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THE MANUFACTURE OF PORTLAND CEMENT FROM MARL

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PREFACE TO BULLETIN NO. 4

The continued interest in the use of marl in making Portland cement and the fact that requests continue to be received for Bulletin No. 2, now out of print, has led to the writing of this bulletin.

The writer desires to acknowledge the generous aid and assistance of many of the members of the university faculty; especially those whose names are listed in the preface to Bulletin No. 2. Mr. R. A. Smith, state geologist of Michigan, and Mr. Ralph W. Perry, of the Perry Testing Laboratory of Detroit, have aided greatly in the preparation of this bulletin by additional information and advice.

The writer is indebted to Rock Products, Chicago, for the photographs of the marl pipe line of the Peninsular Portland Cement Company and to the Virginia Portland Cement Corporation for the pictures of the excavating and washing equipment at Chuckatuck, Virginia. The Edge Moor Iron Company very kindly furnished the photographs of waste heat installations and of plants using such equipment. Mr. Leonard Kleinfield made the drawings showing marl investigations.

The writer desires also to express his appreciation of the courtesy and helpfulness of the officials and companies who generously supplied analyses of their raw materials, kiln fuels, and finished cements. Their permission to publish these analyses has aided greatly in the preparation of the bulletin. The names of the companies and officials appear in the tables of analyses. Mr. M. A. Peterson, chief chemist of the Minnesota State Highway Department, kindly supplied several analyses of marl.

R. E. Kirk

University of Minnesota, 1926

PREFACE TO BULLETIN NO. 2

The 1921 session of the Minnesota Legislature provided for an investigation by the University of Minnesota of the manufacture of Portland cement from marl.

The work was performed by the writer during the summer of 1922. The results are reported in this bulletin.

The writer desires to express his indebtedness to Dr. C. A. Mann, professor of chemical engineering in the University of Minnesota, under whose direction the investigation was made. Dean O. M. Leland, director of the Engineering Experiment Station of the University of Minnesota, has given helpful advice and suggestions. Dr. F. J. Alway and Dr. C. O. Rost, of the Division of Soils of the University of Minnesota, furnished useful information. The writer also wishes to thank Mr. R. A. Smith, state geologist of Michigan; Mr. Ralph W. Perry, of the Perry Testing Laboratories of Detroit, Michigan; and the chemists and operating officials of various cement plants in Michigan and Ontario for information supplied by them. He is indebted to the Hanover Cement Company and the Aetna Portland Cement Company for photographs used in this report. Mr. Charles H. Dow furnished the photographs of the Star Lake marl deposits. Standard works on the manufacture of Portland cement have been freely consulted. Proper acknowledgement has been attempted, in the text and in the bibliography, of all the sources of information utilized in this report.

R. E. Kirk

University of Minnesota, 1923

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INTRODUCTION TO BULLETIN NO. 4

This bulletin represents primarily a complete revision of the material first published in Bulletin No. 2 of the Minnesota Engineering Experiment Station series. In addition the portions dealing with operations on marl and the investigation of marl deposits have been considerably amplified. Certain recent developments in plant practice are discussed and additional information is given concerning new wet process plants operating on deposits of oyster shells and similar materials dredged from bays and swamps.

New sections have been added to present some information about the general character of the clays and shales of Minnesota and about the character, location, and composition of the limestone deposits of the state. Some additional statements about the location and extent of the marl deposits of Minnesota are given. Detailed information is not yet available on these points. A discussion of the occurrence of marl in conjunction with peat in Minnesota is included.

The writer presents in this bulletin tables of analyses of raw materials, kiln fuels, and finished cements which represent current practice. They have been very courteously supplied by the companies and officials named in the tables. Many, if not all, of the analyses given in current text and reference books are analyses made one, two, or three decades ago.

Certain additions have been made to the bibliography as previously published. The bibliography is not intended to be an exhaustive one, but an attempt has been made to list the articles of major importance on the subjects concerned.

INTRODUCTION TO BULLETIN NO. 2

It is the purpose of this report to discuss the possible utilization of marl in the making of Portland cement and to point out the economic and technologic advantages and disadvantages involved in such a use. It does not pretend to give complete information about either the quality or quantity of the marl deposits of Minnesota. The conditions which seem essential for the success of any proposed plant are outlined and suggestions for the investigation of marl deposits of possible value are given.

A summary of the Portland cement industry is presented in order to show its importance.

The methods used in making Portand cement are briefly treated and the various raw materials used are mentioned. A brief consideration of the character and origin of marl is followed by statements as to its use in the making of Portland cement in other states and in Canada.

The quality and quantity of marl needed for a modern cement plant are discussed, typical analyses are given, and suggestions made as to the methods of investigating marl deposits.

The problems of plant operation and design are considered and the general requirements for a marl-using plant outlined.

The chief sources of Portland cement used in the state are mentioned and the shortage within the state of calcareous raw materials for Portland cement discussed.

Anyone interested in further details of the manufacture of Portland cement is referred to the standard works on the subject, especially the books by Richard K. Meade and by E. C. Eckel.

THE MANUFACTURE OF PORTLAND CEMENT FROM MARL

SUMMARY OF THE PORTLAND CEMENT INDUSTRY

Before discussing the manufacture of Portland cement from marl, it seems desirable to summarize the character and extent of the Portland cement industry, and to present briefly the accepted methods of making Portland cement.

MAGNITUDE OF THE PORTLAND CEMENT INDUSTRY

The Portland cement industry has developed so rapidly that the importance of Portland cement in our modern civilization has not been generally appreciated.

Table I compiled from the reports of the United States Geological Survey will give some idea of the growth and magnitude of the industry in the United States:

TABLE I

PRODUCTION OF PORTLAND CEMENT IN THE UNITED STATES BY YEARS

Year	Production Barrels*	Valuation (Estimated)	Average Price per Barrel (at Mills)
1890	335,500	$ 704,050	$2.09
1895	990,324	1,586,830	1.60
1900	8,482,020	9,280,525	1.09
1905	35,246,812	33,245,867	0.94
1910	76,549,951	68,205,800	0.89
1915	85,914,907	73,886,820	0.86
1916	91,521,198	100,947,881	1.10
1917	92,814,202	125,670,430	1.35
1918	71,081,663	113,446,334	1.60
1919	80,777,935	138,130,269	1.71
1920	100,023,245	194,439,025	2.02
1921	98,842,049	186,802,472	1.89
1922	114,789,984	202,030,370	1.76
1923	137,460,238	261,174,455	1.90
1924	149,358,000	....	...
1925	161,202,000	....	...

* One barrel contains 376 pounds.

There is every reason to believe that there will be a continued growth of the industry. New uses are being discovered for Portland cement and, with added knowledge of the proper methods of concrete construction, its known uses are growing in favor. The accelerated building program expected in the next several years will call for increased amounts of cement. The good roads program of the nation and of the states means the use of more and more cement. The prejudice that once existed against concrete is fast losing its hold. As a result the demand for cement will increase.

The technologic improvements in the industry, together with the able management of many of the companies, have made this industry remarkable in that large quantities of a bulky product are produced at a relatively low cost. The growth of the industry has been aided by a careful campaign of education in the proper use of cement. Table II shows the amounts of Portland cement used in Minnesota by years since 1914. These figures were compiled from the United States Geological Survey reports on mineral resources.

TABLE II

ESTIMATED PER CAPITA CONSUMPTION OF PORTLAND CEMENT IN MINNESOTA BY YEARS

Year	Consumption (Barrels)	Per Capita (Barrels)
1914	3,125,930	1.41
1915	3,143,999	1.40
1916	3,338,560	1.46
1917	2,793,371	1.21
1918	2,164,947	0.92
1919	2,979,549	1.25
1920	3,109,243	1.29
1921	3,090,803	1.26
1922	3,555,842	1.43
1923	3,414,916	1.36
1924	3,248,369	1.28
1925	3,458,026	1.35

GEOGRAPHIC LOCATION OF PLANTS PRODUCING PORTLAND CEMENT

Since Portland cement is a bulky product, the plants have been built as close to the large consuming districts as is possible. Availability of raw materials and of fuel has also been an important factor in the location of cement plants. As a result the industry is not highly localized. Plants are found in nearly all sections of the country. In recent years, the outstanding factors in location have been transportation facilities and rates. Many of the plants built in the last three years have been located where, in addition to railway facilities, water transportation was available. In many cases, the raw materials are transported entirely by water. Many individual cases might be cited where the existence of water transportation has been the decisive factor in the location of the plants.

DEFINITION OF PORTLAND CEMENT

The United States Government specifications define Portland cement as "the product obtained by finely pulverizing clinker, produced by calcining to incipient fusion an intimate and properly proportioned mixture of argillaceous and calcareous materials, with no additions subsequent to calcination except water and calcined or uncalcined gypsum."

Portland cement has the property of hardening in air or water when mixed with a suitable amount of water and of remaining hard when immersed in water. The strong bond thus formed gives the cement its value when used in masonry or in the manufacture of concrete structures.

In addition to Portland cements we have on the market various "natural" or "bricklayers" cements and various hydraulic cements. These are very valuable for certain uses but their consumption is small as compared with Portland cement.

The term Portland cement is a generic term used as descriptive of cement made according to the foregoing definition and possessing certain characteristic properties. It has no relation to the place of manufacture or the company making the cement. The term originated with the patent taken out in 1824 by Joseph Aspdin, a bricklayer of Leeds, England, on an improved cement made by grinding and burning limestone and clay. This he called "Portland cement" because the hardened cement had a yellowish gray color resembling in appearance the stone from the quarries of Portland, England.

Recently high alumina cements have been used for special construction work. Such cements give quick hardening, high early-strength concrete. Their use is not as yet very extensive. The cost is rather high, and they are new to the engineer and the contractor. Any possible technologic developments which would lessen their cost will stimulate greatly the use of such cements.

RAW MATERIALS FOR PORTLAND CEMENT

Portland cement may be manufactured from a variety of raw materials. They may be classified under two general heads, calcareous materials and argillaceous materials.

1. *Calcareous.*—Calcareous substances are those in which calcium carbonate predominates. The naturally occurring calcareous materials always contain in addition some alumina, iron oxide, and silica in the form of clay or sand.

2. *Argillaceous.*—Argillaceous substances are those in which the silica and alumina predominate. Calcium and magnesium carbonates are often present but in relatively small amounts.

The usual materials employed are listed as follows:

Calcareous	*Argillaceous*
Limestone	Clay
Marl	Shale
Chalk	Slate
Alkali waste	Blast-furnace slag
Cement rock	Cement rock

Cement rock is a mixture of calcareous and argillaceous materials and is listed in each class. Almost any combination of these materials may be used if the proper proportion is obtained. Table III shows the amount of Portland cement made from each group of materials.

TABLE III

PRODUCTION, IN BARRELS, AND PERCENTAGE OF TOTAL OUTPUT OF PORTLAND CEMENT IN THE UNITED STATES ACCORDING TO TYPE OF MATERIAL USED, 1898-1914, 1920

Year	Type 1—Cement Rock and Pure Limestone		Type 2—Limestone and Clay or Shale		Type 3—Marl and Clay		Type 4—Blast-Furnace Slag and Limestone	
	Quantity	Per-cent-age	Quantity	Per-cent-age	Quantity	Per-cent-age	Quantity	Per-cent-age
1898	2,764,694	74.9	365,408	9.9	562,092	15.2	....	...
1899	4,010,132	70.9	546,200	9.7	1,095,934	19.4	....	...
1900	5,960,739	70.3	1,034,041	12.2	1,454,797	17.1	32,443	0.4
1901	8,503,500	66.9	2,042,209	16.1	2,001,200	15.7	164,316	1.3
1902	10,953,178	63.6	3,738,303	21.7	2,220,453	12.9	318,710	1.8
1903	12,493,694	55.9	6,333,403	28.3	3,052,946	13.7	462,930	2.1
1904	15,173,391	57.2	7,526,323	28.4	3,332,873	12.6	473,294	1.8
1905	18,454,902	52.4	11,172,389	31.7	3,884,178	11.0	1,735,343	4.9
1906	23,896,951	51.4	16,532,212	35.6	3,958,201	8.5	2,076,000	4.5
1907	25,859,095	53.0	17,190,697	35.2	3,606,598	7.4	2,129,000	4.4
1908	20,678,693	40.6	23,047,707	45.0	2,811,212	5.5	4,535,300	8.9
1909	24,274,047	37.3	32,219,365	49.6	2,711,219	4.2	5,786,800	8.9
1910	26,520,911	34.6	39,720,320	51.9	3,307,220	4.3	7,001,500	9.2
1911	26,812,129	34.1	40,665,332	51.8	3,314,176	4.2	7,737,000	9.9
1912	24,712,780	30.0	44,607,776	54.1	2,467,368	3.0	10,650,172	12.9
1913	29,333,490	31.8	47,831,863	51.9	3,734,778	4.1	11,197,000	12.2
1914	24,907,047	28.2	50,168,813	56.9	4,038,310	4.6	9,116,000	10.3
1920*	....	...	....	...	2,767,347	2.7	....	...

* E. F. Burchard, The Cement Industry in the United States, 1914. *Mineral Resources,* 1914, Part II, U.S.G.S.; Cement in 1920. *Mineral Resources,* 1920, Part II, U.S.G.S.

The usual combinations are:

1. Cement rock alone, or cement rock and limestone
2. Limestone and clay or shale
3. Blast-furnace slag and limestone or marl
4. Marl and clay or shale
5. Alkali waste and clay

THE MANUFACTURE OF PORTLAND CEMENT

In the making of Portland cement we may discuss three stages: (1) grinding of raw materials, (2) burning the "clinker," and (3) grinding the "clinker."

1. *Grinding of raw materials.*—The raw materials must, first of all, be finely ground, properly proportioned, and intimately mixed. The machinery and methods used vary according to the character of the materials and the process selected. When hard materials are used preliminary crushing is often accomplished by gyratory or by jaw crushers. In nearly all plants the final reduction is attained in some form of ball mill or tube mill or a combination of these two types. The importance of fine grinding is well established. The factor of grinding costs will be mentioned in connection with the discussion of the advantages and disadvantages of the wet process. Especial attention will be given later to the methods employed in plants using marl. There are two general processes of manufacture, the dry and the wet. In the first, raw materials are ground and mixed dry and introduced into the kilns in the form of a dry powder. In the second, the materials are ground with water and brought together in a "slurry" containing enough water to allow the slurry to be pumped. This liquid is then introduced into the kilns. The merits of these processes will be considered later in their report.

2. *Burning the clinker.*—The properly proportioned mixture is now introduced into rotary kilns and heated to "incipient fusion" by means of the heat generated in the burning of powdered coal blown in with a blast of air. These rotary kilns are inclined somewhat and the material passes by gravity from the upper to the lower end, where the powdered coal burners are located. In the uppermost section of the kiln the incoming material is heated and the moisture present driven off as steam. In its progress down the kiln, the calcium carbonate is decomposed and the carbon dioxide passes off leaving quicklime. In the "clinkering" zone the lime combines with the silica and alumina

and forms the clinker. The temperature here is usually between 2,500° F. and 3,000° F. This clinker, in aggregates about the size of a walnut, falls out of the lower end of the kiln and is cooled. When cool it is passed to the clinker-grinding machinery.

The rotary kilns are made of sheet steel and are lined with some refractory material. They usually vary in length from 60 to 260 feet and from 6 to 12 feet in diameter. The longer kilns are much more efficient, especially with the "wet" process, and few, if any new mills contemplate installing kilns less than 175 feet long. The Phoenix Portland Cement Company is building a new plant at Birmingham, Ala., designed with two kilns 11 feet and 3 inches in diameter and 330 feet long. The wet process will be used.

TABLE IV*

LENGTHS OF ROTARY CEMENT KILNS IN ACTIVE PLANTS IN THE UNITED STATES, 1917-22

Length (Feet)	Number of Kilns					
	1917	1918	1919	1920	1921	1922
40–60	108	77	71	74	74	78
61–99	94	90	87	87	87	91
100–109	84	105	98	98	91	102
110	83	65	55	66	56	54
120	88	88	95	97	99	101
125	194	183	166	172	164	162
126–149	65	63	63	63	64	66
150–199	73	63	66	73	76	75
200–260		15	19	23	29	31
	789	749	720	753	740	760

* *Mineral Resources,* Part II. U.S.G.S. 1920, 1921, 1922.

3. *Grinding the clinker.*—The cooled clinker is finely ground, usually in tube mills. The cement, now ready for use, is sent to storage or to packing machines.

ANALYSES OF PORTLAND CEMENT

Table V shows typical analyses of finished Portland cements from a number of representative plants in the United States. The writer desires to thank the companies listed for supplying these analyses and for permitting their publication.

TABLE V

ANALYSES OF PORTLAND CEMENTS

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Loss	SO_3	Company	Location	Authority
22.10	10.15		64.26	0.87	0.78	1.76	Virginia	Norfolk, Va.	(28 day ave.)
20.78	6.86	2.59	62.03	3.60	1.39	1.81	Alpha	Lehigh Valley Dist.	Anderson
21.27	5.45	3.24	62.58	4.13	1.02	1.49	Alpha	Middle Western Div.	Anderson
22.25	6.75	2.35	62.30	2.20	...	...	Castalia	Castalia, Ohio	Rinehart
22.44	7.00	2.94	64.08	0.68	1.00	1.69	Nebraska	Superior, Neb.	Latimer
22.24	6.65	2.64	62.47	3.27	0.82	1.95	Petoskey	Petoskey, Mich.	Phillips
21.92	6.56	3.44	63.64	1.63	0.80	1.51	Pyramid	Valley Junction, Ia.	Boberg
20.30	8.10	2.50	62.60	2.70	0.80	1.90	Atlas	Northampton, Pa.	Hicks
22.40	5.30	2.50	62.50	3.90	1.00	1.80	Atlas	Hanibal, Mo.	Hicks
22.10	5.80	4.00	63.20	1.10	0.90	1.80	Atlas	Hudson, N. Y.	Hicks
21.00	6.90	2.50	62.50	2.70	2.10	1.60	Atlas	Leeds, Ala.	Hicks
21.90	6.00	2.60	64.80	1.00	1.60	1.60	Atlas	Independence, Kan.	Hicks
22.40	6.99	2.99	63.15	2.70	...	1.74	Peerless	Union City, Mich.	Simmons
22.62	6.84	2.00	63.22	3.02	...	1.48	Peerless	Detroit, Mich.	Simmons
22.34	6.22	3.43	63.18	2.11	0.72	1.97	Wolverine	Coldwater, Mich.	Hutchins
23.18	8.24		63.00	3.19	0.50	1.49	Allentown	Allentown, Pa.	Breerwood
22.82	6.68	2.72	63.63	1.46	0.78	1.66	Sun	Lime, Oregon	Ludgate
21.73	2.46	6.16	63.14	3.70	1.03	1.78	Dixie	Richard City, Tenn.	Fischer
21.52	7.49	2.29	64.00	1.45	1.59	1.69	Clinchfield	Kingsport, Tenn.	Guenther
22.10	6.65	2.14	65.32	0.91	1.80	1.48	Clinchfield	Clinchfield, Ga.	Guenther
21.83	4.83	3.14	63.98	3.00	1.15	1.61	Hawkeye	Des Moines, Ia.	Condon
21.52	7.72	2.08	63.44	4.65	1.16	1.78	Northwestern States	Mason City, Ia.	Blackmore
22.12	6.76	2.28	62.44	2.61	1.41	1.71	Northwestern States	Mason City, Ia.	Blackmore
21.53	9.05		63.61	3.04	1.07	1.65	Coplay	Coplay, Pa.	Johnston
21.64	10.20		62.56	2.49	1.19	1.77	South Dakota	Rapid City, So. Dak.	Ernst
21.04	7.02	2.59	62.12	3.11	1.18	1.73	Nazareth	Nazareth, Pa.	Driesbach
22.57	7.11	2.45	63.06	2.40	...	1.92	Newago	Newago, Mich.	Miller
22.00	6.00	3.00	62.00	3.00	1.50	1.50	Sandusky	Ave. for 4 mills.	Newberry
20.47	7.42	2.69	65.25	1.50	0.79	1.57	Colorado	Portland, Colo.	Banks
21.22	7.40	3.18	63.18	2.48	0.71	1.78	Missouri	St. Louis, Mo.	Block
22.38	6.52	2.88	64.08	1.16	1.06	1.60	Missouri	Kansas City, Mo.	Block
21.06	7.40	3.50	63.60	2.02	...	1.70	Dewey	Dewey, Okla.	Chamberlain

MARL

Many of the first Portland cement plants established in the United States used fresh-water marl and either clay or shale as their raw materials. Just as good Portland cement can be made from such marl as from any other calcareous material. The manufacture of Portland cement from these marls is then to be considered as a question of technology and of economic advantage. We shall first consider the character of these fresh-water marls.

DEFINITION OF MARL

The term marl has been used by geologists and others to describe many very different types of material. The terms marls and marlytes were used in the earlier geologic reports to describe calcareous shales. This practice was so universal that the terminology has persisted in certain regions. It is illustrated in the earlier geologic reports of New York, Ohio, Iowa, etc.

Certain phosphate and potassium bearing deposits of a silicious character have also been called marls. The best known illustrations are found in the greensand marls of New Jersey, Virginia, and other Atlantic Coast states. The term marl as used in New Jersey also includes clay marl, sand marl, and lime-sand marl. Marine shells and other marine fossils are also found in these beds.

The term has also been applied, along the Atlantic and Gulf coasts, to certain chalky, unconsolidated limestones of marine origin containing clay.

The term marl as used in this report is intended to describe the fresh-water marls which have long been used in the making of Portland cement in the United States and Canada.

Marl is an unconsolidated carbonate of lime deposited in the beds of present or extinct lakes in the glaciated regions of the North Central states. In many cases marl deposition is still in progress. In many other cases the lake has disappeared and the marl deposits occur in a swamp or marsh covered with peat or muck. The marl may be mixed with sand or with organic matter. Many deposits, however, are almost pure calcium carbonate. Due to its occurrence in lakes or bogs, the marl contains large amounts of water.

CALCIUM CARBONATE IN SOIL WATERS

The action of the glaciers left a large amount of finely ground calcareous material in the glaciated regions in the form of limey gravels and limey clays. The combined action of carbon dioxide and water leaches out the calcium carbonate from the surrounding soil. The water then contains calcium bicarbonate, $Ca(HCO_3)_2$, giving to water the property usually known as temporary hardness. The chemical equation for this would be:

$$\underset{\text{Insoluble}}{CaCO_3 + H_2O + CO_2} \longrightarrow \underset{\text{Soluble}}{Ca(HCO_3)_2}$$

DEPOSITION OF MARL

The exact reason for the deposition of marl has been the subject of much discussion and investigation. All the investigators agree that waters charged with calcium bicarbonate deposit calcium carbonate if, for any reason, carbon dioxide escapes or is removed. This action may be represented as follows:

$$\underset{\text{Soluble}}{Ca(HCO_3)_2} \longrightarrow \underset{\text{Insoluble}}{CaCO_3 + CO_2 + H_2O}$$

The differences of opinion have to do with the causes of the escape or removal of the carbon dioxide.

1. *Blatchley's theory.*—Blatchley, who has studied the Indiana deposits, attributes the loss of CO_2 to a decrease in pressure and an increase in temperature as the underground waters reached the lake basin.

This spring water as it enters the lake is always colder than the water of the lake itself. The bicarbonate of lime is more soluble in cold water than in warm and a part of the dissolved material is therefore precipitated in the form of a fine powder soon after the cold stream enters the warmer, still water of the lake. Such precipitation of calcium carbonate from cold water as it becomes warm is seen every day in almost every household. The hard water heated in tea-kettles holds while cold a large quantity of bicarbonate of lime in solution. As it becomes warm, much, if not all of this falls and forms a coating of lime carbonate upon the bottom of the kettle. Again, if there is a large amount of carbon dioxide in the percolating waters the percentage of carbonate of lime held in solution will be increased in proportion. As the spring-water enters the lake and rises to the surface the pressure will be decreased and a part of the carbon dioxide will escape and so cause a precipitation of another part of the carbonate of lime according to the following formula (sic):

$$CaH_2(CO_3)_2 + CO_2 = CaCO_3 + H_2O$$

Blatchley states that most of the marl lakes of Indiana are fed by underwater springs and that the larger deposits of marl in these lakes are found close to these springs.

2. *Davis's theory.*—From his studies on Michigan marls Davis decided that most of the marl deposits were due to the action of certain aquatic plants such as Chara and Zonotrichia. His conclusions are as follows:

All green plants, whether aquatic or terrestrial, take in the gas (carbon dioxide) through their leaves and stems and build the carbon atoms and part of the oxygen atoms of which the gas is composed into the new compounds of their own tissues, in the process releasing the remainder of the oxygen atoms. Admitting these facts, we have two possible general causes for the formation of the incrustation (of calcium carbonate) upon all aquatic plants. If the calcium and other salts are in excess in the water, and are held in solution by free carbon dioxide, then the more or less complete abstraction of that gas from the water in direct contact with plants causes precipitation of the (lime) salts upon the parts abstracting the gas, namely, the stem and leaves. But in water containing the salts, especially calcium bicarbonate, in amounts so small that they would not be precipitated if there were no free carbon dioxide present in the water at all, the precipitation may be considered a purely chemical problem, a solution of which may be looked for in the action, upon the bicarbonates, of the oxygen set free by the plants. Of these bicarbonates, calcium bicarbonate is the most abundant, and the reaction may be taken as typical and expressed by the following chemical equation:

$$\underset{\text{Calcium bicarbonate}}{CaH_2(CO_3)_2} + \underset{\text{oxygen}}{O} = \underset{\text{calcium carbonate}}{CaCO_3} + \underset{\text{carbon dioxide}}{CO_2} + \underset{\text{water}}{H_2O} + \underset{\text{oxygen}}{O}$$

in which calcium bicarbonate is converted into the normal (and very slightly soluble) carbonate by the oxygen liberated in the plants, and both carbon dioxide and oxygen are set free, the free oxygen possibly acting still further to precipitate calcium monocarbonate. It is probable that the plants actually do precipitate calcium carbonate in both these ways (i.e., by abstracting carbon dioxide from the water and by freeing oxygen), but in water containing relatively small amounts of calcium bicarbonate the latter would seem the probable method.

The statement of Mr. Davis as to the "chemical" action of oxygen on the bicarbonate is open to the criticism that the action predicated might be due to the purely "physical" effect of the oxygen in decreasing the pressure of the carbon dioxide. It should, however, be noted that no carefully supervised studies have been made of the conditions under which such aquatic plants will exist and cause marl to be deposited. But the influence of Chara in causing marl deposition can scarcely be denied by anyone who has observed the luxuriant growth of Chara in the marl lakes. Davis also notes that Chara abstract calcium salts from the water and build them into their tissues. This calcium is present in part as calcium silicate.

