Frost Stabilization of Several Soils with Sodium-tripolyphosphate and Sodiumpyrophosphate*

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The behavior of three German soils of different origin and composition without and with addition of polyphosphates was investigated in the freezing cabinet. Determination was made of the frost heave and water intake during a freezing period of 4 days. Two of the soils, considered as strongly frost sensitive in accordance with the criterion of A. Casagrande, also showed large frost heave and water intake in the freezing cabinet. Addition of small amounts of polyphosphates sufficiently surpressed the frost heave and water intake during the freezing period so that the water content after the freezing period did not exceed the optimum moisture content at the standard proctor density. The frost stability remained after the polyphosphates had been washed out of the soil.

The dispersing effect of the polyphosphates increased the degree of soil densification achieved, the dry densities obtained being a function of the concentration of the polyphosphates. The connection between frost stabilization and densification is pointed out.

● WITHIN RECENT years, increasingly important new methods based on soil stabilization with chemicals have appeared in road construction. The purpose of such chemical treatment is to render the natural soil in place serviceable for road construction purposes through improvement of its mechanical properties and decrease of its frost sensitivity by means of small amounts of chemical admixtures. Although a considerable amount of research work has already been performed in the United States on chemical soil stabilization, the German effort along this line has been relatively limited. In practice, the desired soil improvement is usually obtained by improving the granulometry of the soil in place or by replacing the unsuitable soil with a layer of gravel, crushed stone, or blast furnace slag. This replacement, though expensive and time-consuming, is still the best practical method of protecting roads against frost action if they are built over frost-sensitive soils. Especially stimulated, by the extensive American investigations and experience which have been reported in a number of publications, German scientists have a growing interest in chemical soil stabilization with the hope that more economical and less time-consuming methods may be developed by such means, particularly in view of the increasing activity in road construction.

The investigations, which started at the beginning of 1959, are mainly concerned with the prevention of frost damage by means of chemical admixtures to frost-susceptible soil materials. Publications by Lambe (1, 2) indicated the effectiveness against frost action of chemicals, especially polyphosphates, that have a dispersing effect on soils. The polyphosphates fulfill a number of requirements that are important for a large-scale use in road construction. These include (a) low cost, which is a precondition for widespread economical application; (b) effectiveness at small concentrations; (c) long-lasting protection against frost action; (d) effectiveness over a wide range of soil composition; and (e) easy and quick incorporation into the soil to be treated.

There exists, on the other hand, a great variability among different soils as to the degree of frost protection imparted by treatment with polyphosphates. As yet this can-

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not be predicted by simple means. Hence, extensive investigations on many different soils must be made before large-scale use of polyphosphates for frost protection can become a reality.

EXPERIMENTATION

Materials

Soils. —The three soils tested are from different parts of western Germany: a loamy soil from Bavaria (I), a silty sand from Franconia (II), and a sandy soil from the vicinity of Cologne (III). The respective soil characteristics are given in Table 1 and the size compositions in Figure 1. All soils were used in their natural state, but due to the admixture of the chemicals they could not be tested in the undisturbed condition. The Casagrande criterion indicated a great frost sensitivity for soils I and II, inasmuch as they were of nonuniform character with a < 0.02 mm content over 3 percent. For the nearly uniformly sized sand III with its very small content in < 0.02 mm material, no marked frost susceptibility was to be expected. The test results confirmed these expectations, with soils I and II showing great susceptibility to frost heave. These soils contained only a few free calcium ions; hence, no interference with the effectiveness of the phosphates was to be expected on their account.

Admixtures. —Sodiumtripolyphosphate and sodiumpyrophosphate of 98 percent purity (remainder being other condensed phosphates) based on thermic phosphoric acid were used. These products correspond to C. P. quality. The finely pulverized chemicals were spread on the soil samples and mixed in by hand. In some cases when water addition was necessary, as in the determination of the maximum Proctor density, the polyphosphates were first dissolved in the mixing water. No difference was observed in the tests made on samples produced by either method. The natural soil moisture combined with the saturation period in the frost cabinet appeared to be sufficient to ensure solution and distribution throughout the specimens of the phosphates added in powder form. The concentration of the admixtures is given as a percentage of the moist weight of the soils.

