Stabilization of Soil with 4-Tert-Butylpyrocatechol

JOHN B. HEMWALL, Dow Chemical Company
DONALD T. DAVIDSON, Iowa State University, and
HENRY H. SCOTT, Dow Chemical Company

This investigation concerns the use of 4-tert-butylpyrocatechol (TBC) as a trace soil additive to mitigate the normally adverse effect of water on the soil, thus rendering the soil a more suitable engineering material. The TBC changes the surface character of the soil particles from a normally hydrophilic to a hydrophobic state.

The results reveal that although almost all soils can be rendered hydrophobic by the TBC, the silty-type soils are benefited most. These soils retain substantial unconfined compressive strengths, even when totally immersed in water and after several cycles of freezing and thawing.

The investigation reveals that the TBC gives best results when added to the soil with sufficient water to bring the soil up to optimum moisture content. The optimum curing conditions are shown to be those that result in drying of the soil after compaction. Thus, curing the treated compacted soil at a relative humidity of 50 percent is very effective.

The results presented are based entirely on laboratory studies. However, the properties imparted to the soil and the results obtained indicate that many soils are potentially suitable engineering materials when treated with TBC.

• THE USE OF CHEMICALS to modify or improve certain physical properties of soils has become a matter of considerable interest to engineers in the last 25 years. Attention has centered around improving the load-bearing capacity or strength of soils, especially under conditions of high moisture. The treatment of soils with chemicals, or chemical soil stabilization, is primarily intended to make soil a suitable alternative to crushed rock or aggregate in road bases and subbases.

Recently Sherwood (1) classified chemical soil stabilizers into the three categories of bonding agents, waterproofing agents, and combination bonding and waterproofing agents. Bonding agents stabilize soil by creating physical and/or chemical bonds between the soil particles which enhance the strength of the soil under both dry and wet conditions. Waterproofing agents do not affect dry strength significantly but allow the dry strength of the soil to be retained in the presence of water by reducing water adsorption.

Davidson and co-workers (2, 3, 4, 5) have studied soils waterproofed with a variety of chemicals. Many of these soils when waterproofed retained sufficient strength in the presence of water to be potentially suitable for base or subbase purposes. Some of the chemicals waterproofed soil more effectively than others. All of the chemicals, however, behaved more or less similarly in soil.

The purpose of this paper is to report results obtained with a new and chemically unique soil waterproofing agent, 4-tert-butylpyrocatechol, hereinafter referred to as TBC. The optimum conditions for the use of this chemical, the soil types in which it is most effective, and the optimum rate of use are discussed.

MATERIALS AND METHODS

Soils

The soils used in this investigation are given in Table 1 together with many of their

TABLE 1

PHYSICAL AND CHEMICAL PROPERTIES OF SOILS USED

Ref No	Mechanical Analysis[a]			pH[b]	$CaCO_3$[c] (%)	Organic Matter[d]	Cat Ex Cap[e] (meq/g)	Plastic Index[f]	Liquid Limit[f] (%)	Opt Moist[g] (%)
	Clay	Silt	Sand							
A-1	16	41	43	7.5	1.1	1.1	14.4	5.4	25.8	14-16
B-1	22	52	26	5.3	0	10.7	39.6	11.1	76.6	33-35
B-2	12	46	42	7.2	3.5	4.1	4.0	1.[illegible]	33.6	17-19
C-1	25	46	29	7.8	7.9	3.1	16.7	8.8	39.1	20-22
D-1	12	46	42	6.0	0	1.0	8.0	0	17.8	10-12
E-1	22	62	16	7.7	4.5	1.4	23.4	13.8	36.6	15-17
F-5	23	35	42	7.1	0	1.1	16.0	5.9	22.2	11-13
F-7	38	35	27	7.4	0	1.6	22.0	47.5	27.5	13-15
H-1	6	14	80	5.5	0	0	3.0	0	13.5	8-10
J-2	55	40	5	7.5	1.7	1.6	31.8	21.4	48.3	16-18
K-1	18	43	39	7.6	1.4	2.3	22.4	6.0	35.1	14-16
L-2	67	27	6	7.6	11.5	1.7	33.0	24.0	63.0	26-28
M-2	42	36	22	6.3	0	1.2	11.2	43.0	38.8	24-26
N-1	48	39	13	6.75	0	2.7	31.1	21.4	49.1	17-19
P-2	57	27	16	7.7	1.2	1.8	18.2	25.0	58.0	19-21
R-1	18[h]	80[h]	2[h]	8.4	9.9[i]	0.1[j]	14.7	7.2	34.2	17-19[k]
R-7	39[h]	61[h]	1[h]	5.6	1.5[i]	0.2[j]	23.5	32.1	52.1	19-21[k]

[a] Determined by hydrometer method
[b] Determined on a non-plastic slurry
[c] By carbonate determination
[d] Determined by wet ash method
[e] Ammonium acetate method
[f] ASTM methods D423-54T and D424-54T
[g] Moisture at maximum density
[h] ASTM method D-422-54T
[i] By versenate method for total calcium
[j] Potassium bichromate method
[k] ASTM method D698-58T

physical and chemical properties. All soils were air dried, pulverized, and screened through a 10-mesh sieve before use.

