NORTH DAKOTA GEOLOGICAL SURVEY

Wilson M. Laird, State Geologist

Report of Investigation Number 38

INVESTIGATION

OF

POZZOLANIC PROPERTIES

OF

THE CRETACEOUS VOLCANIC ASH DEPOSIT

NEAR LINTON, NORTH DAKOTA

by

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Grand Forks, North Dakota

1961

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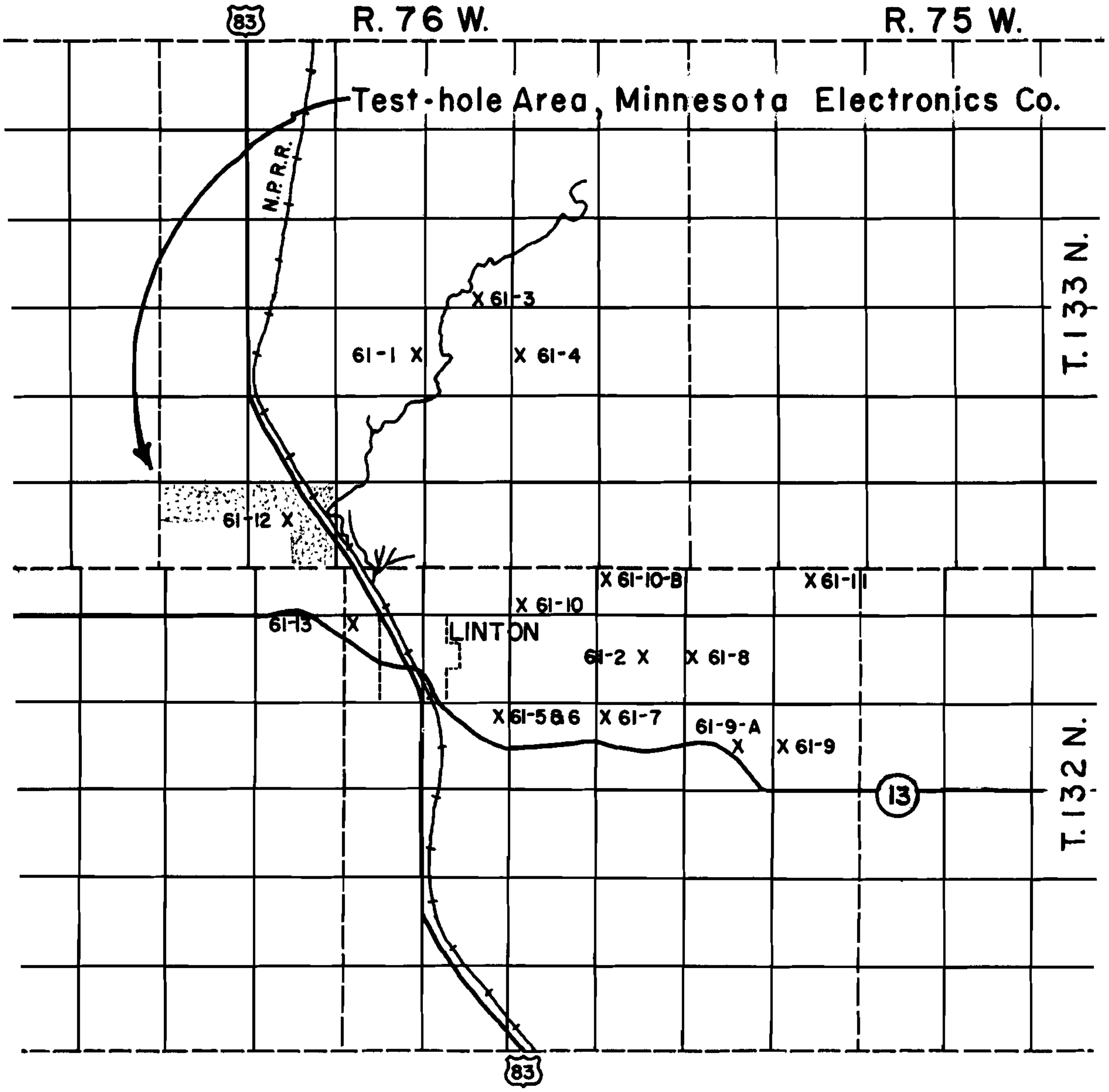

LINTON AREA ASH DEPOSITS
Emmons County North Dakota

x 61-4 Sample location

0 1 2 miles

ABSTRACT

In the past decade, the need for a portland cement-enhancing material to give greater adaptability and range to concrete mixes has created a growing interest in pozzolanic materials like volcanic ash and fly-ash. It is impossible to design fool-proof, all purpose concretes with our present limited standard portland cements. The use of pozzolans may eventually achieve a universal safety cement.

Due to interest in the development of a volcanic ash deposit near Linton, North Dakota, the numerous outcrops were sampled and the following tests performed: pozzolanic activity index of raw and calcined material, with lime and portland cement; material passing a No. 325 sieve; specific gravity; unconfined compressive strength and freeze-thaw resistance of both lime-volcanic ash-soil mixes and soil-cement-volcanic ash mixes.

The results of this investigation indicate that the Linton volcanic ash complies with present day ASTM specifications for raw natural pozzolan for use as an admixture in portland cement concrete. Also, with the addition of lime, it stabilizes certain soils for use as base and subgrade materials capable of withstanding several freeze-thaw cycles.

INTRODUCTION

Pozzolan is defined by Definitions of Terms Relating to Hydraulic Cement (ASTM Designation C219) as "a siliceous or siliceous and aluminous material which in itself possesses little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties."

The natural pozzolans that may be employed as admixtures for portland cement concrete include such materials as diatomateous earths, opaline cherts and shales, tuffs, and volcanic ashes or pumicites, any of which may or may not be processed by calcination; and various materials requiring calcination to induce satisfactory properties, such as some clays and shales. Pozzolans which are industrial by-products include fly-ash and blast furnace slag. There is a great geological and mineralogical variety of pozzolanic raw materials. The term "pozzolan", according to Bauer (1) should be considered a group name, just as the term "portland cement" designates a special group of hydraulic cements. The Concrete Manual of the Bureau of Reclamation (21) discusses types and uses of pozzolans.

According to Davis (2), as portland cement hydrates, calcium hydroxide (hydrated lime) is liberated, and contributes nothing to the strength of the concrete. A pozzolan, added in the right proportion, will react with this lime producing a hydrous calcium silicate of relatively low solubility, which contributes to watertightness as well as to strength.

In the past the main use of pozzolans in concrete has been by the Bureau of Reclamation as a replacement for part of the cement in massive concrete dams like the Bonneville, Friant, Davis and Hungry Horse Dams. Bauer (1) indicates that today there is also a growing demand for pozzolans in tanks and basins, reservoirs, irrigation and water supply canals, sewer pipes, foundations and footings in sea water and acid soils, highways and bridges, pumping and grouting mixes and oil-well cements, and general low and high pressure steam cured products. Characteristically, pozzolans, when used as cement replacements improve plasticity and workability, reduce bleeding, aid watertightness, promote steady strength gain without retrogression, cause lowering of heat of hydration. They also reduce cost of cementing material, since pozzolans can be produced much cheaper than portland cement.

The optimum replacement depends upon: (1) the properties of fresh and hardened concrete which it is desired to enhance, (2) the character and fineness of the pozzolan, (3) the composition of the portland cement, (4) the richness of the mix, and (5) the grading of the aggregate.

In general, pozzolans contribute more to the strength of lean mixes than rich ones, and under moist curing conditions at the later stages this contribution may amount to as much as and sometimes more than that which would have been provided by the cement which is replaced. For moderate percentages of replacement which for certain pozzolans may be as high as 30 per cent, air-entrained concretes containing pozzolans may be expected to exhibit a weathering resistance at least equal to that of corresponding air entrained concrete containing straight portland cement.

