A STUDY OF SOIL CEMENT WITH CHEMICAL ADDITIVES

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The best practical method of stabilization for construction of flexible pavements in Rhode Island was determined by investigating 17 soils with nine different chemical additives. The study was conducted both in the laboratory and in the field. The laboratory study dealt mainly with the selection of the most effective chemical additive for the cement-stabilized Rhode Island soils. The field study was essentially an evaluation of the effectiveness of cement stabilization with and without a chemical additive based on pavement performance. Results indicated that sodium sulfate is the most effective chemical additive. Addition of 1 percent sodium sulfate can significantly increase strength and durability and decrease frost heaving. Pavements containing soil cement plus 1 percent sodium sulfate base possess greater rigidity than those with soil cement alone. Soil cement test pavements developed cracks; an addition of 1 percent sodium sulfate did not appear to significantly influence the cracking behavior of pavement.

•BECAUSE of its successful engineering performance and low cost, soil cement has been used increasingly as a base course material in highway pavements. However, soils are not equally effective for cement stabilization; some soils react poorly with cement and are economically unfeasible for pavement construction. During the last decades, research has been focused on improving soil cement properties by the use of chemical additives (1-7). The main objective of these studies was to enhance the effectiveness of portland cement so that either the quantity of cement required can be reduced or the soils that cannot be stabilized economically with cement alone can be stabilized with the addition of a trace amount of chemical additive.

Among the studies on chemical additives, Catton and Felt (1) evaluated the effectiveness of calcium chloride based on the compressive strength and wet-dry and freeze-thaw test data and concluded that strength can be increased significantly with a small quantity of calcium chloride. Lambe and coworkers (2-5) investigated the compressive strength of cement-stabilized soils with several kinds of chemical additives including sodium compounds. They found that a trace amount of chemical additive could be either beneficial or detrimental to the soil cement depending on the types of soil and chemical additive. Among their findings, sodium sulfate was uniquely effective on sandy soils with organic matter. With silty soils, the strength increase due to sodium additives was smaller at higher cement contents. The effectiveness of sodium compounds on soil cement varied with soil type and decreased with an increase in soil plasticity or organic matter content of the soil or both. For a silty soil, the effectiveness of sodium compounds decreased in the order sulfate, aluminate, metasilicate, carbonate, and hydroxide. In their discussion of the paper by Lambe et al. (3), Norling and Packard (6) reported freeze-thaw and wet-dry durability test results and concluded that the effects of the additive on durability were similar to the effects on compressive strength.

Laguros and Davidson (8) evaluated the effect of compounds of sodium, calcium, magnesium, and commercial lime on the strength property of soil cement for eight

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soils from different horizons. Their results indicate that organic topsoils benefited from the incorporation of sulfates when the soils were acidic and low in clay content. With increasing clay content and an alkaline environment, the addition of calcium and magnesium ions generally resulted in greater strength. In addition, the results of their durability tests verified the strength benefaction derived from adding the chemicals to soil cement mixtures.

The preceding information shows that whether the soil cement can be significantly enhanced depends essentially on the types of soil and chemical additive. The many factors influencing the behavior of admixtures make it virtually impossible to determine the effectiveness of chemical additives for all soils without independently investigating each soil. In addition, nearly all available information was derived from laboratory studies. The complex environment in the field suggests that a successful evaluation of the property of soil cement mixture relies greatly on the field test. All of these constitute the need of the study reported here.

The primary objective of this study was to determine the feasibility of using cement-stabilized local silty soils and also to determine the best practical method of stabilization for road construction in Rhode Island. The study was conducted in two phases. The first phase mainly was a laboratory investigation that emphasized the selection of the most effective chemical additive and determination of treatment level. The second phase was a field study mainly to evaluate the effectiveness of cement stabilization with and without a chemical additive based on test pavement performance.

MATERIALS

The soils studied are typical of glacial till and outwash deposits available in various locations throughout Rhode Island. The area is unique in that, although the whole of it had been subjected to glaciation, almost all clay sizes had been washed out to the sea. Based on the soil map developed by Moultrop (9), 17 soil samples were selected for laboratory investigation. The physical properties of the test soils are given in Table 1. There are essentially only two classes of soils: A-2-4 and A-4. Type I portland cement was used throughout. Distilled water was used for mixing in the laboratory, and tap water was used in the field study. The trace chemicals studied are as follows:

Name	Formula
Sodium sulfate	Na_2SO_4
Sodium aluminate	$NaAlO_2$
Sodium carbonate	Na_2CO_3
Sodium metasilicate	$NaSiO_3 \cdot 9H_2O$
Sodium phosphate	Na_2PO_4
Lithium fluoride	LiF
Sodium fluoride	NaF
Quadrafos	$(NaPO_3)_4$
DAXAD	—

The selection of trace chemicals resulted primarily from the research findings of earlier studies by Lambe et al. (1, 2, 3, 10).

