Cementing

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DEDICATION

This book would not have been possible without the efforts of many people. In acknowledgment of these efforts, I should like to make the following dedication:

To the three women in my life — Lois, Becky, and Beverly.

To each individual who has ever pumped or followed a plug with a measuring line on a cementing job.

To the many people in the Halliburton organization without whose help this book would never have been written.

SPE Monograph Series

The Monograph Series of the Society of Petroleum Engineers of AIME was established in 1965 by action of the SPE Board of Directors. The Series is intended to provide members with an authoritative, up-to-date treatment of the fundamental principles and state of the art in selected fields of technology. The work is directed by the Society's Monograph Committee, one of 40 national committees, through a Committee member designated as Monograph Coordinator. Technical evaluation is provided by the Monograph Review Subcommittee. Below is a listing of those who have been most closely involved with the preparation of this book.

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Preface

The Cementing Monograph is the fourth in a series of books on petroleum technology published by the Society of Petroleum Engineers of AIME. It is a composite review of the technical literature on cementing. Basic principles, materials, and techniques of cementing are reviewed and illustrated, and the applicability and limitations of the various procedures are discussed.

The Monograph series is designed to provide the Society with a state-of-the-art treatment of the fundamental principles in a select field of technology. This particular Monograph brings together the published results of many investigations and the thinking of many persons involved in research and field operations dealing with oilwell cementing. The material is presented in a form that will provide a basic background on the subject to engineers who are not directly involved in drilling and cementing. For those engineers who are directly engaged in the cementing process, it contains an up-to-date review of the literature and an extensive bibliography.

In writing a book of this type, an author is inevitably indebted to more people than he is aware of. The published works that he has read and the discussions that have molded his ideas and opinions often are not fully acknowledged. Any such oversights that I may have committed are regretted and unintentional.

I should like to accord special recognition to the technical effort of all the members of the API Standardization Group since its organization. In particular, I should like to recognize the Chairmen, who have directed much of the technical effort that has led to cement standardization: Carl Dawson, Standard Oil Co. of California; Walter Rogers, Gulf Oil Co. — U.S.; George Howard, Amoco Production Co.; Francis Anderson, Halliburton Services; Bill Bearden, Amoco Production Co.; Bob Scott, Standard Oil Co. of California; and Frank Shell, Phillips Petroleum Co.

Members of the Society's Monograph Committee have also played a very significant role in selecting the content of this Monograph. Their thorough review and constructive suggestions were a valuable help in achieving the balance in coverage of the subject.

I am also grateful to David Riley and Dan Adamson of the Dallas staff of the Society of Petroleum Engineers for their confidence and for their "loyalty to the cause" during the many months of preparation of this publication. Gratitude is extended to Sally Wiley for her editing of this manuscript and for straightening out the circumlocutions of a would-be writer.

My special thanks to the management of Halliburton Services for their cooperation in making this work on cementing possible.

Duncan, Oklahoma
May, 1976

DWIGHT K. SMITH

Contents

Chapter 1

Introduction

1.1 Scope of the Monograph

The oilwell cementing process is used throughout the world, and it has grown in complexity, with many people, organizations, and technologies contributing to the state of the art. To help the practicing engineer with planning and job evaluation, this monograph has been written as a comprehensive reference with information about the variety of materials and techniques used in well cementing.

Chapters are devoted to cements, additives, testing, job planning, and job execution of primary cementing, liner cementing, squeeze cementing, and plugging operations. The importance of planning in achieving zonal isolation is highlighted. Coverage is also given to mechanical and pumping equipment, mixers, bulk handling systems, and various subsurface tools used to place cement properly. The book is assembled in the logical sequence of field cementing operations to provide the petroleum engineer with a working knowledge of better cementing practices.

1.2 Objectives of the Monograph

This monograph has two purposes:

1. To provide the petroleum engineer responsible for the cementing process with information that will help him to judge the merits of various cementing techniques and to know what results can be expected.
2. To provide a comprehensive review of the state of the art.

1.3 The Cementing Procedure

Oilwell cementing is the process of mixing a slurry of cement and water and pumping it down through steel casing to critical points in the annulus around the casing or in the open hole below the casing string (Fig. 1.1).

The two principal functions of the primary cementing process are to restrict fluid movement between formations and to bond and support the casing.

In addition to isolating oil-, gas-, and water-producing zones, cement also aids in (1) protecting the casing from corrosion, (2) preventing blowouts by quickly forming a seal, (3) protecting the casing from shock loads in drilling deeper, and (4) sealing off zones of lost-circulation, or thief zones.

1.4 Historical Background

Early Jobs

The U. S. petroleum industry traditionally dates its beginning with the drilling of the Drake well in 1859; yet it was not until 1903 that a cement slurry was used to shut off down-hole water just above an oil sand in the Lompoc field in California. Frank F. Hill, with the Union Oil Co., is credited with mixing and dumping, by means of a bailer, a slurry consisting of 50 sacks of neat portland cement.[1,2] After 28 days the cement was drilled from the hole, and the well was completed by drilling through the oil sand; the water zone had been effectively isolated. This became an accepted practice and soon spread to other California fields wherever similar difficulties were encountered.

The early dump bailer and tubing techniques[3] were soon replaced with a two-plug cementing method introduced into the California fields by A. A. Perkins in 1910. It was with Perkins' method that the modern oilwell cementing process was born. The first plugs, or spacers, were of cast iron and contained belting discs that functioned as wipers for mud on the casing. When cement was displaced from the pipe by steam, the plug stopped, causing a pressure increase that shut off the steam pump.

The patent issued to Perkins specified the use of two plugs. The courts later ruled that the patent includes any barrier that prevents the cement from mixing with contaminants, whether the barrier is used ahead of or behind the cement.[4]

The services of the Perkins Co. were not available outside the California area, so elsewhere the cementing process had different beginnings. In Oklahoma, it was

TABLE 1.1 — DEVELOPMENT OF PUMPS FOR OILWELL SERVICING

Type of Pump	Service Era	Pressure (psi)	Volume (bbl/min)	hp	lbm/hp
Steam duplex	1921-1940	2,250	6	60	32
Steam duplex	1936-1947	3,500	9	100	24
Power-driven duplex	1939-1955	4,000	7	135	23
Vertical double-acting duplex	1939-1954	6,000	8	200	24
Opposed-piston pendulum	Experimental pump	10,000	6	200	40
Plunger triplex	1947-	10,000	10	330	14.5
Plunger triplex	1957-	20,000	24	600	9
Plunger triplex	1965-	12,000	13	400	9.2
Plunger triplex	1975-	10,000	6	250	10

introduced by Erle P. Halliburton in 1920 in the Hewitt field, Carter County.