It should be recognized that replacement of part of the portland cement by a pozzolan may reduce the early strength of the concrete. Pozzolans may tend to reduce the air content of concrete and therefore, provision should be made to assure the use of an air-entraining agent to entrain the specified amount of air.

OCCURRENCE OF NORTH DAKOTA VOLCANIC ASH

In 1916, Stanton (4) described the Cretaceous volcanic ash bed on the Great Plains in North Dakota, as follows: "Near Linton, North Dakota, in the southern part of the state about 15 miles east of the Missouri River, there are several conspicuous white outcrops that at a distance suggest chalk or diatomaceous earth." At one of the best exposures, 1 mile southeast of Linton, the measured thickness of the white bed is 26 feet, and it lies in the Fox Hills Sandstone about 35 feet above the top of the Pierre Shale. The rock is very fine-grained and mostly massive, though it contains some thin-bedded layers. A sample of it has been examined by Dr. G. F. Loughlin, who finds that it "consists of 80 per cent of volcanic glass, 15 per cent of quartz and feldspar, 2 or 3 per cent of biotite (some-what bleached) and scattered grains of calcite, hornblende, magnetite and chlorite."

No fossils were found in the white ash bed, but in the sandstone directly overlying it distinctive Fox Hills invertebrates were collected at several horizons distributed through a total thickness of about 100 feet. A fossiliferous green band colored by greenalite, which lies 16 feet above the white bed, also contains a considerable amount of volcanic glass, thus showing that volcanic material is not restricted to the white ash bed.

This seems to be the first recorded observation of such a bed of volcanic ash in the Cretaceous sediments of the Great Plains. The nature and location of the deposit are such that its material must have been carried a long distance in the air and finally deposited in the area. The nearest probable source, according to present knowledge of Cretaceous volcanism in the Rocky Mountains, is in the Livingston region, Montana, about 500 miles to the west.

Fisher (5) states that the volcanic ash bed occurs in the Upper Fox Hills, and that he traced the bed from points 6 miles north and east of Linton, where its base is about 45 feet above the Pierre Shale, to the extreme southwest corner of the county where it lies 15 feet above the top of the Lower Fox Hills. The volcanic ash bed, according to Fisher is 25 feet in thickness. Fisher (5A) also states that there are no recognizable Lower Fox Hills beds east of Range 78 West, which is a few miles west of Linton. Russell (6) correlates the Fox Hills with the Eastend, Whitemud, and Battle Formations of Saskatchewan and S. E. Alberta. The U. S. Geological Survey correlates it with the Lennep sandstones of south central Montana.

Laird and Mitchell (7) describe another deposit in southern Morton County in parts of Sections 14 and 15, Township 136 N., Range 83 W. About seven feet of unweathered volcanic ash is exposed in an old lignite mine opening. Shride (8) indicates that another bed is located in Sioux County, Township 130 N., Ranges 82, 83, and 84.

Samples of the volcanic ash from Linton were submitted to Prof. N. N. Kohanowski of the Geology Dept. at the University of North Dakota and to Prof. Schwartz of the Geology Dept. at the University of Minnesota. They both indicated that the material is altered volcanic ash.

Crawford (9) described similar deposits in Saskatchewan and refers to them as pumicite, which he defines as consisting of finely divided powder of a white to gray or yellowish color composed of small, sharp angular grains of highly siliceous volcanic glass, usually rhyolitic in composition. Eardly-Wilmot (10) defines pumicite as a natural glass or silicate, atomized by volcanic explosions and thrown into the air in great clouds which ultimately settle, forming beds of varying thickness.

Figure 1 shows the areas sampled for this investigation.

PUMICITE

According to Crawford (9A) before World War II about 80 per cent of the pumicite used in Canada and the United States was in the manufacture of abrasives, cleansers, and scouring or polishing compounds. Since the war the use has shifted to structural products, and in 1946 in the United States, 77 per cent of the pumicite used was for concrete admixtures and aggregate and only 16 per cent was used for cleaning compounds. Pumicite is also used as an ingredient in ceramic bodies and glazes, glass batches, in brick and tile, glass wool, enamels and in lightweight products. Other uses include fertilizer, asphalt constituent, ingredient of acoustical tile, sweeping compound, paint filler, insecticide carrier, a catalyst carrier in the chemical industry, an absorptive packing material, and in purification of lard and tallow.

Differential thermal analysis curves by Crawford (9B) for some of the Saskatchewan pumicites show that the samples consist mainly of inert material with small per cent of montmorillonite, and with some calcium carbonate or dolomite in some of the samples.

James Eades of the University of Illinois ran an X-Ray analysis which determined that one of the Linton ash samples (61-1) contains a small amount of montmorillonite with the inert material, as well as some quartz and feldspar.

Crawford (9C) made a lightweight product using a mixture of 90 per cent pumicite, 10 per cent sawdust and 15 per cent bentonite, and fired to Cone 1 or approximately 2100^{o} F. He also refers to another mixture for a lightweight product, consisting of 85 per cent pumicite, 10 per cent lignite, and 5 per cent bentonite. About 50 per cent water is required for proper mixing and forming.

During the calcining of the Linton ash samples, from 1000^{o} F to 2000^{o} F, the author saw no indications of bloating or expansion of the material.

Pumice, in contrast with pumicite, is a very highly porous, vesicular lava composed largely of glass drawn into approximately parallel or loosely entwined fibres, which contain sealed vesicles. Lightweight concrete can be made using a mixture of pumice, sand, cement and water.

THE COMING ROLE OF POZZOLANS

Bauer (11) has made the statement that "we stand on the threshold of development of a cement-enhancing material which can only increase the adaptability and range of concrete uses, and put extra meaning into the major sales approach the industry possesses, namely, concrete for permanency. What is good for concrete is good for cement, even if lower cement requirements should develop for concrete employing pozzolans."

In another article, Bauer (1) indicates that "in the last decade there has been a growing interest in pozzolanic materials. We are apparently on the threshold of another new industry situation similar to the lightweight aggregate industry in 1946."

In the past pozzolans have been used to overcome shortcomings of special concretes. The chemical instability of modern rapid strength, high-lime portland cement has been partially met by establishing several classes of cement. However, it is one thing to set up adequate specifications for more stable and resistant types of cements of higher di-calcium and lower tri-calcium silicates and aluminates, or of low alkalie content, but quite another to make such cements available at low cost in every region. Bauer (1) further states that the user, however, can usually depend on modern general-use cements if his use of water, type and grading of aggregate, and techniques in handling, mixing, and placing are correct.

Despite finer grinding and higher burning temperatures for lower free lime and higher tri-calcium silicates and aluminates, it has increased the release of chemically reactive hydrated lime which has little chance to form stable compounds because of the absence of reactive low-lime alumina and silica constituents such as were present often in older low-fired, low-lime portlands.

Despite greater earlier strength and uniformity, or the modern use of air-entraining agents, reactive lime continues to be an unwanted by-product of cement hydration. The free lime may form chemical reaction products with acids, exhaust gasses or sea water which are destructive or bond weakeners within the concrete. As much as 10 per cent of calcium hydroxide by weight of original portland cement content may be released in the first month, and very little of this contributes to the strength of the concrete. However, it can be useful if made to form further silicates or aluminates. It is impossible to design foolproof, all purpose concretes with our present limited standard cements. However, pozzolans "mop up" the free lime and act as stabilizers for excess soluble alkalies, so therefore there may eventually be a universal safety cement achieved. It has been shown that 100 lbs. of freed hydrated lime per cubic yard of concrete can be removed by pozzolan in 90 days. An all-purpose pozzolan would be one of balanced components which would react to neutralize, stabilize, precipitate, and cementize any of the common detrimental soluble salts, weak acids and alkalies to which concrete may be exposed. Tentative ASTM Specification C350-57T for fly-ash and C402-58T for natural raw or activated pozzolans provide no pozzolan identification and classification based on their use with various cements or for various specific purposes. Pozzolans in the past were used for "special buffer" rather than "general buffer" quality concrete, so therefore, a single pozzolanic activity test in the future will not suffice.

