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# Soil Stabilization Research at the Massachusetts Institute of Technology

## Recherche sur la Stabilisation des Sols à l'Institut de Technologie du Massachusett

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### Summary

For over ten years the M.I.T. Soil Stabilization Laboratory has been conducting research on improvement of soil properties with additives. This paper summarizes some of the most recent and important results of this research. The importance of soil technology to soil stabilization is first discussed then illustrated with experimental data.

Trace additives can effect significant changes in the properties of fine-grained soils. Data are presented to show that these trace chemicals can: (1) reduce the permeability of a fine sand to 1/200 of the value of the untreated sand; other chemicals can increase the reduced permeability by 20-fold; (2) reduce the frost heave of dirty gravels to 1/4 to 1/10 of the value of the untreated soil; (3) increase the strength of a silt 2½-fold; (4) increase the strength of silt-asphalt 4-fold; and (5) increase the strength of soil-cement 3-fold.

### Introduction

In 1946 the Massachusetts Institute of Technology, at the request of the Corps of Engineers, U.S. Army, undertook a programme of research aimed at developing materials and techniques for improving the stability of soils. The initial objective of the study was the development of a process which would transform a mud to a solid—'soil solidification'. From 1946 on, M.I.T. continued the research under both military and civil support with ever broadening scope and objectives. This broadened research is called, for lack of a better term, 'Soil Stabilization', to cover the alteration or control of any soil property. Soil stabilization, thus, is thought to include not only improvement in soil strength but also the alteration of such soil properties as permeability, compressibility, water sensitivity and frost susceptibility; soil stabilization covers not only the increase or decrease of any soil property, but also the reduction of variation of any property with changes in environmental conditions, mainly moisture or pressure.

The need for the techniques of soil stabilization is now well recognized. A number of factors—increased construction volume, more severe load conditions and growing shortages of select soils and building sites—have greatly extended and intensified the need and interest in soil stabilization.

Since techniques of soil stabilization are considered only when the soils existing at a site are not entirely acceptable in their present state, economic considerations are of primary importance. Military combat conditions or emergency civil conditions may justify expensive treatments. Large-scale stabilization must usually be cheaper, however, than other available techniques such as replacing the unsuitable soil with a satisfactory one like gravel or crushed stone. Since gravel or crushed stone can usually be placed at \$1.50 to \$3.50 per cu. yd., soil stabilization techniques must cost no more if they are to receive large-scale use under normal conditions.

There are many problems where only a relatively minor change in a soil property is needed. The specifications for

### Sommaire

Depuis plus de dix années, le laboratoire de stabilisation des sols du M.I.T. conduit des recherches dans le but d'améliorer les propriétés d'un sol au moyen d'addition de produits variés. Cette communication résume les plus récents et importants résultats de ces recherches. L'importance de la technologie des sols au point de vue de la stabilisation est en premier lieu discutée, puis illustrée avec des résultats expérimentaux.

Des produits ajoutés en traces peuvent produire des changements significatifs dans les propriétés des sols à grain fin. Des résultats sont présentés pour montrer que ces produits chimiques peuvent: (1) Réduire la perméabilité des sables fins jusqu'à 1/200 de la valeur de celle du sable non traité; d'autres produits chimiques peuvent augmenter la perméabilité ainsi réduite, par un facteur de multiplication de 20; (2) Réduire le gonflement dû au gel des graviers argileux jusqu'à 1/4 et même au 1/10 de celui du sol non traité. (3) Multiplier par 2.5 la résistance d'un silt; (4) Multiplier par 4 la résistance d'un silt-asphalte; et (5) Multiplier par 3 la résistance d'un sol-ciment.

pavement base course material, for example, cause many soils to be rejected even though they narrowly miss being acceptable. Millions of tons of these borderline soils have been discarded that could be used if only a modest improvement in their properties could be effected. Such a modest improvement can often be obtained with a trace (1 per cent or less of the soil dry weight) level of treatment.

