Resistance of Soil-Cement Exposed to Sulfates

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● SOIL-CEMENT has gained widespread acceptance as a stabilized base for both concrete and asphalt pavements. Many miles of highway construction, particularly in the arid west, pass through areas containing "alkali" soils. The destructive action of sulfates on portland cement concrete is well known, and extensive research has developed sulfate-resistant cement and sulfate-resistant concrete structures. Soil-cement also contains portlant cement, but the resistance of soil-cement to sulfates has not been established.

The Portland Cement Association supported a research project at Utah State University during the past several years to establish the durability of soil-cement exposed to sulfate salts, and also the durability of soil-cement made with sulfate soils. The first part of the investigation was a study of the durability of soil-cement specimens, fabricated from soils containing negligible amounts of sulfate salts, when exposed to a solution of sodium and magnesium sulfate in the laboratory and to sulfate soils in the field. Laboratory specimens were stored in a 2 percent solution of sulfate salts while companion field specimens were buried in sulfate soil south of Huntington, Utah, adjacent to the location of Interstate 70.

In the second part of the investigation, soil-cement specimens were made with the same fine-grained and coarse-grained soils, but various percentages of sodium and magnesium sulfate were mixed with the soil-cement at the time of fabrication. The first part of the investigation studied the resistance of soil-cement to sulfate attack from outside sources, whereas the second part of the investigation was designed to determine the durability of soil-cement with sulfate salts mixed integrally.

MATERIALS

Portland Cements

Experience with portland cement concrete indicates that the durability of concrete when exposed to sulfates, depends to a large extent on cement composition and the richness of the mix. Nine different portland cements were used in this investigation. These included three different types, Type I, Type II, and Type V, with three different brands of cement of each type. The cements were secured primarily from the Rocky Mountain area with the exception of two Type V cements, which came from the West Coast. The chemical analysis and the calculated compound composition of each cement are given in Table 1.

Soils

Soils used to fabricate soil-cement specimens included a coarse-grained soil and also a fine-grained soil. Both of these soils were obtained from the drainage area of the Blacksmith Fork River in Cache Valley, Utah. Material retained on the No. 4 sieve was removed from both soils.

Approximately 12 percent of the total coarse-grained soil sample passed the No. 200 sieve, whereas 90 percent of the fine-grained soil passed this sieve size. The grading analysis of both soils is given in Table 2. Both soils were tested for soluble sulfates. The fine-grained soil contained 0.027 percent soluble sulfates, whereas the coarse-grained soil contained 0.014 percent of these salts.

TABLE 1

CHEMICAL ANALYSIS AND CALCULATED COMPOUND COMPOSITION OF CEMENTS

PCA Lot No	Cement Brand	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	Tot Alk as Na_2O	Loss on Ign	Ins Res	Free CaO	Fineness Blaine (sq cm per g)	Calculated Compound Composition, %* C_3S	C_2S	C_3A	C_4AF
TYPE I																		
19691	I	21 05	5 63	2 75	62 70	2 76	2 65	0 17	0 67	0 61	1 70	0 40	0 76	3,550	45 9	25 8	10 3	8 4
19693	E	21 58	5 67	2 29	64 16	1 83	1 79	0 16	1 02	0 83	1 52	0 17	1 56	3,025	50 6	23 8	11 2	7 0
19695	M	22 06	5 64	2 80	64 00	1 05	1 69	0 13	0 80	0 66	1 67	0 15	1 02	2,970	46 1	28 6	10 2	8 5
TYPE II																		
19692	I	22 35	4 82	3 45	62 80	2 94	2 01	0 23	0 46	0 53	1 13	0 28	0 69	3,190	42 7	31 9	6 9	10 5
19694	E	22 83	4 77	2 83	64 54	1 56	1 91	0 09	0 64	0 51	1 08	0 09	0 70	2,945	47 6	29 6	7 9	8 6
19696	M	21,83	5 07	4 54	63 91	0 87	1 87	0 10	0 68	0 55	1 25	0 19	0 64	3,100	48 3	26 2	5 8	13 8
TYPE V																		
19697	M	23 44	3 64	3 43	64 24	0 86	1 73	0 10	0 45	0 40	1 96	0 20	1 06	3,450	49 0	30 3	3 8	10 4
19698	R	23 82	3 25	3 21	63 30	2 08	2 09	0 06	0 54	0 42	1.66	0 06	0 76	3,270	44 2	35 0	3 2	9 8
19699	V	24 34	3 18	2 82	62 76	3 53	1 63	0 10	0 30	0 30	1 26	0 08	0 62	3,170	40 4	39 4	3 7	8 6

*Not corrected for free CaO

TABLE 2

GRADING OF COARSE- AND FINE-GRAINED SOIL

Soil	Sieve Size	% Passing
Coarse-grained	No. 4	100
	No. 10	81
	No. 40	41
	No. 200	12
Fine-grained	No. 4	100
	No. 10	100
	No. 40	98
	No. 200	90

Sulfate Salts

The 2 percent solution of sulfates, in which laboratory specimens were stored, was made up of 75 percent sodium sulfate by weight and 25 percent magnesium sulfate. An anhydrous sodium sulfate, Na_2SO_4, and a dried powder of magnesium sulfate, $MgSO_4$, were used. The equivalent SO_4 content of the solution was 1.42 percent by weight.

Samples of the soil in which the field specimens were buried were tested for sulfate content. Specimens were buried in a fine silty sand which was found to contain 1.77 percent SO_4. A second sample from a slightly different location in the same area contained 1.46 percent SO_4 by weight.

PROCEDURES AND METHODS

Standard tests of the American Society for Testing Materials, and the American Association of State Highway Officials, along with the recommendations and publications of the Portland Cement Association were used in establishing the proper testing methods and procedures. The following standard tests were used in this investigation:

Test	ASTM Designation	AASHO Designation
Moisture-density relationships of soil-cement mixtures	D558-57	T-134-57
Freezing and thawing of compacted soil-cement mixtures	D560-57	T-136-57
Wetting and drying of compacted soil-cement mixtures	D559-57	T-135-57
Optimum cement content of compacted soil-cement	Portland Cement Association Manual	

In establishing the optimum cement content for soil-cement, the Portland Cement Association recommends testing in freezing and thawing and wetting and drying at a medium cement content (6 percent by weight of soil for coarse-grained soils and 10 percent cement by weight of soil for fine-grained soils). The optimum cement content should be sufficient, in each case, so the loss will not exceed the allowable loss suggested by AASHO (not more than 14 percent for coarse-grained soil, Type A-I, and not more than 10 percent for fine-grained soils, Type A-4).

Freezing and thawing and wetting and drying tests made with the soils used in this investigation showed that at a medium cement content the losses were only approximately one-half the allowable loss. Another set of specimens were made in which the cement content was reduced 2 percent in each case. It was found at these cement contents that the losses in freezing and thawing and wetting and drying were approximately twice that suggested by AASHO. It was decided, therefore, that the medium cement content for the coarse-grained soil should be 6 percent cement by weight of soil. The medium cement content for the fine-grained soil should be 10 percent.

In order to establish the influence of richness of mix, cement contents lower than medium and higher than medium were used with each cement. Coarse-grained soil cement specimens were made with 3, 6, and 10 percent by weight of soil. Fine-grained soil-cement specimens were made with 6, 10, and 14 percent portland cement by weight of soil.

A total of 54 different soil-cement mixtures were made in the first part of the investigation. Specimens from each of the 54 mixtures were stored in sulfate solutions in the laboratory and duplicate specimens were buried in sulfate soils near Huntington, Utah. All test specimens were molded at the predetermined optimum moisture content and at maximum density (Fig. 1). If any specimen did not fall within the range of maximum density, ± 3 pcf, or within optimum moisture, ± 1 percent, the specimen was discarded and another specimen molded.

All field specimens were cured in the laboratory for a minimum of 28 days before being buried in the field. Because of the long distance to the area where the field specimens were buried, it was necessary to bury them at one time, and a uniform curing period before being placed in the field could not be maintained. Field specimens were buried approximately 1 ft deep along a bank of sulfate soil close to Seven-Mile Creek south of Huntington, Utah. Photographs of this location and of soil-cement specimens after being buried are shown in Figures 2 and 3.

In the second part of the investigation, soluble salts of sodium and magnesium sulfate were mixed directly in the soil-cement. The salts were first dissolved in mixing water and then added in amounts of 0, 0.5, 1, 2, and 3 percent by weight of the soil. Sulfate salts were combined in a proportion of 75 percent sodium sulfate and 25 percent magnesium sulfate. Higher concentrations of sulfate salts resulted in supersaturated solutions at lower temperatures. This necessitated heating the water before the entire amount of sulfate salt could be put into solution.

Tests used to measure the influence of various concentrations of sulfate salts in soil-cement included the compressive strength, freezing and thawing durability, and wetting and drying durability. The

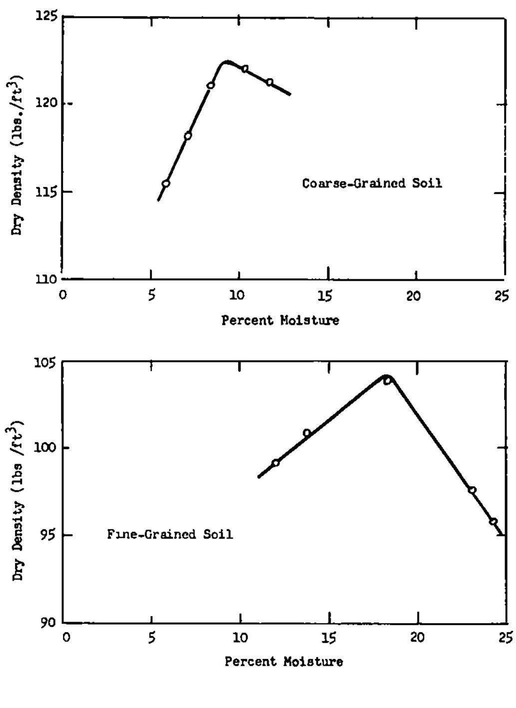

Figure 1. Moisture-density relationships.