LABORATORY TEST PROCEDURES

All test soils were air dried, pulverized, and screened through a No. 10 sieve. Mixing was done in a Hobart kitchen mixer at a low speed. First the dry soil and cement were mixed for 30 sec, and then the molding water and trace chemicals were mixed for 1 min.

Table 1. Properties of test soils.

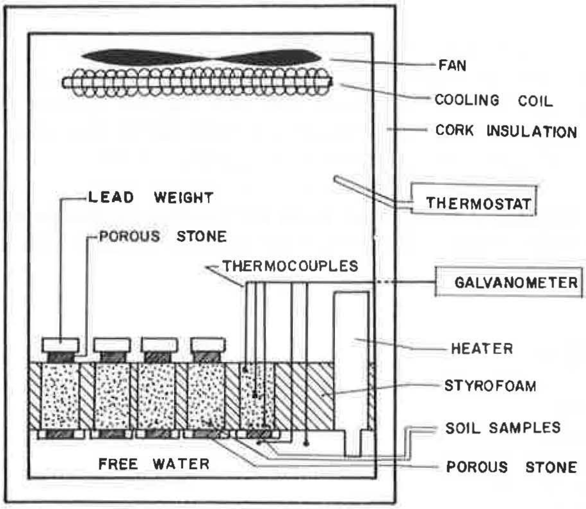
Soil	Sand[a] (percent)	Silt[a] (percent)	Clay (percent)	Liquid Limit	Plastic Limit	Maximum Dry Density[b] (lb/ft³)	Optimum Moisture Content (percent)	Medium Grain Size (mm)	Uniformity Coefficient	AASHO Classification
1	79	21	0	NP	NP	116.0	13.3	0.240	7.4	A-2-4
2	72	28	0	NP	NP	102.3	17.9	0.120	4.5	A-2-4
3	78	21	1	28.2	22.8	117.6	15.6	0.30	24.5	A-2-4
4	80	20	0	NP	NP	117.0	13.8	0.28	12.6	A-2-4
5	78	21	1	NP	NP	118.1	12.0	0.155	11.6	A-2-4
6	72	27	1	NP	NP	118.0	16.0	0.190	11.9	A-2-4
7	45	48	7	30.2	20.1	106.8	16.5	0.068	7.1	A-4
8	40	53	7	29.0	19.5	106.0	17.2	0.055	4.6	A-4
9	68	32	0	NP	NP	107.1	17.5	0.068	13.5	A-2-4
10	12	86	2	27.0	20.2	100.5	21.0	0.020	3.2	A-4
11	30	70	0	26.5	21.3	98.5	21.0	0.040	3.5	A-4
12	31	69	0	26.9	20.8	103.5	19.1	0.048	2.9	A-4
13	50	50	0	NP	NP	105.5	17.6	0.078	4.7	A-4
14	39	61	0	25.8	19.9	101.6	19.4	0.034	3.5	A-4
15	17	81	2	27.1	20.3	102.4	19.7	—	3.9	A-4
16	56	44	0	NP	NP	109.0	15.0	0.12	13.5	A-4
17	1	99	0	28.5	20.5	101.0	19.1	0.018	2.4	A-4

Note: 1 lb/ft³ = 16 kg/m³.

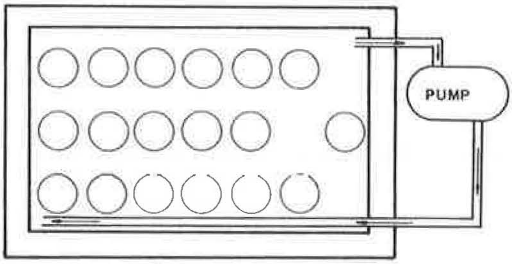
[a] ASTM-ASCE grain size scale.

[b] Standard Proctor with cement plus 1 percent Na_2SO_4.

Figure 1. Frost heave test apparatus.



ELEVATION



PLAN

Specimens were molded in a Harvard miniature mold, and density and water content corresponded approximately to the optimum moisture content and maximum dry density of a standard Proctor test, AASHO T-99-49. Sufficient samples were made to provide at least three values for the immersed unconfined compression test and the durability and laboratory frost heave tests. All specimens were cured at approximately 100 percent relative humidity and 70 F (21 C) for various periods of time.

The soil cement specimens were tested for compressive strength after being moist cured for 7 and 28 days. Specimens were soaked 24 hours and then loaded at a constant rate of strain of 0.05 in./min (1.3 mm/min) to failure.

The durability of soil cement specimens was evaluated by using the standard wet-dry test, AASHO T-135, and the freeze-thaw test, AASHO T-136. The weight loss of the test specimens was determined after 12 cycles.