While the results reported herein are typical, soils have been encountered which do not respond well; in fact, a few have been studied which did not respond to such things as polyphosphates. These facts mean that, in any practical problem, the effectiveness of the trace chemical under consideration will have to be determined with the actual soil involved. This characteristic of trace chemical stabilization is expected, since the process involves a reaction between the chemical and the soil. Full exploitation of this type of stabilization necessitates a better understanding of the basic nature of soil particles.

While the permissive additive cost per volume of soil treated is the same for trace as for regular stabilizers, the permissive unit cost is obviously higher since less is used. For treatment levels varying from 0.01 to 1 per cent of the soil dry weight, the allowable cost ranges from 5 cents to over \$1.00 per lb. Thus, not only the conventional stabilizers, Portland cement and asphalt, can be used for economical stabilization, but also a large group of chemicals can be considered if they are effective at low concentrations.

Two other means of soil stabilization—addition of soil, and moisture adjustment plus compaction—deserve consideration. Under special conditions a satisfactory answer to a particular problem can be obtained merely by the proper addition of some local soil; this can be very economical. As TURNBULL and FOSTER (1956) correctly point out, moisture adjustment and compaction are an integral part of nearly all processes of soil stabilization and are often all that are needed to obtain the particular soil properties desired.

The remaining portion of this paper describes research at M.I.T. both on these useful means of soil stabilization and on fundamental soil characterization underlying soil stabilization.

## Soil Technology

Both compaction and trace-chemical stabilization depend upon the manipulation of soil and reactions of water and/or chemicals with soil. In these processes we cannot, therefore, consider soil as an inert filler as we can often do in soil solidification. The exploitation of the most promising soil stabilization has, therefore, forced the M.I.T. research into what the author has termed 'Soil Technology'. Soil technology is the applied science which treats the geological history and the composition of soil and the influence of these two factors on the engineering behaviour of soil. Soil technology considers not only the nature of the soil components but also the arrangement of them and interaction among them. It draws upon

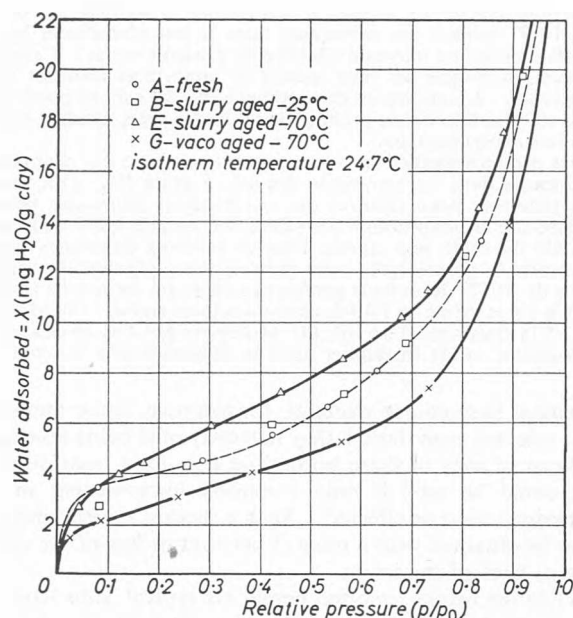


Fig. 1 Water-adsorption isotherms of lithium kaolinite  
Isothermes d'adsorption d'eau du lithium kaolinite

colloid chemistry, mineralogy, sedimentology and soil mechanics to explain soil behaviour and how it may be altered.

The necessity of studying soil technology in order to have a fruitful programme of research in soil stabilization is apparent. How, for example, can reactions between chemicals and soil or reactions between water and soil be understood and controlled without a knowledge of the chemistry of the soil? How can the strength of a clay be most effectively increased unless the source of the natural strength in the clay is understood?

In the following paragraphs the basic importance of soil technology to soil stabilization and, in fact, to the fundamental understanding of soil behaviour is illustrated.