Figure 2. Location of field specimens. Note white sulfate salts on surface.

Figure 3. Specimens uncovered after 1 year.

compressive strength was measured on 4-in. standard compaction cylinders after curing for 7 days, 28 days, 3 months, and 1 year in a moist cabinet. Standard ASTM tests and AASHO tests were used to measure the durability in wetting and drying and freezing and thawing.

DISCUSSION OF TEST RESULTS

First Phase

The primary purpose of the first part of the investigation was to determine the resistance of soil-cement specimens to sulfate attack under different exposure conditions. A photographic record, taken at different time intervals, was considered the best method of demonstrating progress of the attack of sulfate salts. Although this method does not give quantitative test results, it does record many aspects of deterioration which cannot be recorded by laboratory tests. The following procedure was used in making this record. The soil-cement specimens, both in the laboratory and in the field, were brushed and photographed at 6-month intervals. Progressive deterioration of typical soil-cement specimens are shown in Figures 4 to 12. These photographs are arranged so that all specimens fabricated with a typical brand of cement are included in one plate. The variables shown on each plate include laboratory and field specimens of three different cement contents made with both fine- and coarse-grained soils.

Photographs of sulfate deterioration indicate that sulfate attack on soil-cement varies with cement content, type of cement used, type of soil, and also type of exposure. Specimens containing low cement contents generally deteriorated from the outer surface of the specimen. The surface would become soft and flake off as the sulfate salts penetrated the specimen. The specimens containing high cement contents, however, became harder when exposed to sulfate solutions or buried in sulfate soils. The durability and strength of some specimens increased with sulfate exposure. As the inner part of other specimens expanded, cracks would appear and large pieces of the specimen would break off. Some specimens split along the compaction plane formed during molding. The hardening of specimens was more noticeable in laboratory specimens than in field specimens.

Specimens containing fine-grained soils deteriorated more rapidly in field exposure than in the laboratory. Specimens containing coarse-grained soils and low cement contents also deteriorated rapidly under field exposure. The difference between field and laboratory temperatures may account for these differences. The field specimens were not only required to resist the attack of sulfate salts, but in all probability were also subjected to an unknown number of cycles of freezing and thawing.

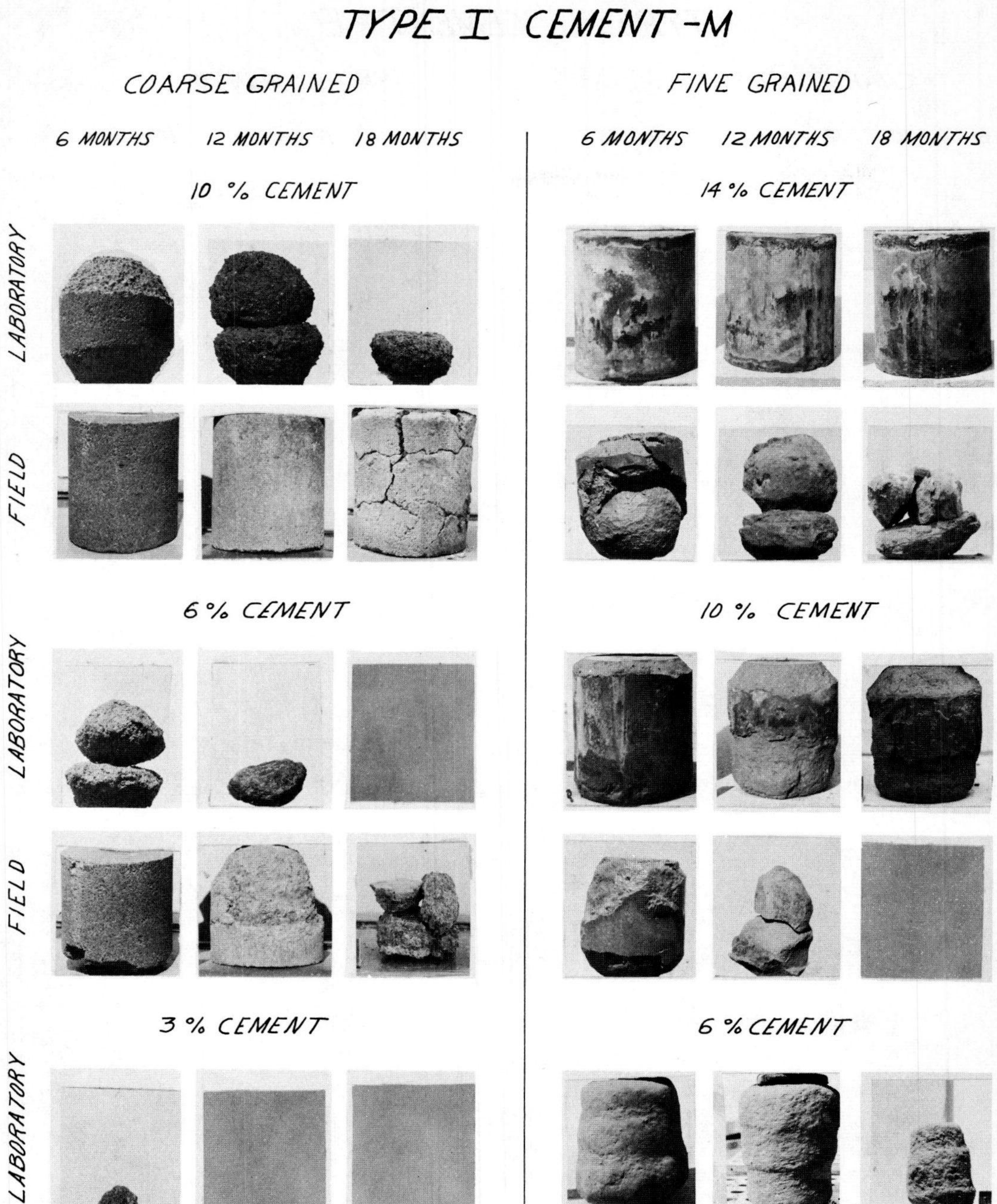
TYPE I CEMENT-M
COARSE GRAINED
FINE GRAINED
6 MONTHS
12 MONTHS
18 MONTHS
6 MONTHS
12 MONTHS
18 MONTHS
10 % CEMENT
14 % CEMENT
LABORATORY
FIELD
6 % CEMENT
10 % CEMENT
LABORATORY
FIELD
3 % CEMENT
6 % CEMENT
LABORATORY
FIELD

Figure 4.

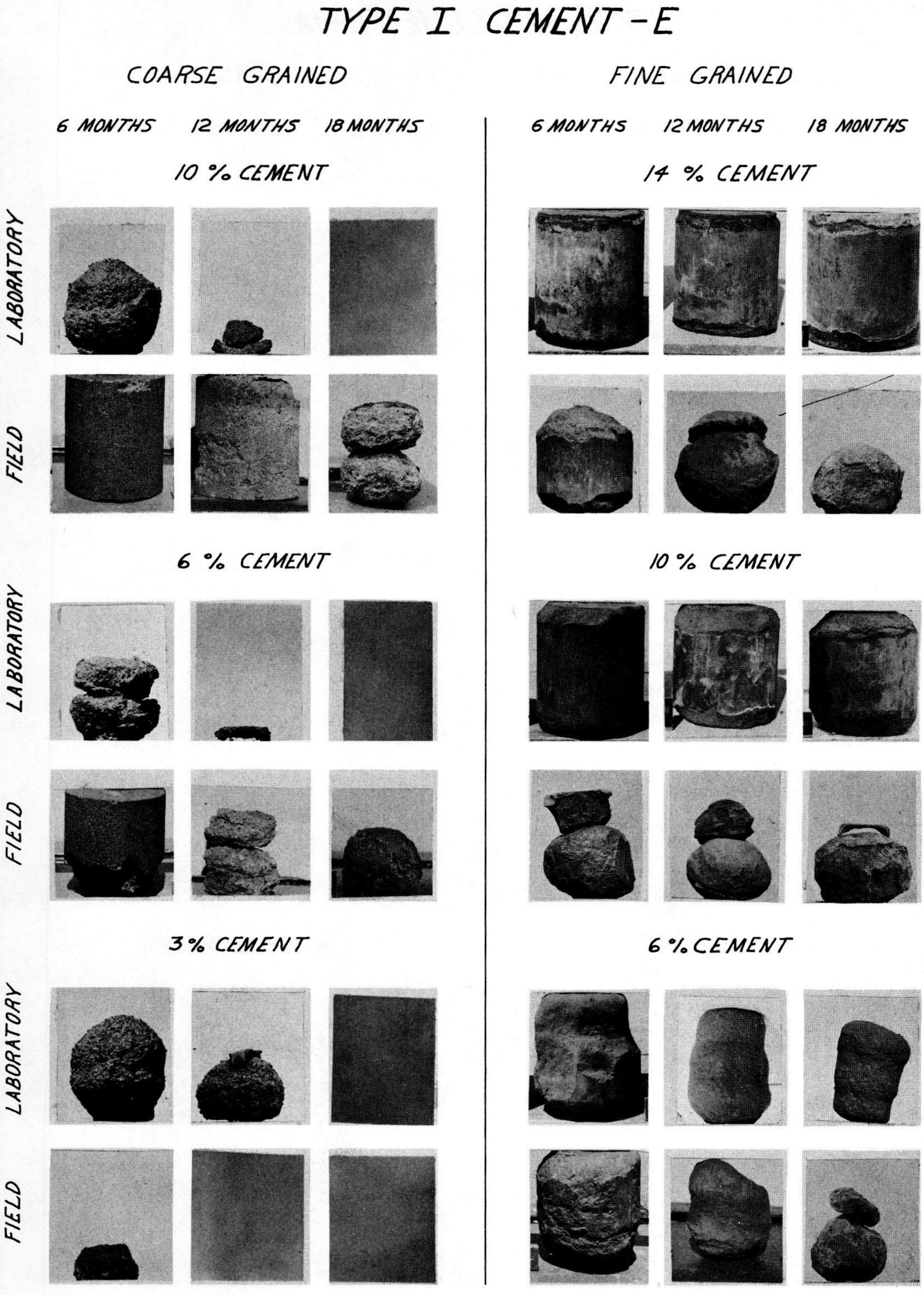
TYPE I CEMENT - E
COARSE GRAINED
FINE GRAINED
6 MONTHS
12 MONTHS
18 MONTHS
6 MONTHS
12 MONTHS
18 MONTHS
10 % CEMENT
14 % CEMENT
LABORATORY
FIELD
6 % CEMENT
10 % CEMENT
LABORATORY
FIELD
3 % CEMENT
6 % CEMENT
LABORATORY
FIELD

