SURFACE CHEMICAL FACTORS OF IMPORTANCE IN THE HARDENING OF SOILS BY MEANS OF PORTLAND CEMENT

By Hans F Winterkorn, Harold J Gibbs and Rollie G Fehrman
University of Missouri

SYNOPSIS

Only by study of the chemical factors influencing cement reaction with soils will it be possible to obtain that insight into soil-cement relationships which is necessary for further theoretical and practical advance in this field The purpose of this work has been to procure test data on four clay soils of different pedologic and, therefore, different chemical character, and on a number of their homoionic modifications The ionic treatment has been used to produce definite variations in the chemical and physical characteristics in the four primary soil types.

Standard soil-cement and compression tests were employed to obtain data on the influence of exchangeable cations, physical soil constants, density of the soil-cement systems, and moisture content of the soil-cement systems at time of compaction.

The results show (a) that the surface-chemical along with other physical factors influence the hardening of clay soils with portland cement, (b) that ionic treatment can improve the hardening action, (c) that the difference between the optimum moisture content and shrinkage limit of inorganic clay soils is a measure of its susceptibility to stabilization; (d) that the water affinity and the accessibility of the internal surface of the soil-cement system controls its behavior in the wet-dry tests; (e) that the permeability of the system and the amount of pore space filled with unadsorbed water determines its behavior in the freezing and thawing tests, and (f) that organic matter of an acid nature affects the soil-cement system adversely

This work also indicates that shorter test procedures may be evolved for the design of soil-cement mixtures

Soil hardening by means of portland cement has become of considerable importance. While the physical aspects have been extensively investigated and testing procedures developed, the chemical aspects have been neglected

Phenomena observed in the field and in the laboratory have strongly indicated that the chemical relations of soil and cement are very important. From research experience with other types of soil stabilization it appears very probable that great insight into the chemical mechanism of soil hardening with cement can be obtained, and great practical benefit can be derived by combining soils of known chemical characteristics with portland cement, and by applying the standard soil-cement tests to the resulting systems.

Data of this sort were obtained and analysed in the work reported in this paper. Beside the general theoretical significance of such data for the understanding of the reactions of soil-cement systems, they appear to possess a direct bearing on at least two practical problems One of these is the reduction of the testing time for soil-cement specimens; the other is the treatment of clay soil by means of cations for the purpose of easier subsequent hardening by means of portland cement.

This project was undertaken from a combined pedological and chemical point of view since a purely chemical investigation in this field cannot be expected to produce engineering data in a limited period of time. On the other hand, a purely pedologic approach, while it may lead to a good empirical solution, appears

TABLE 1

NAMES AND PEDOLOGIC DATA OF THE NATURAL SOIL MATERIALS
(All samples taken from the B-horizon)

Name	Parent materials	Soil group	Percentage of organic matter
Putnam clay	Mixed glacial and loessial	Grey-brown podsolic (planosol)	0 75
Cecil clay	Gneiss	Red and yellow podsolic (lateritic material)	None
Hagerstown clay	Limestone	Reddish-brown podsolic	None
Hays clay	Shales and limestones	Chernozem	1 4

TABLE 2

Mechanical analysis of the natural soils (size in mm)

Soil	Particles smaller than 2 0 mm, per cent			
	Sand 0 84-0 05	Silt 0 05-0 005	Clay 0 005-0 001	Colloids 0 001
Putnam	7	39	21	33
Cecil	43 7	28 3	6 6	21 4
Hagerstown	19 5	37	16 5	27
Hays	7	46	21	26

Subgrade soil constants of the natural soils

Soil	Liquid limit	Plastic limit	Shrinkage limit	Optimun moisture
Putnam	64 3	23 6	17 8	28 8
Cecil	44 6	29.5	22 7	20 5
Hagerstown	46 3	19 3	19 3	18 0
Hays	57 2	24 2	16 3	25.0

to require a framework of chemical facts in order to form a solid basis for interpolation.

CHARACTERIZATION OF THE SOIL MATERIALS EMPLOYED

The soil materials employed in this study are characterized by the data contained in Tables 1 to 3 and Figures 1 to 7.

The different homoionic soils were prepared following the method described last

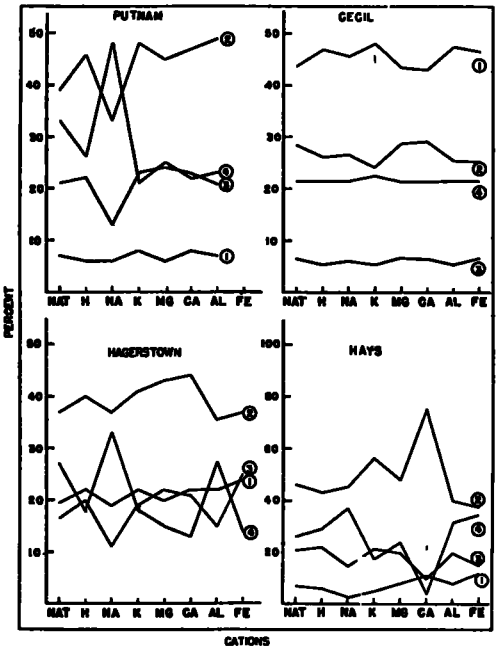

Figure 1. Size Composition of Natural and Homoionic Soils as a Function of the Exchange Ions. 1—Sand. 2—Silt. 3—Clay. 4—Colloids.

year (1)[1], the cation content of the soils was checked by extraction with neutral ammonium acetate and spectroscopic analysis of the extract The data are contained in Table 3. The effect of different cations on the physical properties of soils has been thoroughly discussed in the reference given above. This discussion is gen-

[1] Figures in parentheses refer to the list of references at the end of the paper.

TABLE 3

BASE EXCHANGE CAPACITY AND CATION CONTENT OF THE NATURAL AND HOMOIONIC SOIL MATERIALS

(In milli equivalents per 100 g of soil)

Soil material	Base exchange capacity[a]	Cation content of the natural soils[b]					Cation content of the homoionic soils[c]				
		H[c]	Na	K	Mg	Ca	H[d]	Na	K	Mg	Ca
Putnam Clay	30 8	12 3	1 4	1 0	4 5	11 6	30	30 7	27 8	26 4	33.8
Cecil Clay	4 0	1 0	0 3	0 4	0 7	1 6	4	3.0	3 0	3 4	3 8
Hagerstown Clay	25 0	6 5	0 7	1 0	7 2	9 6	25	19 7	15 2	16 0	18 3
Hays Clay	28 4		0 6	1 7	9 5	19 8	28	35 8	34 8	30 0	25 5

[a] By potentiometric titration of the H-soil
[b] By extraction with ammonium acetate and Spectroscopic analysis (Mr V. R. Ells, Univ of Mo) (the Putnam soil analysis was also checked gravimetrically) [c] By subtraction [d] From base exchange capacity.
[e] Amounts of cations equal to the base exchange capacity had been added in the preparation of the soils.

erally applicable for the physical data contained in this paper and need not be repeated

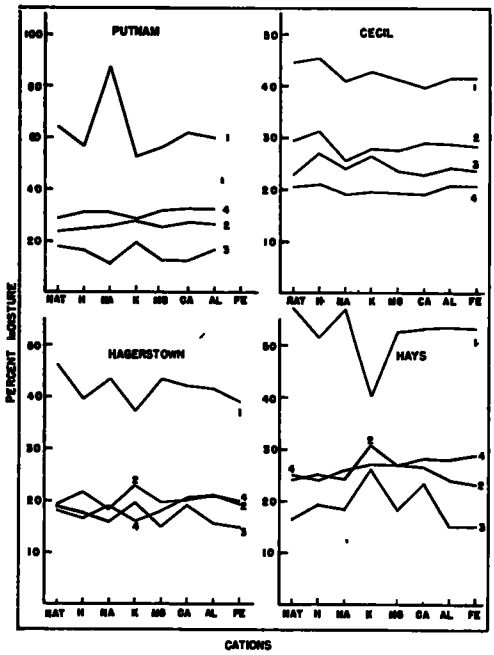

Figure 2. Subgrade Soil Constants of the Natural and Homoionic Soils as Functions of the Exchange Ions. 1—Liquid Limit. 2—Plastic Limit. 3—Shrinkage Limit. 4—Optimum Moisture.

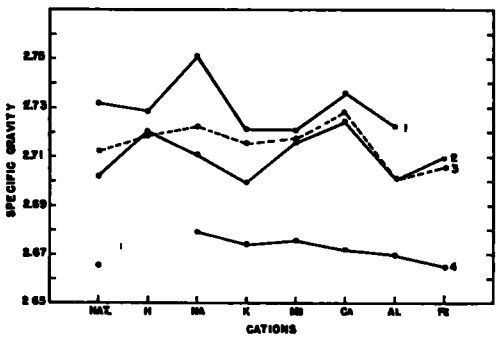

Figure 3. The Specific Gravity of Natural and Homoionic Soils as Determined in Water 1—Putnam. 2—Hays. 3—Hagerstown. 4—Cecil.

The portland cement used in this work was of an ordinary type and was obtained from a local lumber company The entire supply was bought at the same time and came from the same shipment. Airtight containers were used to store the cement. The specific gravity as determined in aniline was 3 15

Distilled water was used in the preparation of all soils and all soil-cement specimens Tap water was used for soaking the wetting and drying test specimens and for furnishing moisture in the moist room.