The frost heave test was conducted in a cold chest (Figure 1). The test specimens, 1.4 in. (35 mm) in diameter by 3.0 in. (76 mm) high, were first cured for 28 days and then placed in the frost chest where they were subjected to 12 cycles of freezing for 2 days at 27 F (-2.8 C) and 1 day of thawing. Freezing conditions were applied only to the top face of the soil, and the bottom face was in contact with water at a temperature of 42 F (5.6 C). The apparatus could accommodate 17 specimens at a time. Specimens were frozen at approximately two-thirds of their height.

Each test soil was stabilized with a number of cement contents. The minimum cement content was determined based on compressive strength requirements, wet-dry and freeze-thaw weight loss limits, and tolerable frost heave values. The minimum compressive strength requirement was based on the Portland Cement Association's 7-day wet unconfined compressive strength criterion, which was expressed in terms of percentage of silt size content. Maximum weight losses of 14 percent for A-2-4 soils and 10 percent for A-4 soils as established by the Portland Cement Association were used as criteria for durability. The criterion for frost heave was quite tentative. Certainly more heave meant more imbibed water, hence less thawed strength. On the basis of a water content change of approximately 4 percent, 3 percent heave was regarded as the indicator of inadequate resistance to frost action.

LABORATORY TEST RESULTS

About one-half of the chemicals studied resulted in an increase in unconfined compressive strength above that obtained by treating the soil with portland cement alone. Figure 2 shows the effect of additive on the 7-day strength for soils 6 and 17. Overall, the chemical that caused the best consistent response for all test soils was sodium sulfate, and the amount of sodium sulfate required to produce maximum efficiency was 1 percent by dry weight of soil.

The 28-day unconfined compressive strength of soil cement with and without 1 percent sodium sulfate for 17 test soils is given in Table 2. Of the 17 soils tested, all but three (soils 2, 10, and 17) benefited significantly from the additive. Although the additive has no significant effect for soil 10 at 6 and 10 percent cement content and essentially no effect for soil 17 at 6 percent cement, it is detrimental to the development of 28-day strength of soil 2 at both cement contents and of soil 17 at 10 percent cement. Of the soils that benefited from the additive, only soils 8, 9, and 12 show a greater percentage of strength increase at higher cement content. For the rest of the soils, the strength increase due to sodium sulfate is small at higher cement content, confirming the finding of Lambe et al. (3).

Table 2 also gives a wide range of variation—from -31 to about 770 percent strength increase—in the effectiveness of sodium sulfate on the 28-day unconfined compressive strength of the test soils. An attempt was made to correlate the plasticity index with the percentage of strength increase; unfortunately, no clear relation was obtained. The organic content of the test soils ranges between 0.3 and 0.7 percent by weight, and the pH value varies approximately from 5.0 to 5.8. No conclusion regarding the effect of organic content and pH on the strength increase was found. Other physicochemical factors such as cation exchange capacity and clay mineral composition may have a

Figure 2. Effect of chemical additives on 7-day wet compressive strength of soil cement.

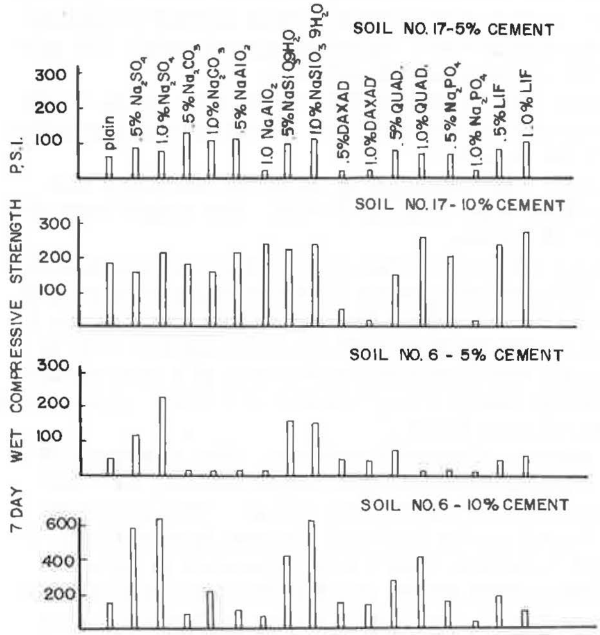


Table 2. Effect of sodium sulfate on 28-day unconfined compressive strength.

Soil	Cement Content (percent)	Unconfined Compressive Strength (psi) Cement Only	Unconfined Compressive Strength (psi) Cement + Na_2SO_4	Percentage of Strength Increase[a]
1	6	50	235	370
	10	402	510	27
2	6	202	173	-14
	10	385	266	-31
3	6	56	205	266
	10	124	361	191
4	6	60	275	358
	10	400	418	5
5	6	72	402	458
	10	147	600	308
6	6	112	524	368
	10	195	766	293
7	6	33	275	732
	10	57	440	672
8	6	50	215	330
	10	100	510	410
9	6	40	250	525
	10	75	650	766
10	6	100	90	-10
	10	235	240	2
11	6	28	136	386
	10	96	238	148
12	6	50	200	300
	10	75	440	486
13	6	50	118	136
	10	115	255	122
14	6	74	112	51
	10	130	182	40
15	6	20	36	80
	10	50	72	44
16	6	54	183	239
	10	137	264	93
17	6	143	143	0
	10	235	175	-26

Note: 1 psi = 6.9 kPa.