**Structure of compacted soil**—Soil technology offers much promise for the more effective use of compaction to obtain desired soil properties. Using MITCHELL'S (1956) technique of microscopic study of thin sections of fine-grained soils, PACEY (1956) has shown that a sample of fine-grained soil compacted wet of optimum moisture content for maximum density has an arrangement of particles more nearly approaching parallel orientation within small zones than a sample of the same soil compacted dry of optimum. This difference in soil structure explains why the sample compacted wet of optimum will shrink more on drying than one compacted dry of optimum to the

same density; also, it explains why a sample compacted dry of optimum and soaked to a moisture content wet of optimum has a higher strength than a sample of the same soil compacted to the same density wet of optimum. Pacey also showed that an increase in compactive effort for soil samples at the same moulding moisture content causes a trend towards a parallel orientation of adjacent particles.

These structure concepts may well permit a fundamental explanation of the significant differences in soil properties obtained by the various methods of compaction. Answers may be forthcoming to such questions as: Why is a soil compacted by dynamic loading to a given density usually much stronger than a sample of the same soil at the same moisture content compacted to the same density with static loading?

**Adsorption studies**—Studies employing a unique high vacuum apparatus are yielding very interesting results. In unpublished work, R. T. Martin, of the M.I.T. Soil Staff has found marked differences in the adsorption isotherms of samples of kaolinite subjected to different environmental conditions. His results in Fig. 1 show, for example, a 60 per cent variation in moisture

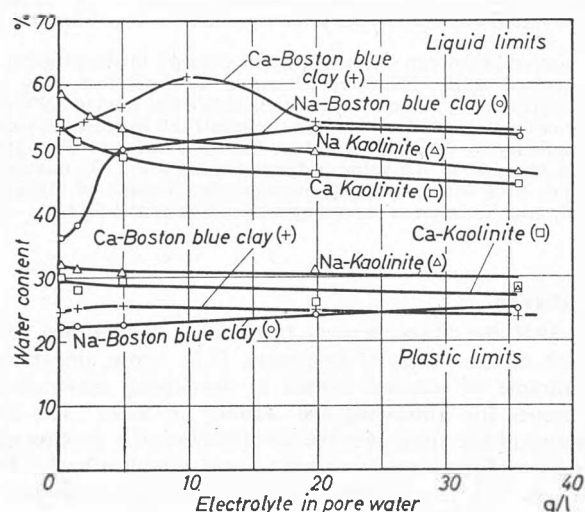


Fig. 2 Atterberg limits of homoionic clays versus electrolyte concentration in pore fluid  
Limites d'Atterberg d'argiles à ion unique versus concentration d'électrolytes dans le fluide

adsorption at a partial pressure of 0.5 for samples of lithium kaolinite, aged under different conditions.

These adsorption studies, aided by chemical analysis, showed that aging kaolinite in water resulted in the removal of aluminium from the gibbsite sheets of the kaolinite. This aluminium replaced the exchangeable lithium and therefore converted the lithium clay to an aluminium one. This type of reaction could play an important part in the gain of strength with time of cohesive soils.

Fig. 1 also shows that drying kaolinite resulted in a 25 per cent decrease in the specific surface of the clay. These measurements help give fundamental explanations of why soil properties, for example plasticity, can be changed when a soil is dried.

**The influence of electrolyte content of pore fluid on soil**—Research on reactions explainable by the principles of colloid chemistry are giving fundamental information. GREEN (1956) studied the effects of electrolytes in pore fluids on the properties of homoionic clays. By employing homoionic clays and mono-electrolyte pore fluids, he excluded ion exchange and thus measured the effects of pore fluid alone on the properties of the clays.

Fig. 2 gives the Atterberg limits of homoionic Boston blue clay and homoionic kaolinite as a function of concentration of electrolyte in the pore fluid. The electrolyte in the pore fluid contained the same cation as that on the homoionic clay; no ion exchange, therefore, occurred.

The results in Fig. 2 show several important points:

(1) The nature of the pore fluid can have a very large effect on the liquid limit of the soil. At the least then, Fig. 2 indicates consideration must be given to the pore fluid in measuring and interpreting laboratory tests on fine-grained soils.

(2) The variation of plastic limit with electrolyte concentration was relatively small and, in general, was in the same direction as the variation of the liquid limit.

(3) The most marked variations occurred at low concentrations of salt.

(4) The variation of liquid limit with salt concentration on the kaolinite is opposite to that of the Boston blue clay. This difference arises because the flocculation of the illitic Boston blue clay is normal colloidal type while the kaolinite is an edge-to-face type (SCHOFIELD and SAMSON, 1954).