3. *Theory of mollusc action.*—There is no doubt that part of the marl has been deposited through the action of molluscs. These animals abstract calcium salts from water and build it into their shells. At their death the shells sink to the bottom and aid in the formation of the marl. In some marl beds these shells are very abundant while in others no traces of shells are found.

4. *Summary of views.*—These ideas of marl deposition may be summarized as follows: the ground water entering the lakes has calcium bicarbonate, $Ca(HCO_3)_2$, in solution. This is deposited as marl due to:

1. Escape of carbon dioxide owing to
   a. Decrease in pressure
   b. Increase in temperature
2. Removal of carbon dioxide by
   a. Action of aquatic plants in utilizing carbon dioxide
   b. Action of oxygen given off by aquatic plants
3. Abstraction of calcium salts by aquatic plants
4. Formation of shell deposits by molluscs

Undoubtedly each of these causes has contributed to the deposition of any one marl bed. The relative amounts deposited due to each cause will certainly vary greatly with the conditions of deposition.

The writer feels that most of the fresh-water marls have been deposited where the influence of aquatic plants is the major factor. He is not so familiar with the Indiana marl lakes described by Blatchley, but he suspects that a study of these lakes would disclose the presence of such plants. The importance assigned by some writers to the presence of the remains of molluscs in fresh-water marls seems unnecessary, and their occurrence is probably more accidental than otherwise. Detailed examination of the marl lakes of Minnesota, Michigan, and Ontario, justifies the statement that these shells occur only in limited amounts and only in particular portions of the deposits. It is possible that the existence in rivers and bays of calcareous deposits, oftentimes called marl, and certainly attributive to the shells of oysters and similar organisms, has influenced unduly the ideas about the fresh-water marls of the glacial lakes of the North Central states.

The evidence in favor of the view that the marl deposits are due primarily to the influence of aquatic plants seems to the writer quite overwhelming. The exact temperature and concentration conditions for their existence are not definitely established. In all of the deposits known to the writer, where marl is still being laid down, the presence of such plants is evident to the most casual observer. The marl lake near Hanover, Ontario, (page 23) is a good example of this. This lake is no longer used as a source of marl. The Hanover Cement Company, having exhausted almost the entire supply of marl in this lake, went over to the use of limestone in their operations. The lake is now a good example of the process by which, in prehistoric times, the first marl was laid down. When the Hanover Cement Company started dredging marl, this lake was almost completely choked with marl. They continued to use marl from this lake until recently. At the present time, the banks of the lake are covered, just below the water's edge, with dense masses of Chara and similar water loving plants. Below the green mass of vegetation may be seen several feet of clean, freshly deposited marl.

The marl lakes of Minnesota, so far as examined, contain similar plants. Dr. C. O. Rosendahl, of the Department of Botany, University of Minnesota, has identified, in addition to Chara and Zonotrichia, a number of other aquatic plants. There seems little reason to doubt that the presence of these plants is the vital factor in the deposition of marl.

Examination of marl deposits from lakes where deposition is still progressing and from bogs where deposition is no longer active points to the same conclusion. Microscopic examination of samples of marl from any of these deposits shows the influence of plants in their deposition. Minute perforations appear where the calcium carbonate was deposited around the bodies of the plants. The best examples known to the writer come from a relatively small deposit located on the farm of Mr. N. W. Olson near Walker, Minnesota. Conditions here were such that the marl after deposition was not subject to wave action, as it might have been in a large lake. Consequently the marl still retains the form it had when laid down. Large fragments of marl may be obtained whose porous structure reminds one of petrified bath sponges. The perforations in the bits of marl are visible to the naked eye.

It can therefore be stated with considerable confidence that most of the marl of the type under discussion has been deposited through the action of aquatic plants.

PRODUCTION OF PORTLAND CEMENT FROM MARL

Marl has been used in the manufacture of Portland cement in New York, Michigan, Ohio, Indiana, Utah, and in Canada. At present one plant in Indiana, one in Ohio, one in Utah, and five plants in Michigan are using marl. Reference to the table on page 4 will show the production of Portland cement from marl as compared with the production of it from other classes of raw materials. It will be noted that the amount of cement produced from marl has been constantly decreasing since 1899.

REASONS FOR DECREASED PRODUCTION OF PORTLAND CEMENT FROM MARL

There are several reasons for the decreased production of Portland cement from marl.

1. *Other raw materials more advantageously located with respect to markets.*—Many of the marl deposits are located at considerable distances from consuming centers. Freight rates are a vital factor in determining the success or failure of a cement plant. The development of limestone deposits near large consuming centers or located where an all-water route will bring the needed limestone to their bins has been a large factor in the location of new Portland cement plants.

2. *Inadequate supply of marl for continued operation of mill.*—Due to lack of careful investigation, many of the plants built to use marl were located at places where the supply of high grade marl was soon exhausted. Such plants boosted the totals for a few years and were then abandoned. Their failure, while due, at least in part, to lack of preliminary investigation, discouraged the building of other marl-using plants. These earlier plants were built when smaller mills were usual and the importance of a large reserve supply of marl was not fully appreciated.

3. *Obsolescence of mills.*—Most of the plants designed to use fresh-water marl were built between 1895 and 1905. These plants are now becoming obsolete. Much of the equipment has been completely worn out and must be replaced if the plants are to continue operations. These plants were built with the short kilns which were in universal use at that time and their fuel consumption is consequently high. Many of these plants are finding that their marl supplies, while adequate for twenty or twenty-five years, are now becoming almost exhausted. Their owners naturally hesitate to install new and modern equipment when the marl deposits left near their present location are limited in amount.

With many of these plants there has been a disposition, after a period of fifteen to twenty-five years, to shift over to the use of limestone. In some cases the limestone is shipped considerable distances. This is economically feasible only because the cost of the plant has been written off by depreciation charges and the only additional equipment cost is for the machinery needed for grinding the limestone. The output of the plant can be greatly increased since ground limestone can be handled in a slurry of about 35 per cent water as compared to 45 to 60 per cent water in the marl slurries. This enables the companies to show a profit even tho the freight charges on the limestone are high. As the old equipment must eventually be replaced, such a scheme, in most cases, is possible for only a few years. In time the plant operations must be moved nearer the raw materials. In order to continue the company's trade, many companies are building new plants near limestone quarries, or where limestone may be shipped in by an all-water route.

4. *Wet process not in favor.*—The almost universal disfavor with which, until within the last few years, the wet process was regarded by most cement technologists, has operated against building new plants for the use of marl. The attempts to dry marl before clinkering have not been successful because of the tenacity with which the moisture is retained and the consequent cost of the large amount of fuel needed to drive off this water. For this reason the wet process is always used with marl. In more recent years the wet process has been growing in favor for reasons to be reviewed later.

5. *Competition with limestone.*—The discovery and exploitation of large deposits of limestone suitable for cement making has caused a decrease in the use of marl. Especially in Michigan and New York the competition with limestone plants has resulted in a lessened production of Portland cement from marl.

6. *Operations of "wildcat" companies.*—The marl-cement industry has suffered greatly from the activities of unscrupulous promoters. Many companies have been organized and plants built by persons interested only in the sale of stocks. Large salaries have been paid to promoters and managers. Some plants have been built solely for the sake of possible commissions paid the manager on machinery purchased. These conditions have discouraged legitimate enterprises. Investors have hesitated to put capital into plants designed to use marl because of the poor financial history of many such plants. Legal restrictions have in recent years been placed on the operations of all enterprises offering their stock to the public. This fact has curbed the "fly-by-night" promoter of cement companies.

MARL-USING PORTLAND CEMENT PLANTS

It seems advisable to discuss the main marl-using plants which have been built in the United States and in Canada.

PLANTS IN MICHIGAN

The first Portland cement plant in Michigan was built near Kalamazoo in 1872 by the Eagle Portland Cement Company. Wet marl and clay were first mixed and then briquetted. These briquets were burned in stationary dome kilns with coke. This plant continued operations until about 1882.

In 1896 the Peerless Portland Cement Company built a plant at Union City. Vertical or dome kilns were installed. These were replaced in 1902 by rotary kilns. This plant is still in operation. At present, marl is brought by rail from Spring Arbor, near Jackson, in dump cars. It is excavated in part by a dredge and in part by a drag line excavator. The plant now has nine kilns $6\frac{1}{2} \times 77$ feet with a rated capacity of 2,100 barrels daily. A deposit of shale and clay from near the plant is used with the marl. The marl carries as high as 2 to 3 per cent sand and may have 5 per cent of organic matter. The slurry as passed to the kilns carries 47 to 50 per cent of water. The operators in the raw materials department are given a bonus if the water content of the slurry is kept below 47 per cent. Powdered coal is used in the kilns—from 150 to 170 pounds of coal being used to clinker each barrel of cement.

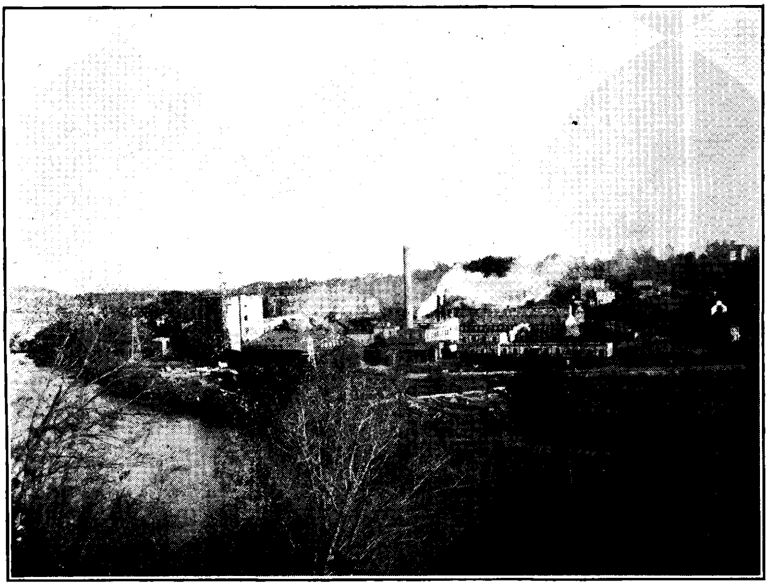


FIGURE I. PLANT OF THE NEWAGO PORTLAND CEMENT COMPANY

This company recently completed a new plant at River Rouge near Detroit. Limestone screenings are shipped by boat from Rogers City. The semi-wet process is used. Clay from near Wayne, Michigan, is mixed to a slip with caustic waste from the caustic soda plant of the Solvay Process Company. Three kilns, 11×175 feet, equipped with waste heat boilers produce 5,500 barrels daily.

The Bronson Portland Cement Company erected a plant at Bronson in 1897 and installed rotary kilns. This plant in 1910 ceased operations on marl, due to the exhaustion of its marl supply and the obsolescence of its equipment.

In 1897 the Coldwater Cement Company, now the Wolverine Portland Cement Company, built plants at Coldwater and Quincy. These plants are still operating. The marl is excavated by a dredge and loaded into scows. These are towed to the bank near the mill and the marl pumped to the plant. The clay comes from a deposit near Coldwater. Altho large amounts of marl have been taken from the lake at Coldwater, a considerable supply remains. At present, however, the dredge is working nearly three miles from the plant. Reserve supplies of marl are available in other near-by lakes.

At these plants a moisture content of 50 per cent in the slurry is considered good operation. From 150 to 175 pounds of coal are used in burning a barrel of cement. The plant at Coldwater has three 8×182 foot kilns and the one at Quincy seven 6×120 foot kilns.

The Newago Portland Cement Company built a plant at Newago in 1900 and 1901 designed for the use of clay and marl. The supply of each proved inadequate almost immediately and the plant has since that time operated on limestone shipped from the vicinity of Petoskey, Michigan. The shale comes from near Ellsworth, Michigan. Because of the fact that this plant was able to use the cheap water power available at Newago it survived despite its location. This plant is modern and well equipped. It uses the wet process. Waste heat boilers are used which now supply the power for the plant. Three kilns 9×160 feet, produce 3,000 barrels of cement daily.

The Egyptian Portland Cement Company, in 1902, built a plant near Fenton in which marl and clay were to be used. This company has passed through several reorganizations and has resumed operations on marl. The marl is obtained from the company's holdings on Silver Lake. It is excavated by a dredge, loaded into scows, and these are towed to the bank near the plant. The marl is then pumped to the mill. The plant now has nine kilns, 6×60 feet. The rated capacity is about 2,500 barrels daily. This company also operates a plant at Port Huron, using limestone shipped in by boat. The dry process is used. Two kilns, $11\frac{1}{4} \times 200$ feet, produce 3,200 barrels of cement each day. The clay for these plants is now being obtained from clay pits owned by the company near Smith's Creek, Michigan.

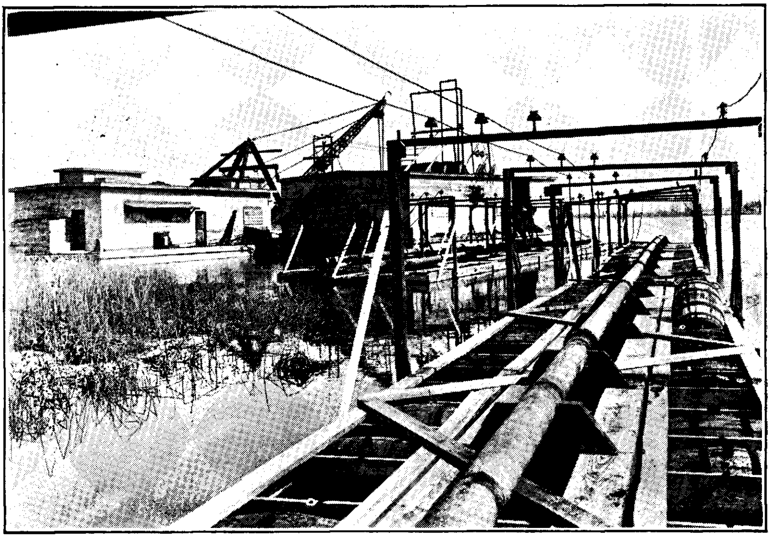


FIGURE 2. MARL DREDGE AND PIPE LINE, PENINSULAR PORTLAND CEMENT COMPANY

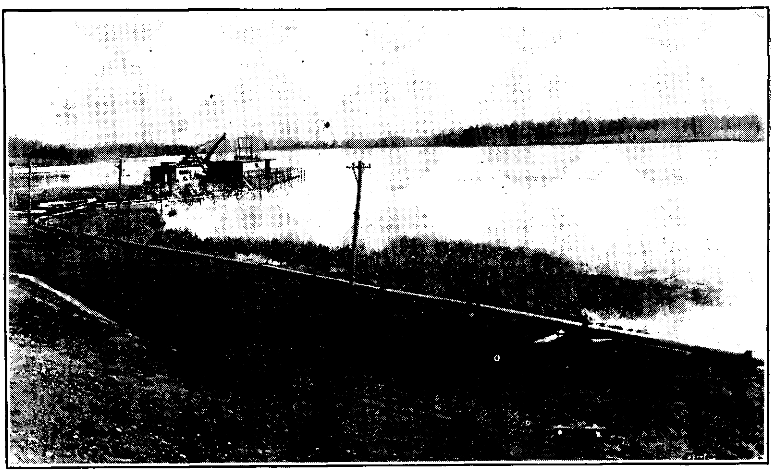


FIGURE 3. MARL LAKE, CEMENT CITY, MICH.

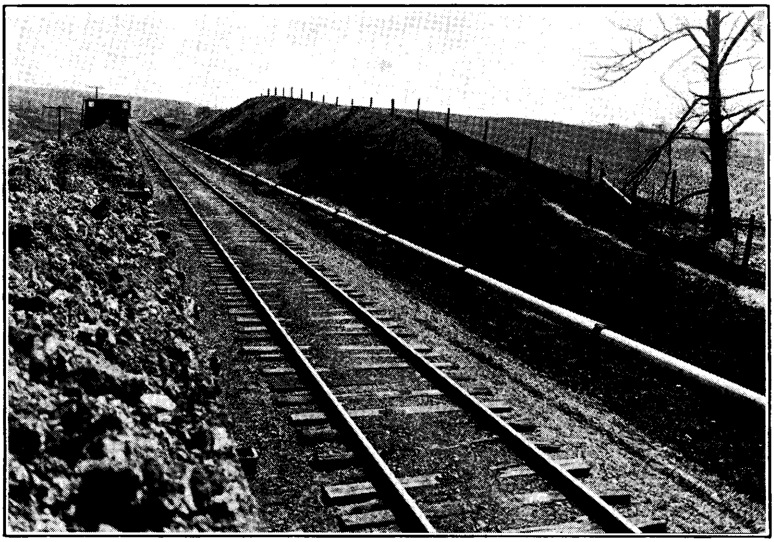


FIGURE 4. PIPE LINE ALONG RAILROAD RIGHT OF WAY

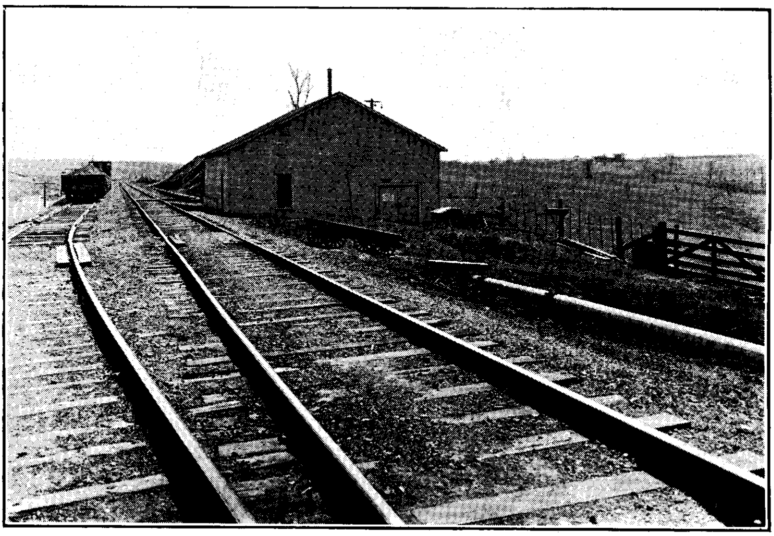


FIGURE 5. PIPE LINE AND RELAY PUMPING STATION

The Aetna Portland Cement Company, a successor to the Detroit Portland Cement Company, located near Fenton, also uses marl from holdings on Silver Lake. The marl is handled in the same way as at the Egyptian plant. The clay is shipped from Corunna, some twenty miles distant on the Grand Trunk Railway. The slurry as it goes to the kilns carries about 48 per cent of water. The plant has two kilns 10 × 175 feet. About 165 pounds of coal are used to clinker one barrel of cement. The company also operates a dry process plant at Bay City which uses limestone brought in by boat. This new plant will presumably supply the company's trade when the present marl supply is exhausted.

Other plants built about the same time and designed to use marl were those of the Elk Rapids Portland Cement Company at Elk Rapids, completed in 1901 and the Omega Portland Cement Company at Mosherville, completed in 1900. The Great Northern Portland Cement Company also built a marl-using plant at Marlborough. These plants are no longer in operation.

Numerous other plants were projected in the decade from 1895 to 1905, and many companies organized to use marl in making Portland cement. The activities of certain of these companies have been previously discussed.

The Peninsular Portland Cement Company completed their factory at Cement City in 1901. They used marl from a near-by lake and acquired the right to exploit the marl deposits in a series of lakes several miles from the plant. Most of the clay used was shipped from Bryan, Ohio. When the marl deposits in the lake adjacent to the plant were exhausted, limestone was shipped in and used, first with clay and then with blast-furnace slag. The success in operating by the wet process with limestone and slag during the season of 1921 led the officials of this company to consider utilizing their reserve supply of marl. The increased freight rates on stone offset the advantage of increased capacity of kilns. A new dredging outfit was procured and a pipe line and pumping stations were built to bring marl from the reserve supply some two miles distant. This equipment cost about $150,000 and renders available a large supply of marl. The marl is mixed with blast-furnace slag. The slurry carries about 50 per cent water. About 125 pounds of coal are used on this mixture for every barrel of cement clinkered. In the spring of 1922 this plant operated for several weeks on a mixture of marl, limestone, and clay. The proportions were approximately 45 per cent marl on the dry basis, 33 per cent limestone, and 22 per cent clay. This mixture could be handled as a slurry containing 40 to 45 per cent water. The marl used at this plant is of high quality, nearly all of it having well over 90 per cent calcium carbonate, dry basis. The plant is well equipped and carefully managed. It has three kilns, 9×205 feet and two kilns 11×175 feet. Two waste heat boilers supply power for the entire plant. At the present time this plant is not operating on marl. Crushed limestone and clay are used. The marl pipe-line is in stand-by condition for possible future use.

At Chelsea near Jackson the White Portland Cement Company, later the Millen Portland Cement Company, built a plant with vertical kilns, designed to use marl and clay. The Michigan Portland Cement Company later acquired the plant and the marl holdings and constructed a rotary kiln plant. This plant has been operated intermittently. It is reported to have suffered from financial as well as technical disadvantages. It has recently been leased by the Michigan State Industries. The plant is to be operated, in part at least, by convict labor from the Michigan State Prison at Jackson.

In May, 1901, there were ten plants operating in Michigan. Of these, eight were using marl. At the same time there were six plants being built and seven projected, all of which were to use marl. Three of the plants operating on marl in 1901 are still using marl and one of them now operates on limestone. One plant built at that time and one built since are continuing to use marl. This makes a total of five plants now using marl. The reasons for the others having discontinued the use of marl are discussed on pages 12-14.

There is a general tendency for the new Portland cement plants in Michigan to locate where water transportation renders available the limestone screenings from the quarries in the Rogers City–Alpena region.

Despite this tendency, active investigations are now on foot looking toward the utilization of other marl deposits in Michigan. The National Portland Cement Company has been organized to use the marl deposits of Coldwater Lake near Mount Pleasant, Michigan. A large deposit of marl near Decatur, Michigan, has been carefully surveyed and sampled with the idea of its possible use in the manufacture of Portland cement. Extensive marl deposits near Kalamazoo are also attracting attention.

PLANTS IN OHIO AND INDIANA

The Sandusky Portland Cement Company operated a plant near Baybridge, Ohio, using marl from a near-by deposit. They discontinued operations when the marl supply became exhausted. The Castalia Portland Cement Company, located near Castalia, Ohio, has long used marl and clay as raw materials. At the present time, due to the diminishing supply of marl, they are using about 25 per cent limestone screenings from a local quarry.

Because of the impending exhaustion of their marl supply, the Sandusky Portland Cement Company recently dismantled its plant at Syracuse, Indiana.

About 1900 the Wabash Portland Cement Company built a plant at Stroh, Indiana, which is still in operation. The marl is loaded on cars by a floating dredge and hauled to the plant. The marl contains from 80 to 90 per cent calcium carbonate, dry basis, and has from 4 to 5 per cent organic matter. The slurry as fed to the kilns has from 53 to 56 per cent moisture. This plant has three kilns $8\frac{1}{2} \times 185$ feet. From 125 to 150 pounds of coal are used to burn each barrel of cement. This company states that a reserve supply of marl is available for future operations.

PLANTS IN NEW YORK

Marl was at one time rather extensively used in the state of New York in the manufacture of Portland cement. The abundant supplies of suitable limestone and cement rock available for making Portland cement have operated against the building of new plants to use marl. The older plants are now obsolete and in many cases their supplies of marl are exhausted.

Newland[1] makes the following statements about the marl-cement industry of New York.

> In 1886 a cement works was put in operation by T. Millen & Sons at Warners, Onondaga county. The materials employed were local Quaternary marls and clays. The plant was purchased by the Empire Portland Cement Company in 1890 who operated it for some 15 years, in the meanwhile changing the equipment from stationary to rotary kilns and extending the capacity. Another plant designed for the use of marl and clay was erected at Montezuma, Cayuga county, in 1890; the installation included a 75 foot rotary kiln in which the cement mix was charged wet and burned with oil injected in vaporized form. This foreshadowed by many years the general practice of burning the raw materials without mechanical preparation in long rotary kilns. The principal changes in subsequent practice have been to substitute pulverized coal for oil and to increase the length and diameter of the kilns. The Montezuma plant was destroyed by fire in 1893.
>
> Also, the employment of marl in the place of hard limestone proved to be an economic, though perhaps not a technical, mistake. Marl plants were erected

[1] D. H. Newland, Mineral Resources of the State of New York. *New York State Museum Bulletin* No. 223. 1921.

at other places in addition to those already noted, namely by the American Cement Company at Jordan, Onondaga county; by the Wayland Portland Cement Company, Waylund, Steuben county; and the Iroquois Portland Cement Company, Caledonia, Livingston county. By 1910 all of the marl plants had either been converted for the use of limestone or had gone out of business.

All of the marl plants that were built in the central part of the State have been destroyed or dismantled, resulting in the loss of considerable manufacturing capacity in this section. The last of the mills to succumb was that of the Marengo Portland Cement Company, near Caledonia, Livingston county, which was dismantled in 1912.

PLANT IN UTAH

The Utah-Idaho Cement Company, formerly the Ogden Portland Cement Company, operates a plant at Bakers, Utah, north of Brigham City. This plant uses marl and clay from an old flat which was an arm of the ancient lake. The deposit of marl is said to be from two to fifteen feet in thickness. The marl is underlain by clay. All the marl is excavated and sufficient clay taken from below the marl to give the proper mix. This plant uses the wet process. Three kilns, one $7\frac{1}{3} \times 125$ feet and two $7\frac{1}{2} \times 100$ feet are in use. The daily output is 1,200 barrels.

Other marl beds of similar character are said to exist in the state, some of them close to a railroad.

PLANTS IN ONTARIO

A considerable number of Portland cement plants, using marl and clay, have been operated in Ontario. Nearly all of these plants have come under the control of the Canada Cement Company and all of them have ceased operations on marl.

Several plants operating at or near Owen Sound, Ontario, used marl from very extensive deposits in Shallow Lake, located several miles west of Owen Sound. The supply of marl in this lake has been almost exhausted and these plants are all dismantled. These plants all used antiquated equipment.

The Hanover Cement Company at Hanover, Ontario, operated on marl until 1920. At that time they changed to the use of limestone shipped by rail from near Walkerton. The plant was partially rebuilt to allow this change. The quarry at Walkerton, first opened and operated by the Ontario Hydro Electric Commission, was acquired by the company. Clay from near the marl lake was used with both marl and with limestone. At the time of the change to limestone, most of the good quality marl had been utilized. This plant is no longer in operation. Its equipment was fast becoming obsolete.