[a] $\text{Percentage of strength increase} = \dfrac{(\text{strength of cement plus 1 percent } Na_2SO_4) - (\text{strength of cement alone})}{\text{strength of cement alone}} \times 100.$

decisive influence on the effectiveness of sodium sulfate. No data are, however, available to make further conclusions possible.

The test results indicate that soils of the same classification do not respond equally to a chemical additive such as sodium sulfate. Thus, the effectiveness of a trace additive cannot be evaluated based on soil classification.

Only 10 of 17 test soils were studied under standard PCA freeze-thaw and wet-dry tests. Soils for durability tests were selected to cover a wide range of gradation and plasticity characteristics of each class of soil. In the durability study, two cement contents, 7.5 and 10 percent, were used. A 7.5 percent cement content rather than 6 percent as used in the wet strength tests was adopted because, at this treatment level, the weight loss under durability tests can be kept as close as 14 percent for A-2-4 soils and 10 percent for A-4 soils, which are the durability criteria established by the Portland Cement Association. Results of the durability study given in Table 3 indicate that addition of 1 percent sodium sulfate to the soil cement resulted in a decrease in the percentage of weight loss for most soils studied. Some soils, especially soils 1 and 8, however, do not benefit from the trace additive.

A comparison of Table 3 with Table 2 reveals that although addition of 1 percent sodium sulfate increased the strength of soils 1 and 8, their durability was not necessarily increased by addition of the same chemical. In other words, a trace additive does not necessarily always improve both strength and durability of a soil cement simultaneously. This result emphasized that the effectiveness of a trace chemical must be determined based on not only its strength property but also the durability of the mixture.

Another measure of the resistance of soil cement to frost action was studied by measuring frost heave. The test apparatus is shown in Figure 1. Because considerable time was lost in designing and constructing the apparatus and each test series is very time-consuming, 40 to 45 days, only five of 17 test soils were studied. Figure 3 shows a typical frost heave for soil 9; the figure indicates clearly the effectiveness of 1 percent sodium sulfate in reducing frost heaving. The results of the frost heave study are given in Table 4 in terms of the minimum cement requirement based on a criterion of 3 percent heaving; the table also gives the minimum cement requirement based on strength, freeze-thaw, and wet-dry durability tests. These minimum cement requirements were used as a basis for designing experimental pavements for the field study.

TEST ROAD

The test road is a two-lane highway with 10-ft (3-m) shoulders and is essentially a section of RI-214, a state secondary highway in Middletown, Rhode Island. It is composed of two control sections of conventional design and five experimental sections of different materials in base and subbase courses as shown in Figure 4. All sections are surfaced with 3 in. (76 mm) of bituminous concrete.

Specifications for construction of the test pavements were modified from PCA suggestions; detailed specifications were given in the initial preconstruction report.

The base and subbase course materials were pulverized and mixed in place with a Trav-L-Plant multiple-pass rotary mixer. A bulk cement truck with a compressed-air distributing system and a pressure distributor truck were used for applying cement and water to the roadway. Normally, one section of subbase or base was constructed per day. Each section was processed in 5 or 6 strips, 8 to 9 ft (2.4 to 2.7 m) wide; compaction of one strip was concurrent with processing of the adjacent one. Sodium sulfate was dumped in to make a 20 percent solution. The solution was kept circulating in the tank.

A light steel-wheeled roller was used on the initial compaction pass to push down stones; subsequent compaction was with a pneumatic roller. In all cases, compaction was above the specified 95 percent, and an average of 99 percent maximum density was attained.

Table 3. Results of freeze-thaw and wet-dry tests.

Soil	Cement Content (percent)	Percentage Loss With 1 Percent Na_2SO_4		Percentage Loss Without Na_2SO_4	
		Wet-Dry	Freeze-Thaw	Wet-Dry	Freeze-Thaw
1	7.5	5.25	4.29	2.91	2.51
	10.0	3.86	4.50	3.44	2.00
5	7.5	5.22	7.02	7.77	8.65
	10.0	1.21	1.62	4.77	3.32
6	7.5	7.15	8.35	4.65	12.12
	10.0	1.95	2.46	3.31	2.05
8	7.5	10.52	9.65	2.85	5.13
	10.0	3.63	6.30	2.62	1.92
10	7.5	12.05	13.62	11.62	100.0
	10.0	9.78	11.75	9.77	10.75
11	7.5	1.65	100.0	2.62	5.31
	10.0	1.65	1.67	3.13	5.11
12	7.5	7.49	14.30	6.62	26.1
	10.0	7.65	3.70	3.38	1.22
13	7.5	3.39	6.00	6.00	100.0
	10.0	2.99	7.31	5.32	100.0
16	7.5	1.61	5.60	6.30	100.0
	10.0	1.02	0.0	2.75	100.0
17	7.5	10.75	15.12	18.55	18.62
	10.0	8.65	10.05	7.23	10.17

Figure 3. Effect of sodium sulfate on frost heave for soil 9.

