Comparison of Type I and Type III Portland Cements for Soil Stabilization

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Test data are presented which indicate the possibility of significant economic and/or structural advantages in using Type III high-early-strength portland cement instead of Type I normal portland cement for soil-cement road construction. The data also indicate that high alkali content in Type I cement may be beneficial to the strength of cement-treated soil if the soil contains a relatively high proportion of clay-free quartz surfaces.

Test methods and criteria for evaluating the strength and durability of cement-treated fine-grained soils are presented and discussed. The minimum Type I and Type III cement requirements for soil-cement indicated by these methods, for the sandy, silty and clayey soils studied, were surprisingly low.

● SOIL-CEMENT is defined as a hardened material formed by curing a mechanically compacted intimate mixture of pulverized soil, portland cement and water. Durability and/or compressive strength are the common criteria for hardness. The standard for hardness varies (1). Soil-cement has an excellent record of successful field service in base courses of roads, airfields, parking lots and similar applications. It has some structural advantages over, and is often cheaper than, equivalent untreated granular base materials. An increase of these advantages would further increase the popularity of soil-cement.

SOME POSSIBILITIES FOR IMPROVING SOIL-CEMENT

Two types of portland cement available on the market for general use in soil-cement are Type I normal cement and Type III high-early-strength cement, as described in ASTM Standard Specifications for Portland Cements, C 150-56 (2). Type I cement is usually used in soil-cement, probably because it is usually most readily available and is slightly lower priced than Type III cement. (The cost of Type III cement is currently about 13 percent higher than that of Type I cement.) However, if the cement requirement for soil-cement is significantly lower with Type III than with Type I, a possibility suggested by the work of Clare et al. (3, 4), Felt (5), and Leyder (6), there could be an economic advantage in using Type III cement.

Soil-cement requires a definite curing period prior to the construction of additional base or wearing courses. This curing period is normally seven days when Type I cement is used. Because curing time affects total construction time, a reduction in curing time made possible by use of Type III cement could be advantageous.

Recent work at Iowa State (7, 8, 9) and M.I.T. (10, 11) indicates that the use of small amounts of alkali additives in soil-cement may accelerate the rate of hardening. This suggests that the alkali content of portland cement may have a significant effect on the strength of soil-cement, a possibility which apparently has not been investigated previously.

OBJECTIVES OF THE INVESTIGATION

This report presents the results of a laboratory investigation to obtain more information on the advantages of Type III cement over Type I cement for soil-cement road construction, particularly in Iowa. A second objective was to determine whether alkali content is an important compositional variable in portland cement used in soil-cement.

PROPERTIES OF MATERIALS USED

Soils

Properties of the three soils used in the investigation are given in Table 1. These sandy, silty and clayey soils are typical of widespread and readily available materials for stabilized road construction in Iowa. The sand-loess mix was sampled from the blended material used in the soil-cement base course of Primary System Highway Iowa 117, constructed in 1957.

TABLE 1

PROPERTIES OF SOILS

Property	Sand-Loess (Colfax Mix)[1]	Friable Loess (20-2-VII)[1]	Kansan Till (409-12C)[1]
Geological description:	Mix of approximately 82% waste sand from hydraulic dredging operations and 18% Wisconsin-age loess, oxidized, calcareous, medium plastic	Wisconsin-age loess, oxidized, calcareous, friable	Kansan-age glacial till, oxidized, calcareous, plastic
Sampling location:	Jasper Co., Iowa	Harrison Co., Iowa	Ringgold Co., Iowa
Soil series:	Loess: Tama	Hamburg	Shelby (Burchard)
Horizon:	Loess: C	C	C
Sampling depth, ft:	Sand: Stock pile Loess: Borrow pit	35-36	4½-10½
Textural composition,[2] %:			
Gravel (> 2 mm)	0.0	0.0	0.0
Sand (2.0-0.074 mm)	70.7	0.4	31.5
Silt (0.074-0.005 mm)	22.3	80.0	30.0
Clay (< 0.005 mm)	7.0	19.6	38.5
Colloids (< 0.001 mm)	6.0	14.5	31.0
Atterberg limits[3]:			
Liquid limit, %	18.9	30.8	42.4
Plastic limit, %	16.4	24.6	20.5
Plasticity index, %	2.5	6.2	21.9
Classification:			
Textural[4]	Sandy loam	Silty loam	Clay
Engineering (AASHO)[5]	A-2-4	A-4(8)	A-7-6(12)
Chemical:			
Cation exchange capacity,[6] m.e./100g	11.0	13.4	29.5
Carbonates,[7] %	11.6	10.2	4.9
pH[8]	8.0	8.7	8.25
Organic matter,[9] %	0.16	0.17	0.17
Non-clay mineral composition,[10] %:			
Aggregates (silicious)	36.3	-	-
Quartz	50.5	56.0	60.2
Feldspars	9.0	21.1	21.1
Calcite	3.8	13.7	-
Others	0.3	9.2	18.7
Clay mineral composition:			
Predominant clay mineral[11]	Montmorillonite	Montmorillonite	Montmorillonite
Clay coatings on surfaces of grains > 0.005 mm[12]	Light to moderate (15-35%)	Moderate (20-80%)	Extensive (75-100%)

[1]Soil Research Laboratory sample designation.
[2]ASTM Method D 422-54T (2).
[3]ASTM Methods D 423-54T and D 424-54T (2).
[4]Triangular chart developed by U.S. Bureau of Public Roads (12).
[5]AASHO Method M 145-49 (13).
[6]Ammonium acetate (pH = 7) method on soil fraction < 0.42 mm (No. 40 sieve).
[7]Versenate method for total calcium.
[8]Glass electrode method using suspension of 15 g soil in 30 cc distilled water.
[9]Potassium bichromate method.
[10]Petrographic microscopical analysis.
[11]X-ray diffraction analysis.
[12]Estimated, based on microscopic examination of random grains > 0.005 mm.

Portland Cements

The three Type I cements and two Type III cements used in the investigation were selected by William Lerch, Assistant to the Vice President for Research and Development, Portland Cement Association. The cements designated Ia, Ib and Ic in Table 2 meet the requirements for the ASTM specifications (C 150-56) for Type I portland cement; those designated IIIa and IIIb meet ASTM requirements for Type III portland cement (2).

The three Type I cements differed mainly in their total alkali content (as Na_2O), which was the desired variable. Cement Ia had low alkali content, cement Ib had medium alkali content, and cement Ic had high alkali content. The 7- and 28-day compressive strengths obtained in 1-2.75 graded Ottawa sand mortars are similar. The difference in 1-day mortar strengths seems to correlate with small variations in fineness and calculated C_3S content.