Green also prepared dilute suspensions of the clays in pore fluids and measured flocculation. He found that, in general, liquid limit was directly related to degree and type of flocculation, as one would expect.

### Trace Chemicals

Modest but significant changes can usually be produced in soils containing some particles finer than 0.074 mm by the addition of 1 per cent or less of various chemicals which react with the soil. These effective trace chemicals employ one or more of the following three mechanisms: dispersion, aggregation, waterproofing.

Dispersants such as the polyphosphates:

- (1) furnish monovalent cations, usually sodium, for exchange reactions with the soil,
- (2) remove polyvalent cations on the soil by chelation or sequestration,
- (3) increase the negative charge on the soil particle by supplying polyvalent anions, such as polyphosphates, which become attached to the soil surface.

Measurements in the M.I.T. Soils Laboratory showed that the addition of polyphosphates to kaolinite increased its cation exchange capacity by 50 per cent. This increase of negative charge of the soil by dispersants is much larger than was originally thought and may, in fact, be the most important of the three actions of the dispersants with soil.

Aggregants, such as polyvalent cations like ferric iron, can cause aggregation of soil fines by depressing their diffuse double layers, that is, reducing the repulsive charges between particles so that the attractive forces control. Polyvalent long-chain polymeric materials can aggregate soil by actually linking adjacent particles together.

Waterproofers are materials which react with the soil surface and, in effect, make the water-sensitive soil surface hydrophobic.

In the remaining paragraphs of this section are presented experimental data which illustrate the effects trace chemicals can have on the engineering properties of soils.

*The effect of aggregants and dispersants on the permeability of a dirty sand*—OLSEN (1956) has measured the effect of several aggregants and several dispersants on the permeability of a sand containing 11 per cent by weight of particles finer than 0.074 mm. This dirty sand had, unfortunately, about 4 per cent organic matter which caused time effects on the results; such time effects have not been observed on other soils. Fig. 3, a plot of some of Olsen's data, shows how large can be the

effects of the trace chemicals on the permeability of fine sand. The dispersant reduced the permeability to 1/200 of the value of the untreated sand; the aggregant increased the dispersant-treated permeability by a factor of 20.

The trace chemicals brought about the permeability changes by reacting with the fines. Two related phenomena occurred: (a) changes in the fabric of the fines, and (b) movement by the permeant of the dispersed fines. Olsen arrived at these explanations by measuring the fines in the effluent from his tests; he also made pore-water pressure measurements at several points in the permeameter in order to compute permeabilities at various positions in the tube.

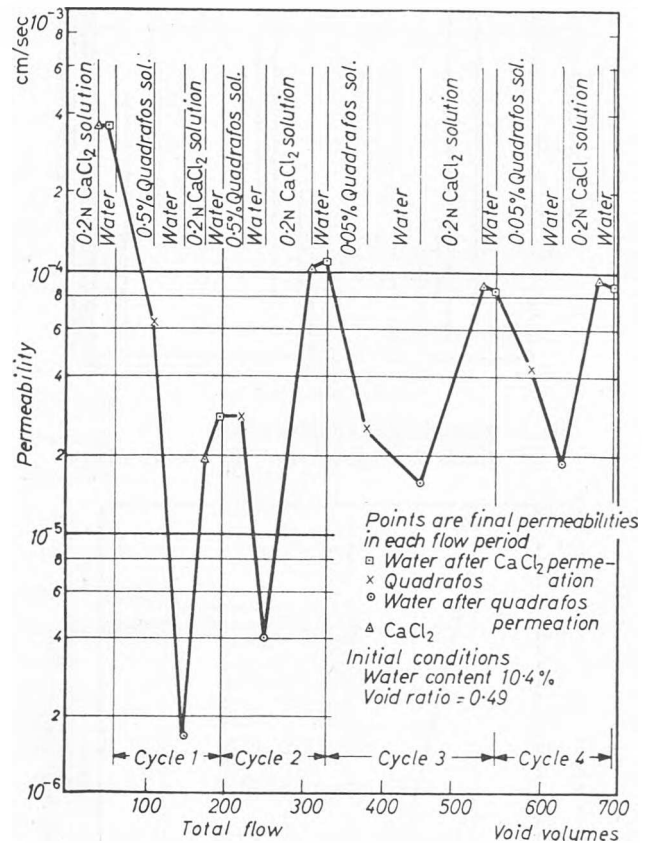


Fig. 3 Permeability of dirty sand leached with different permeants  
Perméabilité d'un sable argileux lavé par différents agents

