

Phosphoric Acid in Soil Stabilization

This paper discusses the effect of phosphoric acid on several of the engineering properties of clay soils. Acid concentration, curing time, moisture-density relations, etc., are presented. This is followed by consideration of the different sources of acidic phosphate and a review of the effect of secondary additives. The mechanism of phosphoric acid stabilization is discussed from a wet-chemical viewpoint. The final part of the paper considers several variables that affect field application of the method; that is, extent of mixing, degree of compaction as percent of standard, etc. Two small test sections are described. The economics of phosphoric acid stabilization are reviewed.

1. Effect on Engineering Properties of Soils

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● IN RECENT YEARS much emphasis has been placed on the need for a chemical treatment to improve fine-grained soils for use in highway subgrade and base course construction (1, 2). Soils containing appreciable amounts of clay minerals generally require some form of stabilization because of the tendency to deteriorate structurally in the presence of excess water. Thus, many clay soils swell markedly in water and lose all, or nearly all, of their ability to support loads of the type encountered in highway or airport use. The alternative to stabilizing these clay soils is removing them and/or interposing a layer of select soil or aggregate beneath the surfacing. This layer of additional material is taken to be sufficiently thick so that the underlying clay soil is not considered at all or only slightly in the structural design. The cost of placing this select material is becoming prohibitive in many areas where sources are distant from the construction site. The need for an economical stabilizer for such clay soils has been growing more acute as construction activity increases. Furthermore, designs have become more stringent because of greater anticipated service requirements.

Phosphoric acid has been shown, in the laboratory, to be a suitable stabilizer for clay soils (3, 10). This series of papers presents laboratory data (some limited field experience is included, but large-scale field testing will be reported separately) showing the effect of several variables on the stability of soil treated with phosphoric acid. Among these variables are moisture content, degree of compaction, degree of mixing and curing, amount of stabilizer, type of soil, and type of exposure. In the second part of the series, the effect of secondary additives, type of phosphoric acid source, and mechanism of stabilization will be discussed. The third part will cover permanency, corrosion, and limited field test work, which led to construction of full-scale test roads. The economics of phosphoric acid treatments will also be reviewed in the third part.

EXPERIMENTAL FACTORS

Atterberg indices were determined by ASTM Procedures D423-39 and 424-39. Tests on stabilized soil were made after humid curing (usually for 5 days at room temperature and 100 percent R.N.), and pulverization with a rubber-covered pestle.

Standard or reference compaction curves were run according to AASHTO T 99-49. Other compaction curves were prepared using a 2- by 4-in. specimen size in a device to be described.

Group index was calculated from the Atterberg indices and results of wet sieving on a No. 200 sieve using the relation shown in AASHTO M 145-49

Unconfined compressive strength and volume change data were obtained from specimens prepared and treated in the following way:

1. Air-dry soil passing the No. 4 sieve was placed in a muller-and-plow mixer; water and chemicals were added to the running machine. Liquids were added with the water; solids were premixed with the air-dry soil unless otherwise noted. The mixer was run for exactly 5 min after chemical and water addition.

2. The mixture was cured under a wet cloth for exactly 15 min after mixing was stopped.

3. An amount of the mixture calculated to give a compacted specimen height of 4.0 ± 0.1 in. was compacted in a 2-in. diameter mold with a 4-lb hammer falling through a distance of 12 in. The number of blows per each of 4 layers of soil was correlated to compaction curves obtained by AASHTO T 99-49 (varying from 6-12 blows per layer). After the first few blows were applied, a wedge was removed from beneath the mold and a lower piston thereby exerted pressure from below with every succeeding blow. (This so-called double-end compaction gave somewhat more uniform densities from top to bottom of each layer.)

4. The compacted specimens were measured, weighed, wrapped in a moisture barrier (Saranwrap), and stored in a humidity chamber at room temperature. The usual curing time was 5 days.

5. The samples were unwrapped, remeasured and reweighed, and immersed totally in water for 2 days. After immersion the samples were briefly drained, remeasured and reweighed, and tested for unconfined compressive strength in a Soiltest AP-170 machine modified to give a rate of strain of 0.25 in. per min. Volume change was computed from the before and after measurements; water absorption, by the weight change.

Test soils were generally air-dried and reduced to $-1/4$ -in. size by tamping or by

TABLE 1
CHARACTERISTICS OF THE TEST SOILS

Soil	Source	Liquid Limit	Plasticity Index	Opt Moist (%)	Max Dry Density (pcf)	Class
Keyport clay loam	Va	46	24	18.7	111.9	A-7-6(12)
Cecil clay loam	Ga ^a	56	25	25.6	95.5	A-7-5(17)
Clay loam	La	32	13	15.2	114.0	A-6(8)
Silty clay loam	La	36	19	15.0	114.0	A-6(10)
Putnam silty clay loam	Mo	40	19	18.1	108.2	A-6-(9)
Putnam clay	Mo	53	35	25.0	95.4	A-7-6(20)
Clay	Creve Coeur, Mo	43	23	17.0	109.7	(14)
Clay	Md	73	44	24.0	94.4	A-7-5(20)
Clay	Md	48	25	18.3	110.0	A-7-6(16)
Clay loam	Co	-	-	15.5	114.5	-

^aSome 17 samples of Cecil clay soils have been received from Georgia and tested. This is a typical material.

cutting in a Fitzmill (with little or no pulverization of stony material or of sand permitted). The chemicals used were of a reagent grade. Distilled water was used throughout.