Today's foreign literature consistently presents results of investigations on reactive silica materials with portland cement. In the United States there has been increased activity in research and evaluation of pozzolanic raw materials by the cement industry, Bureau of Standards and Bureau of Reclamation. Bauer (12) has given a bibliographic review of pozzolans from 1890 to 1959.

SOIL STABILIZATION

The importance of base course and subbase in modern highway construction has been highlighted by tremendous increases in traffic on U. S. highways. To solve the problem in many states of shortages of good road materials, the engineer is forced to employ marginal base course materials, modified or improved by soils or additives, or to stabilize the soil in place with chemical additives. Some of most commonly used types of stabilization are bituminous, soil-cement, calcium chloride, and lime stabilization. In the reaction of lime with soil, the calcium reacts with available silica and alumina to form complicated compounds of non-slaking moncalcium silicates and aluminates. This is referred to as a "pozzolanic reaction" and it has been found that additions of lime and pozzolans, like fly-ash, to some soils greatly increases the unconfined compressive strength of compacted specimens over that obtained with lime alone. The proportions of lime and pozzolaus used are from 4-8 per cent hydrated lime to 8-20 per cent pozzolan by weight of the oven-dry soil. The 7-day strength of a soil-lime-pozzolan road base is important, since this period is about as long as newly constructed roads can be kept closed, and to avoid rutting, base course strength may have to reach 100 to 300 psi. Since strength gain of soil-lime-pozzolan road bases is greatly reduced when the temperature drops to near freezing, 7 days of curing in northern climates may be the maximum obtained in late season construction. For adequate freeze-thaw resistance, lime-soil-pozzolan bases may need 300-500 psi unconfined compressive strength.

NORTH DAKOTA VOLCANIC ASH POTENTIAL

The processing of the volcanic ash near Linton would involve initial crushing to peanut size, drying or possibly calcining, cooling, grinding, and finally bagging or loading into bulk carriers. An estimate of the cost of a plant to include a rotary kiln for calcining to 1400° F, and to produce 300 tons in an 8-hour shift, is $350,000. The author is of the opinion that there is sufficient ash of proper quality requiring only drying to 212° F, and this would greatly reduce the cost of a plant, by eliminating the rotary kiln.

The Minnesota Electronics Company's market survey indicates a potential market in Minnesota of 3/4 million tons annually, and of 80,000 tons in each of the states of North Dakota, South Dakota, and Montana. These estimates are for the replacement of part of the cement in concrete by volcanic ash. A plant would have to have a 50 to 60 year supply of raw material. It is estimated that there is over 500,000,000 tons of volcanic ash in the Linton area, so it would seem that there would be no shortage of material.

The United States Bureau of Mines Minerals Yearbooks give the following figures for production of pumice (includes pumicite, volcanic ash, volcanic cinders, scoria or other forms of pumiceous material ejected during volcanic eruptions):

Pumice sold or used by producers in United States:

Use	1958	1959
Abrasives	26,000 tons	12,000 tons
Acoustic plaster	2,000 "	1,000 "
Concrete admixture and concrete aggregate	862,000 "	975,000 "
Railroad ballast	666,000 "	841,000 "
Other	417,000 "	447,000 "
Total	1,973,000 tons	2,276,000 tons
World total	9,973,000 tons	10,300,000 tons

In 1958, 220,000 tons of pozzolanic material was used in the Glen Canyon Dam in northern Arizona.

The Bureau of Mines Minerals Yearbooks give the following figures for cement production: in 1958 the total production of portland cement and special cements in the United States was 311,471,000 barrels; in 1959 it was 338,527,000 barrels; and in 1960 it was 319,000,000 barrels.

Total shipments of finished portland cement, with destination in the following states:

	1958	1959
Minnesota	6, 197,000 barrels	6,311,000 barrels*
North Dakota	1,657,000 "	2,011,000 "
South Dakota	1,392,000 "	1,666,000 "
Montana	1,394,000 "	1,425,000 "

* one barrel weighs 376 pounds.

The average price per ton of pumice used for concrete admixture and for concrete aggregate was $2.97 in 1958 and the same in 1959.
The average price of cement per barrel was $3.27 in 1958 and $3.30 in 1959.

At present the use of pozzolan as a replacement for part of the cement in concrete is very limited in this part of the country, so therefore, the success of a plant will depend on an educational and promotional program for the use of pozzolans. The promotion of the pozzolans is hampered by the non-existence of a national pozzolan organization similar to the Portland Cement Association and others.

EXPERIMENTAL PROCEDURE

Field Methods

The sampling of the volcanic ash deposit near the town of Linton, N. D. in Emmons County, was done during the early part of June, 1961. Three days were spent in the field sampling the numerous outcrops. Samples averaging 10 lbs.

8 were taken and numbered with the prefix 61 to denote the year and with numbers 1 to 13 for the individual samples. The assistance of Mr. William Fischer, editor of the Emmons County Record and Mr. Ray Hogue, owner of the Willows Hotel and Motel, was greatly appreciated in locating the various outcrops.

During the winter of 1959-60, Mr. Herbert Northenscold, a prospector for the Minnesota Electronics Company of St. Paul, Minnesota, supervised the drilling of twenty test holes to an average depth of 100 feet. These holes were located in the N 1/2 Section 31, N 1/2 Section 32, and SE Section 32, T. 133 N., R. 76 W.

A promising area for further test drilling is located in Township 132 N., R. 76 W., Sections 2, 3, 4, 9, and 10 and portions of adjoining sections. This property is relatively flat with overburden generally less than two feet thick and few areas where the ash bed is likely to be cut out by stream erosion. In Sections 2, 3 and 4 particularly test drilling could easily be done on both sides of the east-west road that traverses these sections.

Laboratory Methods

Pozzolans for use as admixtures in Portland Cement Concrete shall conform to the "Tentative Specifications (13) for Raw or Calcined Natural Pozzolans for Use as Admixtures in Portland Cement Concrete" (ASTM Designation C402). These specifications include physical and chemical requirements, as follows: Analyses of the Linton Ash are provided for comparison

(1) Chemical:	A.S.T.M. Specs.	(1)	(2)
SiO_2 plus Al_2O_3 plus Fe_2O_3, min., per cent	70.00	80.02	84.36
MgO max, per cent	5.00	0.75	0.75
SO_3 max, per cent	3.00	0.01	none
Loss on ignition, max, per cent	10.00	6.36	6.4
Moisture content, max, per cent	3.00	0.37	1.48

(1) Analysis of Linton Ash furnished by H. M. Northenscold

(2) Analysis of Linton Ash furnished by Chicago, Milwaukee, St. Paul and Pacific Railroad Company

(2) Physical:

(a) Fineness: Mean particle diameter, microns, max 9.00

Amt. retained when wet-sieved on No. 325 (44 micron) sieve, max, per cent 12.00

(b) Pozzolanic Activity Index:

With Portland cement, at 28 days, min, percentage of control 75.00

With lime, at 7 days, min, psi (2" by 4" cylinders) 600

(c) Water requirements, max, percentage of control 115

(d) Change of drying shrinkage of mortar bars at 28 days, max, per cent .03

(e) Soundness: Autoclave expansion or contraction, max, per cent .5

(f) Amount of air-entraining admixture in concrete, ratio to control, max 2.00

(g) Uniformity requirements:

The specific gravity of individual samples shall not vary from the average established by 10 preceding samples, by more than, per cent 3.00

The quantity of air-entraining admixture required to produce an air content of 18.0 per cent by volume of mortar shall not vary from the average established by the ten preceding tests by more than, per cent 20.00

(h) Reactivity with cement alkalies:

Reduction of mortar expansion at 14 days, min, per cent 75.00

Mortar expansion at 14 days, max, per cent .020

The US Army Corps of Engineers has a similar specification, Class N (CRD-C262-57), which differs only for the "Pozzolanic Activity Index with Lime." It is based on the use of 2" x 2" cubes and specifies a minimum of 900 psi.