The practice in Oklahoma was to set casing on top of the sand. In rotary drilled holes the casing was frequently set high to avoid drilling into the producing formation.[5] A blowout on Skelly's No. 1 Dillard occurred while casing was being run into a hole drilled into the oil sand. Efforts to control it failed until Halliburton, using crude mixing and cementing equipment, pumped some 250 sacks of portland cement and water into the casing. After a wait of 10 days, the cement was drilled out, and the well was produced without excessive water or gas production. During the following months 61 wells were cemented by this technique.[6] (See Fig. 1.2.)

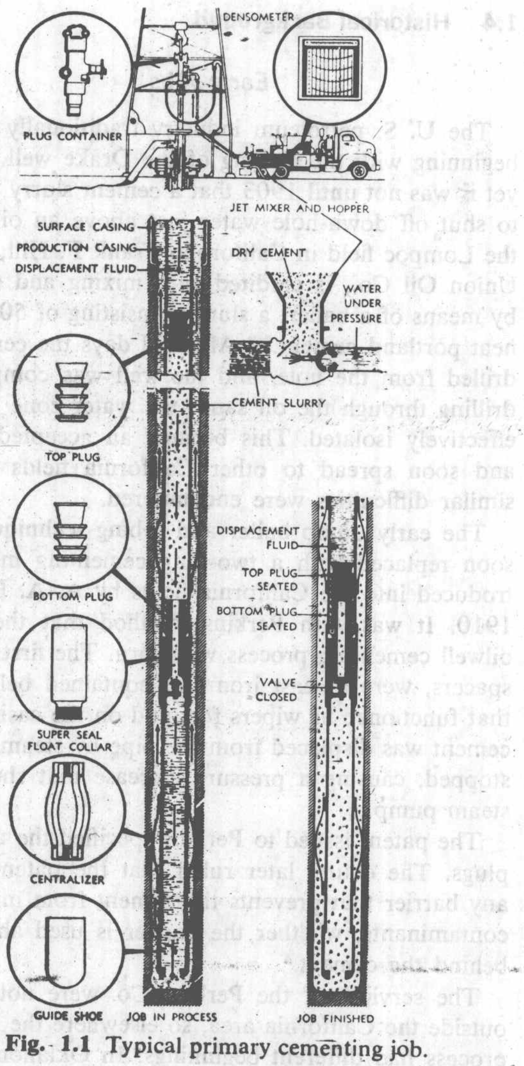

Fig. 1.1 Typical primary cementing job.

Bulk Handling and Additives

Before 1940, wells were cemented with sack cement (Fig. 1.3). Very few additives were used. There were no additives at all in 1930, and only one cement. In 1940, there were two types of cement, and three additives had been developed. Twenty-five years more saw 8 API Classes of cement and 38 additives put on the market. By 1975, although the number of API Classes of cement in common use had decreased to 4, the number of additives had increased to 44.

With the introduction of bulk cement in 1940, the

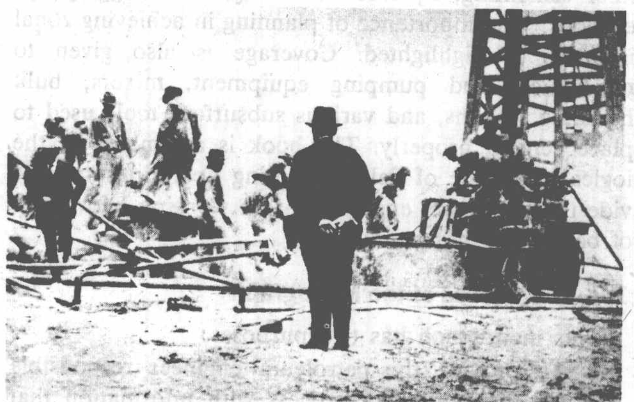
Fig. 1.2 Cementing in the early 1920's — Hewitt field, Oklahoma.

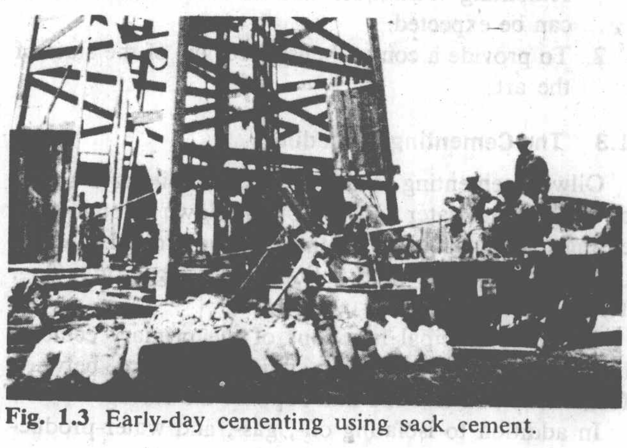
Fig. 1.3 Early-day cementing using sack cement.

handling of additives became more practical, waste was eliminated, and manpower savings were realized. The first bulk cement station for eliminating sack cement was constructed near Salem, Ill., in 1940. Other early-day stations were constructed in California and Texas. These stations transferred bulk cement from railroad cars to overhead tanks, which dumped cement directly into bulk-transport trucks. Bulk cement handling became well established during the 1940's, but the modern era of bulk handling did not begin until pozzolans were introduced in 1949.

Standardization

In 1937 the American Petroleum Institute (API) established the first committee to study cements. There already existed several cement testing laboratories equipped with strength-measuring apparatus and stirring devices to determine the fluidity or pumpability of cement slurries at down-hole temperatures.[7-10] One of the more innovative devices for evaluating cements was the pressure temperature thickening-time tester developed in 1939 by Farris with the Stanolind Oil & Gas Co.[11]

With the establishment of cement-testing laboratories, many new developments occurred in oilwell cements between 1937 and 1950.[12] During that period, a need arose for standardization of cement testing. To fulfill that need, the Mid-Continent API Committee on Oil Well Cements in 1948 prepared the first draft of *API Code 32*.[13] That code was first published in 1952 and has since been periodically modified by a national API committee on cement standardization, formed in 1953.

