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1947 REPORTS OF STUDIES, PART 4, PAGES 53-112, FIGURE 1, PLATES 1-8
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THE MANUFACTURE OF CERAMIC RAILROAD BALLAST AND CONSTRUCTIONAL AGGREGATES FROM KANSAS CLAYS AND SILTS

By

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ABSTRACT

The State of Kansas chiefly is dependent on crushed limestone for such uses as railroad ballast, concrete aggregate, and road metal. Relatively hard limestone is plentiful in the eastern half of the State, but only soft limestone occurs in abundance in the western half.

Under conditions of severe use limestone is regarded as inadequate for railroad ballast due to its softness, dustiness, and tendency to form a water-retaining mud. Concrete made with some limestone aggregates tends to disintegrate under conditions such as those to which concrete highway slabs and bridges are subjected. The needs of the railroads for a durable ballast are particularly acute in this vast central area of the United States where sources of naturally occurring hard rock are inadequate.

A series of tests conducted in the ceramics laboratory of the State Geological Survey has demonstrated that a durable material suitable for use as railroad ballast, concrete aggregate, and allied uses can be manufactured with standard industrial equipment from the cheap and abundant clay and silt resources of Kansas. The method of manufacture involves the vitrification or pyroplastic agglomeration of the raw materials in a rotary kiln, or possibly some other type of firing equipment. In this report the product is termed "ceramic slag" to avoid the use of more accurately descriptive but awkward terms such as "ceramic agglomerate," "ceramic aggregate," or "vitrified clay."

Laboratory production of ceramic slag chiefly was conducted in a high temperature electric kiln. Check runs were made on a number of representative samples in a batch-type gas-fired rotary kiln. Pilot plant tests on one type of material, a Pleistocene clay, have been made by the Mineral Products Company in a 30-foot continuous rotary kiln.

Materials tested included silt, clay, and shale samples of Pleistocene, Cretaceous, Permian, and Pennsylvanian age collected over a wide geographical range. In general, Pleistocene silts and clays, particularly those from loess deposits, have proved to be the most satisfactory materials.

It is estimated that the cost of producing ceramic slag will range from $1.15 to $2.25 per ton if the processing is carried out on a large scale in a rotary kiln.

PURPOSE OF INVESTIGATION

Needs and potentialities.—Throughout the central and western parts of the State of Kansas naturally occurring hard rock suitable for concrete aggregate, road metal, railroad ballast, and riprap is found only in small deposits, and in many areas it is completely lacking. Limestone, which is abundant in the eastern third of the State, is suitable for concrete aggregate for most uses and for riprap, but limestone railroad ballast has several objectionable features, particularly on main lines where modern high-speed trains are used. Although limestone has a relatively low abrasion loss and a sufficiently high compressive strength. it forms a fine dust on abrasion which clogs air-conditioning units. interferes with lubrication of the journals. and is a nuisance to both passengers and train crews. This fine dust when wet forms an impervious mud which accumulates in and at the base of the ballast and retains water around the ties and on the roadbed. When trains pass over the track, "pumping" occurs. The final result is rotted ties and a track which is displaced both horizontally and vertically. Furthermore, limestone lacks the hard sharp edges and rough surfaces which prevent the individual pieces from sliding on each other. This in conjunction with the lubricating effect of the limestone mud tends to cause displacement of the ballast and increased cost of maintenance.

The State Geological Survey has received many inquiries from persons seeking a hard, durable rock for concrete aggregate and railroad ballast. Due to our experience with the various forms of hard-burned clay products such as paving brick, over-burned building brick, and stoneware we were aware that such materials were surpassed by very few others in resistance to weathering and abrasion and in compressive strength. Even clay products such as pottery and bricks which were fired at ordinary temperatures have endured for thousands of years and remain the only material record of past civilizations.

Several years ago we suggested the use of vitrified clay for railroad ballast and concrete aggregate, but the idea met with only slight interest because most persons were acquainted with the burned gumbo ballast which was in common use in the early days of the railroads. This material was an underfired clay produced by crude methods, and was by no means a material suitable for present day uses. Some of the more siliceous blast furnace slags are more nearly comparable to a completely vitrified product made from clay, shale, or clayey silt. For this reason we have given the name "ceramic slag" to the aggregate or ballast made from vitrified clayey materials.

In the latter part of 1945 the Industrial Minerals division of the Geological Survey set up a definite project for the experimental investigation of the possibility of producing ceramic slag on a commercial basis. The project was stimulated by the immediate need for a railroad ballast of a better quality than any available from naturally occurring rock deposits. The Santa Fe Railway Company assisted the project by purchasing a high-temperature electric kiln (Pl. 1A) for our laboratory and also assisted in the collection of samples.

The production of ceramic slag is well suited to the State of Kansas and similar areas in the Midwest not only because of the lack of rock of sufficiently high quality but also because of the abundance of raw materials suitable for the production of ceramic slag and the abundance of gas and oil for use in manufacturing the product.

Geologic factors.—In Kansas the major part of the rock crushed for use for railroad surfacing, concrete aggregate, and railroad ballast is produced from limestones of Pennsylvanian and Permian age. These limestones are available, however, only in the eastern third of the State. In this area the limestone deposits are large and well distributed, particularly in the area of outcrop of the Pennsylvanian rocks. In the western two-thirds of the State deposits of durable hard rock are inadequate at the best, and over fairly large areas none is available. Extensive limestone deposits of Cretaceous age occur in central and western Kansas, but these limestones are soft and chalky and therefore unsuited for aggregate and railroad ballast. Some excellent materials are available in limited quantities such as the cemented sandstone of the Dakota formation, locally called quartzite (Swineford, 1947), and the silicified rock in the Ogallala formation (Frye and Swineford, 1946).

In our tests we have found that the silty clay and clayey silt of Pleistocene age, particularly the loess deposits, are best suited to the production of ceramic slag not only because of the qualities inherent in the material but also because of the uniformity of the material and the thickness, extent, and wide distribution of the deposits (Smith, 1940; Hibbard, Frye, and Leonard, 1944; Frye and Fent, 1947). This is fortunate in that the Pleistocene clays and silts occur in greatest abundance in the western half of the State where the reserves of naturally occurring hard rock are inadequate or entirely lacking.

Materials suitable for the production of ceramic slag also occur in abundance in eastern and central Kansas. These materials include not only clays and silts of Pleistocene age, but clays and silts from Recent alluvial deposits, and clays and shales of

Pennsylvanian, Permian, and Cretaceous age. A ceramic slag of excellent quality can be produced from the Dakota formation clays of Cretaceous age (Plummer and Romary, 1947).

Economic factors.—If a suitable naturally occurring rock is available within an economical shipping range ceramic slag could not be produced in competition with it. In areas where suitable rock is not available ceramic slag can be produced at a cost sufficiently low to permit its uses as concrete aggregate, road material, and railroad ballast. Where naturally occurring rock is not available locally the cost of shipping a relatively short distance would equalize the difference in costs between ceramic slag and natural rock. In special cases the slight additional cost of ceramic slag probably would be justified in that the material could be more or less tailor-made to meet unusual specifications.

Commonly ceramic slag has a specific gravity somewhat lower than limestone, and a much lower specific gravity than quartzite or granite. For this reason a considerable saving can be realized in shipping costs. If a material of high specific gravity is required, however, it can be produced by altering the methods of firing, or by the selection of raw materials.

Types of uses.—Ceramic slag is suitable to any of the uses to which crushed rock is adapted. In addition, a greater variety of physical properties can be achieved in the production of ceramic slag than it is usually possible to find in naturally occurring rock. Variations in density, porosity, and hardness can be produced by selection of materials, variations in time used in firing, and the final temperature (Russell, 1940). For example, either rapid firing or a high temperature tends to lower the density of the product due to the formation of minute closed vesicles (Pls. 4A and 5A). Some types of clay or shale have a natural tendency to froth or bloat. With materials of this type it is possible to produce a light-weight aggregate having a bulk specific gravity of less than 0.5. Detailed consideration of such materials is not within the scope of this report, but a series of tests are now in progress to determine the suitability of various Kansas clays and shales for use in the production of a bloated ceramic product for use as a light-weight aggregate and in light-weight ceramic structural units. A report on these tests will be published in a Geological Survey bulletin in the near future.

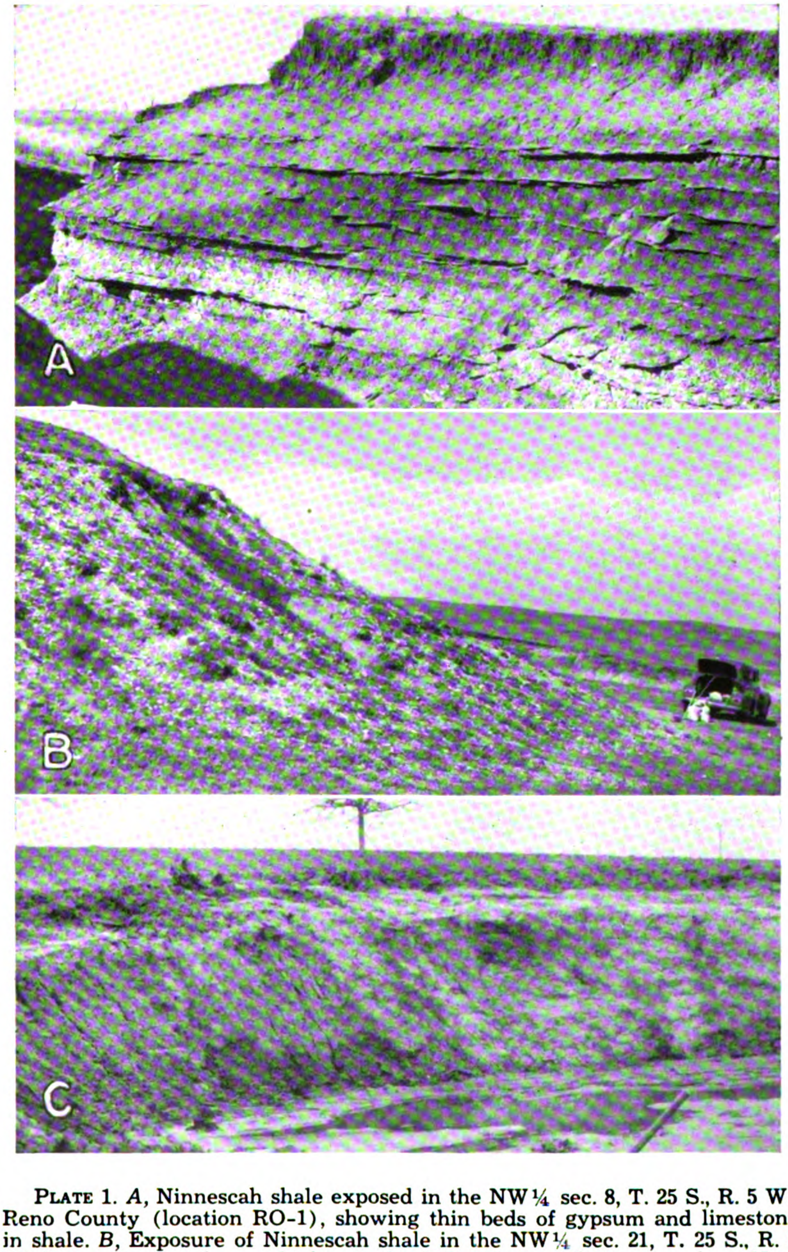

Plate 1. *A,* Ninnescah shale exposed in the NW¼ sec. 8, T. 25 S., R. 5 W., Reno County (location RO-1), showing thin beds of gypsum and limestone in shale. *B,* Exposure of Ninnescah shale in the NW¼ sec. 21, T. 25 S., R. 6 W., Reno County, from which samples RO-2-1, 2, and 3 were taken. Note slight overburden. *C,* Pit from which samples for pilot plant tests were obtained; location JN-2, SE¼ sec. 33, T. 11 S., R. 23 E., Johnson County.

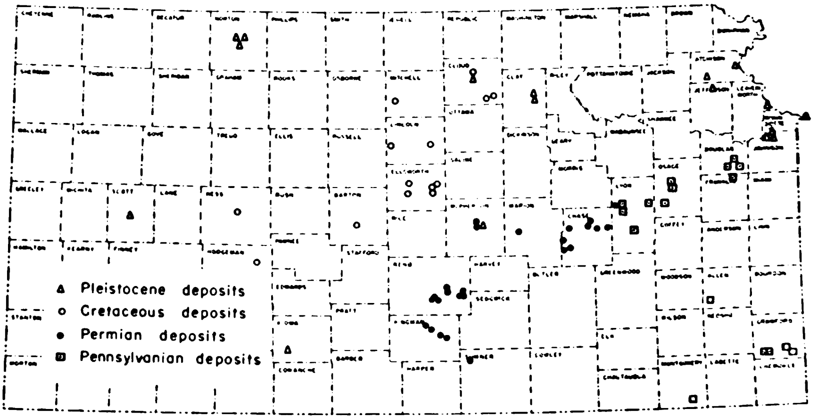

FIG. 1. Map showing location of deposits sampled for ceramic slag.

Ceramic slag is suitable for use as an aggregate in any kind of concrete structure, but is particularly suited for uses in which an aggregate having high compressive strength, resistance to weathering, and chemical stability is required. These same qualities recommend it for use as railroad ballast and as a road material. For the latter type of uses care would need to be taken to obtain a material having a low abrasion loss.

Acknowledgments.—We are especially indebted to the Atchison, Topeka, and Santa Fe Railroad for the contribution of a high-temperature electric kiln for use in testing, and to the Santa Fe officials, particularly Mr. T. A. Blair, assistant chief engineer of the system, and Mr. Frank Helm, district engineer, for their interest and for technical advice concerning the specifications and needs for railroad ballast. We have received valuable assistance from Mr. R. G. Hardy, Mr. George Nettles, and Mr. Kenneth Spencer of the Mineral Products Company who furnished technical advice, data on pilot plant tests, and engineering data on the construction of a plant. Mr. C. T. Griswold, consulting geologist for the Santa Fe Railroad, and Dr. J. M. Jewett of our staff assisted in the collection of samples in the field.

SAMPLING

METHODS OF SAMPLING

The majority of the samples tested were obtained from natural outcrops by the standard channeling method. This method consists of cleaning the exposed face of all weathered or contaminated material, and channeling the cleaned exposure in such a manner that the sample obtained is representative of the entire thickness of the included bed.

Tests of Dakota formation clays were run on samples from our large clay sample file. These samples were originally taken by channeling the face of pits excavated for the purpose of securing unweathered samples (Plummer and Romary, 1942, 1947).

Samples were obtained by augering in Scott County (location SC-1) where adequate surface exposures were not available, in Norton County (NN-1, 2, and 3), and from the prospecting holes at location JN-2 in Johnson County.

GEOLOGIC FORMATIONS SAMPLED

Samples of clay, shale, silt, and sandstone were obtained from beds representing most of the geologic systems exposed at the surface in Kansas. Those included, named in ascending order, are Pennsylvanian, Permian, Cretaceous, and Quaternary (Fig. 1).

Pennsylvanian beds are incompletely represented by samples of Cherokee shale and underclays, two shales from the Bourbon group, the Tonganoxie sandstone, and Vinland shale from the Stranger formation, and the Severy, Willard, and Langdon shale members.

Samples of Permian age were obtained from the Stine, Roca, Eskridge, Florena, Blue Springs, Wellington, and Ninnescah shales (Pl. 1), and shales and silts from the Chikaskia and Kingman members of the Harper sandstone formation (Pl. 2B).

Beds of shale, clay, and silt of Cretaceous age were sampled from the Kiowa shale, the Dakota formation, and the Graneros, Blue Hill, and Pierre shale formations. The majority of the samples tested were taken from the Terra Cotta and Janssen members of the Dakota formation.

All but a very few of the tested materials which are classed as Quaternary in age were sampled from Pleistocene eolian clays and silts (Pls. 1C and 2C), but lacustrine silt (A-4-2), glacial till (JF-1), and alluvial deposits of Pleistocene age (NN-1, 2, and 3) were also included, as well as Recent alluvial silt and sand.