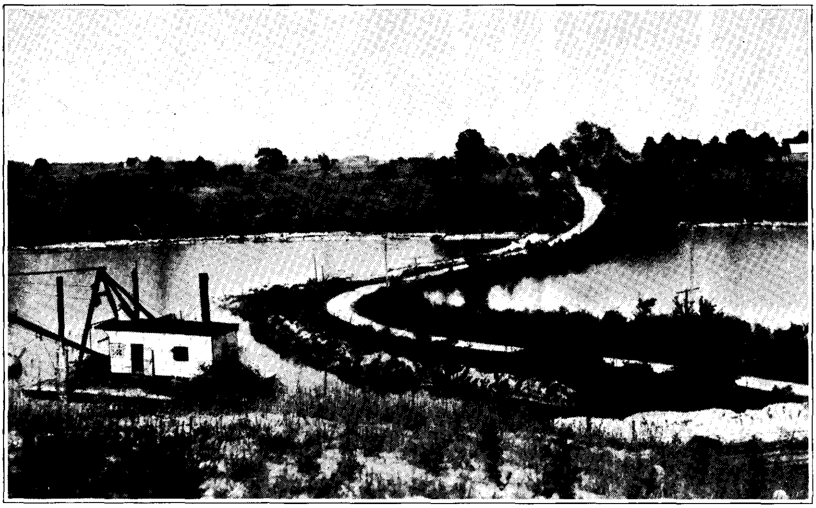


FIGURE 6. ROAD CROSSING MARL LAKE, HANOVER, ONTARIO

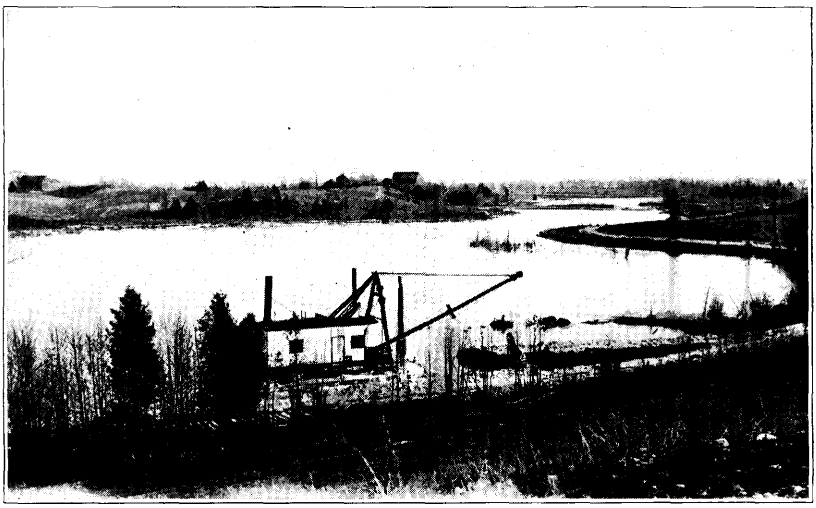


FIGURE 7. MARL LAKES AT HANOVER, SHOWING DREDGE

In nearly all the Ontario plants the impending exhaustion of the marl deposits rendered impractical the improvements in equipment and methods needed to make the plants economically successful, and consequently they were abandoned.

Shirley Bass, chief engineer of the Canada Cement Company, Ltd., makes the following statements in a private communication:

The Canada Cement Company ceased the operation of their marl plants in Ontario because, primarily, the mechanical equipment of their plants was extremely out of date, and secondly, the marl deposits were not of great enough extent to warrant remodeling the mills and replacing the out of date equipment with modern equipment.

Regarding the economic side of operating a marl plant, the writer believes that it is quite possible for a marl plant favorably situated as regards to coal to compete with a modern limestone plant. As you well know, marl is, in the state of nature, very finely divided and needs practically no grinding in order to prepare it for the kilns. This is a great saving when compared with a limestone plant. A more serious objection to the use of marl as raw material for the manufacture of cement is the fact that the marl carries such a high percentage of water. So far as our experience goes we found that we could not handle our marl with less than 45% of water in the slurry and more often our water content would run as high as 50%. This would mean that for every barrel of cement clinker burned in the kilns about 300 pounds of water would have to be evaporated with a very large consequent loss in fuel economy.

With the advent of the long kilns, however, this feature does not carry as much weight as it formerly did as Portland cement clinker can be burned from a wet mix in a 200 foot kiln for about the same number of pounds of coal per barrel as can be done with a dry process kiln. The only difference in operation conditions is that while the temperature of the kiln gases in the stack of the dry process kiln will average from 1,200 to 1,500° F., the temperature of the gases from a long wet process kiln will average not over 800° F., and frequently runs considerably less.

The writer certainly does not believe it would be advisable for anybody to build a plant to use marl as a raw material unless they had a supply of marl in sight large enough to run the plant to its full capacity for a period of at least twenty years. Marl beds of this size are not common and I should consider that anybody who finds a marl bed large enough to run a 2,000 barrel plant to its full capacity for twenty years would be a very fortunate person.

PORTLAND CEMENT PLANTS USING OYSTER SHELLS AND SIMILAR DEPOSITS

Several plants are successfully operating on calcareous raw materials dredged from rivers or bays. Their operations are of interest since their problems are somewhat the same as those of the plants using marl. The material carries large amounts of water and in some cases has adventitious substances which must be removed before the material is passed to the mill.

The Texas Portland Cement Company operates a plant at Manchester, near Houston, Texas, using a shell deposit from the bay. This material may contain some sand and silt which has to be washed out. The material is transported by water to the plant. It is mixed with clay brought to the plant by rail. The slurry fed to the kilns is said to have an average water content of 42.6 per cent. Analyses of these raw materials are given on page 29. This plant has three kilns, $9 \times 8 \times 220$ feet. Oil is used for burning. The company is a subsidiary of the International Cement Corporation. The cement produced at Houston is sold under the Lone Star brand.

The Pacific Portland Cement Company has recently built a plant at Redwood City, California, to use a mixture of oyster shells and clay dredged from certain deposits in South San Francisco Bay. These deposits are of particular interest since they are said to contain the necessary constituents for making Portland cement without additions or without washing. These shell beds are reported to vary from 10 to 300 feet in depth and from a few hundred feet to one mile in length. One bed which has been very carefully investigated is described as having an extent of 50 by 3,000 feet and a depth of 110 feet. The material reaches the kilns as a slurry carrying from 35 to 40 per cent of water. Two oil-fired kilns, 10×235 feet, produce 3,000 barrels of cement each day. This is marketed under the company's Golden Gate brand. This company also operates a dry process plant at Cement, California.

The Virginia Portland Cement Corporation, a subsidiary of the International Cement Corporation, has recently built a plant at South Norfolk, Virginia, to use so-called shell-marl and clay. The shell deposit owned by the company covers some two thousand acres near Chuckatuck, Virginia, located on the Nansemond River. It is from 20 to 50 feet deep and carries, in most places, an overburden of from 3 to 8 feet. The marl is excavated by a drag line excavator and hauled to the washing plant in side-dump cars. At the washing plant most of the clay is washed out bringing the calcium carbonate content of the material up from about 74 per cent to from 88 to 91 per cent and reducing the silica content from about 16.5 per cent to from 7 to 8 per cent. The washed marl is loaded in barges and these are towed by tugs to the plant which is located on the Elizabeth River. Clay is brought in by rail from near Waverly, Virginia. Very careful control is kept over the composition of the slurry as it reaches the kilns. The slurry as fed to the kilns carries from 38 to 40 per cent water. Three coal-fired kilns, $9 \times 8 \times 220$ feet, are used to burn the clinker. The

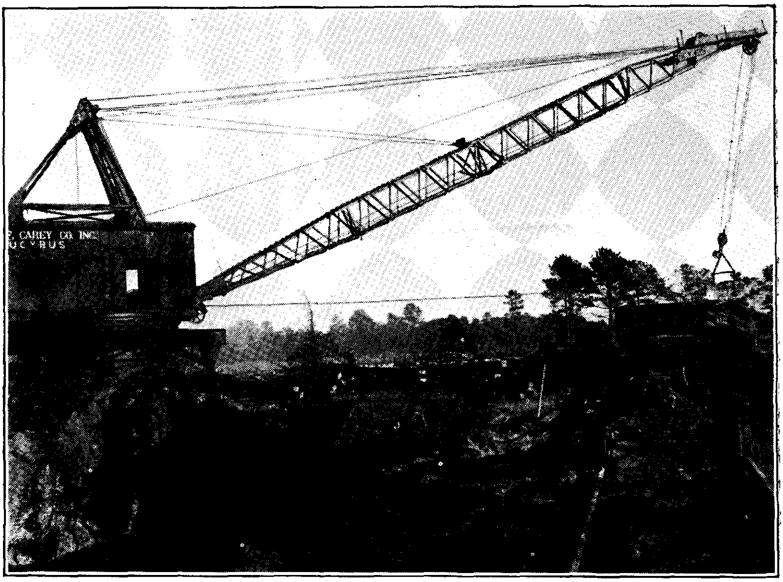


FIGURE 8. EXCAVATING SHELL MARL, VIRGINIA PORTLAND CEMENT CORPORATION, CHUCKATUCK, VA.

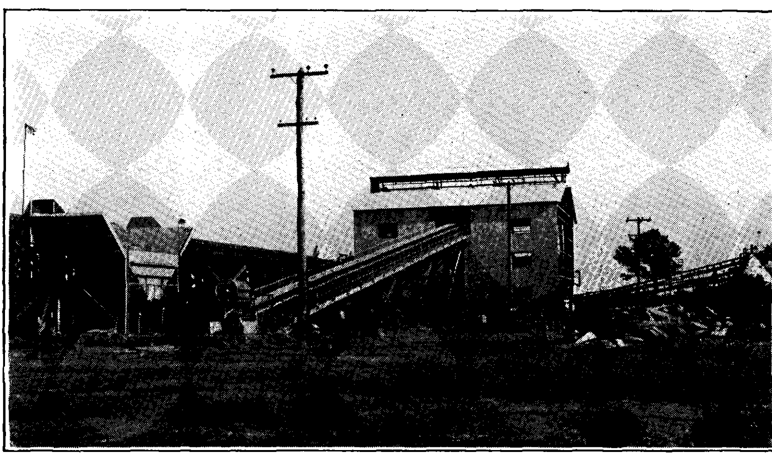


FIGURE 9. WASHING AND CLASSIFYING PLANT AT CHUCKATUCK

plant has an annual capacity of 1,200,000 barrels. It is located on a 30-foot channel where ocean-going vessels may load, and has access to 8 railway lines. This cement is also marketed under the Lone Star brand.

Many other shell deposits are known. Table VI carries the analyses of two shell beds, as given by Eckel.[2] Undoubtedly more such deposits will be used in the making of Portland cement.

QUALITY AND QUANTITY OF MARL AND CLAY

Having described briefly the plants now using marl and similar materials, we shall discuss the factors to be considered in the utilization of marl in the making of Portland cement.

Perhaps more cement plants have failed because of a low grade or inadequate supply of raw materials than for any other reason. A very thoro and systematic investigation of the available deposits of both marl and clay should precede any plans for building a plant.

QUALITY OF THE MARL

The marl must carry a relatively high percentage of calcium carbonate. The higher this percentage the more desirable does the marl become. Above 90 per cent dry basis is desirable, tho plants have operated on marl with a calcium carbonate content of as low as 80 per cent. The lowest limit that can be used will depend on the character of the impurities present.

The amount of magnesium carbonate should be low. More than 3 to 4 per cent would be undesirable, especially if the clay or shale to be used carried some magnesia. Very few marls, however, carry large amounts of magnesium carbonate, even in regions where the surrounding limestones are highly dolomitic. This fact is doubtless due to the effect on the deposition of the marl of the varying solubilities of the carbonates of calcium and magnesium.

The amount of organic matter present in the marl is of vital importance. When organic matter is present the amount of water needed to give a slurry that can be handled by the machinery of the plant is greatly increased. As a consequence the kiln capacity is reduced and the fuel cost raised. The amount of water needed to form a workable slurry will vary greatly with different marls with about the same content of organic matter. It seems that the character and state of division of the organic matter is of as great importance as

[2] E. C. Eckel, Portland Cement Materials and Industry in the United States. *United States Geological Survey Bulletin* No. 522. 1911.

the amount. It also seems probable that the physical condition of the marl itself is a factor in the amount of water needed in the slurry. No exact information is available on this point and experiment alone can tell the amount of water needed for a particular marl. This point has been quite generally overlooked in the evaluation of marls. In practice some plants have been able to operate effectively with amounts of organic matter over 5 per cent. Other plants find difficulty in operating with more than 3 per cent organic matter.

Plant tests, made under normal operating conditions, seem essential to establish the character of the marl and the amount of water needed to give a slurry which can be readily pumped.

Recent work by the British Portland Cement Research Association suggests the possibility of lowering the water content of slurries by adding relatively small amounts of such materials as sodium carbonate. This point will be discussed in greater detail under plant operations.

The presence of sand in marl is usually considered very disadvantageous. Here, too, the physical character of the sand is a factor worthy of note. Coarse gravel can be readily screened out. Very fine sand, most of which will pass 100 mesh, will give little trouble. Its presence must, of course, be taken into account when the mixture is proportioned. If the sand is not so fine the proper intimacy of mixture cannot be obtained. The cost of grinding sand to the desired fineness is very high. Plant practice varies as to the amount of sand that can be used. Some plants encounter difficulty merely because they do not vary the other ingredients of the mix to get the proper chemical relationship. In general, it may be said that the main body of a marl deposit should contain less than 2 per cent of sand. Amounts of sand up to 5 per cent can be tolerated in small areas of the deposit. Their utilization will require careful management on the part of the plant chemist. In the sampling of marl, sand layers of one or two inches in depth are often not noticed. These may cause the amount of sand in the marl bed to be higher than was anticipated from preliminary investigations.

Many marl beds have pockets of clay and in some cases rest on a layer of clay. If this clay is of the proper character for use in cement making, its presence is an advantage. The amount of clay added at the mill must be altered as required. The clay may, however, be high in magnesium carbonate and so be disadvantageous. The amount of alkalies present should be small. Table VI shows the analyses of some marls that have been used to make Portland cement:

TABLE VI

ANALYSES OF MARLS AND SHELLS USED IN CEMENT PLANTS

<table>
<tr><th>Silica SiO_2</th><th>Alumina Al_2O_3</th><th>Iron Oxide Fe_2O_3</th><th>Calcium Carbonate $CaCO_3$*</th><th>Magnesium Carbonate $MgCO_3$*</th><th>Organic Matter</th><th>Company, Location, and Reference</th></tr>
<tr><td></td><td></td><td></td><td>Marls</td><td></td><td></td><td></td></tr>
<tr><td>1.74</td><td>0.90</td><td>0.28</td><td>88.95</td><td>3.66</td><td>4.81*</td><td>Sandusky Portland Cement Co., Syracuse, Ind. (Eckel)</td></tr>
<tr><td>1.78</td><td colspan="2">1.21</td><td>88.43</td><td>2.72</td><td>4.23</td><td>Sandusky Portland Cement Co., Syracuse, Ind.</td></tr>
<tr><td>0.85</td><td colspan="2">0.86</td><td>91.09</td><td>2.74</td><td>...</td><td>Wabash Portland Cement Co., Stroh, Ind.</td></tr>
<tr><td>0.66</td><td colspan="2">0.62</td><td>94.89</td><td>0.98</td><td>2.53</td><td>Wabash Portland Cement Co., Stroh, Ind.</td></tr>
<tr><td>3.80</td><td colspan="2">n.d.</td><td>91.20</td><td>3.22</td><td>1.50</td><td>Millens Portland Cement Works, South Bend, Ind.</td></tr>
<tr><td>0.19</td><td>0.05</td><td>0.07</td><td>91.57</td><td>4.04</td><td>2.25</td><td>Millens Portland Cement Works, South Bend, Ind.</td></tr>
<tr><td>0.22</td><td colspan="2">0.76</td><td>92.01</td><td>2.64</td><td>4.23*</td><td>Peninsular Portland Cement Co., Cement City, Mich.</td></tr>
<tr><td>0.77</td><td colspan="2">0.11</td><td>95.62</td><td>1.90</td><td>...</td><td>Newago Portland Cement Co., Newago, Mich.</td></tr>
<tr><td>1.24</td><td colspan="2">0.80</td><td>90.84</td><td>2.99</td><td>4.09</td><td>Newago Portland Cement Co., Newago, Mich.</td></tr>
<tr><td>0.72</td><td>0.24</td><td>0.12</td><td>98.37</td><td>0.92</td><td>...</td><td>Newago Portland Cement Co., Newago, Mich.</td></tr>
<tr><td>0.06</td><td colspan="2">0.80</td><td>98.16</td><td>...</td><td>...</td><td>Newago Portland Cement Co., Newago, Mich.</td></tr>
<tr><td>1.19</td><td>0.55</td><td>0.25</td><td>93.70</td><td>2.43</td><td>...</td><td>Wolverine Portland Cement Co., Coldwater, Mich.</td></tr>
<tr><td>1.20</td><td>0.55</td><td>0.40</td><td>91.29</td><td>0.77</td><td>...</td><td>Wolverine Portland Cement Co., Coldwater, Mich.</td></tr>
<tr><td>n.d.</td><td>n.d.</td><td>n.d.</td><td>92.63</td><td>1.74</td><td>...</td><td>Wolverine Portland Cement Co., Coldwater, Mich.</td></tr>
<tr><td>1.65</td><td colspan="2">0.81</td><td>90.61</td><td>tr.</td><td>...</td><td>Bronson Portland Cement Co., Bronson, Mich.</td></tr>
<tr><td>0.40</td><td>0.20</td><td>0.20</td><td>95.48</td><td>0.63</td><td>...</td><td>Iroquois Portland Cement Co., Caledonia, N. Y.</td></tr>
<tr><td>0.42</td><td colspan="2">1.08</td><td>93.45</td><td>2.11</td><td>0.86</td><td>Millens Portland Cement Co., Wayland, N. Y.</td></tr>
<tr><td>0.26</td><td colspan="2">0.10</td><td>94.34</td><td>0.38</td><td>1.54</td><td>Empire Portland Cement Co., Warners, N. Y.</td></tr>
<tr><td>0.26</td><td>0.21</td><td>0.01</td><td>90.98</td><td>0.40</td><td>1.68</td><td>Empire Portland Cement Co., Warners, N. Y.</td></tr>
<tr><td>6.22</td><td>1.70</td><td>0.86</td><td>85.41</td><td>0.84</td><td>...</td><td>Montezuma, N. Y. First marl used for cement.</td></tr>
<tr><td>0.14</td><td colspan="2">0.36</td><td>94.87</td><td>3.14</td><td>...</td><td>American Cement Co., Jordan, N. Y.</td></tr>
<tr><td>0.54</td><td colspan="2">0.56</td><td>97.09</td><td>4.89</td><td>...</td><td>Genesee Wayland Portland Cement Co., Perkinsville, N. Y.</td></tr>
<tr><td>1.98</td><td colspan="2">0.97</td><td>90.93</td><td>1.15</td><td>0.25</td><td>Buckeye Portland Cement Co., Harper, Ohio.</td></tr>
<tr><td>0.26</td><td colspan="2">0.20</td><td>94.36</td><td>...</td><td>...</td><td>Castalia Portland Cement Co., Castalia, Ohio.</td></tr>
<tr><td>1.43</td><td>0.20</td><td>0.18</td><td>90.34</td><td>4.37</td><td>3.44*</td><td>Imperial Portland Cement Co., Owen Sound, Ont.</td></tr>
<tr><td>0.46</td><td colspan="2">0.44</td><td>97.16</td><td>0.63</td><td>1.12</td><td>Canadian Portland Cement Co., Marlbank, Ont.</td></tr>
<tr><td>7.12</td><td colspan="2">1-3.4</td><td>72-82</td><td>2-6.25</td><td>(up to 4.5% NaCl)</td><td>Brigham, Utah. (U.S.G.S. Bulletin, 522, p. 349).</td></tr>
<tr><td>1.10</td><td>1.05</td><td>1.55</td><td>94.10</td><td>4.70</td><td>...</td><td>Castalia Portland Cement Co., Castalia Ohio. (C. R. Rinehart)</td></tr>
<tr><td>0.72</td><td colspan="2">0.38</td><td>93.80</td><td>3.48</td><td>...</td><td>Peerless Portland Cement Co., Union City, Mich. (Marl from Spring Arbor. (Simmons)</td></tr>
<tr><td></td><td></td><td></td><td>Shells</td><td></td><td></td><td></td></tr>
<tr><td>0.16</td><td colspan="2">0.04</td><td>98.26</td><td>...</td><td>...</td><td>Texas Portland Cement Co., Houston, Tex. (Durbin)</td></tr>
<tr><td>6.00</td><td>3.50</td><td>2.50</td><td>84.80</td><td>1.05</td><td>...</td><td>Virginia Portland Cement Corp. Norfolk, Va. (Hilts)</td></tr>
<tr><td>1.54</td><td>0.26</td><td>0.20</td><td>94.73</td><td>1.67</td><td>...</td><td>Shells—Atlantic Coast. (Eckel)</td></tr>
<tr><td>5.30</td><td>0.73</td><td>0.57</td><td>89.70</td><td>0.94</td><td>...</td><td>Shells—Biloxi, Miss. (Eckel)</td></tr>
</table>

* Computed from oxides.

TABLE VII

ANALYSES OF CLAYS AND SHALES USED WITH MARLS IN PORTLAND CEMENT PLANTS*

Silica SiO_2	Alumina Al_2O_3	Iron Oxide Fe_2O_3	Calcium Oxide CaO	Magnesium Oxide MgO	Carbon Dioxide CO_2	Water H_2O	
55.27	10.20	3.40	9.12	5.73	...	...	Clay, Syracuse, Ind., Sandusky Portland Cement Co. *Twenty-fifth Annual Report,* Indiana Dept. of Geology, 1901, p. 28.
61.70	18.00		8.40	2.91	13.30		Clay, Stroh, Ind., Wabash Portland Cement Co., 1904.
57.74	17.76		7.80	3.52	12.30		Clay, Stroh, Ind., Wabash Portland Cement Co., 1904.
56.74	19.43	4.83	7.27	3.05	10.39		Clay, Stroh, Ind. W. R. Oglesby, analyst. *Twenty-fifth Annual Report,* Indiana Dept. of Geology, 1901, p. 112.
67.89	29.89		1.42	2.16	...	20.50	Range of composition—Coldwater shale, Union City, Mich., Peerless P. C. Co.
59.20	23.33		0.00	0.26	...	10.00	Range of composition—Coldwater shale, Union City, Mich., Peerless P. C. Co.
57.26	18.12	6.53	1.25	1.49	6.19		Range of composition—Coldwater shale, Coldwater, Mich., Wolverine Portland Cement Co.
61.25	21.59	8.30	1.50	2.31	8.32		Range of composition—Coldwater shale, Coldwater, Mich., Wolverine Portland Cement Co.
54.94	12.14	4.88	9.13	3.65	...	12.44¶	Drift clay, Livingston Co., Mich., Standard Portland Cement Co.
49.75	13.06	5.31	10.86	4.28	15.07		Lacustral clay, Chelsea, Mich. Analysis by E. D. Campbell.
49.34	14.50	5.37	9.75	4.77	15.55		Lacustral clay, Fenton, Mich. Analysis by E. D. Campbell.
62.55	17.46	5.08	2.30	1.67	5.55		Lacustral clay, Milbury, Ohio. Analysis by E. D. Campbell.
61.03	18.10	6.65	1.29	0.53	9.21		Lacustral clay, Bryan, Ohio. Analysis by Dean and Potter.
59.22	20.82		...	3.09	...	...	Clay, Montezuma, N.Y.
65.68	24.08		2.01	1.75	...	...	Clay, Jordan, N.Y., American Cement Co.
40.48	20.95		25.80†	0.99‡	...	8.50¶	Swamp clay, Warners, N.Y., Empire Portland Cement Co.
42.85	13.51	4.49	22.66†	6.92‡	...	...	Swamp clay, Warners, N.Y., Empire Portland Cement Co.
62.50	20.20	7.50	0.80	1.80	...	...	Clay, Canavangus, N.Y., Marengo Portland Cement Co., Caledonia.
45.21	19.08	6.74	19.94†	3.27‡	...	4.17¶	Clay, Mount Morris, N.Y., Empire Portland Cement Co., Wayland.
53.50	24.20		5.15	2.15	14.1¶		Clay, Wayland, N.Y., Wayland Portland Cement Co.
47.45	19.85		17.80	0.09	0.57	...	Clay, Buckeye Portland Cement Co., Ohio.
59.10	24.01		2.20	2.00	...	...	Clay, Ohio, Castalia Portland Cement Co.
51.56	14.50	3.84	9.80	...	7.70	...	Clay, Ohio, Castalia Portland Cement Co.
48.00	16.50		7.60	2.50	...	...	Range of composition—clay near Brigham, Utah.
50.00	18.60		...	2.80	...	...	Range of composition—clay near Brigham, Utah.

* Compiled, with some changes, from E. C. Eckel, Portland Cement Materials of the United States. *United States Geological Survey Bulletin 522.*

† $CaCO_3$. ‡ $MgCO_3$. ¶ **Includes organic matter as well as water.**

QUALITY OF CLAY OR SHALE

Shale or clay should be free from sand and gravel because of the high cost of grinding such material to the fineness necessary for its reaction in the kiln. It is desirable that clays or shales carry from 60 to 70 per cent of silica altho in practice clays have been used with less than 50 per cent silica. The alumina and iron oxides together should be from one third to one half as great as the silica. The lower limit is preferable. The amount of magnesia and the alkalies should be low. The limits will depend on the chemical character of the marl used.

Table VII shows analyses of clays and shales that have been used with marl in the manufacture of Portland cement.

QUANTITY OF MARL

As deposited, marl contains large amounts of water. Very conservative estimates must be made of the amount of calcium carbonate in a marl deposit of given area. Many companies have been disappointed by finding that a bed of marl estimated by them to be large enough to last their plant for thirty years was actually only sufficient for about five years' operation. A wet marl may contain, as it rests in the lake, as high as 60 per cent water. A cubic yard of such marl may weigh about 2,000 pounds and contain only about 800 pounds of dry marl. A dry marl in a well-drained swamp or marsh may have as low as 20 per cent of water. A cubic yard would weigh around 2,600 pounds and contain a ton of dry marl. Plant operations on *wet lake marls* in Michigan would seem to justify a figure of 1.7 barrels as a conservative estimate of the amount of Portland cement which could be made from one cubic yard of marl. (Eckel uses 2 barrels per cubic yard.) The Perry Laboratory of Detroit uses a figure of 2.5 barrels for well-drained marl. We shall see later that the smallest mill that could possibly be built with modern equipment and operated economically would be one with a capacity of at least 2,000 barrels daily. This would require two kilns about 200 feet long. Such a mill, operating 300 days a year for 30 years would produce 18,000,000 barrels of cement. This would require 10,600,000 cubic yards of marl. Each acre of marl 20 feet deep would give 32,266 cubic yards of marl and approximately 320 acres of marl of this depth would be needed to supply the mill for the 30-year period. Most cement plants are either worn out or obsolete in 20 years, so the figures above could be revised for that length of time if desired. This would require approximately 240 acres of marl for successful operation for 20 years. It seems best, however, to make this estimate as conservative as possible.