TABLE 2

PROPERTIES OF THE TYPE I AND TYPE III PORTLAND CEMENTS[1]

Cement Designation Cement Type	Ia[2](13)[3] I	Ib[2](21)[3] I	Ic[2](14)[3] I	IIIa[2](31)[3] III	IIIb[2](33)[3] III
Major oxide composition, %:					
Silicon dioxide (SiO_2)	22.18	23.71	22.17	20.36	20.03
Aluminum oxide (Al_2O_3)	4.70	3.97	4.62	4.96	5.08
Ferric oxide (Fe_2O_3)	2.12	3.21	3.03	2.11	2.52
Calcium oxide (CaO)	64.22	63.98	62.86	63.28	63.81
Magnesium oxide (MGO)	1.07	1.18	2.37	3.20	1.38
Sulphur trioxide (SO_3)	1.62	1.24	1.73	2.23	2.31
Sodium oxide (Na_2O)	0.04	0.22	0.06	0.23	0.21
Potassium oxide (K_2O)	0.19	0.40	1.30	0.22	0.44
Free calcium oxide (CaO)	1.61	0.65	0.19	1.45	1.83
Total equivalent alkali content as Na_2O	0.17	0.48	0.92	0.37	0.50
Calculated potential compound composition, %:					
Tricalcium silicate (C_3S)	53.6	45.4	47.1	60.1	63.2
Dicalcium silicate (C_2S)	23.2	33.7	28.1	13.0	9.8
Tricalcium aluminate (C_3A)	8.9	5.1	7.1	9.6	9.2
Tetracalcium aluminoferrite (C_4AF)	6.4	9.8	9.2	6.4	7.7
Physical properties:					
Fineness, turbidimeter (Wagner), sq cm/g	1660	1630	1880	2800	2530
Fineness, air permeability (Blaine), sq cm/g	3430	2890	3420	5800	5270
Compressive strength of 1-2.75 mortars, ASTM Method C 109					
1 day, psi	720	360	690	1820	2010
3 day, psi	1560	1380	1730	4000	4180
7 day, psi	2350	2450	2880	5630	5910
28 day, psi	4140	4330	4330	7010	6340

[1]Cements and property data furnished by Portland Cement Association.
[2]Designation used in this report.
[3]Portland Cement Association's designation.

The two Type III cements were quite similar and had medium alkali contents, although cement IIIa had a slightly lower alkali content than cement IIIb. They were much finer than the Type I cements and in mortars gave higher compressive strengths at ages up to 28 days. Type III cements had higher C_3S contents and lower C_2S contents than the Type I cements. Sulphur trioxide (gypsum) content was not considered a significant variable in this investigation, because the gypsum content of each cement was adjusted to about optimum for setting and strength properties of the cement paste.

METHODS OF PREPARING AND TESTING SPECIMENS

Mixing

The mixing of materials was done mainly with a Hobart Model C-100 Mixer. Proper proportions of cement and air-dry soil, based on the oven-dry weight of the soil, were placed in the mixing bowl, blended briefly by hand and then dry mixed by machine for 1 min. The materials were mixed for another minute while a predetermined amount of distilled water was added. The mixing bowl was scraped and the materials hand mixed for approximately 1 min to break up any clods which might have formed. The mixture was given a final machine blending for 1 min.

Molding

Test specimens were prepared by use of the molding apparatus shown in Figure 1. The specimens had a diameter of 2 in. and a height of 2 ± 0.005 in. This specimen size also is used for compressive strengths tests by the Portland Cement Association when

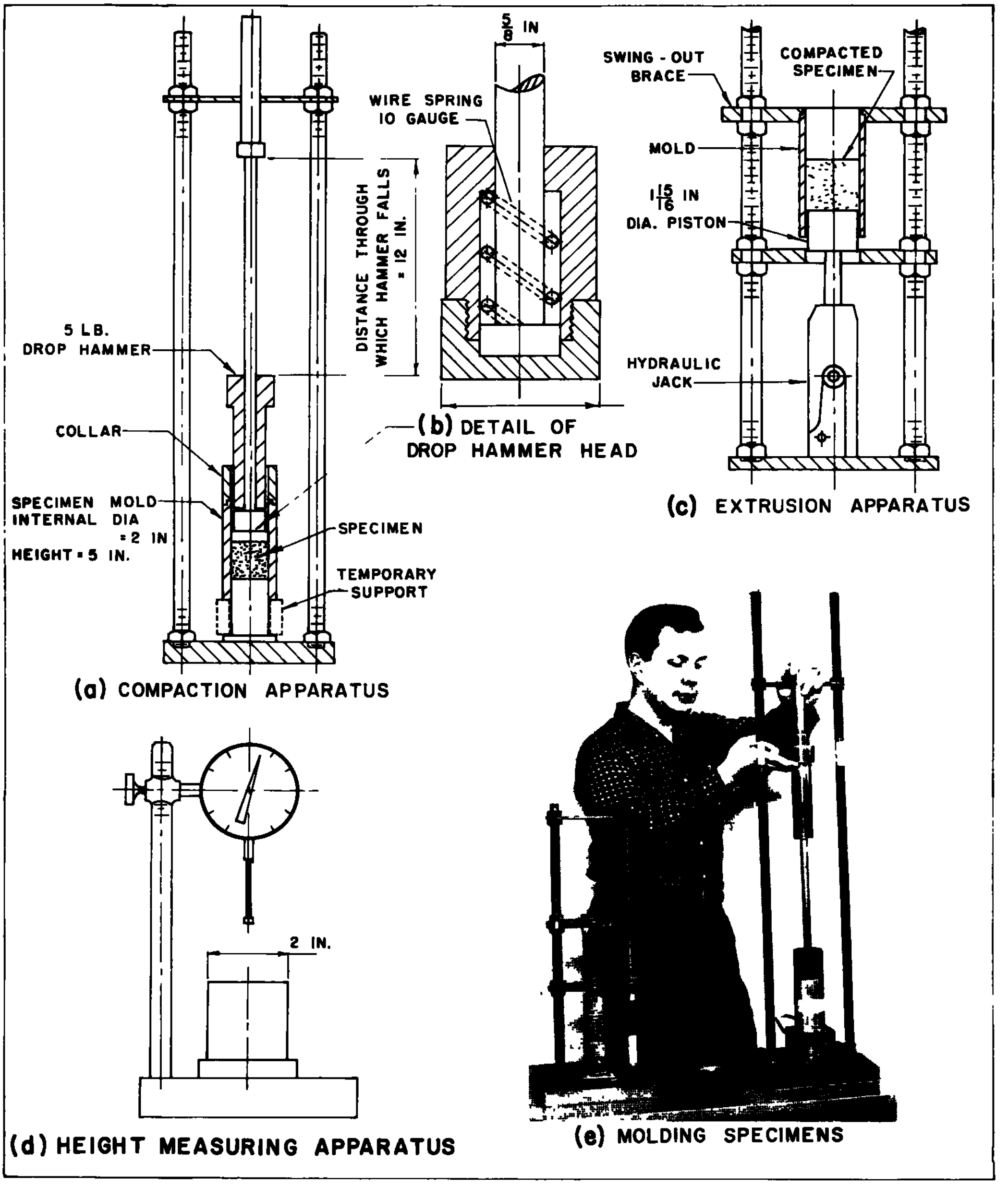

Figure 1. Apparatus used for molding 2-in. high by 2-in. diameter test specimens.

the soil contains no plus No. 4 material (14). A 2- by 2-in. specimen can be compacted to uniform density in one layer with no cleavage planes.

