Evaluation of Phosphoric Acid for Stabilization Of Fine-Grained Plastic Soils

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A laboratory study was made on the effectiveness of phosphoric acid in improving the engineering properties of six fine-grained plastic soils. The properties studied include plasticity, moisture and density relations, volume change, and unconfined compressive strength. The acid was applied at rates up to 4 percent of the weight of dry soil. Tests were also made using 0.5 percent of an amine compound as a supplement to the acid. In general, plastic properties were moderately affected, and there was little change in moisture-density relationships. Pronounced increases in unconfined compressive strength of soaked specimens were obtained for most of the soils when treated with acid alone, and slight additional increases resulted when the amine was also used. Volume change, as measured for five of the soils, was reduced to a level considered satisfactory. Using 2 percent of the acid and 0.5 percent of the amine, a compressive strength of 184 psi was obtained for the Penn soil, which had no strength before treatment. Although strength gains for two of the remaining soils were not of practical magnitude, gains for the other three were quite sufficient to indicate that phosphoric acid offers considerable promise as a stabilizer for a wide variety of fine-grained plastic soils.

● IN 1954, the Bureau of Public Roads, in an effort to stimulate interest in the development of chemical products for use in the stabilization of soils, invited chemical manufacturers to aid in the search for suitable chemicals. Agreements were made with a number of companies under which chemicals would be subjected to preliminary laboratory testing by the manufacturer and, if found promising, submitted to the Bureau for further laboratory testing and possible subsequent recommendation to State highway departments for full-scale trials in the field. As a result of this program, phosphoric acid was proposed by the Monsanto Chemical Company and tested for use in the stabilization of fine-grained plastic soils.

This paper presents some of the results of the laboratory evaluation of phosphoric acid conducted by the Bureau of Public Roads between 1955 and the present time.

The successful use of phosphoric acid with one fine-grained plastic soil was first reported by Lyons (1), who obtained for compacted soil specimens containing about 2 percent of the acid, unconfined compressive strengths ranging from 110 to 200 psi, depending on the length of the curing period. Lyons also found that the addition of 0.5 percent or less of a compound identified as Amine ODT facilitated mixing, practically eliminated the critical dependence of the strength of the soil on the water content at the time of compaction, and rendered the soil water-resistant early in the curing period. Michaels, Williams, and Randolph (2), working with five soils of varying texture, also obtained substantial increases in unconfined compressive strengths as a result of treatment with phosphoric acid or its equivalent of phosphoric anhydride, and with a number of other acidic phosphoric compounds. The latter authors also found that a small amount of a primary aliphatic amine would accelerate curing and improve strength retention on water immersion, although ultimate strengths were somewhat reduced. Michaels and Tausch (3) in studying supplementary additives for improving or reducing the cost of the stabilizing soils with phosphoric acid, found orthorhombic phosphorous pentoxide and phosphate rock plus sulfuric acid to be effective. They also found that, supplemental to phosphoric acid treatment, ferric chloride and octylamine were effective in waterproofing soils. Demirel, Benn, and Davidson (4) found phosphoric acid to increase the unconfined compressive strengths of a number of soils, and showed that calcium carbonate in soils reduced or eliminated strength gains because of the consumption of the acid by the carbonate.

EXPERIMENTAL WORK

The experimental work by the Bureau of Public Roads was conducted with two grades of liquid phosphoric acid, which were supplied by Monsanto Chemical Company: reagent grade furnace acid containing 85 percent H_3PO_4; and "wet process" acid containing 40 to 45 percent H_3PO_4. In preliminary tests, wet process acid was found to produce higher values of unconfined compressive strength in soil-acid mixtures than the reagent grade and was therefore used exclusively in subsequent testing. An organic compound identified as SA-4 amine, used as a supplementary additive, was also supplied by Monsanto Chemical Company.

The characteristics of the experimental soils are given in Table 1. Table 2 lists the tests applied to the raw soils and, except for the mechanical analysis test, also to the soil-acid mixtures. Test values selected as criteria to evaluate whether a given soil had been satisfactorily improved by the stabilizing treatment are also listed in Table 2.