Figure 5.

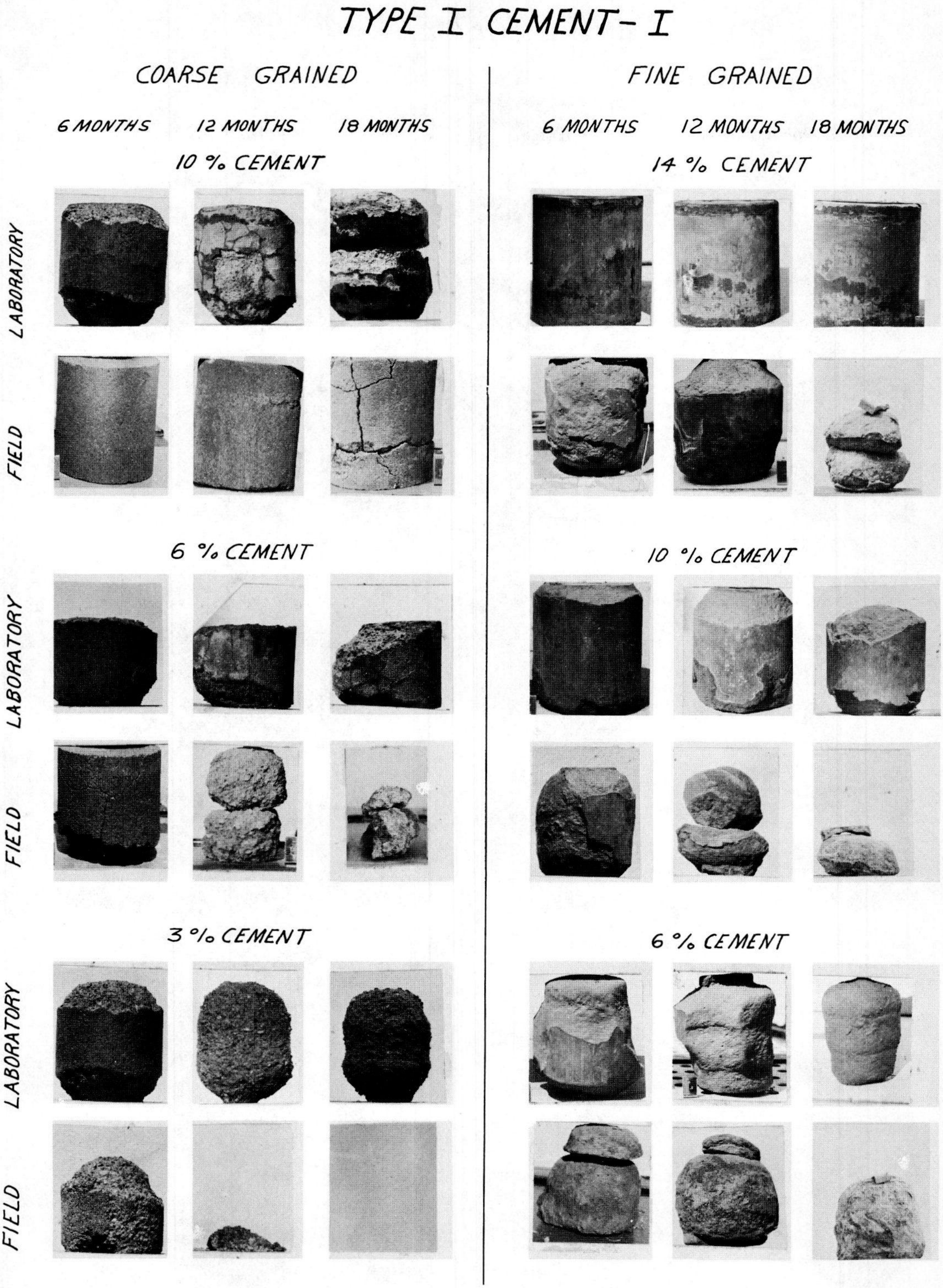
TYPE I CEMENT- I
COARSE GRAINED
FINE GRAINED
6 MONTHS
12 MONTHS
18 MONTHS
10 % CEMENT
14 % CEMENT
LABORATORY
FIELD
6 % CEMENT
10 % CEMENT
3 % CEMENT
6 % CEMENT

Figure 6.

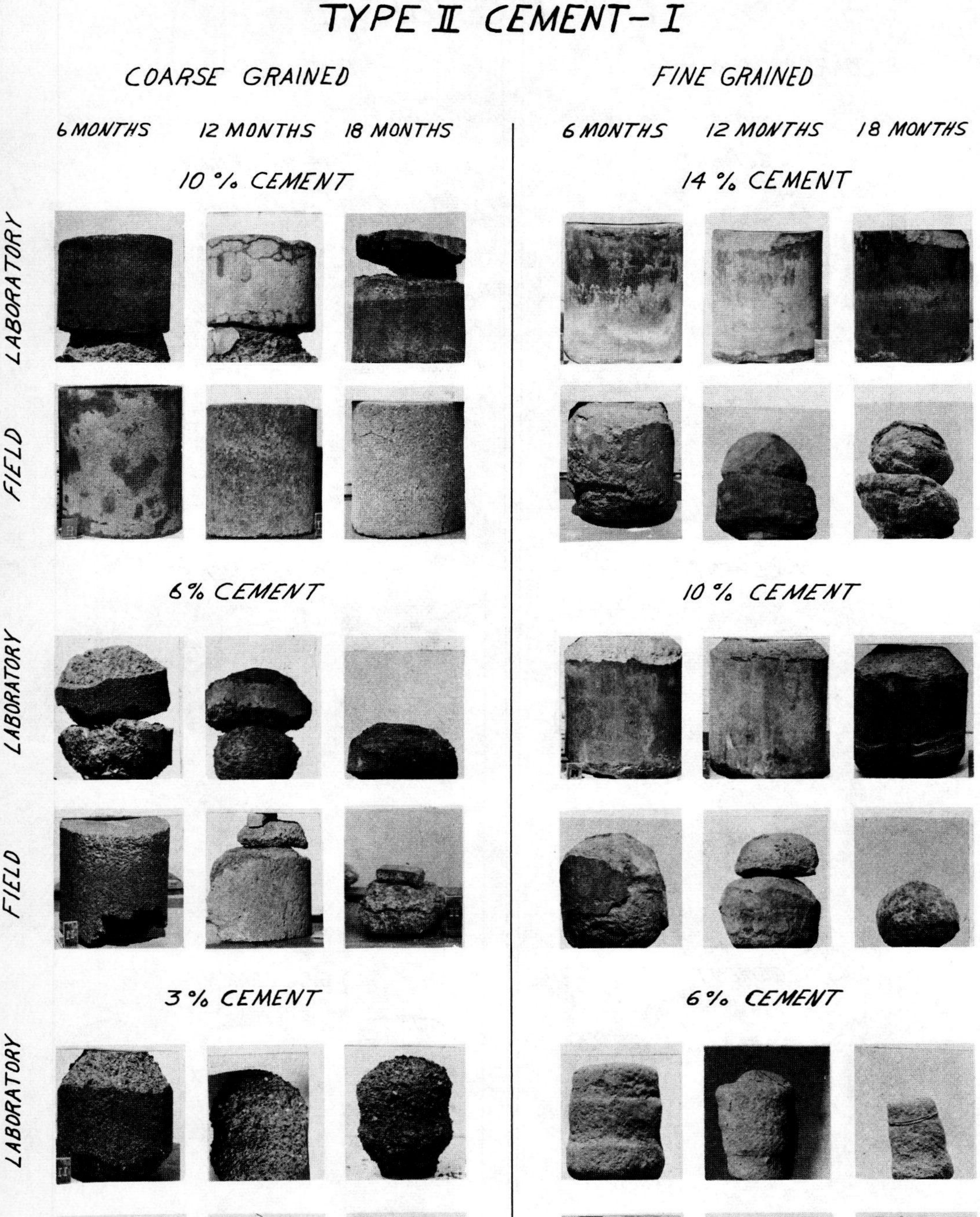
TYPE II CEMENT-I
COARSE GRAINED
FINE GRAINED
6 MONTHS
12 MONTHS
18 MONTHS
6 MONTHS
12 MONTHS
18 MONTHS
10 % CEMENT
14 % CEMENT
LABORATORY
FIELD
6% CEMENT
10 % CEMENT
LABORATORY
FIELD
3 % CEMENT
6 % CEMENT
LABORATORY
FIELD

Figure 7.

