A Rapid Method of Predicting the Portland Cement Requirement for Stabilization of Plastic Soils

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The relation between the cement requirement of soil-cement mixtures and surface area determined by the glycerol retention method was investigated for a group of plastic soils. For soils containing less than 45 percent silt, a strong correlation was found between surface area and the cement content at which 10 percent loss occurred during 12 cycles of the freeze-thaw durability test. A regression equation and procedure were developed for predicting cement requirement from surface area. In a comparison of predicted cement requirements with those derived from freeze-thaw test data, an average deviation of 0.6 percent cement was obtained.

● THE USE OF SOIL-CEMENT for highway base courses has expanded rapidly in recent years, especially in areas where local sources of granular deposits are nonexistent or rapidly being depleted. Present methods for determining the amount of cement necessary to produce a stable material from a given soil involve the use of rather large soil samples and an extended testing program. The freeze-thaw or wet-dry durability tests (1) in particular require considerable time and effort. A short-cut method developed by the Portland Cement Association (P.C.A.) provides an easier alternate procedure for sandy soils, but extended testing is still required for plastic materials. This report is concerned primarily with these plastic materials, and with the development of a shorter, more economical test procedure for estimating their cement requirements.

Despite a number of years of successful use of soil cement, little is known of the physical chemistry of the reactions between the soil and the cement. It has been noted that the more plastic soils generally require larger quantities of cement for effective stabilization. Although there does not seem to be any consistent relation between cement requirement and plasticity index or any of the familiar engineering tests, it was thought that perhaps such a relationship might exist with the surface area of the soil.

Some years ago, Catton, exploring this proposed relation by the use of surface area values computed from grain-size distribution curves, found an almost complete lack of correlation (2). However, an examination of Catton's data reveals that the largest values he computed for surface area were just over 2 square meters per gram (m^2/g), even for A-6 and A-7 soils. Present knowledge indicates that actual surface areas are many times higher than this, often as high as several hundred m^2/g. Catton's low values of surface area could not, therefore, be expected to provide any real correlation.

The method widely considered as "standard" for realistically determining the surface area of fine-grained materials, is known as the Brunauer-Emmet-Teller (B.E.T.) Method, and involves the adsorption of nitrogen or some other gas on the surface of the material at low temperatures. The complicated apparatus and time-consuming procedures required are, however, not suitable for general routine determinations. Further, the method is not particularly applicable to soils since the non-polar gases normally used do not measure the internal surfaces of expanding clay minerals which are present in many soils. The crystals of the clay minerals are formed in sheet-like layers; in an expanding mineral the flat surfaces of the inner layers constitute the internal surface.