OVERBURDEN OF MARL DEPOSITS

Many marl deposits have an overburden of peat or soil. If this is shallow it can be readily stripped as the marl is excavated and dropped in the lake back of the dredge. If the overburden is deep or if it carries trees and bushes, the excavation costs will be much greater. Wherever there is an overburden the amount of organic matter in the marl as delivered to the mill will increase, due not only to intermingling during deposition, but also to mechanical mixing during the stripping and the excavation. It is the general opinion that an overburden of more than about five feet would render the cost of excavation almost prohibitive. In most cases a large overburden is also accompanied by a decided increase in the amount of organic matter in the marl deposit.

DEPTH OF WATER

If the marl is covered by more than fifteen feet of water, the deposit cannot be effectively utilized unless arrangements can be made to lower the water level of the lake. Marl at these lower levels is more apt to be mixed with large amounts of organic matter.

THE INVESTIGATION OF MARL DEPOSITS

The importance of a careful investigation of marl deposits proposed for use in the making of Portland cement is almost self-evident. Nevertheless, many Portland cement plants have been built to use such deposits when the marl supply lasted for only a few years. It, therefore, seems essential to discuss the usual and approved methods of investigating marl deposits with a view to their possible use as a source of calcareous raw material for the making of Portland cement.

SAMPLING TOOLS

Numerous devices have been used in sampling marl beds. The simplest type consists of an auger welded to the end of a section of gas pipe. Additional sections of pipe can be screwed on as the depth of the bed demands. There is danger of mixing various layers with such an instrument and so the origin of the sample may be doubtful. Another type utilizes a section of gas pipe with a slit down the side and a flange of metal so arranged that revolving the pipe causes the section to be filled with marl. Still another type has small metal cups attached to a section of gas pipe in such a way that they are filled when the pipe is withdrawn.

The sampler devised by C. A. Davis, of the United States Bureau of Mines, for use in sampling peat is perhaps the most exact tool known. It is described in *Bulletin* No. 16, of the Bureau of Mines, as follows:

The essential part of this tool is a stout brass tube about a foot long and seven-eighths of an inch in inside diameter. The lower end of the tube is sharpened, and inside the upper end is closely fitted and riveted a shoulder or ring of brass one-sixteenth of an inch thick to serve as a stop for the piston and catch. Inside the cylinder is a brass piston or three-fourths inch rod accurately fitting the opening in the upper part of the tube and bushed out at the lower end by a ring of brass to fit the cylinder. This lower end of the piston is slotted on one side, and in the slot is fastened a brass spring catch which automatically locks when the piston is drawn up and out of the cylinder. A metal peg driven through a hole in the piston at the proper distance from its upper end and at right angles to its long axis prevents its being pushed out of the cylinder at the outlet end. The whole can be quickly and firmly fastened to a rod of gas pipe by a screw thread in the upper end of the piston. When used, this tool is pushed down into the peat (same for marl) the required distance, with a plunger filling the cylinder. A sample is taken by drawing up the rod and the attached cylinder until the catch is heard to lock at the top of the length of cylinder, after which the cylinder is pushed down into the peat about its own length. This action fills it unless the peat is very wet or very hard. After it is full it may be drawn to the surface without danger of loss or of mixing with the overlaying material. The inclosed sample may then be pushed from the cylinder by unlocking and pushing in the piston.

CONTAINERS FOR SAMPLES

The samples of marl should be immediately placed in air-tight containers, sealed, and properly labeled. Mason jars with screw tops are very satisfactory as containers. The samples should always be taken by a representative of the chemical laboratory making the analysis. Samples taken by interested parties or by anyone other than the analyst or his representative are often of little value. Chemical analyses are of value only when the samples are representative of the character of the entire deposit.

PRELIMINARY SURVEY OF MARL DEPOSITS

Before undertaking an exhaustive investigation, a preliminary survey of the marl deposit is advisable. This preliminary survey should cover the following points.

1. *The general extent of the deposit of marl.*—Any exposures of the marl should be carefully noted. Drainage ditches will often serve to indicate something of the extent of the marl. They may or may not give trustworthy evidence about the depth of the marl. Exposures on the banks of lakes are reliable only when interpreted in the light of the geographic character of the depression in which the lake or bog is located. When the general location of the exposed marl is known, more detailed exploration is needed to establish the limits of the deposits. If the sampling devices, noted in a previous paragraph, are available, they should be used. In their absence a posthole digger

will serve to give an idea of the extent of the deposit. The depth and character of the marl can be noted at the same time. When the marl carries an overburden, its depth and character are of especial interest and importance. When the limits of the marl beds are rather generally established, approximate measurements of the distances involved may be made.

2. *The general character of the marl.*—When the extent of the marl deposit has been roughly determined, careful borings should be made at certain selected points. A careful log should be kept of the character of the overburden, the character of the marl at different depths, and the nature of the material under the marl. The occurrence of layers of sand in the marl or the presence of shells should be noted.

3. *The chemical composition of the marl.*—When several records such as have been described are available, samples should be selected for analysis. The greatest care and forethought should be used in selecting these samples. They must be as representative as possible of the deposit as a whole. Complete chemical analyses of these samples are essential. The essential factors to be noted have been previously discussed. The final interpretation should be made by someone familiar with marl deposits and their use in the manufacture of Portland cement.

FINAL SURVEY OF MARL DEPOSITS

If the results of the preliminary survey are such that an exhaustive investigation seems justified, a very carefully planned and executed survey becomes necessary. It would seem wise to have such a survey made by some individual or organization experienced in marl investigations. Certain general features of an exhaustive survey of marl deposits proposed as a source of calcareous material for a Portland cement plant are as follows:

1. *Map of the deposit and locality.*—The marl beds and their surroundings are carefully plotted and all of the landmarks indicated by means of a map or diagram. Any sudden changes in levels are noted. The position of the marl deposits with respect to section lines, public or private roads, water courses, etc., are clearly shown. This plot also gives all the known information about the transportation possibilities and possible plant locations. The areas of marl under water and above water, exposed and carrying an overburden, are shown. The borings made are also shown on this plot. They can, in this manner, be very exactly located.

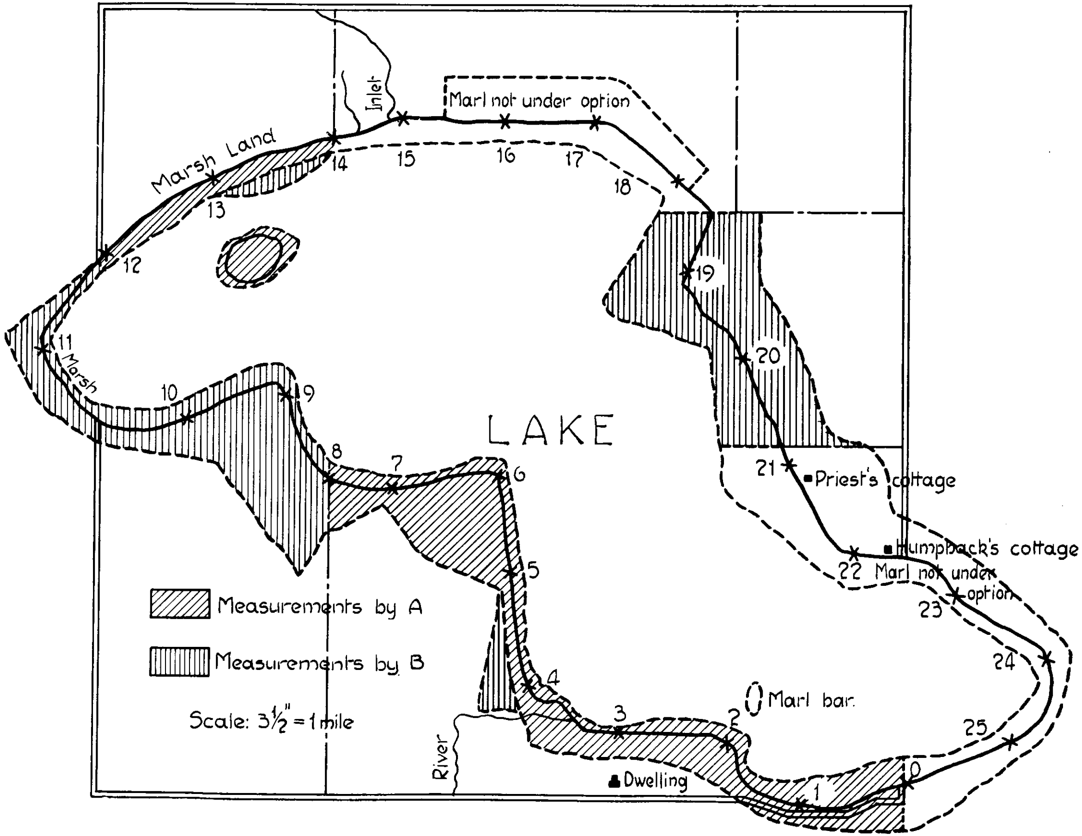
2. *Boring and sampling the deposits.*—When a plot of the marl beds and their surroundings is available, a very careful and systematic

procedure in putting down test holes is made possible. The exact number and location of holes can only be determined by considering the problem at hand. The borings must be made, first of all, to fix very definitely the exact limits of the marl beds. The outline of the marl deposit may be very irregular and no assumptions, even tho based on what seems to be good reasoning from topographic evidences, can be allowed. The depth of the marl beds must also be very exactly established. The depth of the marl may vary greatly even in adjacent portions of the lake or bog. Reference has been previously made to the advisability of checking carefully the character and composition of the marl, noting the presence of sand layers, etc. The depth of the water or peat above the marl is also of great practical importance.

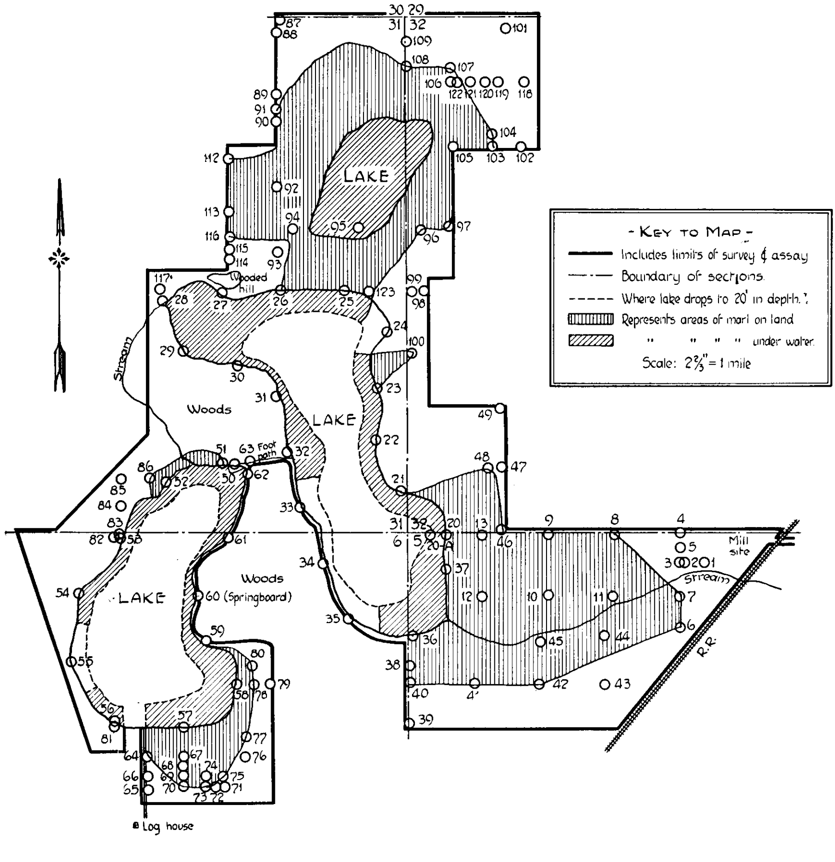
The number of samples of marl to be taken for analysis will vary greatly with the circumstances. In general, at least three samples of marl should be taken. One sample is taken from near the top of the marl, perhaps 8 to 10 inches below the surface. If the marl carries an overburden of peat or soil, the sample should be so taken that no contamination from the overburden is probable. The second sample is taken near the middle of the marl and the third near the bottom of the deposit. When the marl is more than 6 to 8 feet deep, a greater number of samples are taken. These samples should represent as accurately as possible the variations in the marl bed. When the marl is less than about 5 feet deep, two samples are sufficient.

The exact placement of the borings is so much a matter of judgment based on the topography of the land and the exposures of marl noted that it seems best to present two diagrams showing the actual location of borings on marl beds. These diagrams (Plate I and Plate II) represent two deposits actually investigated by a prominent laboratory for persons interested in their possible use in the manufacture of Portland cement. An inspection of these diagrams will show how the points selected for borings have served to delimit the deposits.

3. *Possible locations for the proposed plant.*—The possible locations for the proposed plant should be investigated. The plant site must be such that an orderly sequence of plant operations is possible. Room must be available for possible expansion of the industry. Shipping facilities are perhaps the most important factors. The mode of transportation of marl to be used will influence greatly the recommendations about plant location. In many cases it might be wise to locate a plant from one to three miles from the marl beds if advantages by way of improved shipping facilities or greater accessibility could be so gained.



MARL INVESTIGATION NO. I



MARL INVESTIGATION NO. 2

4. *Transportation of marl.*—The question of marl transportation is to be discussed in a later section of this report. The type and location of the marl deposits may influence greatly the recommendations made about transportation.

ANALYSES OF MARL SAMPLES

The samples taken during the preliminary and the final surveys of marl deposits are very carefully examined. The exact procedure to be followed with any particular sample will depend on the general scheme of the examination. Certain general principles which seem to apply to all such investigations will be discussed.

1. *Physical analyses.*—In some cases a physical examination of certain of the samples is advisable. Visual examination will often disclose sandy marl, etc. Sieve analyses are sometimes useful in establishing the character and amount of sand in any portion of the marl bed. Preliminary tests with representative samples of marl to establish the amount of water needed to make a workable slurry are very valuable.

2. *Chemical analyses.*—Complete chemical analyses are made on a fairly large proportion of the marl samples taken. The calcium carbonate content of all of them is determined. In certain cases, where the marl is very uniform, it may be sufficient to determine only the acid soluble and the acid insoluble portions of the dry marl.

IMPORTANCE OF A THORO INVESTIGATION

It is impossible to overemphasize the urgent necessity of having all of the surveying, sampling, and testing of marl deposits done thoroly and by competent men. The total cost of a thoro investigation carried out by experienced and competent analysts is small compared with the amount of money that is required to build, equip, and operate a modern cement plant. Lack of adequate knowledge may lead to serious financial loss or to complete failure. No one should invest money in a plant designed to utilize marl until a thoro investigation has been made and exhaustive tests carried out by competent and disinterested analysts. The cost of such an examination of a marl deposit might reasonably be expected to be between $2,000 and $5,000. Since a well-equipped plant could not be built and operated with a capital of less than $3,000,000, the investigational cost is relatively quite low. A number of laboratories are prepared to undertake such investigations and report on the feasibility of the projects. State securities commissions and similar bodies usually require such reports before authorizing the sale of stocks.

PLANT OPERATIONS ON MARL

The usual sequence of plant operations when marl is used does not differ from that in any other Portland cement plant. The details of certain operations are different and for that reason shall be discussed in somewhat greater detail than others.

EXCAVATION AND TRANSPORTATION OF MARL

The method of excavating marl will vary greatly with its character and location. When the deposit is well drained a steam shovel or a drag line excavator can be used and the marl loaded into cars and transported by rail to the plant. When the deposit is poorly drained or under water a floating dredge may be used. The marl is taken up from in front of the dredge by a "clamshell" or "orange-peel" bucket and the dredge floats in the excavation thus formed. The marl may be loaded into cars on the edge of the cut if the swamp is solid enough to support their weight. More often the cars will need to be placed on a floating dock or even on scows which can be towed to the shore and then transported to the plant by rail.

In some instances the marl is put through a mixing machine near the dredge and pumped to the mill as a slurry. This method of operation offers great possibilities, especially where the marl deposits are in a chain of lakes, some of which are several miles from the site of the plant. The Peninsular Portland Cement Company at Cement City, Michigan, has pumped marl several miles by such a pipe line. The construction costs are relatively low and the cost of operation is reasonable. This method of transportation deserves serious consideration as one solution of the transportation problem. Other companies transport the marl slurry to the shore in tank scows. At the shore it is pumped to the mill through a pipe line.

The method of excavating and transporting marl for any particular plant should be decided upon after a careful study of the character and location of the marl. The relative costs of various methods of excavation and transportation should be taken into account as well as the condition in which the marl arrives at the mill. If the marl must be moved more than a few miles water transportation may be found the cheaper.

From the standpoint of efficient plant operation that method of excavation and transportation is most desirable which will deliver the marl to the mill with the smallest water content. For this reason excavation of lake marls by an orange-peel dipper and transportation in cars is good practice. With all save very fluid marls the orange-peel

FIGURE 10. EXCAVATING MARL, AETNA PORTLAND CEMENT CO.

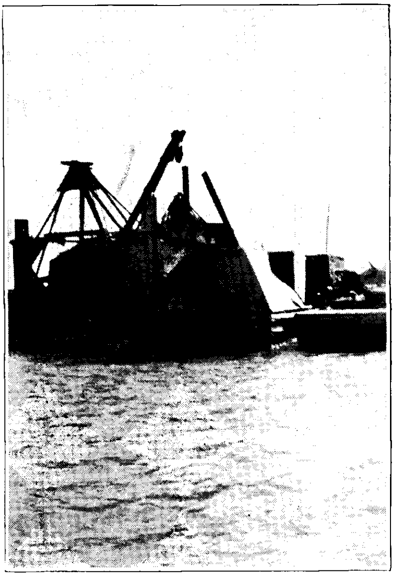


FIGURE 11. LOADING MARL IN SCOWS AT FENTON, MICH.

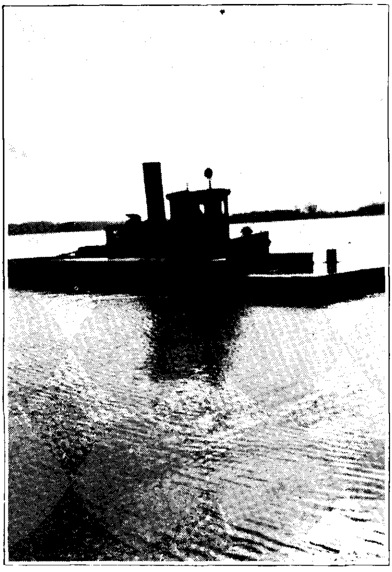


FIGURE 12. TUGGING SCOWS ACROSS THE LAKE AT FENTON

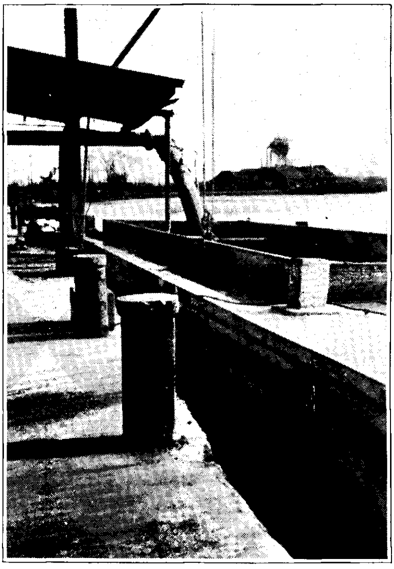


FIGURE 13. PUMPING MARL OUT OF SCOWS AT FENTON

bucket allows the water to drain off quite completely and yet retains the marl. The cars give additional opportunity for the escape of water. It should be noted that a skilled and watchful operator on the dredge can greatly reduce the amount of water in the marl as transported to the mill. Care on his part will also materially reduce the amount of sand or of organic matter taken up with the marl. Care and forethought in excavation will also aid the plant operations by insuring a greater uniformity of material. For this reason the marl should be excavated vertically from the top to the bottom of the deposit, rather than horizontally.

The cost of excavating and transporting marl is relatively low. No blasting is necessary in excavating marl. Not many men are required and the maintenance cost is low as compared with quarry operations. This represents one decided advantage of marl over limestone as a raw material. The necessary marl and clay for a barrel of finished cement will probably cost only about one half as much delivered at the plant as hard limestone and shale. Exact costs are difficult to predict because of varying factors such as wages, cost of power, etc.

EXCAVATION AND TRANSPORTATION OF CLAY OR SHALE

Clay is usually excavated by a steam shovel and loaded on cars for transportation to the plant. Shale may need preliminary blasting before the steam shovel can handle it readily. The methods in vogue for handling clay and shale at marl plants do not differ from those used at limestone plants. The costs will be very nearly the same.

MIXING AND GRINDING OF RAW MATERIAL

The marl comes to the mill in a form that usually requires no preliminary grinding before mixing. It may require screening to remove stones and twigs. When pumped from the deposit or the lake shore it has already been thoroly mixed. If delivered to the plant by cars it is passed through a pug mill to give a uniform material.

When clay is used it is sometimes crushed through rolls and then mixed with water in a "wash mill." A more usual practice at plants using marl is to grind up the clay in a mill of the general type known as "dry pan," "edge runner," or "wet pan" mills. In this type of mill the material is crushed in a pan under a pair of heavy rolls, the rolls having two motions, rotating on a horizontal axis and revolving as a whole about a fixed vertical axis. Shale requires more preliminary crushing before going to the edge runner mill than does clay but is handled in much the same manner.

In wet process plants using limestone the wash mill or wet pan method of handling the clay has some advantages, but for plants using marl dry grinding of the clay is advantageous, since the water content of the marl-clay mixture is more readily kept within the desired limit when the clay is added in the dry condition.

The marl and clay or shale are mixed in the determined proportions in a tank. Here the materials are thoroly intermixed by mechanical agitation.

The mixture is next passed to the grinding equipment. This is of the ball grinding type. Kominuters, ball mills, tube mills, or various combinations of these machines are generally used. The grinding of these soft, wet materials is relatively easy and the costs are relatively low. This represents another decided advantage in the use of marl.

WATER CONTENT OF SLURRY

The one point which should be the most carefully watched in the mixing and grinding department of a cement plant using marl is the water content of the slurry as it goes to the kiln. The equipment and operations should all be those designed to produce a slurry of as low a water content as is possible. Under no circumstances should it go much above 50 per cent, for fuel costs in the kiln increase rapidly as the water content mounts. Because of the tendency of marl to form a semi-colloidal solution with water, it has as yet been impossible to produce slurries with the low water content that is found in wet process plants using limestone. Such plants often operate with slurries bearing as low as 30 per cent water. Many plants have attempted operation using marl when its character and their method of operation were such as to give a water content of 60 to 70 per cent. Such plants were manifestly doomed to failure when subjected to the competition of plants using better methods. Reference has already been made to the suggested possible reduction of water content by adding small amounts of certain chemicals designed to increase the fluidity of the slurry. Such a possibility would seem to merit careful consideration. Plant scale experiments would be necessary to establish the worth of such a process. The following abstract of a pamphlet[3] published by the British Portland Cement Research Association is taken from *Chemical Abstracts* 17:1539. 1923.

[3] J. W. Christelow and E. Bowes. The Viscosity of Raw Material Slurry Used in the Manufacture of Portland Cement. *British Portland Cement Research Association Pamphlet*, No. 2, 1922.

It has been known for many years that small quantities of certain substances, particularly Na_2CO_3, reduce the viscosity of mixtures of clay and water. The object of this investigation was to determine the effect of such substances on the viscosity of slurry and to devise a laboratory method suitable for use in cement plants. Most of the work was carried out with Na_2CO_3 but other Na and Ba compounds were tried out also. The effects of time of storage, temperature, electric current and sol. compounds originally present in the slurry were studied. Viscosities were determined by the use of a viscosimeter consisting of an inverted glass bottle (from which the bottom had been removed) fitted with a cork through which passed a glass tube 5/16 in. in diameter and 2¼ in. long. Both ends were rounded and the upper end of the tube was flush with the cork. The viscosimeter was filled with slurry to a given mark and the time necessary for 250 cc. to flow from the apparatus noted with a stop watch. Readings were made in triplicate on samples that had reached room temperature. No stirrer was found necessary. The viscosity was expressed either in seconds or in water units (which equals the time in seconds for a slurry divided by the time required for water, that is 4.3 seconds). Preliminary results showed that the most advantageous amount of Na_2CO_3 to use is 0.075%. Eighteen samples of slurry from 11 plants treated with this amount showed decreases in viscosity equivalent to 0.6% to 4.6% H_2O. For example, a slurry containing 40% H_2O had the same viscosity after the addition of 0.075% Na_2CO_3 and a decrease in the H_2O content to 36%. Data showing the increase in economy of operation of a plant as a result of decreasing the H_2O content of slurry are given.

The following illustration of the possible application of this idea to plant operation is quoted from the British pamphlet in the mill section of *Concrete*.[4]

A slurry originally containing 40% water can be worked with 36% water by an addition of 0.075% sodium carbonate.

The cost of sodium carbonate per 100 tons clinker is £1.76 from the preceding formula, assuming the price to be £10 per ton.

A reduction of 1% in the water of a slurry results in an average saving of 0.425 tons standard coal per 100 tons clinker. This figure is obtained from the work of the British Portland Cement Research Association on the Thermal Efficiency of the Rotary Kiln.

The reduction of water in the slurry from 40% to 36% therefore represents a saving of 1.7 tons of standard coal per 100 tons clinker.

The value of the coal saved, at £1.5 per ton delivered at the coal firing nozzle, is £2.55 per 100 tons clinker. The *economy* is therefore represented by 15*s* 10*d* per 100 tons clinker.

It is suggested that the sodium carbonate should be added to the slurry as a solution of the proper strength.

The slurry after final grinding is sent to one of a series of storage basins. As each tank is filled a sample is taken and subjected to chemical analysis. If the proper proportion of ingredients is not present the slurry is sometimes corrected by adding the required amount of

[4] Anon. The Viscosity of Raw Material Slurry. *Concrete* (mill sect.) 23:91. 1923.

marl or clay. More often, however, the slurry is corrected by mixing the tank of material low in one ingredient with another tank high in the same ingredient. This mixing is carried out in a blending tank of about twice the capacity of the slurry tanks. An analysis of the contents of the blending tank is usually made before the slurry is fed to the kiln. Evidently this system of handling the material going to the kilns gives an opportunity for very exact chemical control. Consequently the finished cement is very uniform in character.

BURNING THE CLINKER

The slurry is calcined in the usual rotary kilns. The practice in burning is essentially the same whether the raw calcareous material be marl or limestone. From the figures given for water content it is evident that the production of cement from a given kiln will be less with a marl than with a limestone slurry. Evidently, too, the same kiln, using the dry process, will have an even larger production. The fuel cost per barrel of cement will also usually be less with the slurry of low water content and even less with the use of the dry process. This difference is much less with long than with short kilns.