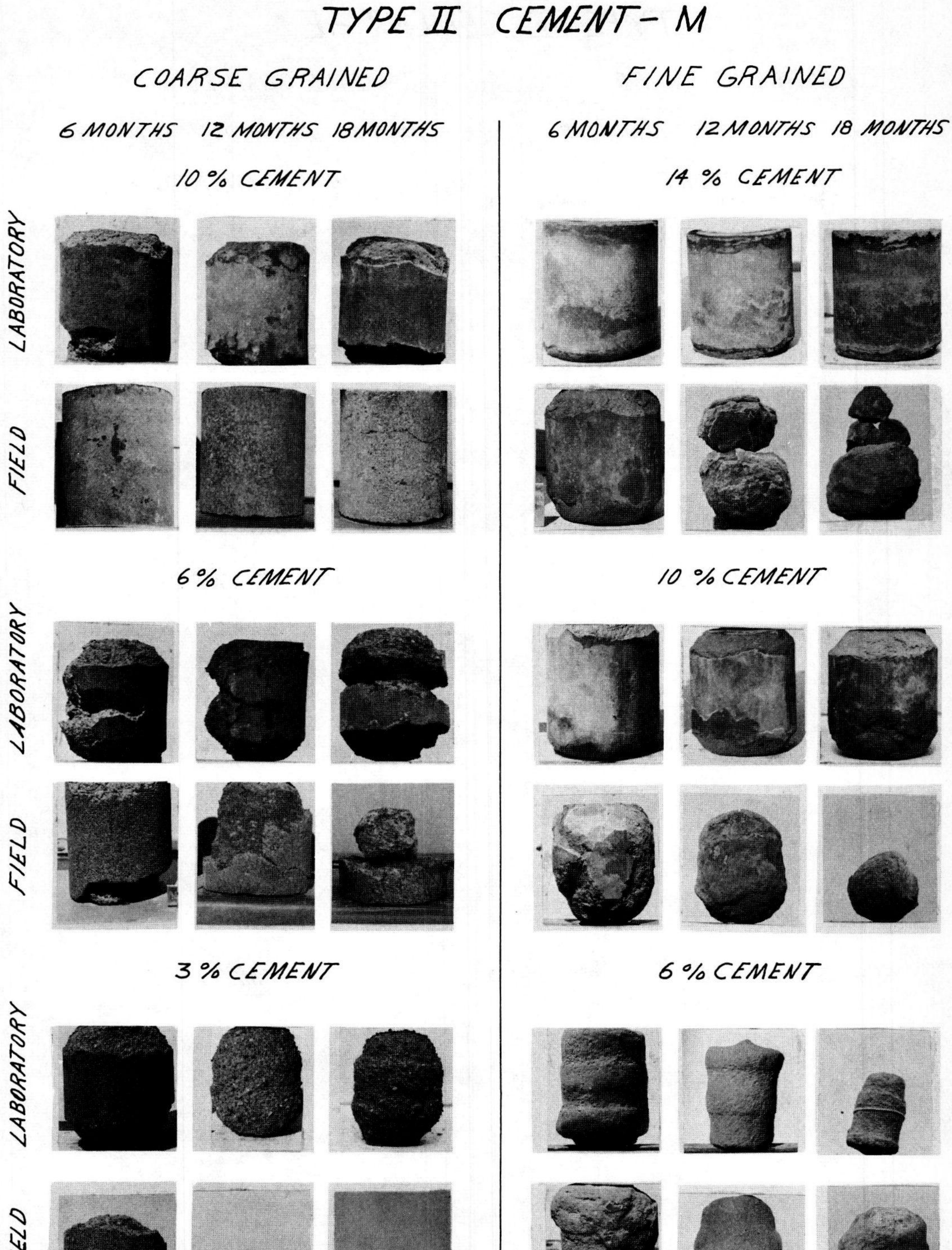
TYPE II CEMENT- M
COARSE GRAINED
FINE GRAINED
6 MONTHS 12 MONTHS 18 MONTHS
6 MONTHS 12 MONTHS 18 MONTHS
10 % CEMENT
14 % CEMENT
LABORATORY
FIELD
6 % CEMENT
10 % CEMENT
LABORATORY
FIELD
3 % CEMENT
6 % CEMENT
LABORATORY
FIELD

Figure 8.

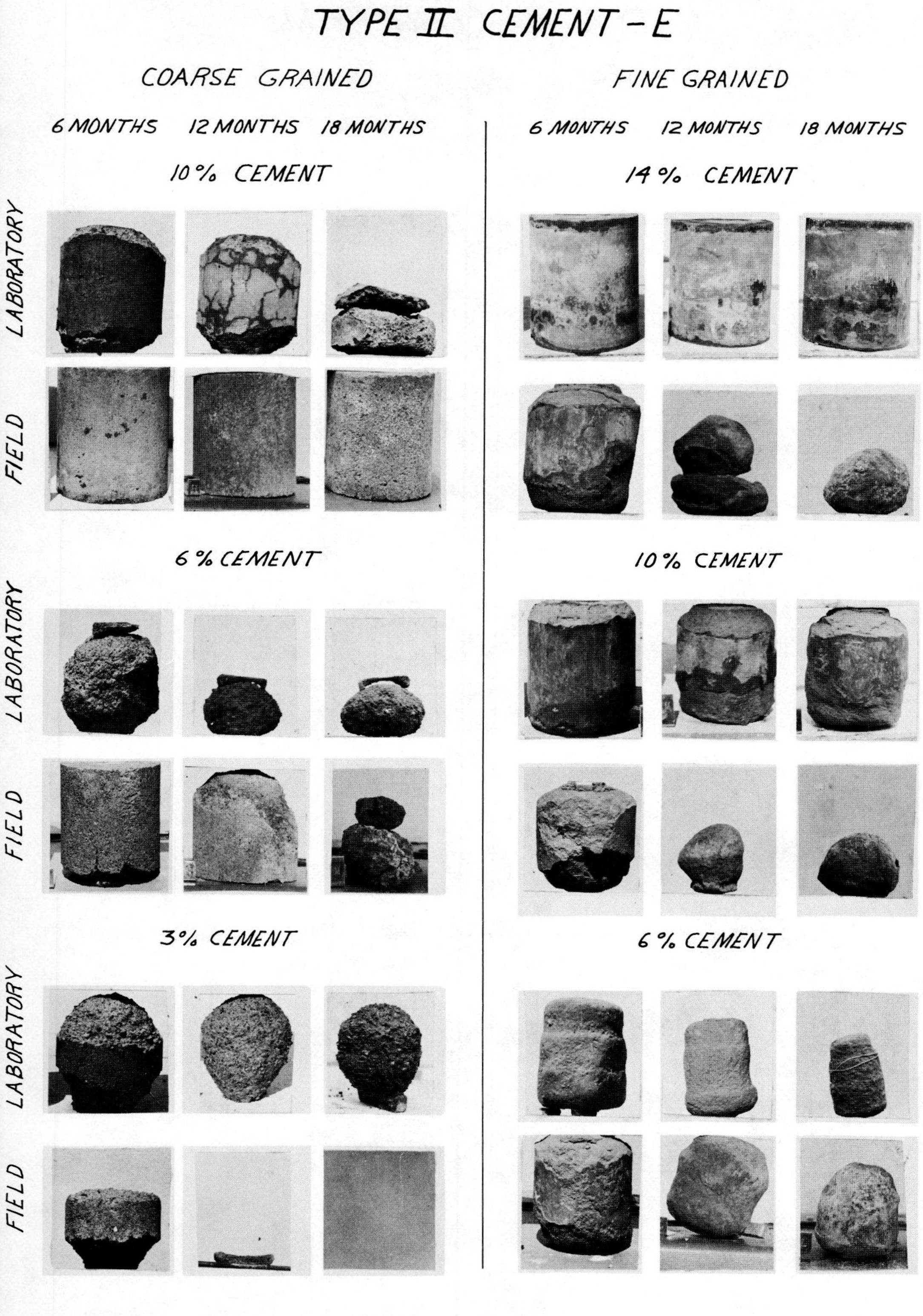
TYPE II CEMENT-E
COARSE GRAINED
FINE GRAINED
6 MONTHS
12 MONTHS
18 MONTHS
6 MONTHS
12 MONTHS
18 MONTHS
10% CEMENT
14% CEMENT
LABORATORY
FIELD
6% CEMENT
10% CEMENT
LABORATORY
FIELD
3% CEMENT
6% CEMENT
LABORATORY
FIELD

Figure 9.