RESULTS

Test Soil Properties

Table 1 gives the characteristics of the soils used in this work. Of these soils, a great deal of work has been done with the Keyport clay loam, and a considerable amount with the Georgia and Missouri soils. Only cursory studies have been made on the others. The soil from Colorado was a highly alkaline sample (pH 8-9), perhaps not typical of all soils west of the Mississippi, but indicative of many soils of that region. Two other samples from Colorado have been studied with results quite similar to those reported for this sample. Two other soils from Louisiana have been studied

briefly, with results similar to those given for the A-6(8) clay loam from that state.

Group Index

Table 2 shows the effect of phosphoric acid on the group index of Putnam clay. A substantial lowering of this index means that the treated soil is much improved as a material of construction. The phosphoric acid treatment reduces the group index by more than half in this particularly plastic and heavy clay.

TABLE 2
EFFECT OF PHOSPHORIC ACID ON GROUP INDEX OF PUTNAM CLAY^a

Treatment	% Passing No. 200 Sieve	Liquid Limit	Plasticity Index	Group Index
Untreated	85.3	75	55	20
1% H_3PO_4	79.7	51	24	16
2% H_3PO_4	68.4	47	19	11
3% H_3PO_4	60.4	45	17	8
4% H_3PO_4	60.3	47	18	9

^aCompacted specimens humid-cured 5 days, immersed 2 days in water, air dried, and repulverized. Samples moistened with water and held overnight before testing to insure equilibration.

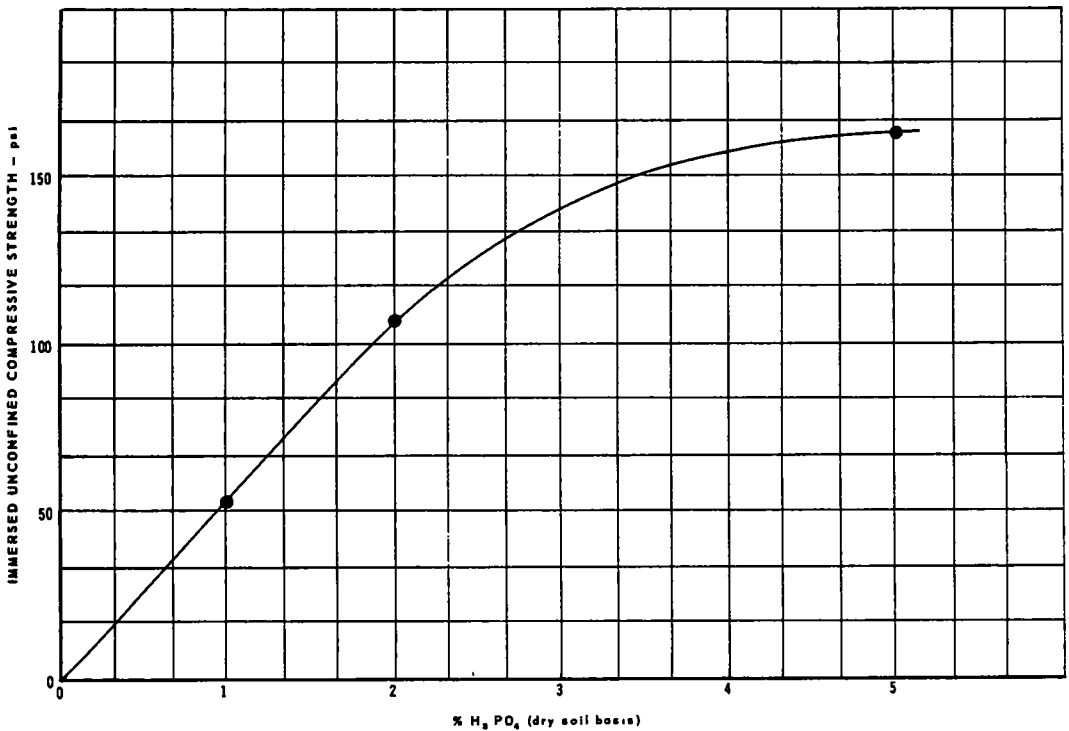


Figure 1. Strength vs phosphoric acid concentration—samples cured at 100 percent R. H. and room temperature 5 days, immersed in water 2 days; Keyport clay loam A-7-6 (12); 2- by 4-in. cylinders, 12 blows per each of 4 layers.

Acid Concentration and Curing Time Before Exposure

Addition of phosphoric acid to clay soil results in an almost linear increase in immersed strength up to about 2 percent H_3PO_4 (based on dry soil weight). Figure 1 shows the strength increases only slowly with greater amounts of acid when the samples are cured just 5 days before immersion. As acid concentration is increased, longer curing times are needed for the formation of the cementing substances (see mechanism discussion in Part II). Thus, Figure 2 shows linear strength increase up to nearly 5 percent H_3PO_4 when curing is extended to 30 days. (Difference in compactive effort in Figs. 1 and 2 is apparent.)

Figure 3 (compaction same as in Fig. 1, greater than in Fig. 2) shows the effect of curing time on immersed strength for a soil treated with 2 percent H_3PO_4 . It is clear that the gain in strength is very rapid in the first week, somewhat slower during the next three weeks, and much slower thereafter.

