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Use of Phosphates in Soil Stabilization

By T. DEMIREL, J. V. ROEGIERS, and D. T. DAVIDSON¹

The use of phosphates for stabilizing soil to be used for road building is a new development. Lyons (1) apparently was one of the first to have appreciated the possibility. He reports that compacted plastic clay soils containing about 2 per cent phosphoric acid have greatly improved resistance to water and weathering, but he gives no explanation of the mechanism of soil-phosphoric acid stabilization. In agriculture it has been known for some time that phosphates are fixed in soil (2). It is also known that sodium phosphates may be used to disperse soils in water for particle size analysis (3).

This paper presents a tentative explanation, based on limited experimental evidence, of the mechanism of soil stabilization with phosphates.

LABORATORY EXPERIMENTS

Mixtures and Materials

Four different soil-chemical mixtures were studied: soil-phosphoric acid, soil-calcium hydroxide-phosphoric acid, soil-aluminum chloride-phosphoric acid, and soil-magnesium acetate-phosphoric acid. Only one soil was used, a silty clay, C-horizon Wisconsin loess (Table 1). The phosphoric acid (75%) was commercial grade; the other chemicals were laboratory grade (Table 2).

Methods

The soil (passing No. 10 sieve) and the solid chemicals in powder form were first mixed in the dry state. Phosphoric acid and distilled water were then added to increase the moisture content of the soil to its optimum value for compaction. Immediately after thorough mixing, 2-inch diameter by 2-inch high specimens were molded to near standard Proctor density. The specimens were weighed, measured and wrapped in Saran Wrap. Half of the specimens were cured for seven days and half for fourteen days in a moisture cabinet at a temperature of $70 \pm 3^\circ\text{F}$ and a relative humidity of not less than 90 per cent. At the end of each curing period the specimens

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Table 1
Properties of Soil Used

| | |
|--|----------------------------|
| Textural composition. % ^a | |
| Gravel (> 2.0 mm) | 0 |
| Sand (2.0 — 0.074 mm) | 0.2 |
| Silt (74 — 5μ) | 58.0 |
| Clay (< 5μ) | 41.8 |
| Colloids (< 1μ) | 31.0 |
| Predominant clay mineral ^b | Montmorillonite and illite |
| Probable predominant exchangeable cation | Calcium |
| Specific gravity, 25° C/4° C. | 2.72 |
| Chemical properties | |
| Cat. ex. cap., m.e./100 gm ^c | 28.2 |
| Carbonates, ^d | 0.8 |
| pH | 6.2 |
| Organic matter, % | 0.5 |
| Physical Properties | |
| Liquid limit, % | 53.1 |
| Plastic limit, % | 25.7 |
| Plasticity index | 27.4 |
| Shrinkage limit, % | 19.9 |
| Centrifuge moist. equiv., % | 21.3 |
| Classification | |
| Textural ^e | Silty Clay |
| Engineering (AASHO) | A-7-6(18) |

^aDispersed by air-jet with sodium metaphosphate dispersing agent.

^bFrom differential thermal analysis and X-ray diffraction analysis of fraction passing No. 200 sieve.

^cFraction passing No. 40 sieve.

^dFrom differential thermal analysis.

^eTextural classification is based on former Bureau of Public Roads system (8, p. 18) except that sand and silt sizes are separated on No. 200 sieve (0.074 mm).

Table 2
Equivalent Terms Expressing Concentration of Additives

| Additive | Dissociating Ions | Amount of Additive % | Corresponding amount expressed as milli-equivalents of positive ions per 100 grams of soil |
|---|-------------------|---|--|
| H ₃ PO ₄ (75%) | H ⁺ | H ₂ PO ₄ ⁻ | 1 |
| | 2H ⁺ | H PO ₄ ⁼ | 1 |
| | 3H ⁺ | PO ₄ ⁼ | 1 |
| | | | |
| AlCl ₃ • 6 H ₂ O | Al ⁺⁺⁺ | | 1 |
| Mg(CH ₃ COO) ₂ • 4 H ₂ O | Mg ⁺⁺ | | 1 |
| Ca(OH) ₂ | Ca ⁺⁺ | | 1 |
| CaCO ₃ * | Ca ⁺⁺ | | 1 |

*CaCO₃ was not used as an additive in this study but is often present in Iowa soils. It is listed here in order to estimate the amount of phosphoric acid required to decompose naturally occurring CaCO₃.

were completely immersed in distilled water at room temperature for 24 hours and then tested for unconfined compressive strength. This strength is hereafter referred to as immersed strength. An X-ray diffraction analysis was made on air-dry, oven-dry (80°C) and wet samples of some of the tested specimens to measure the basal spacing of the montmorillonite in the soil and to check for the presence of crystalline phosphates. Other specimens after testing for strength were air-dried and then immersed again in distilled water to determine their resistance to soaking in the dry state.

FORMATION AND NATURE OF PHOSPHATE GEL

The development of immersed strength by treated specimens is believed due to the formation of insoluble amorphous phosphate compounds,* apparently in a gel (4). The gel concept is supported by the X-ray data which indicated no newly formed crystalline compounds. It is not known whether the gel cements as well as water-proofs, since the effect on dry strength was not evaluated.