According to Bauer (14), pozzolans must be developed to optimum value and reactivity before they are tested for evaluation. He also states that there are two phases of pozzolan development: (1) Basic - initial fact-gathering portion to develop optimum pozzolan properties. (2) Applied - application of these facts to the design of the process. Pilot size equipment is used to produce a ton or two for evaluation of the product. The basic process, according to Bauer (14) involves initial subjection to heat treatment (electric or gas-fired) at 1200° F, 1500° F, and 1800° F with exposure time of 20 minutes and 40 minutes. Mielentz and others (3) used temperatures of 1000, 1400 and 1800° F for most materials, with an exposure time of 1 hour.

After heat treatment, Bauer (14) specifies grinding to 4000 to 8000 sq-cm-gr Blaine specific surface. Samples that then show some lime reaction in the Vicat test are then subjected to the 7-day Pozzolanic Activity test. If the 7-day test is satisfactory then the material is tested further with cement in concrete mixes and mortars. Bauer also indicates that X-ray, differential thermal analysis and petrographic microscope equipment is also useful.

Crawford (9D) states that chemical composition seems to have no significance in the activity of pozzolans, although silica and alumina are the active constituents.

The testing of the volcanic ash samples included in this report was limited both by time and by available equipment. However, additional information obtained from copies of reports submitted by Northwest Laboratories, and covering the complete series of tests for physical requirements, supplemented the information obtained from the laboratory procedure as outlined in the following pages.

(A) Sample preparations: The volcanic ash samples, as received, were dried at 110° C for 24 hours. Preliminary crushing was performed with a Denver Fire Co. jaw crusher with 2 1/2" x 3" opening, and with reduction to approximately No. 4 sieve size. Grinding was done with a small Cincinnati Muller for 2 hours, and any material not passing a 200 sieve was returned for further grinding. The material passing the 200 mesh sieve was checked for sizing by wet sieving on a No. 325 sieve, as outlined in "Test for Fineness of Portland Cement by Turbidimeter" (ASTM Designation C 115). Calcining of the ash samples was done with a Harper Electric kiln which could be held at whatever temperature was desired. When the calcining temperatures of 1000, 1400 and 1700° F were reached stainless steel trays containing the ash samples were put in the kiln and kept there for 1 hour, while the temperature was kept constant. After cooling, the calcined samples were ground again with the Cincinnati Muller and checked for sizing. Specific gravity determinations were made, according to ASTM Designation C-188 (Specific Gravity of Hydraulic Cement).

The various soil samples used for mixing with ash and lime were dried at 110° C for 24 hours, separated into two fractions with a No. 4 sieve, with the plus 4 material being rejected.

The lime used, as received, compiled with ASTM Designation C-6, Type N for Normal Finishing Hydrated Lime.

The cement used was Type 1 Normal to compile with ASTM Designation C 150 for Portland Cement.

(B) Pozzolanic Activity Tests: The activity index with lime was determined in accordance with Section 13(1) of the "Specifications for Portland Pozzolan Cement" (ASTM Designation: C 340). The average compressive strength of the specimens was calculated in accordance with Section 13(L), Item 5 of the Specification C 340, and designated as the pozzolanic activity with lime. The specimens tested contained 2 parts oven-dry pozzolan, 1 part hydrated lime and 9 parts of graded standard sand, by weight.

The pozzolanic activity index with portland cement was determined by molding specimens from a control mix and from test mixes in accordance with the Method" of Test for Compressive Strength of Hydraulic Cement Mortars"(Using 2" Cube Specimens) (ASTM Designation: C 109). In the test mixes 35 per cent of the absolute volume of the amount of cement used in the control mix was replaced by an equal absolute volume of the pozzolan. The pozzolanic activity index with portland cement is $\frac{A}{B}$ x 100, where A is the average compressive strength of the test mix cubes, and B is the average compressive strength of the control mix cubes (composed of 1 part cement and 2.75 parts graded Standard sand, by weight).

Neither the pozzolanic activity index with portland cement nor with lime is to be considered a measure of the compressive strength of concrete containing the pozzolan. The index with portland cement is determined by an accelerated test and is intended to evaluate the contribution to be expected from the pozzolan to the longer strength development of concrete. The optimum amount of pozzolan for any specific project is determined by the required properties of the concrete and other constituents of the concrete and should be established by testing.

Since the molding of 4" diameter by 8" high or of 6" diameter by 12" high concrete specimens would have required considerable material and time, it was decided to rely on the pozzolanic activity tests for the contribution to be expected from the pozzolan to the longer strength development of concrete.

To broaden the scope of this investigation, tests were performed using various combinations of lime and volcanic ash with typical soils of North Dakota in an attempt to stabilize them for evaluation of their possible use as highway bases or subbases. Mixes were used with lime contents varying from 0 to 8 per cent of the oven dry soil, and volcanic ash contents from 0 to 24 per cent of the oven dry soil. 0 1

In addition to the lime-ash stabilized mixes, a few were tested to investigate the effect of replacement of part of the cement in soil cement with volcanic ash.

(C) <u>Molding, Curing and Testing Lime Stabilized Specimens:</u> For the various mixes, the dry soil, ash and lime were dry mixed for 30 seconds in a Hobart Model N-50 Mixer (electrically driven mechanical mixer of the epicyclic type). The distilled water required for near optimum density was added and mixing continued for 5 minutes. Cylinders, 2" high and 2" diameter in size, were compacted with an apparatus similar to one developed by the Iowa Engineering Experiment Station. Chu and Davidson (15) have given the test procedure, described the apparatus and shown a comparison of test results obtained by the "Iowa and the Standard Proctor Density Test" (ASTM Designation D-698). The Iowa apparatus, which uses a 5 lb. hammer dropped 12 inches with 5 blows on each side of the specimen, requires only about 1/10 of the material and less than 1/3 of the time needed to perform the standard Proctor density test. The maximum dry densities and optimum moisture values (15) obtained by the two tests are nearly the same. The standard proctor employs a 4" diameter by 4 1/2" high cylinder, compacted in three layers by a 5 1/2# hammer, with 25 blows per layer.

The various lime-soil and lime-soil-ash specimens were cured under the following conditions:

(a) 1, 3, 7 and 28 days at 140° F, sealed in California Bearing Ratio molds.

(b) 7 and 28 days at $80 \pm 4^{\circ}$ F in sealed plastic bags in a curing room maintained at above 95 per cent relative humidity.

(c) The specimens cured at 140° F for 3 days were further cured for 4 days at $80 \pm 4^{\circ}$ F in sealed plastic bags in a curing room of above 95 per cent relative humidity. This was done to prepare them for the freeze-thaw test so they could begin the test at the same time as those specimens cured for 7 days at 80° F.

(d) The control specimens for the freeze-thaw test, after initial curing of 7 days at 80°F , 28 days at 80° F or 3 days at 140° F (plus 4 days at 80° F), were further cured, immersed in distilled water for 12 days, while companion specimens were being subjected to the freeze-thaw test.

(e) The freeze-thaw test used was the Modified British Freeze-Thaw Test developed by the Iowa Engineering Experiment Station for use with 2" diameter by 2" high specimens. The field conditions which must exist for deleterious frost action are simulated in the test: a freezing temperature, a readily available source of water, a thermal gradient, and cycles of freezing and thawing. Davidson and Bruns (16) have described the apparatus, given the test procedure and shown the equations for calculating unconfined compressive strength and the index of resistance to the effect of freezing. Briefly, the apparatus consists of wide mouth vacuum bottles with plastic holders to hold the 2" diameter by 2" high specimens in place at the top of the bottles. The bottom of the holders are perforated to enable water from the inside of the vacuum bottles to enter the bottom of the specimens. The top of the specimens are exposed and have a coating of asphalt paint to prevent drying out. For the freezing cycle the vacuum bottles are placed in a freezer maintained at $23 \pm 2^{\circ}$ F ($-5 \pm 1^{\circ}$ C) for 16 hours, with the water in the vacuum bottles kept near 46° F (8° C). For the thawing cycle the bottles and contents are removed from the freezer and kept for a period of 8 hours at a temperature of $77 \pm 4^{\circ}$ F ($25 \pm 2^{\circ}$ C). The number of cycles of freezing and thawing should approximate the number of cycles that the stabilized soil will be subjected to in the road each winter. Davidson and Bruns (16) have indicated that 14 cycles simulate maximum winter conditions in Iowa in a soil cement base under a 2-3 inch bituminous wearing course.