*The effect of a dispersant on the frost-heave characteristics of dirty gravels*—In connection with the Arctic Construction and Frost Effects Laboratory, Corps of Engineers, the author (1956) has studied a number of trace chemicals to determine their effectiveness to modify the frost-heaving characteristics of soil. The samples were mixed with the chemical in question, compacted and frozen gradually from the top while the bottom of the sample had free access to water.

Fig. 4 shows the frost-heave of a group of dirty gravels before and after treatment with 0.5 per cent of tetrasodium pyrophosphate, a dispersant. The data show that the dispersant reduced the frost-heave of all of the dirty gravels and reduced the heave of 75 per cent of the gravels to the 'negligible' frost-susceptibility classification of the U.S. Engineers Corps.

Fig. 5 presents the results of four cycles of freeze-thaw on four dirty gravels treated with 0.3 per cent of the tetrasodium pyrophosphate. This illustration shows that the chemical did not lose its effectiveness with cycles of freezing-thawing; the

effects of cyclic freeze-thaws could be important on a clay, however, since the clay does not have the large gravel particles to control its mass structure.

Since the mechanism by which moisture migrates to form ice lenses in freezing soil is not completely understood, the reasons for the effectiveness of the dispersants are not definitely known.

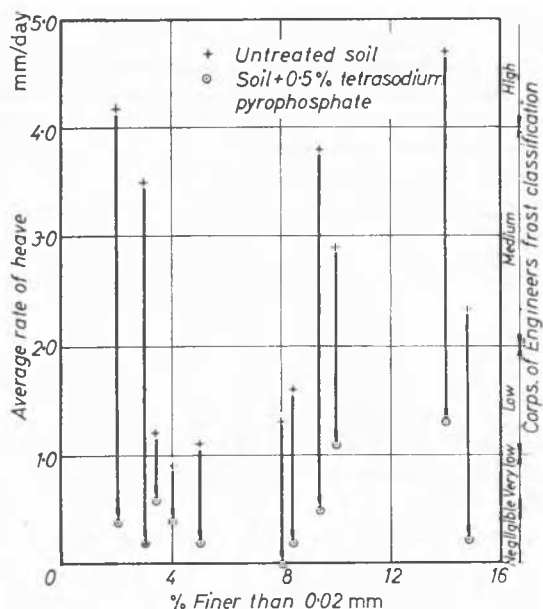


Fig. 4 Freezing tests on dirty gravels  
Essais de congélation sur les graviers argileux

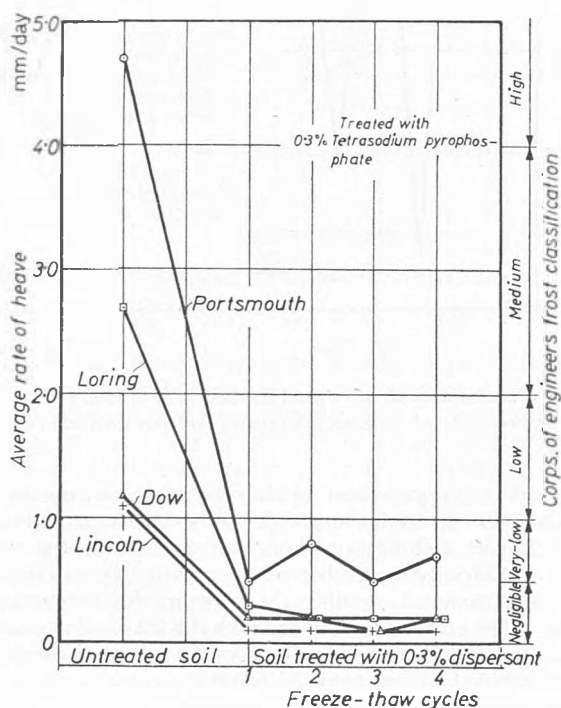


Fig. 5 Freeze-thaw cycles on dirty gravels  
Cycles de congélation et de dégel sur les graviers argileux

The improvements brought about by the dispersants could well be related to the changes in permeability as described in the preceding section. If this explanation is indeed the correct one, treatment by leaching could be more effective than by mechanical blending since we would get the beneficial effect of the leachate moving fines.