DESCRIPTION OF THE EQUIPMENT EMPLOYED

In addition to the usual laboratory equipment the following appliances were used in the investigation

1 Two mechanical Proctor compaction machines (Fig. 8).
2 P.C A device for preparation of two-inch specimens (Fig. 9).
3 Two twelve-quart Hobart industrial mixers (Fig. 10)

Test Methods

1. Determination of optimum moisture content and maximum density for soils. A. A. S. H O Test No T99-38.
2. Determination of optimum moisture content and maximum density for soil-cement mixtures: A. S. T. M. Designation: D558-40T
3. Freezing and thawing tests: A S. T. M Designation · D560-40T.
4 Wetting and drying tests A. S. T M Designation D559-40T
5. Preparation and testing of 2-in specimens P.C.A procedure.
6. Standard physical and chemical tests

DISCUSSION OF THE TYPE OF MOISTURE DENSITY CURVE OBTAINED FOR THE SOIL-CEMENT SYSTEMS

The moisture density curves for the different homoionic soils are given in Figures 4 to 7. For reasons of space and legibility, it was decided not to give

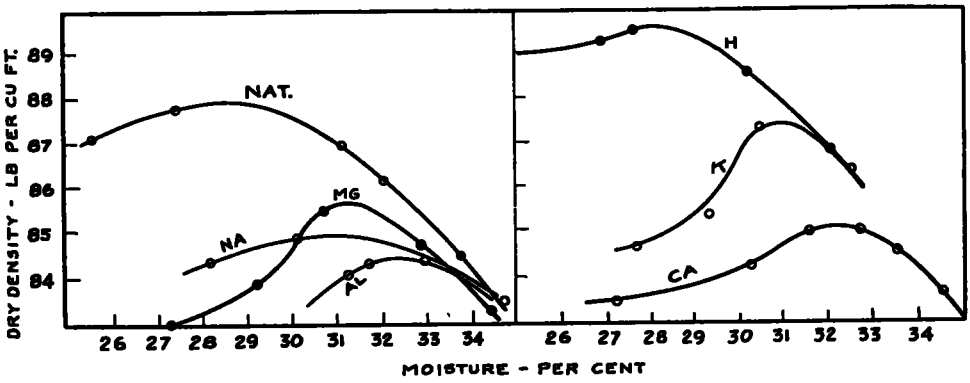

Figure 4. Moisture-Density Curves, Natural and Homoionic Putnam Soils

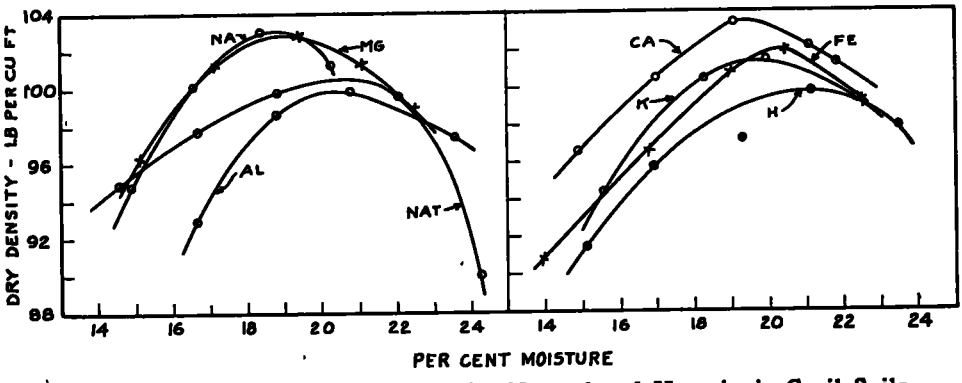

Figure 5. Moisture-Density Curves for Natural and Homoionic Cecil Soils

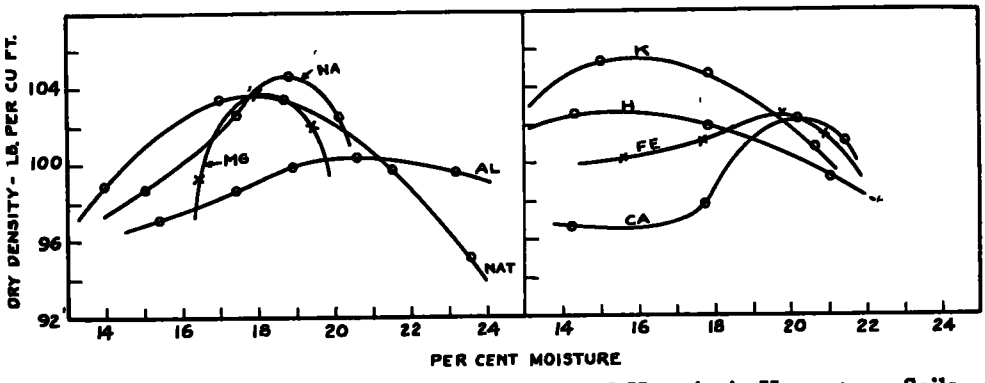

Figure 6. Moisture-Density Curves for Natural and Homoionic Hagerstown Soils

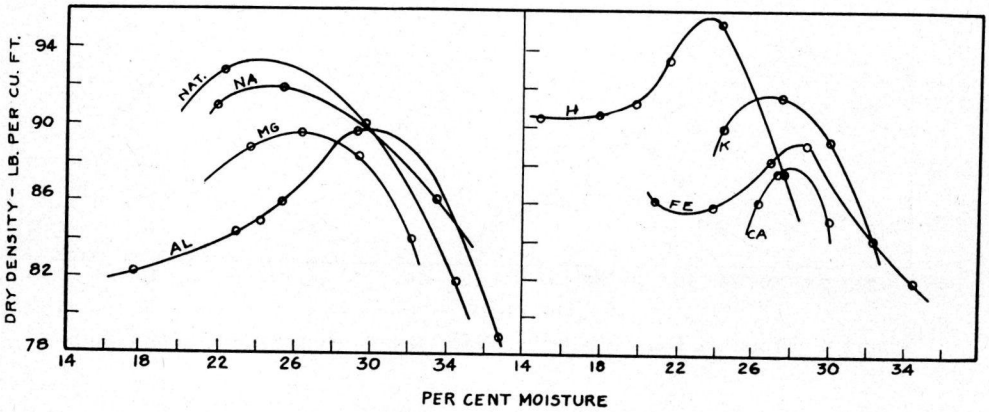

Figure 7. Moisture-Density Curves for Natural and Homoionic Hays Soils

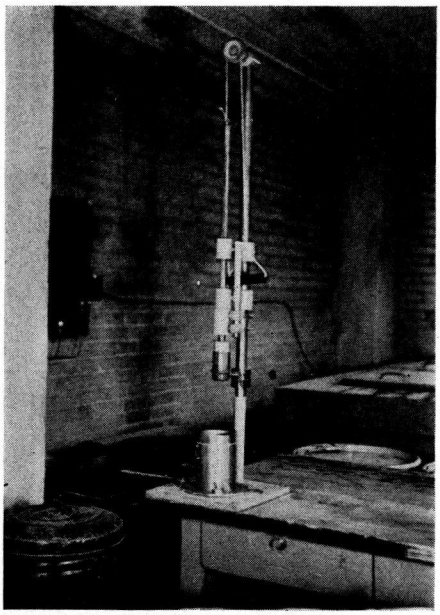

Figure 8. Mechanical Proctor Compaction Machine

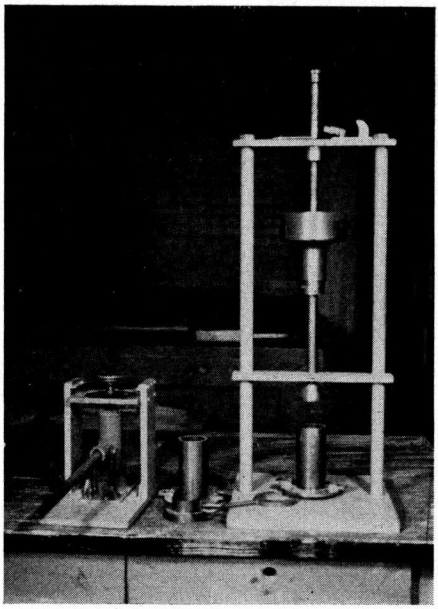

Figure 9. P.C.A. Device for Preparing 2-In. Specimens

the moisture density curves for the different soil-cement specimens but rather to make a short statement on the difference of the respective curves from the shapes of the curves of the natural soils.

Putnam Clay

The moisture density curves for the natural and homoionic Putnam soils showed, in general, a distinct maximum with exception of the potassium soil which gave indication of two maxima. All the soil-cement curves showed more than one maximum, the first one lying at relatively low moisture contents. This one was generally regarded as insignificant. The second maximum which was used in the preparation of the specimens was often indicated only by a slight rise or at times only by an accelerated decrease of the moisture density curve.

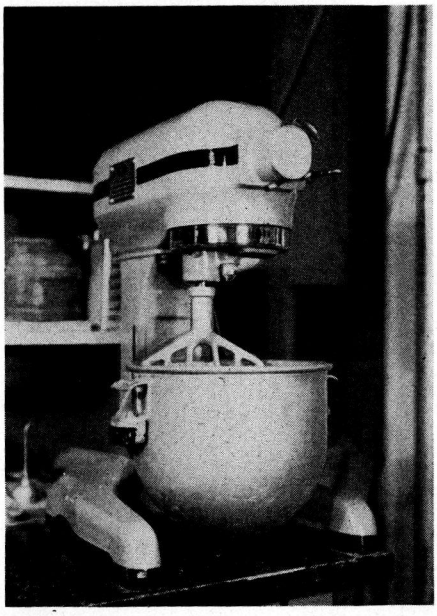

Figure 10. 12-qt. Hobart Industrial Mixer

Cecil Clay

The moisture density curves of the cement-containing Cecil soils were generally regular and followed the curves for the soils containing no cement. The effect of the cement addition was, in most cases, an increase of the maximum density.

Hagerstown Clay

All the soils without cement showed a curve with a distinct maximum with the exception of the iron and aluminum modifications which indicated the possibility of an additional maximum at low moisture contents. The soil-cement mixtures gave curves resembling, in general, the curves of the soils themselves with exception of the iron and aluminum soils which gave only an indication of the maximum density point on a continuously declining density curve.

Hays Clay

The soil-cement mixtures gave curves which possessed the same general shape as the raw soil curves.

RESULTS OF TESTS ON SOIL-CEMENT SYSTEMS

The data obtained in the testing of the soil-cement specimens in accordance with the standard procedures are given in Tables 4(a-b-c-d), 5, and 6, and in Figures 11, 12, 13, and 14. They will be discussed from the point of view of the soil influence and of the ion influence; also differentiation is made between the behavior in the wetting and drying and in the freezing and thawing tests respectively.

