. H. Wood who in 1862 patented the idea of filling a cast-iron column with concrete, and to Hyatt who in 1878 specified either hoops or longitudinal steel, but reinforced concrete columns were little used until after 1900. Between 1902 and 1908 many tests of concrete columns were made in Europe and in America; the specimens were reinforced with spiral steel, with hoops and with longitudinal rods. Mr. A. Considéré in France was the first to study the spirally reinforced type⁶⁹ on which he reported in *Le Génie Civil* in 1902. Other experimenters who early made important contributions to our knowledge of concrete columns are Graf, Bach, von Thullie, and Mörsch in Germany, von Emperger in Austria, Guidi in Italy, and Talbot and Withey in America. These tests showed, in general, that the strengthening effect of spiral steel was greater than the strengthening effect of the same amount of longitudinal steel.

While much experimental work was done between 1908 and 1916 few new facts were revealed in the published material. In the meantime a number of important questions had been raised concerning such matters as: (1) the effect of long-time loadings, (2) the plastic flow of concrete and its effect in transferring load from the concrete to the steel, and (3) the effect of shrinkage of the concrete on the stresses in the steel. In 1929 the American Concrete Institute sponsored a comprehensive investigation of concrete columns reinforced in different ways and of different sizes, up to 28 inches in diameter, and planned so as to give information on the questions stated above. The tests were carried out at Lehigh University and the University of Illinois under the direction of Professor W. A. Slater and Professor F. E. Richart. A final report was made in 1934. In general their findings were satisfactory

⁶⁹A. Considéré, "Résistance à la Compression du béton armé et du béton fretté," *Le Génie Civil*, Tome XLII (1902-03), pp. 5-7, 20-24, 38-40, 58-60, 72-74.

to the design methods which were then in use. A brief summary of their findings shows that the effectiveness of the steel is not affected by the diameter of the column; that the stress in the steel, where the column was held under a load, increased due to the plastic flow of the concrete; and that the ultimate strength of a column which had been held under a load for a year was no different from that of a column which had not been under a load. The ultimate strength of a reinforced concrete column was found to be made up of three elements:

(1) The strength of the concrete core, which is equal to the area within the outside edge of the spiral times 75 to 85 per cent of the strength of the control cylinder.

(2) The total yield point strength of the longitudinal steel.

(3) From $1\frac{1}{2}$ to 2 times the total yield point strength of the spiral.

These conclusions¹⁰⁰ were used in the preparation of the specifications for columns in the 1940 report of the joint committee previously mentioned.

Concrete Bridges

The first plain concrete arch bridge in Europe was built in 1869 to carry the aqueduct of the Paris waterworks. It is known as the Grand Maitre bridge in Fontainebleau Park. The first in the United States was built in 1871 in Brooklyn, N. Y. and it has a span of 31 feet. The first reinforced concrete arch bridge, of which there is a clear record, was built in Copenhagen in 1879, with a span of 71.7 feet, while in the United States E. L. Ransome built one having a span of 35 feet in San Francisco in 1889.¹⁰¹

The Melan system—concrete reinforced with structural shapes—was introduced into the United States by Fritz von Emperger when he built a number of reinforced concrete bridges of long span, at

least long for that time. The first one was built in 1894 at Rock Falls, Iowa, with a clear span of 30 feet and a rise of 6 feet 6 inches. That von Emperger had difficulties in his pioneer construction is evident for he writes concerning this work:

"The difficulties I had to overcome . . . at this time there was no reliable American cement and I had no contractor of . . . experience. I had to build those bridges myself and to be . . . my own foreman."¹⁰²

In a paper¹⁰³ presented in 1894, von Emperger stated that he knew of but three "concrete-iron bridges in this country" and cities, as showing the possibilities in this type of construction, a concrete bridge near Erlach, Germany, built in 1873, with a span of 105 feet, a rise of 13 feet and a crown thickness of 20 inches, and another bridge near Ulm, Germany, of a span of 15 feet and a crown thickness of 6 $\frac{2}{3}$ inches. Seven years later R. S. Buck said that von Emperger's paper was the first introduction of the subject of reinforced concrete bridges in this country.¹⁰⁴

In 1905 Edwin Thacher, who designed and built the concrete-steel arch bridge over the Kansas River at Topeka, Kan., and which was the first large reinforced concrete bridge in the United States,¹⁰⁵ said that about three hundred spans of "concrete-steel" bridges were built or in progress of building under the Thacher, Melan and Emperger patents. Since that time many thousands of bridges have been built, including the great Tunkhannock viaduct, the largest concrete bridge in the world. It has a total length of 2375 feet, is 300 feet above the rock foundation and contains 165,000 cubic yards of concrete. Built in 1912-1914, it was pronounced to be in "substantially

¹⁰²Private Communication to the Author (1930).

¹⁰³"The Development and Recent Improvement of Concrete-Iron Highway Bridges," Transactions American Society Civil Engineers, Vol. XXXI (1894), p. 437.

¹⁰⁴Transactions American Society Civil Engineers, Vol. XLVI (1901), p. 94.

¹⁰⁵Memoirs of Edwin Thacher," Transactions American Society Civil Engineers, Vol. LXXXIV (1921), p. 921.

¹⁰⁰Frank E. Richart and Rex L. Brown, "An Investigation of Reinforced Concrete Columns," Bulletin No. 267, Engineering Experiment Station, University of Illinois.