TABLE 1

DESCRIPTION OF SOILS

Identification						Physical Properties - Data Furnished by P C A													
						Gradation - percent finer than													
						Sieve number													
B P R soil No	P C A soil No	State	County	Soil series	Soil horizon	4	10	40	200	0 05 mm	0 005 mm	0 002 mm	Liquid limit	Plasticity index	AASHO classification	Optimum moisture of soil-cement mixture(%)	Maximum density of soil-cement mixture(pcf)	Cement requirement (P C A) % by vol	Surface area of whole soil m²/g
A (First group)																			
S-32044	7538	Ala.	Madison	-	-	100	85	61	24	21	6	5	17	4	A-2-4(0)	11 4	115 5	7 0	12 5
S-32045	7494	Ala	Montgomery	-	B	100	100	98	70	48	29	28	35	11	A-6(7)	17 7	104 0	13 5	90
S-32046	7537	Ala.	Montgomery	-	B	100	100	94	43	38	29	27	34	12	A-6(2)	17 9	108.0	10 5	49.5
S-32047	7509	Ark	Ashley	Richland	A B C	100	100	98	96	92	27	20	32	11	A-6(9)	16 2	105.5	9 5	63
S-32050	7489	Ark	Ashley	Portland	A	100	99	95	92	90	23	15	27	6	A-4(8)	17 3	103 5	17±	59
S-32051	7490	Ark	Ashley	Portland	B	100	100	97	94	90	23	18	30	9	A-4(8)	18 2	104 7	11 0	79
S-32053	7552	Ark	Nevada	Ruston	C -	100	100	70	30	28	22	18	39	17	A-2-6(1)	15 0	109.0	7.5	48
S-32055	7555	Ark.	Nevada	Ruston	A. B. C	100	99	99	38	32	22	18	20	6	A-2-4(0)	12.7	119 0	7 0	37 5
S-32056	7542	Ark	White	-	A	100	99	97	76	56	19	12	22	5	A-4(8)	12.3	112.6	11.0	36
S-32060	7375	Idaho	Idaho	-	-	55	27	15	9	9	2	2	26	5	A-1-a(0)	10.0	134.7	9 0	14
S-32061	7497	Ill.	Cook	-	-	55	47	35	19	15	7	5	25	6	A-1-b(0)	8 0	125 3	7.0	12
S-32062	7498	Ill.	Cook	-	-	100	99	97	91	88	42	28	41	16	A-7-6(11)	23 4	96 7	14 5	81
S-32063	7h	Ill	Cook	-	-	100	100	97	90	87	48	-	41	24	A-7-6(14)	17 5	104 5	13 0	77 5
S-32064	7460	Ill	Henry	-	-	59	46	28	16	16	8	6	26	6	A-1-b(0)	9 4	130 3	7 0	7 5
S-32065	7558	Ill	Iroquois	Hagner	-	85	83	78	33	22	9	3	18	7	A-2-4(0)	10 2	121 0	7 5	25 5
S-32066	7528	Ill	Massac	-	-	80	74	67	56	49	10	7	22	1	A-4(4)	11 3	117 6	8 5	26
S-32067	7529	Ill	Massac	-	-	77	71	66	60	58	16	13	26	6	A-4(5)	13 3	115 8	10.5	40.5
S-32068	7530	Ill.	Massac	-	-	75	63	50	35	32	9	8	19	4	A-2-4(0)	11 0	120 8	9 0	28 5
S-32069	7560	Ill.	Massac	-	-	55	48	41	36	34	11	8	30	9	A-4(0)	11 2	119 5	7 0	22.5
S-32070	7561	Ill.	Massac	-	-	84	76	73	39	23	8	8	20	3	A-4(1)	11.7	118 6	7.0	19.5
S-32071	7562	Ill.	Massac	-	-	80	71	66	56	51	15	12	26	5	A-4(4)	13.0	117.4	9.5	37.5
S-32072	7563	Ill.	Massac	-	-	55	47	34	12	11	8	8	28	15	A-2-6(0)	9 4	126 8	7 0	14
S-32074	S-7	Ill	McHenry	-	B. C	100	99	99	92	79	13	-	26	7	A-4(8)	15 0	113.0	9.0	42.5
S-32075	6900	Kan.	Grant	-	-	100	97	94	77	69	25	19	29	9	A-4(8)	16 5	106 7	10.5	87 5
S-32076	7520	Ky	Carter	-	-	59	56	52	24	13	4	3	19	3	A-2-4(0)	7 8	130 2	6 5	6
S-32078	7515	Ind	Vandenb'g	-	-	100	100	94	27	26	15	12	20	4	A-2-4(0)	12 2	120 0	7.5	20
S-32082	7525	Mo	Jackson	-	C	100	100	100	94	79	17	14	27	5	A-4(8)	15 5	108 7	9 0	82
S-32083	7526	Mo.	Jackson	-	-	100	100	100	94	80	15	13	28	6	A-4(8)	15 7	108.0	9 5	85 5
S-32085	7514	Okla.	Okmulgee	-	A	92	86	85	36	25	15	10	27	7	A-4(0)	12 0	117 6	7 0	32 5
B (Second group)																			
S-32572	7682	Colo.	Fremont	-	-	67	52	39	29	27	16	10	26	9	A-2-4(0)	11 8	124 2	11 0	14 5
S-32573	7687	Ill.	Will	-	B	100	100	99	97	93	45	37	47	25	A-7-6(15)	22 0	100 3	15.0	143
S-32575	7695	La	Livingston	-	-	100	99	98	94	86	17	12	26	4	A-4(8)	17 7	104 4	15 5	33
S-32576	7701	Tenn	Franklin	-	B	100	99	88	53	48	32	26	32	15	A-6(6)	16 9	109 4	10 0	36
S-32577	7702	Tenn	Franklin	-	A	98	96	83	40	36	21	17	25	10	A-4(1)	13 7	113 5	7 0	34
S-32578	7761	Mont	Silver	-	-	96	83	46	22	20	10	9	30	9	A-2-4(0)	11 8	119 5	7 5	34
S-32579	7762	Mich.	Calhoun	-	A B.	92	87	75	37	31	13	9	23	8	A-4(0)	7 9	115 9	10.0	37
S-32582	7776	Kan	Douglas	-	-	100	100	100	97	85	16	14	29	5	A-4(8)	21 0	97 0	12 0	78
S-32583	7777	Kan.	Douglas	-	-	100	100	100	98	86	16	14	29	6	A-4(8)	18 5	102 2	12 0	73 5
S-32584	7779	Tex	Wichita	-	-	55	39	25	16	13	5	5	25	9	A-2-4(0)	8 4	129 0	7 0	18