Standardization studies are published annually in two booklets. API Specifications are published in *Volume 10A*, and "API Recommended Practice for Testing Oil-Well Cements and Cement Additives" is published in *Volume 10B*. These volumes are now in the 19th and 20th editions, respectively.

Cementing Equipment

Through the years there has been a continuous change in pumping equipment to make it more portable and provide greater horsepower for handling higher

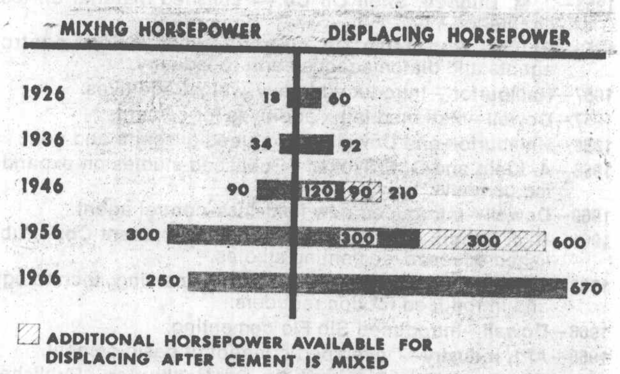

Fig. 1.4 Horsepower of cementing trucks.

pressures. (See Table 1.1 and Fig. 1.4.) To improve primary cementing jobs, a variety of mechanical devices have been used to more effectively place a uniform sheath of cement around the pipe.[14-17] These devices include cementing plugs, measuring lines, centralizers, scratchers, floating equipment, and stage collars.

Field Practices — Primary Cementing

As wells have become deeper and technology has advanced, cementing practices have changed.[18-21] In the 1910 to 1920 period, wells were considered deep at 2,000 to 3,000 ft. In the later 1920's there were several fields developed below 6,000 ft. Higher temperatures and pressures caused cementing problems. Cements used at 2,000 ft were not practical at greater depths because they tended to set prematurely.

Field placement was a matter of trial and error since laboratory testing equipment was still undeveloped. To retard the cement for use at higher temperatures, tons of ice were sometimes put in the drilling mud to cool the hole. This approach was not completely successful. A more reliable one was to mix and pump the cement as quickly as possible.

The time spent waiting for cement to set was considered unproductive. When cementing failures occurred, short waiting-on-cement (WOC) time or bad cement was given as the cause. Cement accelerators were sold under a variety of trade names, but most of them were calcium chloride solutions. WOC times were reduced as cement composition, testing procedures, and chemical acceleration became better understood. At first, 72 hours was generally considered sufficient for cement to set around the shoe joint, and oil industry regulatory bodies adopted this period almost universally. Then in 1946, Farris published his findings on the influence of time and pressure on the bonding properties of cement.[22] As field experience confirmed the validity of those findings, the regulatory bodies reduced WOC times to 24 to 36 hours.

The success of early cementing jobs was evaluated on the basis of a water shutoff test.[23,24] If no water was found on the test, the cement job was ruled successful. But failures were frequent. Studies of those early jobs revealed that cement should reach a certain strength or hardness if a successful job is to be achieved. Cementing studies of Gulf Coast wells were published by Humble in 1928.[6] Cores taken from a large number of deep wells indicated a high frequency of cement failures as a result of mud contamination. To improve the quality of cement, attention was given to conditioning the mud, to circulating the hole before cementing, and to placing a water spacer between the mud and the cement.

Squeezing and Plugging

Procedures and equipment for shutting off water in wells varied considerably in the early days of cementing. From the beginning, pressure was applied to the cement slurry after it was placed in a well. It was reported that as early as 1905 Frank Hill ran tubing and a packer to the bottom of the casing and pumped cement outside the pipe to obtain a better shutoff. Although the method successfully shut off water, the tubing and packer occasionally became stuck when the water was squeezed from the slurry.

On some cementing jobs, cement was dumped on bottom, then the hole was filled with water to apply squeeze pressure. Also, pump pressure was used in fluid-filled holes to obtain an effective water shutoff.

Where large volumes of cement were used, the column of cement and fluid behind the pipe was heavier than the hydrostatic pressure inside the pipe. Therefore, pressure was necessary to hold the cement in place. Long strings of casing were run with backpressure valves, but frequently a backpressure valve would not hold. Pump pressure was applied until the cement had time to set. This was commonly called "squeezing."

The practice of pumping several hundred sacks of cement into a well under high pressure prompted much discussion. It was reasoned that cement slurry (1) displaced mud trapped behind the pipe that had not been removed by the original cement job, or (2) compressed the exposed formation, or (3) fractured the formation along bedding planes.

Drillable cement retainers[25,26] were used as early as 1912, but it was not until 1939 that a retrievable cement

TABLE 1.2 — SUMMARY — SIGNIFICANT DATES IN THE HISTORY OF OILWELL CEMENTING

1903—F. F. Hill—Mixed and dumped 50 sacks of neat cement to shut off bottom-hole water.

1910—A. A. Perkins, Perkins Cementing Co.—Cemented the first well using the two-plug method in California.

1912—R. C. Baker, Baker Oil Tools—Invented the first cement retainer to pack off between casing and tubing.

1914—F. W. Oatman—Reported on the use of calcium chloride to accelerate cement and reduce waiting-on-cement time.

1915—Bureau of Mines, California—Created a staff to inspect and witness water shutoff tests.

1918—A. A. Perkins—Established an office to service wells in the Los Angeles basin.

1919—E. P. Halliburton—Established the cementing business in North Texas.

1920—E. P. Halliburton—Cemented the first blowout—for W. G. Skelly near Wilson, Okla.

1920—Quintana Petroleum Co.—Rotated casing in 50 wells.

1920—E. P. Halliburton—Developed the jet mixer.

1921—J. T. Bachman, Santa Cruz Cement Co.—Developed early testing techniques for oilwell cements.

1922—Halliburton—Was issued a patent in the two-plug cementing method.

1924—Halliburton—Licensed Perkins to use the jet mixer.

1924—Oklahoma Corporation Commission—Proposed the rule requiring that WOC time be reduced from 10 days to 7 if accelerator was used.