Mixtures of soil, water, and the chemicals were prepared with a mechanical mixer. Air-dry soil was placed in the mixer bowl and the calculated amount of chemical in water solution was slowly added while the mixer was in operation. The mixing time was 5 min. Atterberg limit tests were performed on a portion of the mixture cured in a high humidity chamber at room temperature for 8 days. Volume change specimens were made and tested in accordance with AASHO T 116. Triplicate cylindrical test specimens 2 in. in diameter and 4 in. in length were compacted at maximum dry density and optimum liquid content. Moisture absorption

TABLE 1

CHARACTERISTICS OF EXPERIMENTAL SOILS

Soil[1]	Clay Mineral	pH	$CaCO_3$ (%)	Passing Sieve No 10 (%)	No. 40 (%)	No. 200 (%)	Silt 0.05-0 005 mm (%)	Clay <0 005 mm (%)	Liquid Limit	Plasticity Index	Max Dry Density[2] (pcf)	Opt Moist[2] (%)	AASHO Class
Penn	Illite and chlorite	5.0	0	100	81	62	28	45	48	22	110	18	A-7-6(11)
Jordan	Montmorillonite	7.6	10	100	99	91	44	36	34	10	100	21	A-4(8)
Keyport	Montmorillonite	4 6	0	100	93	62	21	36	46	24	111	17	A-7-6(12)
Pierre	Montmorillonite	7 0	0	100	99	98	34	61	79	46	92	26	A-7-5(20)
Hagerstown	Kaolinite and illite	5.4	0	100	99	98	25	72	78	48	91	27	A-7-5(20)
Sassafras	Kaolinite and vermiculite	5 7	0	100	94	75	23	49	48	23	108	19	A-7-6(15)

[1]Penn soil from C horizon, others from B horizon.
[2]AASHO T99-57, Method A.

TABLE 2

TESTS AND CRITERIA FOR EVALUATING NEW SOILS AND SOIL-ACID MIXTURES

Test	AASHO Designation	ASTM Designation	Test Value for Satisfac. Matl.
Mechanical analysis	T 88	D 422	-
Liquid limit	T 89	D 423	Not over 30
Plastic limit	T 90	D 424	-
Plasticity index	T 91	D 424	Not over 6
Compaction	T 99-57	D 698-58	-
Volume change	T 116	-	Not over 2½ percent
Moisture absorption	-[1]	-[1]	Not over 2 percent
Unconfined compressive strength	-[2]	-[2]	100 psi or greater

[1]See text.
[2]Rate of loading in testing machine = 0.05 in. per min.

and unconfined compressive strength were measured for each of these specimens after the specimen was cured for 5 days at room temperature and high humidity and immersed in water for 2 days. If an immersed specimen showed no evidence of slaking, it was surface-dried and weighed to determine the moisture absorption. If complete disintegration of the specimen occurred, measurements of both moisture absorption and compressive strength were naturally obviated, and if there was more than a trace of slaking, the moisture absorption could not be accurately measured. After soaking and weighing, the specimens were tested for unconfined compressive strength.

The 2- by 4-in. cylindrical specimens were prepared by an impact compaction device similar to that developed by the U.S. Waterways Experiment Station (5). This device employs a 4-lb hammer with a 12-in. drop. Depending on the type of soil used, from 8 to 14 blows were required to produce specimens having the same maximum density as obtained in the AASHO T 99 standard method.

RESULTS AND DISCUSSION

Data in Table 3 show the effects of three rates—1, 2, and 3 percent—of phosphoric acid, with and without 0.5 percent of SA-4 amine, on the unconfined compressive strength

TABLE 3

EFFECT OF CONCENTRATION OF PHOSPHORIC ACID ALONE, AND WITH SA-4/ AMINE ADDITIVE, ON THE UNCONFINED COMPRESSIVE STRENGTH OF THREE SOILS

Treatment[1]		Unconfined Compressive Strength of Soil		
Acid (%)	Amine (%)	Keyport (psi)	Jordan (psi)	Penn (psi)
0	0	0	0	0
1	0	75	13	-[2]
2	0	113	15	170
3	0	156	14	202
1	0.5	78	-[2]	-[2]
2	0.5	118	34	184
3	0.5	165	-[2]	226

[1]Based on dry weight of soil (110 C).
[2]Not determined; insufficient material for test.