Lately, a method (3) involving the retention of ethylene glycol by soils has also been used to estimate surface area, but there is some doubt as to the specific quantitative relation between the actual surface area and the amount of ethylene glycol retained under the conditions of the determination. More recently, a new and simpler method involving the retention of glycerol, has been developed at the laboratories of the Bureau of Public Roads (4, 5).

Values of surface area obtained for various clays by this method were shown to agree closely with theoretical values of expanding clays and, for non expanding clays, with those determined by the B. E. T. Method. In the present work, surface areas were measured by this method on a number of soils of known cement requirement. The correlation between the resulting surface area values and cement requirements was then determined. An equation was derived for predicting cement requirements from surface area values, and the predicted cement requirements were compared with the actual cement requirements as determined by test.

MATERIALS AND METHODS

Soils

Soil samples and accompanying engineering test data were supplied by the Portland Cement Association.[1] Of the soils furnished, only those with measurable plasticity indexes were included in this study. The soils of the first group received are described in part A of Table 1. They were not selected as representative of any particular soil area or type of soil but were simply those on hand at the P. C. A. laboratory at the time this study was initiated. They do, however, include samples from a number of different states and of various soil horizons. The last ten soils listed in Table 1

[1]The cooperation of the Portland Cement Association in supplying the soil samples and accompanying test data is gratefully acknowledged. Thanks are especially due to Mr. J. A. Leadabrand and Mr. L. T. Norling, of the Soil Cement Bureau for their interest.

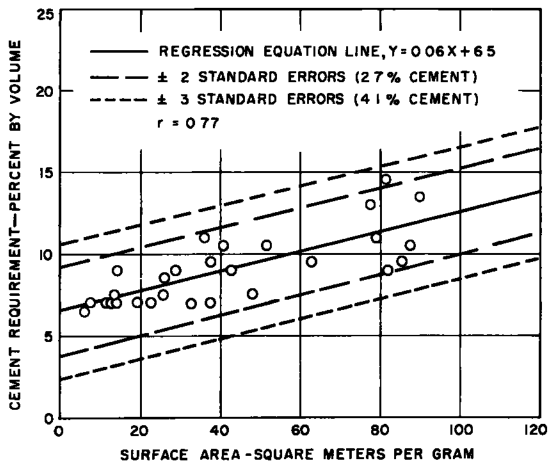

Figure 1. Recommended cement requirement (P.C.A., percent by volume) vs surface area of soils (first group).

(part B) were received as a second group and represent samples processed by the P.C.A. laboratory during the period in which this study was made.