1925—Cement was first packed in a multiwalled paper bag.

1926—D. Birch, Barnsdall Oil Co.—Built a body and valve for special casing and float collar.

1927—Lone Star Cement Co.—Manufactured the first Incor high-fineness cement, in Indiana.

1927-28—Humble Oil and Refining Co.—Made a comprehensive survey of cementing failures along the Gulf Coast.

1929—Pacific Portland Cement Co.—Introduced the first retarded cement

1929—Halliburton—Set up the first laboratory for evaluating properties of cements.

1930—Halliburton, Humble Oil and Refining Co., Standard Oil Co. of California—Instituted research in oilwell cementing.

1930—H. R. Irvine—Patented a device to hold centralizers on pipe.

1930—Bentonite was introduced to the oil industry for use in drilling muds and cement.

1932, 1934—William Lane and Walter Wells—Introduced gun perforating in California and on the Gulf Coast.

1934—Schlumberger—Patented a method for locating the top of cement with a temperature survey instrument.

1934—B. C. Craft *et al.*—Reported on extensive testing of oilwell cements.[8]

1935—E. F. Silcox, Standard Oil Co. of California—Presented a paper on a testing device for measuring thickening time of cement.[7]

1935—M. M. Kinley—Invented the caliper survey instrument.

1935—T. W. Pew—Patented a method of high-pressure squeeze cementing.

1935—Universal Atlas Cement Co.—Introduced Unaflo retarded cement to industry.

1936—Lone Star Cement Co.—Introduced Starcor retarded cement.

1937—J. E. Weiler, Halliburton—Built dual container device for testing oilwell cements.

1937—API—Established committee to study oilwell cements.

1939—R. F. Farris, Stanolind Oil & Gas Co.—Constructed the first pressure temperature thickening-time tester.

1939—Halliburton—Developed the retrievable squeeze retainer.

1939—Humble Oil and Refining Co.—Mixed small amounts of carnotite with cement to determine tops behind the casing with gamma ray log.

1939—Kenneth Wright and Bruce Barkis—Used the first commercial cement scratchers in California.

1940—U. S. Gypsum Co.—Introduced the first gypsum cement.

1940—Halliburton—Purchased Perkins Cementing Co. in California.

1940—M. M. Kinley—Ran first caliper surveys on electric cable to determine the quantities of cement required to fill hole.

1940—Halliburton—Introduced bulk cement.

1946—R. F. Farris, Stanolind Oil & Gas Co.—Published study on WOC time.[22]

1946—Texas Railroad Commission—Changed rules reducing WOC time from 72 hours to 24 to 36 hours.

1946—A. J. Teplitz and W. E. Hassebroek—Published study of cementing centralizers.[20]

1948—G. C. Howard and J. B. Clark, Stanolind Oil & Gas Co.—Published results of displacement studies.[27]

1948—Halliburton—Published company paper on salt cement.

1951—Humble Oil and Refining Co.—Used the first modified cement for permanent well completion.

1952—API—Approved the first edition of *API Code 32* for testing cement used in wells.[13]

1953—J. M. Bugbee, Shell Oil Co.—Published material on lost circulation.[28]

1953—Phillips Petroleum Co.—Introduced fluid-loss-control agents and diatomaceous earth to industry.

1957—Halliburton—Introduced heavy-weight additives.

1957—Dowell—Marketed latex additives for cement.

1958—Halliburton and Dowell—Introduced gilsonite and coal.

1958—A. Klein and G. E. Troxell—Published studies on expanding cements.[30]

1960—Dowell—Introduced new fluid-loss-control agent.

1961—H. J. Beach, Gulf Research and Development Co.—Published squeeze-cementing studies.[29]

1962—Service companies—Developed dispersing technology and introduced friction reducers.

1968—Dowell—Introduced Slo Flo cementing.

1968—API, Industry—Developed concept of basic cement.

1972—Esso Production Research Co. and Halliburton—Published displacement studies.[31]

retainer was introduced to the industry. The Yowell tool, originally used for washing screens and perforations, was redesigned for use as a retrievable cement retainer. Such retainers, which saved both money and time, became widely used where it was not necessary to hold the cement under pressure until it set.

When a perforated formation produced an unexpected volume of water or excess gas, it was squeezed, drilled out, and reperforated. The frequency of squeezing and reperforating was high, particularly along the Gulf Coast, because most operators would "protection squeeze" or "block squeeze" a sand before perforating for completion.[24]

1.5 Summary

Table 1.2 summarizes important events in the history of oilwell cementing.