Freezing Cabinet Test

Frost heave can occur only if three conditions are fulfilled:

TABLE 1

PROPERTIES OF THE INVESTIGATED SOILS[1]

Properties	Soils		
	Loam I	Silty Sand II	Sand III
Size composition (% by wt):			
Gravel > 2 mm	-	8.0	14 0
Sand 2 mm - 0.06 mm	41.0	23.0	79.0
Silt 0.06 - 0.002 mm	54.0	9.0	6.0
Clay < 0.002 mm	5.0	-	1.0
Nonuniformity	10	7	5
Physical properties:			
Simple Proctor density (tons/m^3)	1.82	1.85	1.93
Optimum moisture (%)	18.9	9.6	10.5
Specific gravity	2.64	2.503	2.54
Chemical properties:			
Organic matter (%)	0.8	0.1	0.1
Natural water content (%)	12.2	5.5	6.2
pH	7.1	6.7	6.7

[1]Compaction work=60,000 kgm/M^3 (3 layers).

1. A frost susceptible soil whose capillary spaces do not oppose too much resistance to the upward movement of water;

2. The presence of a reservoir from which water can be supplied for upward movement; and

3. Frost penetration from the surface down and sufficient duration of freezing conditions; it must be kept in mind that the freezing temperature in soils, especially in the case of admixtures, may be below 0 C.

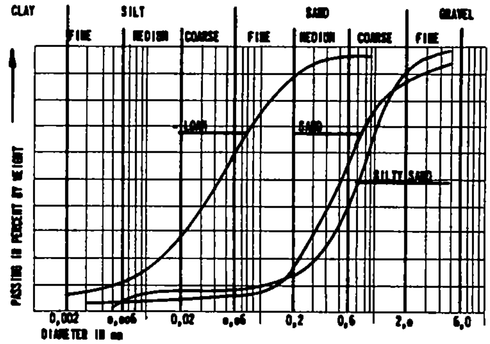

Figure 1. Drain size distribution.

Already because of the normal expansion of water on freezing, by about 10 percent of its volume, moist soils may show a small volume increase on through-freezing without heaving. This volume increase was not observable in the case of these experiments (in which the samples could also freely expand in the lateral direction) and, therefore, did not affect the results of the tests. The particular mechanism of frost heave is, of course, the formation of ice lenses. These result from the solidification at the freezing front of water that is conducted there by capillary action from the water supply below. Because all water that is conducted to the freezing front freezes, the soil can by ice lens formation take in much more water than corresponds to its maximum saturation capacity. The volume increase connected with ice lens formation is much larger than that which would occur if only the normal saturation water would be frozen. When thawing takes place from the surface down, then the melt water cannot drain away through the underlying, still frozen soil and the thawed soil loses its mechanical stability because of its excessive water content.

Because the formation of ice lenses depends on the rate of upward water movement, the rate of penetration of the frost zone plays an important role. Slow penetration results in the formation of thick ice lenses and bands. If the rate of frost penetration exceeds that of water supply, then no ice lenses are formed and no frost heave is noticed even in highly frost susceptible soils.

In comparative investigations of frost heave produced in frost cabinets, the rate of frost penetration should be kept constant. Taking account of the temperature gradient in the specimen and its thermometric conductivity, the surface temperature was regulated so that the rate of frost penetration per day was about 6.5 cm. This value was approximately kept in the case of all comparative investigations. At the completion of each test, the frost penetration into the sample was determined. This eliminated the possibility that frost stabilization could be ascribed solely to a depression of the freezing point of the pore water by the admixtures. All samples investigated had been frozen to a constant depth. No great difference was found in the penetration of the freezing front for the different soils and different treatments.

The required freezing conditions were created in a frost cabinet described by A. Bley (3) as suitable for the direct determination of the frost sensitivity of soils. Similar types of freezing tests and apparatus have also been developed by the Arctic Construction and Frost Effects Laboratory (ACFEL) (4, 5, 6, 7). A description of the experimental procedure is restricted to the following statements. To eliminate as much as possible disturbing influences that may be due to structural variations, relatively large samples (diameter = 8 cm; height = 30 cm) were used. As one of the factors that influence the soil condition, the compaction work required in the molding of the cylindrical test specimens was standardized. To permit comparison with the later determined Proctor curves, the compaction work was standardized at 60,000 mkg per cu m, which corresponds to that employed in the standard Proctor compaction. Before the start of the refrigeration, the densified soil cylinders were saturated for 20 hr by lifting a connected water supply vessel to be level with the top of the cylinders. Excess water thus supplied drained off after lowering of the supply vessel. Each freezing test

was conducted for a period of 4 days. Determinations were made of the amount of saturation water, water intake during freezing, and frost heave.