It should be noted that the general tendency in cement technology has been towards the use of longer and longer kilns. Twenty-five years ago the standard length of a kiln was 60 feet. The proved success of longer kilns (150 feet) at the Edison plant turned the attention of cement plant men to the advantages of the long kilns. At the present time very few, if any, new plants are equipped with kilns less than 150 feet long, regardless of the type of raw materials used. Many kilns of 175 to 200 feet in length are in use and some kilns 275 and 330 feet in length are in operation. The longer kilns have given, with both the dry and the wet process, reduced fuel costs and have shown decided decreases in stack temperatures. Reference has already been made to the 330-foot kilns of the new Phoenix plant. Especially with the wet process has the use of long kilns introduced greater efficiencies. Many of the marl-using plants built with the very short kilns of twenty years ago have found it impossible to continue operations with such antiquated equipment.

Where the supply of marl has been sufficient to justify the installation of long kilns the plants have continued profitable operation. A plant designed to use marl should have kilns at least 175 feet long. If not equipped with waste heat boilers—and it should always be so equipped—the kilns should be not less than 200 feet long. Probably 200-foot kilns with waste heat boilers would be found the most satisfactory equipment. The diameter of rotary kilns seems also to be a factor which deserves study. Some mills have increased the diameter of the lower end of the kiln and feel that this increases the capacity of the kiln.

WASTE HEAT BOILERS

The most recent development in the Portland cement industry has been this successful introduction of waste heat boilers. They utilize the heat of the hot gases leaving the kilns. Otherwise this heat would be lost. This development, while of theoretical interest for many years, was forced upon the manufacturer by the great increases in the cost of fuel during the war and the post-war periods. The results obtained in practice are such as to render it evident that any new installation should include waste heat boilers in order to meet the competition of other plants. Many old plants are installing waste heat equipment and it seems possible that the extraordinarily long kilns being installed by some companies could better be replaced by somewhat shorter kilns equipped with waste heat boilers. This is, however, a debatable question.

Many plants find that waste heat boilers furnish all the power needed. Some plants even have a surplus of power to be disposed of outside of their own establishments. Waste heat installations are especially advisable in plants using the wet process. Altho the stack temperatures are lower than in the dry process, the specific heat of the stack gases is higher, due to the large amounts of steam present. Shaffer[5] makes the following statements after describing the early attempts to use waste heat boilers.

> It will therefore, be seen that the early endeavors to utilize successfully the heat in the kiln exit-gases showed the necessity for the precipitation and the removing of much of the dust before these gases entered the boiler.
>
> Profiting by these early experiences, the next waste heat boiler in the cement industry was somewhat removed from the upper end of the kiln with a substantial flue constructed between the kilns and the boilers. Economizers were placed after the boilers and an induced draft fan after the economizers. Another feature of this installation was the provision for firing the boilers by hand when the kilns were not operating.
>
> In comparison with present efficiencies this installation did not show up very well, but when it is considered that the plant was designed in 1903 and is still operating and developing approximately one-half of the steam required to operate the entire plant, the results are quite creditable.
>
> We also find that some of the earlier installations were designed and constructed without giving proper consideration to air leakage, this condition prevailing both at the kiln openings and boiler settings. Little or no importance was attached to the infiltration of cold air at the upper or rear end of the kiln.

[5] H. A. Shaffer. Waste Heat from Cement Kilns Operates Entire Mill. *Chemical and Metallurgical Engineering* 29:18. 1923.

Regulation and control of draft, another important factor in obtaining maximum efficiency in kiln and waste heat equipment, were also partially neglected, which is another reason the early waste heat boilers in the cement industry failed to show the results of performance attained with present-day equipment.

The modern waste heat boilers are closely connected to the kilns. Air seals are placed on the upper end of the kiln shell to exclude the cold air at this point. All clean-out doors on dust chambers, flues, and at the bottom of each pass in the boilers are tight fitting and in many places are protected with a plastic clay mixture at the joints which is renewed each time the dust is removed. Great care is also used in the construction of the boiler settings, to make them airtight.

Probably the higher percentage of rating developed and over-all efficiency of the boilers installed during the past 6 years over the old equipment are due principally to changes in the design of the boilers utilizing waste gases from cement kilns. Further study and experimentation showed that the rate at which heat is transferred from low-temperature kiln gases to the metal surface of boiler tubes increases as the velocity of the gas increases. Furthermore, if this velocity were increased three times, the heating surface could be reduced one half. It was, therefore, found that instead of a boiler with more than 20 square feet of heating surface for each boiler-horsepower generated, one with 10 square feet of water heating surface would suffice. Lengthening of the gas passages was also found to increase the efficiency of boilers for this purpose. This is best accomplished by rearrangement of the baffle walls in the standard boilers.

One other reason for higher efficiency in the modern waste heat systems in cement plants is the scientific control which is exercised in the handling of the entire system. Analysis of the waste gases is made at regular intervals throughout the day. Hourly readings are recorded of the draft at various points throughout the system. Steam and water flow meters show the amount of water used, and pyrometers and recording thermometers are also installed for the purpose of recording the gas, water, and steam temperatures throughout the entire system.

That intelligent regulation and control is a paying proposition from the front end of the kiln to the fan after the economizers, has been clearly demonstrated in many modern Portland cement plants. Probably the one outstanding feature in the development of the waste heat boiler in the cement industry is the fact that quite a number of plants are now producing all of the power required to operate their entire plants in waste heat boilers. This condition prevails not alone in the dry process but during the past year has been shown possible in the wet process of manufacture.

It should be stated, however, that the ability to develop 100 per cent of the power required to operate any cement plant depends largely on the character of the prime movers and to fairly low kilowatt-hours per barrel consumption in the various mill departments. Some of the older plants with old style reciprocating engines or high steam consuming turbines are obliged to operate some auxiliary boilers in addition to their waste heat equipment. There are, however, plants of later design with low steam consuming prime movers and a satisfactory consumption of power in the raw and clinker grinding departments which are experiencing no trouble at all in generating 100 per cent of their power requirements. It should be borne in mind, however, that in order to effect these savings, which amount to from 30 to 50 pounds of coal per barrel of cement manufactured, large sums of money must be added to the already high investment. As an example, depending upon the size of the cement plant, the cost of the equipment of a modern waste heat plant will vary from $250,000 to $700,000. There are now (1923) thirty Portland cement factories with waste heat boilers installed. Many other companies have plans under consideration which call for this improvement; undoubtedly the high cost of construction and equipment is causing delay on the part of some companies; however, they all recognize the importance of conserving the heat in the waste gases from their rotary kilns.

The Petoskey Portland Cement Company, at Petoskey, Michigan, built the first wet process plant equipped with waste heat boilers, as a part of the original plans. This plant was completed and put into operation in March, 1921. At that time two kilns, 10 × 150 feet, and two boilers constituted the kiln room equipment. Within the last two years, two more kilns and two additional boilers have been added, giving the plant a rated capacity of 5,000 barrels per day.

The Petoskey installation attracted much attention and has been so successful that many existing wet process plants have installed similar equipment and many other plants are considering the advisability of such installations.

The Newago Portland Cement Company, located at Newago, Michigan have recently installed a waste heat system and have disposed of their water rights and their hydroelectric plant. All the power used in their plant comes from the waste heat boilers. The Peninsular Company at Cement City have also recently installed waste heat equipment.

THE POSSIBLE USE OF POWDERED PEAT AS FUEL

The usual fuel used in the kilns is powdered coal. Most of the marl-using plants must ship in their coal. This adds greatly to the cost of producing the cement. The proposal is often made that powdered peat be used to fire the kilns. The marl beds often occur in close juxtaposition to peat bogs. In fact the swamp marls often carry an overburden of peat. In Michigan, about twenty years ago, a company was organized and a cement plant projected to use peat. Little else is known of this attempt. It evidently was not a success as the plant changed over to the use of powdered coal. The high cost of coal and the increased freight rates have again brought this proposal to the minds of cement mill technologists. No adequate experimental basis exists for designing a cement plant to use peat as fuel. Doubtless such a plant would have to pass through the experimental stage and be remodeled in the light of the knowledge so obtained before it would be a commercial success. The excavation and drying of the peat also present many difficulties. However, powdered peat has been used for steam raising purposes with some degree of success.

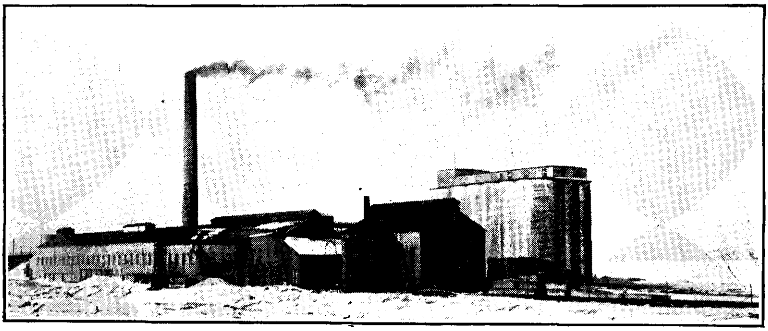


FIGURE 14. PLANT OF THE PETOSKEY PORTLAND CEMENT COMPANY AT PETOSKEY, MICH.

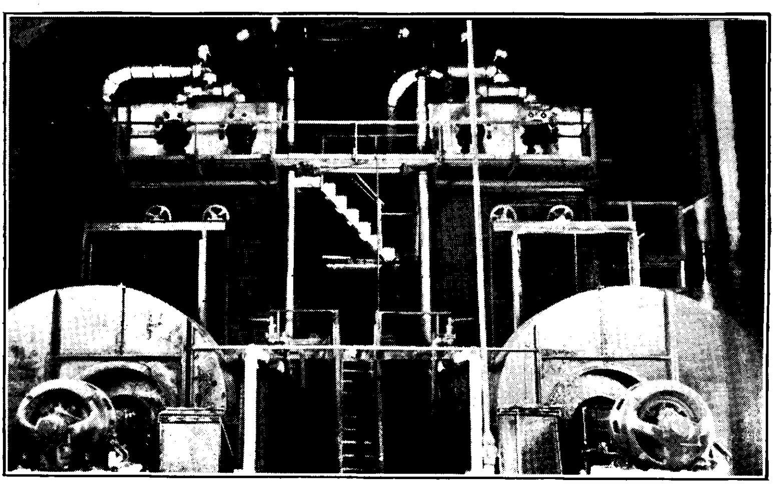


FIGURE 15. WASTE HEAT BOILERS AT PETOSKEY PLANT

The use of powdered peat as fuel is discussed by Soper[6] as follows:

For certain commercial uses powdered peat has many advantages over machine peat. The cheapest way to prepare it is by the airdrying process, by which the moisture may be reduced in the field. If raw peat is allowed to lie in heaps until natural drainage and evaporation have reduced the moisture content to about 50 per cent, it may be prepared for use under steam boilers by driving off about half the remaining moisture with waste heat from flues or other sources and pulverizing the resulting material. The powdered peat may then be blown with compressed air into the furnace, where, by means of forced draft, ignition is almost instantaneous, and instead of burning on the grate the peat forms a gas which gives a uniform fire throughout the combustion chamber. Good peat thus treated, when burned in furnaces designed to give the most complete and efficient combustion, will generate nearly as much energy in the form of live steam as the same weight of powdered coal. According to reports in this country powdered peat has great possibilities, not only for boiler-firing but for metallurgical work and for use in cement and other kinds of kilns in which powdered coal has been successfully burned.

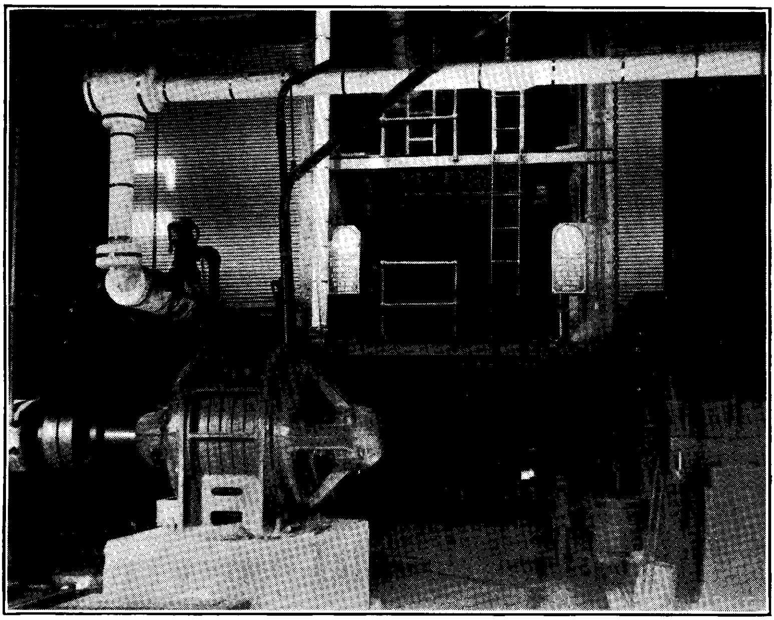


FIGURE 16. WASTE HEAT INSTALLATION AT NEWAGO PLANT

The proposal has also been made to utilize the producer-gas from a peat fired producer-gas furnace to burn the clinker. Here, too, no adequate experimental basis is known for the design and construction

[6] E. K. Soper. Occurrence and Use of Peat in the United States. *United States Geological Survey Bulletin* No. 728, p. 71. 1922.

of such a plant. The present experiments of the Bureau of Mines with peat in a producer-gas furnace may be of value in the future. Cement kilns are fired with natural gas where a plentiful supply of that fuel is available.

It should be said that the use of peat as a fuel for producing cement from marl would be very desirable from the standpoints both of cost and utilization of natural resources. Commercial companies cannot, however, be expected to undertake such a project until they can see their way clear to successful and continuous operation and consequent financial success.

FUEL CONSUMPTION

The fuel consumption is related directly to the length of the kilns, the stack temperatures, and the amount of water in the slurry. The quality of the coal is also a factor worthy of note. Most plants use a good West Virginia soft coal with not to exceed 10 per cent ash. Table VIII gives the proximate analyses of fuels used in burning Portland cement clinker at certain plants in the United States. Where the kilns are long enough that the stack temperatures may be kept between 700 and 800 degrees F., a marl slurry of about 50 per cent water will require from 125 to 150 pounds of such coal for each barrel of cement. The use of waste heat boilers will enable the recovery of at least enough energy from the stack gases to furnish the power for the other operations of the plant.

CLINKER GRINDING AND PACKING

The operations in these departments are the same whether marl or limestone is used and no attempt will be made to discuss them in detail.

STORAGE

Any Portland cement plant must provide adequate storage to ensure its customers a continuous supply of cement. The consumption of cement is seasonal in character. When construction and road building are in full swing, the demand for cement is strong. When severe weather curtails these operations the demand drops off. As a result a plant must have rather extensive storage facilities to enable it to continue operations when the market no longer absorbs its product. Storage space for at least three months' to six months' output of the plant would seem desirable.

WET PROCESS VS. DRY PROCESS

Since the use of marl in the manufacture of Portland cement necessitates the adoption of the wet process (called semi-wet in Europe), a comparison of the two processes will be made.

TABLE VIII

ANALYSES OF KILN FUELS USED IN BURNING PORTLAND CEMENT CLINKER

Volatile Matter	Fixed Carbon	Sulphur	Ash	Moisture	B.T.U. per Pound	Company	Source of Fuel	Authority
38.13	52.35	...	8.48	1.04	13,500	Alpha	Ave. 5 bit. coals	Anderson
39.92	52.00	0.97	8.08	1.46	12,243	Nebraska	Rock Springs, Wyo. coal	Latimer
33.59	52.69	1.20	12.03	1.36	12,595	Petoskey	Slack and screenings ave. 1925	Phillips
28.13	42.24	4.07	18.43	11.20	10,145	Pyramid	Iowa coal	Boberg
36.98	54.07	2.49	8.95	....	13,856	Atlas	West Va. coal used at Northampton, Pa.	Hicks
34.51	52.73	2.72	12.76	2.52	12,399	Atlas	So. Ill. coal used at Hanibal, Mo.	Hicks
31.57	57.28	2.54	11.15	....	13,340	Atlas	W. Pa. coal used at Hudson, N. Y.	Hicks
32.79	55.31	1.27	11.90	....	13,372	Atlas	Central Ala. coal used at Leeds	Hicks
37.40	53.94	...	8.66	....	.....	Allentown	W. Va. gas coal	Breerwood
41.91	46.72	0.63	9.33	2.04	13,320 (dry)	Sun	Utah soft coal	Ludgate
24.69	63.45	...	11.86	....	.....	Dixie	Tenn. soft coal	Fischer
29.71	51.30	...	18.99	....	.....	Dixie	Tenn. soft coal	Fischer
26.66	58.58	...	14.76	....	.....	Dixie	Tenn. soft coal	Fischer
33.16	57.12	0.65	9.72	....	14,100	Clinchfield	Southwest Va. coal used at Kingsport	Guenther
37.35	56.34	0.70	6.31	....	13,715	Clinchfield	Kentucky coal used at Clinchfield	Guenther
42.35	36.13	5.75	21.52	15.00	9,984 (dry)	Hawkeye	Iowa coal	Condon
35.00	52.72	1.68	12.28	4.01	12,328 (dry)	N. W. States	Franklin Co. Ill.	Blackmore
35.28	52.86	1.61	11.86	2.67	12,648 (dry)	N. W. States	Franklin Co. Ill.	Blackmore
36.87	55.41	...	7.72	....	.....	Coplay	W. Va. gas coal	Johnston
38.50	47.70	2.72	13.80	....	13,016 (dry)	South Dakota	Sheridan, Wyo. coal	Ernst
39.65	49.00	2.71	11.35	....	12,437 (dry)	South Dakota	Colorado coal	Ernst
34.67	54.72	0.95	10.62	....	12,914	Newago	Ky. and W. Va. coals	Miller
36.00	55.00	...	8.00	1.00	.....	Sandusky	Ave. coal from various sources	Newberry
33.73	46.89	0.82	18.56	....	.....	Colorado	Colo. coal	Banks
34.47	47.75	2.75	16.43	1.35	12,150	Dewey	Kan. and Okla. coal	Chamberlain
20.55	76.53	0.86	2.21	0.71	16,015	Dewey	Petroleum coke	Chamberlain
33.41	58.92	0.81	7.67	....	13,503	Wolverine	Mixed nut, pea, and slack	Hutchins
34.75	54.35	...	10.90	....	13,245 (dry)	Peerless	W. Va. and Ky. coal	Simmons
32.81	56.53	...	9.52	1.08	.....	Peerless	W. Va. and Ky. coal	Simmons

The wet process involves the mixing and grinding of the materials in the presence of water. The resultant slurry is then introduced into the kilns. This process is always used for marl and may be used for hard limestone and cement rock. It has also been used with blast-furnace slag.

The dry process involves the mixing and grinding of the raw materials in as dry a condition as possible. The resultant mixture is introduced into the kilns dry. This process has been widely used for limestone and cement rock. Much of the blast-furnace slag used for making cement is handled by this process.

The first Portland cements manufactured abroad and in this country were made by the wet process. With the extended use of the dry, hard limestones and cement rocks in this country the dry process was introduced and developed. It was a method ideally fitted to the raw materials most plentiful in the United States from the standpoint of cement mill practice as then known. The great success of this process led cement technologists in general to consider it the best one. Only within the last ten years has the wet process again attracted serious attention and study. The changed economic conditions and the improvements in plant design and construction, especially the lengthened kiln and the waste heat boiler, have caused many companies to build wet process plants, even where limestone or cement rock was to be their raw material. Where the composition of the raw materials varies from time to time the wet process is favored because it affords a better opportunity for blending the materials before they reach the kiln.

1. *Advantages of the dry process.*—The advantages of the dry process may be enumerated as follows:

a. Less fuel is used per barrel of cement—there is no water to be driven off in the kiln. There is not such a decided advantage in this respect with kilns of 200 feet in length and longer.

b. There is a decreased overhead cost per barrel of cement—due to the larger amount of cement burned in the kilns each twenty-four hours.

c. Dry materials may be ground exceedingly fine—thus insuring intimate mixing of materials and complete reaction in the kilns of all the particles.

2. *Advantages of the wet process.*—The advantages of the wet process are as follows:

a. Complete chemical control of the character of the mix is possible—thus giving a more uniform product. Correction of the mix may be readily made before burning. Certain plants using the wet process claim a deviation of only 0.1 to 0.2 per cent in the composition of the slurry entering the kiln.

b. Lower stack temperatures are obtained—around 800° F. being usual practice in wet process plants as compared with around 1500° F. in dry process plants. This tends to offset the increased amounts of fuel needed to drive off the water.

c. The cost of grinding raw materials is less than in the dry process.

d. More intimate mixing of raw materials can be obtained without such fine grinding as is necessary in the dry process.

e. Waste heat boilers can be used to great advantage.

It is worthy of note that the great majority of the plants built within the last few years have adopted the wet process. Indeed, a prominent magazine in the cement trade has recently described a new cement plant as being "the first new dry process plant in three years." While it is impossible to predict accurately the future technologic development of the Portland cement industry, it would seem that in the future wet process plants when properly designed and constructed and especially when equipped with waste heat boilers will be able to compete on at least even terms with dry process plants. In fact many devices for blending raw materials are being introduced by the proponents of the dry process to offset the wet blending of the wet process plants. The introduction into modern cement making of these improvements tending to favor the wet process has also favored the use of wet raw materials such as oyster shells, etc., from bays and rivers.

An advantage has so far accrued to the wet process plants using limestone as compared to those using marl because of the smaller amount of water needed to make a workable limestone slurry. Only from 30 to 40 per cent water is needed for limestone while marl slurries have seldom been produced with a water content below 47 per cent. This is offset, in part at least, by the decreased grinding cost with marl and by the small cost of excavating the marl.

PLANT DESIGN

There is in existence at the present time no plant with complete modern equipment designed to use fresh-water marl. As a consequence a plant intended to use such marl must be designed by adapting certain features developed in the industry where other raw materials are in use. Some rearrangement and remodeling must be anticipated before such a plant can operate to its greatest efficiency. The financial arrangements of a company building such a plant must allow for some adjustments and its financial backers must expect such changes. The failure to realize this has been the cause of the abandonment of projects which might otherwise have succeeded. The financial backers of the companies had been led to expect immediate profits and, when more capital was needed, the projects were discontinued. The operations of the companies that use oyster shells, etc., are of great interest in this connection. Their success with modern equipment indicates what might be done using marl.

In a general way, the requirements which seem quite definite for a plant designed to use marl will be outlined. Attention has already been called to the planning of operations and equipment to the end of keeping as low as is possible the amount of water in the slurry. It would seem that the capacity of the mill could not well be much below 2,000 barrels daily without greatly increasing the overhead costs. While many mills have operated in the past with smaller capacities, this would seem to represent the minimum capacity advisable under present day conditions. Two 10×200 foot kilns of standard construction and equipped with waste heat boilers should produce this amount of cement if well and carefully handled. A larger plant would give greater economies of operation. A plant of this size is suggested as the minimum for fairly efficient operation. The capacity of the raw-grinding and clinker-grinding machinery should be such as to insure continuous kiln operation. The general plan of the plant should be such that the materials would pass in an orderly progression from raw materials storage to finished materials storage. Mechanical transportation of all materials is essential. A bulky product like Portland cement can only be economically produced by utilizing to the utmost mechanical labor-saving devices. Electrical operation of machinery is recommended.

SHIPPING FACILITIES

The shipping facilities are of prime importance in locating a Portland cement plant. A location on two or more railway lines is desirable. As has already been noted water transportation is extremely advantageous. Location near a large consuming center is of major importance.

PLANT MANAGEMENT AND OPERATION

Experienced and competent engineers and chemists will be needed in a plant using marl even more than in one where the practice is more standardized. A large measure of energy and initiative must be added to their knowledge. On the judgment and discretion of the staff will depend in large measure the success or failure of the plant. They must beware of impractical ideas and yet be open-minded to any possible improvements in operation. The operating officials of the plant should be responsible to the company only for results. In matters of plant operation and control they should be given a free hand.

OFFICE ORGANIZATION AND SALES FORCE

The office organization is mentioned here only because some companies have been financial failures because of large overhead costs due to poor office organization or to unreasonably large salaries paid for supervision. Evidently the same principles of economy and efficiency that apply in other lines of enterprise will apply to the office organization and sales force of a Portland cement company.

CAPITAL

A rather large amount of capital must be available for the building and operating of a Portland cement plant. Modern machinery is expensive and its installation difficult. Building costs are still quite high and promise to remain so. Adequate supplies of raw materials must be acquired and means of transporting these materials provided. Men competent to design and construct a cement plant are scarce and high priced.

In addition to all the expense incident to construction of a plant the management must expect to finance at least one year's output before the income from the sale of cement will be sufficient to meet even operating costs. This is because of the difficulty with which a new brand of Portland cement will be introduced to the market. Engineers and contractors are always reluctant to abandon a tried brand for a new and untried brand. As a result any new brand of cement must win its way into favor by a slow process.

It would seem reasonable to say that for a 2,000-barrel a day plant a working capital of at least $3,000,000 would be needed to enable the plant to be constructed and operated, and its product firmly placed on the market.

SUMMARY OF CONDITIONS ESSENTIAL TO THE SUCCESS OF A MARL-USING PORTLAND CEMENT PLANT

To summarize briefly it would seem that the following conditions are essential to the successful operation of a Portland cement plant using marl and clay or shale.

1. An adequate supply of marl and of clay must be known to be available. It has been estimated that 320 acres of marl 20 feet deep would be needed to supply a 2,000-barrel mill for thirty years. Other marl beds near-by would be desirable.

2. The quality of the marl must be high. Careful investigation should be made as to the character of the marl by competent analysts.

3. The plant should be designed by competent engineers and controlled and operated by experienced engineers and chemists.

4. Modern equipment should be used—long kilns and waste heat boilers should be installed.

5. The machinery and methods of handling the raw materials must be such as to keep the water content of the slurry below 50 per cent.

6. No fancy salaries should be paid to managers or salesmen and little money should be spent for promotion.

7. A capital of not less than $3,000,000 is recommended as a minimum figure.

8. The plant must be advantageously located with respect to a market for its product, and with respect to shipping facilities. Freight rates determine quite largely the location of cement plants.

9. The plant should be located in a territory where there is no limestone suitable for use in the making of Portland cement.

In a territory where a quality of limestone suitable for use in cement is available it would probably not be wise to attempt operations using marl. The theory and practice of modern cement making have been almost entirely developed in plants using limestone. The design and operation of such a plant would not present the difficulties that should be expected in a plant designed to use marl. As previously pointed out, a company considering the use of marl must expect to pass through a period of experimental development and must provide funds for possible partial changes in process or equipment.