The amount of mixture needed for a specimen was placed in the calibrated cylinder supported by the temporary support. The mixture was given one blow with the 5-lb hammer, the temporary support was removed, and the mixture given an additional four blows. The molding cylinder was inverted and the specimen was given five additional blows. The resulting specimen was extruded, weighed to the nearest 0.1 gram and the height was measured to the nearest 0.001 in. When the molding is done on a wooden table, the ten blows with the 5-lb hammer dropping 12 in. gives a compactive effort approximately equal to standard ASTM (Proctor) compactive effort (ASTM Method D 558-57 (2)).

Moisture-Density-Strength Relationships

The purpose of the moisture-density and moisture-strength relationship tests was to determine the optimum moisture contents for molding cement-treated soil specimens for subsequent immersed strength and freeze-thaw tests. The tests were performed with the three soils. Each cement in varying amounts was used with each soil.

Sufficient soil for ten specimens was dry mixed with the desired amount of portland cement. Enough of the mixture to mold two specimens was mixed with the required amount of water to obtain a moisture content on the dry side of optimum moisture. Two specimens were molded, measured and weighed, and two samples of the unmolded mixture were taken for moisture content determinations. The procedure was repeated four more times, with the moisture content of the mixture increased approximately 2 percent for each repetition.

The molded specimens of varying moisture content were cured for 7 days, immersed in water for 24 hours, and tested for unconfined compresive strength.

Average values of dry density (at time of molding) and immersed strength were calculated for each moisture content. These data enabled comparisons to be made of the optimum moisture requirements for maximum dry density and maximum immersed strength obtained from curves such as those for the cement-treated Kansan till mixtures in Figure 2. The optimum moisture contents for maximum dry density and maximum immersed strength were nearly identical for cement-treated sand-loess and friable-loess mixtures; therefore only typical moisture-density curves are shown in Figure 2. For cement-treated Kansan till mixtures, optimum moisture for maximum immersed strength was about 1½ percent greater, based on the oven-dry weight of the mixture, than optimum moisture for maximum dry density (Fig. 2). Leyder (6) reported similar results for clays. The type of portland cement did not significantly affect optimum moisture contents or maximum density, which agrees with the findings of Felt (5). Generally, an increase in cement content caused an increase of maximum density but only a slight decrease of optimum moisture contents. Therefore it was possible to select a single molding moisture content for each soil. The "optimum" moisture contents selected for use are indicated in Figure 2.

The moisture-density relations obtained by this method agree closely with those obtained by standard ASTM Method D 558-57 (2).

Curing

Following molding, specimens for immersed strength or freeze-thaw resistance tests were wrapped in waxed paper sealed with cellophane tape and were placed in a moist curing room for designated periods. The desired constants for the curing room were a temperature of 70 ± 5 F and a relative humidity of 95 ± 5 percent. However, the temperature was known to deviate from the desired constant, particularly in the summer and winter, being higher in summer and lower in the winter.

Immersed Strength and Freeze-Thaw Testing

Unconfined Compressive Strength After Curing and 24 Hours Immersion.—For each mixture, sufficient soil for nine specimens was dry mixed with the desired amount of

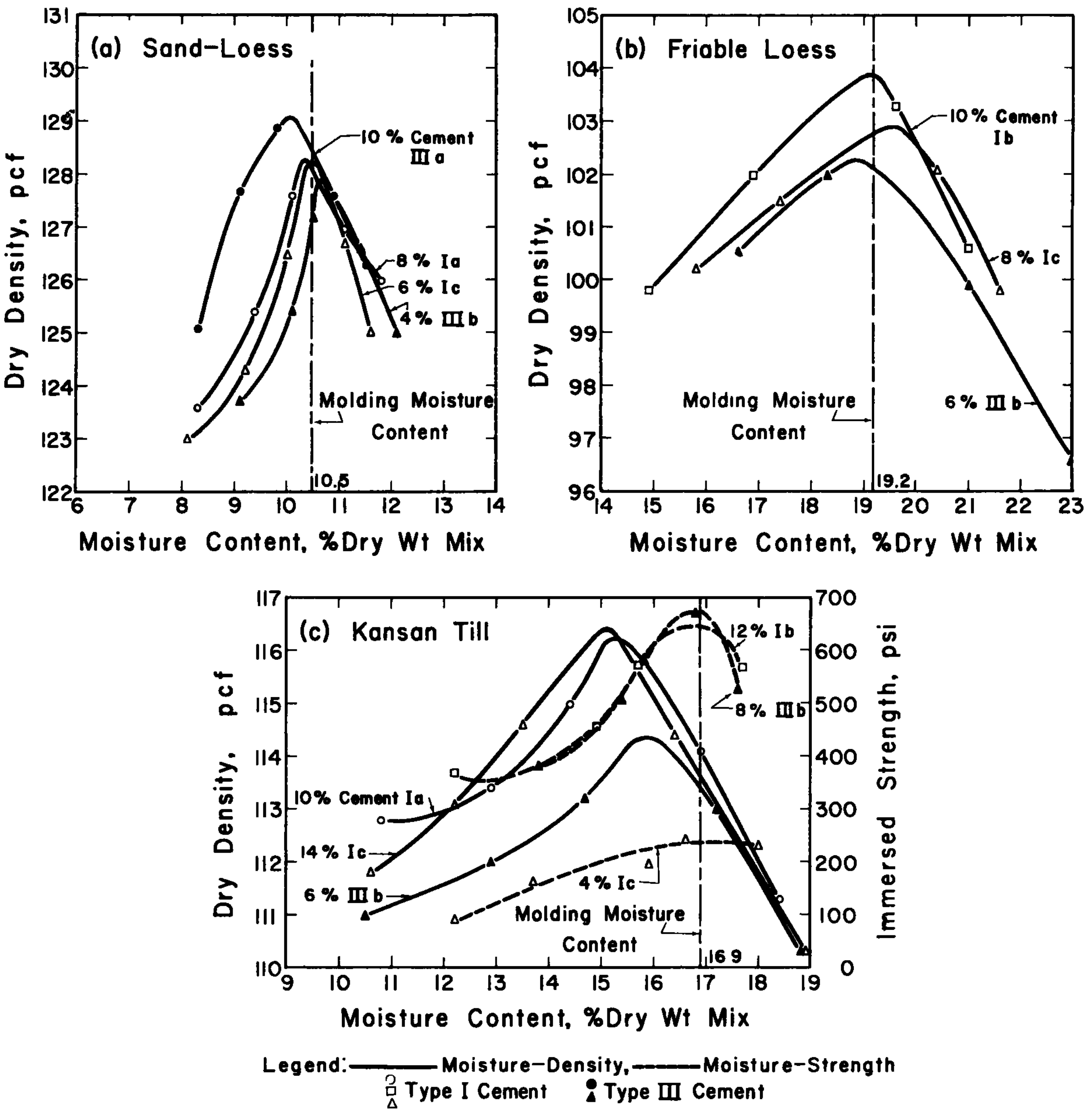

Figure 2. Typical moisture-density and moisture-strength curves for the Type I and Type III cement-treated soil mixtures studied. The molding moisture content indicated for each soil is the selected "optimum" for mixtures of the soil and Type I or Type III cement.

portland cement. Enough water to bring the mixture to optimum moisture was added. After moist mixing, nine specimens were molded, sealed in waxed paper (to reduce moisture loss and absorption of CO_2 during curing) and placed in the humidity room.