RESULTS

Freezing Experiments Without Admixtures

The tests with natural untreated soils gave the absolute values for frost heave and water intake during the freezing period and indicated the accuracy and the comparative value of this type of test. Table 2 gives the average data obtained in series of 4 tests

TABLE 2

FROST EFFECT ON THE UNTREATED NATURAL SOILS

Changes During Freezing	Soils		
	Loam I	Silty Sand II	Sand III
Av. daily frost heave during 4-day period (mm)	11, 11, 12, 10	5, 10, 11, 10	2, 3, 2
Total heave (mm)	44	36	7
Saturation water, 20-hr intake (ml)	170	200	100
Av. daily water intake during freezing period (ml)	70, 85, 85, 62	60, 80, 65, 70	40, 15, 15, 10
Tot. water intake (ml)	302	275	80
Soil moisture after thawing (%)	26.2	19.1	11.6
Water content of natural soils (%)	12.2	5.5	6.0

each. Figure 2 shows the heave of the samples and their water intake as a function of time. The frost heave as well as the water intake are approximately linear functions of time. Small variations that were not caused by temperature variations may be considered as due to small differences in sample composition and structure.

As expected, soils I and II were found to be strongly frost susceptible. The water content after thawing was considerably above the optimum moistur content. Soil III with its good granulometry behaved quite differently and showed very little frost effect. As Table 2 and Figure 2 show, the standardization and uniformity of all test variables resulted in good reproductibility of the results. The experimental errors were within the following limits: absolute amount of frost heave ± 5 percent; saturation water ± 3 percent; freezing water ± 10 percent; and frost penetration ± 5 percent. These results show that the method employed is suitable for a comparative investigation of the frost susceptibility of natural soils without and with protective admixtures. The frost-protective effects of admixtures were found to lie far outside the determined limits of error.

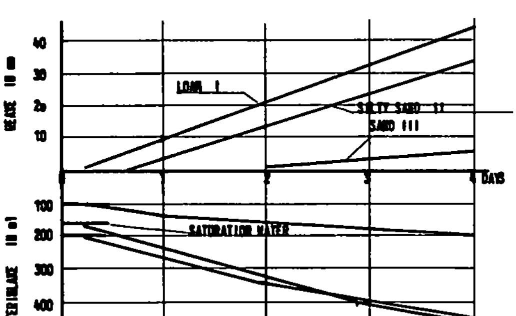

Figure 2. Relation between heave and water intake.

Frost Stabilization by Polyphosphates

The soil samples treated with the polyphosphates were tested in the same manner as described. Although the samples with the admixed polyphosphates were not given a special aging period, one might consider

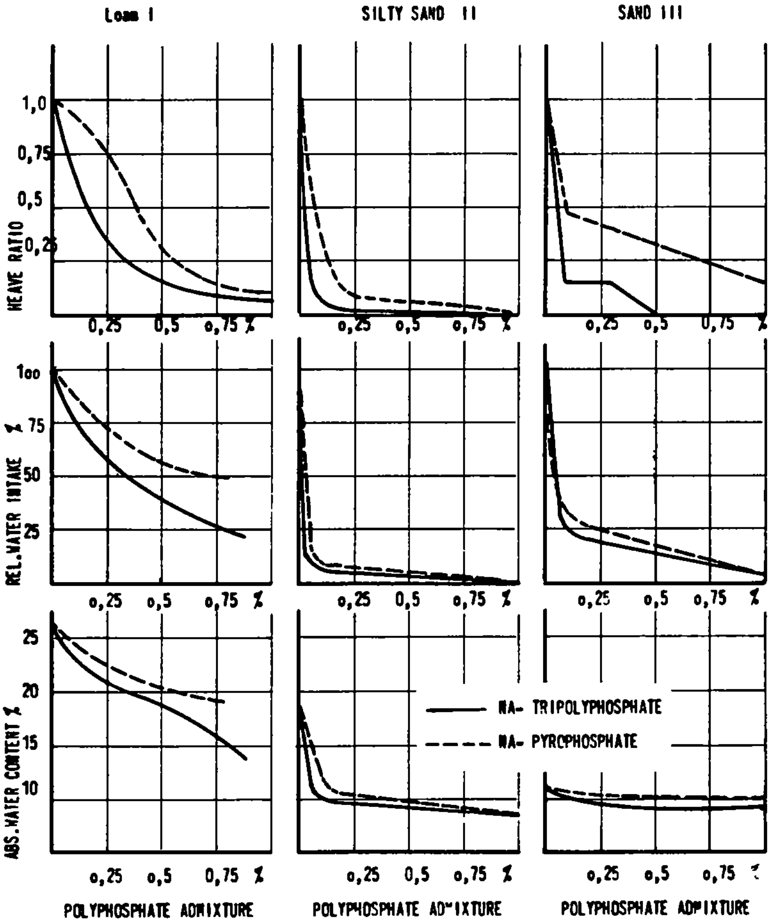

Figure 3. Frost heave water intake and final soil moisture as functions of phosphate additions.