References

1. "California's Oil," API (1948) 12.
2. "On Tour," Union Oil Co. of California (Nov.-Dec. 1952).
3. Tough, F. B.: "Method of Shutting off Water in Oil and Gas Wells," *Bull. 136,* USBM; *Petroleum Technology* (1918) **46,** 122.
4. Perkins, A. A., and Double, E.: "Method of Cementing Oil Wells," U. S. Patent No. 1,011,484 (Dec. 12, 1911), filed Oct. 27, 1909.
5. Swigert, T. E., and Schwarzenbek, F. X.: "Petroleum Engineering in the Hewitt Oil Field, Oklahoma," USBM, State of Oklahoma, and Ardmore Chamber of Commerce (Jan. 1921).
6. Millikan, C. V.: "Cementing," *History of Petroleum Engineering,* API Div. of Production, Dallas (1961) Chap. 7.
7. Silcox, D. E., and Rule, R. B.: "Special Factors Must Be Considered in Selection, Specification, and Testing of Cement for Oil Wells," *Oil Weekly* (July 29, 1935) **78,** No. 7, 21; "Cement for Oil Wells," *Petroleum Times* (Aug. 24, 1935) **34,** 195-197.
8. Craft, B. C., Johnson, T. J., and Kirkpatrick, H. L.: "Effects of Temperature, Pressure, and Water-Cement Ratio on the Setting Time and Strength of Cement," *Trans.,* AIME (1935) **114,** 62-68.
9. Weiler, J. E.: "Apparatus for Testing Cement," U. S. Patent No. 2,122,765 (July 5, 1938), filed May 15, 1937.
10. Davis, E. L.: "Specifications for Oil-Well Cement," *Drill. and Prod. Prac.,* API (1938) 372.
11. Farris, R. F.: "Effects of Temperature and Pressure on Rheological Properties of Cement Slurries," *Trans.,* AIME (1941) **142,** 117-130 (reprint, Page 306).
12. Robinson, W. W.: "Cement for Oil Wells: Status of Testing Methods and Summary of Properties," *Drill. and Prod. Prac.,* API (1939) 567-591.
13. "Code for Testing Cement Used in Wells," *API Code 32,* 1st ed., API, Dallas (1948).
14. Halliburton, E. P.: "Method and Means for Cementing Oil Wells," U. S. Patent No. 1,369,891 (March 1, 1921), filed June 26, 1920.
15. Halliburton, E. P.: "Method of Hydrating Cement and the Like," U. S. Patent No. 1,486,883 (March 18, 1924), filed June 20, 1922.
16. Burch, D. D.: "Casing Shoe," U. S. Patent No. 1,603,447 (Oct. 19, 1926), filed Feb. 25, 1926.
17. Baker, R. C.: "Plug for Well Casings," U. S. Patent No. 1,392,619 (Nov. 18, 1913), filed Nov. 20, 1911.
18. Mills, B.: "Rotating While Cementing Proves Economical," *Oil Weekly* (Dec. 4, 1939) **95,** No. 13, 14-15.
19. Reistle, C. E., Jr., and Cannon, G. E.: "Cementing Oil Wells," U. S. Patent No. 2,421,434 (June 3, 1947), filed Nov. 27, 1944. See also K. E. Wright: "Rotary Well Bore Cleaner," U. S. Patent No. 2,402,223 (June 18, 1946), filed June 26, 1944.
20. Teplitz, A. J., and Hassebroek, W. E.: "An Investigation of Oil Well Cementing," *Drill. and Prod. Prac.,* API (1946) 76-101; *Pet. Eng. Annual* (1946) 444.
21. Jones, P. H., and Berdine, D.: "Oil-Well Cementing — Factors Influencing Bond Between Cement and Formation," *Drill. and Prod. Prac.,* API (1940) 45-63.
22. Farris, R. F.: "Method of Determining Minimum Waiting-on-Cement Time," *Trans.,* AIME (1946) **165,** 175-188.
23. Oatman, F. W.: "Water Intrusion and Methods of Prevention in California Oil Fields," *Trans.,* AIME (1915) **48,** 627-650.
24. Doherty, W. T., and Manning, M.: "Gulf Coast Cementing Problems," *Oil and Gas J.* (April 4, 1929) 48, *Oil Weekly* (April 12, 1929) **53,** No. 4, 47-48.
25. Baker, R. C.: "Cement Retainer," U. S. Patent No. 1,035,674 (Aug. 13, 1912), filed Jan. 29, 1912.
26. Huber, F. W.: "Method and Composition for Cementing Oil Wells," U. S. Patent No. 1,452,463 April 17, 1923), filed May 24, 1922.
27. Howard, G. C., and Clark, J. B.: "Factors To Be Considered in Obtaining Proper Cementing of Casing," *Drill. and Prod. Prac.,* API (1948) 257-272; *Oil and Gas J.* (Nov. 11, 1948) 243.
28. Bugbee, J. M.: "Lost Circulation — A Major Problem in Exploration and Development," *Drill. and Prod. Prac.,* API (1953) 14-27.
29. Beach, H. J., O'Brien, T. B., and Goins, W. C., Jr.: "Formation Cement Squeezed by Using Low-Water-Loss Cements," *Oil and Gas J.* (May 29 and June 12, 1961).
30. Klein, A., and Troxell, G. E.: "Studies of Calcium Sulfoaluminate Admixtures for Expansive Cements," *Proc.,* ASTM (1958) **58,** 986-1008.
31. Clark, C. R., and Carter, L. G.: "Mud Displacement With Cement Slurries," *J. Pet. Tech.* (July 1973) 775-783.

Chapter 2

The Manufacture, Chemistry, and Classification Of Oilwell Cements

2.1 Introduction

Materials for cementing or bonding rock, brick, and stone in construction date from some of the earliest civilizations. Remains of those early cements can still be found in Europe, Africa, the Middle East, and the Far East. Testimony to their durability is that in some instances cements are still in an excellent state of preservation in Egypt (gypsum cement), Greece (calcined limestone), and Italy (pozzolanic-lime cements). The earliest hydraulic cements — materials that will harden and set when mixed with water — may be found in early Roman docks and marine facilities in the Mediterranean area. Such materials were composed of silicate residues from volcanic eruptions blended with lime and water. These earliest pozzolanic cements may be found near Pozzuoli, Italy.[1]

Cementing technology advanced very little through the Middle Ages until the time of the crusades. History usually credits the discovery of portland cement to Joseph Aspdin, an English mason, who was issued a patent[2] covering a gray rock-like material called "cement" in 1824. This composition, termed hydraulic because it would hydrate and set or harden when reacted under water, was the first of the portland cements as we know them today. (See Table 2.1.)

It would be difficult to imagine drilling and completing wells without cement; yet many wells were completed in the Eastern U. S. long before the first reported cement job was performed in California.

2.2 Manufacture of Cement

The basic raw materials used to manufacture portland cements are limestone (calcium carbonate) and clay or shale. Iron and alumina are frequently added if they are not present in sufficient quantity in the clay or shale.[4] These materials are blended together, either wet or dry, and then fed into a rotary kiln, which fuses the limestone slurry at temperatures from 2600° to 3000°F into a material called cement clinker. Upon cooling, the clinker is pulverized and blended with a small amount of gypsum, which controls the setting time of the finished cement. (See Fig. 2.1.)

2.3 Chemistry of Cements

A typical oxide analysis of portland cements used in wells is given in Table 2.2.

When these clinkered products hydrate with water, they combine to form four major crystalline phases with the chemical formulas and standard designations shown in Tables 2.3 and 2.4.