COMPARISON OF THE BEHAVIOR OF THE DIFFERENT NATURAL SOILS TREATED WITH PORTLAND CEMENT

Freezing and Thawing

If we set an arbitrary limit of 10 per cent loss in 12 cycles, then the cement

TABLE 4(a)

SOIL—CEMENT DATA

SPECIFIC GRAVITY—PER CENT AIR VOIDS—VOIDS RATIO

No cement

Soil		Specific gravity of mixture	Density, lb per cu ft	Moisture, per cent	Air voids per cent	Voids ratio
Putnam	Nat	2.731	88 0	28 6	8 1	0 94
	H	2 728	87 4	30 9	5 3	0.95
	Na	2.751	85 0	31.3	7 9	1 02
	K	2 721	89.6	28 4	6 5	0.90
	Mg	2.721	85 6	31.2	6 8	0 99
	Ca	2.736	85 2	32 3	6 0	1.00
	Al	2 722	84 4	32 4	7 4	1 02
Cecil	Nat.	2 664	100 4	20 5	6 6	0 66
	H	2 655	99 6	21.0	6 6	0 67
	Na	2 679	103 0	19 0	7 0	0 62
	K	2 674	101 4	19.5	7.6	0 65
	Mg	2 676	103 0	19 0	6 9	0 62
	Ca	2 670	103 5	19.0	6 3	0 61
	Al	2 670	100 0	20 5	7 2	0.67
	Fe	2 650	102 0	20 5	4 8	0 63
Hagerstown	Nat.	2 713	103.0	18 0	9 5	0 64
	H	2 719	102 6	16 5	12 5	0 66
	Na	2.723	104 6	19.0	6 6	0.63
	K	2 716	105 2	16 0	11 0	0 61
	Mg	2.717	103 6	18 0	9 0	0.63
	Ca	2 729	102 2	20 5	6 3	0.66
	Al	2.701	100 5	21 0	6.5	0.68
	Fe	2.706	102 6	19.5	7.5	0 65
Hays	Nat.	2.703	93 8	25.0	6.8	0 80
	H	2.720	95 8	24.0	6.7	0.77
	Na	2.711	92 0	26.0	7 3	0 84
	K	2 701	91 5	27.0	6 3	0.85
	Mg	2 716	89 6	27 0	8 4	0.89
	Ca	2 725	88 0	28 3	8 3	0.93
	Al	2.700	90 4	28 0	5 7	0.86
	Fe	2 710	89 0	29 0	6 0	0.90

TABLE 4 (b)

8 Per cent Cement

Soil		Specific gravity of mixture	Density, lb per cu ft	Moisture, per cent	Air Voids, per cent	Voids ratio
Cecil	Nat	2 696	99.0	20.5	9 6	0.70
	H	2 697	100 5	20.2	7.8	0 67
	Na	2.699	102.0	19.5	7.4	0.65
	K	2 789	100 5	20.7	8.6	0 72
	Mg	2.708	101.1	19.0	9.5	0 67
	Ca	2 702	101.7	19.0	8.6	0 66
	Al	2 702	98 4	21 4	8 0	0.72
	Fe	2.697	98.0	19.9	10 4	0 72
Hagerstown	Nat.	2.745	99.9	19 6	10.3	0.72
	H	2.745	98.0	19.0	12 9	0 75
	Na	2.750	101 7	19 6	8 7	0 69
	K	2.745	101 1	20 0	8.6	0.70
	Mg	2.745	101.0	19.0	10 3	0.70
	Ca	2.757	101 5	19.2	9.7	0 69
	Al	2.730	101.6	20.6	6 8	0.68
	Fe	2 734	99 9	18.0	12 6	0.71
Hays	Nat.	2.736	87.6	25.0	13.5	0 95
	H	2.751	85 2	25.5	15 5	1.02
	Na	2.743	92.0	27.0	6.5	0 86
	K	2 733	90 9	25 0	10 2	0.87
	Mg	2.750	85 2	33.0	5 3	1.02
	Ca	2 757	86.7	30.0	7.9	0.98
	Al	2 734	87.0	23.8	15.8	0.96
	Fe	2 742	83 0	27.0	15.6	1.06

TABLE 4(c)

10 Per cent Cement

Soil		Specific gravity of mixture	Density, lb per cu ft	Moisture, per cent	Air voids, per cent	Voids ratio
Putnam . .	Nat	2 765	87.4	26 0	12.8	0.97
	H.	2.765	86 8	26 3	13 0	0.99
	K	2.760	90.2	26.5	9 3	0 91
	Mg	2 762	86 5	26 0	13.9	0 99
	Ca	2.776	87.1	24 0	16 2	0 99
	Al	2 764	86 9	26 0	13.4	0 99
Cecil	Nat.	2.705	99 3	21.2	7 3	0 70
	H	2 705	100.5	20 6	7 5	0.68
	Na	2 707	101 4	19 2	8 7	0 66
	K	2.795	101 7	20 0	8 8	0.71
	Mg	2 715	101 4	19 0	9.0	0 67
	Ca	2 710	102.0	19 0	8 5	0 66
	Al	2.710	98 4	21 5	8 0	0 72
	Fe	2 704	99 0	21 0	8 2	0 71
Hagerstown	Nat	2 748	101.4	19.3	9 2	0 69
	H	2 752	98 5	19 0	12.5	0 74
	Na	2 763	102 0	19.3	9 0	0 68
	K	2 750	102 3	20 0	7.5	0.68
	Mg	2 753	101.4	18 2	11 1	0 68
	Ca	2 764	102.0	18 4	10 5	0 68
	Al	2.740	101 0	19 5	9 3	0.69
	Fe	2 742	99.9	18.7	11 7	0 71
Hays . .	Nat	2 745	89 1	26 0	10 7	0 92
	H	2.761	87 6	30 2	6 0	0.96
	Na	2.752	93 0	25 0	8.5	0.85
	K	2 740	94.2	24 6	7 8	0 82
	Mg	2.755	88 8	29.0	6 8	0 93
	Ca	2 765	88.8	28.0	8 4	0 93
	Al	2.737	85 0	27.0	13 5	1 01
	Fe	2.750	85.2	31 0	7 8	1 01

TABLE 4(d)

14 Per cent Cement

Soil		Specific gravity of mixture	Density, lb per cu ft	Moisture, per cent	Air Voids, per cent	Voids ratio
Putnam	Nat	2 780	88 5	29.7	6 9	0 96
	H	2.788	87.8	29 2	8 5	0.98
	K	2 775	91 3	26 3	8 9	0.90
	Mg	2 778	88 7	25.5	12 5	0 95
	Ca	2 790	87 7	28 0	10 3	0.99
	Al	2 780	87 6	29.0	8 8	0 98
Hagerstown	Nat.	2 764	102 3	18 6	10 2	0 68
	H	2 767	100 5	19 9	9 7	0.72
	Na	2 775	102 9	18 5	10 1	0 68
	K	2 766	103 2	20 8	5 8	0 67
	Mg	2.766	103 0	18 7	9 4	0 68
	Ca	2 777	102 7	19.0	9 4	0 69
	Al	2.750	101 7	20 6	7 2	0.69
	Fe	2 752	100 5	20 5	8 3	0 71
Hays	Nat	2.760	90 6	23 1	13 9	0.90
	H	2 777	86 7	27 8	11 3	1.00
	Na	2.766	91 2	27 0	7 8	0.89
	K	2 756	95.0	25 0	6 6	0.81
	Mg	2 722	82 8	31 0	10 0	1 05
	Ca	2 780	88 2	27 6	10 2	0.97
	Al	2 759	86 7	28.0	10 7	0 99
	Fe	2 769	87 0	30 0	7 9	0.99

TABLE 5

SOIL—CEMENT DATA

Varied Density—8 Per cent Cement

Soil		Specific gravity of mixture	Density, lb per cu ft	Moisture, per cent	Air voids, per cent	Voids ratio
Cecil	Nat.	2 700	91 5	19 6	17 0	0 84
	Nat.	2.700	95 5	19 7	13.2	0.76
	Nat.	2 700	100 0	19 4	9 6	0 69
	Nat.	2.700	102.3	19.6	7 1	0.65
	Nat	2 700	105.2	19 2	5 2	0.60
	H	2.703	94 0	17 5	16 9	0.76
	H	2.700	98.0	17.6	14 4	0 72
	H	2.699	102 0	17 6	10 6	0.65
	H	2.699	104 0	17.6	9 0	0 62
	H	2 700	107 0	17 1	7 2	0 58
	K	2 765	97 0	17.0	17 5	0.78
	K	2.704	101 8	17.6	10 9	0 66
	K	2 703	102 0	17 2	11 4	0 65
	K	2.702	104.0	17.0	10 1	0.62
	K	2 702	106 5	17 2	7 7	0 59
Hagerstown	Nat	2.740	91 0	18 5	19.7	0.88
	Nat.	2.740	96 5	18 2	14 2	0 74
	Nat	2.740	100 8	18 0	11 5	0 69
	Nat.	2 740	105 9	18.0	7.3	0 61
	Nat	2.740	109 5	18.0	4 2	0 56
	Ca	2 765	93 9	19 0	16 7	0 83
	Ca	2 762	99.0	19.4	11 6	0 74
	Ca	2.760	102.9	19 5	8 1	0 68
	Ca	2.760	107.4	18 8	5 3	0 61
	Ca	2.761	109.5	18.0	4 7	0.57
	Na	2.757	96.6	18 0	15.9	0 78
	Na	2 750	101 0	18 5	11.1	0.70
	Na	2.756	104 4	18 4	8 7	0.65
	Na	2.753	108 0	18 0	6.0	0 59
	Na	2.756	109.5	18 3	3.9	0 56
Hays	Nat	2.741	79 0	21 4	26 5	1.16
	Nat.	2 741	87.0	21.0	20.2	0 97
	Nat.	2.736	89.0	21 2	18 0	0 93
	Nat.	2 740	94 8	21 2	12.3	0 80
	Nat.	2 740	101 0	20.8	7 2	0 69
	Ca	2.761	81 6	22 7	22 9	1.11
	Ca	2.760	86.0	23.0	18.3	1 00
	Ca	2.760	88 6	24 0	14 4	0.94
	Ca	2.760	93 0	20.6	15.3	0 85
	Ca	2.760	98.0	21.8	8 9	0.76
	Al	2.741	80 6	20 2	26 9	1.12
	Al	2.740	85 8	20.0	22 0	0.98
	Al	2.740	89.0	21.0	17.8	0 92
	Al	2.740	92.5	21.3	14.5	0.85
	Al	2.740	97.0	21.1	10.7	0 77