¹⁰¹F. W. Taylor and S. E. Thompson, "Chapter on Concrete Arches by Frank P. McKibben in A Treatise on Concrete: Plain and Reinforced," p. 536.

perfect condition" after an inspection in 1932.

A few other large bridges may be mentioned, as the Capplen Memorial Arch Bridge at Minneapolis, Minn., the Two-Mile Viaduct at Long Key, Florida, the Bay Bridge at San Francisco, the Lake Pontchartrain Bridge in Louisiana and the James River Bridge at Newport News, the last three named having a total length of 17.49 miles and costing about \$20,000,000. One of the longest concrete arches, if not the longest, in America has a span of 460 feet with a rise of 156 feet.¹⁰⁶ It is the five-span, 1560-foot George Westinghouse Bridge in East Pittsburgh, Pa., and was built in 1932. Then there is the unusual, if not startling, Freyssinet bridge at Saint-Pierre-du-Vauvray, France, which has a span of 432 feet, a rise of 82 feet, and which consists of two hollow ribs with a crown section 8.2 feet square with the walls varying from 8 inches to 13 inches in thickness.¹⁰⁷ The first bridge of this type to be built in America was over the Rogue River, Oregon, in 1932. It is an open-spandrel arch with two ribs and has seven 230-foot spans with a rise of 47 feet. Each rib has a crown section 6 feet wide and 2 feet 9½ inches deep.¹⁰⁸ The principle involved in the construction of this type of bridge is that of largely eliminating the stresses due to shrinkage and deformation by placing hydraulic jacks at the crown to spread the arches to the design position before striking the centers; this crown opening is then filled with concrete.

A bridge having a span of 866 feet was under construction over the Angerman River in Norway in 1939 but the collapse of the timber centering wrecked the structure and the plan was abandoned. Europe has been the leader in long-span reinforced concrete arches as is evidenced by the 590-foot Plaugastel bridge in France and the 593-foot Troneberg bridge in Stockholm.

In addition to the remarkable increase in the number and size of concrete bridges, two important features have developed. One of these is the great attention which has been given to the artistic design of concrete bridges and the most substantial achievement which has been made in this direction. This improvement in the appearance of the bridges designed has been most marked since about 1920. The other feature is the substantial improvement in the structural design and the knowledge of the stresses and strains in reinforced concrete bridges. A comprehensive and important experimental study of the structural action of reinforced concrete arches, sponsored by the Engineering Foundation, the American Society of Civil Engineers and the United States Bureau of Public Roads, was begun in 1928. This investigation continued for six years, mainly at the University of Illinois under the direction of Professor Wilbur M. Wilson, with the result that much valuable information on the structural action of reinforced concrete arches was obtained.¹⁰⁹

Concrete Ships

One transient phase of reinforced concrete development which is worth a passing comment was the attempt to build concrete ships during World War I. Concrete boats and barges had been built in a number of places, including Holland, in 1887, also in Italy in 1896, and in Germany in 1909 but in the main these were all small boats or barges; Becker¹¹⁰ states that at the end of World War I, concrete ship construction was going on in no less than 20 shipyards in Great Britain. In the United States small barges had been built for inland waterway traffic but the first large ship to be constructed was the 5000-ton Faith which was built on the Pacific coast and put into service there in May, 1918. The success of this ship and the publicity given to her pro-

¹⁰⁶Engineering News-Record (July 21, 1932), p. 67.

¹⁰⁷Engineering News-Record, Vol. 92 (Mar. 20, 1924), p. 576 and (Sept. 18, 1924) Vol. 93, p. 463.

¹⁰⁸Engineering News-Record, Vol. 107 (Nov. 28, 1931), p. 841.

March, 1943

¹⁰⁹"Final Report of the Special Committee on Concrete and Reinforced Concrete Arches," Transactions American Society Civil Engineers, Vol. 100 (1935), pp. 1427-1581.

¹¹⁰"Beiträge zur Geschichte der Technik und Industrie," 21 Band (1931-1932), p. 57.

vided an incentive for further work and an organization was perfected in the Emergency Fleet Corporation of the United States Shipping Board to make the necessary investigations, to prepare plans and to build the ships. An extensive research program was undertaken and much valuable information was obtained especially on the resistance to impact, watertightness, and on the shearing strength of short deep beams reinforced at top and bottom. Twelve ships and tankers, mostly from 3000 to 7500 tons, in all were built at Oakland, Calif., and Norfolk, Va. The fate of some of them is described in a newspaper clipping dated July 31, 1932, which reported that they were to be stripped preliminary to being towed to a harbor where they were to be sunk to form a breakwater. The feasibility of the construction and use of concrete ships is well stated in a report¹¹¹ which says that, though the construction costs might be brought down to a reasonable figure, concrete ships have two inherent defects: The first of these is the brittleness of the concrete shell and the other is the small cargo capacity compared with the displacement. At the present time (1942) concrete ships are again under construction in this country both the barge and the self-propelled types.

Concrete Roads

The first concrete pavements were built in Inverness, Scotland in 1865 and in Edinburgh in 1866 and 1872. Those built in Edinburgh in 1872 are reported to be still in use. The first concrete pavement in the United States was laid in 1892 in Bellfountaine, Ohio, where a strip 10 feet wide and 220 feet long was placed on one side of a public square, the other three sides being completed in 1893-1894. This pavement was repaired in August, 1932, all work being done by hand as an unemployment relief measure.