Effect of Compaction

The effect of phosphoric acid on the moisture-density or compaction curve of a soil is of importance to the engineer in designing construction procedures and specifications. Figure 4 shows untreated and treated curves for 4 test soils where dry density is plotted against the moisture content obtained by drying a portion of the soil at 105-110 C. This is not the same as plotting density vs liquid volume, as shown in Figure 5 in which the data of Figure 4 (c) are replotted on a liquid volume basis. In both sets of curves it may be seen that (a) the addition of phosphoric acid shifts the point of maximum dry density from the untreated control and (b) the optimum moisture content is also shifted, considerably in some cases. Density may be lowered with a 2 percent acid treatment

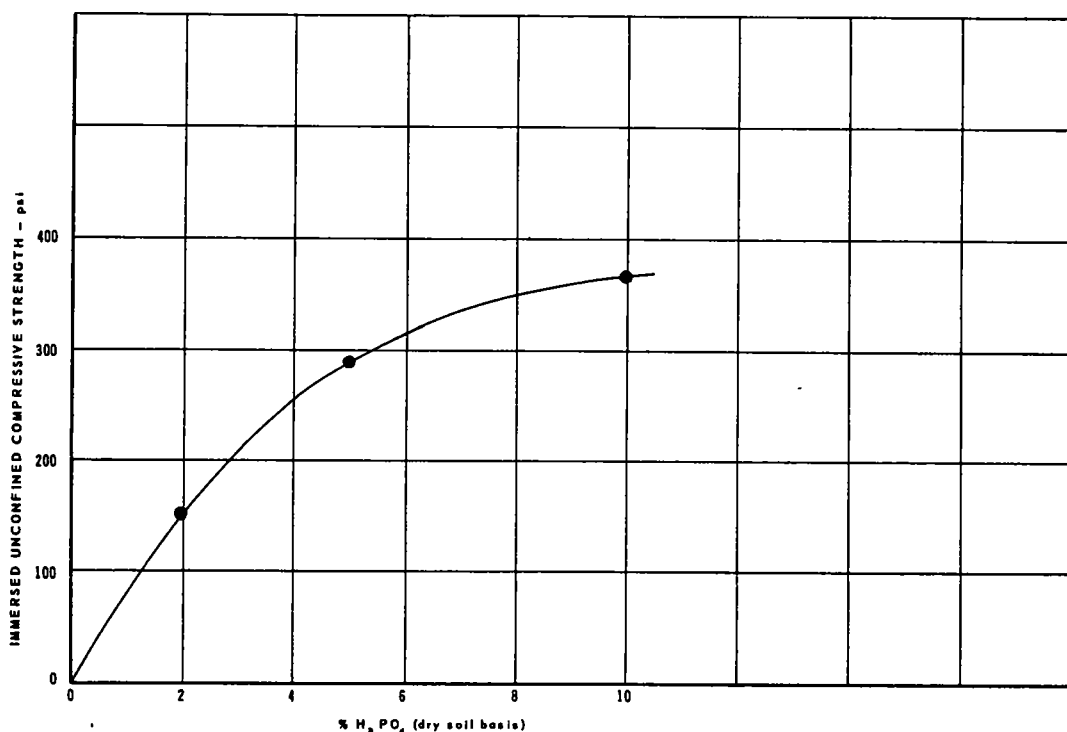


Figure 2. Strength vs phosphoric acid concentration—samples cured at 100 percent R. H. and room temperature 30 days, immersed in water 2 days; Keyport clay loam A-7-6 (12); 2- by 4-in. cylinders, 8 blows per each of 4 layers.

in soils in which the reaction is rapid. Because of the time lapse between mixing and compaction, rapid-hardening samples will be more difficult to compact than the corresponding untreated soils. Table 3 compares optimum moisture and maximum dry density in several soils with and without acid treatment. It points up the variations in effect that are encountered.

The data in Table 3 also point to another important aspect; i. e., that the moisture content for maximum immersed strength may not be at optimum moisture for compaction. Figure 6 shows both strength and dry density plotted against molding moisture for the two Maryland soils. Samples prepared at optimum moisture content for density may exhibit somewhat less than maximum strength. A change in acid concentration shifts the moisture content for maximum strength noticeably. This fact has led to the preparation of samples over a range of moisture contents for every preliminary screening test run in this laboratory. This is to make certain that the true maximum stability is observed.

Effect of Soil Type

Table 3 presents a condensation of test results that gives the effect of soil type on strength and compaction with and without phosphoric acid. With two exceptions (Louisiana silty clay loam and Colorado clay loam), the soils studied were very well stabilized with phosphoric acid. Only two of the soils exhibited any appreciable resistance to water without treatment—Louisiana clay loam (44 psi with no acid) and Maryland clay (35 psi with no acid). Both of these clays benefited markedly from phosphoric acid treatment, thereby upgrading them from a position of questionable utility. It appears that soils high in silt and low in clay (Louisiana silty clay loam) will not be