TABLE 6

SOIL—CEMENT DATA

Varied Moisture—8 Per cent Cement

Soil		Specific gravity of mixture	Density, lb per cu ft.	Moisture, per cent	Air Voids, per cent	Voids ratio
Cecil	Nat	2 702	99 6	18 0	12 2	0.69
	Nat.	2.702	101.0	20 0	7.9	0 67
	Nat	2 702	100 0	22 2	4.3	0.68
	H	2.697	97 5	17 5	14 75	0 73
	H	2.697	98.0	21.0	8 9	0 73
	H	2 697	99 0	23 0	4 7	0 70
	K	2.735	101.0	17.5	12.7	0.69
	K	2 735	101 0	20.0	8 6	0.69
	K	2 735	98 0	22 0	7.1	0.74
Hagerstown	Nat.	2 740	99.8	18.0	12 8	0.71
	Nat.	2.740	100.0	21.0	8.0	0 71
	Nat	2.740	100.0	23.5	4.8	0.71
	H	2.749	99.6	18.0	13.0	0.72
	H	2.749	99 4	21.0	8.8	0.73
	H	2.749	99.5	23.5	4.2	0 72
	K	2.743	101.0	17.5	12.5	0.69
	K	2 743	102.0	20 0	8 0	0 68
	K	2 743	102.0	21.6	5.4	0.68
Hays	Nat.	2.736	87.3	24.6	14 5	0 96
	Nat	2.736	90.0	27.0	8.5	0.90
	Nat	2.736	88.8	29.0	5.6	0.90
	Ca	2.757	87.3	30.0	7.2	0.97
	Ca	2 757	85.5	32.0	6.1	1.00
	Ca	2.757	83.4	33.8	6.1	1.05
	Al	2.734	89.4	23.5	14.1	0.91
	Al	2.734	88.5	26.0	11 2	0.93
	Al	2.734	87 9	28.6	8 1	0.94

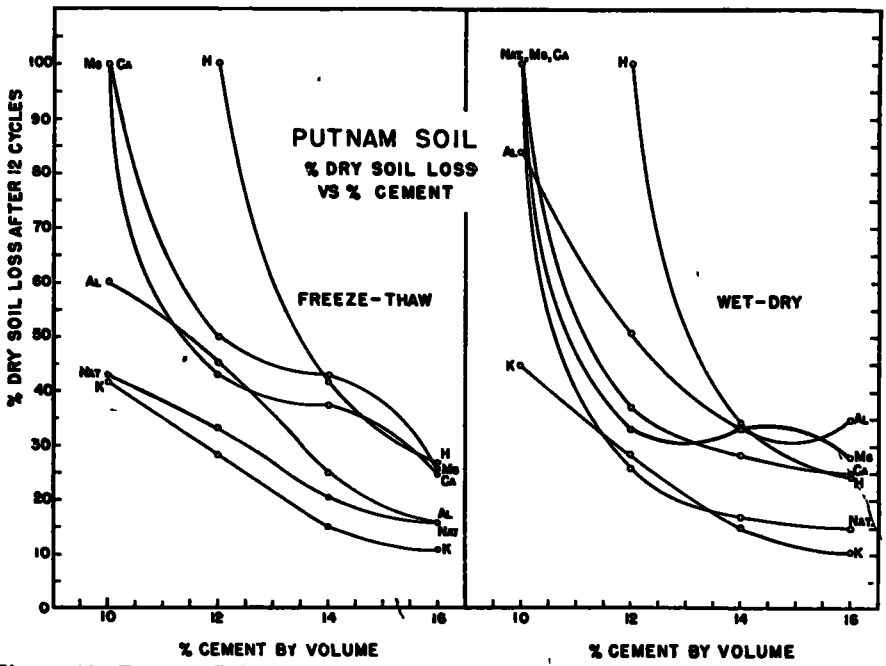

Figure 11. Putnam Soil, Percentage of Dry Soil Loss Vs. Percentage of Cement

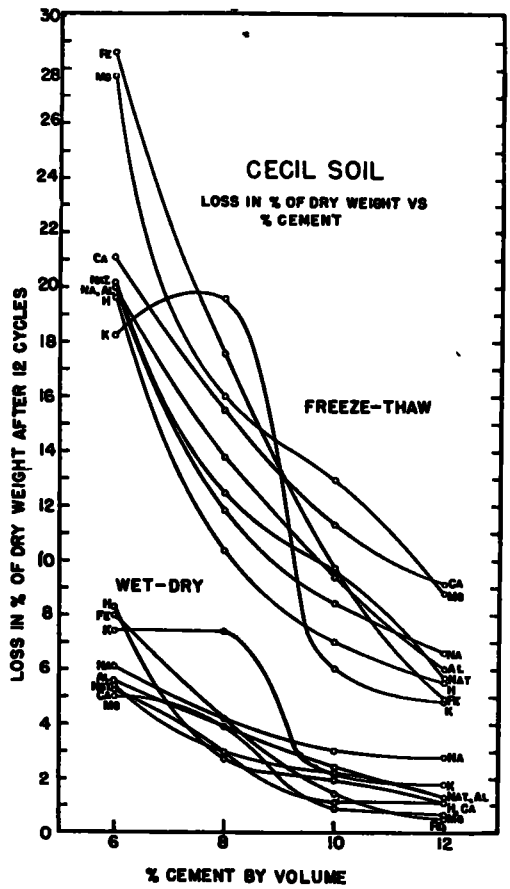

Figure 12. Cecil Soil, Percentage of Dry Soil Loss Vs. Percentage of Cement

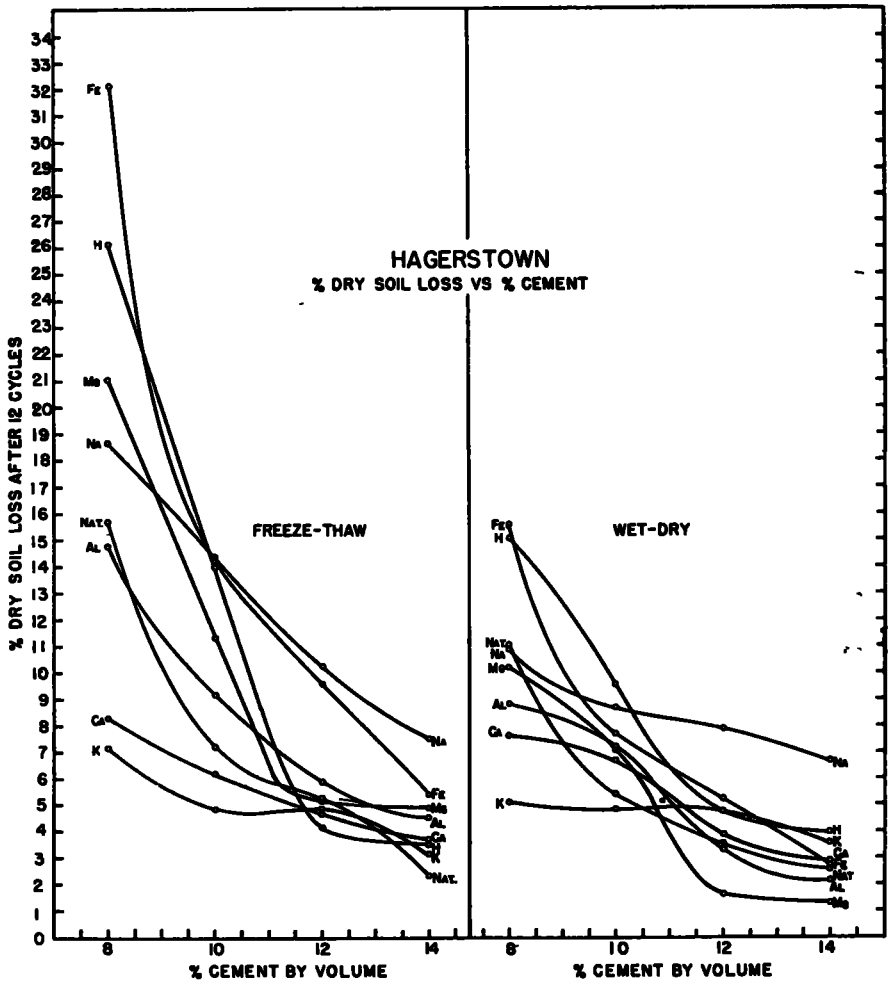

Figure 13. Hagerstown Soil, Percentage of Dry Soil Loss Vs. Percentage of Cement

requirements in volume percentage are as follows for the different natural soils:

	Per cent
Hagerstown	9
Cecil	10
Hays	16
Putnam	16+

If we compare these cement requirements with the size composition and with the subgrade soil constants, no simple correlation can be found. However, if we consider the difference between the optimum moisture content of compaction and the shrinkage limit we find that this difference is large and positive for the bad soils, Putnam clay (11.1) and Hays clay (8.7), and small and negative for the good soils, Hagerstown clay (−1) and Cecil clay (−27).

The question arises whether this could have a general meaning. What primary physical properties do the optimum moisture content and the shrinkage limit indicate for highly cohesive soils?

The optimum moisture contents for compaction may be considered as the amounts of moisture required to give clay soils equal, or at least comparable, shearing resistance (1). The higher the optimum moisture content, therefore, the greater is the affinity of the soil system for water.