Geographic Distribution

An attempt was made to obtain samples which would represent materials available in all parts of the State. The plains loess which is widely distributed throughout the western half of Kansas is sufficiently uniform in character to obviate detailed sampling. In a more restricted sense the same observation applies to the Pleistocene loess and alluvial deposits which occur in the central and eastern parts of the State.

Although only a relatively small part of available materials of Pennsylvanian and Permian age was sampled, a sufficient number have been tested to indicate that suitable materials are available in almost any county in which rocks of these ages crop out.

A disproportionately large number of samples were collected from Chase and Lyon Counties because in the early stages of the project this area was thought to be more critically in need of railroad ballast than any other.

We believe that it is safe to infer from the work so far accomplished that materials suitable for the manufacture of ceramic slags are available in every county in Kansas.

TESTING

Essentially the testing of materials for their suitability for use in the manufacture of ceramic slag consists of heating the sample to incipient or partial fusion and determining the physical properties of the resulting product by examination and by standard methods designated for railroad ballast, concrete aggregate, and structural clay products.

Methods of Preparation

The materials to be tested received various treatments before firing. In the preliminary firing tests the lump sample as received was placed in fire-clay roasting dishes for the electric kiln, or crucibles for the melting furnace. This method of testing made it possible to determine differences in maturing temperature of various parts of the sample.

The standard method of preparing clay samples for testing was also used. This method consists of grinding the clay in a pan mill, mixing the dry clay with 15 to 25 percent water into a stiff mud

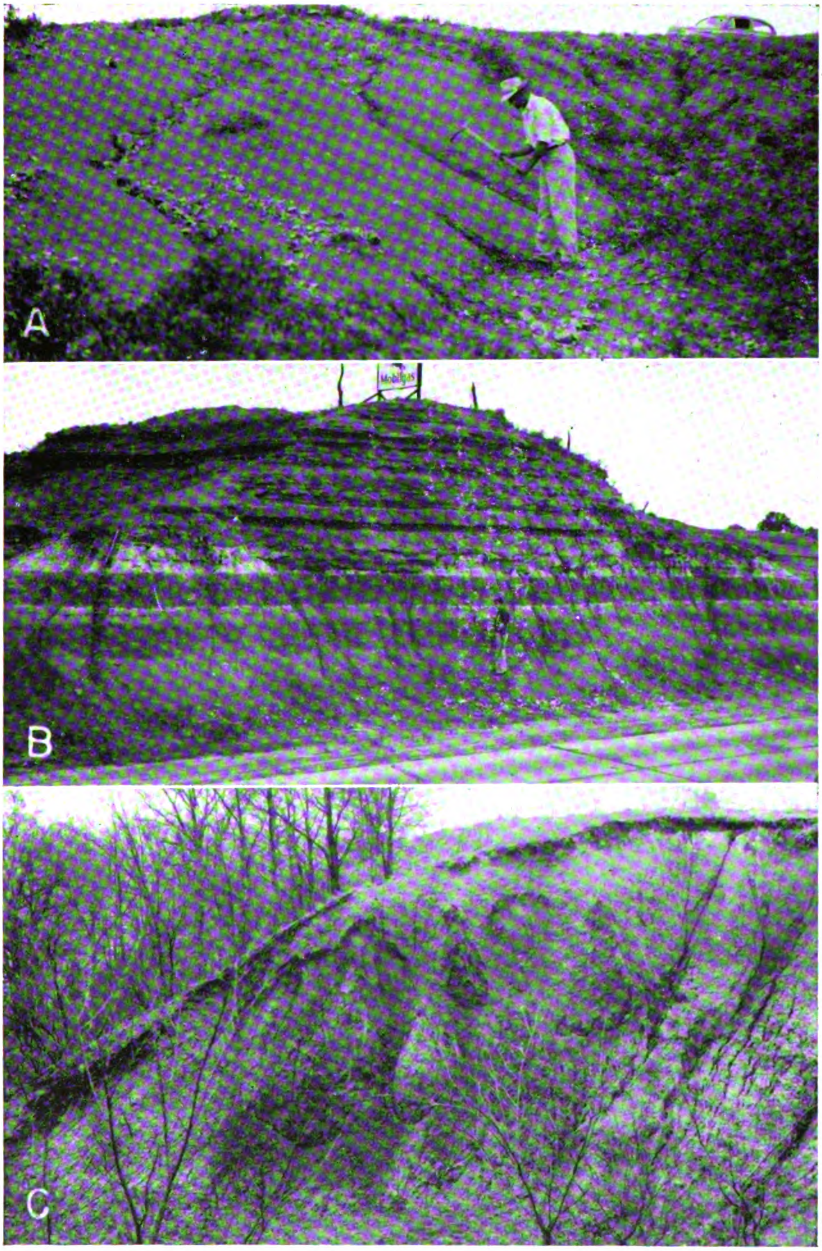

Plate 2. *A,* Blue Hill shale exposed near Cen. N. line sec. 20, T. 10 S., R. 15 W., Osborne County (location OS-1). Note absence of overburden. *B,* Exposure of Harper sandstone; Kingman sandstone member (above white line) and clay in upper part of Chikaskia sandstone member (below white line), in the SE¼ sec. 34, T. 27 S., R. 7 W. (location KN-1), Kingman County. *C,* Pleistocene clay exposed in the SE¼ sec. 33, T. 11 S., R. 23 E. (location JN-2), Johnson County. All the material shown from bottom of picture to top of bank produces ceramic slag of uniformly high quality.

consistency, and molding the plastic clay by hand or extruding it from a laboratory-sized brick machine. The shape most commonly used was 1 inch by 1 inch in a 6- or 9-inch bar.

Dry press shapes were also produced. For this purpose the pan mill pulverized sample was mixed with 7 to 15 percent water and formed into 2½-inch by 2½-inch by 10-inch bricks. A toggle type dry press capable of producing a pressure of approximately 1,500 pounds to the square inch was used for producing these bricks.

In a few cases the loose, pulverized material was placed in fire-clay boxes and heated to the softening point of the clay to determine whether or not a solid block could be formed by this method.

Friable materials which were to be fired in the rotary kiln received no preparatory treatment other than to break up large lumps by hand. The sample as placed in the kiln contained approximately the same amount of moisture as naturally retained in the earth. Shales and other hard materials were grouped in a pan mill to about 4-mesh size if preliminary tests indicated that this treatment was necessary.

Experimental runs were made in the rotary kiln on materials formed into pellets by tumbling in a ball mill, extruded shapes, and clay compacted with a sheep-foot roller.

KILNS AND FURNACES USED IN FIRING

Four types of equipment were used for heating the samples to the desired temperatures. In the early stages of the project we used a gas-fired melting or crucible furnace which held a crucible having a capacity of approximately one quart (Pl. 3A). An optical pyrometer was used to determine temperatures. A periodic gas-fired muffle kiln having a capacity of 12 cubic feet was used for larger samples and for pre-heating in conjunction with the electric kiln. A Leeds and Northrup recording pyrometer with a platinum platinum-rhodium thermocouple was used for determining temperatures in this kiln.

The majority of the samples tested were fired in a Globar-type electric kiln having a capacity of 1 cubic foot, and capable of attaining a temperature of 2900° F. (Pl. 3A). Temperatures were determined with a Bristol radiation type thermocouple and recorder. For most of the tests conducted in the electric kiln the

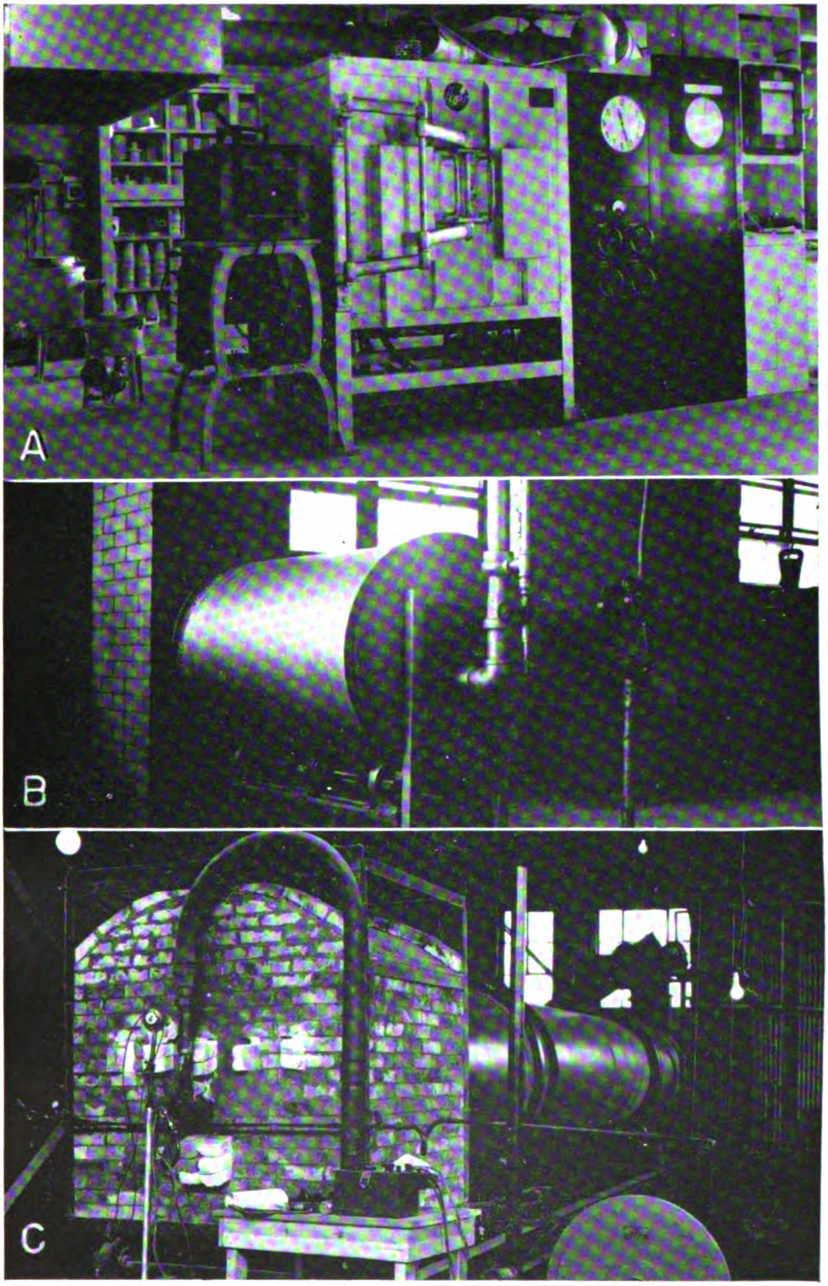

PLATE 3. *A*, View of part of the State Geological Survey's ceramics laboratory. From left to right: crucible type melting furnace, P.C.E. furnace, small electric kiln, high-temperature Globar type electric kiln, control panels, and pyrometers. *B*, Batch-type, gas-fired rotary kiln constructed in the ceramics laboratory of the State Geological Survey for producing test batches of ceramic slag. *C*, Thirty-foot continuous rotary kiln used in pilot plant tests by Mineral Products Company.

samples were pre-heated in the muffle kiln to approximately 700° F., and transferred immediately to the electric kiln at approximately 1500° F.

The last stage of the testing, reserved for selected samples only, was carried out in a batch-type, gas-fired rotary kiln having a capacity of 30 pounds of raw sample (Pl. 3B). Temperatures in the rotary kiln were also determined with the radiation-type thermocouple and recorder.

FIRING PROCEDURE

The firing process in itself varied somewhat with the type of kiln or furnace used for the tests. In view of the necessary economy in commercial firing of ceramic slag the tests were fired at as rapid a rate as was consistent with a sound product.

The rate of firing was determined to some extent by the type of equipment used. The melting furnace tends to heat too rapidly, whereas the electric kiln and the gas-fired periodic kiln have a maximum rate of heating which is relatively slow. To overcome this inherent difficulty in the case of the electric kiln the material to be tested was pre-heated in the gas-fired kiln to about 700° F. and transferred immediately to the electric kiln which had cooled from the previous firing to approximately 1500° F. The temperature was then raised to the maximum attained in 2 to 6 hours at a rate varying from 200° to 400° per hour. The allowable rate of heating varied with the material and the form in which it was fired. Loose, easily oxidized materials can be heated very rapidly, whereas relatively dense materials in large lumps or extruded shapes have to be fired more slowly, especially if the clay is difficult to oxidize. Highly carbonaceous clays, or those containing an appreciable amount of sulfides, require such a long period of oxidation that it is not practical to use them in the production of ceramic slag.

Most materials require at least 4 hours for heating to maturing temperature. Under ideal conditions of raw material and firing the time can be reduced to 2 hours.

In general the density of the finished product decreases with the rate of firing (Pl. 4). Maximum density is achieved by firing slowly enough during the oxidizing period from 900° F. to 1800° F. to completely oxidize carbonaceous materials and iron and sulfur compounds. It is necessary in addition to hold the material at maturing temperatures for a sufficient length of time to permit the formation of a glassy phase. The length of time required for this is short relative to the time required for oxidation (Russell, 1940).

During the preliminary stages of firing in the electric kiln trial pieces were drawn at regular intervals until the temperature of maturity was reached. We judged that the firing was complete when the lumps or the shapes made from the clay were in the pyroplastic condition—that is, when the material was soft enough to be deformed by pressure of the tongs.

Absorption tests were run on the draw trials as well as on the matured sample. In case of accidental overfiring the correct temperature to use for the next firing could be determined from the draw trials.

Overfiring, or firing above the temperature at which maximum density and hardness is attained, results in bloating or frothing with all but a few types of clay or silt (Pl. 5). This vesicular structure, if not too pronounced, is probably desirable in that it decreases the unit weight, tends to make the product more resistant to freezing and thawing, and in the case of its use for concrete aggregate, makes the concrete more resistant to disruption due to growth by recrystallization.

METHODS OF TESTING PHYSICAL PROPERTIES

Tests run on the fired samples are standard for fired clay products, concrete aggregate, and railroad ballast. The physical properties determined were absorptions (cold and boiling water), saturation coefficient and compressive strength (A.S.T.M. Standard designations C 62-41T, C 67-41, and C 127-42), specific gravity and unit weight (A.S.T.M. Standard designations C 127-42, C 27-42, and C 20-4), and apparent porosity (C 20-41). The Los Angeles abrasion test (A.S.T.M. Standard designation C 131-39) was run on selected samples. Selected samples were also used as aggregate in concrete mixtures to determine working properties (A.S.T.M. Standard designations C 143-39 and C 124-39) and compressive strength (A.S.T.M. Standard designations C 31-42 and C 39-42). Specific tests of ceramic slag as concrete aggregate were conducted for the State Geological Survey by the concrete laboratory under the direction of Prof. W. C. McNown, Department of Civil Engineering, University of Kansas.

Separate tests were also run at Kansas State College on samples prepared in our laboratory and the pilot plant kiln of the Mineral Products Company. The work at Kansas State was done under the direction of Prof. C. H. Scholer, Head of the Department of Applied Mechanics, for the State Highway Commission. This laboratory is also running special tests for the Portland Cement Association to determine chemical resistivity of the ceramic slag aggregate.

We have assumed that the determinations of absorptions and the saturation coefficient calculated from these values sufficiently indicate the quality of materials for preliminary tests (Stull and Johnson, 1940). Percentage cold water absorption is calculated from the difference in weight of the dry sample and the weight of the sample after soaking in cold water for 24 hours. The boiling water absorption is determined in the same manner with the exception that the sample is immersed in boiling water for 5 hours and allowed to cool. It is assumed that the sample is completely saturated after boiling for 5 hours. A.S.T.M. Standard designation C 62-41T (1942, p. 1,090) states:

> The saturation coefficient is the ratio of the absorption by 24-hour submersion in cold water to the absorption after 5-hour submersion in boiling water and is defined generally as the ratio of easily filled to total fillable pore space. The theory of the saturation coefficient is that if only a part of the total pore space is occupied by water there is room for expansion on freezing into the remaining pore space without disruption of the material. The data indicate that if the easily filled pore space, that is, the maximum water that might be absorbed . . . does not exceed 80 percent of the total pore space, the remaining space will relieve the pressure due to expansion on freezing.