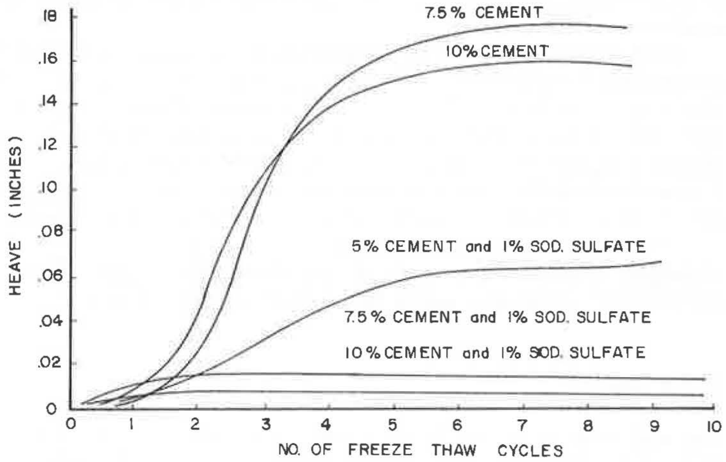


Table 4. Minimum cement requirements (in percentage of dry soil weight) with 1 percent sodium sulfate.

Soil	Based on 7-Day Strength	Based on Freeze-Thaw	Based on Wet-Dry	Based on 3 Percent Frost Heave
1	7.0	5.5	5.5	—
2	11.5	—	—	—
3	9.0	—	—	—
4	7.4	—	—	—
5	3.5	5.0	5.0	—
6	3.5	5.5	5.0	5.0
7	6.0	—	—	—
8	6.3	7.5	7.3	7.0
9	6.0	—	—	5.8
10	10.0	13.5	12.0	—
11	11.2	7.5	6.0	—
12	7.5	7.0	8.5	—
13	10.0	6.0	5.5	—
14	13.0	—	—	7.5
15	8.4	—	—	7.5
16	11.0	5.5	5.5	—
17	10.4	13.5	12.0	—

TEST ROAD PERFORMANCE

The performance of test pavements was evaluated by using the Benkelman beam test, plate bearing test, and roughometer test and on the basis of cracking and response to freezing temperature. Additional information regarding pavement performance evaluated before 1972 is reported elsewhere (11). The following discussion deals mainly with the relative performance of the sections containing soil cement with and without sodium additive.

The Benkelman beam tests were conducted annually in the spring and summer at the locations shown in Figure 5. The test truck had a rear axle load of 18 kips (8154 Kg) and a tire pressure of 80 psi (550 kPa). Detailed testing procedures are given by Roderick and Huston (12).

Test results are shown in terms of mean maximum deflection in Figure 6; each deflection value is the average of 16 measurements. Comparison of the deflection in sections 5, 6, and 7, which contain the same amount of cement in the subbase layer, shows that section 6 (with 6 percent cement plus 1 percent sodium sulfate base) deflects as little as section 5 (with 11 percent cement base), indicating the beneficial effect of the addition of 1 percent sodium sulfate. However, section 7 (with 10 percent cement plus 1 percent sodium sulfate) unexpectedly deflects as much as section 6. A possible reason for this is that the subbase material in section 7 has only about half the strength of the material in section 6 (Figure 7). Figure 7 shows the unconfined compressive strength of the base and subbase material used in the experiment sections. Note that there are two types of specimens tested for base material: One is a 1.4-in.-diameter (35-mm) by 2.8-in.-high (71-mm) laboratory specimen compacted to the same moisture content and density as those in the field and cured in a moist room, and the other is a 4-in.-diameter (102-mm) by 8-in.-high (204-mm) undisturbed core. The greater strength of the base course material in section 7 as compared with that of section 5 verifies further the beneficial effect of sodium sulfate.

The plate bearing tests were conducted annually in different seasons by using a 12-in.-diameter (305-mm) plate at two permanent test sites in each section. The test sites are located on the boundary separating the traffic and shoulder lanes, 150 ft (46 m) from the beginning of each section on the right and 150 ft from the end on the left. A hydraulic jack was used to apply static plate load, and two 0.001-in. (0.025-mm) dial gauges at opposite ends of a diameter were used to measure plate deflection. Test results shown in Figure 8 generally follow those of the Benkelman beam test.

The roughometer tests were conducted by the Rhode Island Department of Transportation by using the BPR roughometer. No conclusive difference in the pavement roughness between experimental sections due to addition of sodium sulfate has been found.