The shrinkage limit of clay soils indicates that water content at which the at-

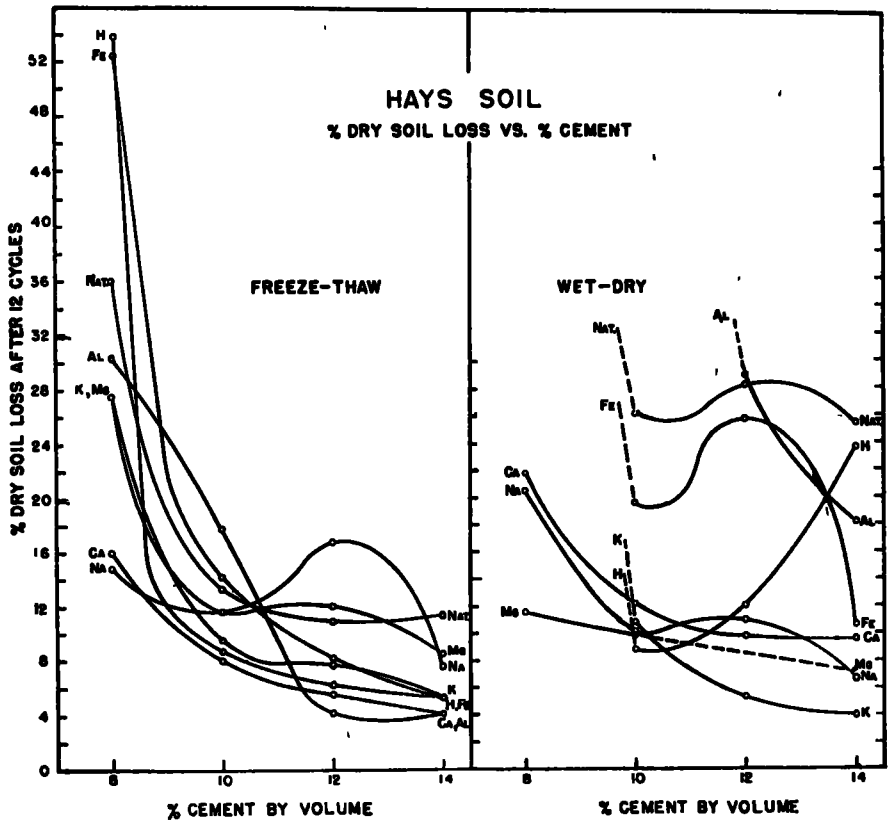

Figure 14. Hays Soil, Percentage of Dry Soil Loss Vs. Percentage of Cement

traction between the solid particles is sufficiently strong to resist the pull of the retreating water films (2). Therefore, one might say that the higher the shrinkage limit, other conditions being equal, the greater is the interparticle attraction. A combination of a low optimum moisture content of compaction and a high shrinkage limit would, therefore, represent a system which possesses great cohesion and correspondingly great structural strength combined with relatively small water affinity If we realize that affinity for water is one of the forces which tend to destroy the structural strength of soils by drawing water into the soil system, this definition appears to be significant It is reasonable, therefore, to assume that a clay soil with a high shrinkage limit and a low optimum moisture content does not need as much cement to overcome the residual water affinity, as does a soil which possesses low interparticle attraction and great affinity for water

However, this is not the whole story From Table 4(b-c-d) we see that the Hagerstown and Cecil clays systems possess low voids ratios of 0 68 and 0.7 respectively, and that the Hays and Putnam clays possess higher voids ratios of 0 95 and 0.97 respectively. Obviously, the greater the voids ratio the greater the chance of water entering the system and destroying it either as a result of the water affinity of the internal soil surface or of the expansive forces occasioned by the freezing of the water Of course, the picture is not complete without a knowledge of that part of the pore volume which is taken up by strongly adsorbed water, which decreases the passageways available for penetration of water, and which does not expand, as does normal water, at freezing temperatures Indications of the amount of strongly adsorbed water are furnished by the subgrade soil constants, by the heat of the wetting of the soil systems and by the difference in specific gravity of the soil particles if measured in water and in decaline The latter is not adsorbed and, therefore, not compressed on the surface of the soil particles However, the most direct and, therefore, best way of measuring the accessibility of the internal surface of a soil system to water is by direct permeability tests.

If it be permitted to formulate a working hypothesis on the basis of the results obtained on the natural soil-cement systems investigated, then it may be stated· the soil requiring the lowest amount of cement for stabilization is one which possesses a small or negative difference between the optimum moisture content for compaction and the shrinkage limit, and which can be compacted with cement to give a system of great density and consequently low permeability

Wetting and Drying

If an arbitrary limit of 10 per cent loss in 12 cycles of wetting and drying is set, then the cement requirements in volume percentage are as follows for the different natural soils:

	Per cent
Cecil	6
Hagerstown	8
Hays	16
Putnam	16

Again we have a group of good soils and a group of bad soils, as in the case of the freezing and thawing tests Only the sequence of the best soils is reversed The reason for this is not difficult to find The severity of the effects of water attack on dry cohesive soil systems, depends, on one hand, upon the accessibility of the internal soil surface, and on the other, upon the affinity of the internal soil surface for water (2). Since the voids ratios of the Cecil and Hagerstown soil-cement systems are of the same order of magnitude, the water affinity of the soils must be the determinant factor While the energy of water attraction (heat of wetting) has not

been determined in the course of this investigation, it is well known to go parallel with the base exchange capacity (3). For the Cecil soil the base exchange capacity was found to be about ⅓ of that for the Hagerstown soil (Table 3).

It is of interest that in the case of the more easily stabilized Cecil and Hagerstown soils the effect of freezing and thawing was relatively more severe than the effect of wetting and drying, while the reverse was the case for the Putnam and Hays soils. The reason for this is the greater water affinity (higher base exchange capacity) of the latter which in the case of wetting and drying results in greater disruptive forces. In the case of freezing and thawing, on the other hand, the greater water affinity results in the formation of thicker strongly adsorbed water layers which are not available for expansive freezing. At this point, it is worth noting that only one of the six known modifications of ice possesses a greater specific volume than liquid water, and that the modification which is stable at very high pressures possesses a greater melting point than the normal melting point of water Adsorbed water films may be pictured as being under very high pressures and, therefore, solid or at least plastic at room temperatures (4).

DISCUSSION OF THE DATA OBTAINED ON THE NATURAL AND HOMOIONIC MODIFICATIONS OF PUTNAM SOILS

The results of the wetting and drying, and freezing and thawing tests on the different homoionic Putnam soils stabilized with 10, 12, 14 and 16 per cent of cement are given in Figure 11. The data show that the different ions have an effect on the susceptibility of the soils to stabilization by means of portland cement. The best showing in the freezing and thawing, and wetting and drying tests was made by the potassium ion and by the ion combination found in the natural soil The worst showing was made in both cases by the hydrogen, the calcium and the magnesium ions.

It is interesting and important to find out what properties the natural and potassium Putnam soils, on one hand, and the calcium, magnesium and hydrogen Putnam soils, on the other hand, possess, which render them the best and the worst acting respectively. Examination of Figure 2 which gives the subgrade soil constants as functions of the exchange ions reveals that the natural and potassium Putnam soils possess the highest shrinkage limits and the lowest optimum moisture contents of their groups. The calcium and magnesium soils as well as the hydrogen soil, possess high optimum moisture contents and low (magnesium and calcium) or intermediate (hydrogen) shrinkage limits.

In Table 7 the cations are arranged in accordance with their effect on the systems containing 10 per cent cement with the quality of the systems decreasing from left to right For comparison, the densities indicating the pore volumes and the differences between the optimum moisture contents and the shrinkage limits are also given.

The rating is based on loss after six cycles each since this permits better differentiation between the inferior soil-cement systems

It is interesting that the rating by the loss in wetting and drying goes parallel with that by the difference in optimum moisture content and shrinkage limit with the exception of the hydrogen system.

The Putnam clay has a relatively high base exchange capacity The hydrogen Putnam soil, therefore, represents an acid material which is liable to take away from the portland cement a considerable amount of calcium ions and thus reduce its cementing power. The fact that with low cement contents the hydrogen Putnam is by far the worst, while with high cement contents it falls in the same group as the

magnesium and calcium soils, indicates the justification of this point of view.

The rating by the loss in the freezing and thawing cycles follows the same order as that in the wetting and drying cycles with the exception of a considerable shift of the position of the hydrogen ion. The shift in the position of the natural and potassium soils is so small that it probably falls within the limits of experimental error.

Consideration of the densities of the different soil-cement systems indicates that best qualities are connected with highest densities, however the density factor does not seem to be as determinant as the difference between the optimum moisture content and the shrinkage limit of the soil itself. This is in line with the hypothesis formulated in the discussion of the behavior of the natural soils

The loss in the wetting and drying cycles should be dependent also on the water affinity of the different soils. Previously determined heat of wetting data for homoionic Putnam clays give 9 5, 13, 13, and 15 calories per gram for the potassium, natural, hydrogen, and calcium modifications, respectively.

TABLE 7

Rating	1	2	3	4	5	6
Freeze—thaw	Nat	K	Al	H	Mg	Ca
Wet—dry	K	Nat	Al	Mg	Ca	H
Density lb. per cu ft	K 90 2	Nat 87 4	Ca 87.1	Al 86.9	H 86 8	Mg 86.5
Optimum moisture content minus shrinkage limit	K 9 1	Nat 10 6	H 14 7	Al 16 1	Mg 19 1	Ca 19.6

DISCUSSION OF THE DATA OBTAINED ON THE NATURAL AND HOMOIONIC MODIFICATIONS OF CECIL SOIL

The data on the behavior of stabilized Cecil soils with respect to soil loss in the wetting and drying, and freezing and thawing cycles, and with respect to compressive strength after different periods of time are given in Figures 12 and 15. The Cecil soil represents the best soil of the group of the four investigated. If we consider the optimum moisture content for compaction and the shrinkage limit of the natural and homoionic Cecil soils from the point of view outlined, then we find that for all the modifications, the shrinkage limit lies above the optimum moisture content.

This appears to strengthen the previously made contentions There is again an influence of the different ions on the quality of the stabilized soil systems, however, because of the general high quality of all the systems, and because of the small base exchange capacity of the Cecil soil, it appears to be rather difficult to find a connection between the influence of the ions on the subgrade soil constants and on the soil-cement systems, respectively. For this reason, the soil-cement systems must be analyzed by themselves on the basis of their densities and optimum moisture contents of compaction.