Where a supply of suitable limestone is lacking, the character and amount of the marl deposits should be carefully investigated. Under the conditions enumerated in the preceding paragraphs a Portland cement plant using marl should be a technologic and a financial success.

MARL DEPOSITS OF MINNESOTA

No adequate survey of the marl deposits of Minnesota has as yet been made. The Division of Soils of the University of Minnesota has collected more data on marl deposits than has any other agency. These data have been accumulated in connection with their work in the liming of soils with marl.

The Minnesota State Geological Survey expects to start in 1926 a preliminary survey of the marl deposits of the state. This is to be followed by a more detailed study of such deposits. These projected surveys will add greatly to our knowledge concerning the character, location, and extent of the marl beds of Minnesota.

Marl deposits are known to be numerous in the state. Their quality is variable. No definite information is at hand as to their extent. It would seem likely that many fairly large deposits exist whose location is unknown. In general the marl deposits of the state are found in the central and northern counties of the state, altho marl deposits have been reported from some southern counties. Many peat bogs prove to be underlaid by marl. This marl may be of high quality but often is mixed with organic matter. Table IX gives some incomplete analyses of Minnesota marls.

TABLE IX

ANALYSES OF MINNESOTA MARLS

Locality	Insoluble in Acid	Organic	$CaCO_3$	$MgCO_3$
Hill City*	3.78	not. det.	90.84	2.45
Coon Creek*	12.84	not. det.	63.60	1.90
Aron†	9.54	not. det.	81.84	Trace
Fergus Falls‡	4.01	not. det.	89.74	4.48
Barrows§	6.80	1.57	91.63	
Benton Co. 2½ miles east of Rice§	17.72	1.02	82.26	
Long Lake, Crow Wing Co. 7 miles east of Pequot§	1.64	3.75	94.61	
Anoka Co. near Central ave. road§	8.14	8.12	83.74	
Do. Semiliquid part of slough§	8.04	21.30	70.66	
Anoka Co. drainage ditch north of road§	8.15	9.47	72.38	
Central ave. pit¶	8.20	13.12	78.68	
Owatonna¶	38.61	5.21	56.18	
Rice Lake near Bena¶	7.54	20.17	72.29	
Rice Lake near Bena¶	5.44	13.16	81.40	
Lake of the Woods Co. Henderson pit¶	68.25	1.84	29.91	
Newman pit near Brainerd¶	8.30	12.79	78.91	

* Division of Soils, University of Minnesota.

† State Highway Department, 1921, R. E. Kirk, analyst.

‡ *Twenty-Third Annual Report United States Geological Survey.* 1894.

§ C. H. Dow, *University of Minnesota Engineering Experiment Station Bulletin.* No. 1. 1923.

¶ State Highway Department, 1923-25, M. A. Peterson, analyst.

LARGE DEPOSITS OF MARL

For possible use in the manufacture of Portland cement only the large deposits are of interest. Several deposits of apparently high grade marl are known which would warrant further investigation to determine their exact extent and character. Other large deposits may be found whose existence is not now known.

Dr. F. J. Alway, of the Division of Soils, reports a large deposit of marl at Hill City. Its exact extent has not been determined. The lake, with a shore line of three to four miles, contains large amounts of marl. The deposit varies from seven to fifteen feet in depth. An analysis is given in Table IX. This marl bed is also worthy of consideration because of its location near a railroad.

Dr. Alway also reports a deposit at Riley Lake south of Taconite. The deposit is estimated to contain about one hundred twenty acres.

A marl deposit near Bacchus has been noted by Dr. Alway and his co-workers. This bed is one-half mile wide and three miles long. The depth where explored is about twenty feet. The marl is of a high grade. The Division of Soils has opened up a marl pit on one end of this deposit. This pit is about one-half mile from the Minnesota and International Railroad. The end of the deposit near the railroad is well drained and could be worked by a steam shovel or drag line excavator. The end of the deposit farthest from the railroad is much wetter. This deposit might well be carefully investigated.

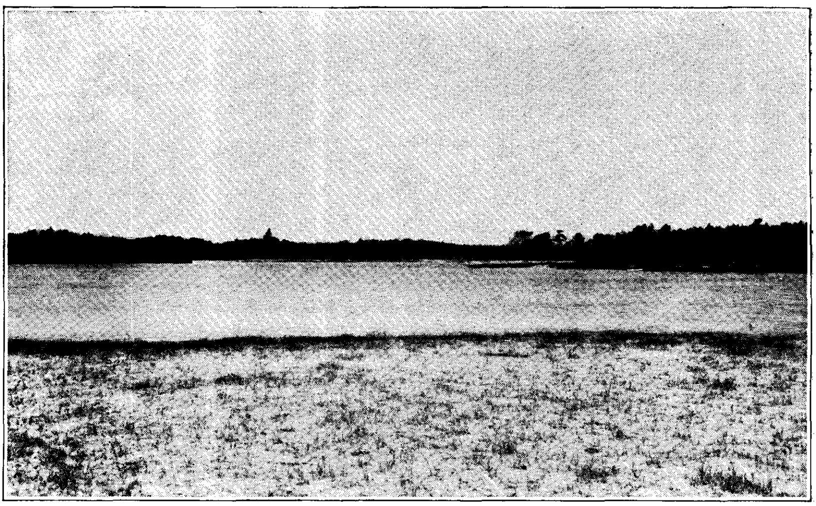


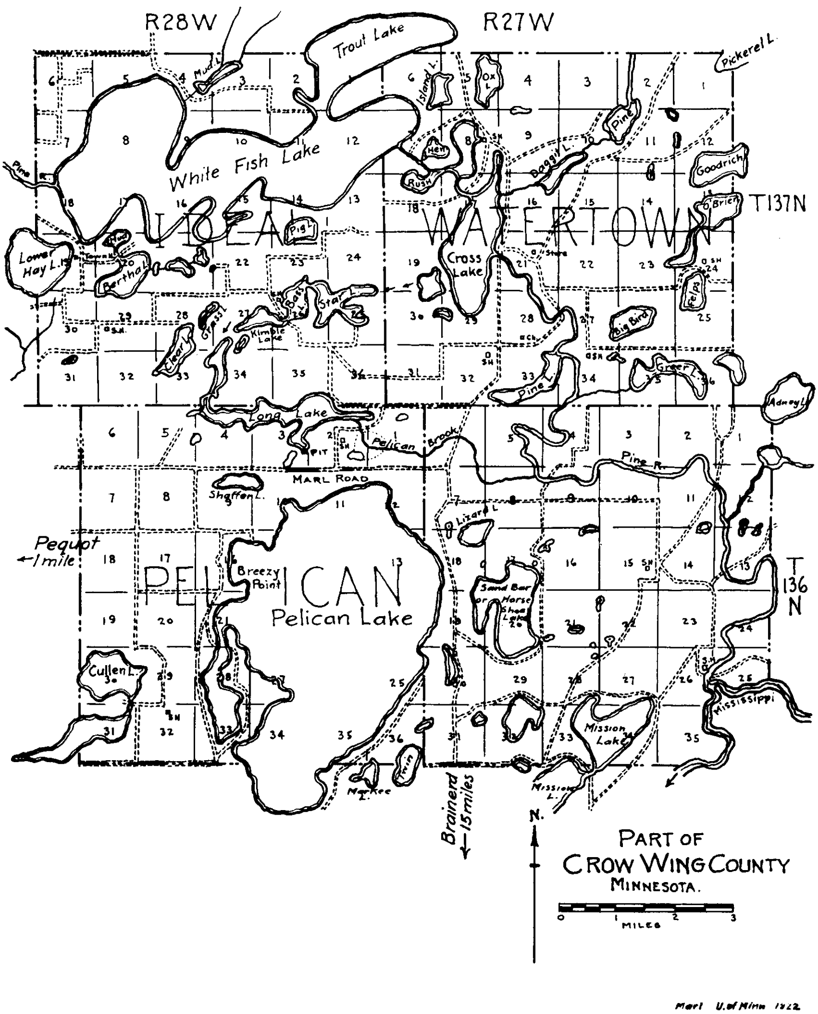
FIGURE 17. MARL DEPOSIT, STAR LAKE

Mr. J. R. Holton reports a deposit about three and one-half miles from Shevlin in Clearwater County. He states that this deposit occurs around and in the bottom of a small lake. Surface exposures indicate that the bed is about 160 rods each way. The marl has been determined to be of good quality. It is claimed to be about twenty feet deep.

FIGURE 18. MARL DEPOSIT, STAR LAKE

FIGURE 19. SWAMP AND PEAT BOG UNDERLAIN BY MARL, STAR LAKE

PLATE III



PELICAN LAKE VICINITY SHOWING THE LOCATION OF STAR LAKE

Star Lake, located in Crow Wing County about ten miles east of Pequot, contains a large amount of marl. This seems to be of high quality. The near-by swamps contain deep deposits of marl. This deposit might prove worthy of careful investigation. It is of especial interest because Bass Lake and Kimble Lake, connecting lakes, also contain marl deposits. Their exact character and their extent is not known. Long Lake, with an additional supply of marl, is only about one mile distant. A survey of near-by lakes and swamps might disclose still other deposits of marl. This series of deposits is located from eight to ten miles from the nearest railroad.

Marl deposits are known near Avon in Stearns County and also between Sauk Center and Little Sauk. The writer has no definite information concerning these deposits. From the standpoint of possible use in cement these deposits should be carefully investigated. Their location near the Twin Cities would be very advantageous if they are of the requisite character and extent. Deposits of marl were used many years ago for making lime in the south edge of the city of St. Cloud and at another locality about half way between St. Cloud and Clearwater. Marl deposits are reported to exist in Wright County near Monticello and between Monticello and Clearwater. These deposits also deserve investigation because of their favorable location.

Marl deposits are reported to be very usual in Becker County. Winchell[7] suggests that the White Earth River and Lake, from which the White Earth Indian Reservation takes its name, were so named because of the deposits of white marl exposed along the shores and banks.

Deposits of marl are reported to exist near Fergus Falls in Otter Tail County and in peat swamps near Parkton in the same county.

Mr. W. S. Foster of Minneapolis reports extensive marl beds under peat in Mille Lacs County about 8 miles east of Milaca. He states that there are about 3,000 acres of marl of unknown depth. The marl is of a very good quality.

Reference has already been made to the interesting marl deposit on the farm of Mr. N. W. Olson near Walker, Minn. This deposit is, however, not large enough to be of commercial importance.

MARL DEPOSITS UNDER PEAT BOGS

The occurrence of marl deposits under peat bogs is rather usual in some parts of the state. A list of the localities where peat deposits are accompanied by marl beds is given by Soper.[8] This list should not be considered as being either inclusive or exclusive.

[7] *Loc. cit.*

[8] E. K. Soper. Peat Deposits of Minnesota, *Minnesota Geological Survey Bulletin*, No. 16, pp. 31-32.

FIGURE 20. MARL DEPOSIT NORTH OF BRAINERD, NEAR MERRIFIELD ROAD

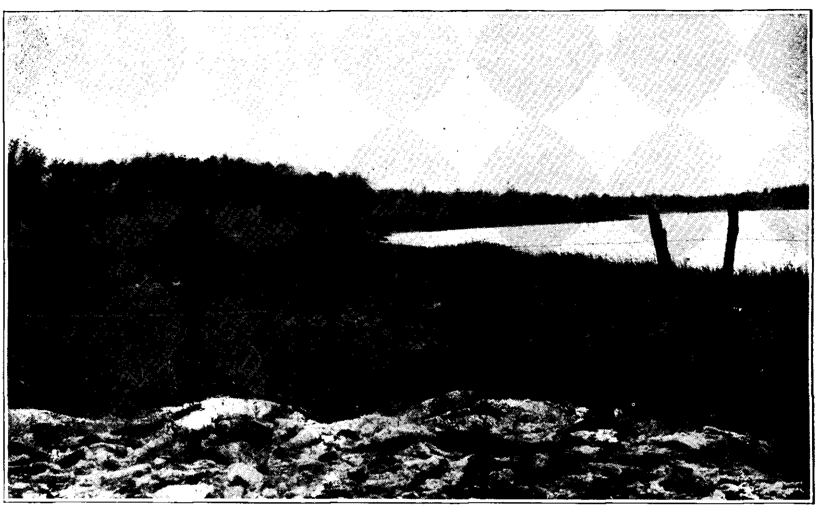


FIGURE 21. MARL DEPOSIT ON LONG LAKE, EAST OF PEQUOT

FIGURE 22. LOADING MARL AT LONG LAKE

FIGURE 23. SEVEN-FOOT EXPOSURE OF MARL, BENTON COUNTY NEAR RICE

It seems likely that more detailed examination of the peat deposits of the state might disclose marl beds whose existence is not as yet known. Since it is to be expected that the character and mode of deposition of the peat will prove to be an indication of the possibility of marl, the following statements are here quoted from Soper.[9]

FIGURE 24. MARL PIT NEAR CENTRAL AVENUE ROAD

1. *History of peat bogs.*—Any discussion of peat must commence with a consideration of the various conditions which caused the formation of the peat.

The history of all the Minnesota peat deposits dates back to the close of the last Glacial Period in North America. After the recession of the ice, the first vegetational zones were controlled by physiographic rather than by soil conditions. There were numerous lakes and vast undrained marshy tracts over which the waters from the receding ice spread their burdens of glacial débris. The drainage of the northern part of Minnesota and the adjacent region was prevented because the waters were held back on the north by the huge dams of ice of the receding glaciers. This resulted in the formation of a vast lake called glacial Lake Agassiz, which covered much of northwestern and north central Minnesota, and extended northward far into Manitoba and Ontario, and westward into North Dakota. It is in the old bed of this lake that most of the great peat bogs in Minnesota are found. As the ice melted and receded farther northward, Lake Agassiz reached its maximum size, and the waters were drained to the south through the Minnesota River. Gradually the level of the lake was lowered, partly by geologic uplift of the land and partly by the cutting down of the outlet. Finally there was a change in the outlet

[9] *Loc. cit.* pp. 34-36, 38, 39, 47, 51, 55, 56, 63-64.

of Lake Agassiz, from the southern end to the northern, and the lake was gradually drained. The southern borders of the lake were the first to dry up, and as the waters became shallower and shallower the lake receded northward to its present position in Manitoba, where Lake Winnipeg is a remnant of this former glacial lake. With the recession of the lake waters, large areas were converted into marshes which became the sites of peat accumulation.

Much of the recently denuded land to the south probably consisted of low tundras upon which there gradually appeared mosses, lichens, and grassy meadows, with occasional stunted trees. This tundra type of vegetation was later displaced by land species, and gradually the surface became more and more like the present one. South of the region covered by glacial Lake Agassiz also there were numerous small lakes and marshes. Many of these lakes have remained as open bodies of water, while others became filled with peat. The marshes have developed into swamps and bogs of various types.

While the draining and drying up of Lake Agassiz was gradual, it probably proceeded more rapidly than the rate of peat formation so that large tracts were converted into marshes of flat, undrained areas. The marshes soon became covered with marsh or swamp vegetation, some of which gained a foothold while the land was still covered with shallow ponds. Among the first plants to appear was sphagnum, or peat moss. Many of the largest peat deposits in this region consist almost entirely of the remains of sphagnum from top to bottom. Numerous exposures were seen in the sides of deep drainage ditches where sphagnum peat rests upon the surface of lake washed glacial till or clay.

2. *Types of peat bogs.*—A classification of peat deposits is given by Soper as follows:

A careful study of the plant remains in the different layers of a peat bog, from bottom to top, together with knowledge of the character of the topography of the bottom, reveals the history of the bog. Upon the basis of such evidence, it is possible to divide the peat deposits of Minnesota into two great groups: (1) filled-in deposits, formed by the filling of lakes or ponds with plant remains; and (2) built-up deposits, which have accumulated on flat, wet, marshy surfaces, and which do not represent filled lakes. These two types correspond to the European "low-moors" and "high-moors." In the subsequent pages of this report, whenever the term "built-up deposit" is used, it refers to a peat deposit which has accumulated in some manner other than by the filling of a lake or open body of water. Since sphagnum does not invade open bodies of water such as lakes and ponds, but appears only after such water bodies become filled or partly filled with peat, it is concluded that the large bogs of northern Minnesota composed of sphagnum from top to bottom, and resting directly on lake-washed glacial till or clay, have not formed by the filling of lakes, and hence represent "built-up deposits." Further evidence to strengthen this conclusion is found in a study of the character of the topography of the bottom of these bogs, as revealed by several thousand test holes. When the peat consists almost entirely of sphagnum, the bottom of the bog is usually flat, though not necessarily level. The bottom often has a uniform slope of ten to twenty feet per mile, and in such cases evidently represents a portion of a large, undrained, glacial, outwash plain, or an expanse laid bare by the disappearance of the waters of a large lake, such as glacial Lake Agassiz. On the other hand, most peat deposits which show from their plant constituents that they represent filled lakes occupy typical basin-shaped depressions, with the deepest peat in the interior, which become shallower in all directions toward the shore. . . . .

The principal types of basins or depressions in which peat has accumulated are:

1. Depressions of glacial origin
   1. Basins between morainic hills
   2. Slight depressions in undulating drift surfaces
   3. Kettle holes
   4. Basins formed by dams of morainic débris across old stream channels
   5. Old lake beds
2. Depressions not of glacial origin
   1. Valleys of existing streams
   2. Depressions due to post-glacial erosion
   3. Basins formed by construction of beaver dams across streams. . . .

In Minnesota, deposits formed by the filling in of lake basins are deeper as a rule than those formed on low, flat, swampy surfaces. On the other hand, in many basins the deposition of vegetation has, for some cause, been arrested, and the process of peat accumulation stopped. Under such conditions, the peat in the built-up deposits might be of greater thickness than in lake basins.

There is a large variation in the thickness of the peat bogs throughout the state. Those in the southern portion are, in general, much more shallow than those in the north. In these southern deposits the peat varies in thickness from merely a thin peaty sod of a few inches, up to 18 feet. Only two or three localities were found south of the Twin Cities, where the latter depth obtained. The average thickness for southern Minnesota is only 4 or 5 feet. In the north, thicknesses of 18 feet are common in the filled lake deposits, and many of these attain a depth of 20 to 25 feet in the center of the bog. The maximum thickness recorded is 63 feet in St. Louis County, near Central Lakes Station, on the Duluth, Winnipeg, and Pacific Railroad. This bog, ... is crossed by the railroad and much trouble has been experienced in keeping the tracks in condition, where they overlie the deeper portions of the deposit. A series of soundings was made by the company's engineers, who have kindly supplied the resulting data which are given elsewhere in this report.

At several other localities, notably the Corona Bog, at Corona, Carlton County, the deposits were so deep in the center that bottom was not reached with a 25-foot Davis sounding rod. These bogs are all of the filled-lake type.

The average depth of peat over the great built-up deposits occupying portions of the bed of Lake Agassiz in north central Minnesota is about 7 to 9 feet. The thickness increases to 18 or 20 feet in many places which apparently overlie depressions and hollows in the former lake bed.

In northwestern Minnesota, in Marshall and Roseau counties, some of the largest unbroken areas of peat in the state occur, but these are usually shallow. The average depth of peat over this region does not exceed 4 or 5 feet. Most of this region has been burned over, which probably accounts for the shallow depths.

In northeastern Minnesota the peat bogs are chiefly of the filled-lake type. In St. Louis County and the western part of Lake County, the thickness is variable. The deepest portion of the deposit is usually near the center, and the thickness gradually diminishes as one approaches the edge of the bog, which corresponds with the rim of the basin in which the peat accumulated. The average depth attained in the center of these bogs is about 12 to 15 feet. . . .

As stated before, the largest, deepest, and most important deposits occur in the "muskeg" swamps and open bogs and marshes of the northern portion. The peat in these muskegs is formed chiefly of sphagnum, or peat moss, and some of the largest bogs, embracing hundreds of square miles, are built up almost entirely by successive layers of this moss. Scattered over these immense swamps of sphagnum peat are smaller areas where the peat is much deeper and of a different character below the upper layers. These deep portions of the bogs represent filled lakes and the peat shows a different orgin and structure from the prevailing sphagnum type of the north. In these filled lakes the peat is formed of sphagnum only in the upper part of the deposit and down as far as the old water level of the original lake. Below this depth, the peat consists of the remains of sedges, grasses, rushes, and pondweeds so characteristic of all deposits which represent filled lakes.

The spagnum peat of northern Minnesota is by far the most abundant and is of better grade than the other varieties. It is probable that at least three fourths of the area covered by peat in this region was originally a flat, undrained, land surface, left in that condition by the gradual draining of glacial Lake Agassiz.

3. *Marl and peat associations.*—Soper makes the following statements about the occurrence of marl under peat:

In several localities in central and northern Minnesota, notably in Crow Wing, Douglas, Itasca, Koochiching, Hennepin, and Clearwater counties, some of the peat bogs were found to be underlain by marl beds. Marl deposits in the beds of existing lakes are of frequent occurrence in some of the north central counties. They have been formed by the precipitation of lime carbonate from solution in the lake waters through the agency of the Chara plants (stoneworts) which abound in these lakes. Marl beds beneath peat bogs have a similar origin. This is shown by (1) the occurrence of the remains of Chara imbedded in the marl, and in the transition zone between the marl and the overlying peat; (2) the occurrence of the marl at the bottom of the deeper basin-shaped bogs; (3) the occurrence of innumerable freshwater shells (chiefly snail shells) throughout the marl, and in the bottom layers of the overlying peat; (4) the occurrence of the typical "pond peat" of greenish or yellowish color, composed chiefly of pond weeds and other aquatic plants immediately overlying the marl. Davis has shown in his paper on the marls of Michigan, that these deposits are formed only in lakes and ponds and the large pure marl deposits are always the result of the influence of Chara or stoneworts.

This occurrence of marl and peat in the same bog is conclusive evidence that those deposits in which such an association exists represent filled lakes or ponds. The change from marl to peat indicates that at a certain time in the history of the lake conditions were brought about unfavorable to the growth of Chara, and favorable to other plants. In a few instances the evidence indicated that the original lake became completely filled with marl, or filled to within a foot or two of the surface before peat began to form. In such a bog the peat is composed chiefly of sphagnum and non-aquatic plants, and is a built-up deposit. Even in the filled lakes, the upper portion of the peat has been built up above the old water level of the lake by successive layers of sedges and sphagnum. The present surface of some of these peat bogs is 10 to 15 feet higher than the original water level of the lake. . . .

In the process of filling a lake the first plants to become established are stonewort (Chara sp.), waterweed (Philotria canadensis) and species of water milfoil (Myriophyllum). Stonewort occurs in water to a depth of fifteen to twenty feet, as does also water milfoil. In water of this depth the growth is never very abundant owing to the greatly decreased intensity of the light. As the water becomes shallower however, all the plants make a more luxuriant growth, sometimes forming a dense layer three to six feet thick. Usually stonewort does not make a very rank growth, the other species replacing it in shallower water.

In a small lake, 3 miles south of Shevlin, now in the process of filling, stonewort makes a very conspicuous zone in water from 5 to 15 feet deep. Here, stonewort forms a dense layer, coming nearly to the surface in 5 to 8 feet of water. The growth of stonewort in this lake has always been heavy as evidenced by the large accumulation of marl. A similar condition, apparently, has prevailed in Rice Lake near Hubert, although stonewort has practically disappeared, the present vegetation consisting mostly of wild rice.

It seems very probable to the writer that the built-up peat deposits are not, in general, underlaid by marl. The deposition of marl could have taken place only under what might be termed lake conditions. When the lake became filled or nearly filled with marl the conditions were such that plants adapted to very shallow water flourished and killed out the marl-depositing flora. Since the built-up peat deposits originated on a flat glacial plain it would not seem reasonable that the conditions needed for marl deposition would prevail over the large areas now covered by peat. Minor depressions in the land might have afforded opportunity for the deposition of marl until the level was raised to that of the surrounding area. Indeed some cases are known where certain parts of the extensive peat beds of the built-up type cover smaller areas where the initial peat formation was clearly of the pond or filled-basin type with its characteristic succession of flora, passing finally to the stage dominant over the greater portion of the deposit. In any such cases, and they must certainly be fairly numerous, there would seem to be a possibility of finding marl beds under such portions of what might seem, on the surface, to be a peat deposit of the built-up variety.

These areas, however large, can be of only small relative size as compared to the immense extent of the built-up peat deposits in such a region as the old bed of the glacial Lake Agassiz.

The filled-basin type of peat deposit would seem to offer more possibilities in any search for extensive marl deposits under peat. It should of course be remembered that other factors than the type of peat deposit were the vital ones in determining whether marl was to be laid down in any particular lake during its being filled up. The presence in the lake waters of sufficient calcium bicarbonate was certainly a most important factor. The depth of the water was most certainly another vital factor. The stonewort (Chara) can exist at depths of 15 to 25 feet in clear water and seems most dense at 3 to 8 feet. When the water is shallower the plants, such as, for example, the water lily, which root under the water and spread their leaves in whole or in part above the water seem to predominate. They cut off the sunlight from the marl-depositing organisms and so either prevent or stop the continuance of marl deposition. Other influences such as conditions of temperature and pressure were perhaps contributing factors in making the conditions in any given lake favorable or unfavorable to the growth and action of the various marl-depositing plants.

CHARACTER OF THE SOIL WATER

The character of the soil water in any given locality is certainly a very vital factor in fixing the conditions for marl deposition. It is very interesting to speculate on the possible influence of the gray drift and the red drift of Minnesota as factors in marl depositions. These drifts are described as follows by Leverett and Sardeson.[10]

The glacial deposits also show some variations that relate to the kind of rock formations over which the ice passed. Thus, the northeastern portion of the state has a rather stony drift from the volcanic and hard crystalline rocks of that region. This stony material was carried as far south as Dakota County and forms the red drift of eastern and northeastern Minnesota. As indicated below, the red drift is the product of more than one ice sheet. The western and southern parts of the state have a large amount of clayey drift material with limestone pebbles imbedded. This material was gathered by this ice as it passed in its southward course from the shales and limestone of southern Manitoba, into the area of granite and other crystalline rocks. These clayey and limy deposits form what is known as the gray drift of Minnesota, and the ice sheet which formed it, as the Keewatin ice sheet.

It has been found through a study of the deposits in Minnesota and neighboring states that the glacial deposits which form so extensive a mantle in Minnesota are the result of more than one invasion of the ice from the Canadian highlands. At each invasion the ice left a deposit of drift gathered partly from Canada and partly from the deposits over which it passed in Minnesota. The advances were so widely separated in time that the drift deposits of one invasion had large valleys cut in them by the action of streams before the next invasion occurred. The later advances failed to reach the limits of the earlier deposits, so they are still exposed to view, and the degree of erosion of the surface of the older can be compared with that on the surface of the younger deposits. It is found that the older drifts have been so greatly eroded and are so ramified by drainage lines that no lakes or undrained basins remain on them, while the younger drift deposits have numerous lakes and undrained basins and also large, poorly drained areas which the streams have not yet reached. It is because

[10] F. Leverett and F. W. Sardeson. Surface Formations of Minnesota. *Minnesota Geological Survey Bulletin* No. 14, pp. 12-15. 1919.

they are not covered by the latest drift that Rock and Pipestone counties in southwestern Minnesota have no lakes and basins such as characterize neighboring counties that were covered by that drift.