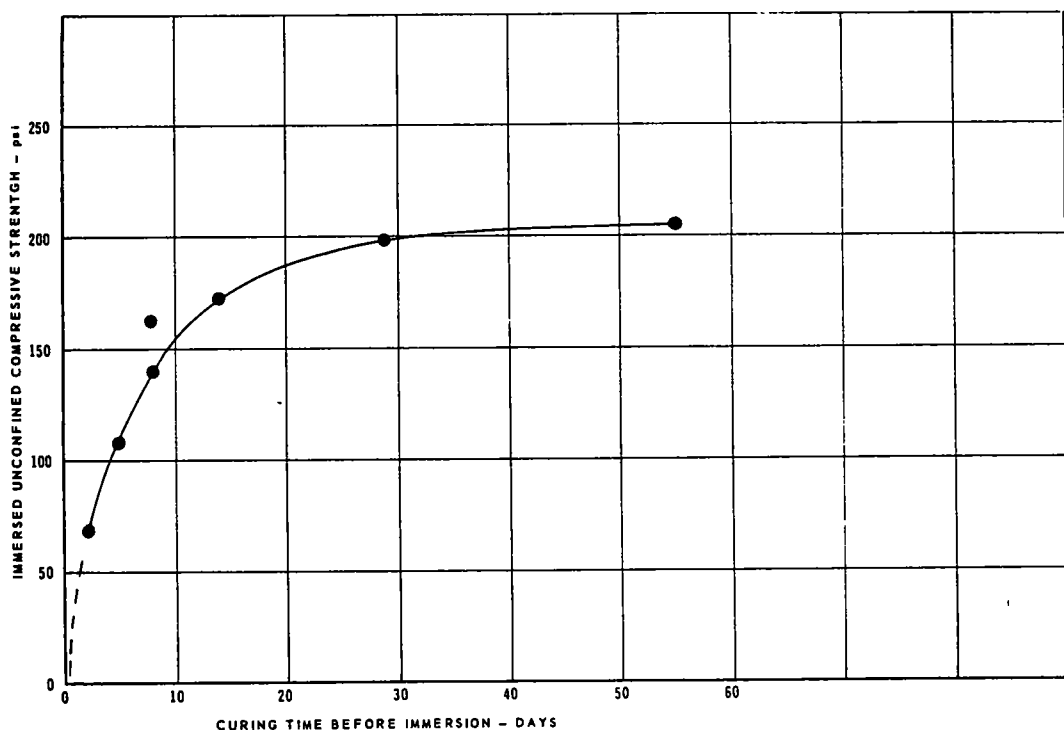


Figure 3. Immersed strength vs curing time—samples cured at 100 percent R. H. and room temperature, then immersed 2 days; Keyport clay loam A-7-6(12); 2 percent H_3PO_4 , 2- by 4-in. cylinders, 12 blows per each of 4 layers.

well stabilized by phosphoric acid alone, although some improvement is noted. Highly alkaline soils, such as the Colorado sample, require excessive amounts of acid for relatively inferior stabilization.

Some idea of the anticipated performance within a variable series of related soils can be obtained from Figure 7. This plot shows results for 13 samples taken at 100-ft intervals from a Georgia roadside. Samples from stations 1, 2, 3, 12, and 13 were quite similar in all respects. The intervening samples contained some partially disintegrated shale of a granular nature. The effect on compaction as expressed by