Immersed Unconfined Compressive Strength

The TBC was added to soil in all cases as an emulsion in the molding water. The amount of water used was sufficient to bring the soil up to optimum moisture for maximum density. The soil was then compacted, cured for 7 days, and immersed for 24 hr in distilled water before determining the unconfined compressive strength. Whenever a modification of this general procedure was used, it has been noted in the description of the specific experiment. Auxiliary data such as weights, moisture contents, etc., were determined by classical procedures.

Some of the experiments reported were conducted at the Iowa Engineering Experiment Station, Ames, whereas others were conducted in the laboratories of the Dow Chemical Company in Seal Beach, Calif. Although the general procedure previously described was used in both laboratories, some of the details differed. The California procedure involved soil plug specimens 3.0 cm in diameter by about 6 cm in height. These specimens were compacted via two-end loading in a hydraulic press at a pressure of 750 psi on the plug specimen. The specimens were stressed to failure on a motor-driven Soiltest Model U-160 unconfined compression test apparatus using a loading rate of 0.07 in. per min.

The Iowa procedure involved specimens 2.0 in. in diameter and about 2 in. in height. The specimens were compacted via a conventional drop-hammer apparatus (5) and were stressed to failure on an unconfined compression test apparatus using a loading rate of 0.10 in. per min. The descriptions of the specific experiments indicate whether the Iowa or California method was used.

Freeze-Thaw Test

Soil specimens prepared via the Iowa method were subjected to 10 cycles of freezing and thawing as described previously (6). The apparatus and procedure were essentially the same as the British Method, except that the freezing temperature was 20 ± 2 F and the temperature of the water inside the vacuum flask was controlled at 35 F. The plastic

TABLE 2

EFFECTS OF TBC ON OPTIMUM MOLDING MOISTURE CONTENTS FOR MAXIMUM DRY DENSITY AND MAXIMUM IMMERSED STRENGTH, AND ON VALUES OF MAXIMUM DRY DENSITY AND MAXIMUM IMMERSED STRENGTH

Soil	TBC (%)	Optimum Molding Moisture (%)		Max Dry Density (pcf)	Max Immersed Strength[a] (psi)
		Max Dry Density	Max Immersed Strength		
R-1	0	18 0	--	106 5	0
	0 042	18 7	19 3	107 4	115
	0 085	17 3	17 3	106 8	132
	0 212	18 4	17.9	107.1	155
	0.425	19 6	19 3	107 7	180
	0 850	17.7	17.2	108.5	180
R-7	0	18 9	--	108 9	0
	0 042	17.8	19.0	108 1	40
	0.085	18 4	18 8	108 5	52
	0 212	18.6	19 7	107 6	45
	0 425	18.1	18 8	107.9	50
	0 850	18 4	19.1	107 9	42

[a] Cured for 7 days at 60 percent RH before 24-hr immersion.

specimen containers used restricted the volume change of the specimens to the upward direction.

RESULTS

Four major factors relative to the performance of TBC as a soil waterproofing agent were investigated: (a) the optimum conditions for treatment with TBC, (b) the limitations of TBC with respect to soil type, (c) the necessary treatment rates, and (d) the stability of the treated soil to freezing and thawing.

Moisture content at compaction is one of the major factors influencing the strength of stabilized soil. Generally, the optimum moisture content for maximum strength is that resulting in the maximum compacted dry density. Two soils were treated with several rates of TBC and were compacted at several moisture contents in an effort to determine the optimum moisture for both maximum dry density and maximum immersed strength. The samples were compacted by the Iowa method, cured for 7 days at approximately 60 percent relative humidity, and immersed for 24 hr in water before determining the unconfined compressive strength. The dry density of the samples was determined immediately after compaction. The soils used together with a summary of the results are given in Table 2. In addition, the complete results for soil R-1 treated with 0.085 percent TBC are shown in Figure 1.

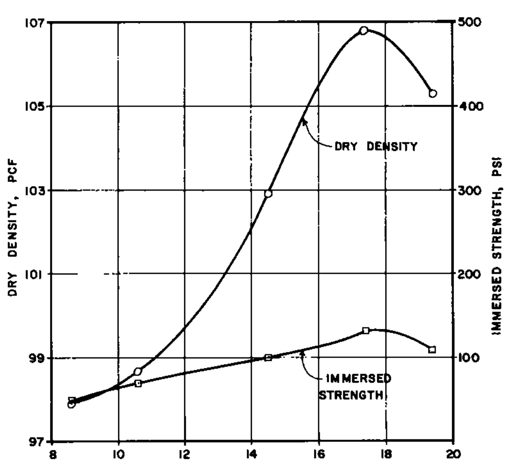

Figure 1. Dry density and immersed strength of soil R-1 treated with 0.085 percent TBC against moisture content of soil.