The building of concrete roads really began in the United States in Wayne County, Mich., in 1909 when three ex-

Built during Year	Equivalent miles of 20-foot Roadway
1908*	2.9
1910	13.0
1912	160.0
1914	900.0
1916	1350.0
1918	1110.0
1919	3520.0
1928	7960.0
1931	9570.0
1932	7430.0
1934	2570.0
1940	3270.0
* Includes all previous construction.	

TABLE IV
Concrete Roads Built in the United States; exclusive of City Pavements and Alleys

perimental strips having a total length of about 2 miles and of different types were constructed. The low maintenance cost of this strip gave it much favorable publicity and from then until 1918 there was a fairly gradual increase in concrete roads. Then, beginning in 1919, under the enlarged program of advertising carried on by the Portland Cement Association there was a pronounced impetus in concrete road building. This condition continued with a steadily increasing volume of concrete roads until the depression of 1929-1932 interfered with the program in some places. Table IV shows the approximate amount of concrete roads which have been built during recent years as taken from "Cement and Concrete" (1941), published by the Portland Cement Association.

One of the factors which has had an important bearing on the construction of concrete roads has been the invention of elaborate paving machines for placing and leveling the concrete on the wide pavement and in the smoothing of the surface. Other factors in promoting increased road construction of concrete

¹¹¹Proceedings American Concrete Institute, Vol. XVII (1921), p. 291.

have been the tremendously increased use of the automobile and the improved scientific design of pavements. This improved design has come from a number of sources of which "Test Roads" is one. The "Bates Test Road," in which a number of types of road surfaces were built and tested to failure by the Illinois Department of Highways, was responsible for the detection of places of stress concentration, particularly along the edges. From the knowledge thus obtained, "It has been possible to reduce the thickness of the pavement to seven inches and still have a stronger pavement than the original eight-inch thickness used the years before."¹¹² The Pittsburg, Calif., tests were conducted by the Columbia Steel Company with the cooperation of the California Highway Commission and the United States Bureau of Public Roads.¹¹³

¹¹²Fourth Annual Report of the Department of Public Works and Buildings. Division of Highways (July, 1920-Dec., 1921), p. 8.

¹¹³Report of Highway Research at Pittsburg, California (1921-1922); Department of Public Works. California State Printing Office, Sacramento (1923).

In these tests a number of types of slab were built and tested to destruction. Many strain measurements were made which gave information on the action of slabs, particularly thin ones. Other factors which affected the growth of the use of concrete pavements were the physical tests of cores cut from the finished pavement, better control of the mix, better and faster curing and extensive mathematical studies of pavement action¹¹⁴ all with resultant lower cost and better service.

The topic of concrete roads seems a fitting one with which to close this brief history. Aspdin took the raw materials for his portland cement from the roads, necessarily in small quantities, and now portland cement is going back into the roads in quantities of which Aspdin and the other early workers never dreamed.

¹¹⁴H. M. Westergaard, "Stresses in Concrete Pavements Computed by Theoretical Analysis," Public Roads, Vol. 7, No. 2 (Apr., 1926).



Part 11

Landmark Papers



Documents

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INTRODUCTION

BY HOWARD NEWLON, JR.

Chairman, ACI Committee 120, History of Concrete

Just as the roots of the United States political system and its people extend back in time and across the Atlantic Ocean, so do the beginnings of the United States contributions to the history of cement, concrete, and reinforced concrete. The senators who debated in the Roman Forum provided input for our form of government while at the same time the technologists of the Roman Empire were establishing the foundations (both figuratively and literally) for concrete construction with hydraulic cements. Some 1800 years later when the newest democracy was taking its first steps, the initial steps were being taken in England to develop commercially practical artificial cements. This development was essentially a British enterprise, supplemented by notable contributions from France. The major developments in reinforced concrete that occurred about a half century later were, on the other hand, largely accomplishments of Frenchmen supplemented by important refinements in England. These technologies were subsequently to arrive in the United States as had immigrants from these same countries two centuries earlier.

Surviving structures in the Southeastern United States built of a primitive concrete made from sand, shells, and lime remind us of the Spanish influence upon our heritage. This type of construction, commonly called “Tabby” (Spanish-tapia), contributed what is probably the oldest “concrete” in the United States in the form of floors in the Castillo de San Marcos, begun in 1656 in St. Augustine, Fla.

The new land provided new challenges and new opportunities to adapt and to refine Old World ideas and practices in a variety of areas, including construction techniques. Some indication that those characterized as “backwoods ragamuffins” were able to meet these challenges is given by a twentieth century Briton, S. B. Hamilton, in his excellent summary, “A Note on the History of Reinforced Concrete in Buildings,” published in London in 1956. He writes:

Turning now to developments in the U.S.A., in 1878 a patent was granted to Thaddeus Hyatt (1816-1901) for construction in reinforced concrete.

Hyatt based his proposals on tests made for him by Kirkaldy's Laboratory in London and by others in New York. The tests are described in "An Account of some Experiments with Portland Cement Concrete Combined with Iron as a Building Material with Reference to Economy in Construction and for Security against Fire in the Making of Roofs, Floors, and Walking Surfaces." This book was published privately in 1877. Hyatt recognized the importance of the virtual equality of the coefficients of thermal expansion of concrete and iron; he gave the modular ratio as 20; he regarded concrete as fireproof. He showed that bars were more economical than rolled beams as reinforcement, and advocated the use of deformed bars. He does not appear to have developed any of his ideas to the point of actual application.