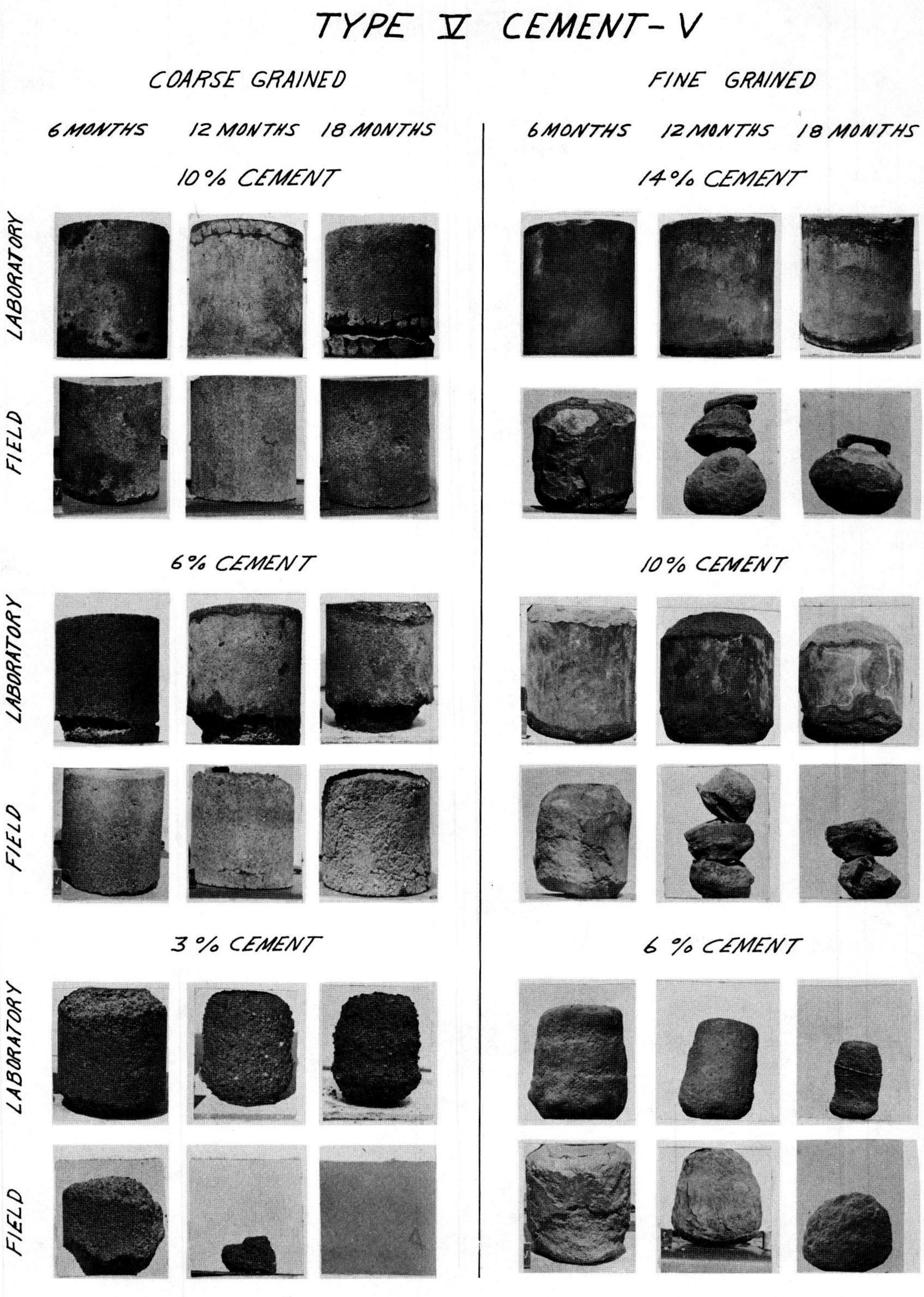
TYPE V CEMENT- V
COARSE GRAINED
FINE GRAINED
6 MONTHS
12 MONTHS
18 MONTHS
6 MONTHS
12 MONTHS
18 MONTHS
10 % CEMENT
14 % CEMENT
LABORATORY
FIELD
6 % CEMENT
10 % CEMENT
LABORATORY
FIELD
3 % CEMENT
6 % CEMENT
LABORATORY
FIELD

Figure 10.

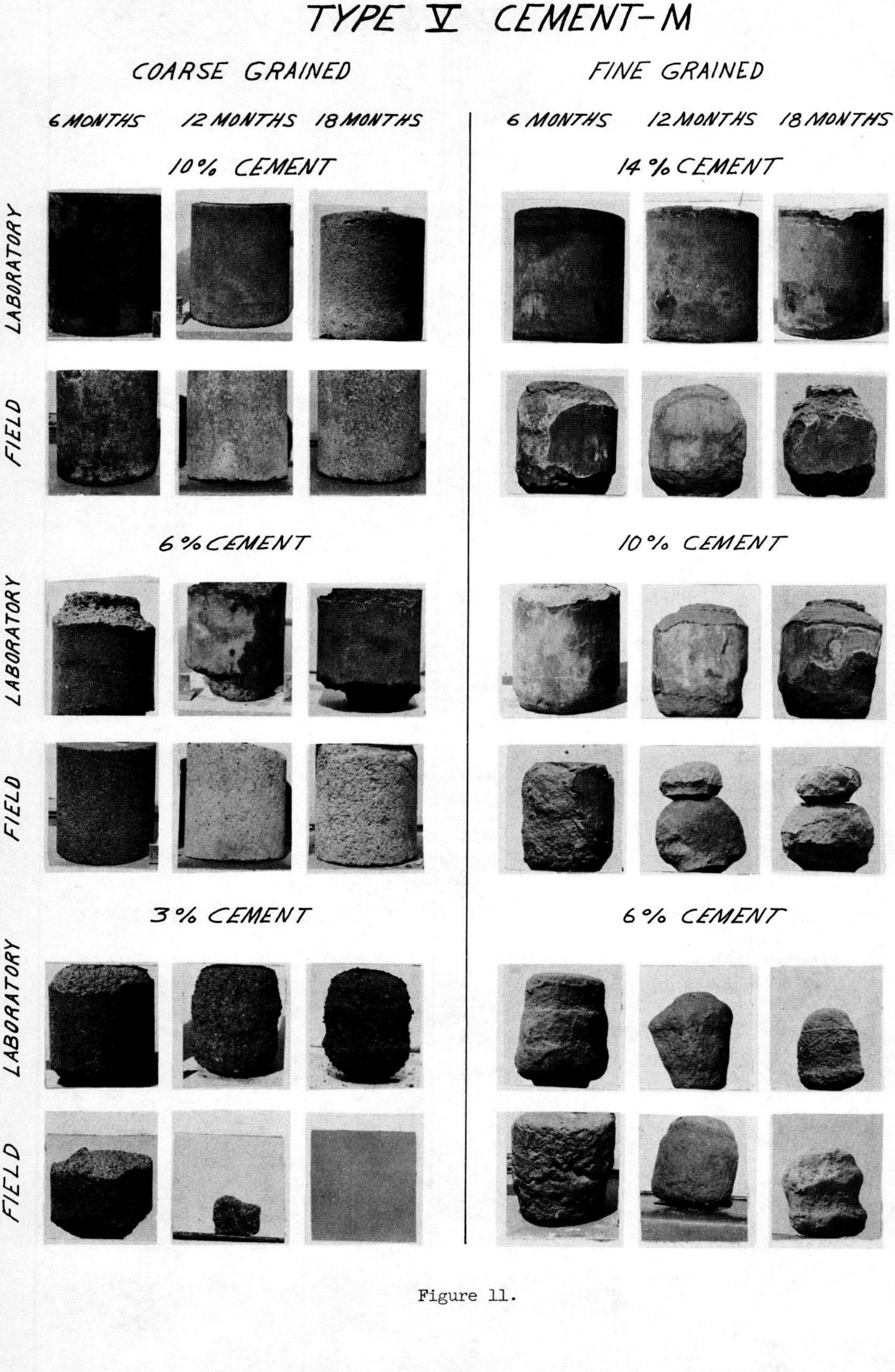
TYPE V CEMENT-M
COARSE GRAINED
FINE GRAINED
6 MONTHS
12 MONTHS
18 MONTHS
6 MONTHS
12 MONTHS
18 MONTHS
10% CEMENT
14% CEMENT
LABORATORY
FIELD
6% CEMENT
10% CEMENT
LABORATORY
FIELD
3% CEMENT
6% CEMENT
LABORATORY
FIELD

Figure 11.