The same mechanism would apply in the case of pressures due to crystal growth in a concrete.

McMahon and Amberg (1947) conducted extensive tests to determine the correlation of saturation coefficient and absorption with laboratory freezing and thawing tests supplemented by seven years exposure to the weather at Alfred, New York. They concluded that the ability of a brick to withstand years of freezing and thawing can be predicted with a fair degree of probability from absorptions and saturation coefficients, but that the strength of the fired clay and the method of manufacture should also be taken into consideration.

Ceramic slag rates well on all four points. The absorptions and saturation coefficients are low, the strength is unusually high,

PLATE 4. Ceramic slag produced in pilot plant rotary kiln from Pleistocene clay taken from pit at location JN-2 (Pl. 1C). *A*, Bloated due to incomplete oxidation; specific gravity, 1.20. *B*, Dense material produced by complete oxidation and no overfiring; specific gravity, 1.93.

and the method of manufacture precludes internal structural defects in the separate lumps of ceramic slag.

TEST DATA

CHEMICAL AND MINERALOGICAL PROPERTIES

Chemical analyses were run on only enough samples to determine the general relationship of chemical composition to firing behavior and resulting physical properties. Those listed in Table 1 are grouped according to geologic age.

The Pleistocene clays uniformly contain a high percentage of silica and a relatively small percentage of alumina. Alkalies and calcium and magnesium oxides are present in relatively small amounts, with the exception of sample SC-1-A which contains 9.05 percent CaO and 2.18 percent MgO. As a result of the high ratio of silica and alumina to fluxes these clays require a temperature for maturity somewhat above the average, and do not readily fuse into a glass at any commercially usable temperature.

The Permian clays, on the other hand, are relatively low in both silica and alumina, and contain a rather high percentage of fluxes, particularly magnesium. Other Permian clays not analyzed are much siltier than those given, and of course contain a higher percentage of silica. Judging from the low maturing temperatures we can safely assume, however, that these Permian silty clays or silts have a clay content similar to the less silty ones.

The clay content of Pennsylvanian shales is chiefly illite, which clay mineral contains iron, magnesium, and potassium as part of the molecule. This fact is demonstrated fairly clearly in the chemical analyses, and was verified by relatively low vitrifying temperatures and a tendency to bloat. The same observation holds true for the Kiowa, Graneros, Blue Hill, and Pierre shales of Cretaceous age.

The Dakota clays, on the contrary, are composed dominantly of the clay mineral kaolinite, with varying proportions of finely divided quartz. Despite this fact some of the Dakota clays contain appreciable percentages of alkalies. Sample H-1-O contains 3.54 percent. Part of this is present in the illite clay minerals which are a minor constituent of Dakota clays. Possibly the remainder is due to the presence of feldspathic minerals. Almost all the Dakota clays contain enough finely divided quartz to

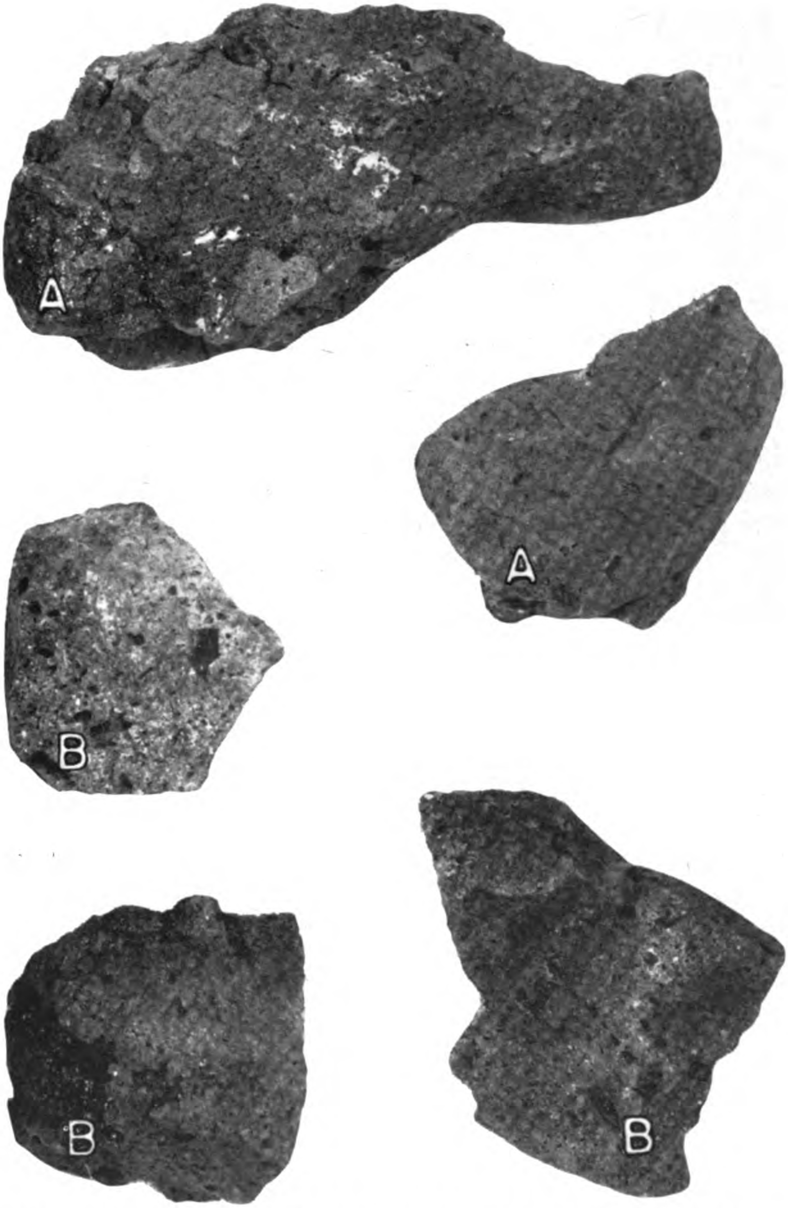

Plate 5. Ceramic slag produced in pilot plant rotary kiln from Pleistocene clay taken from pit at location JN-2 (Pl. 1C). *A,* Slightly overfired; specific gravity, 1.50. *B,* Overfired, specific gravity, 1.40.

TABLE 1.—*Chemical analyses of typical raw materials used in production of ceramic slag*
(Analyses by R. T. Runnels)

	Sample No.	SiO_2	Al_2O_3	Fe_2O_3	FeO	CaO	MgO	K_2O	Na_2O	MnO	TiO_2	P_2O_5	SO_3	Ign. loss	Total
Pleistocene	KC-U.S.B.M.	74.46	12.26	3.15	0.12	0.69	1.12	1.43	1.83	0.02	0.14	0.09	0.06	3.31	99.83
	KC-444-D	74.16	15.14	2.43	N.D.	1.26	1.16	N.D.	N.D.	N.D.	1.14	N.D.		2.68	97.87
	JN-1-A	68.64	16.28	4.15	”	2.17	1.58	”	”	0.98	1.21	”		5.66	100.72
	JN-AG-19A	74.50	11.24	3.38	”	0.64	1.60	”	”	N.D.	1.60	”		5.16	98.12
	JN-AG-19B	77.04	11.36	2.62	”	0.46	1.25	”	”	”	1.11	”		5.02	98.86
	JN-AG-21A	73.90	12.38	3.26	”	0.63	0.99	”	”	”	1.34	”		6.42	98.92
	JN-AG-21B	77.03	8.85	3.32	”	0.69	1.57	”	”	”	1.46	”		4.62	97.57
	NN-5	68.80	11.92	4.20	”	3.30	1.95	”	”	”	1.45	Tr.	N.D.	4.58	96.26
	SC-1-A	61.98	12.02	3.44	”	9.05	2.18	”	”	”	0.63	N.D.	N.D.	7.93	98.23
	A-6	70.98	15.98	3.32	”	2.28	0.42	”	”	”	1.39	”	”	4.60	98.96
Permian	RO-1-1	58.39	9.67	4.72	”	3.16	6.38	4.55		S.Tr.	6.35	none	”	6.55	99.77
	RO-1-2	52.00	17.04	6.23	”	2.40	6.83	3.69		”	5.59	none	”	6.66	100.40
	MP-7	52.59	15.76	1.96	”	5.63	6.31	5.80		N.D.	0.57	0.32	”	10.23	99.17
Dakota	C-51-7	68.61	16.16	4.62	”	0.72	1.03	N.D.		”	2.66	none	0.04	6.34	99.98
	EL-32-A	67.00	21.11	3.20	”	0.38	0.85	1.15		Tr.	0.20	Tr.	”	5.86	99.75
	H-1-0	59.13	15.30	9.48	”	0.48	0.91	3.54		N.D.	4.66	N.D.	”	5.92	99.42
Penn.	DG-12-A	54.46	25.05	6.78	”	0.25	0.39	4.51*		”	0.98	”	”	7.31	100.00
	LW-1	68.31	13.91	5.26	”	0.44	0.98	N.D.		”	0.93	”	”	4.18	94.01
	LY-22	58.81	29.39		”	0.94	2.11	”		”		Tr.	”	5.17	96.42

*Alkalies calculated by difference. In other analyses difference between 100% and total given is largely alkalies.

bring the silica content above 60 percent and the alumina content is high in proportion to the silica if the other clays and shales described are used as a standard of comparison. The purer Dakota clays have a softening temperature above the range practical for commercial use, but some of the more impure clays can be used. They are characterized by a long maturing range and the production of a fired product of high density and durability. This is to be expected of a material containing constituents similar to those of a high-temperature porcelain.

Inasmuch as the ceramic slag is produced by heating to partial fusion, or to approximately the pyrometric cone equivalent of the material, the constituents necessarily react rather completely to form new combinations. The materials containing only small amounts of calcium and magnesium compounds and 1 to 5 percent alkalies would, after incipient fusion, contain tridymite, mullite, leucite, albite, faylite glass, and some undissolved quartz (Dear, 1939). Calcareous clays on incipient fusion would also contain anorthite and wollastonite (Wilson, 1939). Numerous other minerals are of course present but the above mentioned are the most plentiful and conspicuous. In a brief petrographic examination of slides made from six samples of ceramic slag (Pl. 6) quartz, tridymite, and mullite were positively identified; leucite and faylite were thought to be identified and are certainly present in some cases. The light-colored areas on the slides (Pl. 6) are quartz, tridymite, leucite, and pores due to vesicular structure. Mullite crystals are well distributed throughout the field and occur in both light and medium shaded areas. The glass occurs in the darker areas.

The leucite, glass, and mullite are the most important constituents of the ceramic slag. The glass and leucite bond the more refractory materials and the mullite due to felting of its needle-like crystals promotes rigidity in the semifused mass, and contributes greatly to the strength and toughness of the finished product.

PHYSICAL PROPERTIES

Table 2 lists not only the firing data and physical properties determined in the tests, but also stratigraphic position, thickness of bed sampled, and location at which the bed was sampled.

In the case of several samples the data are incomplete, usually in respect to maximum temperature to which the material should be fired. Generally this indicates that the sample was eliminated from the tests before the series was completed because of its obvious unsuitability for use in production of ceramic slag. The most common reason for elimination from further tests was the presence of excessive quantities of calcium carbonate in the sample, or highly calcareous portions. Highly calcareous clays or shales are difficult or impossible to use in the production of a highly vitrified product because the material remains soft and porous to near the temperature of fusion. At fusion the material quickly becomes fluid, rather than pyroplastic but relatively rigid as is the case with noncalcareous clay or shale. Up to 10 percent calcium plus magnesium oxide may be beneficial, however, in that the maturing temperature is lowered, and the material on reaching the pyroplastic stage is soft enough to press together in a solid mass under its own weight as it rolls over and over in the kiln. Many of the purer clays and shales do not become soft enough to accomplish this purpose until temperatures are far above the initial pyroplastic state. At these elevated temperatures the materials tend to bloat. For this reason it may be advisable in some cases to add pulverized limestone to the clay. In the case of one Pleistocene clay (JN-2) the maturing temperature was lowered about 60° F., and a slightly denser product was obtained by adding 10 percent minus 20-mesh limestone. The length of time the material had to be held at maximum temperature was also lessened by the addition of the limestone.

In Table 2 the data on samples taken from the Pennsylvanian, Permian, Cretaceous, and Quaternary (Pleistocene) Systems are listed in separate groups. In general the firing behavior and the physical properties of the fired materials are characteristic for the geologic system from which the samples were collected. The same general uniformity also characterizes the occurrence and the physical and chemical properties of the raw materials. This geologic uniformity is far from complete, however, and properties of individual samples may resemble those typical of another group. In highly calcareous or dolomitic samples all other properties are obscured by the effects produced by the presence of proportionately large amounts of calcium or magnesium and calcium compounds. As would be expected, such

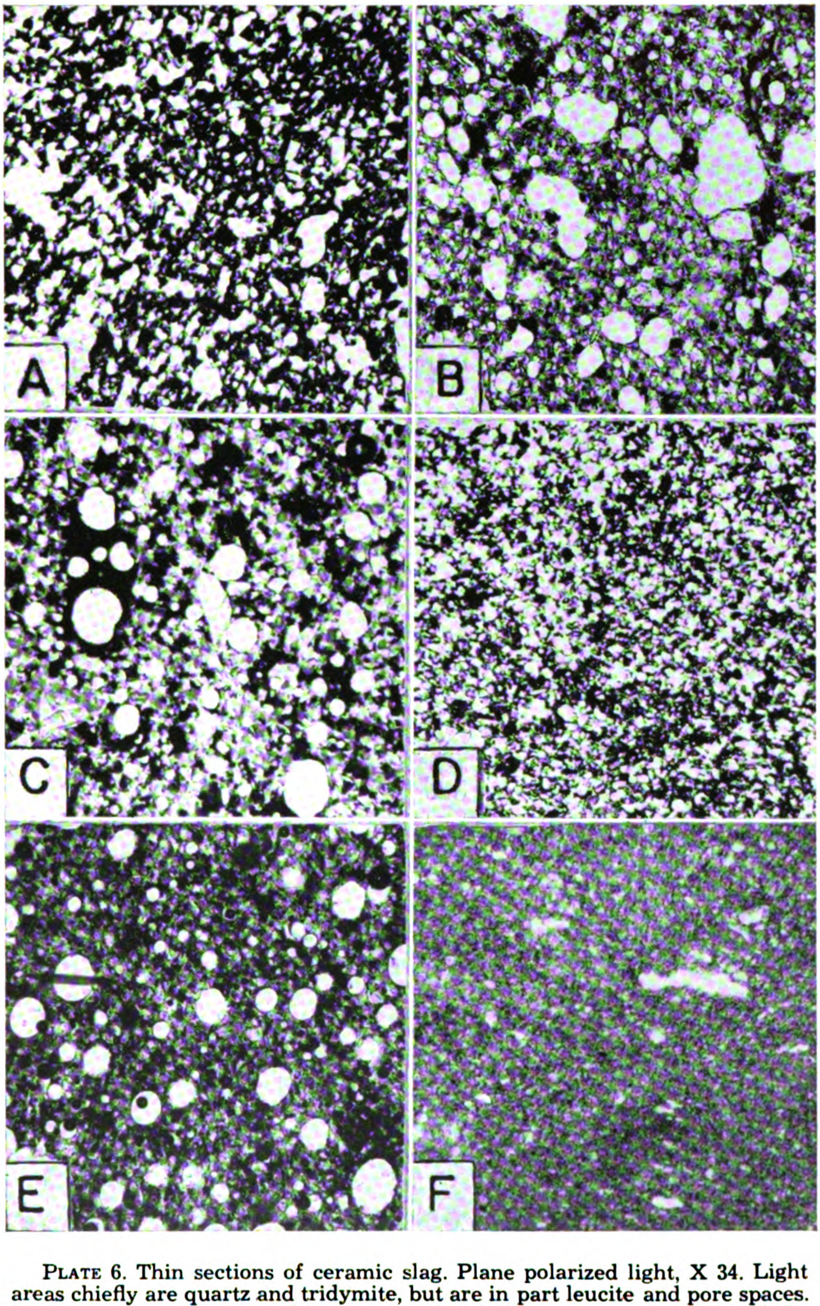

Plate 6. Thin sections of ceramic slag. Plane polarized light, X 34. Light areas chiefly are quartz and tridymite, but are in part leucite and pore spaces. Mullite does not show at this magnification but is present in both the light and the medium shaded areas. Dark areas are glass and in part titanium and iron-bearing minerals. *A* and *B*, Pleistocene clay (JN-2); *C*, Pleistocene clay, calcareous (SC-1-A); *D*, An extremely dense-firing Pleistocene silt (KC-44D); *E*, Dakota clay, very dense, vitrified but not heated to pyroplastic state. The mineral grains are small.