2.4 Classifications of Cement

Portland cements are usually manufactured to meet certain chemical and physical standards that depend upon their application. In the U. S. there are several agencies that study and write specifications for the manufacture of portland cement.[5,6] These groups include ACI (American Concrete Institute), AASHO (American Association of State Highway Officials), ASTM (American Society for Testing Materials), API (American Petroleum Institute), and various departments of the Federal government. Of these groups, the best known to the oil industry are the ASTM, which deals with cements for construction and building use, and the API, which writes specifications for cements used only in wells. Cement specifications written by either society are prepared by representatives of both users and manufacturers working together for the com-

TABLE 2.1 — DEVELOPMENT OF EARLY CEMENTS

Egypt	Plaster of Paris ($CaSO_4$ + Heat)
Greece	Lime ($CaCO_3$ + Heat)
Roman Empire	Pozzolan-lime reactions
England	Natural cement (1756 John Smeaton)
	Portland cement (1824 Joseph Aspdin)
United States	Portland cement[3,4] (First manufactured 1872)

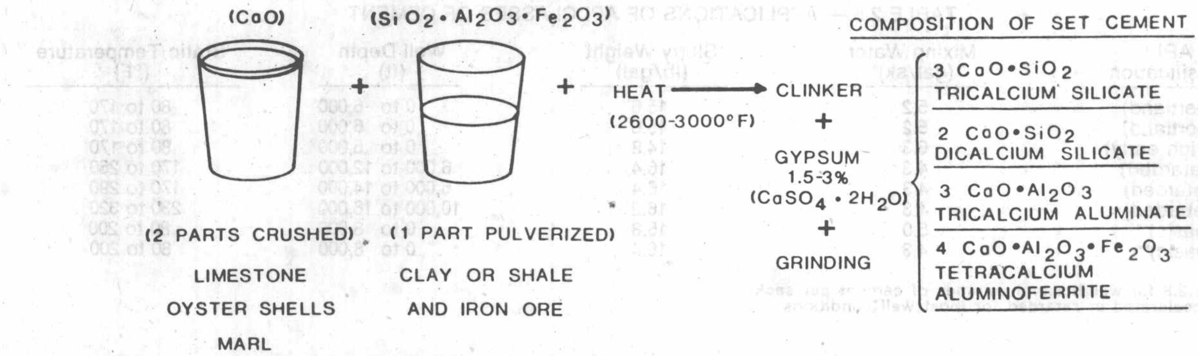

Fig. 2.1 Manufacture of portland cement.[3]

mon interest of their industry.

The ASTM specifications provide for five types of portland cement: Types I, II, II, IV, and V. Cements manufactured for use in wells are subject to wide ranges of temperature and pressure and differ considerably from the ASTM types that are manufactured for use at atmospheric conditions. For these reasons the API provides specifications covering eight classes of oilwell cements, designated Classes A, B, C, D, E, F, G, and H.

API Classes A, B, and C correspond to ASTM Types I, II, and III; ASTM Types IV and V have no corresponding API Classes.

API Classifications

The oil industry purchases cements manufactured predominantly in accordance with API classifications as published in *API Standards 10A*, "Specifications for Oil-Well Cements and Cement Additives."[6] These standards have been published annually by the American Petroleum Institute in Dallas, Tex., since 1953, when the first national standards on cements for use in wells were issued. These specifications are reviewed annually and revised according to the needs of the oil industry. The different classes of API cements for use at downhole temperatures and pressures are defined below. They are as listed in the *API Standards 10A* dated Jan. 1975.

Class A: Intended for use from surface to a depth of 6,000 ft when special properties are not required. Available only in Ordinary type (similar to ASTM C150, Type I).

Class B: Intended for use from surface to a depth of 6,000 ft when conditions require moderate to high sulfate resistance. Available in both Moderate (similar to ASTM C150, Type II) and High Sulfate Resistant types.

Class C: Intended for use from surface to a depth of 6,000 ft when conditions require high early strength. Available in Ordinary type and in Moderate and High Sulfate Resistant types.

Class D: Intended for use at depths from 6,000 to 10,000 ft and at moderately high temperatures and pressures. Available in both Moderate and High Sulfate Resistant types.

Class E: Intended for use at depths from 10,000 to 14,000 ft and at high temperatures and pressures. Available in both Moderate and High Sulfate Resistant types.

Class F: Intended for use at depths from 10,000 to 16,000 ft and at extremely high temperatures and pressures. Available in High Sulfate Resistant type.

TABLE 2.2 — TYPICAL OXIDE ANALYSIS OF PORTLAND CEMENTS (API Class G or H basic cement)

Oxide	Percent
Silicon dioxide (SiO_2)	22.43
Calcium oxide (CaO)	64.77
Iron oxide (Fe_2O_3)	4.10
Aluminum oxide (Al_2O_3)	4.76
Magnesium oxide (MgO)	1.14
Sulfur trioxide (SO_3)	1.67
Potassium oxide (K_2O)	0.08
Lost on ignition	0.54

TABLE 2.3 — CHEMICAL COMPOUNDS FOUND IN SET PORTLAND CEMENT[5]

Compound	Formula	Standard Designation
Tricalcium aluminate	$3CaO \cdot Al_2O_3$	C_3A
Tricalcium silicate	$3CaO \cdot SiO_2$	C_3S
B-dicalcium silicate	$2CaO \cdot SiO_2$	C_2S
Tetracalcium aluminoferrite	$4CaO \cdot Al_2O_3 \cdot Fe_2O_3$	C_4AF

TABLE 2.4 — TYPICAL COMPOSITION AND PROPERTIES OF API CLASSES OF PORTLAND CEMENT[6]

API Class	Compounds (percentage) C_3S	C_2S	C_3A	C_4AF	Wagner Fineness (sq cm/gm)
A	53	24	8+	8	1,600 to 1,800
B	47	32	5−	12	1,600 to 1,800
C	58	16	8	8	1,800 to 2,200
D & E	26	54	2	12	1,200 to 1,500
G & H	50	30	5	12	1,600 to 1,800

Property	How Achieved
High early strength	By increasing the C_3S content, grinding finer.
Better retardation	By controlling C_3S and C_3A content and grinding coarser.
Low heat of hydration	By limiting the C_3S and C_3A content.
Resistance to sulfate attack	By limiting the C_3A content.