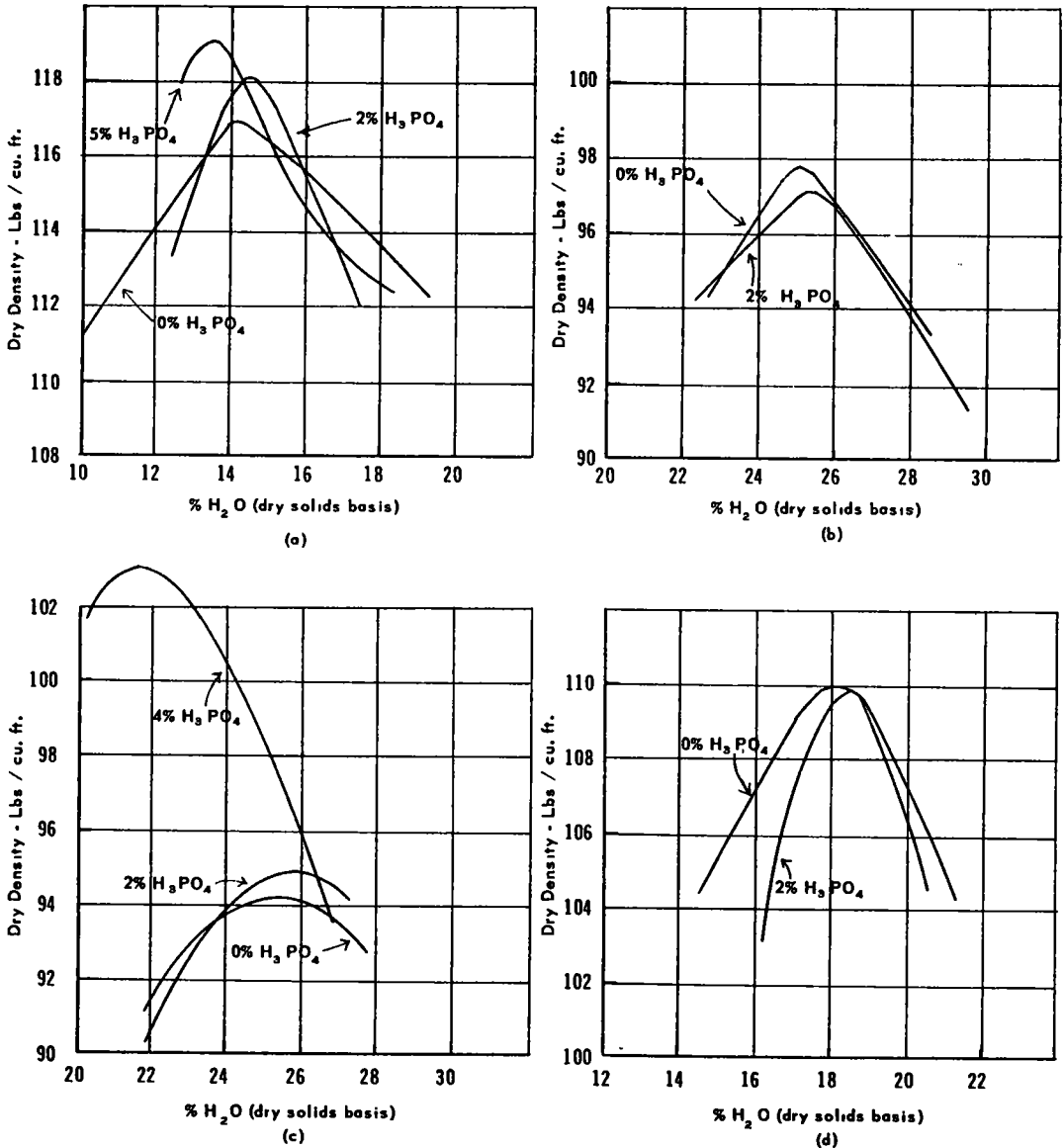


Figure 4. Dry density vs moisture content—2- by 4-in. cylinders compacted in 4 layers: (a) Keyport clay loam, A-7-6(12), 12 blows per layer; (b) Cecil clay loam, A-7-5(17), 8 blows per layer; (c) Putnam clay, A-7-6(20), 8 blows per layer; and (d) Clay, A-7-6(16), Maryland, 8 blows per layer.

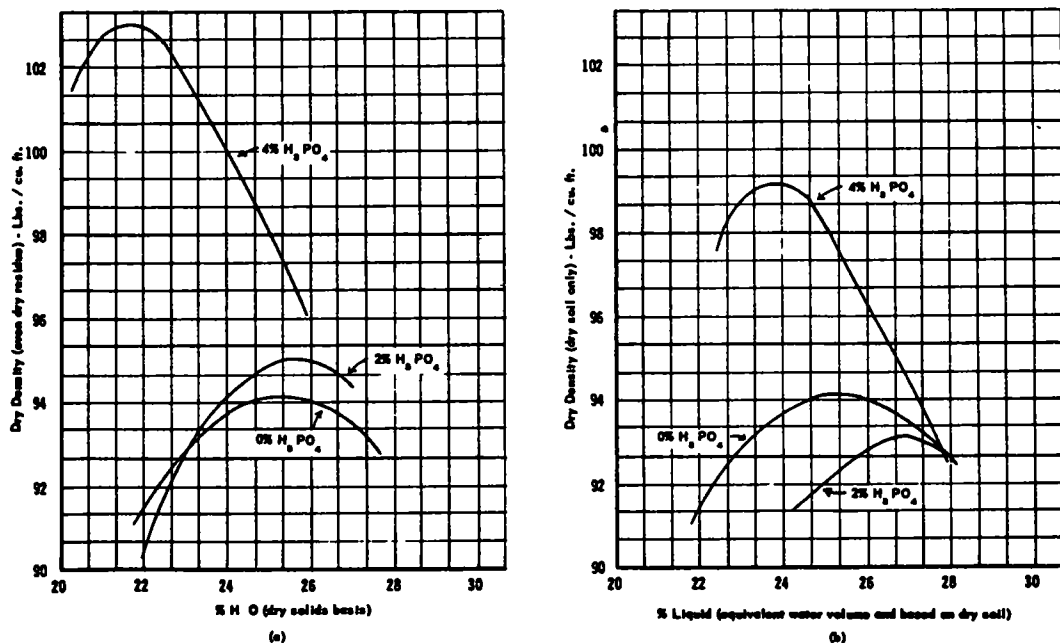


Figure 5. Compaction curves for Putnam clay A-7-6(20)-2- by 4-in. cylinders, 8 blows per each of 4 layers (a) as taken from volatile content in oven at 105-110 C and (b) subtracting the 100 percent H_3PO_4 from density and adding equivalent volume of water to liquid content (assuming 1 gr 100 percent $\text{H}_3\text{PO}_4 = 0.537 \text{ cc H}_2\text{O}$).