It is well known that the more accessible the interior of a construction material is to the weathering agents, the more easily it is destroyed. For instance, the denser a concrete, other conditions being equal, the more resistant will it be to corrosive agents The Cecil soil-cement systems showed a much greater loss in the freezing

and thawing than in the wetting and drying tests. This is significant because it indicates the limitations of the merits of a high shrinkage limit We have indicated previously that a high shrinkage limit is desirable, other conditions being equal, because it indicates a great affinity between the soil particles themselves, resisting consolidation in drying. On the other hand, it is desirable that the soil systems possess as small a coefficient of permeability as possible. Lateritic soils are more pervious than podsolic soils of the same gradation; therefore, they are more easily penetrated by water. If the latter freezes, the expansive forces may become so enormous that they easily break the cohesion of the systems. It is important to realize that the response of soil systems to water attack depends on the affinity of the internal surface for water, governing the general behavior in wetting and drying, and on the accessibility of the internal surface or on the pore space governing the speed with which the attack proceeds It is the amount and the average size of the pore space which governs the behavior of a saturated soil under freezing conditions

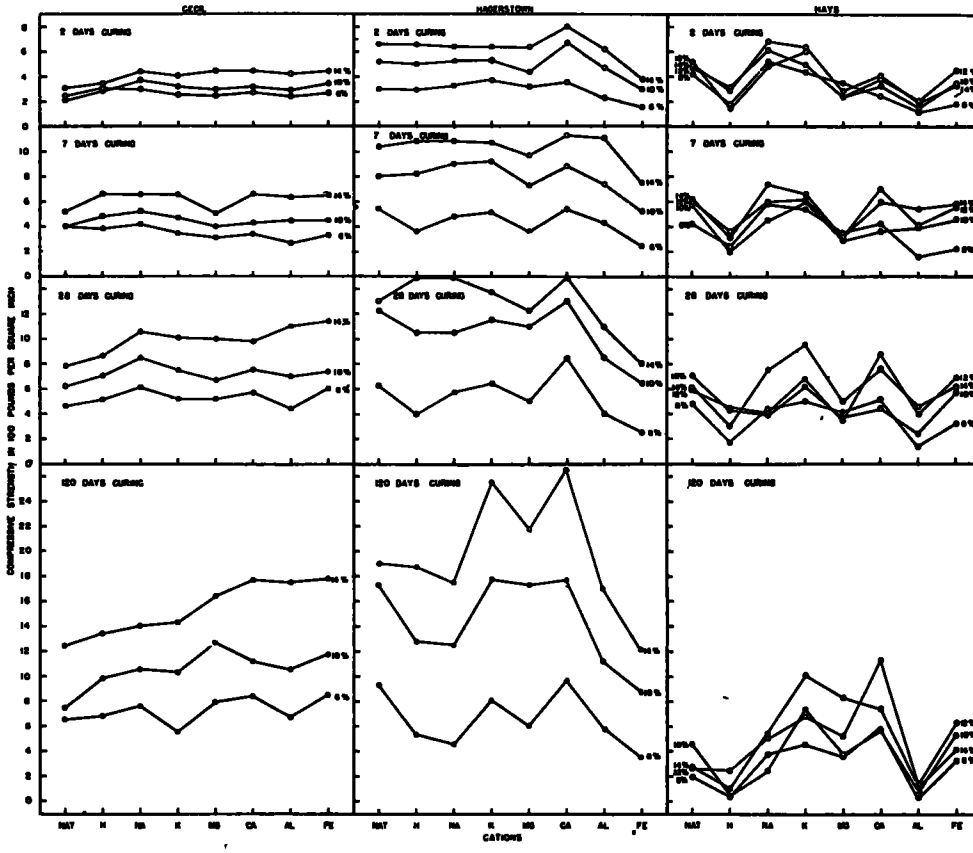

Figure 15. Compressive Strength of Natural and Homoionic Soil-Cement Systems

The data obtained on all four natural soils appear to indicate that those which possess low shrinkage limits and a great affinity for water suffer most in the wetting and drying cycles, while the soils possessing a high shrinkage limit and low

water affinity, though, in general, of higher quality than the others, are markedly affected in the freezing and thawing cycles. Fortunately, the latter types of soils are found mostly in warmer climates where freezing does not often occur However, it must be kept in mind that the water affinity of the soil systems and the inter-particle attraction determine only the behavior after extended exposure and after reaching what might be called equilibrium conditions. As has been stated, the speed with which these equilibrium conditions are attained depends upon the permeability of the soil systems; that is their accessibility to the destructive agent. This brings forth the importance of the time factor: freezing and thawing, wetting and drying cycles of short duration may not always be comparable to those of long duration, as equilibrium conditions may not be obtained during short tests. It is likely that this time factor makes itself evident in different ratings of the ionic influence on the basis of soil losses representing surface conditions of the specimens and of compressive strength data respectively. In Table 8 the natural and homoionic Cecil soils containing 10 per cent of cement are rated from different points of view.

In the freezing and thawing tests, the soil modifications containing potassium, hydrogen, and sodium ions are the most favorable These three respective modifications possess in the same order, the largest negative values of the difference between optimum moisture content and shrinkage limit. The other ionic variations except those containing calcium and magnesium follow in a somewhat similar order.

This order for the best and worst soils is reversed for the wetting and drying tests. This reversal suggests that the thickness of strongly adsorbed water films in the case of the magnesium, calcium and iron systems is so small that practically all the pore water is freezable and therefore, a destructive agent. On the other hand, this small water affinity makes for a low energy of adsorption in wetting and drying with concomitant small destructive action.

TABLE 8

Rating	1	2	3	4	5	6	7	8
Freeze—thaw Wet—dry.	K Mg	H Ca	Na Fe	Al H	Nat Nat	Fe K	Ca Al	Mg Na
Compressive strength at 7 days	Na	H	K	Fe	Al	Ca	Mg	Nat
Compressive strength at 28 days	Na	K	Ca	Fe	H	Al	Mg	Nat
Density in lb per cu ft	Ca 102	K 101.7	Na 101 4	Mg 101.4	H 100 5	Nat 99 3	Fe 99	Al 98.4
Optimum moisture content minus shrinkage limit of soils	K −7 0	H −6 0	Na −5.0	Mg −4 5	Ca −3.5	Al −3.5	Fe −2 5	Nat −2 5
Optimum moisture content of soil and 10 per cent cement	Al 21 5	Nat 21.2	Fe 21.0	H 20.6	K 20.0	Na 19 2	Ca 19	Mg 19

The voids ratios of the soil-cement systems increase in the following ionic order: sodium, calcium, magnesium, hydrogen, natural, potassium, iron and aluminum, while their rating on the basis of increasing percentages of air voids is natural, hydrogen, aluminum, iron, calcium, sodium, potassium and magnesium.

The sodium, potassium, and calcium ions conferred upon the respective soil-cement systems the highest densities and also the highest values for compressive strength. From these facts it seems that the density of a soil-cement system determines pretty much the compressive strength. Soils possessing low optimum moisture contents can usually be compacted to high densities. However, the density alone is not a sufficient indicator of the weathering resistance The latter is determined also by the water affinity of the internal surface of the soil system and by the volume and dimensions of the pore space available for water movement It is to be kept in mind that strongly adsorbed film water decreases the volume available for the movement and also the freezing of free water. For this reason, the soils which possess the least affinity for water and a large pore volume available for capillary water give a bad showing in freezing and thawing tests. However, this small water affinity involves only small energy changes in the wetting and drying tests with a resulting good showing of the soil system in the latter The behavior of the calcium and magnesium soil systems is a good example of these relationships

TABLE 9

Rating	1	2	3	4	5	6	7	8
Freeze—thaw	K	Ca	Nat	Al	Mg	H	Na	Fe
Wet—dry	K	Nat	Ca	Mg	Al	Fe	Na	H
Compressive strength at 7 days	K	Na	Ca	H	Nat	Al	Mg	Fe
Density in lb. per cu. ft soil and 10 per cent cement	K 102 3	Ca 102 0	Na 102.0	Nat 101 4	Mg 101 4	Al 101 9	Fe 99 9	H 98.5
Optimum moisture content minus shrinkage limit of the soil	K −3 5	Nat −1	H −1	Ca 1 5	Na 3 0	Mg 3.0	Fe 4 5	Al 4 5
Optimum moisture content of soil and 10 per cent cement	K 20	Al 19 5	Nat 19 3	Na 19 3	H 19 0	Fe 18 7	Ca 18 4	Mg 18.2

DISCUSSION OF THE DATA OBTAINED ON THE NATURAL AND HOMOIONIC MODIFICATIONS OF HAGERSTOWN SOIL

The data obtained on the behavior of the stabilized Hagerstown soils with respect to soil loss in the wetting and drying, and freezing and thawing cycles, and compressive strength after different periods of time are given in Figures 13 and 15.

In Table 9 the cations are arranged in accordance with their effect on the systems containing 10 per cent of cement with the quality of the systems decreasing from left to right

Consideration of these ratings shows that for cement contents of 10 per cent and lower the potassium confers upon the soil the best resistance to wetting and drying, and freezing and thawing. The potas-

sium soil also rates best in the density of the soil-cement systems and in the optimum moisture minus shrinkage limit function. It is also significant that the potassium soil-cement system possessed the highest moisture of compaction. The influence of these three functions on the quality of soil-cement systems is well indicated, but the evidence is not yet sufficient for a quantitative mathematical formulation. The ratings in the wetting and drying tests go, in the main, parallel to those in the freezing and thawing tests. However, there exists a distinct difference, at least in the better group, between these ratings and those made on the basis of compressive strength Also, the ratings on the latter basis differ among themselves if the data are obtained after different periods of time. However, it seems that high compressive strength is usually, though not always, associated with high densities. It would appear that strength data to be important must be obtained on soil-cement systems which have been definitely saturated with water under well-controlled temperature conditions The tests for compressive strength also should be made at controlled temperatures. The parallelity of the ratings for the wetting and drying, and freezing and thawing tests and their divergence from the rating for compressive strength appears to indicate the dominance of the permeability factor.