The results in Figure 1 and Table 2 reveal that the optimum molding moisture contents for both maximum dry density and maximum immersed strength are essentially the same. Furthermore, the optimum molding moisture content is essentially the same regardless of the presence or absence of TBC or the rate applied. Thus, the optimum molding moisture content for soils being treated with TBC is

TABLE 3

INFLUENCE OF CURING METHOD ON IMMERSED STRENGTH OF SOIL R-1 TREATED WITH 0.425 PERCENT OF TBC

Method of Curing[a]	Immersed Strength (psi)
7 days at RH > 95%	54
14 days at RH > 95%	58
7 days at RH > 95% followed by 7 days at RH = 60%	178
2 days at RH = 49%	64
7 days at RH = 52%	218
14 days at RH = 56%	217

[a]RH = relative humidity.

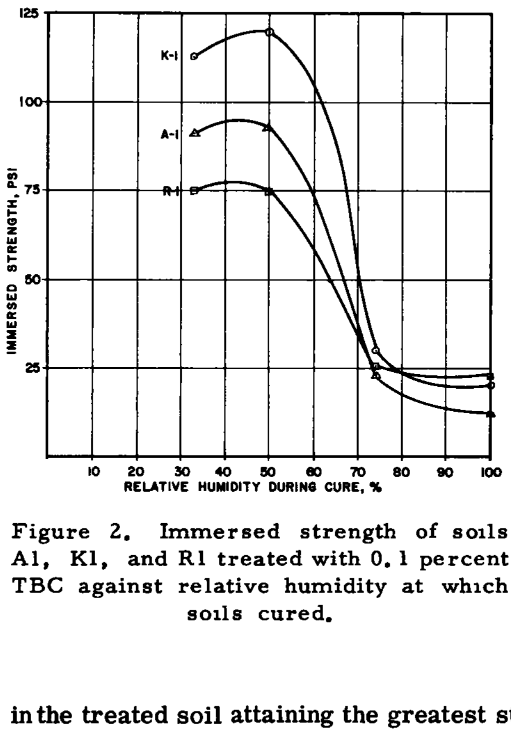

Figure 2. Immersed strength of soils A1, K1, and R1 treated with 0.1 percent TBC against relative humidity at which soils cured.

the optimum moisture content of the untreated soil for maximum dry density.

Maximum dry density for soil R-1 increased slightly with increasing TBC content. However, with soil R-7 the reverse was true. Because density can be controlled only to about ± 3 pcf in field operations, the changes noted are not considered especially significant.

Another factor influencing the strength attained by a chemically stabilized soil is the cure conditions. In a preliminary experiment several samples of soil R-1 treated with 0.425 percent of TBC were compacted at optimum moisture by the Iowa method, cured under the variety of conditions given in Table 3, and immersed for 24 hr in water before determining unconfined compressive strength.

The data in Table 3 indicate that curing at low relative humidity results in superior immersed strengths compared to curing at high relative humidity. At low relative humidity a cure period greater than 2 days and not more than 7 days is needed to maximize the strength. The data also show that cure at high humidity is somewhat inferior, although acceptable as long as it is followed by several days at a lower relative humidity. The untreated soil under all conditions of cure had zero immersed strength. Hence, the TBC-stabilized soil is superior regardless of cure conditions.

The reason that cure under drying conditions is superior to cure under humid conditions is undoubtedly because the drier a soil is before immersion, the drier it will be kept by the waterproofing agent during immersion. Also, the drier the soil after immersion, the more strength it will have. Furthermore, the maximum strength under any relative humidity condition will be attained at such time as the soil has dried to an equilibrium value.

The previous experiments have indicated that curing under drying conditions results in the treated soil attaining the greatest strength. The next experiment was designed to determine the optimum relative humidity conditions. Samples of three soils were treated with 0.1 percent TBC and compacted at optimum moisture by the California method. Samples of each soil were then cured at four different relative humidities for 7 days, immersed in water for 24 hr, and finally tested for unconfined compressive strength. The relative humidities used for curing are shown in Figure 2 together with the results.

It is quite clear that the optimum relative humidity is between 40 and 50 percent. Curing at relative humidities in excess of 70 percent results in strengths decidedly inferior to the strengths attained under optimum conditions. However, the untreated soils in all cases had an immersed strength of zero. Therefore, regardless of cure conditions, the treated soil is superior to the untreated.