Surface Area Measurements

In the glycerol retention method advantage is taken of the ability of clay and other soil constituents to adsorb glycerol molecules on their surfaces. Conditions are maintained under which only a single layer of the glycerol molecules is adsorbed and retained. The amount of glycerol adsorbed is measured by weighing the sample before and after treatment, and the weight of the adsorbed glycerol can be related to the surface area of the sample.

As applied to this study, the method involves the following steps:

1. Dry duplicate small samples (about 1 gm each) of the passing 40-mesh fraction of the soil at 110 C in aluminum foil dishes, and weigh to 0.0002 gm on an analytical balance.
2. Add 10 ml of a dilute (2 percent) water solution of glycerol to the sample, and swirl the container gently to mix the contents.
3. Heat at 110 C (±3 C) in a mechanical-convection oven containing a supply of glycerol to provide a source of free glycerol vapor in the oven chamber. Under these conditions, glycerol in excess of a monomolecular layer and water are both removed.
4. Reweigh after equilibrium has been attained, normally after over-night heating. The gain in weight over the original oven-dry weight of the sample is due to the monomolecular layer of glycerol adsorbed on both the internal and external surfaces. The adorbed glycerol is expressed as a percentage of the 110 C dry weight of the soil.
5. A distinction must be made between that portion of the glycerol retained on external surfaces of all clay minerals and that retained on internal surfaces of expanding minerals such as montmorillonite and vermiculite. On the internal surfaces both the top and bottom of the monomolecular layer of glycerol are in contact with clay surfaces. On the outside of the particles, however, only one side of the monomolecular layer is in contact with clay surface. Therefore, a given amount of glycerol on internal surfaces accounts for twice as much clay surface area as the same amount would if it were on external surfaces.

To make this distinction, a second determination is required. This is accomplished by determining the percentage of glycerol retained by replicate samples previously heated to 600 C, the glycerol retention being determined by the same procedure as described above. Heating to 600 C normally collapses and irreversibly closes the internal spaces and thus renders them inaccessible to glycerol molecules. The difference between the original percentage of glycerol retained and that retained after heating to 600 C is attributable to internal surfaces; the percentage measured after this preliminary heating is due to external surfaces only

Based on x-ray diffraction evidence concerning the thickness of a monomolecular layer of glycerol, it has been shown that one-hundredth of a gram of glycerol covers 35.3 sq m of internal clay surfaces (5); thus a glycerol retention of 1 percent on internal surfaces corresponds to 35.3 m^2/g. Similar deductions indicate that a retention of 1 percent glycerol on external surfaces corresponds to a specific surface of 17.65 m^2/g.

For the soils used in this study the surface area value of the whole soil was computed by multiplying the surface area found for the passing 40-mesh fraction by the percentage of the whole soil which passes the 40-mesh sieve. The surface area of the particles coarser than 40 mesh is so small as to be negligible. A hypothetical example of these computations is as follows:

Glycerol retention of passing 40-mesh fraction:	3.50 percent
Glycerol retention of same after preliminary 600 C heating:	1.50 percent
Retention due to external surface:	1.50 percent
Retention due to internal surface: 3.50 - 1.50 percent	2.00 percent
Indicated surface area of passing 40-mesh fraction	

External: $1.50 \times 17.65 = 26.5\ m^2/g$
Internal: $2.00 \times 35.3 = 70.6\ m^2/g$
Total $97.1\ m^2/g$

Percentage of whole soil passing 40-mesh sieve:	65 percent
Surface area of whole soil: $97.1\ m^2/g \times 0.65$	$63.1\ m^2/g$

For this study this figure would be rounded to the nearest half-square meter per gram, or 63 m^2/g.