TABLE 10

Rating	1	2	3	4	5	6	7	8
Freeze—thaw	Ca	H	K	Na	Mg	Nat	Fe	Al
Wet—Dry	H	Na	Mg	K	Ca	Fe	Nat	Al
Compressive strength at 7 days	K	Nat	Fe	Na	Al	Ca	Mg	H
Compressive strength at 28 days	Nat	K	Fe	Ca	H	Na	Mg	Al
Density in lb per cu. ft soil and 10 per cent cement	K 94 2	Na 93 0	Nat 89 0	Mg 88 8	Ca 88 8	H 87 6	Fe 85 2	Al 85 0
Optimum moisture content minus shrinkage limit of the soil	K −1 7	Ca 5 0	Na 8 9	Nat 9.7	H 11 0	Al 12 2	Fe 16 1	Mg 17 8
Moisture of compaction of soil and 10 per cent cement	Fe 31 0	H 30 2	Mg 29 0	Ca 28 0	Al 27.0	Nat 26 0	Na 25 0	K 24 6
Per cent of air-voids of soil and 10 per cent cement	H 6 0	Mg 6.8	K 7 8	Fe 7 8	Ca 8.4	Na 8.5	Nat 10 7	Al 13.5

DISCUSSION OF THE DATA OBTAINED ON THE NATURAL AND HOMOIONIC MODIFICATIONS OF HAYS SOIL

The data obtained on the behavior of stabilized Hays soils with respect to soil loss in the wetting and drying, and in the freezing and thawing cycles, and with respect to compressive strength at different periods of time are given in Figures 14 and 15.

In Table 10 the cations are arranged in accordance with their effect on the systems containing 10 per cent of cement with the quality of the systems decreasing from left to right.

These data show that the natural, iron and aluminum modifications are the worst from a consideration of the behavior in

the wetting and drying, and of the freezing and thawing tests. On the other hand, the natural soil-cement system gives the highest compressive strength after 28 days. Again, good weathering resistance appears to be connected with one or more of the following factors: high density, small or negative value of the difference between the optimum moisture content of the soil and its shrinkage limit, sufficient moisture of compaction, and small percentage of air voids in the soil-cement system.

Because of the difference in character of the Hays soil from the other soils, being the only pedocal or calcium-accumulating soil in the series and possessing the highest amount of organic matter, a more general discussion of its behavior appears to be in order.

With exception of the Putnam soil, the Hays soil was the worst in the group investigated. As in the case of the Putnam and Hagerstown soils, the hydrogen modification showed the worst behavior together with the iron modification at low cement contents. The best behavior at low cement contents was shown by the calcium and sodium modifications as evidenced in the results of the freezing and thawing tests, and by the magnesium, calcium and sodium modifications as evidenced in the wetting and drying tests. The wetting and drying tests were much more severe than the freezing and thawing tests. In the case of the former, it appears to be important that the hydrogen system behaved best with a content of 10 per cent of cement and deteriorated up to a content of 14 per cent of cement. For most ions, satisfactory stabilization appears to be obtainable with a cement content of 10 to 12 per cent by volume. Modifications which cannot be stabilized with this amount of material are the aluminum, the natural and iron systems. The iron and aluminum soils possessed relatively high optimum moisture contents and the lowest shrinkage limits. The next higher shrinkage limit was possessed by the natural soil. The bad showing at low cement contents of the hydrogen systems in the case of the Hays, Hagerstown and Putnam soils which all possess a relatively large base exchange capacity appears to be due to the same cause, namely the deprivation in calcium ions of the portland cement. These ions are used up in the neutralization of the hydrogen soils.

THE INFLUENCE OF DENSITY AND MOISTURE OF COMPACTION ON THE WEATHERING RESISTANCE AND COMPRESSIVE STRENGTH OF SOIL-CEMENT SPECIMENS

The data reported so far were obtained on the cement-treated natural and homoionic soils which were compacted at their specific optimum moisture contents and to their maximum densities determined by means of the Proctor method.

In the case of the homoionic soils, this method resulted not only in variations due to the different ions, but also in variations of the moisture contents and densities of the specimens representing different cationic soil modifications. The data may, therefore, be considered as controlled by three different factors pertaining respectively to the cations as such, to the density, and to the moisture content at compaction. It appeared desirable to show the specific effects of the density and moisture factors in additional experimentation. For this reason, specimens of natural and homoionic soils were prepared in which either the moisture content was kept constant and the density was varied or the density was kept constant and the moisture content was varied. Wetting and drying, freezing and thawing, and compressive strength tests were made on these specimens. In order to obtain the higher densities involved, the specimens were compacted in five layers, of equal thickness

by varying blows of the hammer as follows:

Blows per layer	Density likely to be obtained
7	8 lb per cu ft below maximum density
11	4 lb per cu. ft below maximum density
15.	Equal to maximum density
25..	4 lb per cu ft above maximum density
50	8 lb. per cu ft. above maximum density

Preliminary information for making these specimens was obtained from the Portland Cement Association.

For the variations in density, the moisture content for the densest specimens was first determined and this moisture content was used for the specimens of lower densities. In the case of the specimens with constant density and varying moisture contents, the density chosen was that which was obtained from the regular moisture-density curves. These specimens were made by the standard method of compaction. Of course, it was unavoidable that slight variations in density occurred within the constant density series as well as slight variations in moisture content within the constant moisture series. Reference will be made to the respective data in the text.

Effect of Varied Density

The effect of density at constant moisture content with respect to the behavior in freezing and thawing, and wetting and drying cycles, and to the compressive strength after 2, 7 and 28 days of curing are shown in Figures 16 and 17. The specimens were made with a cement content of 8 per cent by volume. Figure 16 shows that there is a general increase in weathering resistance with an increase in density. In the case of the freezing and thawing tests, the rating of the different ions at times differs at higher densities from that at lower densities. The Cecil soil which possesses a low base exchange capacity shows a converging of the behavior in the freezing and thawing tests of the homoionic soils at higher densities In the case of the wetting and drying tests, there exists also a converging of the behavior of the different ionic modifications at higher densities indicating the decreased accessibility of the internal surface of the soil-cement systems However, it might be supposed that exposure to more extended cycles of wetting and drying would not show this converging. Of the Hays soil systems, only the potassium modification stood up in the test.

The compressive strength data are shown in Figure 17. Disregarding some minor variations which might be due to normal experimental errors, there is a general tendency of increase in compressive strength with increase in density. These test results corroborate the general conclusions drawn on the basis of the results obtained in the previous tests.

Effect of Variations in Moisture Content

The data concerning the variation in moisture content are shown in Figures 18 and 19. The increase in moisture content results in a general improvement of the weathering resistance. This is shown in the respective graphs. However, a few remarks must be made concerning the latter. As previously stated, it was not always possible for the freezing and thawing and wetting and drying specimens to obtain identical densities Accordingly, a density effect appears to be superimposed in some cases on the moisture effect. For instance, the potassium Cecil soil system at a moisture content of 22 per cent possesses a density of only 98 lb. per cu. ft. as compared with 101 lb. for moisture contents of 17 and 20 per cent respectively This lower density is reflected in an inferior behavior of the potassium soil system in the freezing and thawing as well as in the wetting and drying tests. It

should be noted that the potassium soil possesses the least water affinity, and, therefore, might also be susceptible to a detrimental effect of excessive water. The data obtained on the Hagerstown soil systems indicate that the potassium modification is not so much benefited by an increase in water content as is the hydrogen modification. This might also be a result of the small water affinity of the potassium soils A definite benefit appears to be derived in the case of the wetting and drying resistance for all modifications tested The natural Hagerstown soil shows best resistance to freezing and thawing in the case of an intermediate moisture content of 20 per cent but a small resistance at the same moisture content in the wetting and drying cycles Since the involved differences are relatively small, it is difficult to ascertain whether the obtained data are significant or whether they are due to expected experimental variations.

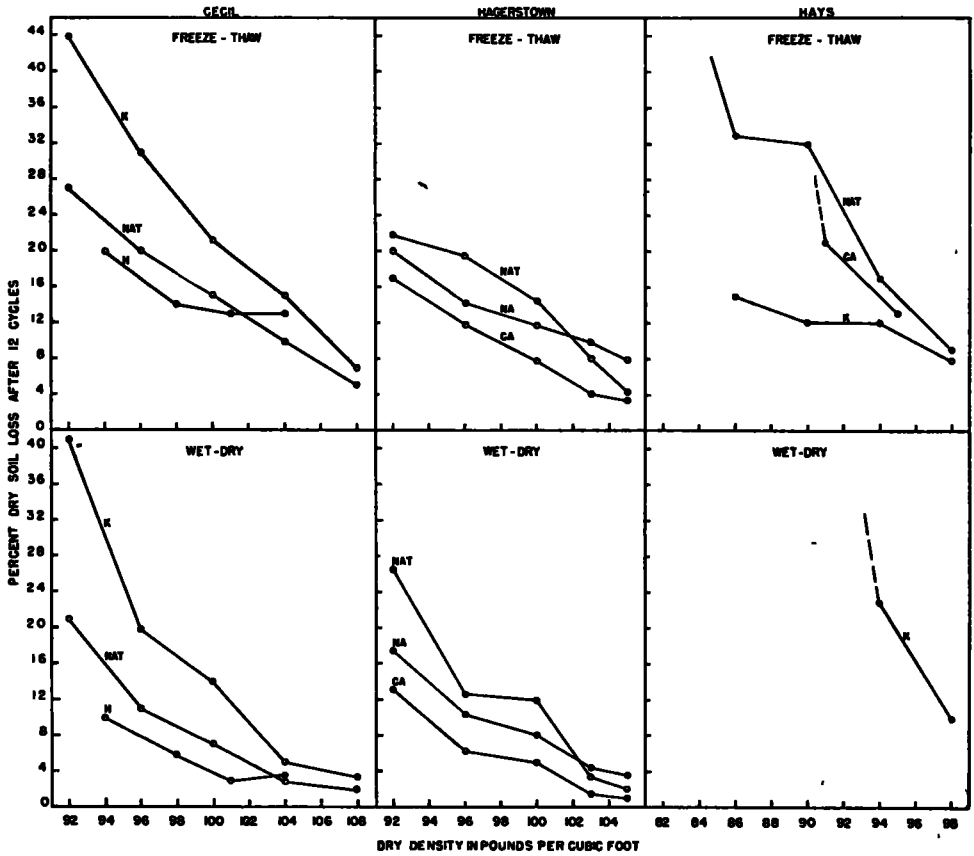

Figure 16. Effect of Density on Soil Loss in Freezing and Thawing and Wetting and Drying Tests

In the case of the Hays soil, increase in moisture content appears to affect favorably the behavior in the freezing and thawing tests of the natural and aluminum variations However, the effect on the calcium and potassium variations is indefinite The data obtained do not permit definite conclusions in regard to the effect

of increasing moisture content on the behavior in the wetting and drying tests performed on these soil systems.