The real pioneer in the use of reinforced concrete in America appears to have been E. L. Ransome (1844-1917). He was the son of the superintendent of Ransomes and Sims Ironworks in Ipswich, and served an apprenticeship in his father's works. In 1870 he went to San Francisco to manage the Patent Concrete Stone Co. which was marketing a burrstone made by cementing together with silicate of lime the hard waste from dressing mill stones.

Portland cement concrete was little used in California at that time, except for foundations and arches, as the cement had to be imported and was very expensive. Rolled sections of wrought iron and beams of cast iron were also costly, but were used with jack-arches of concrete spanning between them in "fireproof" factory floors. Ransome introduced an economy by eliminating the beam, making iron tiebolts from wall to wall take the place of the tension flange and the concrete in the haunch of the arch serve as the compression flange. To save the cost of threading the ends of the rods but still provide good bond, he next substituted square twisted bars for the long round bolts. In 1884 he took out an American patent (No. 305,226) for the twisted square rod which he found to be stronger than the plain though he did not know why. In 1888 he put up his first important building with these reinforced concrete beams and arches, and cast-iron columns. The following year he introduced a "ribbed floor," that is a tee-beam construction with reinforcement in the bottom of the ribs. A few years later, to ensure proper bond between the rib and the slab, he laid helices of wire with axes horizontal, half embedded in the rib when poured, the other half to engage the slab concrete when poured later. The final development of this, with the beams precast, complete with helix half-exposed, he patented in 1902 (No. 694,577) as "The Ransome System of Unit Construction." Ransome erected his first fully concrete-framed building in Greensburg, Pa. in 1903. He argued that a wet-mixed concrete was both denser and stronger than a dry, an opinion which unfortunately was shared by many of his contemporaries and successors and led them to use mixes far too wet for strength or watertightness (see E. L. Ransome and A. Saurbrey, "Reinforced Concrete Buildings," New York, 1912). C. B. Porter, in an article

“Railway Concrete” in the *American Concrete Institute Journal* (1952, 23, 725) stated that at the turn of the century very dry mixes were used, but that the period between 1905 and 1910 might be called the “wet-mix era.”

A patent for the “flat slab” without beams was granted to Orlando W. Norcross in 1902. Its use became common about 1910 when the drop panel was added by Arthur R. Lord, and the enlarged “mushroom head” to the column by C. A. P. Turner; but these were held to be covered by the original Norcross patent. The American Joint Committee on Reinforced Concrete first met in 1904. It issued a draft report in 1908 and revised it in 1912. The final report did not appear until 1916. (*American Society of Civil Engineers Transactions*, 1917, 81, 1102-52). Subsequent reports appeared in 1924 and 1940 . . .

The accomplishments and individuals recognized by Hamilton in large measure coincide with those reflected in the papers selected by Committee 120 for inclusion in this volume.

The papers by Hyatt, Ransome, Lord, and Turner provide opportunity for the reader to reflect in more detail upon the contributions judged by both Committee 120 and Hamilton to be significant. The paper by Ransome additionally provides an interesting personal narrative and, to some extent, the view of a practically oriented constructor rather than a theoretician or experimentalist. Additional accounts of construction experience and an excellent summary of the various patented reinforcing systems are provided in the chapter from C. A. P. Turner’s book and in the brief description from a nineteenth century *Scientific American*. The remainder of Turner’s book, which is not reproduced, provides fascinating examples of construction and load testing of buildings in the early part of this century.

The paper by Abrams is included because his water-cement ratio law is one of the most widely referenced American contributions to concrete technology. While this law has been too literally applied and broadly interpreted by some, there can be little question but that it was a genuine milestone, because it represents the initial experimentally verified statement of the important relationship that had been qualitatively applied to good concreting practice since the Romans, and which was also stated qualitatively by Smeaton. In addition, Abrams stands as a classic example of the twentieth century American experimentalist and theorist who quantified and defined many of the ideas that had been developed qualitatively over the years. Another significant attribute of the Abrams paper is that it was “Bulletin No. 1” of the Lewis Institute in Chicago, the forerunner of the Portland Cement Association, which has had a singular influence upon concrete technology in the United States and abroad.

Ward’s paper is included as a description by a mechanical engineer with

inventive genius whose singular and sole contribution to the heritage of concrete is the oldest reinforced concrete building in America.

Talbot's contribution was not only pioneering research such as that reported in his paper, but also the establishment of a focal point at the University of Illinois for efforts that greatly expanded the use and understanding of reinforced concrete. The industrial expansion accompanying the turn of the century provided a unique opportunity for immediate practical application of the rapidly developing field of reinforced concrete. The academic and experimental program in engineering mechanics which had begun at Illinois during the last years of the nineteenth century with Professor A. N. Talbot as its head became a major focal point for the study of reinforced concrete which later attracted men such as Newark, Westergaard, and Cross, in addition to those whose papers are included in this volume.

While Drassin's summary has provided the necessary historical perspective of developments from ancient times through the first quarter of the twentieth century, a few supplemental notes will be given to close this introduction.

One vital influence of the revolution upon America's development was that when ties and dependence of the colonies upon England were broken, the country had to look to the development of its own Western resources. This necessity demanded transportation in the form of canals, which in turn demanded waterproof cements. Until that need arose, there had been no real impetus to seek sources for hydraulic cements, and such needs as there were could be met by importation. Once the need was identified and the ties with England broken, Canvas White's discovery was inevitable.