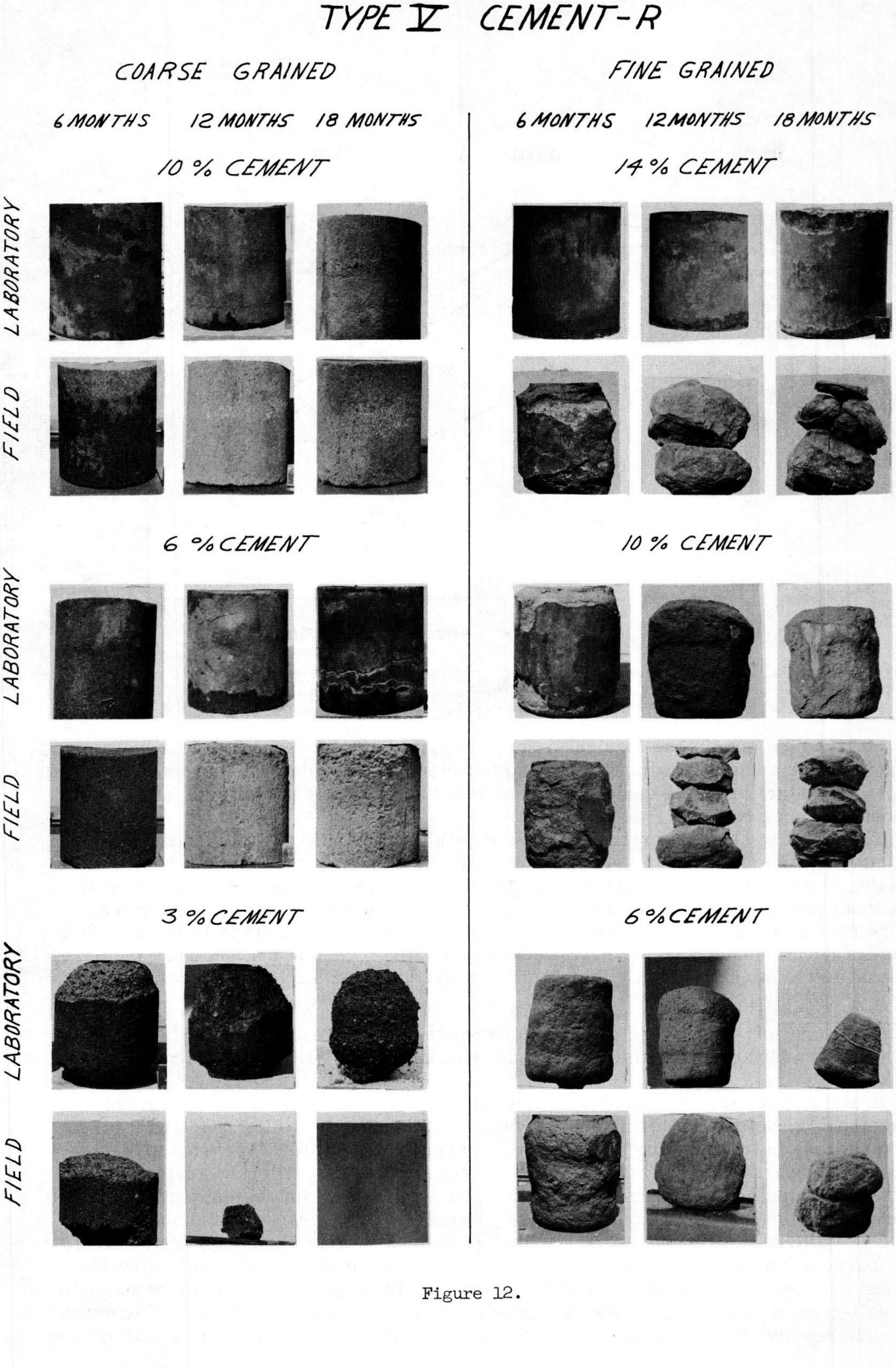
TYPE V CEMENT-R
COARSE GRAINED
FINE GRAINED
6 MONTHS
12 MONTHS
18 MONTHS
6 MONTHS
12 MONTHS
18 MONTHS
10 % CEMENT
14 % CEMENT
LABORATORY
FIELD
6 % CEMENT
10 % CEMENT
LABORATORY
FIELD
3 % CEMENT
6 % CEMENT
LABORATORY
FIELD

Figure 12.

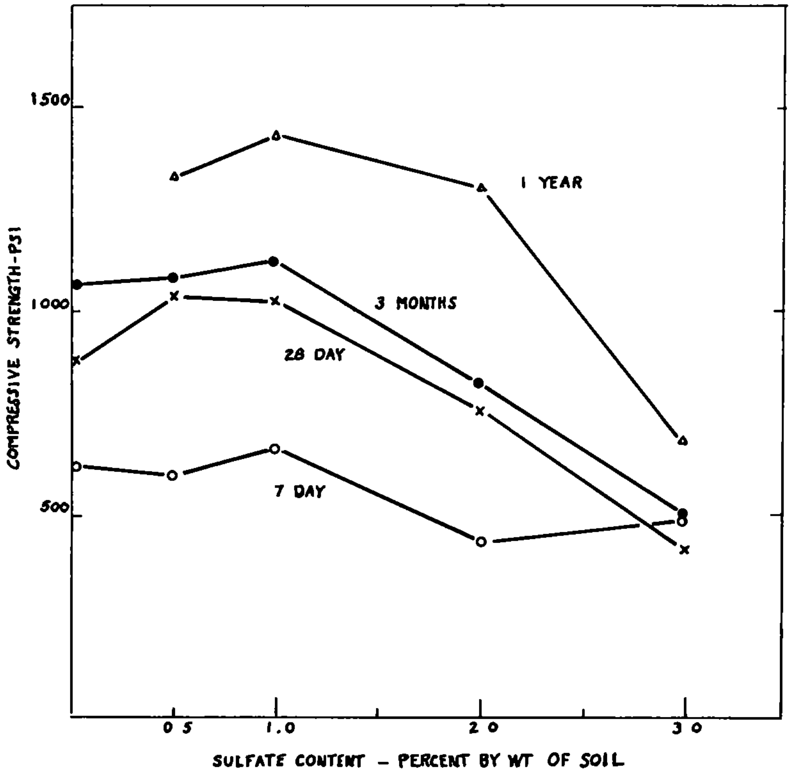

Figure 13. Influence of sulfate salts on the compressive strength of coarse-grained. soil-cement, 6 percent cement.

Soil-cement specimens studied in the first part of the investigation corroborate conclusively the original assumption that soil-cement deteriorates when exposed to sulfate salts. The fact that soil-cement is less dense than concrete permits sulfate salts to penetrate more rapidly.

The effect of cement content and the compound composition of the cement is also apparent in the photographic record of the soil-cement specimens. Soil-cements containing high cement contents resist the attack of sulfate salts much better than soil-cements containing low cement contents. Type V cements and, to a lesser extent, Type II cements are more resistant to the attack of sulfate than Type I cement. Soil-cement specimens containing Type I cement and a high cement content were more resistant to the attack of sulfate than Type V soil-cement with a low cement content.

Second Phase

The results of tests made in the second phase of the investigation in which sulfate salts were added directly to the soil-cement mixture at the time of fabrication are given in Tables 3 and 4.

In some cases the soils containing the higher salt concentrations deteriorated in less than 12 cycles of freezing and thawing. The number of cycles required for 100 percent loss in freezing and thawing are in parenthesis. Table 3 includes all tests made with coarse-grained soils. Table 4 gives test results with fine-grained soils. All soil-cements used in this investigation contained a medium cement content of 10.0 percent for the fine-grained soil and 6.0 percent for the coarse-grained soil.

The influence of various concentrations of sulfate salts on the compressive strength of coarse-grained soil-cement is shown in Figure 13. It is indicated in Figure 13 that small amounts of sulfate salts in soil-cement may improve the compressive strength of soil-cement cylinders. Sulfates added in amounts up to 1 percent caused no decrease in compressive strength in any of the specimens tested. As the amount of sodium and

TABLE 3

COMPRESSIVE STRENGTH AND DURABILITY TEST RESULTS—COARSE GRAINED SOIL

Cement			Percent Sulfate Salts by Wt. of Soil	Compressive Strength				Durability Losses	
Brand	Type	%		7 Day	28 Day	3 Mo	1 Yr	Freeze and Thaw	Wet and Dry
I	I	6	0	640	920	1,280	----	7.04	4.4
	I	6	0.5	710	990	900	1,270	3.8	---
	I	6	1.0	570	1,105	1,020	1,390	10.8	4.0
	I	6	2.0	420	505	565	1,110	100 (10)	5.8
	I	6	3.0	520	310	210	80	100 (6)	5.6
I	II	6	0	571	860	1,080	----	----	---
	II	6	0.5	560	892	1,010	1,230	5.5	---
	II	6	1.0	520	865	1,060	1,380	11.6	2.3
	II	6	2.0	420	605	805	1,410	9.8	1.8
	II	6	3.0	485	400	565	820	100 (6)	6.5
E	I	6	0	748	1,000	1,100	----	----	---
	I	6	0.5	720	1,140	1,105	1,360	3.15	---
	I	6	1.0	825	890	1,220	1,570	3.3	2.1
	I	6	2.0	535	560	650	1,110	100 (10)	3.5
	I	6	3.0	590	0	0	0	100 (5)	4.3
E	II	6	0	707	970	1,300	----	3.60	3.7
	II	6	0.5	705	1,135	1,305	1,305	3.70	---
	II	6	1.0	870	1,230	1,260	1,510	3.0	2.3
	II	6	2.0	465	790	910	1,410	4.6	1.5
	II	6	3.0	580	500	415	745	100 (8)	2.4
M	I	6	0	563	890	1,180	----	----	---
	I	6	0.5	560	970	1,020	1,420	3.15	---
	I	6	1.0	860	1,110	1,160	1,470	3.4	2.3
	I	6	2.0	340	840	635	1,380	100 (10)	2.6
	I	6	3.0	440	290	360	475	100 (5)	7.2
M	II	6	0	650	960	1,210	----	----	---
	II	6	0.5	630	1,040	1,090	1,510	3.28	---
	II	6	1.0	815	1,260	1,200	1,530	2.9	1.8
	II	6	2.0	630	970	955	1,400	2.7	1.5
	II	6	3.0	560	650	685	1,390	100 (7)	3.2
M	V	6	0	628	840	1,100	----	8.58	5.2
	V	6	0.5	535	1,110	1,070	1,500	4.23	---
	V	6	1.0	510	1,080	1,195	1,420	3.0	2.0
	V	6	2.0	475	900	1,080	1,340	2.7	1.5
	V	6	3.0	475	645	805	1,280	100 (9)	2.8
R	V	6	0	660	820	1,230	----	----	---
	V	6	0.5	520	1,000	1,225	1,130	3.8	---
	V	6	1.0	535	840	955	1,370	3.0	1.6
	V	6	2.0	575	770	865	1,280	5.0	1.6
	V	6	3.0	305	570	650	1,030	100 (9)	2.4
V	V	6	0	437	740	1,050	----	----	---
	V	6	0.5	460	1,040	1,030	1,370	3.15	---
	V	6	1.0	520	965	1,035	1,340	5.0	1.9
	V	6	2.0	515	835	970	1,410	3.2	1.6
	V	6	3.0	455	640	750	430	100 (7)	3.2

Number in parenthesis denotes number of cycles to complete disintegration.