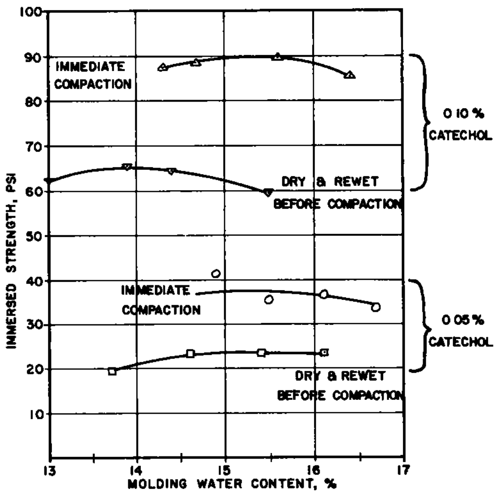

Figure 3. Immersed strength vs molding water content for soil K-1 treated with 0.05 and 0.10 percent TBC, both dried and rewet after treatment and before compaction, and compacted immediately after treatment.

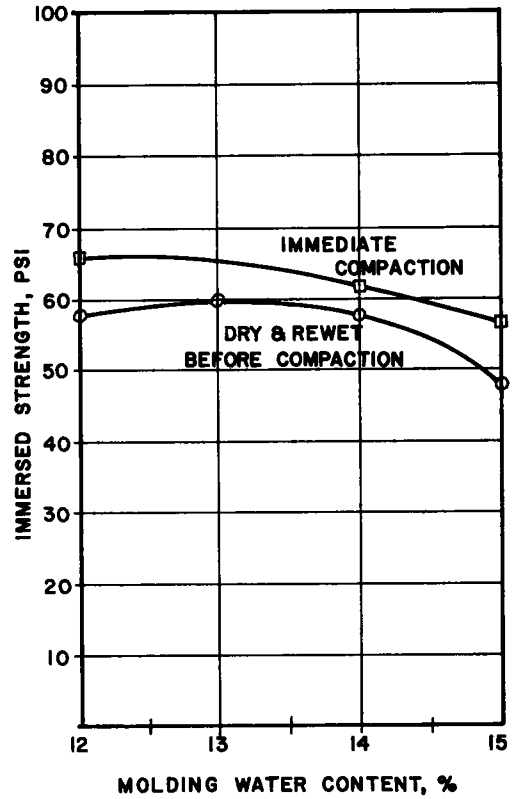

Figure 4. Immersed strength vs molding water content for soil R-1 treated with 0.07 percent TBC, both dried and rewet after treatment and before compaction, and compacted immediately after treatment.

Another factor that can influence the strength attained by a soil stabilized with TBC is the condition in which the soil is maintained subsequent to treatment and the time interval before drying of the compacted soil is initiated. Usually a soil will be compacted and drying will be initiated almost immediately after treatment, but situations in which this would not be so are possible.

An experiment was conducted to determine the effect of allowing the soil to dry before compaction. Samples of soil K-1 were treated with two rates of TBC and allowed to air dry for 72 hr prior to addition of molding water and to compaction by the California method. A second set of samples also were treated with two rates of TBC, but were compacted immediately after treatment. Several rates of molding water were used in both sets of samples and all samples were cured for one week at 50 percent RH prior to immersion and determination of strength. The levels of TBC used, the amounts of molding water, and the immersed strengths are shown in Figure 3. An analogous experiment was conducted using soil R-1 except that only one rate of TBC was used. The results of this experiment are shown in Figure 4.

Figures 3 and 4 reveal that the strength attained by the treated soil is reduced by allowing the soil to dry for 72 hr after treatment and before addition of molding water and compaction. An experiment was conducted to determine whether the drying or the time between treatment and final compaction and/or cure was responsible for this result. Soil K-1 was treated with 0.1 percent TBC at optimum moisture content and stored for 72 hr at a relative humidity of 100 percent. At various times during the 72-hr period, aliquots of the soil were taken, compacted by the California method, and returned to the 100 percent relative humidity condition for the remainder of the 72-hr period. After 72 hr, all the samples were cured for 7 days at a relative humidity of 50 percent. In addition, a sample of soil K-1 treated with TBC was compacted immediately after treatment and cured for 7 days at a relative humidity of 50 percent. All

TABLE 4

IMMERSED STRENGTHS OF SOIL K-1 TREATED WITH 0.10 PERCENT TBC[a]

Time at 100% RH (hr)		Immersed Strength[b] (psi)
Total	Before Compaction	
0	0	90
72	0	62
72	1	65
72	2	65
72	4	79
72	8	62
72	24	69
72	48	66
72	72	72

[a]As a result of compacting soil at various times during storage at 100 percent relative humidity as compared to compacting soil immediately after treatment and with no storage at 100 percent relative humidity.
[b]After 7 days cure at 50 percent relative humidity.

samples were then immersed for 24 hr before determining the unconfined compressive strength. The various times during the 72-hr period at which the samples were compacted are given in Table 4, together with the results.

Table 4 reveals that all samples which were kept for 72 hr at 100 percent relative humidity prior to cure at 50 percent relative humidity have essentially the same immersed strength regardless of when they were compacted. Further, all of these samples have lower strengths than the samples that were compacted immediately after treatment and immediately cured at 50 percent relative humidity. These results, together with the results shown in Figure 3, indicate that allowing 72 hr to elapse between treatment of the soil with TBC and commencement of drying of the compacted soil has an adverse effect on the strength obtained, regardless of whether the soil dries out before compaction and cure, and regardless of whether the soil is in a compacted or friable condition before cure.