While White's discovery and the accompanying development of the natural cement industry early in the nineteenth century provided a cement that could be used for buildings, such use is not widely documented. In 1835 Obadiah Parker constructed, at 107 Ainos Street in New York, a Greek Revival house of concrete that was described in the August 1835 issue of *Mechanics Magazine and Register of Inventions and Improvements* as "... a small building about 16 by 12 feet on the ground and 12 feet high, having four beautiful columns and pediment, with a door and two windows in front, an arched roof entirely of cement, and sky light in the top—thus forming an entire building including floor, walls, and roof, of one solid piece, and imperishable material; alike proof against fire and water." The kind of cement used by Parker is not clear, but in the same article it is noted that "American Cement, or Artificial Stone, or, as it is more generally at this time known, 'Parker's Cement,' is an article of great and increasing value to this community." Because Parker lived near Syracuse, it is very likely that he was involved in the natural cement industry that was growing in the area.

While it is tempting to attempt a connection between Obadiah Parker and James Parker, who in 1796 had obtained the English patent on natural cement, no such connection has been made. The fate of what may have been the first concrete building in America built with hydraulic cement is unknown.

Considerable attention has been directed toward the Milton Inn and a group of other buildings constructed in Milton, Wis., by Joseph Goodrich in the 1840s. These have often been cited as the first concrete construction in the United States, and some references describe importation of cement from Europe and passage by wagon from New York to Milton. Apparently these accounts are in error, since the binding cement of the concrete in these buildings consists of lime and is typical of “gravel wall” construction promoted by Orsen Fowler, the advocate of octagonal buildings during the period.

The Centennial Year of the Ward House, described by its builder in the paper included in this compilation, fittingly coincides with the country's Bicentennial observance. Until 1973 it served as the residence of the Ward family. Excellent examples of large houses of unreinforced concrete remain in the Hudson Valley area of New York State. These were built during the mid-1850s, but have not been extensively studied.

The houses of Parker and Ward are important and interesting as first examples of United States concrete buildings. According to Condit (*Technology and Culture*, Jan., 1968), the design and construction of three buildings early in the twentieth century brought the new structural technique of reinforced concrete to maturity in the United States. These three buildings were the Ingalls Building in Cincinnati (1902-03), the Terminal Station in Atlanta (1903-04), and the Marlborough Hotel in Atlantic City (1905-06). Among them, the 16-story Ingalls Building was the most daring and influential, and it ranks as the first concrete “skyscraper” in the United States. It embodies the following basic techniques: (1) Ransome's heavy monolithic beam-and-slab construction with tension reinforcing, (2) the two-way reinforcing systems of Monier and Wayss, (3) the bent bars and stirrups of Hennebique, and (4) the hoops and continuous helixes for compression members, the former originally proposed by Hyatt and the latter by Considère.

The large concrete dams associated with the industrial development of the Western States are among the most impressive American engineering achievements of this century. Much of the research and many of the refinements associated with United States concrete technology were outgrowths of these projects. Just south of San Francisco stands Crystal Springs Dam, constructed between 1877 and 1888. This dam was the first to embody all the essential features of the modern arch-gravity concrete dam. In 1890 its

height was increased by 30 ft and in 1923 a highway bridge was constructed on its top.

Another surviving example of early reinforced concrete construction in the United States is the Alvord Bridge at the eastern edge of Golden State Park in San Francisco, Calif. This bridge, constructed by Ransome in 1889, still carries traffic on a busy urban street. The bridge, of course, predates the automotive age but it is fitting that it was built in California, an area that subsequently was to be so closely associated with the development of the urban freeway and its demanding structural requirements. Thus the small Ransome bridge was the forerunner of many graceful and useful structures that today serve the transportation needs of our country.

When Columbus, not satisfied with the prevailing explanations of world geography, sailed from Palos in search of new answers, little did he realize the consequences of his efforts. When John Sincaton, dissatisfied with the existing understanding of the technology of mortars, sought by experiments to expand this understanding, he did not realize that he was in the forefront of a revolution in construction materials. When David O. Saylor burned limestone in his Pennsylvania cookstove, he certainly could not anticipate that within 100 years the United States would be utilizing domestically-produced cements to provide concrete to the extent of approximately 1.5 tons per person per year. The same point could be made concerning each of the contributions chronicled in this volume. The United States Bicentennial observance provides a climate for recalling and reflecting upon the successes and failures of our past, but more importantly, it provides an opportunity for dedicating ourselves to meeting the challenges of the future.

In the speech made famous by his plea for liberty or death, Patrick Henry observed, "I have but one lamp by which my feet are guided, and that is the lamp of experience. I know of no way of judging the future but by the past." If we accept this and similar statements, then we should not stop with just a recitation of the exploits of our forebears, but rather we should use these backsights as references for the future. It is in this spirit that ACI Committee 120 presents this volume.



Fig. 1—Canvas White, while an engineer on the Erie Canal, obtained the first United States Patent on natural cement in 1820. (Photo courtesy of the Munson-Williams-Proctor Institute, Utica, N. Y.)