Cement Requirements

The cement requirement determinations were performed by the staff of the P.C.A. Soil Cement Laboratory, using the methods described in their "Soil Cement Laboratory Handbook," 1956. Briefly, this method is as follows:

1. Determination of the grain-size distribution and Atterberg limits of the soil.
2. Determination of the moisture-density relations of a mixture of the soil and an assumed percentage of cement.
3. Molding durability test specimens at optimum moisture and at cement contents thought to bracket the cement requirement, and testing through 12 cycles of freezing and thawing. (Wet-dry tests may also be made, but were not used for the soils of this investigation.) For A-1, A-2-4, and A-2-5 soils, the cement requirement is specified by P.C.A. as that cement content at which test specimens lose 14 percent of their weight during the 12 cycles and the accompanying brushing procedure. For A-2-6, A-2-7, A-4, and A-5 soils, the loss permitted is 10 percent, and for A-6 and A-7 soils, it is 7 percent. These loss criteria are based on information from a great many laboratory tests, the performance of field projects, and outdoor exposure of several thousand specimens.
4. Checking the estimated cement factor by molding and testing small specimens for compressive strength to insure that adequate hardening takes place at this cement content.
5. For reporting and for field use, the cement factor is converted from a weight basis to a volume basis by use of the relation percent cement by vol= $\frac{D - \frac{D}{C}}{94} \times 100$, where D=oven-dry density of the soil-cement specimen in lb per cu ft, and C=100 plus the percent cement by weight of oven-dry soil, the quantity divided by 100.
6. The final recommended cement content is based to some extent on the judgment of the testing engineer. For example, the cement content indicated by the durability test data might be in a critical range, i.e., where a small decrease in cement content would lead to very much higher than allowable freeze-thaw losses. In such a case, inadequate mixing on the job could result in an unsatisfactory product, and to insure against this, the testing engineer would recommend a slightly higher over-all cement content than that provided for by the durability test data.

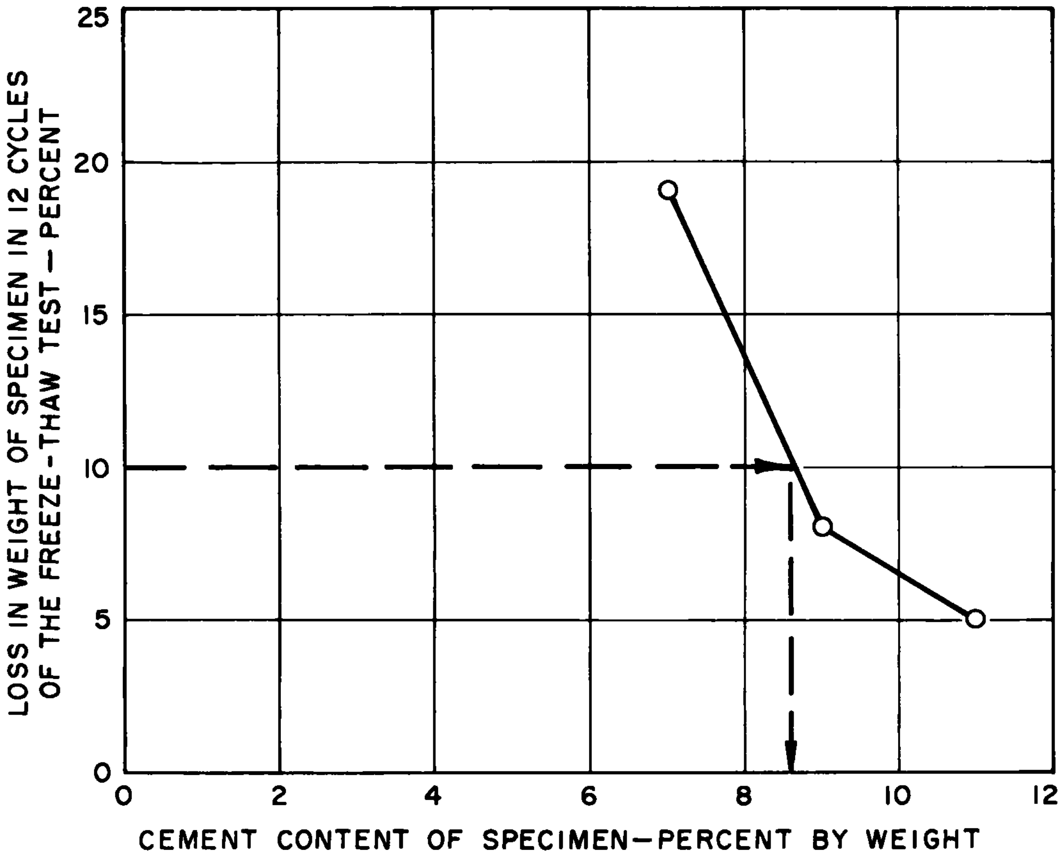

Figure 2. Method of determining cement content (by wt) at which 10 percent loss would occur in the freeze-thaw test (12 cycles). For this illustration the required value is 8.6 percent.