The probable explanation for this is that TBC does not reach adsorption equilibrium with soil for a matter of 3 or 4 days, although within 1 hr most of it is adsorbed. Thus, when the soil is in a loose and friable condition for 3 days, whether it is drying or not, the TBC adsorbed onto the soil surfaces is homogeneously distributed. However, when drying takes place immediately after the soil has been compacted, water containing TBC flows through the capillary pores during the time that the soil specimen

TABLE 5

CLAY CONTENT, UNIMMERSED COMPACTED STRENGTH AT OPTIMUM MOISTURE FOR NATURAL SOIL, AND WATER CONTENT AFTER IMMERSION AS PERCENT OF PLASTIC LIMIT AND STRENGTH AFTER IMMERSION AT TREATMENT LEVELS OF TBC OF 0.10 AND 0.25 PERCENT FOR SEVERAL SOILS

Soil	Clay Content (%)	Untreated Compacted Strength at Optimum Moisture[a] (psi)	Water Content After Immersion of Treated Soil (% plastic limit)		Strength After Immersion of Treated Soil (psi)	
			0.25% TBC Treatment	0.10% TBC Treatment	0.25% TBC Treatment	0.10% TBC Treatment
H1	6	10	21	20	33	26
D1	12	27	28	28	88	87
B2	12	65	29	32	100	102
R1	16	50	31	33	83	82
A1	16	59	37	47	110	95
K1	18	97	43	48	157	139
B1	22	72	65	110	53	18
E1	22	143	82	94	57	46
C1	25	90	53	70	85	37
F7	38	118	53	61	65	42
M2	42	84	82	92	79	52
N1	48	112	91	116	31	5
J2	55	144	93	105	6	5
P2	57	149	>100	>100	0	0
L2	67	155	>100	>100	0	0

[a]All soils when immersed had zero strength.

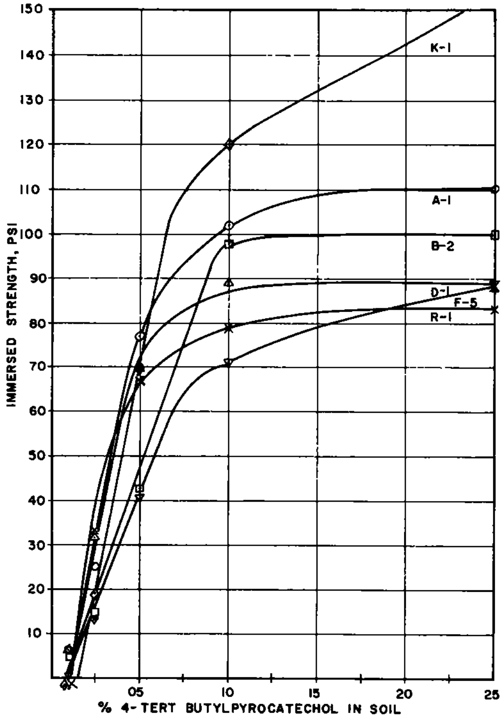

Figure 5. Immersed strength vs TBC content in six soils compacted by California method.

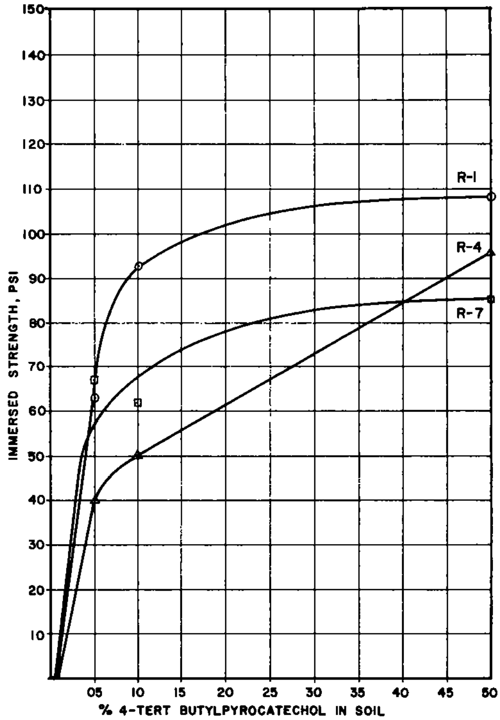

Figure 6. Immersed strength vs TBC content in three soils compacted by Iowa method.

is losing water via volatilization. This results in a somewhat disproportionate share of the TBC being adsorbed onto the soil surfaces adjacent to these capillary pores. Because it is these capillary pores that, when waterproofed, reduce the movement of water back into the soil, immediate compaction and drying results in a TBC distribution that is optimum for maximum exclusion of water, and hence, maximum immersed strength.