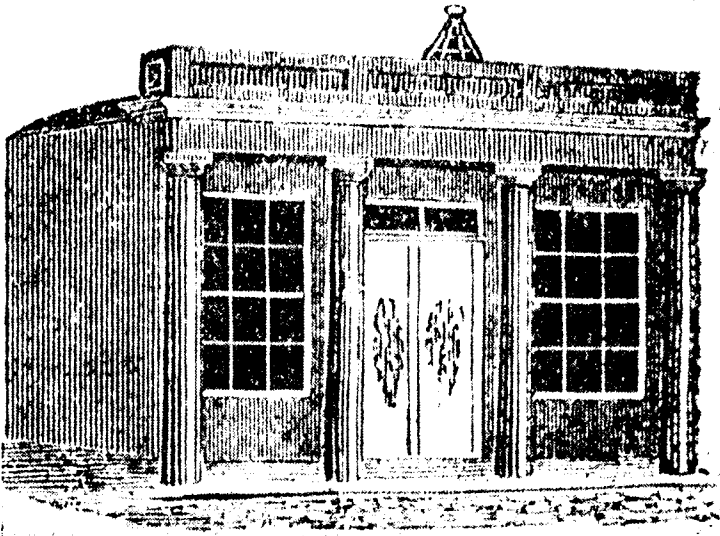


Fig. 2—A drawing of the concrete house constructed by Obadiah Parker in New York about 1834. (Photo from *Mechanics Magazine and Register of Inventions and Improvements*, 1835.)



Fig. 3—The first reinforced concrete building built in America by William E. Ward at Port Chester, N. Y., between 1871 and 1876. (Photo courtesy of the Construction Industries Board of New York.)

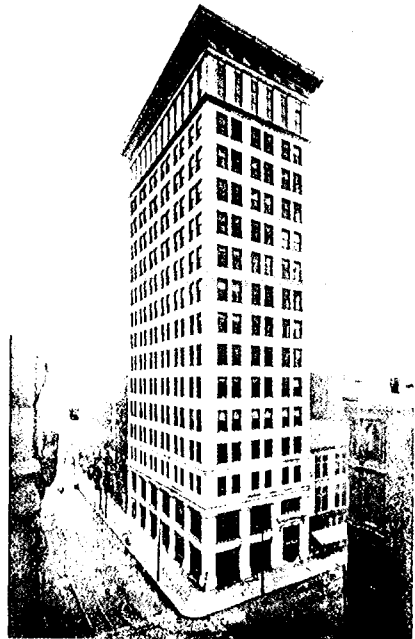


Fig. 4—The Ingalls Building in Cincinnati, Ohio, built in 1902-03, was the first concrete “skyscraper” in the United States. The building has been designated an ASCE Landmark Structure. (Photo from *Technology and Culture*, 1968.)



Fig. 5—The Alvord Bridge, designed and built by Ernest L. Ransome in San Francisco, Calif. in 1889, was the first reinforced concrete bridge in the United States. It has been designated an ASCE Landmark Structure. (Photo by Howard Newlon, Jr.)



Fig. 6—The Crystal Springs Dam, San Mateo, Calif., constructed between 1877 and 1888, was the first concrete arch dam in the United States. (1929 photo courtesy of the U. S. Army Corps of Engineers.)



Thaddeus Hyatt

(1816-1901)

Thaddeus Hyatt was born in New Jersey in 1816. The son of a schoolmaster, he was educated as a lawyer but did not practice, spending most of his life in New York City and London. Early in his career (about 1840-50) he invented and manufactured what he called an “illuminated sidewalk grating” made of iron, concrete, and glass. It appears to have been the first acceptable nonskid surface to be used in lieu of flagstone in city sidewalks so that light and fresh air could enter the basements of buildings. Hyatt claimed that at least \$100 million worth of American real estate was “redeemed from dankness and waste.” These illuminated gratings and other enterprises brought to Hyatt sufficient wealth so that he was able to pursue several varied and interesting activities, including the work reflected in his 1877 treatise.

Hyatt is not so well known as later pioneers, but in the words of E. L. Ransome, “In 1878, T. Hyatt ended the ‘period of discovery’ and put the theory of reinforced concrete construction on a rational basis . . .”

He also experimented with heavier-than-air flight, publishing his work in 1882 in “The Dragon-fly; or Reactive Passive Locomotion: A Vacuum Theory of Aerial Navigation, Based on the Principle of the Fan Blower.”

As engaging as are Hyatt’s technical contributions, his interests were much broader. In his later years he wrote and published a nine-volume work of poems entitled “Love’s Seasons, or, Tides of the Heart.” His anti-slavery convictions and organizational ability caused him to assume the presidency of the National Kansas Committee in 1856, at which time he became acquainted with Captain John Brown, the abolitionist fanatic. His contacts with Brown induced an extraordinary subcommittee of the United States Senate, charged with an investigation of the Harper’s Ferry affair, to summon Hyatt to testify in January 1860, a summons which Hyatt refused to honor. At great length Hyatt challenged the constitutionality of the Senate’s action in ordering a citizen from his home to testify, but he further stated that he would gladly testify if requested rather than ordered to do so. Neither party would concede the point and Hyatt was imprisoned for several months until the subcommittee, having discharged its obligation, was dissolved.

Hyatt’s work in Kansas gave name to the town of Hyattsville. In addition, this man of strong will leaves to us a heritage of social consciousness, inventive thinking, and great theoretical insight as an early American contributor to the science of reinforced concrete.

Hyatt died in 1901.