Cracking behavior of the experimental sections was carefully surveyed and mapped annually. The depths of the cracks were determined by taking core samples across a crack. It was found that the cracks generally go through the entire base course but only to about middepth of the subbase course. Except for some transverse cracks that developed along the construction joints between sections and that had widths of about ¼ to ⅜ in. (6.3 to 9.5 mm), the widths of the cracks were in general smaller than ⅛ in. (3.2 mm), and once cracks developed no further change in width was noted.

The surface crack pattern mapped in March 1972 is shown in Figure 9. It is interesting to note that all surface cracks developed in transverse and longitudinal directions only. Some transverse cracks apparently developed along the construction joints between sections, and longitudinal cracks appeared to develop along the joints of the strips produced during construction. Most cracks are, however, primarily caused by cement hydration and thermal stress.

Figure 10 shows the crack length surveyed. Cracking increases with time for all experimental sections. The rate of increase in cracking, however, varies for various sections. Data obtained in April 1974 indicate that (a) section 3 (9 percent cement) developed the greatest amount of longitudinal cracks (most of the cracking, however, appeared along the centerline of the pavement) and section 6 (6 percent cement plus 1 percent sodium sulfate) developed the least; (b) transverse cracks developed the most

Figure 4. Bases and subbases of experimental road sections.

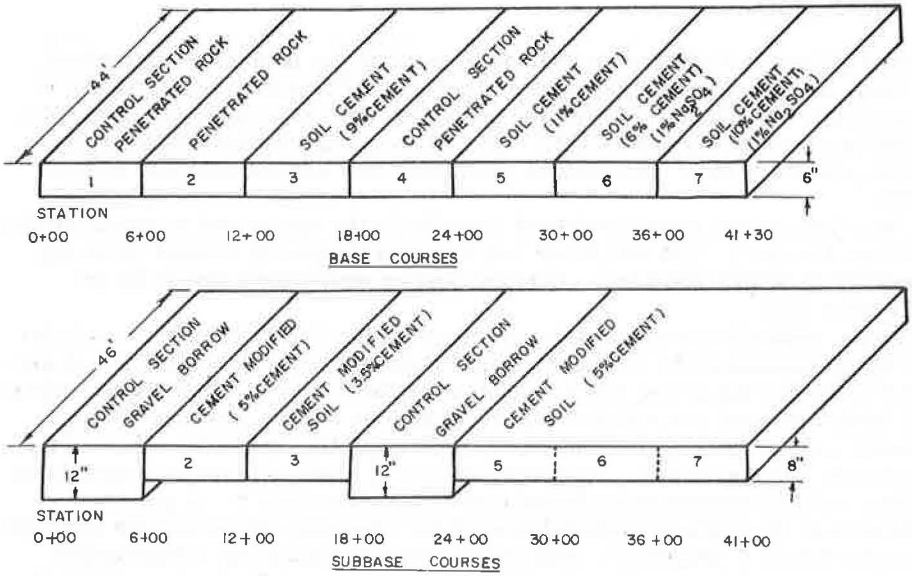


Figure 5. Layout of Benkelman beam deflection test sites.

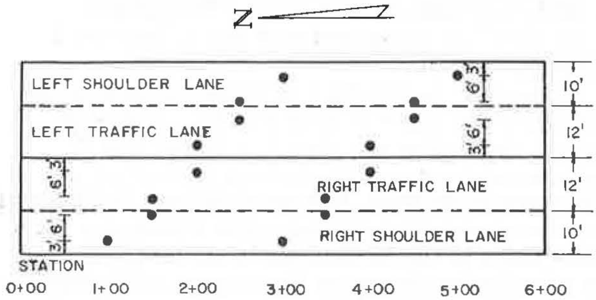


Figure 6. Mean maximum pavement deflection in Benkelman beam test.

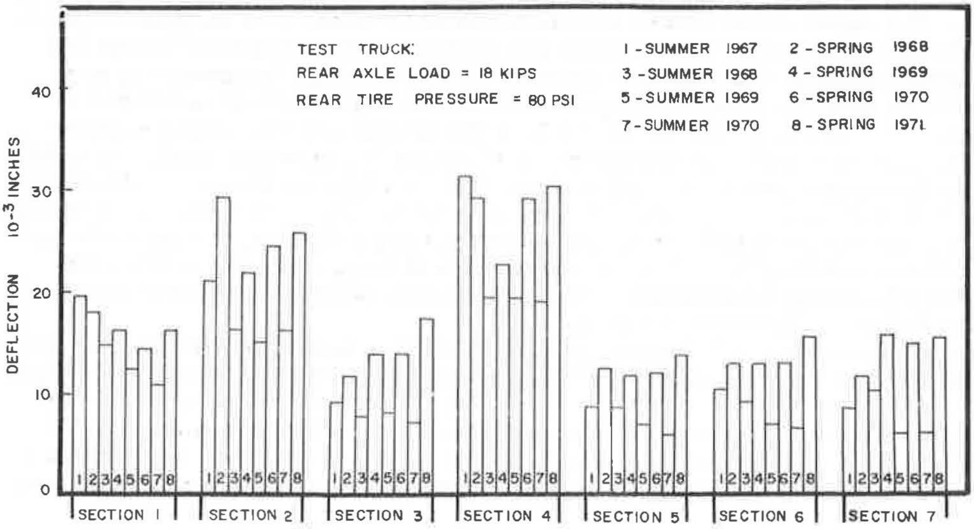


Figure 7. Unconfined compressive strength of base and subbase materials.