TABLE 2.—*Data on firing and physical properties of cer*

Sample no.	Stratigraphic position	County	Thickness of bed in feet	Location	Temp. °F.
	PENNSYLVANIAN				
DG-10-1	Tonganoxie ss	Douglas	10	NE¼ 3-15-19E	2550
DG-10-2	do	Douglas	10	NE¼ 3-15-19E	2550
DG-11	do	Douglas	5-25	7-15-21E	2240
DG-12-A	Stranger fm.	Douglas	12	SW¼ 11-14-20E	2530
FR-10	Tonganoxie ss.	Franklin	5	NE¼ 28-15-20E	2250
HUM	Lane-Bonner Springs sh.	Allen	30	SE¼ 33-23-18E	2300
LY-22	Langdon sh.	Lyon	5	SE¼ 35-17-12E	2210
LY-22	do	Lyon	5	SE¼ 35-17-12E	2240
LY-22	do	Lyon	5	SE¼ 35-17-12E	2180
LY-28-A	Willard sh.	Lyon	8	SE¼ 2-20-11E	2220
LY-28-A	do	Lyon	8	SE¼ 2-20-11E	2210
LY-28-A	do	Lyon	8	SE¼ 2-20-11E	2110
LY-28-B	do	Lyon	8	SE¼ 2-20-11E	2220
LY-28-B	do	Lyon	8	SE¼ 2-20-11E	2110
LY-28-B	do	Lyon	8	SE¼ 2-20-11E	2110
LY-28-A-B	do	Lyon	16	SE¼ 2-20-11E	2360
LY-29-A	Langdon sh.	Lyon	7.5	Cen. 3-18-13E	2240
LY-29-A	do	Lyon	7.5	Cen. 3-18-13E	2210
LY-29-A	do	Lyon	7.5	Cen. 3-18-13E	2220
LY-29-B	do	Lyon	7.5	Cen. 3-18-13E	2240
LY-29-B	do	Lyon	7.5	Cen. 3-18-13E	2110
LY-29-B	do	Lyon	7.5	Cen. 3-18-13E	2220
MG-LC	Bourbon sh.	Montgomery	20		2465
OG-37	Willard sh.	Osage	5	NW¼ 32-17-14E	2220
OG-37	do	Osage	5	NW¼ 32-17-14E	2210
OG-37	do	Osage	5	NW¼ 32-17-14E	2210
OG-38-B	Severy sh.	Osage	7	SW¼ 8-16-15E	2145
OG-38-B	do	Osage	7	SW¼ 8-16-15E	2282
OG-38-B	do	Osage	7	SW¼ 8-16-15E	2210
CR-4-21-22	Cherokee sh.	Crawford		NW¼ 35-32-22E	2380
CR-7	do	Crawford		16-30-24E	2170
CR-8	do	Crawford		16-30-24E	2230
	PERMIAN				
CS-5	Florena sh.	Chase	4	26-19- 7E	2100
CS-6	Eskridge sh.	Chase	4	7-19- 8E	2210
CS-6	do	Chase	4	7-19- 8E	2220
CS-10	Roca sh.	Chase	5	SW¼ 23-19- 9E	2110
CS-10	do	Chase	5	SW¼ 23-19- 9E	2150
CS-13	Blue Springs sh.	Chase	7	SE¼ 2-21- 6E	2120
CS-13	do	Chase	7	SE¼ 2-21- 6E	2100
CS-14-A	Gage sh.	Chase	6	SW¼ 8-21- 6E	2280
CS-14-A	do	Chase	6	SW¼ 8-21- 6E	2210
CS-37-1		Chase	6	SW¼ 19-20- 6E	2250
CS-37-1		Chase	6	SW¼ 19-20- 6E	2210
CS-37-2		Chase	6	SW¼ 19-20- 6E	2240
CS-37-2		Chase	6	SW¼ 19-20- 6E	2210

lag produced from samples taken at 71 locations

	*Absorption 5 hrs. boiling			Sat. coefficient	Bulk spec. gravity	Form of testing	Remarks
	Max.	Min.	Avg.				
1						Lumps	Underfired, too refractory
2						Lumps	Underfired, too refractory
3	17.66	3.27	9.95		1.97	Lumps	Underfired to mature at 2360°F.
4	2.90	2.14	2.53	.51	1.91	Rotary Kiln	Not suitable for rotary kiln
5	9.32	6.35	7.92		1.87	Lumps	Good material, but platy
6	1.20	.78	1.04	.53	1.90	Rotary Kiln	Excellent material
7	10.79	7.18	8.90	.59	1.85	Test Bars	Good material
8	5.07	.93	2.90		2.25	Lumps	Good material
9	.95	.49	.72		2.39	Dry Pressed	Excellent material
10						Lumps	Slightly underfired
11	5.56	4.10	4.75		2.21	Test Bars	Good material
12	7.00	6.67	6.79	.40	2.18	Dry Pressed	Good material
13						Lumps	Slightly underfired
14	1.04	.20	.61		2.33	Test Bars	Good material
15	5.78	4.88	5.51	.52	2.24	Dry Pressed	Good material
16	7.16	5.77	6.60	.42	1.95	Rotary Kiln	Not suitable for rotary kiln
17	8.92	3.87	6.79	.67	1.80	Lumps	Does not fire uniformly in lumps
18	11.06	7.84	10.30		1.84	Test Bars	Good material
19	9.08	4.76	7.46		1.90	Dry Pressed	Good material
20	9.40	7.12	8.56		1.77	Lumps	Lumps do not fire uniformly
21	.11	.00	.06		2.34	Test Bars	Good material
22	3.70	3.18	3.44	.33	2.13	Dry Pressed	Good material
23	6.24	5.31	5.77	.62	1.87	Rotay Kiln	Not suitable for rotary kiln
24	9.91	2.82	6.05		2.07	Lumps	Good material, but underfired
25	.45	.41	.43	.63	2.24	Test Bars	Good material
26	3.85	3.25	3.54		2.52	Dry Pressed	Good material
27	17.44	7.19	13.94		1.90	Lumps	Does not fire uniformly in lump form
28	2.36	1.42	1.89	.51	1.89	Test Bars	Good material
29	10.00	7.87	8.49		2.09	Dry Pressed	Good material
30	4.97	2.54	3.70	.34	1.56	Rotary Kiln	Fair material
31	29.55	25.22	27.34	.53	1.16	Crucible	Bloated, light-weight material
32	69.48	49.65	60.14	.32	0.84	Crucible	Bloated, light-weight material
33	4.82	3.31	4.33	.84	2.22	Test Bars	Good material
34	8.00	7.40	7.76	.77	2.00	Test Bars	Too calcareous
35	9.91	2.82	6.05		2.07	Lumps	Calcareous, not uniform
36	18.13	16.51	17.19	.68	1.79	Dry Pressed	Fairly good material
37						Lumps	Highly calcareous, not uniform
38	1.38	.34	.86		2.14	Dry Pressed	Not uniformly fired in lump form
39	8.76	7.27	8.02	.52	2.04	Test Bars	Fairly good material
40						Lumps	Calcareous, not uniformly fired
41	5.67	3.36	4.14	.60	2.10	Test Bars	Some limestone pocks
42						Lumps	Does not fire uniformly
43	3.40	.47	1.37	.58	1.93	Test Bars	Fairly good material. Some Ls pocks
44						Lumps	Lumps not uniformly fired
45	16.30	6.49	11.83	.13	1.58	Test Bars	Some limestone pocks

TABLE 2.—*Data on firing and physical properties of ceram*

Sample no.	Stratigraphic position	County	Thickness of bed in feet	Location		Temp. °sF.	
CS-38	Blue Springs sh.	Chase	5	SE¼	28-19- 6E	2165	46
CS-38	do	Chase	5	SE¼	28-19- 6E	2100	47
CS-38	do	Chase	5	SE¼	28-19- 6E	2120	48
KN-1	Harper ss.	Kingman	15	SE¼	34-27- 7W	2180	49
KN-2	do	Kingman	10	SW¼	5-28- 6W	2120	50
KN-4	do	Kingman	12.5	NE¼	33-27- 7W	2120	51
LY-23-X	Stine sh.	Lyon	6	SW¼	14-18-10E	2210	52
LY-23-X	do	Lyon	6	SW¼	14-18-10E	2210	53
LY-23-X	do	Lyon	6	SW¼	14-18-10E	2250	54
M-2-A	Wellington sh.	Marion	5	Cen.	29-19- 2E	2150	55
M-2-A	do	Marion	5	Cen.	29-19- 2E	2140	56
M-2-B	do	Marion	5	Cen.	29-19- 2E	2150	57
M-2-B	do	Marion	5	Cen.	29-19- 2E	2110	58
M-2-B	do	Marion	5	Cen.	29-19- 2E	2140	59
RO-1-1	Ninnescah sh.	Reno	3	NW¼	8-25- 5W	2120	60
RO-1-1	do	Reno	3	NW¼	8-25- 5W	2125	61
RO-1-1	do	Reno	3	NW¼	8-25- 5W	2100	62
RO-2-1	do	Reno	5		21-25- 6W	2080	63
RO-2-1	do	Reno	5		21-25- 6W	2090	64
RO-2-1	do	Reno	5		21-25- 6W	2100	65
RO-2-2	do	Reno	13	SW¼	21-25- 6W	2100	66
RO-2-3	do	Reno	5.3	SW¼	21-25- 6W	2100	67
RO-2-4	do	Reno	4	SW¼	21-25- 6W	2140	68
RO-3-1	do	Reno	18	NE¼	28-25- 6W	2090	69
RO-3-1	do	Reno	18	NE¼	28-25- 6W	2060	70
RO-3-1	do	Reno	18	NW¼	28-25- 6W	2100	71
RO-3-2	do	Reno	6.8	NW¼	21-25- 6W	2110	72
RO-3-2	do	Reno	6.8	NW¼	21-25- 6W	2090	73
RO-3-2	do	Reno	6.8	NW¼	21-25- 6W	2100	74
RO-BU	do	Reno	20-75	NW¼	8-25- 4W	2180	75
RO-BU	do	Reno	20-75	NW¼	8-25- 4W	2160	76
SU-PK-2	do	Sumner	10	NW¼	5-31- 4W	2220	77
MP-15	Wellington sh.	McPherson	12-18		34-18- 5W	2120	78
MP-7	do	McPherson	8	SW¼	8-18- 3W	2000	79
	CRETACEOUS						
BT-D	Dakota Janssen mbr.	Barton	20	SW¼	21-18-13W	2545	80
C-27-5	Dakota Terra Cotta mbr.	Cloud	7.5		32- 8- 2W	2160	81
C-4-A	do	Cloud	26.2		19- 8- 1W	2400	82
C-4-A	do	Cloud	26.2		19- 8- 1W	2540	83
C-51-7	Dakota Janssen mbr.	Cloud	5.2	NW¼	12- 6- 3W	2470	84
EL-12-A	Dakota Terra Cotta mbr.	Ellsworth	17.8		29-15- 6W	2400	85
EL-12-A	do	Ellsworth	17.8		29-15- 6W	2460	86
EL-12-A	do	Ellsworth	17.8		29-15- 6W	2540	87
EL-13-B	do	Ellsworth	16.3		5-16- 6W	2300	88
EL-26-A	do	Ellsworth	30.5		13-15- 9W	2400	89
EL-26-A	do	Ellsworth	30.5		13-15- 9W	2540	90
EL-26-3	do	Ellsworth	13.7		13-15- 9W	2130	91
EL-32-A	do	Ellsworth	95		21-15- 6W	2280	92
EL-32-A	do	Ellsworth	95		21-15- 6W	2460	93
EL-32-A	do	Ellsworth	95		21-15- 6W	2540	94

lag produced from samples taken at 71 locations (continued)

	*Absorption Max.	Min.	Avg.	Sat. coeffi- cient	Bulk spec. gravity	Form of testing	Remarks
	5 hrs. boiling						
46						Lumps	Lumps do not fire uniformly
47	18.51	16.24	17.44	.75	1.83	Test Bars	Too calcareous
48			3.02		2.19	Dry Pressed	Fairly good material
49	5.43	1.88	3.43		1.66	Lumps	Fairly good material
50	9.35	1.10	3.51		2.16	Lumps	Fairly good material
51	5.26	2.20	4.11		2.09	Lumps	Fairly good material
52	1.65	1.27	1.42		2.03	Test Bars	Slightly bloated, but good material
53	1.51	.65	1.18	.70	2.13	Dry Pressed	Good material
54						Lumps	Hard fired and vitreous
55	4.61	3.11	3.80		2.23	Lumps	Fairly good material
56	3.72	2.07	2.88		2.28	Dry Pressed	Good material
57	4.64	3.11	4.34		2.02	Lumps	Good material
58	4.81	4.36	4.56	.71	2.23	Test Bars	Good material
59	1.58	.75	1.18		2.32	Dry Pressed	Good material
60	14.07	.67	1.38		2.17	Lumps	Does not fire uniformly
61	9.04	6.44	7.42		2.14	Dry Pressed	Good material
62	8.80	7.34	8.08	.50	2.12	Test Bars	Good material
63	7.83	.61	2.86		2.12	Lumps	Fairly good material
64	4.10	2.88	3.34		2.28	Dry Pressed	Good material
65	1.66	.62	1.27	.22	2.27	Test Bars	Good material
66	10.90	1.26	4.79		1.84	Lumps	Calcareous, not uniform
67	15.77	2.57	8.33		1.46	Lumps	Calcareous, not uniform
68	8.92	.83	2.87		2.18	Lumps	Too calcareous in lump form
69	3.70	1.88	2.57		2.19	Dry Pressed	Good material
70	13.96	.86	7.42		1.86	Lumps	Does not fire uniformly in lumps
71	2.79	1.68	2.11	.27	1.88	Test Bars	Good material
72	1.88	1.28	1.39	.14	1.89	Lumps	Slightly calcareous
73	1.13	.75	.92		2.14	Dry Pressed	Good material
74	1.88	1.04	1.39	.42	1.84	Test Bars	Good material
75	4.39	2.79	3.57		1.94	Lumps	Good material
76	2.37	1.28	1.96	.57	1.90	Rotary Kiln	Good material
77	6.33	1.54	3.58		1.92	Lumps	Good material
78	2.93	1.12	1.97		2.16	Test Bars	Good material
79			2.60		2.26	Test Bars	Good material (PCE, Cone 3-4)
80	4.79	4.68	4.74	.53	1.79	Rotary Kiln	Excellent material
81	3.10	2.10	2.56		2.26	Test Bars	Excellent material
82			1.82	.59	2.23	Test Bars	Good material
83	7.85	6.55	7.08	.34	1.97	Test Bars	Good material, slightly bloated
84	3.72	3.31	3.56	.50	2.00	Rotary Kiln	Excellent material
85	6.00	2.50	3.12		2.26	Test Bars	Good material
86	2.83		2.83	.86	2.22	Test Bars	Good material
87			4.79	.42	2.07	Test Bars	Good material
88	3.69	2.25	2.30		2.30	Test Bars	Good material
89			2.61	.59	2.32	Test Bars	Good material
90			6.79	.39	1.99	Test Bars	Good material
91	4.20	2.40	3.10		2.20	Test Bars	Good material
92	6.16	4.05	5.20		2.15	Test Bars	Good material
93			3.75	.51	2.12	Test Bars	Good material
94			5.77	.48	1.98	Test Bars	Good material