Three specimens were cured for 2 days, three for 7 days and three for 28 days. At the end of each curing period, the specimens, with waxed paper removed, were immersed in distilled water, at room temperature, for 24 hr. Immediately after removal from the water bath, the specimens were tested for unconfined compressive strength. The maximum load to break a specimen, with a load travel rate of 0.1 in.

per min, was taken as the compressive strength. Average values, based on the three specimens, are reported. With very few exceptions, the difference between the individual values and the average value did not exceed 10 percent of the average value.

Freeze-Thaw Resistance.—The freeze-thaw test used to evaluate selected cement-treated soil mixtures is a modification of British Standard Test 1924:1957, "Determination of the Resistance of a Stabilized Soil Mixture to Damage by Frost (for fine-grained soils only)" (15). The modifications are as follows: using 2- by 2-in. instead of 2- by 4-in. test specimens, using waxed paper sealed with cellophane tape instead of paraffin to reduce moisture evaporation from specimens during curing, and using a resin-base paint (Plax) instead of tar as the seal coat on the tops of specimens. The freeze-thaw apparatus used is shown in the Appendix (Fig. 6), where the details of the modified British test are given.

Two identical specimens were molded for each mixture and curing period studied. (Specimens of cement-treated sand-loess were cured for 2 and 7 days, specimens of cement-treated friable loess and Kansan till were cured for 7 days only.) One specimen was designated the control specimen and the other the freeze-thaw specimen. After moist curing, the flat top surface of each specimen was sprayed with the resin-base paint to a thickness of approximately 1 mm. Then the control specimen was immersed for 15 days in distilled water at a temperature of 77 ± 4 F; the freeze-thaw specimen was immersed for one day, then subjected to the 14 cycles of freeze-thaw (14 days) as described in the Appendix. The unconfined compressive strengths in psi of the control (immersed) specimen (p_c) and the freeze-thaw specimen (p_f) were then determined. The index of the resistance to the effect of freezing (R_f) was calculated from the formula:

$$R_f = \frac{100p_f}{p_c} \quad \text{(percent)}$$

The modified British freeze-thaw test is thought to simulate field freeze-thaw conditions better than the brushing test developed by the Portland Cement Association (14) and standardized by the American Society for Testing Materials (ASTM Method D 560-57 (2)). The modified British test is simpler, faster and requires less soil and additive materials than the ASTM test; these advantages are particularly important when a large number of specimens are to be evaluated. The use of the modified British test is limited to fine-grained soils which pass the No. 4 sieve.

TEST RESULTS AND INTERPRETATIONS

Unconfined Compressive Strength After Curing and 24 Hours Immersion

The purpose of these immersed strength tests was to obtain a comparison of the relative strength gain from the use of the Type I and Type III cements in mixtures with each of the three soils. Plots of immersed strength versus cement content, for each soil, cement type and curing period are shown in Figure 3. Plots of immersed strength versus curing time, for each soil, cement type and cement content are shown in Figure 4. Cement contents are expressed as percentages of the oven-dry weight of the soils.

Sand-Loess.—Type III cements gave higher strengths than Type I cements at all cement contents except 4 percent cement IIIb, which gave approximately the same strength as the same amount of the three Type I cements (Figs. 3a, b, c and 4a, b, c, d). Generally the rate of strength gain with increasing cement content was greater with Type III than with Type I cements, the strength difference being more pronounced after curing periods of 2 and 7 days than after 28 days.

The higher early strengths up to 28 days obtained with the Type III cements probably can be attributed to their fineness and C_3S contents. Being finer ground than Type I cement, Type III cement has a considerably larger surface area which serves to accelerate the hydration process and give a better distribution of gel. Furthermore C_3S, abundant in Type III cements, is the component of portland cement which contributes most to early strength (16). As expected, shown by the curves in Figure 3, the rate of strength gain of cement-treated soil generally increases with an increase in amount of Type III cement, and strengths are higher than with equal amounts of Type I.

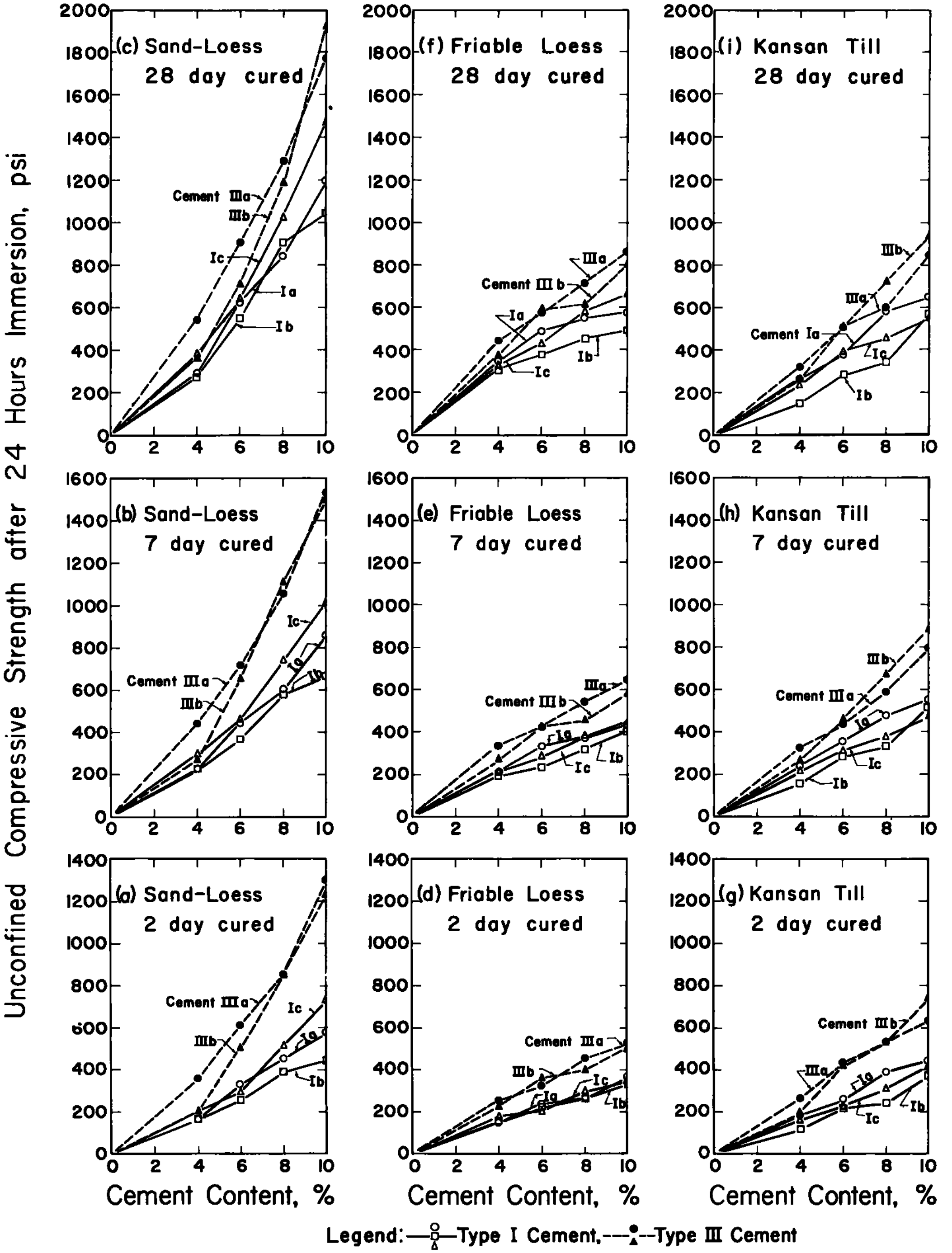

Figure 3. Immersed strength versus cement content, for each soil, cement type and curing period studied. Cement contents are percentages of the oven-dry weight of the soils.