the 20-hr saturation period as such. The ratio of the frost heaves observed in the treated and untreated samples, respectively,

$$HV = \frac{\text{Frost heave with admixture}}{\text{Frost heave without admixture}},$$

as well as the relative water intake during the freezing period as compared to that of the untreated soil were considered as criteria of the frost-stabilizing effectiveness of sodiumtripolyphosphate and sodiumpyrophosphate. The sum of the original water content, saturation water, and water intake during freezing gives the total soil-water after thawing. The amounts of frost heave and water intake vary as functions of the added amounts of polyphosphates. Figure 3 shows the relative frost heave and water intake as functions of the weight percentages of polyphosphate. The resulting total soil moisture after thawing contains the saturation water, which also is reduced due to the effect of the admixtures. Inasmuch as the relative values are of primary interest, the absolute data have not been shown. The latter, however, may be easily calculated from the data in Table 2. The experimental data bring out the following facts:

1. Despite the great difference in origin and size composition of the three soils tested, addition of polyphosphates resulted in stabilization against frost action in all three cases. The effectiveness of sodiumtripolyphosphate is somewhat greater than

that of sodiumpyrophosphate, especially for the very frost-susceptible fine-grained soil I.

2. Frost heave can be prevented almost completely by addition of polyphosphates. The curves for the relative frost heaves in case of soil III are somewhat deceptive because of the very small absolute values involved. Despite the high HV-values, the absolute heaves in this case are very small and almost within the limits of error. A polyphosphate admixture of less than 0. 5 percent by weight, which is within economic limits, reduces frost heave by at least 85 percent. Admixtures above 0. 5 percent do not give proportionate increases in effectiveness.

The water intake during the freezing period shows the same dependence on phosphate admixture as does the relative frost heave. This is in accordance with the indicated mechanism of frost heave as a result of ice lens formation. The relative water intake can be reduced by more than 75 percent. In this connection, it is of interest that the water permeability of soils is greatly reduced by phosphate admixtures. This effect persists even after washing out of the polyphosphate.

3. The total water content after thawing of frost-stabilized soils does not exceed the value of the optimum moisture content at standard Proctor density. The observed increase in moisture content is due mainly to the sorbed saturation water. The test specimens had been molded at the natural water contents of the soils. Greater densification would have required a higher water content. This, however, would not have changed the total water content after thawing.

If one considers the use of chemicals in road construction, one wants to know first of all how fast these will be washed out of the soil and to what extent the effect of frost stabilization is thereby lost. Because of the normal water movements in soils, such washing out must be considered in the case of all chemicals. In an investigation that has not yet been completed, but deserves mentioning at this place, the frost-stabilizing effect has been found to persist in the tested soils despite washing out of the polyphosphate under extreme conditions. This effect, which probably is due to the dispersing action of the polyphosphates, permits a permanent frost stabilization with their use.

Soil Densification with the Help of Polyphosphates

The chemical-physical phenomena in soils are so complicated that until today there has been no complete and generally accepted clarification of the water transport to the location of ice lens formation and its modification by means of added chemicals. Such soil properties as grain size distribution, pore volumes, water permeability and soil-water interfacial characteristics play important roles.

Polyphosphates have a dispersing effect on soil particles which permits the achievement of a higher degree of order in particle arrangement with resulting decrease in pore volume; i. e. greater density at equal moisture content and compactive effort. The reduction in pore size is one of the determinant factors with respect to capillary water transport in soils. Thus, a connection exists between densification and frost stabilization.

The effect of polyphosphate addition on densification was investigated by means of Proctor compaction curves. The results of the frost stabilization and densification experiments are directly comparable, because the same amount of densification work in kgm per cu m were employed in the molding of the samples. Figure 4 shows the standard Proctor densities of the silty sand II and the uniform sand III as functions of water content at different polyphosphate contents. Because of insufficient supply of soil I, no tests on these relationships could as yet be run. The Proctor curves are easily reproduced if fresh material is used for each tamping; otherwise, marked deviations occur despite efforts toward loosening of the soil. The standardized amount of compaction work was 60, 000 kgm per cu m and the soil was compacted in three layers. The frost-susceptible soil II showed a change in maximum dry density from 1. 852 to 1. 90 tons per cu m at a polyphosphate admixture of 1 percent by weight. This corresponds to an improvement by about 2. 5 percent of the maximum Proctor density. As was to be expected from its grain size, composition, and small frost susceptibility, soil III did not show any increase in maximum Proctor density on polyphosphate addition;

sodiumtripolyphosphate and sodiumpyrophosphate are equally effective, aside from small differences. With the increase in dry density, go changes in optimum moisture content. The increase in optimum moisture content in the case of larger amounts of the polyphosphates probably is the result of an additional water-binding influence of the polyphosphates which, however, is noticeable only at higher polyphosphate concentrations. Because the investigated soils possessed only a small optimum moisture content for maximum Proctor density, the decrease in optimum moisture on addition of the polyphosphates was small.