The invasions of the ice into Minnesota not only took place at different times, but have come from more than one direction at about the same time. In the earlier invasions the greater part of the state was covered by ice coming from Manitoba as shown by limestone fragments and pebbles derived from rock formations of that country which are imbedded in the lower part of the drift over all of the state except its northeast part. The movements in the closing stage of the glacial epoch were more largely from the northeast, but more than half of the state was invaded from the northwest. The ice sheets were as follows: 1. The Superior lobe of the Labrador ice sheet, an extension of ice southwestward from the Superior basin nearly to Mille Lacs Lake; 2. The Patricial ice sheet, with southward movements from the highlands north of Lake Superior across eastern Minnesota to points a little beyond St. Paul; 3. The Keewatin ice sheet, which moved southward through Manitoba and across western Minnesota. After the melting away of the ice that came from the northern highlands, the Keewatin ice sheet extended over some of the ground that ice had vacated. It crossed the Mesabi Range into the St. Louis basin, and also moved northeastward from near Minneapolis into Wisconsin. This advance over earlier drift deposits is known from the presence of a thin deposit of clayey and limy drift containing rock material brought from Manitoba which covers the drift that was deposited by ice coming from the highlands northwest of Lake Superior. The drift from these highlands together with that from the Lake Superior basin forms the stony red drift of eastern Minnesota, while that from Manitoba forms the clayey and limey gray drift which covers almost all of the remainder of the state.

Sufficient information is not at hand to enable any decision as to the effect of such influences in the laying down of marl. It is a point, however, which may be clarified when more data is available concerning marl deposits in Minnesota.

CLAYS AND SHALES OF MINNESOTA

A very valuable survey of the clays and shales of Minnesota has been made under the direction of F. F. Grout, of the University of Minnesota. The results of that survey are printed in *Bulletin* No. 678 of the United States Geological Survey.

ANALYSES OF CLAYS AND SHALES OF MINNESOTA

Table XI shows partial analyses of the clays and shales of Minnesota compiled from Dr. Grout's bulletin.

ANALYSES OF CLAYS AND SHALES USED IN THE MAKING OF PORTLAND CEMENT

The character of the clay or shale to be used in the making of Portland cement has been briefly discussed on page 31. Table VII shows analyses of clays and shales that have been used with marl for making Portland cement. In Table X are presented typical analyses of clays and shales utilized by other than marl-using plants.

TABLE X

ANALYSES OF CLAYS AND SHALES USED IN PORTLAND CEMENT MAKING

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Loss	Company	Location	Authority
54.50	18.88	6.58	4.16	...	...	13.94	Texas	Houston, Texas	Durbin
62.50	18.40	8.50	...	...	...	7.60	Virginia	Norfolk, Va.	Hilts
54.09	21.22	5.91	3.97	2.88	...	9.08	Alpha	Various plants	Anderson
65.40	15.88	3.18	4.52	1.66	...	9.02	Nebraska	Superior, Neb.	Latimer
45.88	15.56	7.64	6.60	5.87	0.65	11.40	Petoskey	Petoskey, Mich.	Phillips
48.60	9.56	7.52	11.78	2.97	...	16.23	Pyramid	Quarry at Gilmore City, Iowa	Boberg
57.90	19.03	5.07	1.69	2.87	...	9.96	Atlas	Hanibal, Mo.	Hicks
62.33	16.68	5.68	2.68	2.19	...	5.28	Atlas	Hudson, N. Y.	Hicks
67.76	20.57		2.54	1.71	...	7.31	Atlas	Independence, Kan.	Hicks
48.71	13.50	5.45	12.08	4.25	...	...	Peerless	Quarry near Wayne, Mich.	Simmons
60.82	18.05	7.61	2.78	1.79	1.21	7.34	Sun	Lime, Oregon	Ludgate
53.16	17.18	6.08	4.26	2.87	...	11.15	Dixie	Richard City, Tenn.	Fischer
43.80	18.22	5.95	13.74	2.04	...	14.78	Clinchfield	Kingsport, Tenn.	Guenther
57.80	19.72	5.20	1.03	1.36	...	15.57	Clinchfield	Fullers' earth, Clinchfield, Ga.	Guenther
53.14	33.35	1.10	trace	...	...	12.61	Clinchfield	Kaolin, Clinchfield, Ga.	Guenther
44.07	12.43	4.93	15.50	2.05	...	15.38	Hawkeye	Quarry at Earlham, Ga.	Condon
54.36	18.58	4.00	5.52	3.28	...	12.36	N. W. States	Mason City, Ia.	Blackmore
51.88	18.10	4.14	6.12	3.15	...	12.00	N. W. States	Mason City, Ia.	Blackmore
56.38	20.00	5.52	0.74	2.33	1.64	12.00	South Dakota	Rapid City, S. Dak.	Ernst
46.48	11.60	3.76	11.56	8.22	...	16.76	Newago	Quarry Ellsworth, Mich.	Miller
55.00	16.00	4.00	8.00	3.00	...	12.00	Sandusky	Ave. 4 plants Middle West	Newberry

TABLE XI
ANALYSES OF CLAYS AND SHALES OF MINNESOTA

Silica SiO_2	Alumina Al_2O_3	Iron Oxide Fe_2O_3	Calcium Oxide CaO	Magnesia MgO	Moisture H_2O	
50.65	10.25	4.00	10.65	4.68	1.20	Gray laminated clay, North Minneapolis, Anoka Co. (F. F. Grout, analyst).
60.49	12.62	7.80	3.87	3.68	1.94	Red drift clay, Coon Creek, Anoka Co. (F. F. Grout).
...	65.90†		12.20	5.10	...	Calcareous clay, Bemidji Lake, Beltrami Co. (————).
70.29	18.71		2.02	1.35	2.15	Surface clay, Good Thunder, Blue Earth Co. (F. F. Grout).
61.32	12.27	8.00*	0.99	1.76	...	Gray shale, Cottonwood River, Brown Co. (T. M. Chatard).
63.65	17.27	4.75	0.06	1.21	2.03	Shale, Springfield, Brown Co. (F. F. Grout).
50.51	15.89	8.21	7.10	5.14	2.44	Red glacial clay, ————, Carlton Co. (A. W. Gauger).
48.79	12.08	4.60	12.10	5.54	1.26	Gray glacial clay, Wrenshall, Carlton Co. (A. W. Gauger).
53.39	14.26	13.71	3.03	1.74	9.99	Red glacial clay, ————, Cook Co. (C. P. Berkey).
56.35	18.63	6.19	0.96	2.97	2.41	Decorah shale—lower, West St. Paul, Dakota Co. (F. F. Grout).
54.66	24.04	6.53	0.45	1.08	2.35	Decorah shale—lower, West St. Paul, Dakota Co. (F. F. Grout).
50.81	20.25	5.18	4.05	2.13	2.16	Decorah shale—lower, West St. Paul, Dakota Co. (F. F. Grout).
71.53	8.07	5.63	2.36	1.74	2.30	Loess clay, Preston, Fillmore Co. (F. F. Grout.)
54.90	13.94	5.15	7.36	3.28	...	Laminated clay, Albert Lea, Freeborn Co. (G. W. Walker).
57.60	14.19	2.89	7.00	3.51	...	Swamp clay—Rice Lake, Albert Lea, Freeborn Co. (A. D. Meeds).
69.92	17.39	1.68	0.60	1.11	1.10	Clay, Red Wing, Goodhue Co. (F. F. Grout).
63.32	12.68	2.66	5.08	3.94	1.83	Alluvial clay, Frontenac, Goodhue Co. (F. F. Grout).
47.70	13.58	6.51	11.70	3.13	1.79	Laminated clay, Net Lake Rapids, Koochiching Co. (A. W. Gauger).
56.70	28.50	0.18	0.69	0.23	...	Clay (average), Ottawa, Le Seuer Co. (————).
58.85	7.25	4.97	9.42	3.45	...	Gray drift clay, Hutchinson, McLeod Co. (F. F. Grout).
57.20	18.23	11.04	0.72	1.02	2.48	Clay from decomposed biotite schist, Two Rivers, Morrison Co. (A. W. Gauger).
63.64	24.95	4.90	1.02	0.20	...	Clay, Brownsdale, Mower Co. (C. F. Sidener).
48.30	8.16	2.84	16.34	4.93	...	Leached silt—Red River, Grand Forks, Polk Co. (————).
53.32	8.87	4.71	9.21	6.62	1.94	Leached silt—Red River, East Grand Forks, Polk Co. (A. W. Gauger).
57.79	12.63	8.88	3.33	4.11	2.50	Red laminated clay, St. Paul, Ramsey Co. (F. F. Grout).
60.61	18.12	7.51	0.03	1.14	0.28	Decomposed gneiss, Morton, Redwood Co. (F. F. Grout).
54.43	18.15	4.20	3.98	...	...	Gray clay, Sec. 8. T. 70 N. R. 21 W. St. Louis Co. (Minn. School of Mines).
49.60	15.82	...	1.70	...	...	Red clay, Sec. 8. T. 70 N. R. 21 W. St. Louis Co. (Minn. School of Mines).
48.92	18.45	16.88	0.70	3.68	7.14	Red shale, Fond du Lac, St. Louis Co. (————).
77.89	13.55	1.83	trace	0.36	4.45	Banded "silica kaolin," Sec. 6, T. 58 N. R. 17 W. St. Louis Co. (C. F. Sidener).
60.00	11.45	3.90	6.48	4.05	2.32	Swamp clay, Meriden, Steele Co. (E. P. Harding).

* Approximation.

† Includes insoluble matter.

It should, of course, be remembered that the exact chemical composition of clay or shale needed will vary somewhat with the character of the calcareous raw material used. If the marl or limestone contains clay or sand the composition of the clay or shale selected may vary from that previously referred to as desirable. Since the magnesium carbonate content of marl is almost invariably low, the clay or shale selected for use with marl in making Portland cement may be much higher in magnesia than in plants where the calcareous material contains several per cent of magnesia.

GENERAL CHARACTER OF CLAYS AND SHALES OF MINNESOTA

No attempt is to be made in this bulletin to discuss the location and extent of all the possible deposits of clay and shale which might conceivably be used in the manufacture of Portland cement. For the guidance of those who might be interested, it has, however, seemed appropriate to indicate briefly the general character of such deposits.

Grout[11] discusses the general character of the clays and shales of Minnesota as follows:

Decorah shale.—Lying on top of the Platteville limestone is a series of green shales with a maximum thickness of more than 100 feet, though the common thickness is much less than this—probably not more than 50 feet. Interbedded with these shales are numerous layers and lenses of hard granular limestone, some of which are composed almost entirely of fossils. In places these limestone layers constitute more than one-half of the total thickness of the formation. They range in thickness from 1 inch to several feet, but most of them are less than a foot thick. At the base is usually a thick shale (about 10 feet), above which the shale and limestone alternate in similar layers. The shale is fissile and crumbles easily. . . . . .

The Decorah is one of the most valuable clay formations in Minnesota. The shales, when crushed and pulverized and mixed with water yield a greenish plastic clay that is used extensively near St. Paul and in Goodhue County for the manufacture of pressed brick, fancy brick, hollow ware, draintile, and common brick. . . . . .

The shale is exposed in only a few places and should be sought by the stratigraphic method of prospecting. The top of the shale is likely to be marked by series of springs on grass-covered hillsides. . . . . .

Devonian system.—The Devonian rocks in Minnesota, which consist of not more than 100 feet of sandstone and limestone with some shale, overlie the Ordovician unconformably. They are confined to the extreme southern part of the State (Mower, Fillmore, and Faribault counties), into which they extend from Iowa. The shales are not of specially high quality and are too thin to be of much importance as a source of clay. In the vicinity of Austin marly layers of the Devonian have been used to mix with an overlying plastic clay, which has been described as Cretaceous but which may be residual from Devonian

[11] *Loc. cit.*

rocks. The effect of the added lime is to improve the working quality and lighten the color.

Where Bear Creek crosses the line between Fillmore and Mower counties the shale beds were found to be as much as 1 foot thick and to show every indication of extending over considerable territory. They are yellow to buff in color, are very sandy and lean, and, of course, could not be separated commercially from the interbedded limestone. . . . .

Cretaceous system.—The Cretaceous rocks found in Minnesota consist of soft sandstones, shales, and clays and locally have thin beds of conglomerate at the base. They lie immediately below the drift in much of the western part of the State and also in numerous scattered areas in the southern, central, and northern parts. Outcrops are few on account of the drift cover, but numerous well records have helped to show their general distribution. Their maximum thickness in Minnesota is about 550 feet. Their upper portion is composed chiefly of soft blue or gray shales and clay (Benton shale); lower down they consist of white sandstone and kaolins (representing the Dakota sandstone). In a few places in the northern part of Minnesota a Cretaceous conglomerate containing pebbles of hard hematite lies at the base of the shale overlying beds of iron ore. In the western part of the State the Cretaceous rocks rest upon the decomposed Archean granites and gneisses; the base of the shale is white clay of conglomeratic or concretionary texture that contains quartz pebbles. In a few places where the Cretaceous lies in contact with Paleozoic sediments the conglomerate is not prominent, but the clays are similar to those just mentioned. The variation of the conglomerate with variations in the bedrock indicates that the white clay is colluvial.

The Cretaceous beds contain the highest-grade clays found in Minnesota. Some of these clays are used for stoneware, pottery, sewer pipe, and fire brick. At present, few good bodies of Cretaceous clays that lie close enough to the surface to be profitably excavated are known, but it is very probable that more detailed prospecting in the drift in the vicinity of Cretaceous areas would result in the discovery of other deposits of valuable clay. . . . .

Gray drift clays.—Glacial drift, consisting largely of clay, generally gray, with a surficial alteration to yellow, covers more than half of Minnesota. Apparently it was brought from the northwest by glaciers, which in a few places reached the eastern border of the State. The map shows its general distribution, but the area delineated includes some local sandy areas in which there is little or no clay. The gray drift may be the product of more than one ice invasion, but the clays do not differ sufficiently to permit correlation of the type with the age. Several samples of Kansan drift gave much the same results as the more abundant material of Wisconsin age.

Most of the gray drift contains abundant limestone pebbles, which were probably derived from the Devonian limestone far to the northwest. In most places the drift is covered only by a few inches of soil. Loess may have accumulated over much of the area, but on hillsides it is in many places mixed with surface wash and is not readily differentiated. . . . .

Locally drift clays may be largely affected by the character of the bedrock passed over by the ice just before it deposited its load. An example is found near Goodhue in Goodhue County, where much Cretaceous clay is incorporated in the drift.

Gray laminated lake and river clays.—In many parts of Minnesota, chiefly along the valleys of Minnesota and Mississippi rivers and their tributaries, there are beds of glacial clay which are stratified in distinct, nearly horizontal layers from a fraction of an inch to 8 inches in thickness. These layers are dark blue-gray where fresh and yellow where they have been exposed to oxidation. In many places these beds are interlaminated with thin layers of fine sand. They tend to split along the darker partings, which extend continuously without grading into one another. The beds are nearly level but may dip a few degrees in either direction or may even be locally folded into arches or basins. Some clean exposures show 60 layers, all similar, in a depth of 5 feet. It is evident that these were produced by varying conditions. Deposition of sand alternated with deposition of clay a great many times, the changes in sedimentation being due possibly to seasonal variations in the water of the glacial streams. Along the flood plain of an ordinary river clay settles only in hollows outside the path of the main current. The structure of this clay and its occurrence only in glaciated regions, or valleys drained from glacial drift indicate that it was formed by large streams probably coming from a melting ice sheet. Such streams flow in greater volume and carry coarser sediments in summer than in winter and might thus have produced the alternating layers. . . . .

Such clays have long been known and used along the Minnesota River at Chaska and Jordan and along the Mississippi River from Minneapolis to Brainerd. They are calcareous and are suitable mainly for common brick and for fireproofing. The clay of Wrenshall is similarly laminated. The present investigation shows a much wider distribution than has heretofore been reported, and there is every reason to expect that still other deposits will be developed.

In the northern part of Minnesota large bodies of similar laminated clays occur in less accessible localities, as along the Bigfork and Littlefork rivers in and near Koochiching County. Samples from widely separated outcrops show surprising uniformity, though some laminated deposits are more sandy than those sampled. The clays are a little better in quality than those farther south, and they constitute a natural resource of future importance. They were formerly mapped as Cretaceous, but the present field studies show clearly that they are Pleistocene. This determination is corroborated by the character of the clay, which shows a much more rapid vitrification than any Cretaceous samples tested. The analysis also furnishes evidence of closer relation to glacial clays than to Cretaceous clays in other parts of the State. . . . .

Red drift clays.—The red drift lies generally in the eastern part of Minnesota, from Dakota County on the south to Lake County on the north. It is most conspicuous in counties that touch the border, and in the region of Mille Lacs, Brainerd, and St. Cloud, in Morrison and adjacent counties it extends westward to and beyond Mississippi River.

In the areas shown on the map between the western boundary of the red drift and the eastern boundary of the gray drift, the red drift is overlain by a thin layer of gray drift. Much the larger part of the red drift is sandy and gravelly, but it contains locally valuable deposits of clay. . . . . .

Along the eastern border of Minnesota and extending a considerable distance into Wisconsin are a series of deposits of laminated clay that have a striking red color, though otherwise similar to the gray laminated clays previously described. There can be very little doubt that their origin was dependent on the same seasonal alteration of sand and clay deposits brought by water from the melting ice sheet. . . . .

Red clays of Lake Duluth.—The retreat of glacial ice fronts toward the north and northeast probably occupied thousands of years. When the ice had vacated the western part of the basin of Lake Superior and the southern part of the Red River valley and while it still blocked the former, the obstructions caused the accumulation of immense lakes. Around the west end of Lake Superior are large deposits of a very sticky plastic red clay, with some sand grains and pebbles, apparently formed during one of the high stages of the lake known as Lake Duluth. . . . .

Outwash clays.—In some parts of Minnesota, especially in the area of the red drift, there are glacial outwash plains that contain sandy but valuable clays. Few of these clays have been developed, but they are of fine quality. . .

Loess.—The loess of Minnesota is generally considered a wind-blown deposit. It is composed of mineral derived chiefly from the glacial drift. Its origin appears to be similar to that of sand dunes, but loess, being finer grained than sand, is carried farther by the wind. In Minnesota the largest deposits of loess occur in the southeastern counties near the Driftless Area. It also occurs in the southwestern corner of the State. Over the uplands the loess ranges from 2 to 4 feet in thickness, but in the valleys and especially on the terraces along the sides of the valleys it is much thicker. At a great many of the small brick plants in the State the main deposit of clay is overlain by loess, and the two are mixed for the manufacture of brick. . . . . An analysis is reported in the discussion of Fillmore County.

Clays of Red River Valley.—Very thick beds of stratified clay, however, occur in the central portion of the Red River valley, and their position shows that they were not deposited by the waters of the lake, which must have spread over the entire valley. At the present time much of the area of stratified clay is covered by the higher floods of Red River, and probably no part of it is more than 10 feet above the high-water line of Red River or its tributaries. As the river may have been much larger about the end of the glacial epoch, it seems clear that the clays were deposited as alluvium, partly in glacial and partly in recent time. . . . . .

River clays.—The chief deposits of river clay in Minnesota lie along Minnesota River, but Mississippi and St. Louis rivers also have a number of these deposits, and many of the smaller streams contribute smaller amounts. . .

Lake and swamp clays.—For the most part the sedimentary deposits of the recent lakes do not differ very greatly from those of the lakes of glacial time. The surface of the surrounding country still consists of the red and gray drift which furnished the sediments when the glaciers were melting away. Some slight differences, however, may appear, for during the glacial time the melting ice furnished immense volumes of water that have not been duplicated since. Erosion and filling of the lake beds have also tended to decrease the size of the bodies of water. . . . . .

Clays of fair quality have accumulated in glacial and recent lakes in parts of Anoka County. Such a deposit was developed about 25 years ago by P. P. Kelsey, 2½ miles north of Anoka, near the shores of Round Lake. At this locality smooth yellow clay covers many acres.

These citations should serve to indicate something of the distribution of clays in Minnesota.

CLAYS OR SHALES TO BE USED WITH MARL IN MAKING PORTLAND CEMENT

It would seem possible that wherever a suitable and properly located supply of marl was found a clay or shale deposit could be located to use with the marl. No serious economic disadvantage would seem to follow if such a deposit were located as far as fifty miles distant. While a suitable clay or shale deposit located near the marl beds would be very desirable, such materials are often transported considerable distances by rail or water. The transportation of clay or shale would not be as serious a problem as the transportation of marl since the moisture content of the clay or shale is uniformly low.

LIMESTONE IN MINNESOTA

Any proposal to use the fresh-water marls of Minnesota involves the question of optional raw materials. For this reason it seems best to discuss briefly the location, character, and composition of the limestones of Minnesota. For purposes of comparison, some analyses of limestones and cement rocks now being used in the making of Portland cement are listed in Table XII. The thanks of the writer are due the companies therein listed for these analyses and for permission to publish them.

It will be noticed that the limestones listed are all low in magnesium carbonate. This is very important since the finished cement must contain less than 5 per cent of magnesium oxide.

CHIEF LIMESTONE FORMATIONS OF MINNESOTA

An outline of the chief formations concerned in the limestone deposits of Minnesota is given by Bowles[12] as follows:

The Cambrian rocks, consisting of shales, limestones, and sandstones of marine origin, rest unconformably on the earlier tilted rocks.

Dresbach Sandstone and Underlying Shales and Sandstones.—The lower part of the Cambrian in Minnesota includes the Dresbach sandstone, of Upper Cambrian age, which outcrops near the town of Dresbach. Thicknesses of 50 to 100 feet are shown in drilled wells in southeastern Minnesota. At Taylors Falls the Dresbach contains marine fossils and lies in contact with tilted Keweenawan lavas. In other parts of the State it is separated from the pre-Cambrian rocks by older sandstones and shales.

[12] Oliver Bowles, Structural and Ornamental Stones of Minnesota. *United States Geological Survey Bulletin* No. 663. 1918.

TABLE XII

ANALYSES OF LIMESTONES AND CEMENT ROCKS USED IN THE MANUFACTURE OF PORTLAND CEMENT

SiO_2	Al_2O_3	Fe_2O_3	$CaCO_3$	$MgCO_3$	Company	Location	Authority
					Limestones		
2.10	1.48		95.27	1.22	Alpha	Middle western plants	Anderson
5.36	3.60	1.14	88.61	1.13	Nebraska	Superior, Neb.	Latimer
3.16	1.80		92.30	4.60	Petoskey	Petoskey, Mich.	Phillips
1.22	0.43	0.24	95.13	3.04	Atlas	Northampton, Pa.	Hicks
8.47	1.73		85.15	4.51	Atlas	Hanibal, Mo.	Hicks
4.70	1.68	0.96	90.67	1.60	Atlas	Hudson, N. Y.	Hicks
...	(clay 4.19)		90.45	5.36	Atlas	Leeds, Ala.	Hicks
5.86	2.18	0.93	88.96	1.51	Atlas	Independence, Kan.	Hicks
2.74	1.84		93.23	2.09	Peerless	Quarry at Rogers City, Mich.	Simmons
2.24	1.48		95.93	trace	Allentown	Quarry—Annville District, Pa.	Breerwood
0.40	0.46		97.68	1.55	Sun	Lime, Oregon	Ludgate
0.78	0.55		98.03	0.61	Dixie	Richard City, Tenn.	Fischer
3.19	0.87	0.52	93.23	2.11	Dixie	Richard City, Tenn.	Fischer
0.47	0.40	0.18	98.90	0.67	Clinchfield	Kingsport, Tenn.	Guenther
7.98	1.28	0.82	88.72	2.45	Clinchfield	Clinchfield, Ga.	Guenther
6.74	2.46	1.30	83.01	6.31	Hawkeye	Quarry at Eartham, Ia.	Condon
...	(clay 3.84)		90.32	7.52	Northwestern states	Mason City, Ia.	Blackmore

TABLE XII—*Continued*

SiO_2	Al_2O_3	Fe_2O_3	$CaCO_3$	$MgCO_3$	Company	Location	Authority
...	(clay 5.64)		92.95	2.19	Northwestern states	Mason City, Ia.	Blackmore
1.60	2.00		96.05	0.30	Coplay	Annville, Pa. District	Johnston
1.22	0.34	0.44	97.21	1.00	South Dakota	Rapid City, S. Dak.	Ernst
3.32	2.97	0.75	92.82	2.47	Newago	Quarry at Petoskey, Mich.	Miller
4.00	...	...	92.00	4.00	Sandusky	Ave. 4 mills	Newberry
10.80	3.84	1.66	81.91	2.19	Colorado	Portland, Colo. ("High Limestone")	Banks
20.05	7.04	2.75	67.85	0.73	Colorado	Portland, Colo. ("Low Limestone")	Banks
2.96	0.63	1.11	94.71	1.07	Dewey	Dewey, Okla.	Chamberlain
6.94	2.44	1.36	85.29	2.28	Dewey	Dewey, Okla.	Chamberlain
					Chalk		
3.83	2.31		93.09	0.29	Western	Yankton, S. Dak.	Eckel
6.80	3.00		89.77	0.85	Portland	Salt Lake City, Utah	Utah
					Cement Rocks		
15.09	6.90		71.53	4.53	Alpha	Lehigh Valley District	Anderson
12.62	6.30		74.73	5.59	Alpha	Lehigh Valley District	Anderson
11.88	4.24		77.79	5.96	Alpha	Lehigh Valley District	Anderson
15.04	6.82		72.50	4.09	Atlas	Northampton, Pa.	Hicks
13.60	6.20		74.88	5.12	Allentown	Allentown, Pa.	Breerwood
17.62	7.34		69.53	5.51	Coplay	Coplay, Pa.	Johnston
12.39	6.33		75.36	4.41	Nazareth	Nazareth, Pa.	Driesbach

Franconia Sandstone.—The Franconia sandstone, consisting of 100 or more feet of white micaceous sandstone, with greensand at the base in some areas, overlies the Dresbach and is typically exposed at Franconia, in Chisago County.

St. Lawrence Formation.—Above the Franconia sandstone is the St. Lawrence formation, 100 to 200 feet thick. It consists of a somewhat sandy and porous buff magnesian limestone and layers of green shale and white and green sandstone. It outcrops near Judson and St. Lawrence siding, on Minnesota River, and at many points along the Mississippi bluffs from Red Wing to the Iowa line.