Strength gain from C_3S begins to diminish after curing periods of 28 days, and C_2S becomes chiefly responsible for strength gain thereafter (16). Type I cement contains considerably more C_2S than Type III cement, and it seems probable that Type I strength curves would intercept Type III curves at some curing time beyond 28 days (Figure 4).

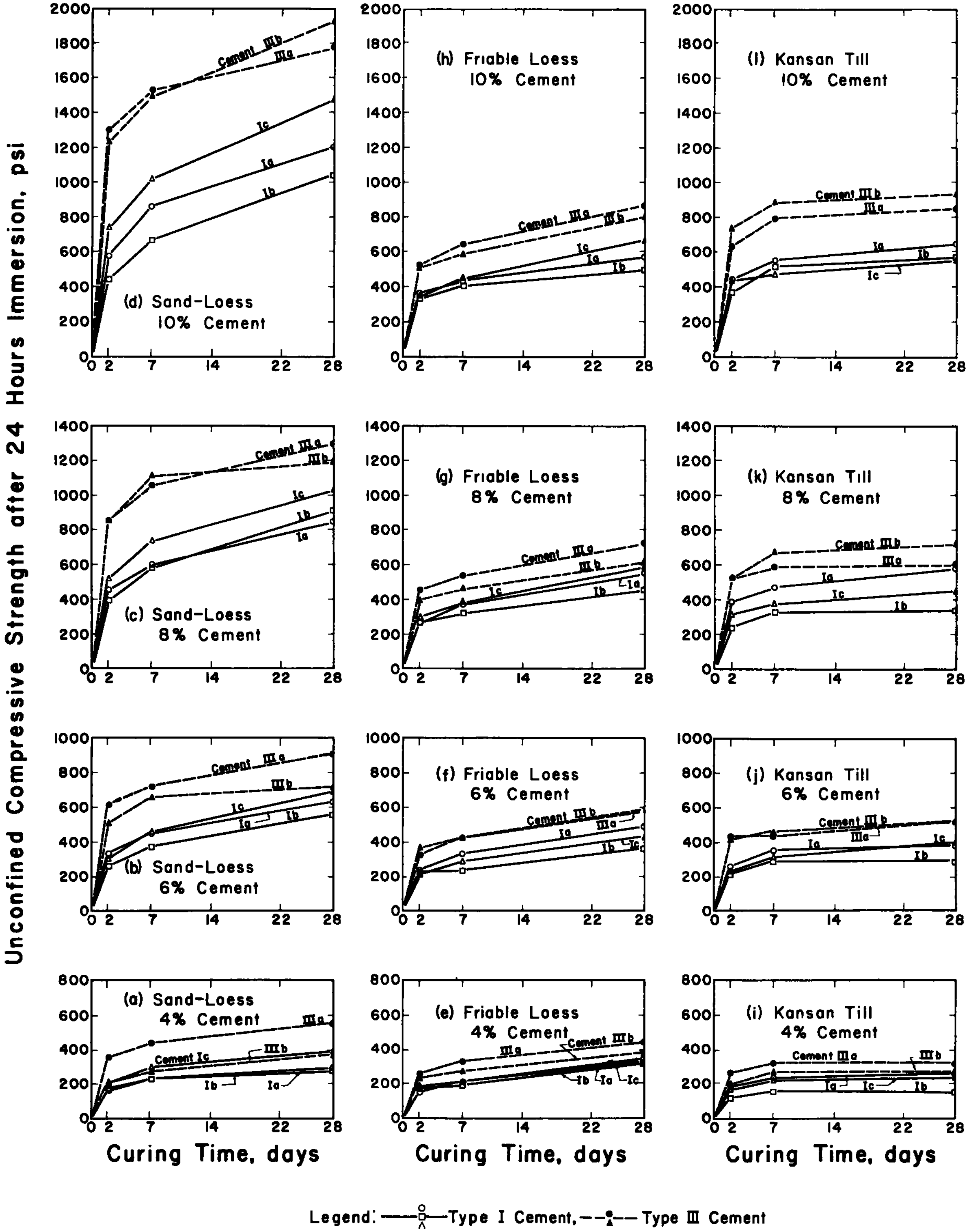

Figure 4. Immersed strength versus curing time, for each soil, cement type and cement content studied. Cement contents are percentages of the oven-dry weight of the soils.

Among the three Type I cements, cement Ic produced highest strengths, this being particularly evident at 10 percent cement content after 28 days curing. Properties of the cement (Table 2) suggest the comparatively high alkali content may be the reason for the better performance, since the C_3S content was lower than and the cement fineness about the same as in cement Ia. Cement Ia, the low alkali cement, generally rated second best, but the medium alkali content Ib was coarser and contained less C_3S than cement Ia, which probably subtracted from the benefits derived from alkali reactions. The mineralogical properties of the sand-loess (Table 1) are considered conducive to benefits from alkali reactions, in that this soil contains a relatively large amount of quartz, and clay coatings on grain surfaces are comparatively light. Studies of the use of alkali additives to improve cement-treated soil have shown that greatest benefits to strength are obtained with soils having a relatively large proportion of uncoated quartz surfaces (8, 9, 11).

At the lower cement contents cement IIIa, the finest ground Type III cement, gave much higher strengths than cement IIIb, despite the fact that cement IIIb had slightly higher alkali and C_3S contents. However, its slightly higher alkali and C_3S contents may explain why the performance of cement IIIb improved as cement content increased. At 8 percent cement the two Type III cements gave similar strengths after 2 and 7 days curing. At 10 percent cement, cement IIIb gave higher strengths than cement IIIa, the difference being greatest (about 200 psi) after 28 days curing.

If an immersed strength of about 300 psi after 7 days curing is taken as indicative of satisfactory quality soil-cement prepared from the sand-loess (23), selection of cement contents that give this strength by interpolating from the curves of the best Type I and Type III cements in Figure 3b indicates that about 3 percent cement IIIa is equivalent to 4 percent cement Ic, making possible a 22 percent reduction in the cost of portland cement. If construction requirements necessitated an immersed strength of 300 psi after only 2 days curing (Figure 3a), about 3 percent cement IIIa is equivalent to about 6 percent cement Ic, cost-wise a 44 percent saving.