TABLE 2.—*Data on firing and physical properties of cera*

Sample no.	Stratigraphic position	County	Thickness of bed in feet	Location	Temp. °F
EL-58-6	Dakota Janssen mbr.	Ellsworth	8.2	2-16- 9W	2400
EL-58-6	do	Ellsworth	8.2	2-16- 9W	2540
H-1-0	Dakota Terra Cotta mbr.	Hodgeman	5.3	SW¼ 24-22-22W	2325
L-4-A	Dakota Janssen mbr.	Lincoln	57.7	36-11- 7W	2540
L-4-B	do	Lincoln	28.9	36-11- 7W	2400
L-4-B	do	Lincoln	28.9	36-11- 7W	2540
L-4-1	do	Lincoln	7.8	36-11- 7W	2400
L-4-01A	do	Lincoln	9.4	36-11- 7W	2240
L-38-A	Dakota Terra Cotta mbr.	Lincoln	14.3	19-12-10W	2240
MT-1	Blue Hill sh.	Mitchell	95.4	NW¼ 26- 8-10W	2180
NS-TH	do	Ness	40	SW¼ 31-17-23W	2400
	PLEISTOCENE				
A-4-2	Aftonian	Atchison	38	NE¼ 2-16-20E	2260
A-4-2	do	Atchison	38	NE¼ 2-16-20E	2300
A-6	Sanborn fm.	Atchison	50	NE¼ 12-17-19E	2300
A-6	do	Atchison	50	NE¼ 12-17-19E	2400
C-51-LS	do	Cloud	20	NW¼ 12- 6- 3W	2180
C-51-LS	do	Cloud	20	NW¼ 12- 6- 3W	2180
JN-1-2	do	Johnson	30	SE¼ 34-11-23E	2300
JN-1-2	do	Johnson	30	SE¼ 34-11-23E	2260
JN-1-3	do	Johnson	30	SE¼ 34-11-23E	2300
JN-1-3	do	Johnson	30	SE¼ 34-11-23E	2260
JN-1-4	do	Johnson	30	SE¼ 34-11-23E	2300
JN-1-A	do	Johnson	30	SE¼ 34-11-23E	2200
JN-2	do	Johnson	30	SE¼ 33-11-23E	2300
JN-2	do	Johnson	30	SE¼ 33-11-23E	2320
JN-2	do	Johnson	30	SE¼ 33-11-23E	2400
JN-2-A	do	Johnson	30	SE¼ 33-11-23E	2250
JN-2-AG	do	Johnson	30	SE¼ 33-11-23E	2400
JN-2-V	do	Johnson	30	SE¼ 33-11-23E	2350
JN-2AG-LS	do	Johnson	30	SE¼ 33-11-23E	2360
JF-1	Kansas till	Jefferson	20	NW¼ 3- 8-18E	2300
K-1-1	Sanborn fm.	Kiowa	8	31-29-19W	2310
K-1-A	do	Kiowa	24	NW¼ 31-29-19W	2100
LW-2	do	Leavenworth	20	NW¼ 3- 9-23E	2360
LY-30	do	Lyon	20	SW¼ 11-19-10E	2470
MP-12	do	McPherson	20	23-19- 3W	2245
MP-12	do	McPherson	20	23-19- 3W	2240
MP-16	do	McPherson	5	SW¼ 27-19- 4W	2380
NN-5	do	Norton	19	26- 2-23W	2090
NN-5	do	Norton	19	26- 2-23W	2270
SC-1-A	do	Scott	9	19-18-32W	2140
SC-1-A	do	Scott	9	19-18-32W	2210
CY-2L-A	do	Clay	30	SE¼ 18- 8- 3E	2430
CY-2L-B	do	Clay	18	NE¼ 19- 8- 3E	2390

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*Absorption after 24 hours submersion in cold water equals average absorp *lag produced from samples taken at 71 locations (concluded)*

	*Absorption			Sat. coefficient	Bulk spec. gravity	Form of testing	Remarks
	Max.	Min.	Avg.				
	5 hrs. boiling						
95	6.63	7.92	7.36	.53	1.86	Test Bars	Good material
96	4.27	4.31	4.29	.30	1.94	Test Bars	Good material
97	2.88	2.78	2.82	.41	1.88	Rotary Kiln	Excellent material
98	4.27	4.31	4.29	.30	1.94	Test Bars	Good material
99			2.55	.40	2.01	Test Bars	Good material
100	9.51	8.61	9.05	.30	1.87	Test Bars	Good material
101	7.08	6.57	6.83	.25	1.93	Test Bars	Good material
102	.08	.30	.19	.32	2.38	Test Bars	Good material
103	2.28	1.66	1.98		2.32	Test Bars	Good material
104			21.00		.44	Rotary Kiln	Good material (Light weight)
105	21.15	16.49	18.32	53.71	.41	Crucible	Good material (Light weight)
106	1.72	1.67	1.69		2.09	Dry Pressed	Good material
107	5.36	2.29	3.10		1.90	Dry Pressed	Good material
108	10.55	11.36	10.94		1.77	Dry Pressed	Excellent material
109	7.42	5.37	6.56	.68	1.89	Rotary Kiln	Excellent material
110	1.38	1.25	1.32		2.19	Dry Pressed	Excellent material
111	.80	.50	.67	.40	1.97	Test Bars	Excellent material
112	.81	1.25	1.03		2.02	Extruded Cyl.	Excellent material
113	3.22	2.02	2.64		1.99	Test Bars	Excellent material
114			.80		1.93	Extruded Cyl.	Excellent material
115	3.87	2.91	3.18		1.95	Test Bars	Excellent material
116			1.90		1.98	Extruded Cyl.	Excellent material
117	6.99	4.22	5.58		1.99	Extruded Cyl.	Excellent material
118			1.90		2.05	Test Bars	Excellent material
119	3.91	3.62	3.70		1.83	Test Bars	Excellent material
120							
121	3.00	1.73	2.49	.42	1.86	Rotary Kiln	Excellent mat. (Lab. kiln batch)
122	2.35	2.32	2.34	.65	2.19	Test Bars	Excellent material
123	5.43	4.06	4.69	.57	1.85	Rotary Kiln	Excellent material
124	3.13	2.76	2.99		1.88	Extruded Cyl.	Excellent material
125	1.74	1.36	1.57	.58	2.00	Rotary Kiln	Excellent material
126			4.69		2.06	Extruded Cyl.	Good material
127	4.30	2.30	3.08	.78	1.97	Rotary Kiln	Good material
128	3.56	1.86	2.60	.39	2.22	Test Bars	Excellent material
129	3.69	2.16	2.71	.58	1.56	Rotary Kiln	Excellent mat. (Could use 2300°F)
130	5.35	3.40	4.16	.63	1.83	Rotary Kiln	Good material, but refractory
131	7.14	2.07	3.99	.50	1.92	Rotary Kiln	Good material
132	5.79	5.51	5.68	.33	1.98	Dry Pressed	Good material
133	5.58	5.10	5.30	.75	1.76	Rotary Kiln	Good material, but refractory
134	4.50	1.32	2.98		2.28	Test Bars	Good material
135	5.02	1.87	2.42	.48	1.80	Rotary Kiln	Good material
136			.87		2.31	Dry Pressed	Excellent material
137	2.78	1.41	2.10	.65	2.00	Rotary Kiln	Excellent material
138	3.77	3.02	3.49	.75	1.73	Rotary Kiln	Excellent material
139	3.74	3.51	3.58	.77	1.84	Rotary Kiln	Excellent material

after 5 hours submersion in boiling water multiplied by the saturation coefficient.

materials resemble each other, so far as firing behavior and fired properties are concerned, regardless of their geologic age.

With the exception of a few thin underclays the available materials of **Pennsylvanian** age are illite shales containing varying amounts of finely-divided free quartz. Calcareous shales occur in the Pennsylvanian rocks, but they are easily detected in the field and were purposely not sampled. Many of the shales containing no free quartz or only moderate amounts can be vitrified at relatively low temperatures (2100-2200° F.) without excessive distortion. In fact, many have been used in the production of excellent paving bricks in Kansas plants. Some of these shales are still being used in the production of hard-fired face bricks and other clay products.

It is possible to produce an excellent quality of ceramic slag at temperatures ranging from 2100° to 2300° F. from the majority of the Pennsylvanian shales which we sampled. If correctly fired the product is dense and fairly tough. If a lighter weight product is desired it can be produced by more rapid firing. The color of the slag is usually dark red to reddish brown if completely oxidized. If incompletely oxidized it tends to be black in color.

These shales must be fired more slowly than most of the materials tested, especially through the oxidation temperature range. If fired rapidly they tend to bloat. This is characteristic of illitic shales. Perhaps the most serious objection to the purer Pennsylvanian shales as a raw material for the production of ceramic slag is the fact that if fired in a rotary kiln the material does not readily form a roll or slug with partial fusion. Also, if it is fired as it comes from the pit the shale structure tends to persist in the material even after heating to the pyroplastic condition. This shaly structure causes planes of weakness and when crushed results in flat-sided or tabular pieces which are not desirable either as concrete aggregate or railroad ballast.

The more siliceous shales require less care in firing and have less tendency to retain the shale structure after firing in the original lumps. The maturing temperature increases, unfortunately, with increasing proportions of silica. Slightly calcareous shales, such as that from the pit of the Humboldt Brick and Tile Company, will produce a dense solid ceramic slag in the rotary kiln.

Many of the better Pennsylvanian shales are available in thick deposits of relatively uniform quality. Due to their hardness they are more costly to mine than the friable Pleistocene clays or silts, and in many cases are overlain by an overburden consisting of inferior shale and limestone. This does not mean that the Pennsylvanian shales should be eliminated from consideration as possible material for ceramic slag, but that careful consideration would have to be given to thickness and nature of overburden, as well as the costs of mining and pulverizing the shale, before choosing a deposit.

So far as the production of ceramic slag is concerned the important shales in the **Permian** are the Wellington and Ninnescah shales of the Sumner group. Their importance chiefly is due to the thickness of the deposits and the ease with which they can be mined without running into excessive overburden. Aside from these, workable deposits occur in the Doyle shale and the Harper sandstone formation (Pl. 2B) and possibly in the Blue Springs shale. So far as we are able to determine from our tests, the Permian shales which occur stratigraphically below the Wellington usually are calcareous and in many cases soft. It is difficult to find deposits of these shales which are not overlain by beds of limestone or entirely unusable shale. The beds are also relatively thin.

The Wellington and the Ninnescah, in contrast to the above, are thick deposits of relatively uniform materials. The Wellington has an average thickness of 700 feet and the Ninnescah an average thickness of 300 feet with a maximum of 450 feet (Moore, Frye, and Jewett, 1944). We have not attempted to determine what proportion of the beds in these formations is suitable for the production of ceramic slag, but it is evident that beds of usable thickness, free from excessive overburden, are quite common. It it were not for the presence of thin shaly limestones and gypsiferous shales (Pl. 1A) almost the entire thickness of both formations would be usable.

Although the argillaceous material in these formations is commonly designated as shale, it is not shale in the sense of having a fissile or laminated structure, but on the contrary, it is a blocky indurated clay which breaks out with a pronounced conchoidal fracture. Due to this hardness the Wellington and

Ninnescah shales can be run through a rotary kiln in lump form without breaking up.

All the Permian shales tested with the exception of the extremely calcareous ones were remarkably uniform in firing characteristics and fired physical properties, and from the few chemical analyses run we judge this uniformity extends to the chemical composition. The shales commonly contain as much as 5 percent calcium oxide, about 6 percent magnesium oxide, and an appreciable percentage of alkalies. As would be expected from this composition the shales have a low fusion temperature and temperature of maturity. Due to the high calcium and magnesium content they also have a short firing range. Despite this they retain sufficient rigidity in the pyroplastic state to permit the aggregation of the crushed material into a solid mass in a rotary kiln.

Individual lumps of the same sample, although identical in appearance in the raw state, have maturing temperatures varying as much as 60° F. If the more refractory lumps are fired to maturity, the more fusible ones become fluid. If these shales are crushed to pass a 10-mesh to the inch screen this difficulty is overcome, and a roll or slug of uniform material is produced. If such treatment is necessary, however, it would be obviously impossible to process the material in the lump form.

It is possible that the relatively low temperature of 2100° to 2200° F. at which ceramic slag can be made from the Permian shales, and the moderate cost of mining the material, would offset the additional cost of grinding before firing. It is also possible that sufficiently uniform beds can be found to permit firing in the lump form.

So far as the production of a dense ceramic slag is concerned, the only **Cretaceous** materials of importance are the clays of the Dakota formation. Light-weight aggregate can be produced from the marine shales of the Kiowa, Graneros, Blue Hill, and Pierre formations, and especially promising results were obtained with samples of the Blue Hill shale (e.g., sample NS-TH).

The Dakota clays are kaolinitic, and when sufficiently pure are extremely refractory, requiring temperatures much too high for the economical production of ceramic slag (Plummer and Romary, 1947). The more impure clays, however, mature within the range of the other materials tested. Ceramic slag produced from Dakota clays is extremely dense, tough, and durable (Pl.

6E). Considered solely from the point of view of the finished product a ceramic slag superior to that produced from any other plentiful supply of Kansas raw material can be produced from the clays of the Dakota formation.

The quality of the finished product is offset by the lack of vertical uniformity and the areal irregularity of the clay deposits. In order to insure a sufficient quantity of material for a large-scale operation rather extensive prospecting would be necessary, and probably more than one site would have to be prospected before an adequate supply was found. The lack of vertical uniformity in the maturing temperature of the clay beds can be overcome by grinding and mixing the clay. It is also probable that if sufficient care were exercised in the prospecting and selection, deposits of sufficient uniformity to permit processing in the lump form could be found. This would be desirable because the Dakota clays break out in large irregular lumps which can be vitrified readily in a rotary kiln. By using this method of processing slightly lower temperatures could be used, and the cost of grinding and mixing the raw material eliminated.

If we take into consideration all the economic factors involved in the processing of ceramic slag the clays and silts of **Pleistocene** age (Pl. 1C and 2C) are the most promising raw materials available. The quality of the finished product compares favorably with that produced from other materials, and the temperatures required for processing are not too high. Added to this is the fact that the Pleistocene clays, especially the loess deposits, are friable, easily mined, free from excessive overburden, and occur in extensive deposits of uniform quality (Hibbard, Frye, and Leonard, 1944; Frye and Fent, 1947). The uniformity is not limited to individual deposits, but extends to the entire area in which they cover the surface.

The Pleistocene clays can be processed in a rotary kiln without previous preparation, and form a solid roll or slug in the pyroplastic stage. If it is thought desirable to process the material in the lump form, compaction of the damp clay will permit this method being used on all but the most silty materials.

Several types of Pleistocene clays and silts were tested, most of which were from loess deposits. The loess deposits which cover the bluffs along the Missouri River have a maturing temperature ranging from 2280° to 2380° F. The product is dense, somewhat glassy, tends to break with a conchoidal fracture, and has a high compressive strength (20,000 psi). A possible objection to the fired material is that it tends to have slick surfaces.