It was decided to use only 12 cycles to facilitate the testing of more specimens after it was discovered that if a specimen withstood 5 or 6 cycles without visible signs of deterioration, then they would be able to withstand several more cycles.

The cylinders that did not deteriorate during the freeze-thaw cycles were tested in unconfined compression and compared with the control specimens. Davidson (17) indicates that an unconfined compressive strength of 300 pounds per square inch after 28 days curing and 10 cycles of freezing and thawing is considered indicative of satisfactory resistance to frost action. Another criterion of satisfactory freeze-thaw resistance is an index of resistance of at least 80 per cent: $R_f = \frac{100P_f}{P_c}$ (%) where P_f is the unconfined compressive strength of the freeze-thaw specimen and P_c is the strength of the control specimen. Davidson and others (18) have indicated that when both P_c and P_f greatly exceed 250, a lower minimum P_f may be permissible, for example 75%.

(D) Molding and Testing Soil-Cement Specimens: Essentially the same procedure as for the lime-soil specimens was followed in making the soil-cement-volcanic ash specimens. The replacement of 35% of the cement by volcanic ash was on an equal volume basis. They were cured for 7 days and 28 days at 100 per cent relative humidity and then tested in unconfined compression. Also, specimens which had been cured for 7 days were subjected to 12 cycles of freeze-thaw.

(E) Miscellaneous tests: Sieve analyses of the volcanic ash and the various soils used were performed, using ASTM Method 422-55T. The liquid and plastic limits were determined and from these values, the plasticity indexes were calculated by ASTM Methods D 423-54T and D 424-54T.

OBSERVATIONS AND DISCUSSION

The volcanic ash samples tested for this report are all from an area within a five mile radius of Linton, North Dakota. The sample locations are shown on Figure 1.

General Discussion

Field sampling revealed that the volcanic ash material is essentially the same in all the outcrops, namely, light gray in color, mostly massive and very fine grained. Referring to Appendix I, the bottom of the ash bed is exposed at only one location, that of sample 61-13, and it appears that the underlying material is dark gray shale of the Pierre Formation. Fisher (5) has indicated that the ash bed occurs as a 25 foot bed near Linton and is about 45 feet above the Pierre Shale. Northenscold in his twenty test holes, located in the stippled area in Figure 1, indicated 25-30 feet of volcanic ash underlain by dark gray to black shale.

Since it was felt that the ash exposed in the numerous outcrops was uniform throughout the area, sample 61-1 was picked as representative of the area and was used to run most of the tests. In addition, the pozzolanic activity index test was performed on samples 61-5 and 61-13 as a check on the uniformity of the deposit.

Table 1, gives sieve analyses and Atterberg limits for the soils used for the lime-volcanic ash stabilization study and for the soil cement. Using the American Association of the State Highway Officials' classification, based on the sieve analysis and Atterberg limits, it is observed that soil A is an A-7 clayey, poor subgrade material, whereas soils B and D are A-1 granular, excellent subgrade material. Although no tests were run on sample C, it is very similar to sample A, and from the same general area. The sieve analyses of two of the ash samples, with almost 100 per cent passing the No. 200 sieve, verifies the field observation.

Pozzolanic Properties of the Volcanic Ash

Referring to the commercial testing laboratory report, submitted by the Northwest Laboratories to the Minnesota Electronics Company, and reproduced as Table 2 it is possible for a material to comply with all the specifications for "Raw or Calcined Natural Pozzolans for Use as Admixtures in Portland Cement Concrete" (ASTM Designation C 402-58T or CRD C-262-57), with the exception of the pozzolanic activity indexes with lime or portland cement, and yet be rejected as a pozzolan. As shown in Table 2, the composite sample failed as a pozzolan in the oven-dry state and when calcined to 1000° F, but when calcined to 1400° F it showed sufficient gain in activity to pass both the ASTM and Corps of Engineers' specifications.

Table 3 gives pozzolanic activity indexes and other test results for some of the samples collected by the author. However, it is noted that in contrast with the results shown in Table 2, the samples which were oven-dried at 212° F and tested by the author, complied with both pozzolanic activity index specifications. The use of this ash without calcining would be most advantageous because of the reduced cost of processing, and secondly, because the light gray color of the non-calcined material would be more acceptable to the public than the buff-colored calcined material. The latter is true because the gray color of the ash is hardly distinguishable from most portland cements, and will not change the color of the concrete if it is to be used as a replacement for part of the cement. The fact that the results of the analyses shown in Table 2 indicate the necessity for calcining may be due to the incorporation of some of the underlying Pierre Shale in the composite sample.

Lime-Volcanic Ash Stabilization Results

Table 4 gives the unconfined compressive strength values for 2" x 2" cylinders compacted from various proportions of lime (0-8%) and volcanic ash (0 to 24 per cent) with soil samples A, B, or C, and cured at 140° F for 3 and 7 days, as well as at 80° F for 7 and 28 days. In table 5 are given the unconfined compressive strengths of both the control specimens and those which were subjected to from 6 to 12 cycles of freezing and thawing.

Referring to Table 4, the following has been observed:

A. Additions of lime and volcanic ash to soil sample No. B

1. The addition of either 4 or 8 per cent lime to the soil increases the strength of the soil with no additions, by several hundred per cent.

2. The addition of 8 per cent lime results in about 20 per cent less strength than the mix with 4 per cent. The additions of 4 and 8 per cent results in lower dry density and higher optimum moisture values than those from the soil alone.

3. Mix No. 4, containing 12 per cent volcanic ash (oven-dried) and 4 per cent lime produced twice the strength of Mix No. 2, containing 4 per cent lime and no ash. The use of 4 per cent dolomitic lime and 12 per cent ash (oven-dried), in mix No. 5, increases by 25 per cent the 7 day strength of specimens cured at 80° F.

4. The doubling of the ash content to 24 per cent in Mix No. 6, with the lime kept at 4 per cent, produced lower strength values than mix 4 when cured 3 days at 140°F and 7 days at 80°F, but gives higher strength after 28 days at 80°F.

5. Mix no. 7, containing 8 per cent lime and 12 per cent ash (oven-dried) produces from 25 to 33 per cent higher strength than mix No. 4 when cured 3 days at 140°F and for 28 days at 80°F, but is slightly less after 7 days at 80°F.

6. The boosting of the ash content to 24 per cent, with the lime at 8 per cent, as in Mix no. 8, greatly increases the strength after 3 days at 140°F and 28 days at 80°F but does not affect the strength after 7 days at 80°F.

7. Mix no. 9, containing 4 per cent lime and 12 per cent ash (calcined to 1000°F), and Mix No. 10, containing 4 per cent lime with 12 per cent ash (calcined to 1400°F), gave slightly higher strength than Mix No. 4 after 3 days at 140°F and 28 days at 80°F, but gives about 25 per cent less strength after 7 days at 80°F.

Mix No. 11, with 12 per cent ash calcined to 1700°F, gives much greater strength than mixes 9 and 10.

8. Reduction of the lime to 2 per cent and with the ash content at 12 per cent (calcined at 1700°F) gives 50 per cent less strength than that of Mix No. 11 after 3 days at 140°F, but gives slightly higher strength after 7 days at 80°F.