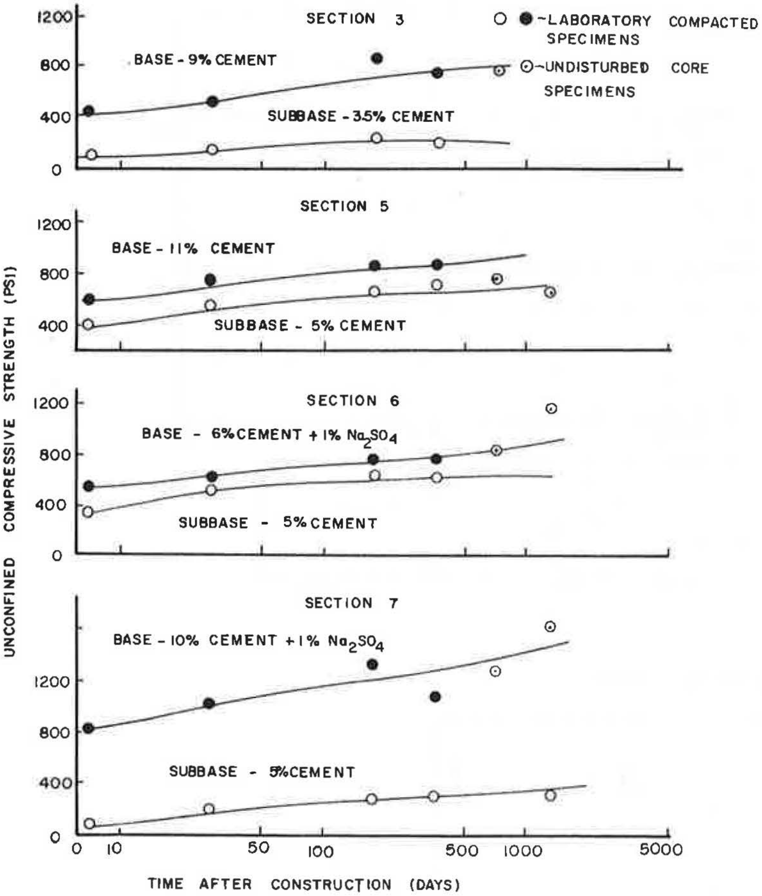


Figure 8. Pavement deflection under 15-kip (67-kN) plate load.

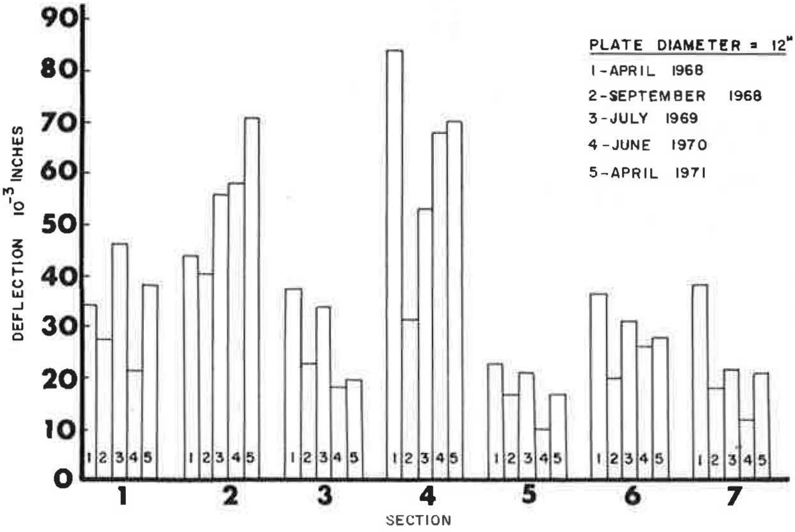


Figure 9. Cracks pattern mapped on March 28, 1972.