The red-brown loess and/or alluvial deposits (Sample JN-2) which are found along the Kansas River and north, probably are directly derived from glaciation. These clays have a maturing temperature ranging from 2300° to 2400° F. The product tends to be less dense than that made from the Missouri River loess, and if fired rapidly and overfired develops a vesicular structure with a density as low as 1.2 (Pls. 4 and 5). It breaks with a rough fracture and is somewhat brittle, having a Los Angeles rattler loss ranging from 37 to 45 percent. The compressive strength is more than 15,000 psi. This material has been studied intensively because of the accessibility of the deposits in important areas. Samples from widely separated deposits were very similar in firing characteristics and physical properties, although there is some vertical variation in the individual deposits. A carload of railroad ballast manufactured in the Mineral Products Company's pilot plant rotary kiln has been placed under a section of Santa Fe main line tracks for a service test (Pl. 8). The raw material was obtained from location JN-2 (Pl. 1C).

A few deposits of High Plains loess were sampled at widely separated points. Although at least two distinct formations were represented, so far as the production of ceramic slag is concerned the differences were barely discernible. The maturing temperature of 2270°-2300° F. is slightly lower than the two types previously mentioned. The fired product tends to be somewhat granular rather than vesicular or glassy. This ceramic slag is hard, sufficiently dense, and fairly resistant to abrasion (Los Angeles abrasion loss, 31.5 percent on sample NN-5).

A loess deposit sampled in Scott County (SC-1-A) proved to be quite different from the other Pleistocene materials tested. The difference was due chiefly to the fact that the clay contained more than 11 percent calcium and magnesium oxides. This resulted in lowering the maturing temperature (2180°-2210° F.) and in producing an extremely dense product which broke with a stony fracture. The Los Angeles abrasion loss (18 percent on bricks and 25 percent on the rotary kiln product) was lower on this material than any other tested, and the compressive strength higher (26,000 psi).

In view of the excellent results obtained with this and other calcareous materials we concluded that a calcium or magnesium carbonate content of 10 to 20 percent produces desirable results in some cases. To test the effects of calcium carbonate we added 10 percent minus 20-mesh crushed limestone to a noncalcareous Pleistocene clay (JN-2), and fired the mixture in the batch rotary kiln. The maturing temperature of the mixture (JN-2AG-LS) was lowered at least 50° F., and the viscosity of the pyroplastic material was greatly reduced, permitting the separate particles to crowd together and form into a dense roll. Furthermore, the calcareous material had to be held at maturing temperature a much shorter time than was the case with the original noncalcareous clay.

A McPherson County Pleistocene loess containing fairly large lumps of soft caliche (a form of calcium carbonate) was run in the 30-foot pilot plant kiln with results similar to those noted for the batch in which 10 percent limestone had been added to a noncalcareous clay.

A small sample of loess sent to this laboratory from Seward County which contained approximately 25 percent volcanic ash produced an excellent dense gray ceramic slag. Nothing is known of the extent of this deposit, but fairly extensive deposits of mixed clay, silt, and volcanic ash are known to occur in Kansas.

In order to facilitate comparisons of firing temperatures and the more significant physical properties of ceramic slag produced in the ceramics laboratory rotary kiln, we have listed this information separately in Table 3. The results of the few tests made to determine compressive strength and percentage loss in the Los Angeles abrasion tests are also given separately in Table 4.

The results of firing in the rotary kiln are of particular interest because the results of commercial production in a large rotary kiln would be nearly identical. "Sticking" temperatures, or the temperature at which the clay first begins to stick together and to the kiln lining, range from 2140° to 2400° F., with an average of 2243° F. Final maturing temperatures range from 2160° to 2545° F., and average 2376° F. The pyrometric cone equivalent (P. C. E.) of 13 clays tested ranges from cone 3 to above cone 15. The P. C. E. of the clays is significant in that it tends to fall within the range of initial sticking and the maximum temperature of firing in most cases. This test therefore provides a quick

TABLE 3.—*Data on the rotary kiln production of ceramic slag from 21 samples, listed in order of firing temperatures*

Sample No.	Max. temp. °F	Sticking temp. °F	P.C.E. -cone	P.C.E. kiln temp. °F.	Absorption (pct.) 24 hrs. in cold water	Absorption (pct.) 5 hrs. in boiling water	Satur-tion coeffi-cient	Bulk specific gravity	Remarks
RO-BU	2160	2140	3-4	2100	1.12	1.96	.57	1.90	Good material
*MT- 1	2180	2070				21.00		0.44	Excellent mat. (light weight)
SC-1-A	2210	2180	6	2140	1.36	2.10	.65	2.00	Excellent material
MP-12	2245	2175			2.01	3.99	.50	1.92	Good material
NN-5	2270	2160	6-7	2140	1.15	2.42	.48	1.80	Excellent material
Humboldt	2300	2220	7	2175	0.55	1.04	.53	1.90	Excellent material
H-1-0	2325	2220	13-14	2445	1.16	2.82	.41	1.88	Excellent material
LW-2	2360	2200	13+	2360	1.56	2.71	.58	1.56	Excellent material
LY-28-A & B	2360	2250			2.76	6.60	.42	1.95	Not suitable for rotary kiln use
CR-4-21 & 22	2380	2230			1.26	3.70	.34	1.56	Fairly good material
CY-2L-B	2390	2250			2.75	3.58	.77	1.84	Good material
JN-AG	2400	2280	13+	2360	2.67	4.69	.57	1.85	Excellent material
JN-2	2400	2285	13+	2360	1.05	2.49	.42	1.86	Excellent material
A-6	2400	2180	12	2330	4.43	6.56	.68	1.89	Excellent material
K-1-1	2400	2150			2.39	3.08	.78	1.97	Good material
CY-2L-A	2430	2400			2.62	3.49	.75	1.73	Good material
MG-LC	2465	2230			3.57	5.77	.62	1.87	Not suitable for rotary kiln use
C-51-7	2470	2400	(above 16)	(above 2560)	1.77	3.56	.50	2.00	Superior material
EI-58-6	2490	2400			3.90	7.36	.53	1.86	Not rolled at this temperature
DG-12-A	2530	2260	13-14	2450	1.30	2.53	.51	1.91	Not suitable for rotary kiln use
BT-D	2545	2260			2.52	4.74	.53	1.79	Excellent material
Averages	2376	2243			2.10	3.58	.56	1.85	

*Not included in averages.

TABLE 4.—*Data on compressive strength and Los Angeles abrasion loss tests of ceramic slag*

Sample no.	Maximum temp., Degrees F.	How Formed	Compressive Strength psi	Los Angeles Test % Loss
LY-28-A	2110	Dry Pressed	16,850	
LY-28-B	2110	Dry Pressed	16,333	
LY-29-A	2220	Dry Pressed	15,050	
LY-29-B	2220	Dry Pressed	26,333	
JN-1-A	2250	Extruded		36.8
JN-2-A	2200	Extruded		37.0
MP-12	2245	Rotary Kiln		49.2
NN-5	2270	Rotary Kiln		31.5
SC-1-A	2140	Dry Pressed	26,600	
SC-1-A	2210	Rotary Kiln		25.2
MG-LC	1890	Extruded	25,000	
KC-Loess	2170	Extruded	21,550	18.0

means of determining whether or not the firing temperatures of a clay is within a commercially feasible range. The "Humboldt," C-51-7, and H-1-0 samples are interesting exceptions. The Humboldt sample, a slightly calcareous Pennsylvanian shale, has a P. C. E. temperature lower than the initial sticking temperature, whereas C-51-7 and H-1-0, kaolinitic Dakota clays, have a P. C. E. temperature above the temperature at which the material had formed into a compact roll in the rotary kiln. Absorptions after 24 hours' immersion in cold water range from 0.55 to 4.43 percent, with an average of 2.10 percent. Absorptions after 5 hours' submersion in boiling water range from 1.04 to 7.36 percent with an average of 3.58 percent. Saturation coefficients range from 0.41 to 0.78, with an average of 0.56—well below the allowable maximum of 0.80. Specific gravities are lower than naturally occurring rocks available in Kansas. The average of 20 ceramic slags is 1.85, and the range from 1.56 to 2.00. The above ranges and averages include only the 20 dense materials, but not the one light-weight slag, MT-1.

The values shown for the rotary kiln batches are characteristic of "overfired" clays. A clay is overfired when the firing temperature has passed the point of maximum density or of vitrification, because the clay becomes sufficiently glassy at these temperatures to permit the formation of small enclosed vesicles by the gases that are evolved. Vitrified clays have bulk specific gravities ranging from 2.0 to 2.5, and boiled absorptions ranging

TABLE 5.—*Comparison of physical test data on ceramic slag and other construction materials in Kansas* (Swineford, 1947)

Geologic age	Formation	Member	Rock type	Sample location	Specific gravity Apparent	Specific gravity Bulk	Absorption, pct.	Los Ang. abras. test loss pct.
Pleistocene	Sanborn		clay (ceramic slag)	Johnson Co. (JN-2)	2.56	1.97	2.78	40
Pleistocene	Sanborn		clay (ceramic slag)	McPherson Co. (MP-12)	2.08	1.92	2.01	49
Pleistocene	Sanborn		clay (ceramic slag)	Norton Co. (NN-5)	1.88	1.80	1.15	31
Pleistocene	Sanborn		clay (ceramic slag)	Scott Co. (SC-1-A)	2.09	2.00	1.36	25
Pennsylvanian	Lane-Bonner Springs		shale (ceramic slag)	Allen Co.	1.94	1.90	0.55	-
Tertiary	Ogallala		"Quartzite" opaline sandstone	NW Kansas SW Nebraska	2.45	2.38	1.95	39
Cretaceous	Niobrara	Fort Hays	Chalky limestone	Jewell Co.	2.50	2.08	15.50	49
Cretaceous	Dakota		"Quartzite" calc. ss.	Ellsworth & Lincoln Cos.	2.67	2.65	0.56	47
Permian	Barneston	Ft. Riley	Dolomite	Marshall Co.	2.67	2.40	7.20	64
Pennsylvanian	Deer Creek	Ervine Cr.	Limestone	Elk Co.	2.69	2.62	1.52	34
Pennsylvanian	Oread	Plattsmouth	Limestone	Atchison Co.	2.68	2.56	2.16	32

from nearly zero to about 3 percent. If higher densities are desired in a ceramic slag it would be necessary to fire the material in lump form and only to vitrification. Absorption values are lower on vitrified than on overfired clay, but the difference between boiled and cold water absorptions is greater on the overfired clay, resulting in a lower saturation coefficient for the overfired material, and probably a greater resistance to freezing and thawing.

A comparison of physical test data of ceramic slag and natural crushed rock (Table 5) reveals very little so far as the relative durability of the materials is concerned. The specific gravities of the ceramic slag are much less than those of the natural materials, but this property is not related to durability. Abrasion losses in the Los Angeles tests are comparable, but not significant. The Dakota "quartzite," the rock which is conceded to be one of the best in the State, has an abrasion loss of 47 percent. The absorption of this rock is low (0.56 percent), but a Pennsylvanian limestone which showed a very poor service record as aggregate in concrete pavements (Peyton, 1946) has an absorption that is only slightly higher (1.52 percent).

Such properties as resistance to freezing and thawing, saturation coefficient, hardness, and compressive strength, on which comparative data are not available, would be more revealing. The record of well-fired brick under such severe service conditions as sewer conduits, pavements, and foundations indicates that a ceramic slag of equal or superior resistance is practically indestructible except by mechanical means.

It is desirable that a series of tests be made with ceramic slag as a concrete aggregate. These tests should include not only the determination of the cement-water ratio, the cement factor, and modulus of rupture and compressive strength at various stages of aging, but also tests to determine the liability of the concrete made from ceramic slag to disintegration produced by the expansion of the concrete resulting in map-cracking and loss of strength.

Kansas State College Engineering Experiment Station in cooperation with the Portland Cement Association (1946) is carrying out an extensive investigation to determine causes and discover means of eliminating this type of disintegration. The problem is especially acute in concrete made with a natural sand-gravel aggregate. It is desirable to use as much of this type aggregate as possible because of its availability and low cost. Tests to date indicate that the addition of one of several materials including soft limestone, "quartzitic" sandstone, volcanic ash, roasted loess, and powdered overburned clay tile, produces beneficial results.

Two types of ceramic slag (JN-2 and LW-2) are now being tested at Kansas State College as part of the above research project. The test requires a year before significant results can be obtained, but previous experiments with somewhat similar materials indicate that the ceramic slag aggregate will not cause disintegration by expansion when used as the complete aggregate, and probably that it will prove beneficial in concrete containing some of the trouble-causing sand aggregates as a portion of the aggregate.

Kansas State College in cooperation with the State Highway Commission has run standard tests on a concrete containing one type of ceramic slag aggregate (JN-2) produced in a pilot plant kiln. The concrete mix that was used is given below:

Cement	12 pounds
Blue River sand	31 pounds
Ceramic slag	31 pounds
Water	6.64 pounds

The weight per cubic foot of the concrete was 123.2 pounds, the slump was 2.5 inches, and the cement factor (barrels of cement per cubic yard of concrete) was 1.32. For each sack of cement 6.25 gallons of water was used. After four days the modulus of rupture was 443 psi, and after 10 days 536 psi. Compressive strength at seven days age was 2,702 psi. Maximum compressive strength after 28 days was 4,440 psi.

On the freeze and thaw test the ceramic slag rated 0.99, whereas the average stone rates about 0.96. The cement factor for stone and sand is about 1.32, or about the same as for ceramic slag and sand. Sand and gravel, on the other hand, has a cement factor of about 1.65.

W. E. Gibson (personal communication) reports that the ceramic slag tested is a superior aggregate, and that its low density is decidedly in its favor in that it will result in a saving in concrete and reinforcing owing to the decrease in dead load.

Additional tests are being run. When completed the results of these tests will be available at the ceramic laboratory of the Geological Survey.

CONCLUSIONS

It is possible to produce ceramic slag of a quality equal or superior to naturally occurring rocks now used for railroad ballast, concrete aggregate, and general highway construction. Material suitable for the production of ceramic slag occurs in large deposits in almost all the counties of Kansas. For the most part the materials can be taken from the deposits by open pit methods at a relatively low cost. In many instances no stripping of overburden would be necessary.

Taking into consideration the size, uniformity, and wide distribution of deposits, the low costs of mining, and ease of processing, the loess deposits of Pleistocene age are considered by us to be of first importance as raw material for the production of ceramic slag.

Considered solely from the standpoint of firing characteristics and physical properties of the finished product the clays of the Dakota formation are perhaps superior to any other raw material available in Kansas, but because the outcrop area is confined to a rather limited area, the reserves are difficult to estimate, and vertical and horizontal uniformity in many deposits is lacking, the Dakota clays must be given second place in the choice of raw materials.

Clays and shales of Pennsylvanian age can be made into an excellent ceramic slag, but are less desirable raw materials than those of Pleistocene and Dakota age because of relatively higher mining and processing costs. Permian shales or clays can be fired into a high quality product at relatively low temperatures, and they can be mined at fairly low cost. The most serious defects of many Permian shales are due to their high calcium and magnesium content and the uneven distribution of calcite and dolomite in seemingly uniform shale beds. Permian shales of this type must be ground before firing, and temperatures must be controlled rather carefully to avoid overfiring. Under the best of conditions of deposit and fuel supply a good quality ceramic slag could be produced from Permian shales at a relatively low cost.

Raw materials from beds of any geologic age represented in the rocks of Kansas can be used successfully in the production of ceramic slag of excellent quality at relatively low cost if sufficient care is taken in the selection of the deposit.

Ceramic slag can be manufactured by a number of methods including stiff-mud extrusion and dry pressing, followed by burning in a kiln of any kind capable of attaining the necessary temperature. The most economical method, however, consists of firing the material as taken from the pit in a rotary kiln, producing either highly vitrified lumps, or a solid mass at the pyroplastic stage.

COMMERCIAL APPLICATIONS AND ENGINEERING CONSIDERATIONS

In a strictly technical sense ceramic slag is not a new product. It is an old and well-known product for which greatly extended uses are suggested. Likewise, the methods of manufacture are well known and industrially proved, but the suggested use of a sintering or nodulizing rotary kiln for the burning of ceramic slag involves a new combination of materials and processing equipment. It is to be expected that problems will arise both in determining the complete qualifications of ceramic slag for new uses and in applying suggested methods of manufacture. We do not hope to answer here all the problems that will arise, but merely to indicate the problems and make general suggestions for their solution.