Treatment with Phosphoric Acid Only

The formation of phosphate gel (4) is thought to be the result of the reaction between the phosphoric acid and the cations in the soil. There may be three sources of cations, namely, exchangeable cations of clay minerals. Cations of other compounds present in the soil such as Fe_2O_3 or CaCO_3 , and cations from positions in the lattices of clay minerals. Cations from the last source would be predominantly aluminum, magnesium, or iron. Adsorption of the H^+ cations of phosphoric acid by clay minerals is believed to be of great significance in the availability of cations from the clay mineral lattices (5). The adsorption of phosphate anions through anion exchange may also be effective in this cation migration (5).

Since the formation of the gel must take place in solution, moist curing of the soil specimens is essential. Examination of the curves in Figure 1 shows that the immersed strength of soil-phosphoric acid specimens is a function of both amount of phosphoric acid and the length of curing. In the range of acid treatment studied an optimum strength occurred with seven day curing, but the strength increased with fourteen day curing when increased amounts of acid were used. The point of intersection of the curves may represent the minimum treatment level for satisfactory long term strength. From the data it appears that for a certain amount of phosphoric acid a certain time interval is essential for the formation of the insoluble phosphates, and the gel, once formed, undergoes a physical and/or chemical

*Phosphates of aluminum, iron or alkaline earths (2)

rearrangement, which for small amounts of phosphoric acid may be at the expense of the immersed strength of the soil.

Use of Metallic Salts as an Additional Source of Cations for Phosphate Gel Formation

In the order of abundance, the cations present in the soil from any of the three sources mentioned above which give insoluble phosphates are calcium, aluminum, magnesium and iron (2). For this reason additives of salts of calcium, aluminum and magnesium were studied as an additional source of cations for insoluble phosphate formation in soil-phosphoric acid mixtures.

Effect of Calcium Hydroxide

Only 0.5 per cent of calcium hydroxide was used in this experiment and the effects on the seven day and fourteen day strengths of soil-phosphoric acid mixtures are shown in Figure 1. In general the

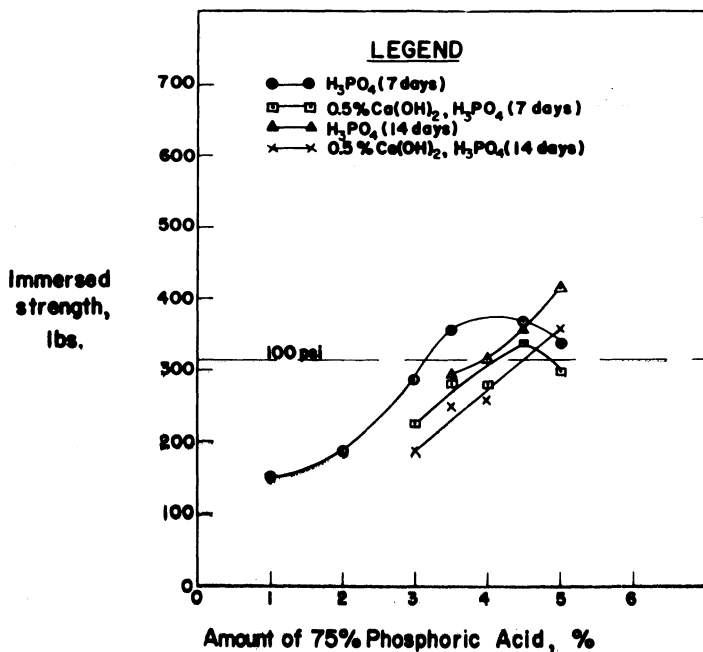


Figure 1. Unconfined compressive strength of soil - phosphoric acid and soil-lime-phosphoric acid mixtures after 24 hours immersion in water (2 inch diameter by 2 inch high specimens).

trends of data representing calcium hydroxide treated specimens are similar to those obtained for soil-phosphoric acid alone. Although strengths were slightly lowered by calcium hydroxide treatment, the differences between seven day and fourteen day strengths were less, perhaps indicating less sensitivity to curing time. It also is of interest to note that the seven and fourteen day curves intersect at about the same phosphoric acid content as the previously discussed curves for soil-phosphoric acid alone, lending further support to the concept of a "critical" minimum phosphoric acid content. Further study is needed to determine the effects with larger additions of calcium hydroxide.

A limited amount of experimenting was done with soil-phosphoric acid mixtures treated with 0.5 per cent and 1.0 per cent of aluminum chloride and magnesium acetate. Test results indicate that aluminum and magnesium cations may react with phosphoric acid to form better phosphate gels for soil stabilization than those obtained with calcium cations or with the acid alone.

Effect of Air Drying on Immersed Strength

Upon the completion of the immersed strength tests, some soil specimens were air-dried and again immersed in distilled water as previously discussed. All specimens thus treated, except those containing aluminum chloride or magnesium acetate, slaked in water.

The resistance to slaking is further indication of the waterproofing effectiveness of aluminum or magnesium phosphates.

SUMMARY

Use of phosphoric acid alone or with salts of calcium, magnesium or aluminum improves the water resistance of compacted, moist cured soil, probably through the formation of amorphous phosphates of these metals in a gel. When salts of these metals are not added with phosphoric acid the metallic cations may be furnished by the soil.

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