*The effect of trace chemicals on soil stability*—Massachusetts Institute of Technology has conducted extensive studies to determine the effect of trace chemicals on the stability of soil. Work of OLENTINE and PARISH (1955) indicates how effective the trace chemicals can be. They mixed the various chemicals with a uniform silt from New Hampshire, compacted the treated soil, immediately soaked the samples with a surcharge of  $\frac{1}{2}$  lb./sq. in. for 24 hours and then tested them for water content and cone penetration resistance. They prepared and tested samples over a wide range of moulding water contents; Table 1 summarizes the results on the samples at optimum

Table 1

Effect of trace chemicals on equilibrium water content, cone index and density of New Hampshire silt  
Effet des produits ajoutés en trace sur la teneur en eau d'équilibre, indice de cône et densité d'un silt du New Hampshire

Additive	Optimum water content (moulding) in %	Peak dry density lb./cu. ft.	Maximum cone index lb./sq. in.	Equilibrium water content* in %
Control-zero additive	20.5	100.8	136	28.1
0.1% Alkyl dimethyl benzyl ammonium chloride	21.5	100.8	330	24.5
0.1% Arquad 2HT	19.5	102.0	320	22.7
0.05% Arquad 2HT	20.0	101.8	290	22.6
1.0% Agrilon	23.8	96.8	268	24.7
0.1% Tetrasodium pyrophosphate	19.8	103.0	171	26.1
0.1% Aluminium phosphate	20.0	103.0	140	25.2
0.1% Ethylene diamine dihydrochloride	20.5	100.1	143	23.2
0.1% Ferric sulphate	21.0	102.6	156	25.5
0.1% Aluminium sulphate	20.0	101.3	172	25.5
0.1% Zinc sulphate	19.0	102.8	146	24.8
0.1% Ferric chloride (sample oven-dried before soaking)	19.8	101.5	340	24.5

\* Equilibrium water contents listed are those corresponding to optimum moulding water contents.

moisture content. The data in Table 1 show that all of the additives studied were effective in reducing the moisture pickup of the silt on soaking and increased the cone penetration resistance of the soaked sample. The waterproofers, alkyl dimethyl benzyl ammonium chloride and Arquad 2HT, and the aggregants, agrilon and ferric chloride, were the most effective. The results in Table 1 were obtained on samples tested with no cure, except for the ferric chloride treated sample which was oven dried prior to soaking. Subsequent testing has shown that the ferric chloride is sometimes more effective when accompanied by drying than it is without drying.

#### Effect of Additives to Asphalt and Portland Cement

The well-known stabilizers, asphalt and Portland cement, have a proven record of good performance where used properly. Additives which would increase the effectiveness of these two stabilizers would, therefore, be useful. These additives could permit treatment with less stabilizer, improve the properties of the treated soil, and might even permit treatment of soils which could not otherwise be stabilized with the asphalt or cement

alone. Described in the following paragraphs of this section are some of the extensive studies conducted at M.I.T. in search of additives to improve asphalt and Portland cement.

**Additives to asphalt**—The effect of many additives on both cutbacks and emulsions when added to a silt from Massachusetts have been conducted. MICHAELS and PUZINAUSKAS (1956) have described the asphalt studies conducted at M.I.T. Tables 2 and 3, taken from their paper, illustrate the significant improvement of asphalt stabilization which can be obtained by trace additives. As noted in Table 3, the phosphorus pentoxide markedly accelerated the development of water resistance.