Friable Loess.—In mixtures with the friable loess, the Type III cements gave the highest immersed strengths after all curing periods (Figs. 3d, e, f and 4e, f, g, h). The occurrence previously noted with the sand-loess, greater strength differences between the Type III and Type I cements with increasing cement content, is evident although not as marked. In general the strengths obtained were considerably below those obtained with the sand-loess. This probably is largely due to the greater surface area of the friable loess. An increased soil surface area without a proportional increase of cement may result in a less perfect distribution and functioning of cement gel on grain surfaces, and consequently lower strengths.

Comparisons of strengths obtained with cements Ia and Ic, low and high alkali cements, respectively, show little evidence of alkali reactions benefiting strength. Generally these two cements gave similar strengths. Cement Ib gave the lowest strengths, except after 2 days curing, when all three Type I cements produced about the same strengths. The only indication of beneficial alkali reactions is that cement Ic gave appreciably higher strength than cement Ia at 10 percent cement content after 28 days curing. This suggests that due to a smaller amount of uncoated quartz surface (Table 1) the alkali reactions did not occur as readily as in sand-loess and that for the alkali reactions to have an appreciable effect required a relatively high concentration of alkalis and a fairly long curing period.

As with sand-loess, cement IIIa usually gave higher strengths than cement IIIb, presumably because fineness was the major cement property variable (Table 2) affecting strength.

Assuming that an immersed strength of 275 psi after 7 days curing is indicative of satisfactory quality soil-cement prepared from the friable loess, (tentative minimum value based on limited correlation tests by the Soil-Cement Bureau, PCA). Figure 3e shows that 3 percent cement IIIa could be used instead of 5 percent cement Ia with a 35 percent saving in the cost of cement. A similar comparison after 2 days curing (Figure 3d) indicates that for an immersed strength of 275 psi, 4 percent cement IIIa is about equivalent to 8 percent cement Ic, and 44 percent cheaper.

Kansan Till.—Kansan-age glacial till contains approximately equal amounts of sand, silt, and clay sized particles (Table 1); hence it has a better gradation than friable loess which is approximately 80 percent silt and 20 percent clay. This may account for the higher immersed strengths obtained with some of the cement-treated Kansan till mixtures. The Type III cements again gave higher strengths than the Type I cements, the difference being greatest at the higher cement contents (Figs. 3g, h, i, and 4i, j, k, l).

Strengths obtained with the Type I cements do not correlate with the alkali contents of the cements, indicating no significant benefits to strength from alkali reactions. This seems reasonable in that quartz surfaces in Kansan till were heavily coated with clay particles. Cement Ia generally gave the highest strengths, possibly due to its relatively high C_3S and free CaO contents. The presence of an appreciable amount of free CaO in portland cement may improve the gel production process or provide additional cementation compounds by reacting with soil grain surfaces. The occurrence of the latter might also improve the chemical bonding of cement gel to grain surfaces. Previous work with Kansan till in soil-lime mixtures indicates that it contains minerals which are exceptionally reactive with $Ca(OH)_2$ (17).

Cement IIIa gave higher strengths than cement IIIb when the cement content was 4 percent. At 6 percent cement the two Type III cements gave similar strengths; at higher cement contents, cement IIIb generally gave highest strengths. Cement IIIb had slightly higher free CaO, alkali and C_3S contents than cement IIIa, and the cumulative beneficial effects from the extra amounts of these components may account for the improved performance of cement IIIb at the higher cement contents.

An immersed strength of 250 psi after 7 days curing may be indicative of satisfactory soil-cement prepared from the Kansan till (tentative minimum value based on limited correlation tests by the Soil-Cement Bureau, PCA). Use of this value and the curves in Figure 3h shows that 3 percent cement IIIa is equivalent to 4 percent cement Ia. The use of cement IIIa would reduce the cement cost by about 22 percent. Using the same strength criterion with the curves for 2 days curing (Fig. 3g) shows that either 4 percent cement IIIa or 6 percent Ia would produce satisfactory soil-cement. The use of the Type III cement would reduce the cement cost about 25 percent.

Conclusion.—The immersed strength test results for the cement-treated sandy, silty and clayey soils indicate the possibility of significant economic and/or structural advantages from using Type III high-early-strength portland cement instead of Type I normal portland cement for either normal or emergency soil-cement construction. A high alkali content in portland cement appears to be beneficial to the strength of cement-treated soil only when the soil has a relatively high proportion of quartz surface that is uncoated with clay minerals.

Freeze-Thaw Resistance

The modified British test (Appendix) was used to determine whether the soils stabilized with Type III portland cement were as resistant to freeze-thaw deterioration as when stabilized with Type I portland cement. The Type I and Type III cements used with each soil were the ones that generally had given the best results in the study of unconfined compressive strengths after curing and 24 hr immersion. The results of the freeze-thaw study are graphed in Figure 5 to show the effect of increasing cement content (percent oven-dry weight of soil) on the unconfined compressive strengths of the control (cured + 15 days immersed) specimens and the freeze-thaw (cured + 1 day immersed + 14 cycles of freezing and thawing) specimens. Also shown is the effect of cement content on the index of the resistance to the effect of freezing (R_f), the ratio of the freeze-thaw specimen strength (p_f) to the control specimen strength (p_c), expressed as a percentage.

General Comparison of Type I and Type III Cements.—Almost without exception mixtures with the Type III cement had much higher control and freeze-thaw specimen strengths than similarly proportioned mixtures with Type I cement. The strength differences were sometimes as much as 300 psi, clearly indicating the superior durability of the 2-day and 7-day cured specimens containing the Type III cement. The reason is probably the greater surface area of Type III cement as compared to Type I cement.