Commercial Uses

MAJOR USES

This report previously has emphasized the use of ceramic slag for railroad ballast and concrete aggregate because these uses represent the most urgent demands and commercial possibilities. The properties which qualify ceramic slag for a high-grade railroad ballast also qualify it for an excellent unbonded aggregate or road metal. A high-grade concrete aggregate can be expected to serve equally well in mortars and bituminous road surfacing. In our opinion the major uses of ceramic slag should be considered to have the following order of importance:

railroad ballast, concrete aggregate, road metal, aggregate for bituminous road surfacing, and other aggregates.

MINOR USES

Several minor uses have been suggested for ceramic slag. These uses include filter beds, acid-tower packing, asphalt fillers, roofing gravel, roofing granules, and nonskid flooring.

The slightly bloated and rough-textured varieties of ceramic slag should be extremely efficient in a *filter bed* because of the high ratio of surface area to volume, and because it is almost completely inert chemically.

Ceramic slag should be a superior material for use in *packing acid towers*. The more siliceous materials are almost completely resistant to all acids except hydrofluoric. It can be produced either in dense, angular, smooth pieces, in vesicular, rough angular lumps having a high ratio of surface area to volume, or in a variety of intermediate grades.

Asphalt fillers include the inert material or aggregate used in bituminous road surfacing (mentioned under major uses), roof coatings, grouts, and mastics. There is no reason to believe that ceramic slag would in any respect be inferior to materials commonly used, and due to the variety of densities and angularity possible to produce in ceramic slag it is probable that it may prove superior in some respects.

Roofing gravel is the top dressing used on built-up asphalt or bituminous flat roofs. The roughness, angularity, durability, and variety in colors recommend ceramic slag for this use.

Roofing granules are used on "tar-paper" roofing for the purpose of protecting the surface and adding color. It is possible that some of the brownish-red, brown, yellow, or gray ceramic slag would be suitable for this purpose. Cobalt oxide or chromium oxide added to a light-firing clay would produce blue or green. We understand that some ceramic roofing granules are fired in a rotary kiln, and in this case the only difference between ceramic slag and roofing granules is the scale of operation and the intended purpose.

QUALIFICATIONS REQUIRED

RAILROAD BALLAST

Standard specifications reveal very little as to the exact qualities desired in a railroad ballast. The following letter from Mr. T. A. Blair, Chief Engineer of the Atchison, Topeka and Santa Fe Railway System, describes the best material now available to the Santa Fe, and gives detailed specifications for all types of material with specific reference to ceramic slag and its qualifications for use as railroad ballast.

At the inception of your experiments to determine whether a suitable ballast could be manufactured under the ceramic process, I gave you some notes as to the type of material you should seek to produce.

From a practical standpoint, the ideal ballast varies from local conditions and the density of traffic. The major requirement is that the ballast resist disintegration under the action of traffic and necessary tamping under ties. Such disintegration as takes place should produce a material that will not cement and churn when wet.

For the area in Kansas where ceramic slag would be used, the present ballast used that would most nearly approach this ideal would be Colorado Fuel & Iron slag ballast, now being used in Colorado and western Kansas. This material is crushed to maximum 1½″, minimum ⅜″. Our specification, based on square sieve percentages by weight, provide that all must pass 2″, 95 to 100 percent pass 1½″, 20 to 55 percent pass 1″, 5 to 15 percent pass ¾″, all retained on ⅜″. This material, sized as above, weighs from 2200 to 2300 pounds per cubic yard. Apparent specific gravity is 2.65, compressive strength 8000 pounds, and the percent of absorption after being emersed in water 96 hours 0.1 percent. Deval abrasion test loss by weight is 5.3 percent.

You will note I have designated a light material as the ideal ballast. We have numerous ballasts that weigh from 2600 to 3300 pounds per cubic yard, but our experience indicates that this weight is not essential to hold the track in line, provided the lighter weight ballast is rough and has sharp edges. There is a tremendous advantage to us in the use of lighter weight materials as they permit us to completely fill our ballast cars. A 2000 pound material permits us to load 60 cubic yards to the car, where a 3000 pound material only permits 40 cubic yards.

I pointed out to you that a sample of CF&I slag showed all of the edges of the ballast sharp so that when the track is surfaced these edges engage the tie and hold the track in line. This ballast has a large percentage of pieces roughly cubical, and there are no flats.

The material we seek would not necessarily break cubical so long as the edges are sharp and there is a very low percentage of flats, which are defined as pieces of material whose depth, compared with length and breadth is one third or less. Flats cause the ballast shoulder to shake down and have a tendency to let the tie crawl.

Initially we sought a material that would weigh crushed 2200 to 2000 pounds per cubic yard, with the idea of approaching CF&I slag. As your experiments progressed, we found that material of that weight did break with sharp edges and irregular shapes, but that the surfaces tended to be smooth. You demonstrated that crushed ceramic slag, weighing approximately 1800 pounds per cubic yard crushed with sharp edges and irregular shapes, but had the advantage of rougher surfaces giving a ballast with less tendency to shift or crawl.

In Arizona we use a volcanic cinder for ballast that weighs approximately 1500 pounds per cubic yard. This material has sharp edges and is extremely rough, and due to these characteristics we have no more difficulty holding the track alignment than with heavier materials.

After considering the successful use of these volcanic cinders, together with the increased roughness of lighter weight ceramic material, and the comparative characteristics of the heavier and lighter weight ceramic slags, viz., compressive strength, abrasion tests and absorption tests which you made, we decided that crushed ceramic slag weighing approximately 1800 pounds per cubic yard would be the most suitable ballast.

A test installation was made in track near Wilder, Kansas, and although this material which resulted from use of a small pilot kiln was not uniformly burned, this test does show that the ballast is suitable and that it holds up better than present used ballast in the track adjacent to this location.

Blair has assumed in his letter that a durable ballast is obviously necessary. Durability in the case of railroad ballast includes not only resistance to weathering agencies, but the ability to stand up under loads and to withstand tamping under the ties. Physical tests indicate that ceramic slag will exceed the minimum requirements by a considerable margin.

CONCRETE AGGREGATE

A number of detailed specifications are given for concrete aggregate, such as absorption, saturation coefficient, specific gravity, resistance to freezing and thawing, and maximum loss permitted in the Los Angeles abrasion test, as well as the usual screen size specifications. These specifications vary with the locality and the use for which the aggregate is intended. Available data on concrete aggregates that have been used extensively in the State show the following range in physical properties: bulk specific gravity, 2.08 to 2.65; absorption, 0.56 to 15.5 percent; percentage loss after five cycles of freezing and thawing, 0.0 to 5.54; percentage loss in Los Angeles abrasion test, 32.0 to 63.5 (Swineford, 1947). The properties of these commonly used materials can be compared to those of ceramic slag in Table 5.

The physical tests are valuable insofar as they reveal the resistance of the aggregate to weathering agencies such as freezing and thawing and its ability to withstand the relatively small compressive loads to which it will be subjected in the structure. This load is seldom as high as 3,000 pounds to the square inch. Loss by abrasion does not have any apparent value in specifications for concrete aggregate. Specific gravity is not a measure of durability but is useful in calculating the weight per unit volume of the finished concrete.

In cases where the aggregate is the chief contributing factor to the disintegration of concrete structures by continued expansion and map-cracking, the cause of disintegration is not completely known (Peyton, 1946), but the chemical reactivity of the aggregate is thought to be an important factor. As stated previously in this report, the Kansas State College Engineering Experiment Station in cooperation with the Portland Cement Association (Anonymus, 1946) is conducting a long-range research program to determine the cause of and a means of correcting this type of disintegration. It is obviously desirable, however, that a concrete aggregate should not contribute to the disintegration, and its value is greatly enhanced if it tends to prevent expansion and map-cracking when used with the less desirable aggregates, such as river sands and gravels.

OTHER CONSTRUCTIONAL AGGREGATES

In the case of crushed aggregate which is to be used for road metal without the protection of a bonding material, it is essential that the aggregate withstand the loads and abrasion to which it will be subjected. It is also desirable that the aggregate resist sliding on itself under impact and loads.

Fillers for bituminous road surfacing should be angular, have a low absorption, and should have surfaces sufficiently rough to resist movement of the individual pieces on each other. For any type of use it is obvious that the aggregate should be able to withstand freezing and thawing and wetting and drying without disintegration.

Manufacturing Methods

The processes involved in the production of ceramic slag are extremely simple and well known. Every brick plant probably has at some time produced ceramic slag by overburning the brick in its kilns. In some cases these overburned or partially fused bricks are used for concrete aggregate, road surfacing, and railroad ballast. High-grade, well-vitrified paving brick is essentially the same thing as ceramic slag, and when crushed and properly sized make an excellent material for concrete aggregate or railroad ballast. The processes involved other than firing, such as excavating the raw material, feeding it to the kiln, and crushing and sizing the finished product, will differ in no essential detail from those now used in handling similar materials.

If ceramic slag is to be produced in a plant designed solely for that purpose, and not as a by-product of some other operation, the manufacturing costs obviously must be kept to a minimum if the finished material is to sell within the necessary price limits of $1.25 to $3.00 per ton.

The manufacturing costs can be kept sufficiently low only in a nearly completely mechanized plant, and on a scale large enough to insure maximum production efficiency. In our opinion, and in the opinion of engineers we have consulted, the rotary kiln most nearly meets the requirements of a highly mechanized and efficient method of firing the raw material.

The car tunnel kiln probably is more efficient than the rotary kiln so far as fuel consumption per ton of finished product is concerned, but the use of such a kiln would necessitate forming the raw material into more or less regular shapes and setting these shapes on kiln cars. No completely successful method has been devised for mechanically hacking or setting bricks or other shapes for this purpose. Furthermore, the initial cost of the tunnel kiln would be considerably greater than for a rotary kiln of the same capacity. Despite these disadvantages the economy of fuel consumption and the ease with which temperatures can be controlled in a tunnel kiln, plus the assured production of a uniformly burned finished material, make it worthy of careful consideration. The problems involved in the use of a tunnel kiln are not those of kiln operation, but rather those involved in the pre-processing which the use of a tunnel kiln necessitates. If the costs of forming the material into shapes and setting them on kiln cars could be reduced by nearly complete mechanization it is possible that a better product than that possible with a rotary kiln could be manufactured at the same cost.

It is possible also that ceramic slag could be burned in a scove kiln at sufficiently low cost. Crude shapes in fairly large unit sizes would have to be made by extrusion or pressing, then set on drier cars or directly into the scove kiln by means of lift trucks. Inasmuch as the kiln itself would be built from the bricks or other shapes to be burned, the initial investment would be small. This method might be suitable for a brick plant which would have the equipment necessary to form the raw shapes ready for firing or burning. Most brick plants use their machinery less than 8 hours a day, and at times run at much less than full capacity because of lack of a market for their product. The production of ceramic slag in such periods, even at a small profit, would permit continuous employment, and fill in a period which otherwise would be all overhead and no profit. A scove kiln would be suitable for burning only easily vitrifiable clays or shales which would not be softened sufficiently to cause the kiln to collapse at maturing temperatures. This would necessitate the production of some under burned shapes in each kiln.

PROBLEMS INVOLVED IN THE USE OF A ROTARY KILN

If a rotary kiln is to be used to fire the ceramic slag there are a number of technical problems involved which require careful consideration, as we have learned from the operation of our small laboratory kiln, and have been advised by the Mineral Products Company (Hardy, 1948) from their experience in operating a 30-foot pilot plant kiln (Pl. 3C). The chief problem involved is one encountered in processing any material to sintering or partial fusion temperatures. At this stage the material, whether it be cement clinker, phosphate, iron or manganese ore sinters, or ceramic slag, tends to stick to the refractory lining of the kiln and form rings which eventually build up to such an extent that the material will not flow through the kiln. In the case of ceramic slag, ringing occurs just past the point where the material first becomes softened enough by the heat to stick together. The cohesion of the individual lumps is not sufficient to overcome the tendency of the material to adhere to the lining of the kiln.

This problem is never completely solved, but it can be made less serious and less irritating by one or all of several methods. The first consideration is that of the material itself. Some clays or silts are much more inclined to stick and ring than others. For

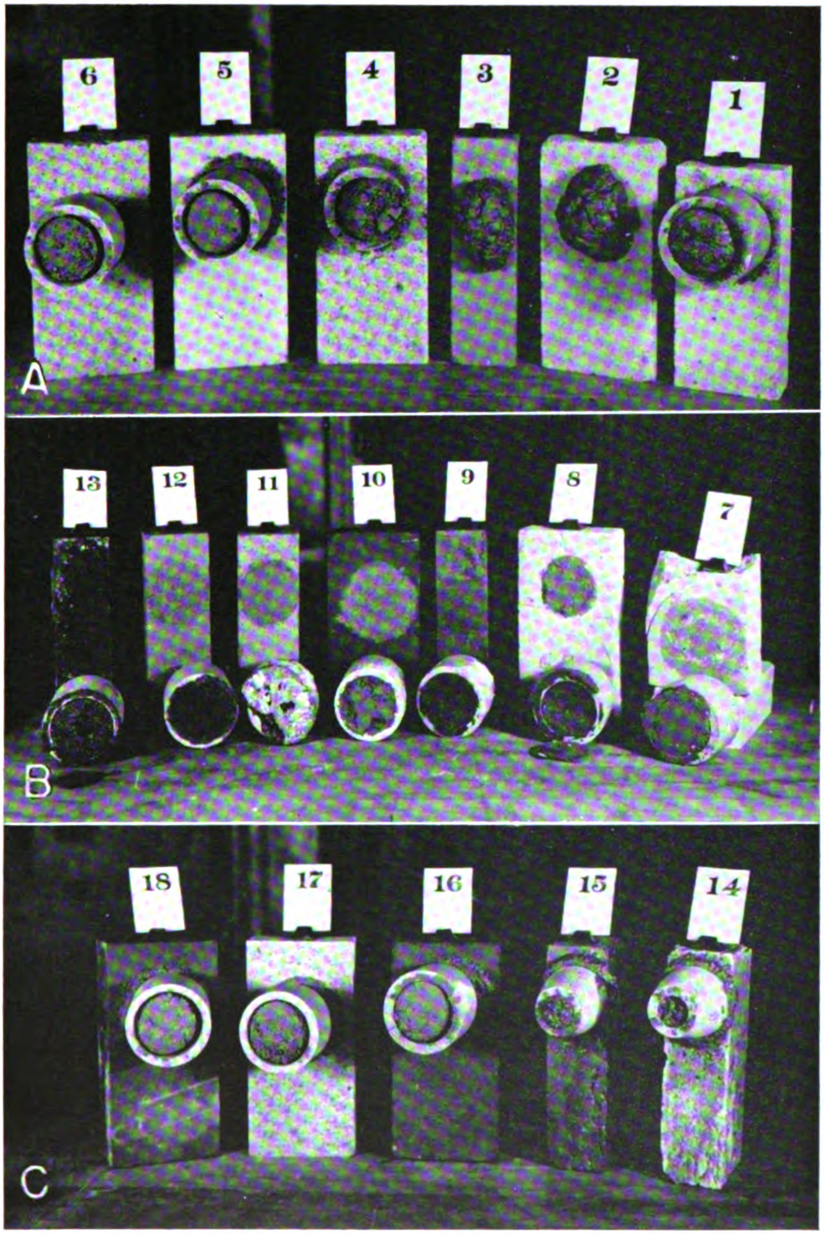

Plate 7. Results of tests to determine tendency of ceramic slag (JN-2) to stick to various types of refractories at 2400° F. *A*, Sticking to bricks (right to left): No. 2 fire clay, No. 1 fire clay, 80-percent alumina, sillimanite, zirconia, 90-percent fused alumina. *B*, Not sticking to bricks (right to left): silica, Ritex magnesia, silicon carbide, dark magnesite, light magnesite, medium magnesite, chrome. *C*, Sticking to bricks (right to left): cast mullite (light), cast mullite (dark), raw chrome, mullite grain, forsterite.

example, the clayey Pennsylvanian shales seem to be particularly bad in this respect, possibly due to the high percentage of alkalies which they contain. As a matter of fact, all shales which we tested tended to stick more than the clays such as those from the Dakota formation and the silty Pleistocene clays. Even with clays of the same type, however, distinct differences were noted in their tendency to stick to the lining of the kiln, or to fire-clay roasting dishes. Ringing is much more serious in a kiln of small diameter than in one with a large cross section. This is a mechanical phenomenon. The top of the kiln forms a small arch in one and a large one in the other, and naturally less bridging occurs in the large arch. Furthermore, the total weight of the charge in a large kiln is often sufficient to pull the sticking mass loose as it rides to the top of the kiln, whereas the small mass in the smaller kiln has not sufficient weight to pull loose. The length of the kiln relative to its diameter also seems to affect the degree of sticking. In the long kiln the heat gradient is less sharp than in the short kiln with the result that the material at any one point in the kiln tends to be at the same stage of firing. If all the material is soft, but not fluid on the outside of the lumps, the mass of material is more likely to form a solid roll and break loose from the lining. In a short kiln underfired lumps, heat softened lumps, and some fluid material tend to mix at one point in the kiln and result in rapid ringing. This same condition is produced by a short, hot, highly radiant flame. Less sticking occurs with natural gas, for example, than with oil.