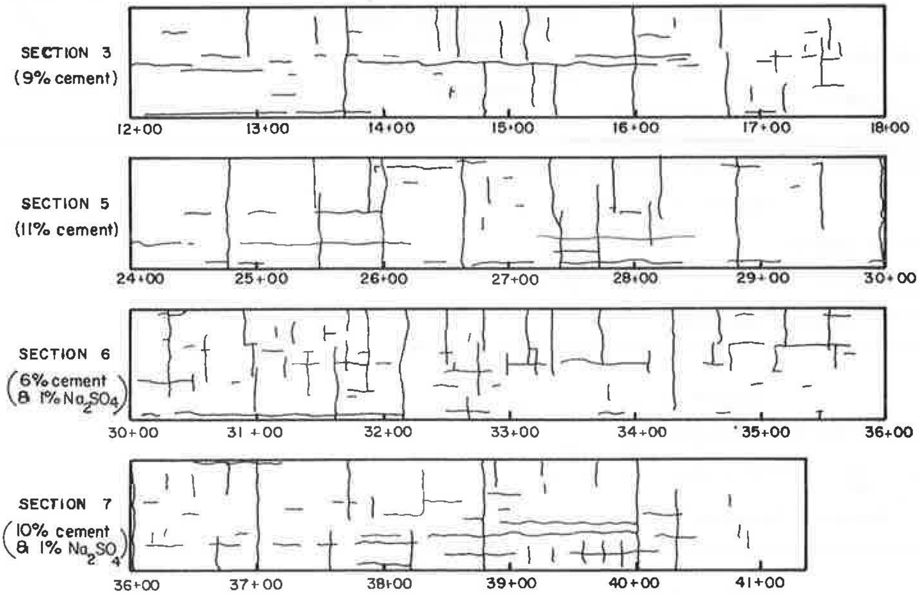
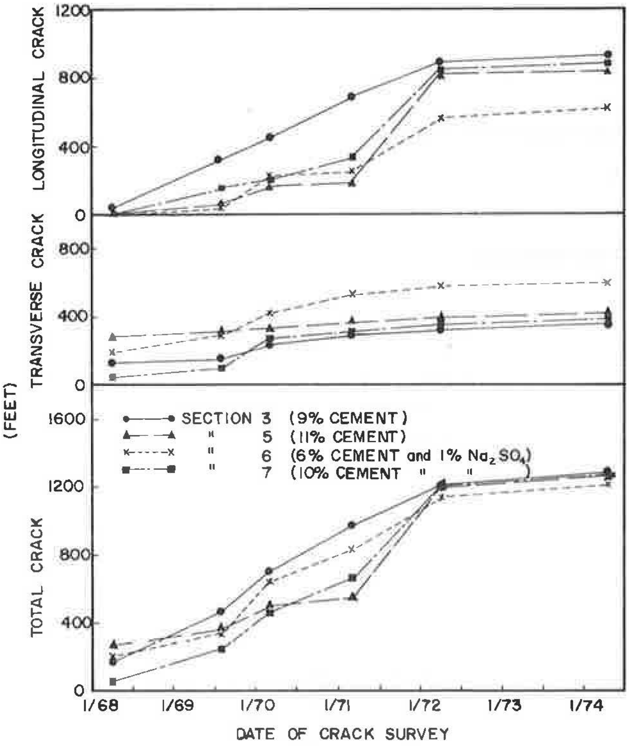


Figure 10. Length of surface crack in test sections.



in section 6 and the least in section 3; and (c) the total length of the cracks was shortest in section 6 and was almost equal in the other three sections. The results obtained to date seem to suggest that cracking of the experimental pavement tends to level off after 6 years' service; the intensity of cracking is greater at higher cement content. The addition of 1 percent sodium sulfate does not influence the cracking behavior significantly, although the strengths are increased considerably as has been reported.

The response of the experimental pavements to freezing temperature has been reported elsewhere (11). No conclusion regarding the relative response of each soil cement section to frost penetration can be drawn from the data available.

SUMMARY AND CONCLUSIONS

The effect of chemical additives on the cement-stabilized Rhode Island soils was studied with 17 natural soils that are typical of glacial till and outwash deposits. The study was conducted both in the laboratory and in the field. In the laboratory, nine chemical additives of reagent grade were investigated by using strength, durability, and frost heave tests. Test results indicate that, of the nine chemicals studied, sodium sulfate generally improved the strength and durability of cement-stabilized Rhode Island soils better than the others. Furthermore, soils of the same classification do not respond equally well to sodium sulfate.

In the field, a test road was constructed to study the effectiveness of sodium sulfate in soil cement. The test pavements were evaluated according to their relative performance under loading, cracking behavior, and resistance to frost action. Under the same subbase support, the pavement containing soil cement plus a sodium sulfate base layer deflects as little as that containing a base layer without sodium sulfate but with greater cement content. The increase in pavement stiffness due to the addition of 1 percent sodium sulfate provides a further indication of the beneficial effect of sodium additive strengthwise. Results of the crack study seemed to suggest that pavements containing base course with a higher cement content developed more cracks; the addition of 1 percent sodium sulfate did not appear to influence cracking behavior significantly. The effect of sodium sulfate on the frost resistance of soil cement pavement could hardly be seen from the available field test data.

Based on the test results, it is concluded that sodium sulfate is the most effective chemical additive of those studied for the cement-stabilized Rhode Island soils. Addition of 1 percent sodium sulfate does not result in a significant influence on cracking behavior; however, it significantly improves strength, durability, and frost resistance of the soil cement.

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