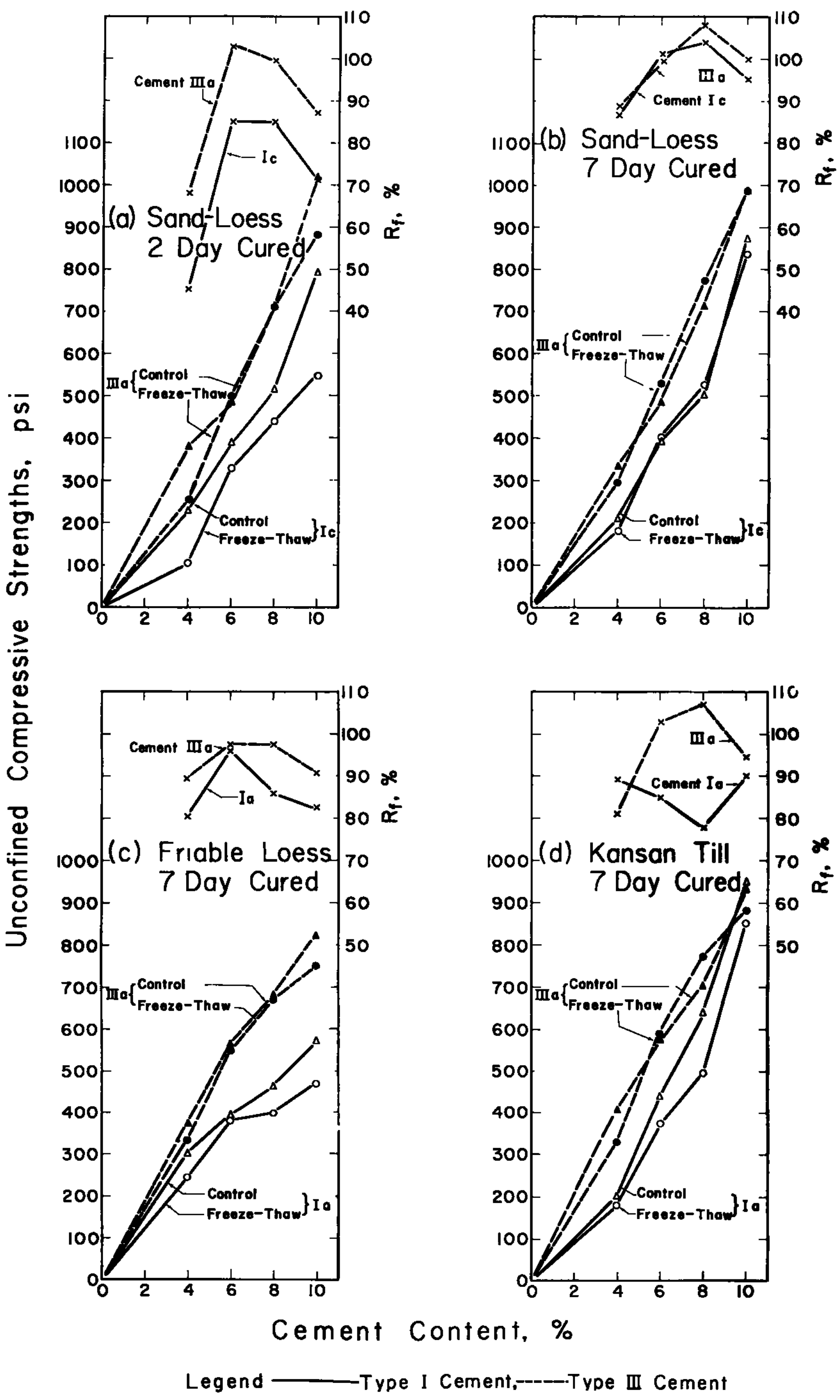

Figure 5. Modified British freeze-thaw test results for selected Type I and Type III cement-treated soil mixtures, showing the effect of cement content on the unconfined compressive strengths of the control and freeze-thaw specimens, and on the index of the resistance to the effect of freezing (R_f). Cement contents are percentages of the oven-dry weight of the soils.

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REFERENCES

1. "Definition of Terms Relating to Soil-Portland Cement Stabilization." Highway Research Abstracts, 29:28-29 (June 1959).
2. ASTM, "1958 Book of ASTM Standards, Part 4." Philadelphia, Pa. (1958).
3. Clare, K.E., and Pollard, A.E., "Relationship Between Compressive Strength and Age for Soils Stabilized with Four Types of Cement." Magazine of Concrete Research, 8:48 (Dec. 1951).
4. Clare, K.E., and Farrar, D.M., "The Use of Cements of Different Fineness in Soil-Cement Mixtures." Magazine of Concrete Research, 8:24, 137-144 (Nov. 1956).
5. Felt, E.J., "Factors Influencing Physical Properties of Soil-Cement Mixtures." HRB Bul. 108, pp. 138-162 (1955).
6. Leyder, J.P., "Stabilization du Sol au Ciment." Rapport de Recherche, pp. 1-164, Centre de Recherches Routieres, Brussels (Jan. 15, 1957).
7. Handy, R.L., "Stabilization of Iowa Loess with Portland Cement." Unpublished Ph.D. thesis, Iowa State Univ. Library, Ames (1956).
8. Handy, R.L., "Cementation of Soil Minerals with Portland Cement or Alkalis." HRB Bul. 198, pp. 55-64 (1958).
9. Tawes, R.H., "Improvement of Soil-Cement with Chemical Additives." Unpublished M.S. thesis, Iowa State Univ. Library, Ames (1959).
10. Lambe, T.W., and Moh, Z.C., "Improvement of Strength of Soil-Cement with Additives." HRB Bul. 183, pp. 38-47 (1957).
11. Lambe, T.W., Michaels, A.S., and Moh, Z.C., "Improvement of Soil-Cement with Alkali Metal Compounds." HRB Bul. 241, pp. 67-108 (1960).
12. Spangler, M.G., "Soil Engineering." Scranton, Pa., International Textbook Company (1951).
13. AASHO, "Standard Specifications for Highway Materials and Methods of Sampling and Testing, Part I Specifications." Washington, D.C. (1950).
14. Portland Cement Association, "Soil-Cement Laboratory Handbook." Chicago (1959).
15. British Standards Institution, "1958 Yearbook." London (1958).
16. Blanks, R.F., and Kennedy, H.L., "The Technology of Cement and Concrete, Volume I Concrete Materials." John Wiley and Sons, Inc., New York, N.Y. (1955).
17. Davidson, D.T., Noguera, G., and Sheeler, J.B., "Powder Versus Slurry Application of Lime for Soil Stabilization." ASTM Proc. (1959).
18. Bruns, B.W., "Comparison of Type I and Type III Portland Cements in Soil-Cement Mixtures." Unpublished M.S. thesis, Iowa State Univ. Library, Ames (1959).
19. Hicks, L.D., "Design and Construction of Base Courses." HRB Bul. 129, pp. 1-9 (1956).
20. Portland Cement Association, "Concrete Paving Design." Chicago (1951).
21. Aldrich, H.P., Jr., "Frost Penetration Below Highway and Airfield Pavements." HRB Bul. 135, p. 131 (1956).

22. Davidson, D.T., Katti, R.K., and Handy, R.L., "Field Trials of Soil-Lime-Flyash Paving at the Detroit Edison Company, St. Clair Power Plant, St. Clair, Michigan." Detroit (1958).

23. Norling, L.T., and Packard, R.G., "Expanded Short-Cut Test Method for Determining Cement Factors for Sandy Soils." HRB Bul. 198, pp. 20-31 (1958).

Appendix

MODIFIED BRITISH (B.S. 1924:1957) FREEZE-THAW TEST

Scope

1. This method covers the determination of the change in the unconfined compressive strength of 2-in. high by 2-in. diameter specimens of stabilized fine-grained soil when subjected to cycles of freezing and thawing under specified conditions. The test specimens are prepared as described under Methods of Preparing and Testing Specimens in this paper or as described in the Portland Cement Association's Soil-Cement Laboratory Handbook (14, p. 32).

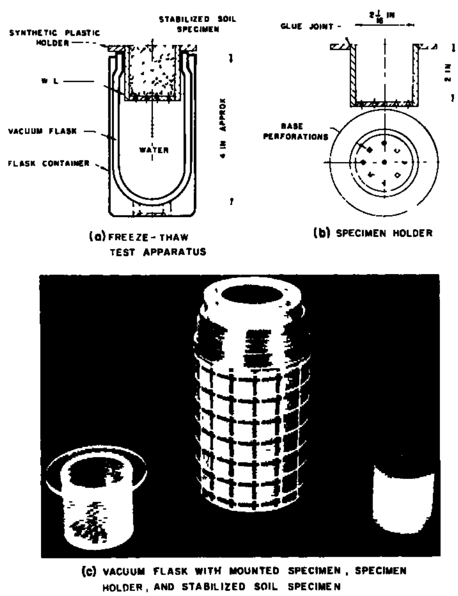

Figure 6. Apparatus used in the modified British freeze-thaw test.