We ran a number of tests in our laboratory to determine whether or not sticking could be eliminated by the selection of the type of refractory lining. One material only was used in these tests, a Pleistocene clay (JN-2), which was about average in its tendency to stick. Eighteen different types of refractory bricks were tested (Pl. 7) by placing the loose, coarsely ground clay on top of the bricks and held in place by fire-clay cylinders 2½ inches in diameter and 2½ inches high. The bricks with test cylinder filled with clay were first fired to 2400° F., the maturing temperature of that particular sample. If the clay was sticking to the brick after firing and cooling the brick was again placed in the kiln, but this time with the sticking cylinder of partially fused clay hanging to a vertical face, and again fired to 2400° F. In all but two cases, bricks to which the clay stuck on firing horizontally, also stuck on firing vertically (Table 6).

TABLE 6.—*Results of tests used to determine tendency of a Pleistocene clay to stick to various types of refractories at 2400°F.*

Refractories to which clay stuck (Pl. 7A and 7C)		Refractories to which clay did not stick (Pl. 7B)	
No.	Type	No.	Type
1.	No. 2 fire clay	7.	Silica brick
2.	No. 1 fire clay	*8.	Ritex type magnesite
3.	80 percent alumina	9.	Silicon carbide
4.	P.B. sillimanite	10.	Magnesite (dark)
5.	Zirconia	11.	Magnesite (light brown)
6.	90 percent fused alumina	12.	Magnesite (medium brown)
14.	Cast mullite (light)	*13.	Chrome
15.	Cast mullite (dark)		
16.	Raw chrome (Ritex)		
17.	Mullite grain		
18.	Forsterite		

*Stuck horizontally, and cleared vertically.

It will be noted in Table 6 that only four general types of refractories are included in the seven test bricks to which the nearly fused clay did not stick. These are silica, magnesite, chrome, and silicon carbide. The silica brick probably would not be practical to use in a rotary kiln because they will not stand sudden heating or cooling. The chrome brick had a tendency to stick. The magnesite brick, however, showed very little tendency to stick except the one which is manufactured without burning. Magnesite brick, unfortunately, are quite expensive and not too durable. Silicon carbide bricks are extremely expensive, and usually very durable. If used, these more expensive bricks would be installed only in the zone in which sticking occurs so that the relative cost might not be prohibitive. An engineering company that sells and installs rotary kilns recommends the use of No. 1 fire-clay bricks for the lining, and suggests that a heavy water-cooled boring bar be used for breaking loose the accumulating ring of fused material. (Thyrre, 1941).

In general the rotary kiln used in firing ceramic slag will differ little from the conventional kiln used for burning cement clinker, except that the diameter of the ceramic slag kiln will not be the same throughout its length. It will be a counter-current kiln; that is, the flame will travel in the opposite direction to the material. Any type of fuel can be used, presumably, but it seems that a fuel which will produce a long, nonluminous flame, such as natural gas, produces better results in that the heat is distributed more evenly through the length of the kiln, thus promoting oxidation and reducing the tendency of the material to stick.

To judge from the results obtained in the 30-foot pilot plant kiln operated by Mineral Products Company, and opinions expressed by rotary kiln engineers (Hardy, 1948) the kiln most nearly suited to the production of ceramic slag, both from the standpoint of economy of operation and quality of product, will be about 250 feet in length and have an average inside diameter of about 12 feet. The design of this kiln is the same as those used in the sintering of iron, manganese, and phosphate ores. Lindhard (personal communication) states:

> In general, these sintering kilns have fairly long and relatively small-diameter drying and preheating zones which are followed by a shorter and much larger diameter section called the control zone, in which the material is brought gradually up to a temperature somewhat below the point at which it would become sticky and form nodules. The last short section of the kiln is of a smaller diameter than the control zone. The actual sintering or nodulizing takes place in this section of the kiln.
>
> The special shape of the kiln enables the operator to control the sintering so that the tendency of the sintered material to adhere to the kiln lining may be limited to the relatively short sintering zone where it can readily be removed by means of a mechanically-operated scraping device. This operation takes place while the kiln is running and has no adverse effect on the normal operation of the kiln.
>
> The scraping device consists essentially of a heavy water-cooled boring bar carried on a counter-weighted carriage. The overhung end of the bar is guided by a roller support mounted on the kiln hood. The actual removal of the coating is done by a blade mounted on the end of the bar.

It is probable that a kiln as small as 60 feet in length and an inside diameter of 3 feet would produce a ceramic slag of a quality equal to that produced in the larger kiln, but the cost of fuel would be 50 to 100 percent higher per ton of finished product, and rings would form more readily in the smaller kiln than the larger kiln.

If the material is processed in the lump form and allowed to soften with the heat only to the point where smaller particles are beginning to stick to the larger, it is not likely that any difficulty will be experienced with ringing or sticking. The objection to processing in the lump form is that the raw material must go into the kiln in fairly large and uniform lumps unless a considerable portion of fines can be tolerated. Furthermore, the finished

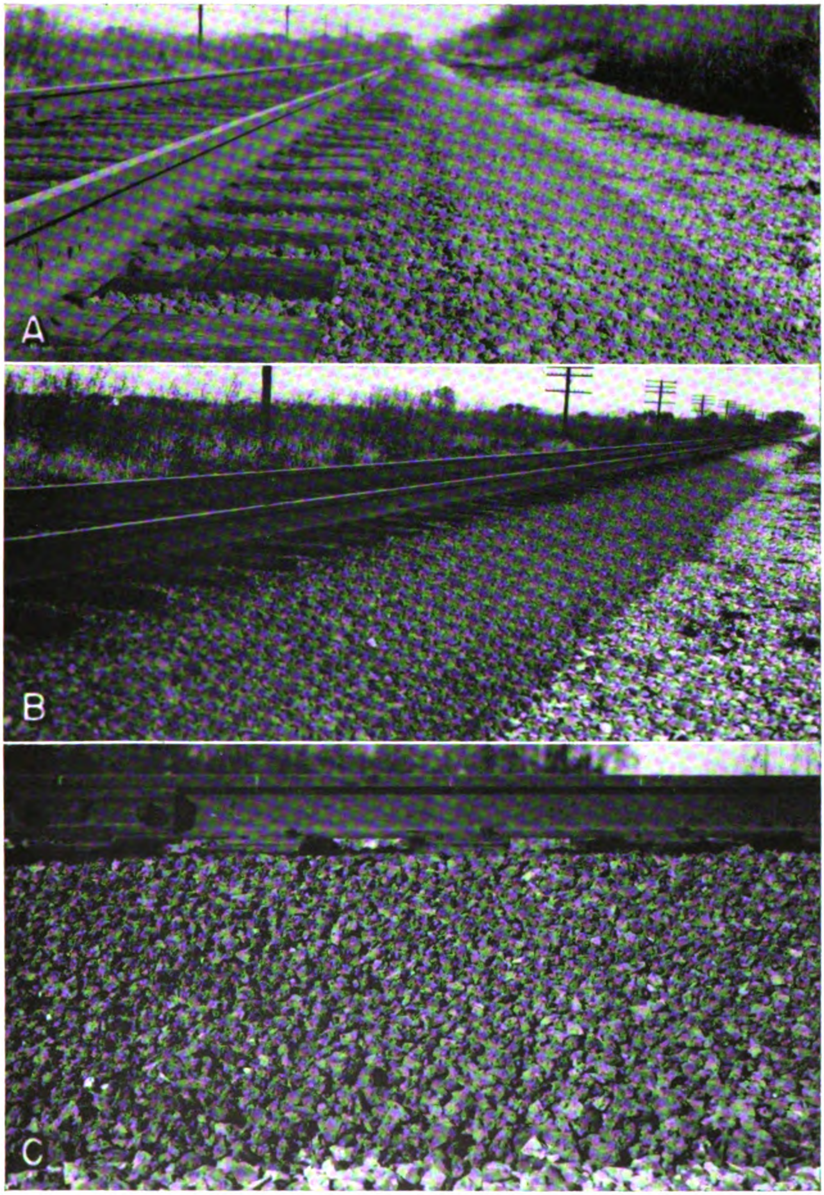

Plate 8. Three views of ceramic slag used as railroad ballast under a section of Santa Fe main-line track east of Eudora, Kansas.

product is not as sharp and angular as that produced by crushing a solid slug or roll produced by partial fusion and aggregation at higher temperatures.

Shales or platy clays tend to retain a tabular structure even after aggregation into a semi-fused roll in the rotary kiln, and if fired in the lump produce an undesirably platy ceramic slag. Such materials should be crushed to destroy the platy structure. If they are to be fired in the lump form it is necessary to dampen the materials and re-form them into fairly large pieces. This can be done by extrusion, dry pressing either in a standard type press or between rollers, or by tumbling to form pellets or roughly rounded balls. Forming into balls by tumbling is by far the least costly method. Most of the clays or shales tested will lump into balls or chunks if dampened when introduced into the upper end of the rotary kiln, although this work could be done more effectively in a rotating cylinder designed for the purpose. It is probable that all the materials except the hard, massive clays, whether shaly or not, will produce a better ceramic slag (unless agglomerated into a roll in the semi-fused state) if the lumps are artificially formed by one method or another.

COST OF PRODUCING CERAMIC SLAG

The cost of producing ceramic slag depends to a great extent on the price of the fuel, inasmuch as fuel probably will constitute from 30 to 50 percent of the total cost of the finished product. Other variables are the capacity of the plant and the cost of mining the raw material and bringing it to the kilns. It is obvious that all unnecessary and costly methods of handling materials, especially those involving hand labor, must be eliminated. These requirements indicate that the rotary kiln is probably the only method of firing that will be practical to use except in special cases.

Careful estimates of the cost of producing ceramic slag under nearly ideal conditions have been made. At this selected plant site a deposit of friable clay with no overburden is available. The deposit is close enough to the plant to be excavated and conveyed to the plant by drag line scraper. Two rotary kilns operating at 2400° F. and having a total capacity of 1,000 tons of crushed slag per day will be used. If natural gas can be obtained for 14 cents per thousand cubic feet the finished product will cost

$1.10 to $1.50 a yard, averaging 1,800 pounds to the yard. If oil is used at current prices the cost will be $1.30 to $1.70 per yard. Fuel consumption estimates are based on figures given by Thyrre (1941) on the heat used in sintering a similar product in rotary kilns. He estimated the heat consumption at 2,250,000 B. T. U. per ton of sinter heated to 1900° F. With final temperatures around 2400° F. the heat consumption would probably be 2,500,000 to 3,000,000 B. T. U. per ton of sinter. The cost of excavating and conveying the clay to the plant should be between 8 and 15 cents per ton, if the known cost of stripping and removing the overburden above a clay deposit can be considered comparable.

The above estimate of $1.10 to $1.70 as the cost of producing a yard of ceramic slag includes all operations, and is based on the crushed and sized material delivered to the cars on the track. It also includes plant depreciation and interest on the investment.

Under ideal conditions such as minimum maturing temperatures and minimum fuel costs the total cost of the finished product could be substantially lower, although it is doubtful if the cost could be reduced to less than $1.00 per yard.

The specific gravity of ceramic slag ranges from 1.2 to about 2.4. The bulk of the samples, however, fall into specific gravity range of 1.7 to 1.9. The crushed and sized ceramic slag weighs from 1,200 to 2,000 pounds per cubic yard, with an average of around 1,800 pounds. These weights per unit volume are considerably less than those of crushed limestone, sandstone, or sand and gravel. Despite the lighter weight per cubic yard the ceramic slag exceeds most of these materials in strength and durability.

Due to the lighter weight per unit volume shipping costs on the ceramic slag will be relatively smaller. Furthermore, the weight of structures built on ceramic slag concrete aggregate will be less, resulting in a saving in foundations, wall thickness, and structural steel. These savings should be used in estimating the cost of ceramic slag relative to the natural materials which it is to replace.

ADVANTAGES OF CERAMIC SLAG OVER OTHER MATERIALS

There are several excellent reasons why ceramic slag should be produced even if it should cost $3.00 a yard rather than the estimated $1.25 to $1.50. In the first place there are many areas, especially in the western half of Kansas, where no local materials are available, or where those available consist of sand and gravel not suitable for more exacting uses. In other areas various grades of limestone as well as sand and gravel are available, but not satisfactory for all uses. The materials which are universally acceptable, such as the "quartzitic" sandstones of Cretaceous age (Swineford, 1947), occur in limited tonnage. Ceramic slag is chemically inert, resistant to all types of weathering, breaks into angular, rough fragments when crushed, and has a relatively low density, although not in the density range of light-weight aggregates such as Haydite. The relatively low density of ceramic slag aggregate results in a lower cement factor and a decrease in the dead load of the concrete structure, which results in a further saving in that a thinner section and a smaller volume of concrete can be used to obtain the same load-bearing capacity.

The superiority of ceramic slag over other available materials is most obvious in respect to its use as railroad ballast. The railroads definitely have decided that crushed limestone is not satisfactory on lines carrying heavy traffic. Limestone is soft and breaks down into a fine dust harmful to bearings and air-conditioning units. When saturated with water this dust forms an impervious mud which interferes with drainage. Ceramic slag, on the contrary, breaks down into angular fragments forming a sand, but not dust. This sand does not create a dust nuisance or interfere with drainage. Furthermore, the ceramic slag is angular and rough. Individual particles tend to cling together, eliminating creep, and the sharp, angular lumps hold the ties in place. It is also very resistant to weathering as determined by freezing and thawing tests and by the saturation coefficients. Other materials available for use as railroad ballast are either relatively scarce or unsatisfactory.

A carload of ceramic slag produced in the Mineral Products Company pilot plant rotary kiln was used to replace chat ballast on a section of main line Santa Fe tracks (Pl. 8), several months ago. It has proved to be highly satisfactory up to the present.

An important characteristic of ceramic slag is the wide range in physical properties which can be achieved by a combination of the selection of raw materials and variations in methods of processing. Bulk specific gravity varied on one sample, for example, from 2.0 to 1.6. The higher specific gravity was produced at vitrification, and the lower specific gravity at a temperature 100° F. higher. The decrease is due to the formation of closed pore spaces at the higher temperature. With various types of raw material the specific gravity may range from 0.40 to 2.40. The lower values place the finished product in the light-weight aggregate class. The absorptions of durable materials may range from 10 to less than 1 percent. Textue and fracture may range from glassy and conchoidal to rough and stony.

Inasmuch as the chemical composition of the raw materials varies widely it is reasonable to assume that the chemical reactivity of the finished product will also vary. Probably the chemical reactivity as described above also varies greatly with the temperature at which the ceramic slag is burned.

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