As shown in Fig. 6, Michaels and Puzinauskas found, for all

Table 2

Effect of chemical additives on re-wet strength of asphalt cutback stabilized silt

Effet de l'addition des produits chimiques sur la résistance après réhumidification d'un silt stabilisé au cutback

Additive*	Concentration, % on asphalt	% Residual volatiles after curing	% Water adsorption	Re-wet compressive strength lb./sq. in.	% Improvement
None	—	1.0	4.2	129	—
DDI	10	0.9	2.5	230	78
TDI	10	1.0	3.0	268	108
TTI	10	1.0	5.0	150	16
P <sub>2</sub> O <sub>5</sub>	20	4.4	2.8	245	90
P <sub>2</sub> O <sub>5</sub>	10	3.9	2.5	202	56
Epon 828	10	0.8	2.9	152	18
+ DETA	2				

\* DDI: Diphenyl methane diisocyanate

TDI: Toluene diisocyanate

TTI: Triphenylmethane trisocyanate

Epon 828: An epoxy resin manufactured by Shell Chemical Corporation

DETA: Diethylene triamine

2 weeks cure at 50 per cent R.H., 25° C.; 1 week water immersion at 25° C.; cutback: 2 parts straight-run asphalt per 1 part gasoline; 5 per cent asphalt on soil; 11 per cent moulding water

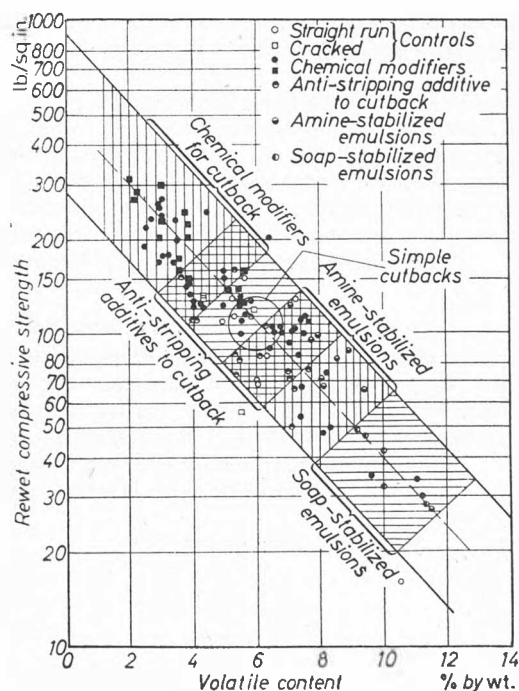


Fig. 6 Re-wet strength of soil-asphalt versus volatiles content  
Résistance après réhumidification d'un sol-asphalte versus teneur en matières volatiles

forms of asphalt stabilization on the Massachusetts silt, a general correlation between re-wet strength and volatile content of the specimen at time of test; all samples contained 5 per cent

Table 3

Effect of P<sub>2</sub>O<sub>5</sub> on silt stabilized with 2:1 asphalt cutback  
Effet de P<sub>2</sub>O<sub>5</sub> sur un silt stabilisé au cutback 2:1

P <sub>2</sub> O <sub>5</sub> %	Curing time, days	% Residual volatiles	Cured compressive strength lb./sq. in.	% Water adsorption	Re-wet compressive strength lb./sq. in.	% Improvement in re-wet strength
0	2	1.48	199	7.17	18.5	—
	7	1.65	226	5.15	67	—
	14	1.75	270	4.83	84	—
5	2	1.34	193	6.34	40	116
	7	1.65	281	6.16	73	9
	14	1.55	336	5.03	94	12
10	2	1.94	208	5.94	65	252
	7	1.65	279	5.70	109	63
	14	2.02	353	5.61	110	31

Cured at 50 per cent R.H., 27° C.; immersed in water for 7 days at 27° C.; M21 soil; straight run asphalt, 2 parts/1 part gasoline; 5 per cent asphalt on soil; 11 per cent moulding water; as-moulded density: 119-121 lb./cu. ft.