Apparatus

2. The apparatus required (Fig. 6) is as follows:

a. A commerial vacuum flask having a neck with an internal diameter of approximately 2½ in. and an internal depth of at least 4 in.

b. A specimen holder of low thermal conductivity and resistant to deformation under the test conditions, and capable of supporting a stabilized soil specimen 2 in. high and 2 in. in diameter within the vacuum flask, so that the upper flat surface of the specimen is flush with the top of the flask (Fig. 6). The base of the carrier shall be perforated to permit free access of water to the underside of the specimen.

c. A refrigerated space within which is maintained a temperature of -5 ± 1 C (23 ± 2 F), and which is large enough to contain the vacuum flask with its enclosed specimen. A thermometer mounted inside the refrigerated space.

d. A supply of asphalt or resin-base paint.

e. A supply of self-adhering membrane (the commercial product "Saran Wrap" was found very satisfactory).

f. About 100 ml of distilled water, cooled to 8 ± 2 C (46 ± 4 F).

Preparation of Specimens for Test

3. For each determination two identical specimens 2 ± 0.05 in. high and 2 in. in diameter shall be prepared. (If greater accuracy is desired four or six identical specimens may be prepared for each determination.)

Test Procedure

4. a. After the desired curing period any covering material on the specimens

shall be removed and both specimens shall be weighed. The method and length of curing will depend on the method of stabilization. If either specimen has lost more than 2 g in weight during storage in a moist room maintained at a temperature of 21 ± 1.7 C (70 ± 3 F) and a relative humidity of at least 90 percent, both specimens shall be discarded. If dry curing is used to reduce the volatile content of specimens to a desired percentage of the original volatile content, the difference in weight between the specimens should not exceed 1 g.

b. After weighing, a coating of asphalt or resin-base paint, about 1 mm thick, shall be applied to the flat top surfaces of both specimens and allowed to dry. The specimens shall then be immersed in distilled water at 25 ± 2 C (77 ± 4 F).

c. After immersion for 24 hr one of the specimens shall be removed from the water and dried with blotting paper. A collar, 1½ in. deep, of a self-adhering membrane ("Saran Wrap") shall be placed around the top of the specimen.

d. Sufficient water at a temperature of 8 C (46 F) shall be poured into the vacuum flask so that when the specimen dealt with in (c) is inserted in the holder and the latter placed in the flask, the bottom ¼ in. of the specimen is immersed in water. The vacuum flask and its contents shall then be placed in the refrigerated space maintained at -5 ± 1 C (23 ± 2 F) for a period of 16 hr.

e. The flask and contents shall be removed and thawed for a period of 8 hr at a temperature of 25 ± 2 C (77 ± 4 F). If, after thawing, the level of the water inside the vacuum flask has dropped so that it is no longer in contact with the base of the specimen, water at 8 C (46 F) shall be added to restore the level.

f. The procedure described in (d) and (e) constitutes one cycle of freezing and thawing. Testing shall continue until the specimen has been subjected to 14 such cycles: the 8-hr thawing period may be extended to 66 hr for a maximum of 4 cycles of the total 14 cycles if this is required for experimental convenience. (The number of cycles of freezing and thawing in the test should approximate the number of cycles that the stabilized soil will be subjected to in the road each winter. Thus 14 cycles may not be appropriate in all climates or for all components (base, subbase, subgrade) of roads.)

g. At the conclusion of the freezing and thawing cycles the thawed specimen shall be removed from the holder and, together with the second (control) specimen which has been stored in water during the entire period (15 days), shall be allowed to drain for 15 min. The heights of both specimens shall be measured.

h. The unconfined compressive strengths of the two specimens shall then be determined. Each specimen shall be placed centrally on the lower platen of the compression testing machine, and the load shall be applied to the ends of the specimen. The load shall be applied so that the rate of deformation is uniform and approximately 0.10 in./min. The maximum load in pounds exerted by the testing machine shall be noted and recorded (p_f for the freeze-thaw specimen and p_c for the control specimen).

i. The moisture contents of representative samples of fragments taken from the interiors of the specimens shall be determined. In the case of soil stabilized with a fluid stabilizer, an additional representative sample of the fragments shall be set aside and their non-aqueous fluid stabilizer content(s) determined.

Calculations

5. a. The unconfined compressive strengths (p_f and p_c) of the two specimens shall be calculated from the formula:

$$p = 0.318\ P\ \text{(psi)}$$

in which

P = the maximum load recorded in pounds.

b. The index of the resistance to the effect of freezing (R_f) shall be calculated from the formula:

$$R_f = \frac{100 p_f}{p_c}\ (\%)$$

Reporting of Results

6. a. The values of p_c, p_f, and R_f shall be reported, the latter to the nearest 5 percent. The report shall also include relevant details of the composition of the stabilized soil mixture, the dry density at time of molding, and the moisture content and linear dimensional changes of specimens.

Discussion

D.J. MACLEAN, Head of Soils Section, Road Research Laboratory, Harmondsworth, Middlesex, England. — The stabilization of soils with portland cement is today accepted in many parts of the world as one of the principal methods of road base construction. Its advantages are the low cost of construction and the ability almost invariably to make use of local materials especially where there is a lack of hard rock, the traditional road-building material. These advantages are obtained however, only at the price of closer scientific control in designing the composition of the material and in constructing the stabilized base. This paper is therefore particularly welcome as a valuable contribution to the development of sound laboratory techniques for evaluating the strength and durability of soil-cement as a road base material.

The approach adopted by the authors is the one favored in the United Kingdom; that is, the stabilized material is required to have a compressive strength exceeding a specified minimum value and to be subject to a loss in compressive strength, when subjected either to immersion in water or to alternate freezing and thawing, that does not exceed some specified maximum percentage of the compressive strength when cured at constant moisture content. It is believed that this approach has a number of advantages including the ability to select more reliably the appropriate design cement and moisture contents and the possibility of allowing for different traffic and climatic conditions.

In the United Kingdom a minimum compressive strength of 250 psi at 7 days has been used successfully to design soil-cement for bases of lightly-trafficked roads, but for heavily-trafficked roads, the results obtained from the performance of special experimental road sections indicate that a material with a minimum strength of the order of 400 psi at 7 days is probably required.

The indications from the present work that high-early-strength portland cement has economic and structural advantages over ordinary portland cement are in agreement with the findings of laboratory studies made by Clare, Pollard and Farrar at the Road Research Laboratory to which the authors refer in their paper, but road experiments are required to confirm whether there is a corresponding difference in the long-term performances of materials made with the two types of cement.

A result of particular interest in the present paper is that with cement-treated Kansan till the optimum moisture content for maximum immersed strength was 1½ percent higher than the optimum moisture content for maximum dry density. This suggests that where a cement-stabilized clay soil base is used in circumstances where it is likely to be affected by water after construction, there are advantages to be gained by compacting the material at the higher of the two optima.