9. Mix No. 13, with 8 per cent lime and 12 per cent ash (calcined to 1700°F) gives slightly higher strength than Mix No. 11 after 3 days at 140°F and 7 days at 80°F. It also gives greater strength than Mix No. 8 which also contains 12 per cent ash, but has been oven-dried. With reference to Table 3 it is noted that the pozzolanic activity index at 1700°F is slightly higher than that at 212°F.

Referring to Table 5:

10. Although only 12 cycles of freeze-thaw were run instead of the 14 set up by the Iowa Experiment Station, a freezing resistance index value of 79.5 per cent for Mix No. 5, containing 4 per cent dolomitic lime and 12 per cent ash (oven-dried), after a curing period of 7 days at 80°F, is the highest value for the series containing soil B. The next lowest indexes for 7 day initial cure at 80°F are for Mixes Nos. 8 and 6, with values of 68.2 and 64.6 per cent.

11. Twelve cycles of freeze-thaw were conducted on specimens from 4 mixes which had been cured for 28 days at 80°F. With the exception of Mix No. 10, which has an index of 92.0 per cent, Mixes Nos. 4, 6 and 11 all have indexes between 105 and 115 per cent. It seems strange that specimens which have undergone 12 cycles of freeze-thaw should be stronger than the control specimens. Similar results are seen for Mixes Nos. 2, 10 and 11 after 3 days curing at 140°F and 12 cycles of freeze-thaw.

12. With the exception of Mix No. 3, containing 8 per cent lime, there is a marked increase in the freezing index for specimens which have had an initial 3 day cure at 140°F.

For northern climates where temperatures of 70°F or higher prevail during the construction season, the test results in Table 5 indicate that, unless dolomitic lime is used, a road base of lime-ash-soil B would have to be cured for probably 2 to 3 weeks before undergoing freeze-thaw cycles. Although curing at 140°F for 3 days produces a satisfactory freezing resistance for most of the mixes, it is not likely that this temperature will be met in the north. Eade of the University of Illinois, in private correspondence, has indicated that his findings in Virginia show a correlation between samples cured at 140°F for 3 days and the 360 day test for the field section. However, the field section was laid late in September, and he felt that if it had been laid in May or early June it would have reached the same strength by the end of the summer. The North Dakota State Highway Department Special Provision for Lime Stabilized Base (19) states that lime base cannot be laid after September 1st.

13. It appears from Table 4 and 5 that calcining does not produce enough increase in strength to warrant the added cost of calcining the raw material. The best combination of lime and volcanic ash seems to be 4 per cent lime and 12 per cent ash. As previously mentioned, the use of dolomitic lime in place of the calcitic lime produces better strengths in the 4-12 mix. Since a road base of lime-ash-soil B will produce strength comparable to soil-cement, it is economically advantageous to use as little lime and ash as possible.

With reference to Tables 4 and 5, the 12 day immersion strengths of the freeze-thaw control specimens are 25 to 33 per cent less than the corresponding strengths of the specimens after curing for 3 days at 140°F. However, for the specimens subjected to the 7 day cure at 80°F the strength of the control specimens are 25 to 50 per cent greater, except for the mixes containing 4 and 8 per cent lime. The latter are slightly lower in strength. The 28 day strengths at 80°F have increased from 50 to 100 per cent over the strength of the control specimens which had an initial cure of 7 days at 80°F, in addition to being immersed for

12 days. Since water will be usually readily available in the road base or subgrade, it is certainly more realistic to conduct tests on samples which have been immersed. Most investigators subject specimens to at least 24 hours immersion after any particular period of curing, before running the unconfined compression test. Most soils when compacted without the addition of lime or some other stabilizing agent will not withstand a subjection to immersion and is vivid proof of the benefit derived by adding stabilizers.

B. Additions of lime and ash to soil No. A & C.

The results in Table 4 and 5 for lime-ash mixes with soils A and C indicate that much lower dry densities and higher optimum moistures are obtained than with soil B mixes. The type A-7 soil would account for this, because of high clay content.

For lime-ash-soil B mixes, curing at 140°F for 3 days produces strengths from 2 to 4 times as high as those obtained at 80°F for 7 days. However, for lime-ash-soil A mixes, curing at 140°F for 3 days produces less than twice the strength of the 7 day at 80°F specimens. The strengths obtained after 3 days at 140°F and after 7 days at 80°F for the mixes with soil A are comparable to the strengths obtained for the same curing temperatures and times with soil B and either 4 or 8 per cent lime, with no ash.

The addition of 12 per cent or even 24 per cent ash together with 4 per cent lime produces at the most a 33 per cent increase in strength over that containing 4 per cent lime and no ash. The mix containing 8 per cent lime and 12 per cent ash produces the same strength as that containing 4 per cent lime and 12 per cent ash.

Time did not permit obtaining more data on freezing and thawing but it is interesting to note from Table 5 the relatively high freezing resistance values and the corresponding relatively low p_c and p_f values, even though they are the results of only six cycles. With reference to Tables 4 and 5 the decrease in strength due to immersion for 6 days is from 33 per cent of the corresponding strength before immersion for the 4 per cent lime mix to 25 per cent for the lime-ash mixes. These decreases are comparable to the mixes containing soil B and cured for 3 days at 140°F.

The freezing resistance values for the mixes containing ash and lime are less than the mix containing only lime. A possible explanation for the small benefit obtained from additions of volcanic ash or pozzolan to lime-soil A mixtures is noted by Hilt and Davidson (20). They state that montmorillonite will react with lime to produce a cementing material equal to or greater in strength producing qualities than the cementing agents produced in the reaction of lime with fly-ash, which is also a pozzolan. They concluded that it is not necessary to add fly-ash to soils containing large amounts of montmorillonite when treating with lime. Such additions may even be detrimental. The clay material in soils A and C is probably montmorillonite.

C. Replacement of cement in soil-cement by volcanic ash.

Referring to Table 6 the replacement of 35 per cent of the cement by volume in soil-cement with volcanic ash results in strength losses of around 33 per cent and reduces the freezing resistance from 77 per cent to 0 per cent.

With reference to Table 3, the pozzolanic activity index with portland cement for this same volcanic ash is 118 per cent. However, the per cent of cement before replacement by volcanic ash is higher than that for the soil-cement. It appears that soil-cement mixes contain too low a cement content to be benefitted by replacement with volcanic ash.

CONCLUSIONS

1. The Linton area ash bed is generally overlain by sand and underlain by shale. Contamination of the ash by this adjacent material is detrimental. If the ash is carefully mined, with no admixture of sand or shale, the volcanic ash need only be dried at 212°F and finely ground, in order to comply with ASTM Specifications C 402-58T for "Raw or Calcined Natural Pozzolans for Use as Admixtures in Portland Cement Concrete."
2. More test drilling is recommended.
3. A stabilized base, which can be subjected to freeze-thaw cycles after 7 days curing at 80°F, can be attained with a type A-1-b soil by adding 12 per cent Linton volcanic ash and 4 per cent dolomitic lime. If calcite lime is used, the curing period must be increased to over 3 weeks.
4. The freeze-thaw resistance of a stabilized base composed of lime and type A-7 soil is not improved by the addition of volcanic ash.
5. The quality of soil-cement is not improved by replacement of 35 per cent of the cement by volume by Linton volcanic ash.

SUGGESTIONS FOR FURTHER RESEARCH

1. As recommended by the ASTM, it is suggested that the volcanic ash be tested in concrete mixes to show the effect of the following:
   (a) water-cement ratio, and (b) the per cent of replacement of cement by volcanic ash.
2. If possible, since the Minnesota Electronics Company is promoting the establishment of a processing plant in the Linton area, samples from the individual test holes should be checked for pozzolanic activity index of the oven-dried material.
3. The completion of the freeze-thaw testing for all the lime-ash-type B soil mixes after an initial curing at 80°F for 28 days.

4. The completion of freeze-thaw testing for the lime-ash-type A & C soil mixes after an initial cure of 7 and 28 days at 80°F.
5. Substitution of dolomitic lime for calcitic lime in several of the mixes.
6. Other typical soils of North Dakota should be checked for lime-ash stabilization potential.
7. Testing the volcanic ash for other ceramic and non-ceramic uses.
8. From the mineralogical aspect, it is suggested that differential thermal analyses, X-Ray diffraction and chemical analyses be run.