TABLE 2.5 — APPLICATIONS OF API CLASSES OF CEMENT

API Classification	Mixing Water (gal/sk)*	Slurry Weight (lb/gal)	Well Depth (ft)	Static Temperature (°F)
A (portland)	5.2	15.6	0 to 6,000	80 to 170
B (portland)	5.2	15.6	0 to 6,000	80 to 170
C (high early)	6.3	14.8	0 to 6,000	80 to 170
D (retarded)	4.3	16.4	6,000 to 12,000	170 to 260
E (retarded)	4.3	16.4	6,000 to 14,000	170 to 290
F (retarded)	4.3	16.2	10,000 to 16,000	230 to 320
G (basic)**	5.0	15.8	0 to 8,000	80 to 200
H (basic)**	4.3	16.4	0 to 8,000	80 to 200

*See Table 2.8 for weights and volumes of cement per sack.
**Can be accelerated or retarded for most well conditions.

2.6 — CHEMICAL REQUIREMENTS FOR API CEMENTS[6]

1	2	3	4	5	6	7
	Cement Class					
	A	B	C	D,E,F	G	H
ORDINARY TYPE (O)						
Magnesium oxide (MgO), maximum, per cent	5.00	......	5.00	......	......	......
Sulfur trioxide (SO_3), maximum, per cent[1]	3.50	......	4.50	......	......	......
Loss on ignition, maximum, per cent	3.00	......	3.00	......	......	......
Insoluble residue, maximum, per cent	0.75	......	0.75	......	......	......
Tricalcium aluminate ($3CaO \cdot Al_2O_3$), maximum, per cent[2]	......	......	15.00	......	......	......
MODERATE SULFATE-RESISTANT TYPE (MSR)						
Magnesium oxide (MgO), maximum, per cent	......	5.00	5.00	5.00	5.00	5.00
Sulfur trioxide (SO_3), maximum, per cent	......	3.00	3.50	2.50	2.50	2.50
Loss on ignition, maximum, per cent	......	3.00	3.00	3.00	3.00	3.00
Insoluble residue, maximum, per cent	......	0.75	0.75	0.75	0.75	0.75
Tricalcium silicate ($3CaO \cdot SiO_2$), maximum, per cent[2]	......	......	......	......	58.00	58.00
Tricalcium silicate ($3CaO \cdot SiO_2$), minimum, per cent[2]	......	......	......	......	48.00	48.00
Tricalcium aluminate ($3CaO \cdot Al_2O_3$), maximum, per cent[2]	......	8.00	8.00	8.00	8.00	8.00
Total alkali content expressed as sodium oxide (Na_2O) equivalent, maximum, per cent[3]	......	......	......	......	0.75	0.75
HIGH SULFATE-RESISTANT TYPE (HSR)						
Magnesium oxide (MgO), maximum, per cent	......	5.00	5.00	5.00	5.00	......
Sulfur trioxide (SO_3), maximum per cent	......	3.00	3.50	2.50	2.50	......
Loss on ignition, maximum, per cent	......	3.00	3.00	3.00	3.00	......
Insoluble residue, maximum, per cent	......	0.75	0.75	0.75	0.75	......
Tricalcium silicate ($3CaO \cdot SiO_2$), maximum, per cent[2]	......	......	......	......	65.00	......
Tricalcium silicate ($3CaO \cdot SiO_2$), minimum, per cent[2]	......	......	......	......	48.00	......
Tricalcium aluminate ($3CaO \cdot Al_2O_3$), maximum, per cent[2]	......	3.00	3.00	3.00	3.00	......
Tetracalcium aluminoferrite ($4CaO \cdot Al_2O_3 \cdot Fe_2O_3$) plus twice the tricalcium aluminate ($3CaO \cdot Al_2O_3$), maximum, per cent[2]	......	24.00	24.00	24.00	24.00	......
Total alkali content expressed as sodium oxide (Na_2O) equivalent, maximum, per cent[3]	......	......	......	......	0.75	......

[1]When the tricalcium aluminate content (expressed as C_3A) of the Class A cement is 8% or less, the maximum SO_3 content shall be 2.50%.

[2]The expressing of chemical limitations by means of calculated assumed compounds does not necessarily mean that the oxides are actually or entirely present as such compounds. When the ratio of the percentages of Al_2O_3 to Fe_2O_3 is 0.64 or less, the C_3A content is zero. When the Al_2O_3 to Fe_2O_3 ratio is greater than 0.64, the compounds shall be calculated as follows:

$$C_3A = (2.65 \times \%\ Al_2O_3) - (1.69 \times \%\ Fe_2O_3)$$

$$C_4AF = 3.04 \times \%\ Fe_2O_3$$

$$C_3S = (4.07 \times \%\ CaO) - (7.60 \times \%\ SiO_2) - (6.72 \times \%\ Al_2O_3) - (1.43 \times \%\ Fe_2O_3) - (2.85 \times \%\ SO_3)$$

When the ratio of Al_2O_3 to Fe_2O_3 is less than 0.64, an iron-alumina-calcium solid solution [expressed as ss $(C_4AF + C_2F)$] is formed and the compounds shall be calculated as follows:

$$ss(C_4AF + C_2F) = (2.10 \times \%\ Al_2O_3) + (1.70 \times \%\ Fe_2O_3) \text{ and } C_3S = (4.07 \times \%\ CaO) - (7.60 \times \%\ SiO_2) - (4.48 \times \%\ Al_2O_3) - (2.86 \times \%\ Fe_2O_3) - (2.85 \times \%\ SO_3)$$

[3]The sodium oxide equivalent (expressed as Na_2O equivalent) shall be calculated by the formula:

$$Na_2O \text{ equivalent} \doteq (0.658 \times \%\ K_2O) + \%\ Na_2O$$

Class G: Intended for use as a basic cement from surface to a depth of 8,000 ft as manufactured. With accelerators and retarders it can be used at a wide range of depths and temperatures. It is specified that no addition except calcium sulfate or water, or both, shall be interground or blended with the clinker during the manufacture of Class G cement. It is available in Moderate and High Sulfate Resistant types.

Class H: Intended for use as a basic cement from surface to a depth of 8,000 ft as manufactured. This cement can be used with accelerators and retarders at a wide range of depths and temperatures. It is specified that no additions except calcium sulfate or water, or both, shall be interground or blended with the clinker during the manufacture of Class H cement. Available only in Moderate Sulfate Resistant type.

Table 2.5 lists the API classes of cement and indicates the depths to which they are applicable.