Soil Type Amenable to Treatment with TBC

The next series of experiments was devoted to determining what types of soils are most responsive to treatment with TBC. Several soils of widely varying properties were treated with two rates of TBC. They were compacted by the California method, cured for 7 days at 50 percent RH, and immersed for 24 hr before determining unconfined compressive strength and moisture content. In addition, the unimmersed compacted strengths of the untreated soils at optimum moisture were determined. The various soils used and the rates of TBC used are shown in Table 5, together with the results.

There are several soil factors that can influence the response of a soil to treatment with TBC. Clay content, however, appears to be the predominating factor. The results in Table 5, therefore, are listed in order of increasing clay content of the soils. They show that the unimmersed compacted strengths of the untreated soils at optimum moisture generally increase as the clay content increases. However, the data for the water contents of the treated soils expressed as a percent of the plastic limit reveal that as clay content increases, the effectiveness of TBC at keeping water out of the soil generally decreases. Consequently, the soils with the most natural strength are least amenable to having that strength protected from the deleterious effects of water. These two opposing effects of the clay content result in the net effect on the immersed strengths of the various soils given in Table 5. As clay content increases to about 20 percent, the

TABLE 6

LINEAR EXPANSION, MOISTURE CONTENT, AND UNCONFINED COMPRESSIVE STRENGTH OF SOIL R-1 TREATED WITH SEVERAL RATES OF TBC AFTER SUBJECTION TO 10 CYCLES OF FREEZING AND THAWING COMPARED TO SOIL NOT SUBJECTED TO FREEZING AND THAWING

Treatment Level (%)	Linear Expansion (%)		Moisture Content Increase (%)		Unconfined Compress Str. (psi)	
	Capillary Absorption	Freeze-Thaw	Capillary Absorption	Freeze-Thaw	Capillary Absorption	Freeze-Thaw
0.0	10.1	38 0	24.3	Mud	0	0
0.042	1.6	3.4	6.8	13.5	62	21
0 064	1.2	2.8	4.1	10 5	92	31
0.085	1.1	1.5	3 8	4.0	90	73

immersed strengths generally increase. As clay content increases beyond 20 percent, the immersed strengths generally decrease. Soils with clay contents in the range of 10 percent to 40 percent generally have reasonably high immersed strengths when treated with TBC. Thus, the soils that can be most effectively stabilized with TBC are limited to those with a moderate but not excessive percentage of clay.

Rates of TBC Necessary for Stabilization

The next series of experiments was designed to determine the rates of TBC necessary to obtain suitably stabilized soils. Several soils were treated with several rates of TBC, compacted by either the Iowa or California method, cured for 7 days at a 50 percent RH, and immersed for 24 hr before determining unconfined compressive strength. The soils, the rates of TBC, and the result obtained are shown in Figures 5 and 6.

Figures 5 and 6 show that for most soils about 0.1 percent TBC is essentially optimum. Rates exceeding this do not generally result in appreciable additional immersed strength. Many soils even retain a substantial portion of the maximum immersed strength at the 0.05 percent treatment level. All soils, however, lose strength quite rapidly as the treatment level is reduced below 0.05 percent, although in some instances the strengths at these very low levels are quite substantial. Thus, treatment levels of 0.05 to 0.10 percent appear to be suitable for obtaining maximum or near maximum immersed strengths. Lower levels may be acceptable in some soils if the strength imparted to the soil meets engineering specifications. If the strength obtained at the 0.10 percent level does not meet specifications, it is doubtful that higher levels should be considered.

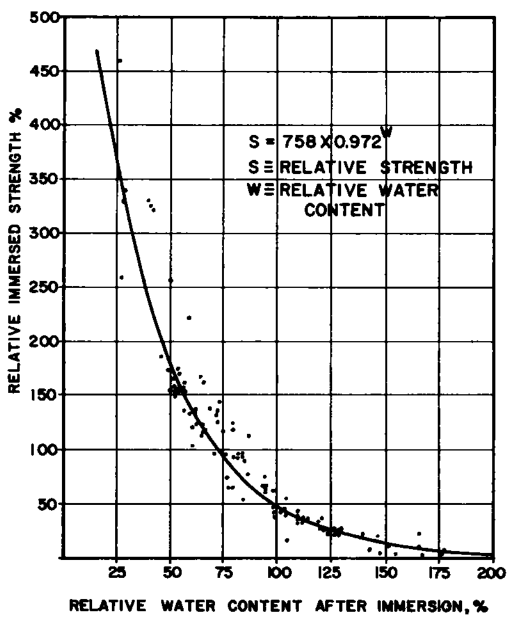

Figure 7. Plot of relative water content after immersion vs relative immersed strength for several soils treated with several rates of TBC under several varying treatment and cure conditions.

Effect of Freezing and Thawing on TBC Stabilized Soil

For a chemically stabilized soil to be of practical use it must be resistant to the deleterious effects of freezing and thawing. An experiment was conducted, therefore, to determine the effect of alternate freezing and thawing on TBC-stabilized soil.