Table 1

Sieve Analyses, Atterberg Limits, and Classification

Soil	A	B	D	61-1	61-5
Sieve Analysis: Per cent passing					
3/4"	100.0	100.0	100.0		
3/8"	93.4	86.5	97.5		
#4	83.2	68.0	90.4		
#10	75.0	52.2	78.6		
#20	67.0	47.4	66.6		
#40	59.9	44.7	65.0		
#140	51.4	26.4	18.8		
#200	50.2	25.5	16.8	100	99.0
Atterberg Limits:					
Liquid Limit, %	50.0	22.5			59.7
Plastic Limit, %	18.2	19.7			61.2
Plasticity Index, %	31.8	2.8	0		-1.5
Classification:					
Engineering (AASHO)[a]	A-7 (clayey, poor subgrade)	A-1-b (granular, excellent subgrade)			

[a]American Association of State Highway officials Method M 145-49

Table 2

Copy of Report Submitted to Minnesota Electronics Company, St. Paul, Minn., by the Northwest Laboratories, Seattle, Wash., in 1960**

	Material			Specified	
	212° F	1000° F	1400° F	ASTM C402-58T	CRD C-262-57*
Specific Gravity	2.2624	---	2.404	----	----
Blaine Fineness	9770	---	9767	----	----
Mean Particle Diameter, Microns	2.715	---	2.555	9.00 max	9.00 max
Material Retained on #325 Sieve	7.85	---	10.26	12.00 max	12.00 max
Pozzolanic Activity Index with Lime at 7 days, psi					
2" x 4" Cylinders	611	---	1030	600 min.	----
2" x 2" Cubes	665	680	1120	----	900 min.
Pozzolanic Activity Index with Portland Cement at 28 days, %	64.0	---	80.6	75 min.	75 min.
Water Requirements, %	107	---	108	115 max.	115 max.
Soundness-Autoclave Expansion, %	0.32	---	+0.26	0.50 max.	0.50 max.
Change of Drying Shrinkage at 28 days, %	---	---	+0.025	0.03 max.	0.03 max.
Reduction of Reactivity at 14 days, %	---	---	90.1	75 min.	75 min.

** These tests were performed on composite samples of volcanic ash from twenty test holes. The portions from each test hole are taken from the 1 foot to around 25 to 30 foot levels. The material was crushed and ground in a ball mill. Calcining was done at 1000° F and 1400° F for 15 minutes.

* Corps of Engineers Specifications, Class N

Based on the tests conducted and the sample submitted, the material when calcined at 1400° F, complies with both ASTM C402-58T and CRD-C262-57.

Table 3

Pozzolanic Activity Indexes and Other Test Values for Volcanic Ash Samples Numbers 61-1, 61-5 and 61-13*

	Samples					Specified
	61-1 212° F	61-1 1400° F	61-1 1700° F	61-5 212° F	61-13 212° F	ASTM C402-58T
Specific Gravity	2.37	2.50	2.39	---	---	---
Material Retained on #325 Sieve	2.9	3.2	---	0.6	---	12.0 max.
Pozzolanic Activity Index with Lime at 7 days, psi						
2" x 4" cylinders	952	1375	1015	1090	1010	600 min.
2" x 2" cubes**						
Pozzolanic Activity Index with Portland Cement at 28 days, %	118	111	---	---	---	75 min.
Water Requirements, %	110	112	114	110	110	115 max.
Color of Sample	lt. gray	light buff	dark buff	light gray	light gray	---

<u>Note</u>: * The materials tested were ground with a muller. Calcining was done at 1400° F and 1700° F for a period of 1 hour.

** The Corps of Engineers Specifications Class N (CRD-C262-57) is identical with ASTM C402-58T, except for the use of 2" x 2" cubes for the Pozzolanic Activity Index with Lime, and the requirements at 7 days, psi of 900, minimum.

Table 4

Dry Density, Optimum Moisture and Unconfined Compressive Strength Values for Lime-Volcanic Ash Stabilized Mixes

Mix No.	Soil	% Lime	Ash Type	Ash %	Ash Temp. F	Dry Density pcf	Optimum Moisture	Unconfined Compressive Strength, psi, for Specimens cured: 3 days at 140°F	7 days at 140°F	7 days at 80°F	28 days at 80°F	Misc.
1	B	0	- -	0	- -	122.7	13.7	87				
2	B	4	- -	0	- -	119.0	15.5	675	- -	223	450	
3	B	8	- -	0	- -	120.5	16.0	540	938	175	358	19 days at 140° 1360
4	B	4	61-1	12	212	113.7	15.5	1103	- -	382	620	
5	B	4*	61-1	12	212	115.3	14.9	1082	1265	500	660	28 days at 140° 1257
6	B	4	61-1	24	212	113.5	15.8	906	1113	484	739	19 days at 140° 1183
7	B	8	61-1	12	212	113.5	15.9	1376	- -	323	863	50 days at 80° 1115
8	B	8	61-1	24	212	110.0	16.9	1772	2890	493	1050	46 days at 80° 1535
9	B	4	61-1	12	1000	113.5	14.8	1175	- -	358	676	28 days at 140° 1605
10	B	4	61-1	12	1400	112.3	17.4	1230	- -	285	779	
11	B	4	61-1	12	1700	114.7	16.3	1398	- -	318	1018	
12	B	2	61-1	12	1700	114.3	15.3	628	- -	350	- -	
13	B	8	61-1	12	1700	110.3	15.5	1407	- -	397	- -	
	A	4	- -	0	- -	97.6	20.9	421	493	219	326	
	A	4	61-1	12	212	95.0	22.2	405	533	282	425	
	A	4	61-1	24	212	93.7	25.6	485	596	254	- -	
	A	8	61-1	12	212	91.3	28.6	485	- -	- -	- -	3 days at 80° 135
	C	4	61-1	24	212	97.2	21.0	310	652	302	- -	19 days at 80° 437

See note on next page pertaining to Table 4.

Note: (Table 4) * This mix contained Type N Dolomitic Lime, supplied by the Rockwell Lime Company, whereas all the other mixes contained Type N, High Calcium Lime, supplied by the Cutler Magner Company.

Table 5

Unconfined Compressive Strength Values and Freezing Resistance Indexes for Lime-Volcanic Ash Stabilized Mixes

Mix No.	Soil	Lime %	Ash Type	Ash %	Ash Temp. F	Pc 3 days at 140° 4 days at 80° 12 days soak	Pf	Index R_f	Pc 7 at 80 12 soak	P_f	Index	Pc 28 at 80 12 soak	Pf	Index
1	B	0	- -	0	- -	0			0			0		
2	B	4	- -	0	- -	413	477	115	178	0	0			
3	B	8	- -	0	- -	430	0	0	167	0	0			
4	B	4	61-1	12	212	938	748	79.7	446	0	0	700	771	110
5	B*	4	61-1	12	212	842	826	98.1	580	461	79.5	- -	- -	
6	B	4	61-1	24	212	- -	- -	- -	628	406	64.6	795	843	106
7	B	8	61-1	12	212	1208	985	81.4	477	111	23.3	- -	- -	
8	B	8	61-1	24	212	1573	1105	70.2	699	477	68.2	- -	- -	
9	B	4	61-1	12	1000	1065	819	77.0	461	95	20.6	- -	- -	
10	B	4	61-1	12	1400	953	1065	111.5	453	0	0	691	635	92.0
11	B	4	61-1	12	1700	1113	1208	108.5	612	270	44.2	691	795	115.0
12	B	2	61-1	12	1700	493	326	66.2	334	0	0	- -	- -	
13	B	8	61-1	12	1700	1290	1017	78.7	525	278	52.9	- -	- -	
						3 days at 140° 4 days at 80° 6 days soak								
	A	4	- -	0	- -	255	231	90.4	- -	- -				
	A	4	61-1	12	212	302	262	86.7	- -	- -				
	A	4	61-1	24	212	- -	- -							
	A	8	61-1	12	212	- -	- -							
						8 soak								
	C	4	61-1	24	212	254	255	88.5	326	112	34.4			

Note: * This mix contained Type N, Dolomitic Lime whereas the other mixes contained Type N, High Calcium Lime.