The effect of varied moisture content on compressive strength is shown in Figure 19 for the different Cecil, Hagerstown, and Hays soils. There appears to be a general improvement in compressive strength with increase in moisture content for all soils studied except the potassium modifications Again, the low water affinity of the potassium soils may be the reason for this showing

land cement depends upon surface-chemical as well as upon physical factors.

2. Ionic treatment appears to be applicable for improving the susceptibility of certain clay soils to hardening by means of portland cement.

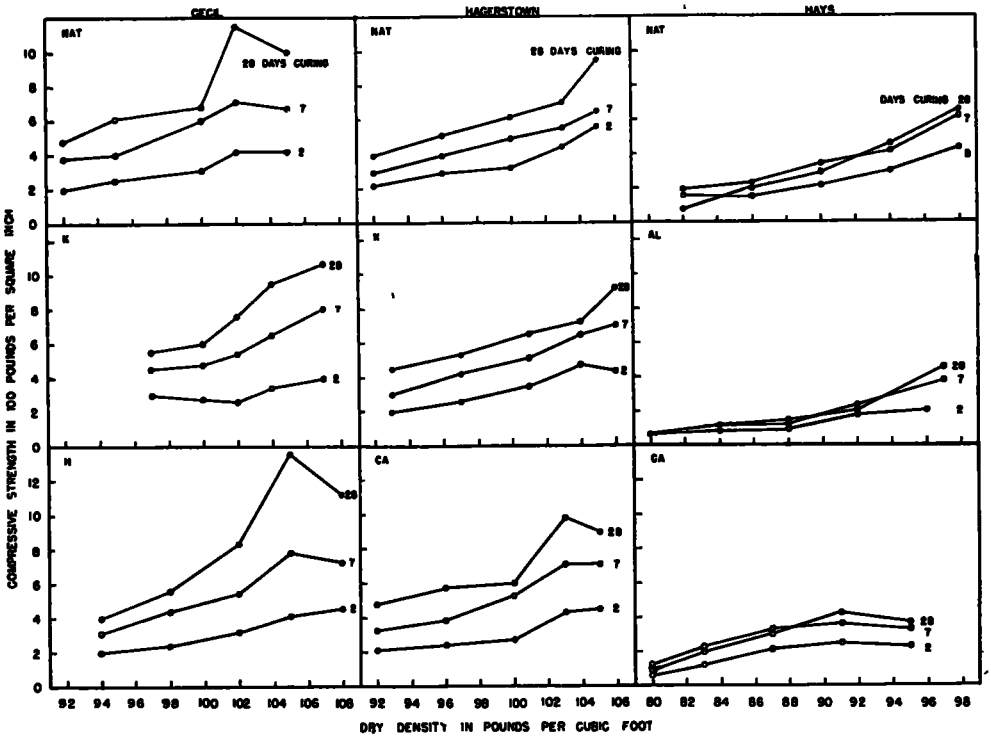

Figure 17. Effect of Density on Compressive Strength

CONCLUSIONS

The data and discussions presented in this paper suggest the following conclusions·

1 The ease with which a clay soil can be hardened by means of port-

3 The difference between the optimum moisture content and the shrinkage limit of an inorganic clay soil appears to be an indicator of its susceptibility to stabilization.

4. The behavior of a soil-cement system in the wetting and drying cycles depends upon the water affinity and upon the accessibility of its internal surface

5 The behavior of a soil-cement system in the freezing and thawing

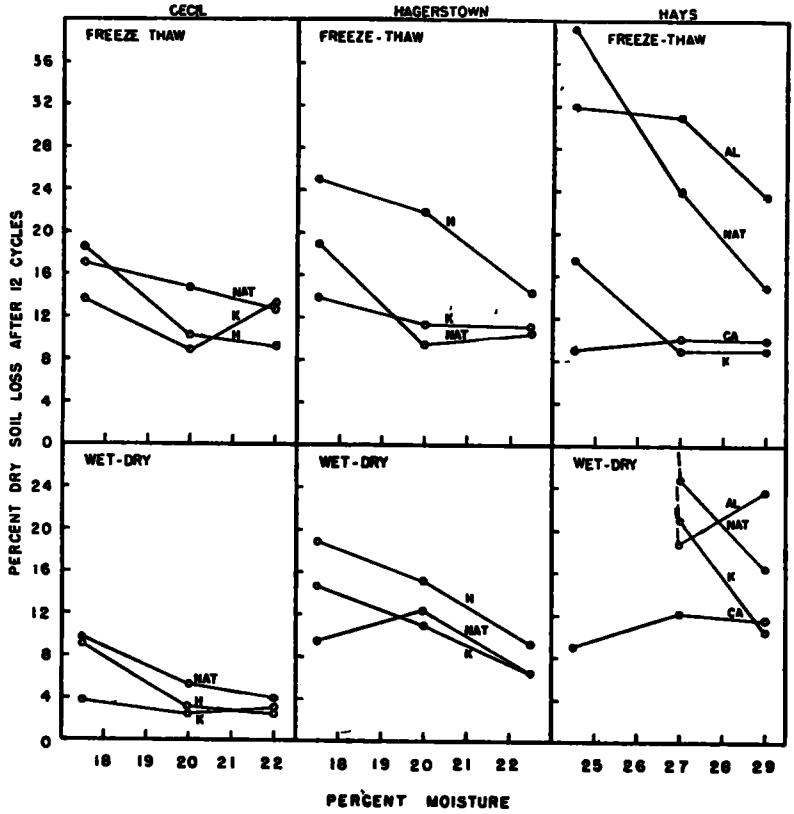

Figure 18. Effect of Moisture Content on Soil Loss in Freezing and Thawing and Wetting and Drying Tests

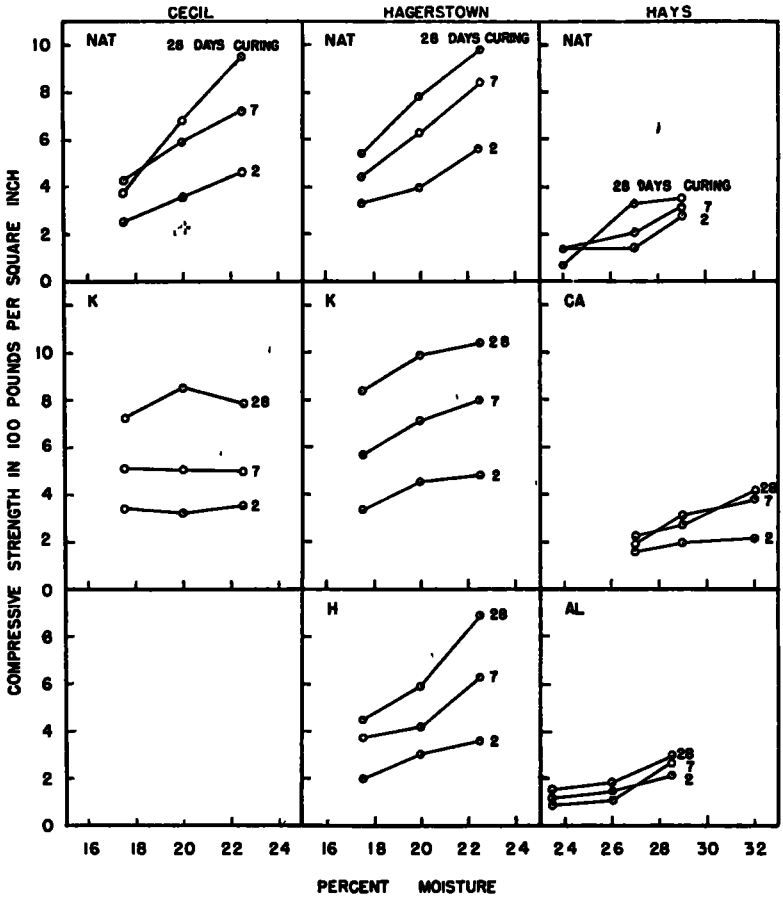

Figure 19. Effect of Moisture of Compaction on Compressive Strength

cycles depends upon the permeability of the system and especially upon the amount of pore space filled with water which is not strongly adsorbed on the internal soil surface

6. Increasing density at constant moisture content decreases the accessibility of the internal soil surface and the pore space available for freezing water, with resulting improvement of the weathering resistance of soil-cement systems.
7. Increasing moisture content at constant density exerts a general beneficial effect. The reason for this may be an increased satisfaction of the water-binding ability of both soil and cement.
8. The presence of soil organic matter appears to be undesirable, especially if it is of an acid nature.
9. Compressive strength tests performed on soil-cement systems appear to give a general indication of their quality However, such tests cannot be considered as reliable if they are not performed at a standardized temperature and on samples which have attained equilibrium conditions with water throughout the entire volume.
10. From a general point of view, the brushing procedure appears to be preferable since there is more assurance that the surface layer of the specimens is in equilibrium with the weathering agent
11. It appears feasible to design shorter test procedures based on the relative magnitude of the optimum moisture content and the shrinkage limit of inorganic soils, and upon the permeability and water affinity (heat of wetting) of soil-cement systems

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