TABLE 4

COMPRESSIVE STRENGTH AND DURABILITY TEST RESULTS—FINE-GRAINED SOIL

Cement Brand	Cement Type	Cement %	Percent Sulfate Salts by Wt. of Soil	Compressive Strength 7 Day	Compressive Strength 28 Days	Compressive Strength 3 Mo	Compressive Strength 1 Yr	Durability Losses Freeze and Thaw	Durability Losses Wet and Dry
I	I	10	0	600	920	----	-----	----	3.57
	I	10	0.5	760	950	910	1,090	36.6	3.53
	I	10	1.0	685	980	1,000	1,230	35.4	4.42
	I	10	2.0	540	805	940	900	57.8	5.53
	I	10	3.0	545	725	790	920	61.5	6.16
I	II	10	0	560	820	---	----	----	----
	II	10	0.5	670	870	860	1,430	42.4	4.13
	II	10	1.0	590	1,060	1,040	1,250	40.7	4.67
	II	10	2.0	520	620	860	830	58.8	5.02
	II	10	3.0	445	635	875	820	67.0	6.32
E	I	10	0	575	890	---	----	----	----
	I	10	0.5	700	1,150	990	1,280	35.0	4.58
	I	10	1.0	615	1,220	1,020	1,250	58.5	4.70
	I	10	2.0	575	820	970	930	65.4	4.72
	I	10	3.0	525	735	965	890	73.0	6.18
E	II	10	0	570	835	---	----	----	2.78
	II	10	0.5	725	955	970	1,440	24.4	3.38
	II	10	1.0	680	1,260	1,150	1,410	36.5	5.16
	II	10	2.0	580	750	1,010	930	51.8	5.88
	II	10	3.0	515	685	940	900	56.4	4.71
M	I	10	0	705	790	---	----	----	----
	I	10	0.5	630	850	900	1,270	55.3	2.95
	I	10	1.0	655	1,160	870	1,270	41.3	8.45
	I	10	2.0	520	780	960	900	55.7	5.30
	I	10	3.0	540	620	925	830	65.7	5.16
M	II	10	0	555	910	---	----	----	----
	II	10	0.5	675	955	950	1,190	51.3	4.58
	II	10	1.0	655	1,200	1,130	1,340	41.0	4.42
	II	10	2.0	520	700	990	760	44.5	4.72
	II	10	3.0	560	725	980	830	51.5	5.32
M	V	10	0	565	890	---	----	----	----
	V	10	0.5	645	955	840	1,310	29.9	3.68
	V	10	1.0	655	1,195	1,030	1,240	31.8	4.41
	V	10	2.0	520	765	1,060	920	40.4	5.90
	V	10	3.0	500	780	1,060	715	49.6	4.87
R	V	10	0	605	885	---	----	----	----
	V	10	0.5	695	970	820	1,200	25.2	4.00
	V	10	1.0	575	960	1,070	1,020	29.7	4.72
	V	10	2.0	520	830	1,060	940	45.5	4.71
	V	10	3.0	550	730	935	780	50.4	5.01
V	V	10	0	500	835	---	----	----	----
	V	10	0.5	645	940	740	1,030	30.1	4.44
	V	10	1.0	605	1,035	930	1,180	35.4	4.43
	V	10	2.0	540	805	1,070	880	47.5	6.20
	V	10	3.0	460	780	910	750	73.0	5.30

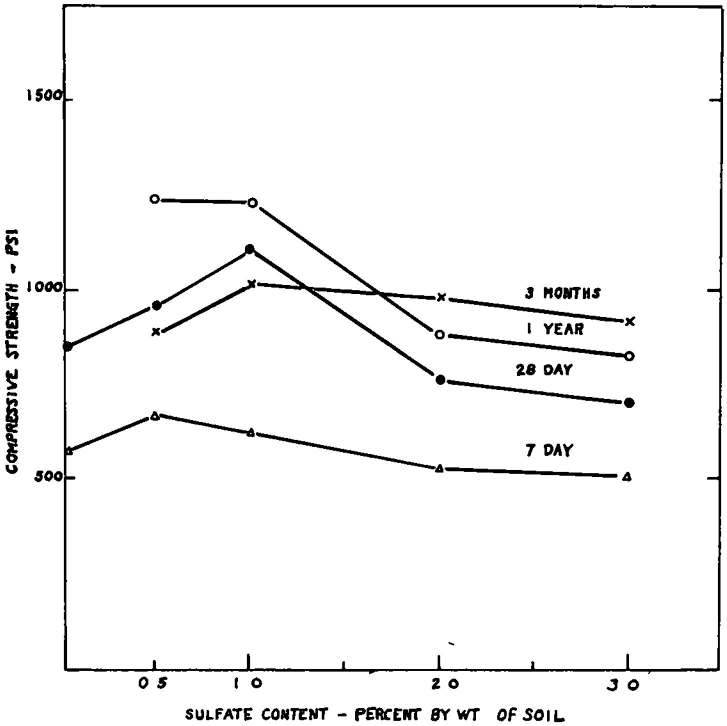

Figure 14. Influence of sulfate salts on the compressive strength of fine-grained soil-cement, 10 percent cement.

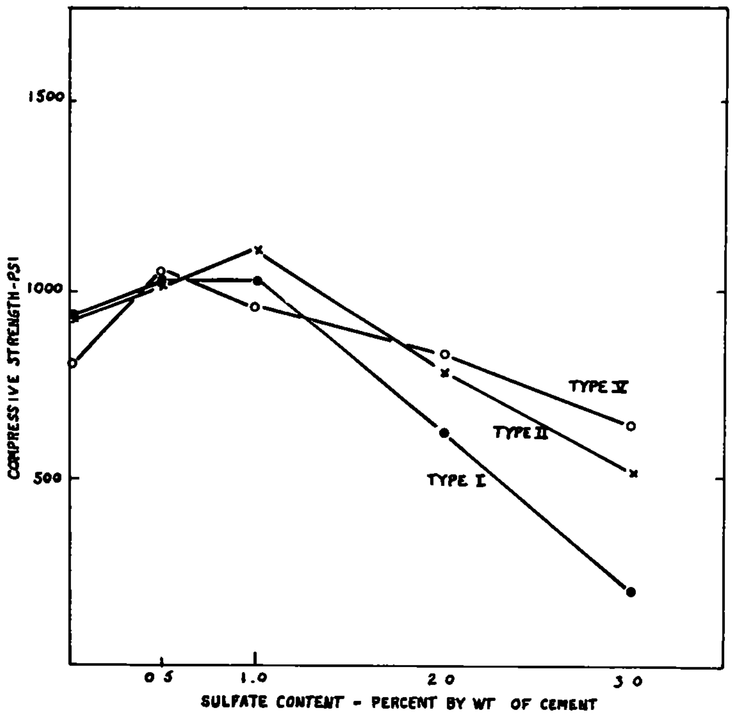

Figure 15. Influence of the type of cement on the compressive strength of coarse-grained soil-cement containing sulfate salts.