Jordan Sandstone.—Above the St. Lawrence is a white to yellow incoherent sandstone, 75 to 200 feet thick, consisting of medium to coarse well-rounded grains. It appears along the valleys of Minnesota and Mississippi rivers and a number of their tributary streams.

The Ordovician rests conformably on the Cambrian. The lowest rocks included in the Ordovician are the Prairie du Chien group, which consists mainly of dolomites and is divided into the Oneota dolomite below and the Shakopee dolomite above.

Oneota Dolomite.—The Oneota dolomite, which is 75 to 200 feet thick, occurs in heavy uniform beds of buff color, and is somewhat porous in its upper part. It outcrops at Kasota and Mankato in the Minnesota River valley and almost continuously along the Mississippi and many of its tributaries from Red Wing to the Iowa line. Most of the limestone quarries of the State are in this formation.

Associated with the dolomite of the Oneota or the Shakopee is a bed of white calcareous sandstone, sometimes called New Richmond, which reaches a maximum thickness of 40 feet, though in many places it is much thinner. It is useless as quarry rock on account of its friability.

Shakopee Dolomite.—The Shakopee dolomite is similar to the Oneota. It ranges from 25 to 75 feet in thickness, is buff in color, fine grained, and somewhat sandy. Outcrops occur along Minnesota River, notably at Shakopee, and on the bluffs of Mississippi River between St. Paul and Hastings. It is quarried at a few places in Scott and Washington counties.

St. Peter Sandstone.—Above these dolomites is the St. Peter sandstone. It is 80 to 200 feet thick, white to yellowish in color, and consists of very pure quartz in well-rounded grains. It is very friable and is useless for structural purposes. It outcrops along the Mississippi near the Twin Cities and at many points throughout the southeastern counties. At its top is 3 to 6 feet of blue shale.

Platteville Limestone.—The Platteville limestone, which is 12 to 30 feet thick, contains a smaller proportion of magnesium carbonate than the underlying Shakopee and Oneota, and is blue rather than buff in color. Outcrops are prominent in Minneapolis and St. Paul, where it was quarried extensively in earlier years for structural use, and it caps many hills in the southeastern counties at some distance from the large rivers. Numerous shaly layers, one-fourth to one inch thick, alternate with the beds of limestone. In the southern part of Minnesota these layers are several inches thick.

Decorah Shale.—Above the Platteville limestone is the Decorah shale, which has been traced through several counties southeast of St. Paul. It has a maximum thickness of about 100 feet and an average of about 50 feet. It is not useful as a building material except as it is employed in the manufacture of brick.

Galena Limestone.—The Galena limestone, which overlies the Decorah shale, reaches a maximum thickness of 70 to 80 feet in Minnesota and is represented at only a few places. The most prominent outcrops are in Dodge, Mower, and Fillmore counties, where it supplies quarry rock of good quality. It is a somewhat sandy, buff to bluish magnesian limestone.

Maquoketa Shale.—Above the Galena limestone is the Maquoketa shale, a dolomitic shale and sandstone having a thickness of about 100 feet.

Devonian.—After a period of erosion 50 to 100 feet of Devonian sediments were deposited. These constitute the northern part of a large area that outcrops principally in Iowa. In Minnesota the main portion of the rock is limestone, interbedded with shales at the base and grading into sandstone at the top. Small areas appear in Mower, Fillmore, and Faribault counties, where they supply limestone for structural purposes. . . . .

General character of the limestones.—Bowles makes the following statements about the limestones of the state:

Practically all the limestones of Minnesota are dolomitic and many of them are nearly pure dolomite. Though nearly flat lying and showing little deformation, they are more or less recrystallized—in certain beds so much so that the rock takes a good polish. Limestone suitable for many purposes is obtained. Polished or unpolished slabs for wainscoting and flagging; carvings for interior or exterior decoration; cut stone, range rock, and rubble are all obtained in large amounts. Riprap is quarried extensively, and the production of crushed stone for macadam and concrete is increasing year by year. Lime is manufactured in several places, and a limited amount of stone is quarried for cement, for sugar refining, iron-ore flux, and fertilizer.

Many of the beds are nearly pure white. Such limestones under the microscope are seen to consist of pure calcite or dolomite, with the possible admixture of clay or sand grains. Others are yellow to buff, from rocks containing minute particles of iron oxide. Certain beds, such as the lower bridge ledge at Mankato, are blue when first quarried but rapidly turn buff on exposure, probably from the oxidation of iron originally present in them in carbonate form; the Platteville limestone is blue where unweathered but is yellow along joint planes. In some of the blue ledges, however, the color is more permanent. This is well shown in a farmhouse in Dakota County which has stood for 47 years, and still retains the distinct blue color.

At Ottawa, St. Peter, and Kasota, near Minnesota River, the color of the Oneota dolomite in different beds ranges from deep yellow to pink. Winchell states that the dark color of the "Kasota" stone is probably due to the absorption of material from the waters of Minnesota River, when it flooded the terrace now being excavated.

LIMESTONE AVAILABLE IN MINNESOTA FOR THE MANUFACTURE OF PORTLAND CEMENT

There are no known deposits of limestone in Minnesota of the proper character for making Portland cement and large enough in extent to warrant the building of a Portland cement plant. The amount of magnesium carbonate is above the limit which can be allowed, at present, for Portland cement making.

TABLE XIII

ANALYSES OF MINNESOTA LIMESTONES

Quarry	Town	County	Insoluble HCl	Fe_2O_3	Al_2O_3	$CaCO_3$	$MgCO_3$
Platteville Limestone							
St. Peter's Church abandoned*†	Mendota	Dakota	26.66	....		45.77	24.75
Carey†	Spring Valley	Fillmore	1.96	....		76.44	20.45
Akre and Dahl (Old Highland)†	Rushford	Fillmore	6.34	....		51.50	38.98
M. C. S. Co. Composite sample†	Minneapolis, Johnson and 15th ave. N.E.	Hennepin	12.50	(FeS–2.13 Al_2O_3–0.84)		70.30	13.54
Mpls. S. Co. Composite sample†	Minneapolis, Johnson and Central ave. N. E.	Hennepin	9.00	1.95	1.32	80.00	6.10
Blue L. S. Co.†	Minneapolis, Central and 15th ave. N. E.	Hennepin	11.90	0.71	1.04	82.06	3.72
Bielenberg, East George St. (Yellow stone)†	South St. Paul	Ramsey	13.54	....		55.57	29.11
Weeks and Holscher‡	Minneapolis	Hennepin	16.22	0.90	3.16	54.53	36.00
Foley and Herbert‡	Minneapolis	Hennepin	29.93	4.03		41.88	24.55
Eastman‡	Minneapolis, Nicollet Island	Hennepin	14.45	1.70		75.48	6.81
A. Rau‡	St. Paul	Ramsey	13.39	1.63	2.67	79.18	6.42
				(SiO_2–8.16)			
Taylors‡	Fountain	Fillmore	9.89	1.30		86.11	0.47
M. C. S. Co.§ (2 ft. below top)	Minneapolis	Hennepin	15.38	3.50		46.68	26.18
M. C. S. Co.§ (5 ft. above floor)	Minneapolis	Hennepin	10.46	1.40		81.35	4.94
M. C. S. Co.§ (Upper 8 ft.)	Minneapolis	Hennepin	13.19	2.70		46.15	29.98
M. C. S. Co.§ (Lower 8 ft.)	Minneapolis	Hennepin	11.41	1.38		77.42	6.39

TABLE XIII—*Continued*

Quarry	Town	County	Insoluble HCl	Fe_2O_3	Al_2O_3	$CaCO_3$	$MgCO_3$
M. C. S. Co.§ (Middle 8 ft.)	Minneapolis	Hennepin	20.40	3.40		45.76	26.44
M. C. S. Co.§	Minneapolis	Hennepin	36.53	4.76		39.51	15.22
M. C. S. Co.§	Minneapolis	Hennepin	39.05	3.20		34.92	20.55
M. C. S. Co.§	Minneapolis	Hennepin	11.76	1.96		70.33	8.92
M. C. S. Co.§	Minneapolis	Hennepin	18.52	0.86		78.20	0.68
St. Paul Crushed Stone Co.§ (Lower)	St. Paul	Ramsey	10.72	1.56		70.67	13.66
St. Paul Crushed Stone Co.§ (Middle)	St. Paul	Ramsey	15.82	1.92		72.67	9.67
St. Paul Crushed Stone Co.§ (Upper)	St. Paul	Ramsey	33.45	3.40		40.07	21.81
State C. S. Co.§ (Upper beds)	Faribault	Rice	12.45	4.46		67.43	14.87
State Hospital§	Rochester	Olmstead	12.28	5.20		64.88	15.99
State Hospital§	Rochester	Olmstead	8.63	2.48		63.75	19.28
Buff limestone Representative sample‖			8.16	2.43	2.67	79.18	6.38
Clear parts of buff limestone‖			5.79	1.89	2.04	83.24	5.40
Dark bands of buff limestone‖			15.84	4.00	4.93	56.47	14.21
Lower strata of buff limestone‖			20.38	15.31	26.77	28.86	11.18
Buff limestone‖			1.30	1.20	1.30	80.60	18.00
Buff limestone‖			9.99	2.69	3.43	77.21	3.91
Carey†	Spring Valley	Fillmore	1.96	....		76.44	20.45
Oneota Dolomite							
Bradley†	Mankato	Blue Earth	...	8.6		52.62	38.78
McClure and Widell (Bridge ledge)†	Mankato	Blue Earth	SiO_2 7.35	0.96	4.51	48.26	38.67
Bjork†	Red Wing	Goodhue	6.02	....		50.00	39.79

TABLE XIII—*Continued*

Quarry	Town	County	Insoluble HCl	Fe_2O_3	Al_2O_3	$CaCO_3$	$MgCO_3$
Frontenac†	Frontenac	Goodhue	4.27	....		52.50	41.24
Several near†	Winona	Winona	11.93	....		45.83	39.42
Leatherman†	Elba Township	Winona	2.92	....		54.50	37.75
Coughlin§ (Thin beds)	Mankato	Blue Earth	14.66	1.34		48.72	33.95
Coughlin§ (Thicker beds)	Mankato	Blue Earth	9.59	2.08		50.97	33.01
Breen Stone & Marble Co.§	Kasota	Le Seuer	11.12	2.06		49.54	32.34
Breen Stone & Marble Co.§	Kasota	Le Seuer	7.26	1.68		54.58	30.99
Hastings C. S. Co.§	Hastings	Dakota	2.26	1.00		56.82	40.02
Biesanz Stone Co.§ (Near quarry floor)	Winona	Winona	10.78	0.62		54.04	28.76
Biesanz Stone Co.§ (Upper beds)	Winona	Winona	7.50	0.84		52.79	28.20
Devonian Limestone							
Bly‡	Spring Valley	Fillmore	1.39	....		56.50	40.27
Shakopee Dolomite							
McGee†	Stillwater	Washington	9.26	....		50.00	40.21
Breckenridge, Stewart, and Buttar‡	Kasota	Le Seuer	13.06	1.09		49.16	37.53
Breckenridge, Stewart, and Buttar‡	Kasota	Le Seuer	13.85	1.49		47.90	35.23
————¶	Ottawa	Le Seuer	7.25	1.55		58.65	29.15
————¶	Kasota	Le Seuer	13.85	1.49		47.90	35.23
Clapp¶	Kasota	Le Seuer	2.82	1.39		52.22	36.04¶¶
Beatty**	Mankato	Blue Earth	19.88	2.43	3.72	44.68	31.59
Maxfield and Mather**	Mankato	Blue Earth	15.52	5.64		46.86	33.56

TABLE XIII—*Continued*

Quarry	Town	County	Insoluble HCl	Fe_2O_3	Al_2O_3	$CaCO_3$	$MgCO_3$
Standard Cement Co.**	Mankato	Blue Earth	21.00	2.73	0.85	40.00	31.50
St. Lawrence Formation							
Tosterin‡	Frontenac	Goodhue	2.93	0.36	0.31	54.78	42.53
Hersey, Staples, and Hall‡	Stillwater	Washington	4.52	1.11		53.50	40.21
Hersey, Staples, and Hall‡	Stillwater	Washington	8.54	0.78	0.64	50.22	37.39
Chas. H. Porter‡	Winona	Winona	6.32	0.96		51.23	41.33
Sugar Loaf	Winona	Winona	24.21	3.32		47.11	20.67††
Mill Co.‡	Lanesboro	Fillmore	3.45	0.37	0.33	49.65	42.06
Mill Co.‡	Lanesboro	Fillmore	7.35	1.05		62.14	28.49
Sweeney‡	Red Wing	Goodhue	10.94	0.55	0.34	50.68	33.61
Galena Limestone							
Lime City	Spring Valley	Fillmore	4.57	0.73	...	70.53	23.49
Hook‡	Mantorville	Dodge	6.33	1.77		50.20	38.96‡‡
McDonough§ (Near quarry floor)	Mantorville	Dodge	15.71	2.34		49.38	31.12
McDonough §	Mantorville	Dodge	9.58	2.00		52.93	32.58
Lindersmith's‡	Owatonna	Steele	25.51	1.94		57.c8	15.90

* This rock was used in the Sibley house in 1835.

† Oliver Bowles, Structural and Ornamental Stones of Minnesota. *United States Geological Survey Bulletin* 663. 1918.

‡ N. H. Winchell, Final Report on the Geology of Minnesota. *Minnesota Geological Survey* 1:195-203. 1884.

¶ *Idem.* p. 638.

§ Partial analyses of samples taken by State Highway Department in 1921. R. E. Kirk, analyst.

‖ Hall and Sardeson, Paleozoic Formation of Minnesota. *Bulletin of the Geological Society of America* 3:358. 1892.

** *Idem.* pp. 449-51.

†† $CaSO_4$, 4.32%.

‡‡ Na_2O, 10.6.

¶¶ $CaSo_4$, 6.74%.

Some analyses are available of low magnesia limestone found in Minnesota, but so far as is at present known the deposits so represented are small in amount. Perhaps the largest one known is that at Le Roy, Minnesota. It is of course always possible that investigation might disclose an adequate supply of low magnesia limestone. The logical place one might expect to find such a deposit, if it exists, would be in certain of the southeastern counties of the state where the Platteville limestone is exposed, or in the south central counties where there are outcrops of Devonian rocks. The writer is inclined to doubt the probability of finding a large enough deposit of high-calcium limestone to justify the erection of a Portland cement plant. Any such deposit must be large enough to last the plant at least twenty and better thirty to forty years.

The question of the possible existence of a limestone deposit of a size to render the building of a cement plant commercially feasible is so persistent that it seems worth while to discuss certain of the limestone formations very briefly.

1. *The Platteville formation.*—The Platteville limestone which outcrops near Minneapolis and St. Paul, and which is so extensively quarried there for use as crushed stone in concrete work contains certain layers which are low in magnesium carbonate. Certain other layers contain a great deal of shale and are high in magnesium carbonate.

This is shown by the series of analyses in Table XIII covering samples taken at various points on the quarry face in the quarry of the Minnesota Crushed Stone Company in northeast Minneapolis. It will be noted from these analyses that in general the lower layers contain less magnesium carbonate.

The analysis shown from Bowles[13] of the rock once quarried by the Blue Limestone Co. illustrates the same point, since that stone was from the lower layers of the Platteville.

Bowles[14] describes the outcrops of this formation in Ramsey County as follows:

> The Platteville formation is the only structural rock in the county. It outcrops almost continuously along the river bluff and has been quarried at numerous points. In general, it falls into three rather distinct parts that have fairly constant characters: An upper layer, 6 to 10 feet thick, of drab to buff magnesian limestone, containing many fossils and masses of crystalline calcite, a bed of about the same thickness of argillaceous limestone or shale, and at the bottom a 12 to 15 foot layer of blue limestone, interbedded with thin shale

[13] *Loc. cit.*
[14] *Loc. cit.*

bands, which has supplied most of the structural stone in and around St. Paul. The weathering out of the shale layers causes the hard layers to stand out in relief and thus to form the characteristic horizontal ridges so prominent in all the old stone walls of the city. On this account the rock is not very durable. A bed of blue shale 3 to 6 feet thick lies between the blue limestone and the underlying St. Peter sandstone. The only quarries now actively engaged are in South St. Paul and near the Fort Snelling Bridge on the north side of the river.

The South St. Paul quarry, near East George Street, has been operated by C. Bielenberg since 1904. The rock is variable in its different beds.

Two distinct types of stone, an upper yellow and a lower blue bed, are quarried. The 3-foot bed of porous yellow rock is used for structural purposes. Immediately below this are two contiguous beds, 5½ and 6 inches thick, which are of high quality. The rock is a uniform, fine-grained, yellow limestone, containing many small grains of crystalline calcite. The rock is a magnesian limestone. The insoluble portion is probably mostly clay, but the presence of clay distributed uniformly throughout a rock mass has little effect on its durability.

The three analyses shown in Table XIII of limestone from the quarry of the St. Paul Crushed Stone Co. show a similar change in chemical composition.

A similar variation in chemical character is disclosed by the analyses shown from the paper by Hall and Sardeson.[15]

It should be noted that the Platteville formation, near Dubuque, Iowa, bears limestone of a character such that it can be used in the making of Portland cement.[16] Even here the outcrops carry certain layers of shale and of magnesian limestone.

The Platteville formation is also being used by the Sandusky Portland Cement Co. at Dixon, Illinois.[17] This quarry is in Lee County. Two counties north of this near Winslow in Stephenson County, Illinois, the outcrops of the Platteville limestone are typically dolomitic, their magnesium carbonate content being about 35 to 40 per cent.

The change in the character of the Platteville formation is well summarized by Winchell[18] as follows:

The Trenton (Platteville) limestone as quarried near Fountain, is found in the bottom of the formation, within ten feet of the St. Peter Sandstone in horizontal strata, and is exposed along the railroad cut east of the village. It is stratigraphically the equivalent of the beds quarried more extensively at

[15] C. W. Hall and F. W. Sardeson, Paleozoic Formations of Southeastern Minnesota. *Bulletin of the Geological Society of America,* No. 3, pp. 331-68. 1892.

[16] E. F. Burchard. Portland Cement Materials near Dubuque, Iowa. *United States Geological Survey Bulletin,* No. 315, pp. 225-31. 1906.

[17] Frank Krey and J. E. Lamar. Limestone Resources of Illinois. *Illinois State Geological Survey Bulletin* No. 46. 1925.

[18] N. H. Winchell. Final Report on the Geology of Minnesota. *Minnesota Geological Survey* 1:170-71. 1872-85.

St. Paul and Minneapolis, but the stone differs from the latter in being nearly free from shaly impurities. It is of a drab color, but passes to a bluish color on being opened more deeply, and has a very compact or dense texture. There are here beds of shale, but they are distinct from the limestone beds. They facilitate the operations of the quarrymen, but do not impair the quality of the rock. In quarrying the layers rarely exceed five inches in thickness. On the weathered bluff they appear even thinner than that, being apparently not more than two inches. They are tough and hard, and when broken they often fracture chonchoidally and in unexpected directions. The same kind of stone is quarried at Chatfield, in the upper bluffs, also near Faribault and Northfield, both in Rice county. In passing northward, however, and thus approaching the old shore-line of the palaeozoic ocean, more argillaceous shale is found mingled with the rock; so that, even in those comparatively quiet times, when marine animals flourished and on their death supplied a calcareous deposit, there was present so much shaly (or clayey) sediment that the resulting rock is not so pure a limestone as farther south. At the southern points the quiet, lime-producing epochs were less characterized by this impurity, but were separated more distinctly by periods of agitation when large amounts of shale were deposited. Hence in this formation at Minneapolis and St. Paul the argillaceous ingredient is distributed with the calcareous and also constitutes heavy beds of itself; while, at Northfield and Faribault, the calcareous layers are more nearly pure, and at Fountain are almost free from alumina and silica. At the same time in passing toward the north the purely argillaceous beds become thicker as the calcareous become thinner.

2. *Devonian limestones.*—The Devonian limestones appear in small areas in Mower, Fillmore, and Faribault counties in Minnesota. These rocks occur on hilltops in western Fillmore County. An analysis of the stone quarried from this formation at the Bly quarry near Spring Valley is given in Table XIII. Chemically it is a highly magnesian limestone. Most of the Devonian limestone in Mower County is listed as being dolomitic, but certain areas near Le Roy are reported to be high calcium stone. Very little seems to be known about the character of the Devonian limestones in Faribault County. No quarries are operating in the formation and but few outcrops are reported.

The character of the Devonian formations in Iowa is of interest. Certain portions of the middle Devonian outcrop near Mason City as the Cedar Valley limestone. This is used as a Portland cement material by the Mason City mills. This formation in the southern portion of its area of outcrop is non-magnesian. An analysis of the deposit used at Mason City by the Northwestern States Portland Cement Company is found in Table XII. Both Cerro Gordo County (Mason City) and Mitchell County (Osage) show outcrops of white, compact brittle limestone high in calcium carbonate. Toward the north the Cedar Valley limestone becomes more magnesian until in Howard County (adjoining Mower County, Minnesota) it is a massive dolomite. There are still some intermediate beds of high calcium limestone, but their thickness is limited.

While the possibility of finding a large deposit of high calcium limestone in Minnesota is to be admitted, the probability of such a discovery would seem rather unlikely.

PORTLAND CEMENT IN MINNESOTA

Reference has been previously made to the annual consumption of Portland cement in Minnesota.

PORTLAND CEMENT PLANTS IN MINNESOTA

The only Portland cement plant in the state of Minnesota is located at New Duluth in the Duluth industrial district. This plant is owned and operated by the Universal Portland Cement Company, a subsidiary company of the United States Steel Corporation. This plant uses blast-furnace slag from the near-by plant of the Minnesota Steel Company and limestone screenings shipped in by boat from quarries in Michigan. This plant is very advantageously located with respect to rail and water transportation. It uses cheap raw materials and commands a good trade territory. The company can sell to very good advantage in the Duluth-Superior district and the Iron Range country. The plant is well built and modern and very well managed. The dry process is used. The plant has four 10×150 foot kilns and one 10×200 foot kiln. These produce about 7,000 barrels of Portland cement daily. Electrical dust collectors are used. The plant officials claim a coal consumption in the kilns of 67 pounds of coal per barrel of cement burned. This low fuel consumption is accounted for, in part at least, by the fact that the calcareous matter in the slag has already been calcined and no heat energy needs to be supplied for that purpose.

The Universal plant at Duluth produces a high grade Portland cement of standard quality. Its product is well and favorably known. Together with the plants of the same company near Chicago it supplies large amounts of cement to the Twin Cities market.

The Huron Portland Cement Company, with plants at Alpena, Michigan, and Wyandotte, Michigan, maintains a packing plant at Duluth. The cement is brought in by water from the plants in Michigan. The Huron Company is at present the exclusive sales agent for the cement produced by the Ford Motor Company in their wet process plant at River Rouge, Michigan. This plant uses blast-furnace slag.

IOWA PORTLAND CEMENT PLANTS

The cement plants located in Iowa with a combined capacity for producing cement estimated at nearly 30,000 barrels daily, are a factor in the cement trade of southern Minnesota and of the Twin Cities. Since Iowa is well supplied with low magnesium limestones, all these plants use limestone. No attempt has been made to develop the marl deposits of Iowa. It seems likely that the Iowa marl deposits are small and widely scattered, altho no accurate information is available concerning them.

The Northwestern States Portland Cement Company built the first plant in Iowa at Mason City. Its product is well known on the Minnesota markets.

The Lehigh Portland Cement Company operates a plant at Mason City on a tract of land adjoining the Northwestern States' holdings. The Hawkeye Portland Cement Company, at Des Moines, and the Pyramid Portland Cement Company at Valley Junction, near Des Moines, are also important factors in the cement production of Iowa. The two last named plants use the wet process. The Gilmore Cement Company operates a plant at Gilmore City, near Fort Dodge.

The Linwood Cement Company built a plant at Linwood, near Davenport, in 1925. The Davenport Cement Company has purchased a site of 400 acres at Buffalo, near Davenport, and plans to erect a Portland cement plant in the near future.

In addition to the plants mentioned, companies have been organized to build Portland cement plants at Dubuque and at Rutledge, Iowa.

THE BEST POSSIBLE LOCATION IN MINNESOTA FOR A PORTLAND CEMENT PLANT USING MARL

Numerous factors enter into the matter of the possible locations in Minnesota for plants designed to produce Portland cement from marl. First of all the plant must be located near an adequate supply of raw materials. This factor could only be evaluated by careful investigation of the deposits of marl and clay. The distances that marl could be economically transported would depend on other factors such as availability of clay and shipping facilities for the finished cement.

In the second place, a location within a reasonable distance of the Twin Cities would be very desirable. This would give the plant an advantage in placing its product in this industrial center, and would also protect it from too strenuous competition with the Iowa plants on the south or the Duluth plant on the northeast. For these reasons a location somewhat to the west or northwest of the Twin Cities would be most suitable.

Finally it would be best to locate such a plant, if possible, where it could be served by more than one railway system.

If adequate river transportation becomes available on the Mississippi, the plant might be located where such shipping facilities can be used. This would of course mean that a location on the navigable portion of the river should be selected. Under present conditions this consideration would dictate a site somewhere below the head of navigation at the Falls of St. Anthony. Since a site for such an operation could scarcely be secured within the corporate limits of Minneapolis or St. Paul, save at a prohibitive figure, a location on the river somewhere below St. Paul would seem the most logical site for such a plant. The Decorah shale of Dakota County (see analyses in Table XI) might conceivably be used to mix with marl. Such a location, however, would involve transporting the marl for rather long distances since no marl deposits are available in the region below St. Paul. The successful navigation of the river above Minneapolis would bring up an interesting possibility in transporting marl by barge from some point in north central Minnesota to a location in the approximate vicinity of Anoka, where the Coon Creek clays might be used.

CONCLUSIONS

1. Portland cement can be made from marl and clay, of as good quality as that made from any other raw materials.

2. Modern methods and equipment enable the wet process for the manufacture of Portland cement to compete with the dry process.

3. The use of limestone should be favored where a sufficient supply of the proper character for cement making is available.

4. Where a supply of limestone is not available, the possibility of using marl should be given serious consideration. The conditions essential for the probable success of such an undertaking are summarized on pages 55-56.

5. There is no evidence at hand to show that Minnesota contains deposits of limestone of sufficient extent and of the proper character to warrant the establishment of a Portland cement plant.

RECOMMENDATIONS

1. It is therefore recommended that a careful investigation be made of the larger marl deposits of the state to ascertain whether their character, extent, and location are such as to justify the erection of a Portland cement plant designed to use marl.

2. A study of the economic factors of the Minnesota trade territory with regard to the use and consumption of Portland cement might well be undertaken by the appropriate authorities. Such a study would supply data on which to base a decision as to the economic advantages and disadvantages of a Portland cement plant in the Twin Cities region.

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