RESULTS AND DISCUSSION

Surface area values and cement requirements for the Group A samples (numbers S-32044 to S-32085) are listed in Table 1. The surface areas range from 6 to 90 m^2/g. The cement requirement values quoted (in terms of percent by volume) are those actually recommended for construction by the P. C. A. laboratory. Analysis shows that a statistically significant correlation[2] exists, r = 0.77, significant at the 0.1 percent level. The following regression equation was derived from the data: Cement requirement = 0.06 (surface area) + 6.5. The standard error of estimate from this equation is 1.37 percent cement by volume. A plot of the relation is given in Figure 1.

The statistical significance level of the correlation coefficient (0.1 percent) clearly indicates that a correlation actually exists. Nevertheless, the degree of correlation indicated by the correlation coefficient (0.77) is not strong enough to permit accurate predictions of cement requirement directly from surface area measurements.

Assuming the validity of the hypothesis that the surface area should be intimately associated with the cement need, a number of possible reasons for not obtaining the expected closer correlation could be deduced.

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[2] See appendix for definition of statistical terms.

1. The surface area values used are based on the weight of the soil, surface area being expressed in square meters per gram, whereas the cement requirements are expressed on a volume basis. This naturally would weaken the correlation because there can be no over-all relation between values expressed by weight and those expressed by volume, due to the variation in the densities of the different soil-cement products.

2. As noted earlier, the cement requirement determined by the P.C.A. laboratory is based on the cement content at which maximum losses of 7, 10, or 14 percent occur during the 12-cycle freeze-thaw test, the limit applying depending on the AASHO classification of the soil. Two soils containing different clay minerals might have identical surface areas, but have greatly different grain-size distributions and plasticity indexes, thereby falling into different classifications. Accordingly, the cement requirement of one might be based on the 7 percent loss limit and that of the other on the 14 percent loss limit, despite their identical surface areas. In effect, this inserts a bias in the cement requirement values which is not correspondingly reflected in the surface area, and so tends to weaken the correlation.

3. The cement requirements recommended are not derived solely from freeze-thaw loss data, but, as noted earlier, may be modified somewhat by engineering judgment. This added factor, while perfectly justified from a practical standpoint, is not related to a physical measurement such as surface area, and thus also tends to weaken the correlation.

4. The cement requirement data are rounded to the nearest half-percent of cement. Since the range in cement requirements encountered with these soils (6.5 to 14.5 percent) is only 16 times this figure, this rounding, while again justifiable from the practical standpoint, tends to weaken the correlation.