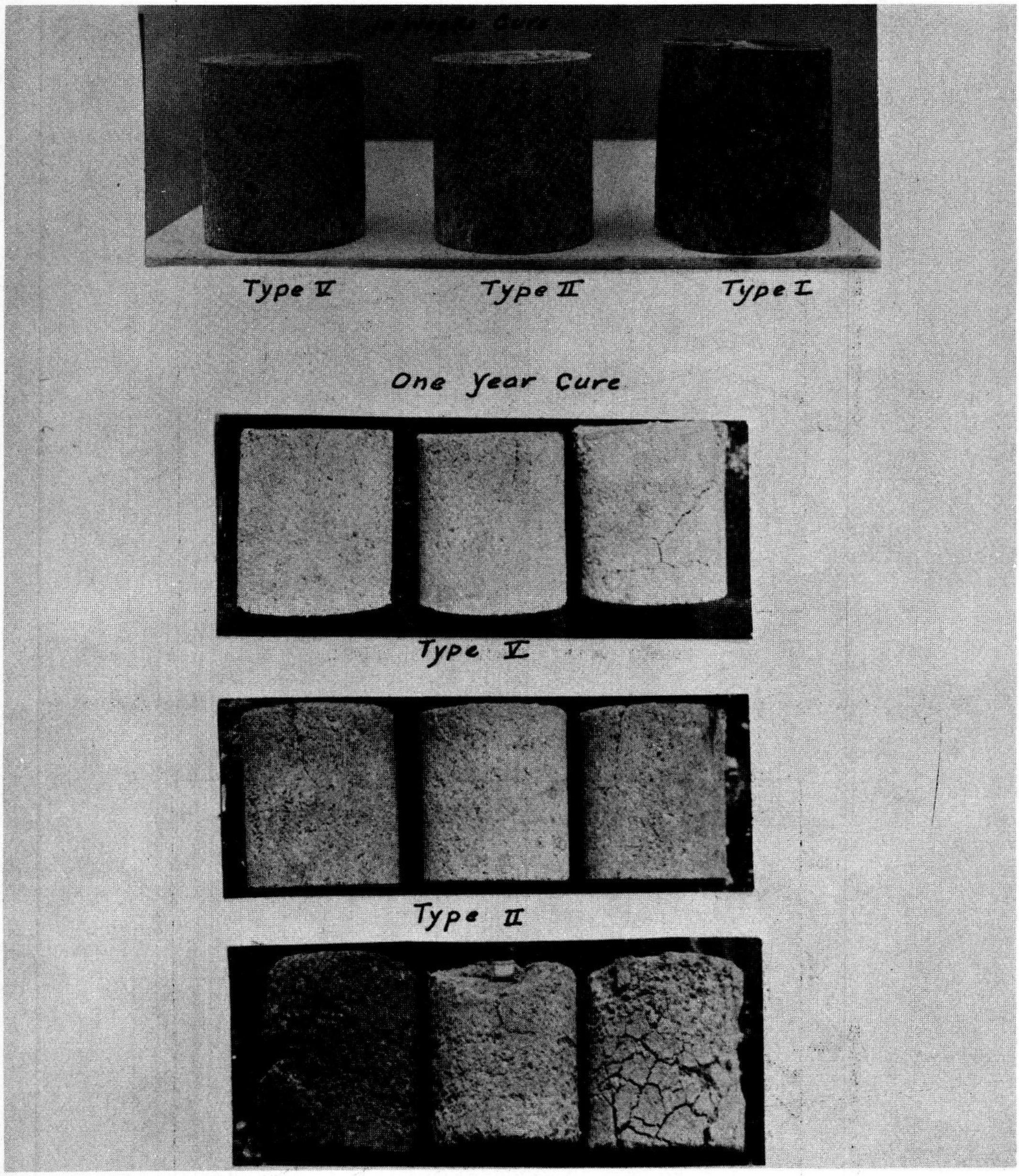

Figure 16. Specimens containing 3 percent sulfate.

magnesium sulfate increased to 2 and 3 percent, there was a definite decrease in compressive strength, particularly at later ages. The test points shown in Figure 13 are the averages for nine different cements including all three types.

Results of fine-grained soil-cements are shown in Figure 14. In this case, a decrease in compressive strength with excessive concentrations of sulfates in the soil was not as pronounced as with the coarse-grained soil. Even with 3 percent sulfate by weight of soil, the decrease in strength was not pronounced. Figure 14 also indicates that the presence of sodium and magnesium sulfate up to 1 percent by weight of soil improves the compressive strength of the soil-cement specimen.

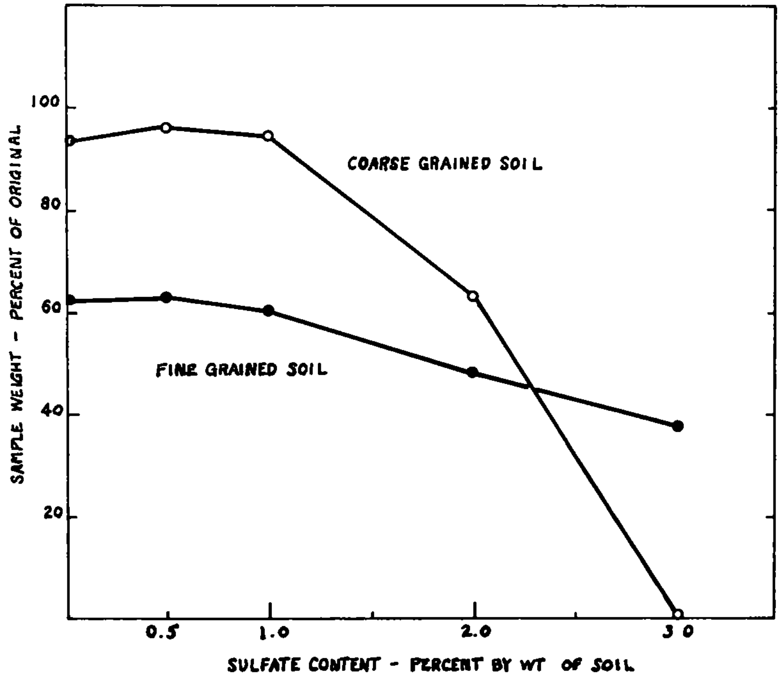

Figure 17. Deterioration of soil-cement specimens after 12 cycles of freezing and thawing.

The influence of the type of cement on the compressive strength of coarse-grained soil-cement containing various amounts of sulfate salts is indicated in Figure 15. Results from three Type I, three Type II, and three Type V cements were averaged in each case to obtain the points on this figure. Figure 15 also shows an increase in compressive strength with all three types with sulfate contents up to 1 percent by weight of soil. Apparently the type of cement had little influence when the concentration of sulfate salts was low. There was a definite difference between Type I, Type II, and Type V cements with high concentrations of sulfate. Type I cement deteriorated very noticeably with 3 percent sulfate, whereas Type II and Type V cements showed less deterioration as measured by the compressive strength. The influence of the type of cement is shown more dramatically in the photographs (Fig. 16). These photographs show specimens containing 3 percent sulfate after 10 weeks curing in a moist cabinet and after 1 year moist curing. The type of cement has a very definite bearing on the expansion and cracking of the soil-cement specimens.

There was also a hardening of some soil-cement specimens containing sulfate salts similar to that found in the first part of the investigation. The specimens became hard and would expand and crack. Cracked specimens indicated compressive strength as shown in Tables 2 and 3. Only one Type I cement at 3 percent sulfate and none of the Type II and Type V soil-cement specimens showed complete loss of compressive strength strength. Yet, the photographs (Figure 16) indicate excessive cracking and deterioration.

The durability of coarse-grained soil-cement with various percentages of sulfate salts added at the time of fabrication is indicated in Figure 17. Specimens containing less than 1 percent sulfate salts showed no loss of durability when subjected to freezing and thawing. As the amount of sulfate increased, however, complete deterioration was experienced in this test. This provides further indication that small amounts of sulfate salts mixed with soil-cement may improve its quality.

CONCLUSIONS

1. Soil-cement is subject to attack of sulfate salts much in the same manner as concrete. Deterioration in soil-cement is more rapid than concrete specimens primarily because soil-cement is less dense and sulfate solutions penetrate at a more rapid rate.
2. Soil-cement specimens of high cement contents are more resistant to the attack of sulfate than soil-cement of low cement content.
3. Soil-cement specimens fabricated with Type V and Type II cements are more resistant to the attack of sulfate salts than salts than soil-cement specimens fabricated with Type I cement.
4. Cement content of richness of mix is apparently more important in producing a sulfate resistant soil-cement than the type of cement used.
5. Soil-cement specimens made with fine-grained soils deteriorate more rapidly under field exposure (subjected to alternate cycles of freezing and thawing in addition to the attack of sulfate salts.)
6. Coarse-grained soil-cement specimens at low cement content deteriorated more rapidly when exposed to alternate cycles of freezing and thawing under field exposure than when exposed to sulfate salt solutions at laboratory temperatures.
7. Soil-cement specimens made with coarse-grained soil, high cement content, and sulfate resisting cements produced the most resistant soil-cement to the attack of sulfate salts.
8. Soil-cement specimens of high cement content crack and expand on deterioration but do not revert back to the original characteristics of the soil. Many of the fine-grained soil-cement specimens broke up into small pieces of cemented soil. It can be assumed that although sulfate salts attack soil-cement, stability of a highway base may not be destroyed by this action.
9. Small amounts of sulfate salts mixed with soil-cement at the time of fabrication increase the compressive strength and the resistance of the specimen to the action of freezing and thawing. Sulfate salts mixed with coarse-grained soil have a greater influence on strength and durability than when mixed with fine-grained soil.
10. High concentrations of sulfate salts mixed with soil-cement at the time of fabrication will cause cracking, expansion, and reduction in compressive strength and reduction in durability in soil-cement specimens.
11. Soil-cement specimens tested in the first phase of the investigation were subjected to high concentrations of sulfate salts which caused deterioration of many of these specimens. Results obtained in the second phase of the investigation, however, would indicate that if these same specimens had been exposed to low or moderate concentrations of sulfate salts, their durability and strength may not have been impaired. This leads to the conclusion that sulfate salts cause deterioration of soil-cement only when they are used in the soil-cement mixture in high concentrations, above 1 percent by weight of the soil, or when soil-cement specimens are placed in sulfate soils having high concentrations of sulfate salts.
12. Possible sulfate problems encountered in the construction of soil-cement bases on highways should first be investigated as to the concentration of sulfates encountered, and second, the cement content which might be required to withstand the attack of the sulfate salts.