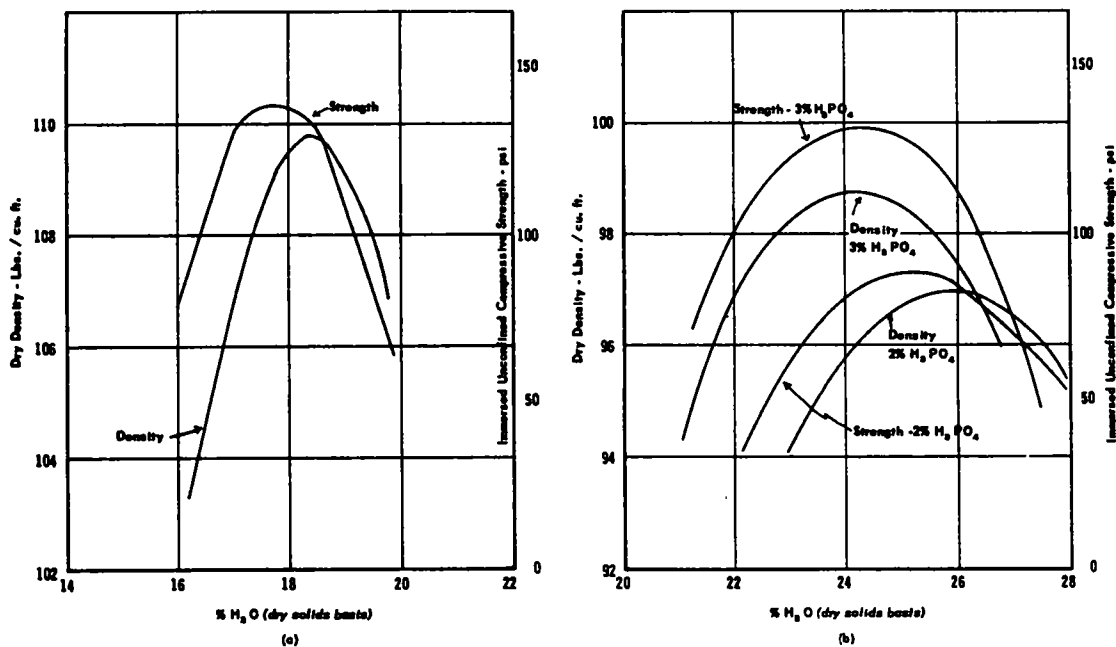


Figure 6. Immersed strength after 5 day humid cure and dry density vs molding moisture content for (a) clay from Maryland A-7-6(16) with 2 percent H_3PO_4 and (b) clay from Maryland A-7-6(20) (2- by 4-in. cylinders, 8 blows per each of 4 layers).

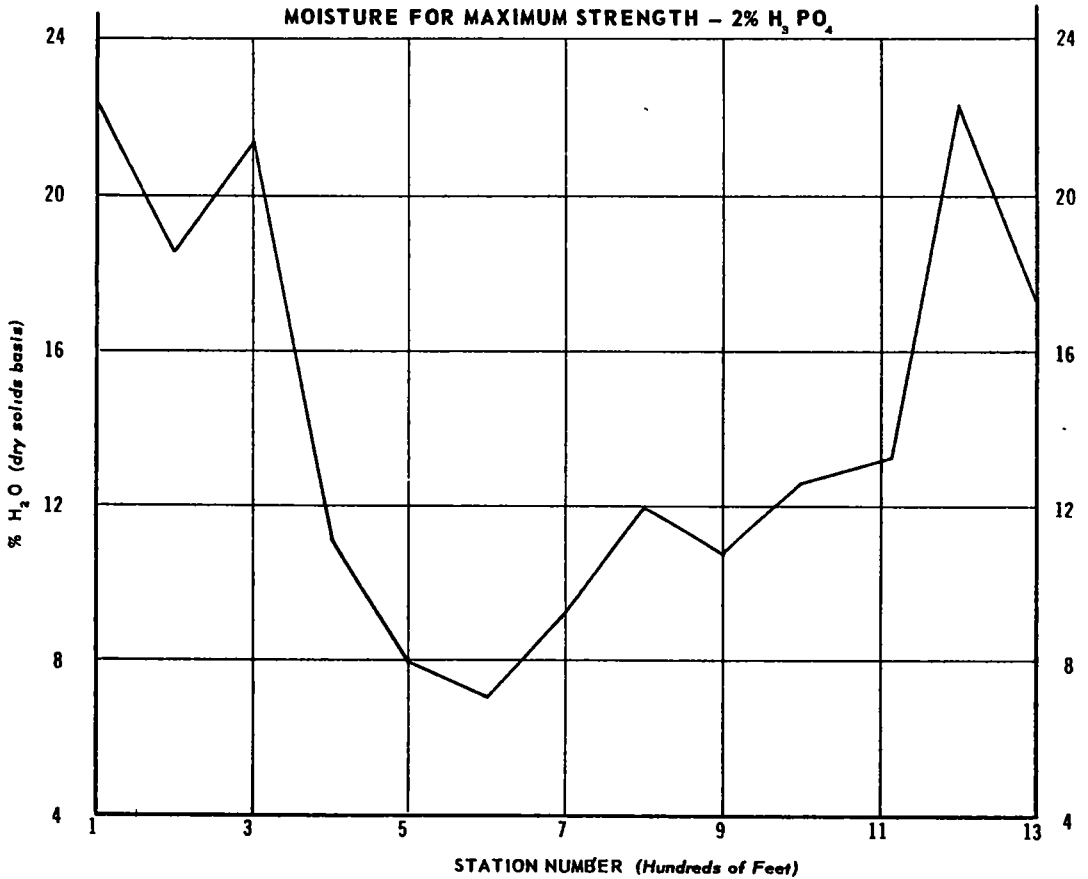
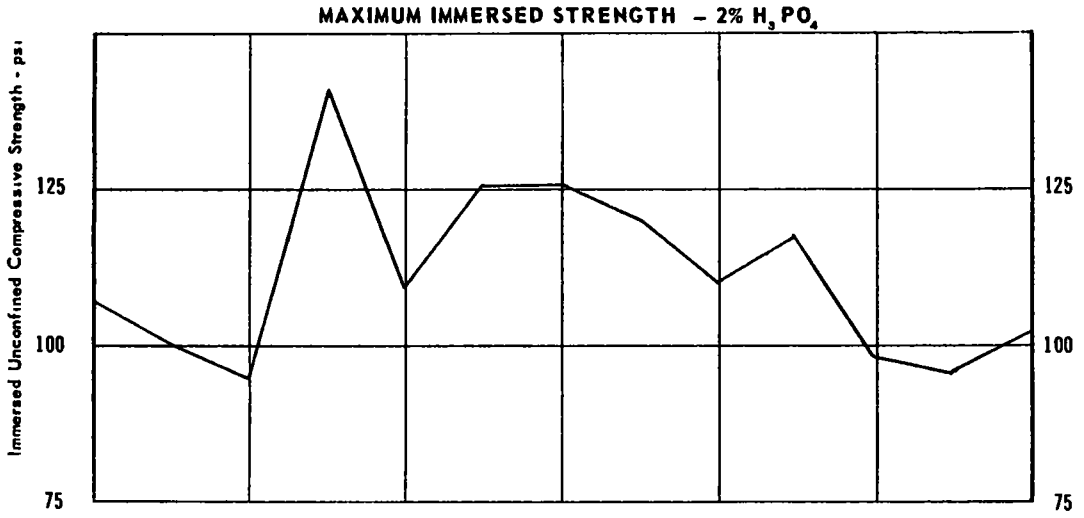