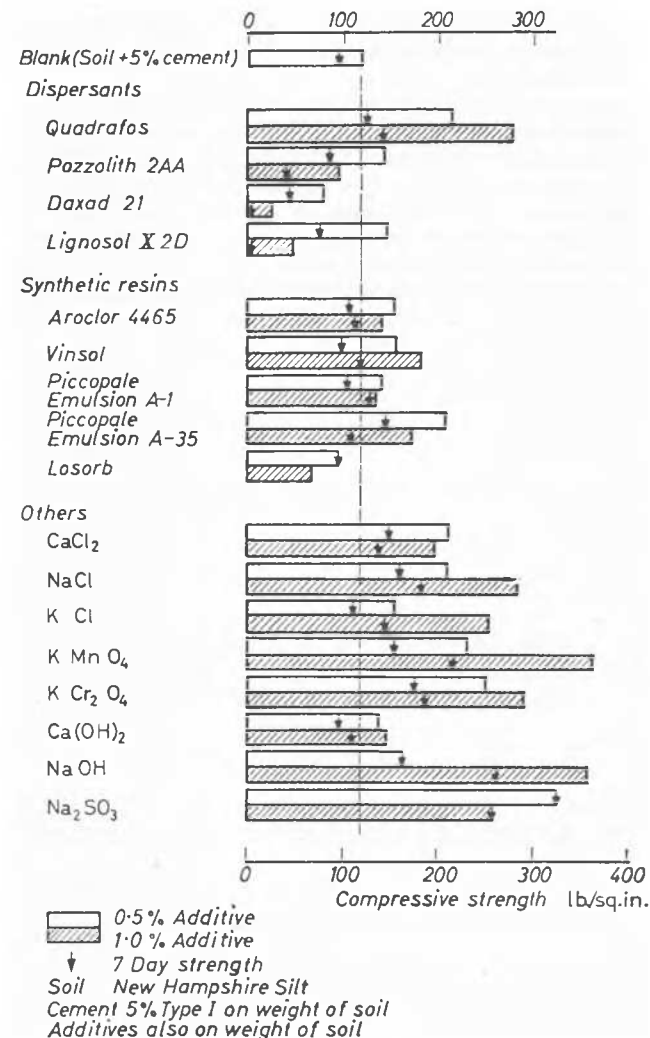


Fig. 7 Effect of trace additives on the strength of soil-cement  
Effet de produits, ajoutés en traces, sur la résistance d'un sol-ciment

asphalt. From this correlation they concluded that asphalt, irrespective of its method of incorporation with the soil or its chemical alteration, functioned primarily as a waterproofing agent for the soil. The various additives improved incorporation and thus merely enhanced the characteristic waterproofing ability of the asphalt.

**Additives to cement**—Massachusetts Institute of Technology has been searching for some time for additives which would improve the effectiveness of Portland cement when mixed with soil. The first group of additives studied were dispersants; this choice was based on the hope that, since the dispersants increased the compacted density of a soil-water system, they might do the same for a soil-water-cement system and, therefore, increase the strength of the cement-treated soil. DENZ and STEINBORN (1953) found that this hope could indeed be realized. Moh, who continued and expanded the work of Denz and Steinborn, and others at M.I.T., obtained the results shown in Fig. 7. Moh blended the water with trace additive dissolved in it with the dry soil-cement in a sigma-blade mixer, compacted the mixture at optimum moisture, cured the specimens 7 or 28 days at 100 per cent relative humidity, immersed them in water for 24 hours and then tested them in unconfined compression.

The results in Fig. 7 are most encouraging. Sodium chloride, costing less than 1 cent a lb., more than doubled the 28-day strength of the soil-cement when only 1 per cent of the salt was added. Sodium sulphite, another cheap chemical, increased the 7-day strength of the soil-cement over threefold at 1 per cent of salt concentration.

The soil used for the test reported in Fig. 7 was a uniform silt from New Hampshire. This silt plus cement has responded to more trace additives than any of the other soils studied. While certain additives such as sodium hydroxide were beneficial to all soils tested, the performance of the other additives was spotty—good on some soils and ineffective and, in fact, detrimental in certain cases on other soils.

Moh is working on the chemistry of the reactions in the soil-

cement water-additive system in order that the most effective additive can be found and the reasons that certain soils do not respond as well as others determined.

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