In connection with frost stabilization, densification at natural moisture contents at which the specimens for the freezing experiment were molded was of particular interest. The respective curves show that at water contents from 5.5 to 6 percent phosphate addition resulted in increased densities. Although the increases in dry density in these cases are small in comparison with the maximum values, they appear to be sufficient for frost stabilization. In the case of frost-sensitive soils, it cannot be predicted to what extent the pore space must be changed so that the absorbed water hulls of the soil

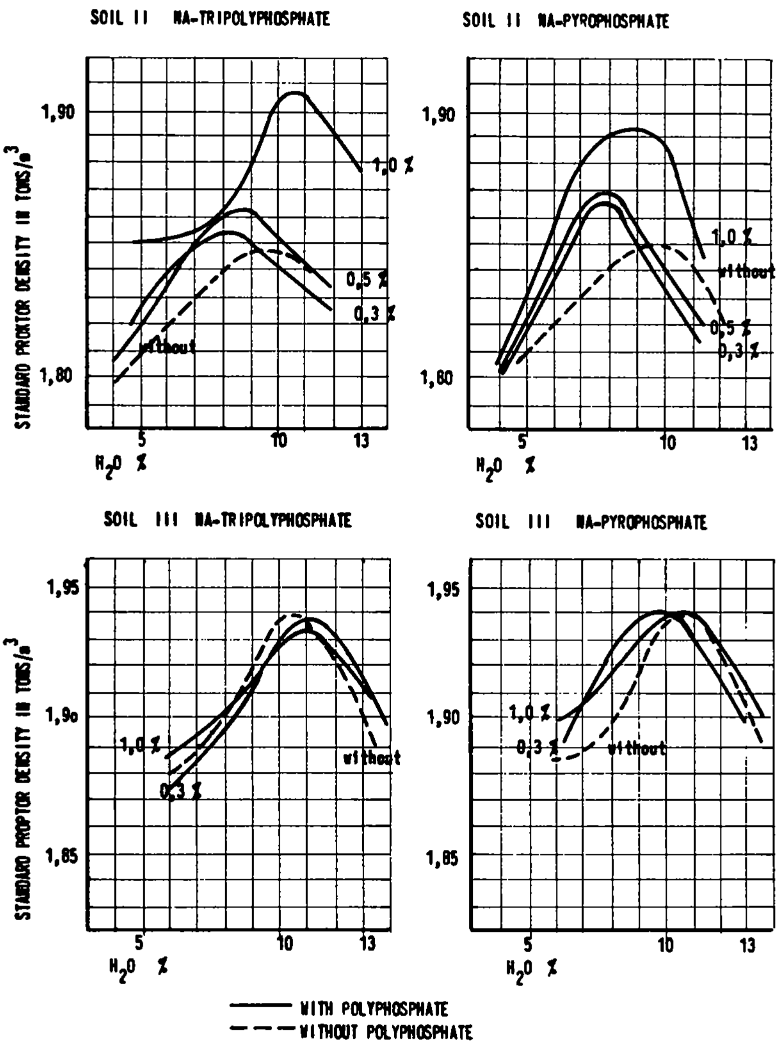

Figure 4. Proctor curves as influenced by admixtures of NA-tripolyphosphate and NA-pyrophosphate.

particles may impede the capillary upward transport of free water. Another problem concerns to what extent the surfaces of thė soil particles themselves are changed by admixtures that possess dispersive action.

SUMMARY

Several soils were tested in the laboratory for frost sensitivity in a freezing cabinet and the possibility of their stabilization against frost action by means of polyphosphates was investigated. Polyphosphate admixtures in amounts that can be justified economically resulted in good stabilization; i.e. prevention of frost heave and reduction of water intake during the freezing period. Connected with stabilization against frost action is an increase in dry density. Although it can be expected that the polyphosphates are similarly effective for all frost-susceptible soils, the investigations must be extended over a larger number of soils because of the wide range in composition and properties of soils found in nature. It is felt that the safest way to extensive field tests on frost susceptibility and stabilization is one that starts with a thorough laboratory study of representative samples.

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