Figure 7. Maximum immersed strength after 5 day humid cure and moisture content for maximum strength vs location by station number (2 percent H_3PO_4 , 2- by 4-in. cylinders, 7 blows per each of 4 layers).

TABLE 3
EFFECT OF PHOSPHORIC ACID ON PROPERTIES OF COMPACTED SOILS^a

Soil	Degree of Compaction (blows/layer)	H ₃ PO ₄ (%)	Opt H ₂ O (%)	Max. Dry Density (pcf)	Curing Time (days)	Maximum Immersed Strength (psi)	H ₂ O for Max. Str (%)	Vol Change ^b at Opt. H ₂ O for Strength (%)
Keyport clay loam, A-7-6(12), Va	12 ^c	0	14.8	117	5	0	-	slaked
		1	14.9	117	5	53	16.4	0.0
		2	14.6	118	5	107	16.1	0.0
		5	13.6	119	5	162	14.7	0.5
	8 ^e	0 ^d	16.7	111.9	5	0	-	slaked
Cecil clay loam, A-7-5(17), Ga.	12 ^c	2	15.0	113.7	5	107	15.8	0.12
		0	21.9	102.8	5	0	-	slaked
	8 ^e	2	21.8	103.6	5	103	22.5	0.12
		0	25.2	97.7	6	0	-	slaked
Clay loam, A-6-(8), La.	12 ^c	2	25.5	97.0	6	104	25.4	0.12
		0	14.0	118.6	5	44	15.8	0.25
	24 ^c	2	13.0	121.2	15	210	12.1	0.0
		2	11.3	127.2	15	375	11.0	0.02
Silty clay loam, A-6-(10), La.	6 ^{3/4} ^e	0	16.5	113	5	12	18.8	8.0
		2	16.6	111.3	5	36	16.6	3.4
Clay, Creve Coeur, Mo	8 ^e	0	16.8	110.9	5	0	-	slaked
		2	16.3	111.3	5	154	16.6	0.0
Putnam silty clay loam, A-6-(9), Mo.	8 ^e	0	17.5	107.7	5	6	21.3	1.95
		2	17.8	106.9	5	117	17.6	0.0
Putnam clay, A-7-6(20), Mo.	8 ^e	0	25.3	94.1	5	1	-	64.0
		2	25.8	95.1	5	68	23.4	0.02
		4	21.7	103.1	5	93	22.0	0.56
Clay, A-7-5(20), Md	8 ^e	0	23.9	94.4	5	9	28.0	7.1
		2	26.0	97.0	5	89	25.1	0.12
		3	24.1	98.8	5	132	24.2	0.02
Clay, A-7-6(16), Md	8 ^e	0	18.3	110.0	5	36	19.2	0.02
		2	18.4	109.8	5	130	17.6	0.0
Clay loam, Col.	8 ^e	0	15.4	114.5	5	0	-	slaked
		2	15.5	112.7	5	7	17.6-19.1	20.5
		4	15.5	114.2	5	36	12.0 ^f	1.95

^aData obtained from complete curves, such as shown in Figures 4 and 6.

^bObtained by cubing the percent change in height obtained on immersed specimens.

^cCorrelated to a density between standard and modified AASHO; modified AASHO density referring to compaction via a 10-lb hammer falling through 18 in. instead of the standard 5-lb hammer dropping 12 in. as in AASHO T99-49.

^d4- by 4.6-in. samples for untreated series; 2- by 4-in. for treated series.

^eStandard AASHO.

^fNo maximum observed; strength rising with decreasing H₂O (max. probably slightly less than 12 percent).

optimum moisture contents is apparent. However, all samples contained considerable quantities of clay minerals. A fairly uniform degree of stabilization was achieved with 2 percent acid in all 13 samples. Proper moisture adjustment would be critical on this job site. Some degree of soil blending would seem to be required to achieve good compaction control. The data show that good stability will be reached provided this variability in moisture requirement for proper compaction is taken into account.