An Account of Some Experiments with
PORTLAND-CEMENT-CONCRETE

COMBINED WITH IRON, AS A BUILDING MATERIAL,

WITH

REFERENCE TO ECONOMY OF METAL IN CONSTRUCTION, AND FOR
SECURITY AGAINST FIRE IN THE MAKING OF ROOFS,
FLOORS, AND WALKING SURFACES.

BY

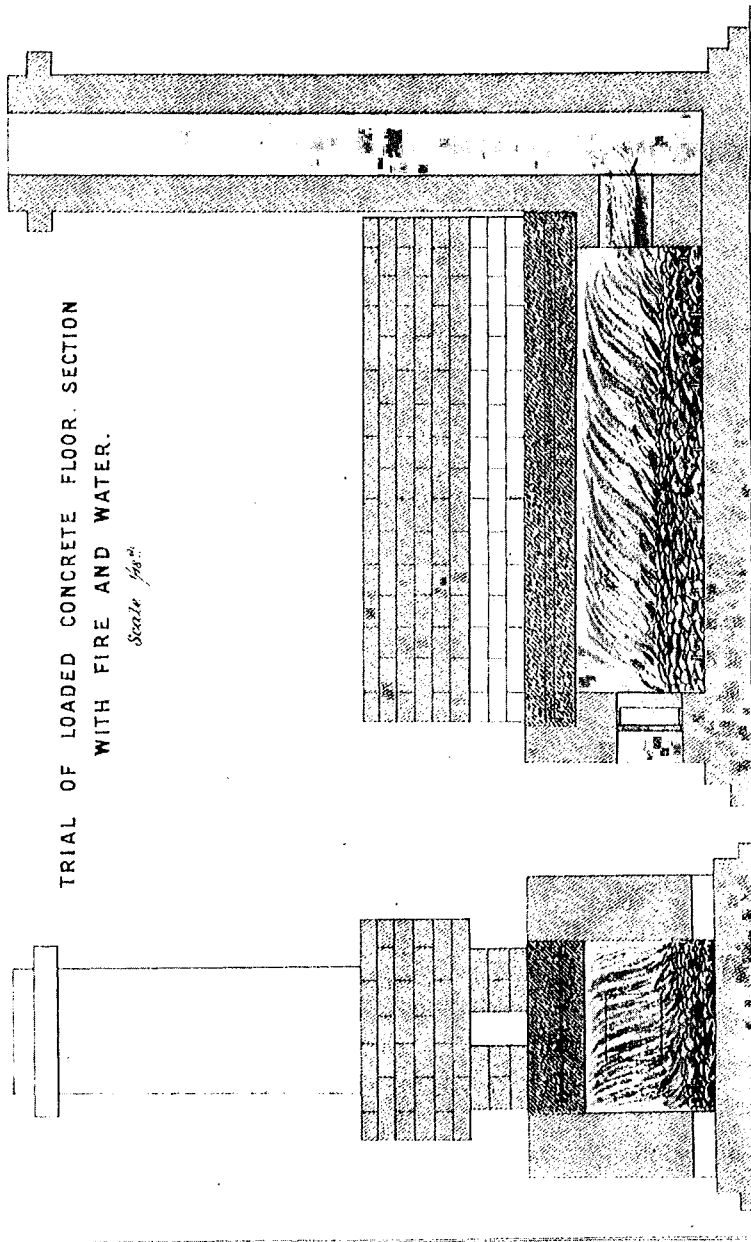
THADDEUS HYATT.



LONDON:
PRINTED FOR PRIVATE CIRCULATION,
AT THE CHISWICK PRESS.
1877.

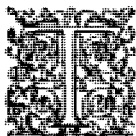
TRIAL OF LOADED CONCRETE FLOOR. SECTION
WITH FIRE AND WATER.

Scale $\frac{1}{8}" = 1'$





PORTLAND-CEMENT-CONCRETE.



THE experiments made by the writer, and which will be explained in the following pages, had for their object a possible means of obtaining cheaper and more reliable fireproof constructions than those in common use.

Fairbairn, in his work "On the Application of Cast and Wrought Iron to Building Purposes," tells us that "the first instance on record of the successful application of cast-iron beams to the purposes of building is that of a fireproof cotton mill

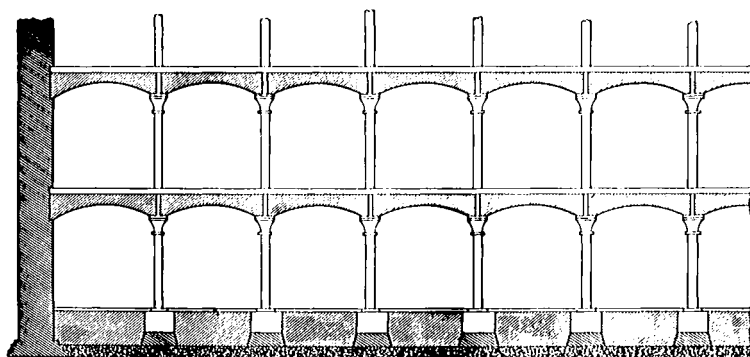


FIG. 1.

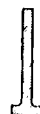


FIG. 2.