TABLE 4

EFFECT OF PHOSPHORIC ACID AND SA-4 AMINE ON THE PROPERTIES OF SIX SOILS

Soil	Acid (H_3PO_4) (%)	Amine (%)	Unconf. Compress. Str. (psi)	Vol. Change (%)	Moist. Absorp. (%)	Opt. Moist. (%)	Max. Dens. (pcf)	Liquid Limit	Plastic Limit	Plasticity Index
Penn	0	0	0	9.7	-[2]	18	111	48	26	22
	2	0	170	-[1]	1.0	17	114	-[1]	-[1]	-[1]
	2	0.5	184	-[1]	0.1	18	111	-[1]	-[1]	-[1]
Jordan	0	0	0	9.0	-[2]	20	104	34	24	10
	2	0	15	1.1	2.4	23	101	40	24	16
	2	0.5	34	1.5	2.9	23	99	36	25	11
Keyport	0	0	0	9.2	-[2]	17	111	46	22	24
	2	0	113	1.5	1.0	15	114	43	22	21
	2	0.5	118	0.3	1.2	18	110	40	24	16
Pierre	0	0	0	21.7	-[2]	26	92	79	33	46
	2	0	2	0.7	-[2]	24	91	68	34	34
	2	0.5	8	1.2	-[2]	25	91	56	36	20
	4	0	28	-[1]	7.0	24	92	56	35	21
	4	0.5	77	-[1]	6.0	25	91	50	36	14
Hagerstown	0	0	5	3.9	4.2	27	91	78	30	48
	2	0	37	-[1]	0.7	26	88	52	30	22
	2	0.5	38	-[1]	3.9	26	86	51	33	18
Sassafras	0	0	31	1.0	1.0	19	108	48	25	23
	2	0	74	0	0.2	20	107	33	22	11
	2	0.5	85	0	1.1	20	103	35	25	10

[1]Insufficient material for test.
[2]Specimen completely or partially disintegrated when immersed.

of soaked specimens of three soils. There was considerable strength development with Keyport and Penn soils, the effect increasing with increasing rates of acid. In contrast, very little strength was developed with the Jordan soil. This may be largely attributed to the calcium carbonate content of this soil, which is more than sufficient to prevent the desired soil-acid reaction and, therefore, the strength development (4). The strengths developed in Keyport and Penn soils with 2 percent of the acid more than meet the 100 psi criterion selected for this property. Small additional increases resulted from the addition of amine.

Inasmuch as satisfactory strengths were provided by 2 percent of the acid, this rate was used for most of the subsequent work. Data showing the effects of 2 percent of the acid on the properties of several soils are given in Table 4. In the case of the Pierre soil, a 4 percent rate of acid was also used and, for all of the soils tested, data were also obtained for treatment with 2 percent of acid plus 0.5 percent of amine.

The effectiveness of the acid is seen to vary considerably, depending on the soil and the specific property under consideration. Values of compressive strength obtained with the Penn and Keyport soils were well over the selected criterion of 100 psi, but were slightly less (74 psi) for the Sassafras soil, considerably less for the Jordan and Hagerstown soils, and very low (for the 2 percent rate) with the Pierre soil. Volume change and moisture absorption values were in most cases brought to satisfactory levels. Maximum density, optimum moisture, and the plastic limit were not greatly affected for any soil tested. Marked reductions in the liquid limit were obtained for the Pierre, Hagerstown, and Sassafras soils, but there was very little effect with the Keyport soil and the liquid limit of Jordan soil was actually raised slightly. Inasmuch as addition of the acid had little effect on the plastic limit, the changes in plasticity index corresponded closely to the changes in liquid limit. The reduction in the liquid limit values of the Pierre soil at the low rate of acid application was accompanied by a large decrease in volume change, but there was little effect on other properties. The higher rate of acid further decreased the liquid limit and greatly increased compressive strength. These pronounced effects on the properties of the Pierre soil are particularly notable because it contains 61 percent of a high volume change clay (particles smaller than 0.005 mm).

The 0.5 percent amine supplement to the acid appreciably reduced the liquid limit of the Pierre soil, but there was little change in the plasticity values of any of the other soils. It also increased the compressive strength of all of the soils, but the effect was pronounced only with the Pierre soil. There was little effect of the amine on any of the other properties studied.

An additional experiment was performed with the Keyport soil to determine the importance of the time interval between the preparation of the soil-acid mixture and the molding of specimens. Compressive strengths obtained for ¼-, 6-, and 24-hr intervals were 104, 80, and 70 psi, respectively, indicating that for the development of maximum compressive strength, there should be very little delay between the mixing and compaction operations.

CONCLUSIONS

Phosphoric acid produced marked increases in the unconfined compressive strength of two fine-grained plastic soils, 2 percent of the acid bringing the strength to a level considered satisfactory for practical stabilization. With four other fine-grained plastic soils treated with 2 percent of the acid, strength development was unsatisfactory.

When calcium carbonate was present, the effectiveness of the acid was sharply reduced.

Values of volume change and moisture absorption were generally brought to satisfactory levels, but changes in moisture-density relations were slight.

For some soils, the liquid limit was greatly lowered, but for others, there was little effect. Plastic limits were practically unchanged. Consequently, changes in the plasticity index corresponded closely to changes in the liquid limit.

For most of the experimental soils, the addition of an amine compound moderately increased the compressive strength and produced moderate decreases in the liquid limit. With the highly plastic Pierre soil the amine caused a pronounced decrease in the liquid limit.

It was shown for one soil that the effectiveness of the acid in increasing compressive strength was appreciably reduced by too long an interval between the mixing and compaction operations.

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