Table 6

Dry Density, Optimum Moisture and Unconfined Compressive Strength Values For Soil-Cement Mixes

Soil No.	Cement % by wt. of oven-dry soil	Ash % by vol. of cement	Ash Type	Ash Temp. F	Dry Density pcf	Opt. Moist. %	7 day str. psi	21 day str.	35 day str.	7 days at 80 F 12 days soak P_c	7 days at 80 F 12 cycles Freeze-Thaw P_f	Index R_f
D	7	0	- -	- -	127	8.6	588	683	732	588	453	77
D	4.55	35	61-1	212	126	9.6	397	513	557	509	0	0
D	4.55	35	61-1	1700	126	10.2	389	345	421	429	0	0

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Appendix I

LOCATION AND DESCRIPTION OF SAMPLES FROM LINTON AREA

Sample No. 61-1

NE SE Sec. 21, 133 N, 76 W (0.3 miles north of junction of Sections 21, 22, 27 and 28)

Blocky, volcanic ash exposed in recent cut on west bank of road. The exposure is 12 feet thick with 1 foot of overburden. This same material is exposed in the ditch on the east side of the road. Traveling north on this road there is volcanic ash exposed in the ditches on both sides for 0.2 miles, and at the 0.2 mile point there is a 4 foot cut on the west side of the road. This cut is the last exposure visible going north on this road. At a point 1 mile north of sample 61-1 there is a 12 foot cut exposing brown sandstone with iron concretions and staining.

Sample No. 61-1-A

SW NE Sec. 21, 133 N, 76 W

A 15 foot outcrop with 3 feet of overburden is exposed for 500 feet along the west bank of a creek, and is about 600 feet west of a farm house.

Sample 61-2

SW NE Sec. 10, 132 N, 76 W

Blocky, volcanic ash from 6 foot exposure in hill in pasture of Geo. J. Horner. There is 2 feet of overburden. This same material is visible at the surface around the entrance to numerous gopher holes in the pasture.

Sample No. 61-3

SW SE Sec. 15, 133 N, 76 W

A 6 foot cut on the north side of road 0.4 miles east of bridge over Spring Creek. From the bridge to this cut, volcanic ash is visible at the road surface. There is another exposure on the west bank of the creek for 600 feet north of the bridge. This has a thickness of 15 feet with 6 feet of overburden.

Sample No. 61-3-A

NW Sec. 22, 133 N, 76 W

Volcanic ash exposed for 300 feet on west bank of Spring Creek just south of the barn on a farm on the east side of the road. There is 15 feet exposed with 6 feet of overburden.

Sample No. 61-4

NW SW Sec. 23, 133 N, 76 W

A 6 foot exposure on the east side of primitive road cut, and extending along the cut for 150 feet, with 1 foot of overburden. The cut is 0.3 miles north of an east-west road. At a point 0.3 miles west of this primitive road there is a 6 foot exposure. Also, it is exposed in a cut on both sides of the road 0.4 miles west of the primitive road. At a point 0.7 miles west there is an 8 foot exposure with 2 feet of overburden on the south side of the road. The same volcanic ash is visible in 2 hills a few hundred feet to the south of the last exposure.

Sample No. 61-5

NE NE Sec. 17, 132 N, 76 W

Blocky volcanic ash near top of a butte SE of Linton. There is 20 to 25 feet of ash exposed with a 6 foot sandstone cap.

Sample No. 61-6

NE NE Sec. 17, 132 N, 76 W

A 20 foot exposure in another butte about 1000 feet east of the one containing Sample No. 61-5. This butte has a 40 foot sandstone cap.

Sample No. 61-7

NW NW Sec. 15, 132 N, 76 W

A 12 foot seam exposed at top of a butte and with 2 feet of overburden. Located in the pasture of Geo. J. Horner.

Sample No. 61-8

SW NW Sec. 11, 132 N, 76 W

A 12 foot seam in road cut on north side of farm road to Mike Singer's farm. There is 2 feet of overburden. Also visible from this location is an exposure at the boundary of sections 2 and 11.

Sample No. 61-9

NW SW Sec. 13, 132 N, 76 W

A 12 foot exposure of ash with 15 feet of brown sand above and an additional 15 feet of overburden. This is located on the west side of a road cut located 0.4 miles north of Highway No. 13. At a point on this same road, but 0.6 miles north of Highway 13, there is a 4 foot exposure with 6 feet of overburden. At 0.75 miles there is another exposure, as well as at the 0.8 and 0.9 mile points.

Sample No. 61-9-A

SW NE Sec. 14, 132 N, 76 W

An 8 foot exposure with 4 feet of overburden on north side of road. At a point between 0.3 and 0.35 miles to the east is a 4 foot seam.

Sample No. 61-9-B

NW SE Sec. 14, 132 N, 76 W

A 15 foot bed near top of two buttes and with 6 feet of overburden. These buttes are north of Highway No. 13.

Sample No. 61-10

SW SW Sec. 4, 132 N, 76 W

A 12 foot exposure on the west side of a hill in a pasture and located about 800 feet east of the road. There is 1 to 2 feet of overburden.

Sample No. 61-10-A

NE SE Sec. 5, 132 N, 76 W

At the Linton city dump, volcanic ash was dug out 6 feet below the surface in a trench 500 feet long and 8 feet wide.

Sample No. 61-10-B

SW NW Sec. 2, 132 N, 76 W

A 5 foot exposure in a cut on the north side of the road, and with no overburden.

Sample No. 61-10-C

SE NE Sec. 1, 132 N, 76 W

A 3 foot exposure on the south side of road in a cut which is located 0.2 miles east of a small bridge.

Sample No. 61-11

SE NE Sec. 6, 132 N, 75 W

A 6 foot exposure in cut on south side of road, with 12 feet of sand and 10 feet of overburden.

Sample No. 61-12

SE NW Sec. 32, 133 N, 76 W

Sample taken 2 feet below surface in farm yard of Valentine Vetter, and with 6 inches of overburden.

Sample No. 61-13

NW NW Sec. 7, 132 N, 76 W

A 20 foot exposure with no overburden on west side of a butte. It is underlain by dark gray shale. There is another exposure in SE SE Sec. 1, 132 N, 77 W, and this seems to be the last exposure west of Linton.

Additional exposures

SW NW Sec. 27, 133 N, 76 W

On east side of road, 0.4 miles south of bridge.

NE NW Sec. 34, 133 N, 76 W

Exposure on west side of hill in a pasture.

SE NW Sec. 33, 133 N, 76 W

A 12 foot exposure at top of east side of a butte, and with 3 feet of overburden.

Appendix II

LOCATION AND DESCRIPTION OF SOIL SAMPLES

Sample No. A

SE SE Sec. 2, 162 N, 53 W

Black sticky soil with gravel mixed, taken from top 6 inches of west-east county highway, one mile east of town of Bathgate, N. D. This same material has been mixed in place with 5 per cent lime for a stabilized base.

Sample No. B

SE Sec. 4, 138 N, 89 W

Material typical of the gravel found south and west of the Missouri River. Sample taken from North Dakota State Highway Dept. stockpile at Eagles Nest. Owners of pit are John and Joseph Wanner.

Sample No. C

NW SW Sec. 9, 153 N, 53 W

Gravel mixed with black gumbo, taken from top 6 inches of street in Gilby, N. D.

Sample No. D

NW SW Sec. 11, Middle River Township, Marshall County, Minnesota

A pit run sand taken from pit near Argyle, Minn. and used to mix with 7 per cent cement for 10 miles of soil-cement.