"erected by Messrs. Phillips and Lee of Manchester. This mill was built in the year 1801: "the iron beams and columns were designed by Messrs. Boulton and Watt. . . . The "above woodcut (fig. 1) exhibits a longitudinal section of portions of the basement and first "storeys of the mill, with sections of the iron beams and arches." Fig. 2 represents the form of beam used by Boulton and Watt. "This beam," says Fairbairn, "was the first of the kind made; "and considering the limited state of our knowledge at that period, it reflects great credit on the

"skill of the designer." Fig. 3 (from the same work) illustrates the method of construction employed at the date of the author's publication, 1854; and contrasting the two as represented by the figures, it will be seen that the only difference between the structure of 1801 and that of 1854 consists in the improved form of the beam. Any one who reads Mr. Fairbairn's work will perceive that down to the date of the last edition of his book (the fourth, 1870) the author continues to regard iron as practically and substantially a *fireproof* material; and it may be asserted without exaggeration that all the so-called fireproof floors that have ever been made, with scarcely an exception,¹ have been constructed in accordance with this belief. A filling between the iron beams of some material other than iron was made simply because the metal

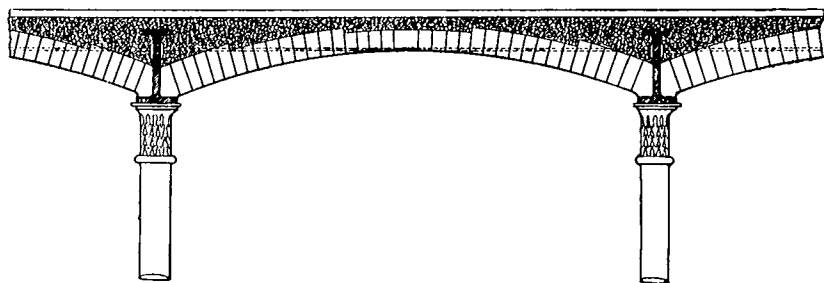


FIG. 3.

itself was too dear to make the entire floor of it; otherwise the floor would have been constructed wholly of iron. Now, it is important at the outset to have a clear line of distinction drawn between two systems so entirely opposite as those, in one of which iron is regarded as a fireproof material, and in the other of which iron is regarded as incombustible only, and not fireproof.

The purpose of the writer in the foregoing illustrations from Mr. Fairbairn's work, and others that are to follow, is to show that the original mistake as to the ability of naked iron to resist heat and flame, has vitiated every floor construction of the kind made from that day to this; and that, notwithstanding the knowledge of late years, gained at a frightful cost, the early mistake is still kept up, and hence, that genuine fireproof floors do not, as a rule, exist. This fact is so well known among men whose business it is to risk their lives in burning buildings that it has become a standing rule among them to beware of "fireproof buildings."² An inspection of

¹ The Safe Deposit Building, London, is probably one of the exceptions.

² It is well known that firemen dread the so-called "fireproof" structures more than those built of wood, and would sooner trust their lives in the latter than in the former. The time required to burn a stick of timber can be pretty well calculated. Not so with unprotected iron beams, carrying a load of brick arches or concrete. Some

figs. 1 and 3 will show the weak point of the construction with respect to fire. Leaving out of account the unprotected iron columns on which the girders rest, it will be seen that the bottom flanges of all the beams are naked and exposed to flame. Now, when it is considered that this flange is *the tie*, and that the integrity of the whole beam is consequently dependent upon it, no argument is needed to show that the fireproof filling between the beams is of not the slightest account so long as the ties are exposed: soften the tie by heat, and the resistance of the beam begins to give way; at each successive increment of deflection the leverage of the load upon it increases, the destructive influence of combined load and flame acting with wedge-like power until the destruction of the beam is effected. Such unquestionably is the philosophy of fireproof floor destruction, and the only way to account for its suddenness and completeness. Fireproof floors can be made, and within reasonable limits as to thickness (span considered) and cost, that can be guaranteed as good for 3, 6, 9, 12, 24, or even 48 hours under the play of the fiercest flames and the heat of the hottest fires,—in short, equal to the best fireproof safes ever yet invented; but not if the bottom flanges of the beams are left exposed, or too lightly covered. The bottom flange or tie is the vital part of the construction, and must be protected at all hazards. To make fireproof floors it is necessary to know the law of heat conduction with respect to the material relied upon to protect the bottom flanges of the beams, in order to calculate the thickness of material needed to give protection during the hours determined on as the fireproof capacity of the floor. As has been already remarked, the system or method according to which iron beams were originally employed in building constructions, proceeded upon the assumption that iron is a fireproof material; which assumption has been kept up ever since so far as the practice of making such structures is concerned, however much the theories respecting iron may have changed in the public mind. The system adopted by the writer proceeds upon the assumption that iron is not fireproof, and that in a floor where this material is the sole or main reliance for strength the first thing to be done is to protect it with a fireproof coating on all sides sufficient to give it a power of resisting fire during the number of hours required; this application of fireproof material being based upon actual

public experiments have recently been made in elucidation of this fact, and to call attention to the value of *solid* timber floors, or floors constructed on what the writer has termed “the all-beam” principle. As this method of construction is being now largely advertised as the patented property of other parties, it becomes necessary for the writer to claim his invention by calling the attention of the public to his patent, No. 3381, 1873, for the construction of solid wood floors as a safeguard against fire. He would also state that a floor of this kind was laid by him at his Patent Light Works, 25, Waverly Place, New York, U.S. America, in the early part of the year 1873, and also a footway of the same construction, which formed a flat, non-condensing roof, warm and dry, to a portion of the basement, that by this means was extended twenty feet out under the street to the curb line.