Samples of soil R-1 were treated with several rates of TBC compacted by the Iowa method, and cured for 3 days at 100 percent RH and 4 days at 30 percent RH. One-half the samples from each treatment were then subjected to 10 cycles of freezing and thawing and the other half were placed on wet felt pads kept continually wet from a source of free water. The latter half of the samples were kept on the felt pads for a period of 10 days and allowed to adsorb an equilibrium amount of capillary water. All samples were then measured for linear expansion, moisture content increase from that at compaction, and unconfined compressive strength. The rates of TBC used in this experiment are given in Table 6 together with the results.

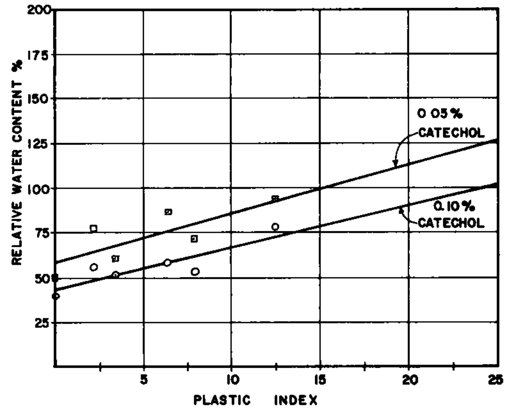

Figure 8. Relative water contents of several soils treated with 0.10 and 0.05 percent TBC vs plastic index of untreated soils.

It is evident that TBC greatly decreases the linear expansion and moisture absorption by the soil as a result of both freezing and thawing and capillary absorption. At the 0.042 and 0.064 percent rates of TBC there is some expansion and moisture absorption due to freezing and thawing over that resulting from simple capillary absorption. However, at the 0.085 percent level there is essentially no expansion or moisture absorption due to freeze-thaw over that caused by capillary absorption. The effect of the increased moisture content and consequent expansion caused by the freezing and thawing cycles on the unconfined compressive strength is shown in the last two columns of Table 6. The more the absorption of water due to freeze-thaw is decreased, the closer the strength of the soil subjected to freeze-thaw approaches that of the soil not subjected to freeze-thaw. Thus, at the 0.085 percent level of TBC the freeze-thaw cycles result in only a 19 percent loss in strength. Hence, the treated soil can be considered to be quite resistant to the deleterious effects of freeze-thaw.

Basic Function of TBC in Soil

The basic function of TBC in soil is strictly that of reducing the absorption of water by the soil. This becomes evident by plotting the relative immersed strength of any soil treated with any rate of TBC under any treatment conditions against the relative moisture content after immersion.

The relative moisture content can be expressed in percent as the ratio of the absolute water content after immersion to the optimum moisture content. The reason for using relative moisture content rather than absolute moisture content is that the relative moisture content is based on the free energy of the water in the soil. Soil physicists consider that the most valid statement of the moisture status of a soil is one based on the free energy, rather than the percentage of water in the soil. The use of the optimum moisture content as the base for the relative moisture content is somewhat arbitrary but nevertheless valid because all soils at optimum moisture contain water with approximately equal free energy.

The relative immersed strength can be expressed in percent as the ratio of the absolute immersed strength to the strength of the untreated compacted soil at optimum moisture. The reason for using the relative immersed strength is that this value removes the variation in natural strength between soils. The use of the strength of the untreated compacted soil at optimum moisture as a base is somewhat arbitrary. However, the natural strength of various soils should be reflected by their strength at any comparable moisture content on a free energy basis such as optimum moisture. Therefore, the strength of the untreated compacted soil at optimum moisture is a valid and convenient base on which to express relative immersed strength.

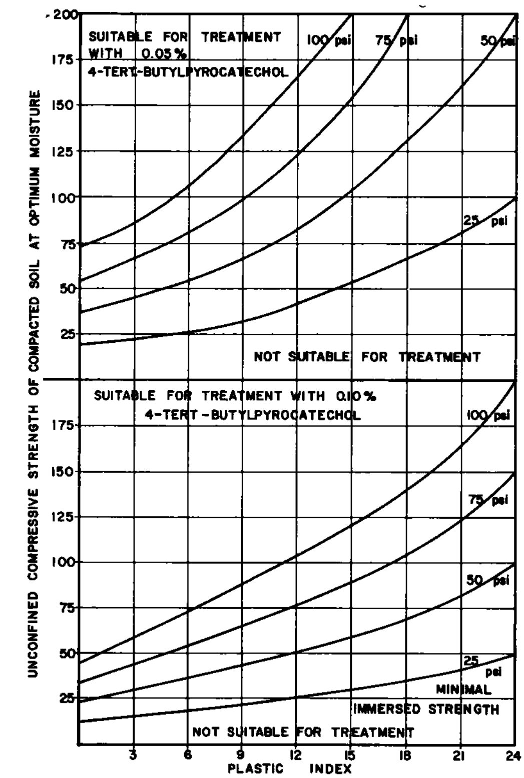

Figure 9. Nomograms of plastic index vs unconfined compressive strength at optimum moisture for untreated soil that will determine if soil will have above minimal immersed strength for treatment with 0.05 and 0.10 percent TBC.