2.5 Properties of Cement Covered by API Specifications

In well completion operations, cements are almost universally used to displace the drilling mud and to fill the annular space between the casing and the open hole. To serve this purpose, cements must be designed for wellbore environments varying from those at the surface to those at depths exceeding 30,000 ft, where temperatures range from below freezing in permafrost areas to more than 700°F in wells drilled for geothermal steam production. Specifications do not cover all the properties of cements over such broad ranges of depth and pressure. They do, however, list physical and chemical properties for different classes of cements that will fit most well conditions. These specifications[6] include chemical analysis and physical analysis. The latter comprises (1) water content, (2) fineness, (3) compressive strength, and (4) thickening time.

Although these properties describe cements for specification purposes, oilwell cements should have other properties and characteristics to provide for their necessary functions down hole.[7,8]

The physical and chemical requirements of API Classes of cements as defined in *API Standards 10A* are shown in Tables 2.6 and 2.7. Typical physical properties of the various API classes of cement are shown in Table 2.8.

API Specifications are not enforced by an official agency; however, use of the API monogram indicates that the manufacturer has agreed to make cement according to the specifications outlined in the *API Standards 10A*. Although the API defines eight different classes of cement, only A, B, C, G, and H are available from the manufacturers and distributed in the U. S.

2.6 Cement Standards Outside the U. S.

In cementing wells in countries other than the U. S., or in their territorial water, it may be necessary to use local products. Table 2.9 lists classifications that have been established in various countries for the most common types of portland cement used for construction.[10]

For some cements, additional classifications have been made — for example, OCI (Ordinary Portland Cement Type I), OCII, OCIII. However, such classifications cause problems in fixing a clear dividing line between types, as OC Type II or III can easily be confused with RHC or HSC cement.

In some countries a specific manufacturer may, for speed and simplicity, use a symbol to identify various types of cement. Table 2.10 lists equivalent identifications for various types of portland cements as used by some countries commonly associated with the oil industry.

Listed below are some manufacturers who hold the API monogram and market cements for the oil industry.

Belgium	Ciments Belges
Canada	Canada Ciment Lafarge
	Inland Cement
Colombia	Cementos Especiales
Ecuador	La Cemento Nacional C.A.
England	Associated Portland Cement Mfg.
	Cement Lafarge
Germany	Dyckerhoff Zementwerke
Italy	Italcementi
Iran	Tehran Cement
	Doroud Cement
Japan	Ube Cement
	Nihon Cement
Lebanon	Cement Libanais
Norway	Norcem A/S
Thailand	Jalaprathan Cement
Trinidad	Trinidad Cement
Venezuela	C. A. Venezolana de Cementos
Mexico	Cementos Apasco

Note: The German-made cement is available world wide.

2.7 Specialty Cements

A number of cementitious materials, used very effectively for cementing wells, do not fall in any specific API or ASTM classification. While these materials may or may not be sold under a recognized specification, their quality and uniformity are generally controlled by the supplier. These materials include (1) pozzolanic-portland cements, (2) pozzolan-lime cements, (3) resin or plastic cements, (4) gypsum cements, (5) diesel oil cements, (6) expanding cements, (7) refractory cements, (8) latex cement, and (9) cement for permafrost environments.

Pozzolanic Cements

Pozzolans include any siliceous materials, either natural or artificial, processed or unprocessed, that in the presence of lime and water develop cementitious qualities. They can be divided into natural and artificial pozzolans. The natural pozzolans are mostly of volcanic

TABLE 2.7 — PHYSICAL REQUIREMENTS FOR API CEMENTS[6]
(Parenthetical values are in metric units.)

1	2	3	4	5	6	7	8	9	10	11	12	13
Cement Class				A	B	C	D	E	F	G	H	J★
Water, per cent by weight of cement				46	46	56	38	38	38	44	38	★
Soundness (autoclave expansion), maximum, per cent				0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	
Fineness *(specific surface), minimum, cm^2 per g				1500	1600	2200						
Free water content, maximum, ml.										3.5**	3.5**	
Compressive Strength Test, Eight Hour Curing Time	Schedule Number, Table 6.1 RP10B	Curing Temp, F C	Curing Pressure psi kg/cm^2	Minimum Compressive Strength, psi (kg/cm^2)								
		100 38	Atmos.	250 (18)	200 (14)	300 (21)						
	1S	95 35	800 56							300 (21)	300 (21)	
	3S	140 60	3000 211							1500 (106)	1500 (106)	
	6S	230 110	3000 211				500 (35)					
	8S	290 143	3000 211					500 (35)				500(35)
	9S	320 160	3000 211						500 (35)			
Compressive Strength Test, Twenty-four Hour Curing Time	Schedule Number, Table 6.1 RP10B	Curing Temp, F C	Curing Pressure psi kg/cm^2	Minimum Compressive Strength, psi (kg/cm^2)								
		100 38	Atmos.	1800 (127)	1500 (106)	2000 (141)						
	4S	170 77	3000 211				1000 (70)	1000 (70)				
	6S	230 110	3000 211				2000 (141)		1000 (70)			
	8S	290 143	3000 211					2000 (141)				
	9S	320 160	3000 211						1000 (70)			
	10S	350 177	3000 211									1000(70)◆
Pressure Temperature Thickening Time Test	Specification Test Schedule Number Table 7.2 RP10B	Simulated Well Depth, ft m	Maximum Consistency 15-30 Minute Stirring Period, Uc†	Minimum Thickening Time, minutes***								
	1	1,000 310	30	90	90	90						
	4	6,000 1830	30	90	90	90	90					
	5	8,000 2440	30	—	—	—	—	—	—	90	90	
	5	8,000 2440	30	—	—	—				120 max.‡	120 max.‡	
	6	10,000 3050	30				100	100	100			180
	8	14,000 4270	30					154				
	9	16,000 4880	30						190			180

★Class J cement is tentative. Water as recommended by the manufacturer.
*Determined by Wagner turbidimeter apparatus described in ASTM C 115: Fineness of Portland Cement by the Turbidimeter, current edition of *ASTM Book of Standards*, Part 9.
**Based on 250 ml volume, percentage equivalent of 3.5 ml is 1.4%.
◆Compressive strength after 7 days shall be no less than the 24-hour compressive strength on Schedule 10S.
†Units of slurry consistency (U_c), formerly referred to as "poises".
***Thickening-time requirements are based on 75 percentile values of the total cementing times observed in the casing survey, plus a 25 per cent safety factor
‡Maximum thickening-time requirement for Schedule 5 is 120 minutes.