TABLE 2

TEST DATA FOR 12 CYCLES OF FREEZING AND THAWING AND DATA DERIVED FROM THEM

B.P.R. soil No.	Test data furnished by P.C.A. Specimen 1 Cement % by wt	Specimen 1 Loss %	Specimen 2 Cement % by wt	Specimen 2 Loss %	Specimen 3 Cement % by wt	Specimen 3 Loss %	Specimen 4 Cement % by wt	Specimen 4 Loss %	Derived data: Cement content at 10% loss % by wt	Loss allowed freeze-thaw test %	Cement content at which allowed loss occurs % by wt	Cement content at which allowed loss occurs % by vol
A (First group)												
S-32044	5	13	7	5	-	-	-	-	5.8	14	4.8	5.7
S-32045	10	13	12	10	14	6	-	-	12.0	7	13.5	13.2
S-32046	6	13	8	9	10	7	-	-	7.5	7	10.0	10.4
S-32047	8	10	10	5	12	4	-	-	8.0	7	9.2	9.7
S-32050	9	48	11	42	13	33	15	30	n.a.[1]	10	n.a.[1]	n.a.[1]
S-32051	9	36	11	8	13	5	-	-	10.8	10	10.8	10.9
S-32053	7	23	9	2	-	-	-	-	8.2	10	8.2	8.8
S-32055	5	13	7	8	-	-	-	-	6.0	14	4.5[2]	5.4[2]
S-32056	8	35	10	7	12	6	14	5	9.6	10	9.6	10.5
S-32060	3	18	5	6	7	1	-	-	4.3	14	3.6	5.0
S-32061	5	3	7	2	9	2	-	-	n.a.[1]	14	n.a.[1]	n.a.[1]
S-32062	12	25	14	14	16	4	-	-	14.8	7	15.3	13.7
S-32063	8	13	10	10	12	8	-	-	10.0	7	12.9[2]	12.6[2]
S-32064	3	20	5	2	-	-	-	-	4.0	14	3.6	4.8
S-32065	4	100	6	11	8	7	-	-	6.5	14	5.9	7.0
S-32066	8	6	10	5	-	-	-	-	n.a.[1]	10	n.a.[1]	n.a.[1]
S-32067	10	7	12	6	14	5	-	-	n.a.[1]	10	n.a.[1]	n.a.[1]
S-32068	5	20	7	15	-	-	-	-	n.a.[1]	14	7.4[2]	8.7[2]
S-32069	6	7	8	5	-	-	-	-	n.a.[1]	10	n.a.[1]	n.a.[1]
S-32070	4	18	6	9	8	5	-	-	5.7	10	5.7	6.8
S-32071	7	13	9	5	11	4	-	-	7.7	10	7.7	8.8
S-32072	3	18	5	9	-	-	-	-	4.9	10	4.9	6.3
S-32074	6	5	8	3	10	3	-	-	n.a.[1]	10	n.a.[1]	n.a.[1]
S-32075	10	10	12	6	14	5	-	-	10.0	10	10.0	10.3
S-32076	3	17	5	6	-	-	-	-	4.3	14	3.4	4.8
S-32078	4	24	6	13	-	-	-	-	n.a.[1]	14	5.8	7.0
S-32082	7	11	9	7	11	6	-	-	7.5	10	7.5	8.1
S-32083	7	19	9	10	11	6	-	-	9.0	10	9.0	9.5
S-32085	5	11	7	7	-	-	-	-	5.7	10	5.7	6.8
B (Second group)												
S-32572	7	44	9	9	-	-	-	-	8.9	14	8.6	10.4
S-32573	11	13	14	8	17	5	-	-	12.8	7	15.0	13.9
S-32575	13	22	15	13	17	4	-	-	15.6	10	15.6	15.0
S-32576	8	8	10	6	12	5	-	-	n.a.[1]	7	9.0	9.5
S-32577	6	10	8	8	10	5	-	-	6.0	10	6.0	6.8
S-32578	4	21	6	14	8	6	-	-	7.0	14	6.0	7.2
S-32579	8	12	10	8	-	-	-	-	9.0	10	9.0	10.1
S-32582	13	7	16	4	19	2	-	-	n.a.[1]	10	n.a.[1]	n.a.[1]
S-32583	11	12	14	4	17	2	-	-	11.7	10	11.7	11.3
S-32584	3	28	5	4	-	-	-	-	4.5	14	4.2	5.5