Most of the data already presented were recalculated in terms of relative immersed strength. In addition, the corresponding relative moisture contents were calculated from unreported data. These results are plotted against each other in Figure 7, and the curve and its equation fitting these points is shown.

The points plotted in Figure 7 all fall quite close to the curve indicating the relatively exact nature of the relationship between relative immersed strength and relative water content after immersion. Thus it would seem that the relative strength is merely a function of the relative amount of water in the soil after immersion. Consequently, the relative strength imparted to a soil by TBC under any set of conditions and using any rate of TBC is simply a function of the ability of the TBC under the particular set of conditions and rate of use to keep water out.

REMARKS

The results presented thus far suggest several conclusions regarding the use of TBC as a soil waterproofing agent. As with all other chemical soil stabilizers, including cement, TBC will not do an acceptable job of stabilizing in all situations. The practicing engineer is, of course, interested in simple general criteria that will indicate the practicality of using the TBC in any given situation.

Such criteria can be presented, but will be contingent on certain assumptions regarding the ultimate design criteria for waterproofed soils in bases and subbases. Criteria for aggregate and cement or lime stabilized soils in bases and subbases have been established, but these criteria do not necessarily apply to waterproofed soil. Hopefully the criteria needed can be determined in the laboratory, but undoubtedly field experience with test roads also will be necessary.

Nevertheless, assuming that immersed unconfined compressive strength will be important in the ultimate design criteria for waterproofed soils, nomographs relating relatively simple soil properties can be prepared from which the suitability of any particular soil for treatment with TBC can be assessed. These nomographs can be prepared based on the results shown in Figure 7, which is a plot of relative immersed strength of soils vs relative water content after immersion.

First, it is necessary to determine if there is a relationship between the relative water content after immersion and any soil property. Figure 8 is a plot of relative water content of various soils treated with two levels of TBC vs the plastic indexes of the various soils. It is evident from Figure 8 that a reasonably good linear relationship exists. Thus, based on plastic index, it is possible to predict from Figure 8 the relative water content of any soil treated with either 0.05 percent or 0.10 percent TBC under optimum conditions. Then, referring to Figure 7, it is possible to determine the relative immersed strength of any soil based on the relative water content after immersion. Absolute immersed strength can then be determined on the basis of a knowledge of the maximum compacted strength of the particular soil. Thus, on the basis of maximum compacted strength and plastic index for any untreated soil, the immersed unconfined compressive strength can be predicted for treatment levels of either 0.05 percent or 0.10 percent TBC.

In the absence of any accepted design criteria regarding the immersed unconfined compressive strength of a waterproofed soil, four strengths were arbitrarily chosen as minimal and the nomographs shown in Figure 9 were constructed from the data in Figures 7 and 8 by essentially reversing the previously described process for predicting immersed strength. It is apparent from Figure 9 that as the plastic index of soils increases, the compacted strength of the soils must increase in order to maintain any given constant immersed strength. The practical use of these nomograms, however, is that for any soil with a known plastic index and maximum compacted strength, it is possible to determine if the soil falls above or below the line delineating the minimum acceptable immersed strength. If the soil falls on or above the minimal line, it probably can be effectively stabilized with TBC. Conversely, if the soil falls below the minimal, it cannot be stabilized with TBC. As pointed out previously, the appropriate minimal line to use as yet has not been determined.

CONCLUSIONS

TBC is a potentially useful chemical for rendering some soils acceptable substitutes for aggregate in highway bases and subbases. The optimum method for treatment with TBC is to add it in sufficient molding water to bring the soil up to optimum moisture for maximum dry density. The soil should then be compacted immediately and allowed to cure for about a week, preferably at a relative humidity of 30 to 50 percent. These conditions are optimum although they are not necessary prerequisites for successful treatment.

Generally, the soils that are most responsive to stabilization with TBC are silty in nature and contain between 10 percent and 40 percent clay. The rate of TBC necessary to stabilize these soils is in the range of 0.05 percent to 0.10 percent.

Extensive results regarding freezing and thawing were not presented, but treatments with TBC in the indicated range appear to maintain a substantial portion of their strength through 10 cycles of freezing and thawing. Because the moisture content of the soil is maintained at a relatively low level by TBC, it is to be anticipated that soils that can be effectively treated will be resistant to freeze-thaw.

The function of TBC in soil is merely to keep water out. The material does not appear to bind soil particles together. However, by keeping water out it permits the soil, regardless of moisture conditions, to retain a substantial portion of its dry strength.

In the absence of accepted design criteria for waterproofed soils in bases and subbases, it is difficult to determine how broad a range of soils will be amenable to treatment with TBC. However, it is possible by assuming various minimal strength criteria to determine whether a soil is suitable on the basis of its plastic index and optimum compacted strength.

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