Volume Change

In the absence of chemical treatment, the soils studied exhibited appreciable volume change when immersed in water. Those having zero immersed strength (completely slaked in water) had an indeterminate but large volume change. Untreated samples that survived the soaking period nevertheless expanded considerably. The two exceptions—A-6(8) from Louisiana and A-7-6(16) from Maryland—exhibited considerable strength without stabilizer. Addition of phosphoric acid reduced the volume change to negligible proportions (less than 0.6 percent) in all cases where a high degree of sta-

bilization was achieved. The Louisiana silt and the alkaline Colorado soil showed reductions in volume change but not to acceptable levels. These latter two soils were not stabilized to a satisfactory degree as previously pointed out, with regard to immersed strength data.

DISCUSSION

Phosphoric acid is an effective stabilizer for a broad range of clay-containing soils. Improvement in engineering properties is marked in nearly all cases.

The immersed strengths reported in Table 3, largely for 5-day curing intervals, are sufficient for subgrade construction and, in certain pavements, for base courses. It should be noted that immersed strengths represent the least strength expected from the treatment. Unsoaked strengths are usually considerably higher than immersed strengths. Some investigators have reported unsoaked (as-cured) strengths as a basis for determining stability. Early experience with as-cured strength data in this investigation disclosed that there was often no correlation with immersed strength. The most obvious case was for dried clay soils where strengths range as high as 2,000 psi and yet fall to zero in water. Instances were noted where samples cured at 100 percent R. H. gained considerably in strength over controls, but the immersed strength did not increase. Because the objective of the research was to confer resistance to exposure to water and other destructive effects, the collection of as-cured data was discontinued and none is reported in this paper.

The effective concentration range varies from 1 to 5 percent phosphoric acid, or perhaps even higher. A level of about 2 percent is generally sufficient for subgrade purposes. It is to be remembered that the listed strengths are for a short curing interval and that much more strength will be developed with the passage of time. Figure 3 indicates that a doubling of the 5-day strength may be expected after 30 days. Thus an immersed strength of 75 to 100 psi after 5 days is considered to be excellent stability. Figure 3 brings up an important point for laboratory investigators; i. e., the need for curing before testing. The reaction in the treated soil mass clearly requires at least a few days before a substantial amount of cementing takes place. It is essential that the investigator distinguish between treated and raw soil systems in this respect. As an example, the AASHTO Standard Method of Test for Determination of Volume Change of Soils T 116-54 may be employed. This procedure calls for molding the sample, curing 15 min, adding water, and beginning the measurement. If this procedure is used with a sample treated with phosphoric acid, the result will be a measure of volume change of the unreacted mixture. In this case, the recommended procedure would be to compact the sample, place it in a humid curing chamber for, say, 5 days, and then resume the test procedure. The same holds for measurement of properties such as Atterberg limits, C. B. R. value, group index, or strength testing. This reasoning also holds true for most other methods of chemical stabilization. There is little value in testing a soil unless the stabilization reactions are allowed to go to at least partial completion.

Most acidic soils containing an appreciable amount of clay minerals will respond well to phosphoric acid treatment. Of the two soils in Table 3 that responded poorly to the treatment, one was highly alkaline and the other was largely silt. The alkalies neutralize the acid before attack at the clay surfaces can begin. Presumably a large quantity of acid would produce a satisfactory degree of stability, but the economics become unreasonable. Phosphoric acid will attack silica (silt) only very slowly at room temperature. Poor stabilization would be expected in samples predominantly made up of silica flour. The remaining soils in the table are neutral or acidic and contain large quantities of aluminosilicates. As discussed in Part II, it is the aluminosilicates that react with the phosphoric acid to produce the cementing substance. The clay soils in the table come from many different sources across the eastern half of the United States, indicating the broad usefulness of the method. Figure 7 further confirms the suitability of phosphoric acid in a range of soil types found on one site. The variation in compaction characteristics is broad, yet the response to the acid is uniform. One further point is brought out in the data shown in Table 3 and Figures 4

and 6—the necessity for preparing samples over a range of moisture contents. The recent literature on chemical soil stabilization contains descriptions of countless experiments in which samples are prepared at only one moisture content, often the optimum for compaction of the untreated soil. This is a potentially misleading practice that can lead to erroneous interpretation of results. To illustrate, suppose one is studying Putnam clay and uses a moisture content of 25.3 percent (optimum for compaction). Table 3 indicates that maximum strength with 2 percent H_3PO_4 was found at 23.4 percent moisture. Maximum with 4 percent H_3PO_4 was at 22.0 percent moisture. The investigator with information at 25.3 percent would report a strength appreciably less than maximum. The above is not to decry the effect of density on strength. Rather it is to point out the fact that the immersed strength does vary with density but that the maximum strength is not always coincident with maximum density. This undoubtedly has to do with internal pore water pressures during immersion (the point of best strength is frequently slightly wetter than optimum) and other factors peculiar to the exposure of the samples. In short, preparation of a series of five or six unreplicated samples over a broad moisture range may be much more valuable than a series of three replicates at one moisture content.

The use of phosphoric acid as a stabilizer for heavy clay soils has apparent merit. Because of the importance of this to engineers, more extensive work dealing with secondary additives, different sources of P_2O_5 , and various practical aspects connected with field testing have been carried out and are reported in the subsequent parts.

ACKNOWLEDGMENTS

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