[1] n.a. — not available from data supplied.
[2] Obtained by extrapolation

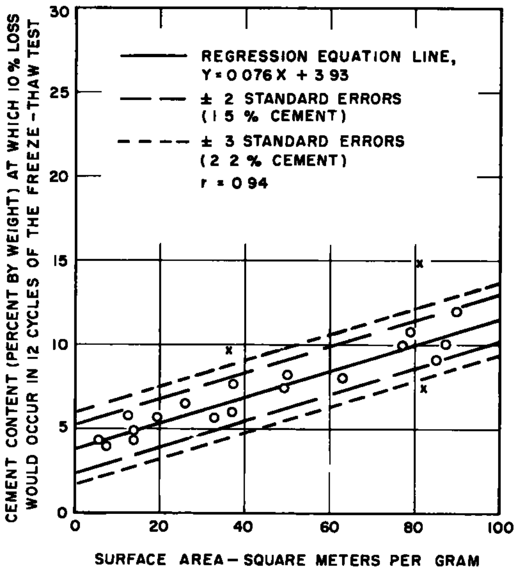

Figure 3. Cement content (percent by weight) at which 10 percent loss would occur in 12 cycles of the freeze-thaw test vs surface area of soils (first group.)

It was thought that expressing the cement requirement in a different way would obviate these difficulties. Strictly for purposes of correlation, in place of the recommended cement requirement, it is proposed to use for all soils that cement content (in percent by weight) at which 10 percent loss occurs in the freeze-thaw test. This places the cement content on a weight basis as is the surface area; it eliminates the bias due to different limits of allowable loss for different soil groups by placing all of the soils on a uniform basis of 10 percent loss; it eliminates personal judgment factors; and when the cement contents are expressed to the nearest 0.1 percent, it eliminates bias due to excessive rounding of the values.

This expression of cement requirement was obtained by the following procedure, as illustrated in Figure 2: For the several freeze-thaw specimens prepared from the same soil at various cement contents, a plot was made of the actual test loss vs cement content, and the points were connected by straight lines. The cement content at which 10 percent loss would occur was then read directly from this plot, by interpolation if necessary. The actual loss data and corresponding cement contents for all the soils are given in Table 2.

The relation between this new cement factor and surface area was investigated, with results as shown in Figure 3. The analysis showed a distinct and marked improvement in the degree of correlation existing, the correlation coefficient r being 0.94, which demonstrates both the validty of the original hypothesis that cement requirement and surface area are closely related, and also, that the disturbing factors discussed above have been largely avoided by this method of estimating the required cement content.

The regression equation appropriate for predicting the cement content by weight at which 10 percent loss occurs was calculated as:

$$Y = 0.076 \text{ (surface area)} + 3.93$$

The standard error of estimate from this equation is 0.74 percent cement. It should be noted that for several of the samples, the available freeze-thaw test data could not be used to obtain the test value of the cement content at which 10 percent loss would occur, except by questionable extrapolation; these samples have accordingly not been included in this correlation. In addition, three samples for which data were available (Nos. S-32056, S-32062, and S-32082) did not fit the correlation. Since these were more than three standard errors from the regression equation line, it is statistically valid to discard them from consideration on the grounds that they presumably do not belong to the same statistical population as the remainder of the samples. These three samples will be discussed later in the report.

A sufficiently close correlation has thus been established to permit prediction of the cement content at which 10 percent loss occurs from surface area measurements. It now remains to develop a procedure to convert the cement content so predicted for an individual soil, back to an estimated cement requirement based on the specific freeze-thaw loss allowable for soils of its class. For those soils where a maximum of 10 percent loss is allowed (A-2-6, A-2-7, A-4, and A-5 soils), no adjustment of the predicted value is of course necessary; for those (A-6, A-7) having a maximum allowable loss of 7 percent, the predicted cement content would be increased; similarly for soils (A-1, A-2-4, A-2-5) where loss up to 14 percent is allowed, the predicted cement content would be decreased. By examination of the loss data, the appropriate corrections were estimated to be +2.0 percent, and -0.7 percent, respectively. The corrected cement contents by weight can then be converted to a predicted cement requirement by volume through the use of the formula previously listed.

The above procedure was followed to obtain predicted cement requirements in percent by volume, which were then compared with the cement requirement (by volume) computed directly from the freeze-thaw test results. Agreement for Group A samples (Nos. S-32044 through S-32085) was only reasonably good. The coefficient of correlation between the predicted and the test cement requirements was r = 0.87, and the standard error of estimate was 1.3 percent cement.

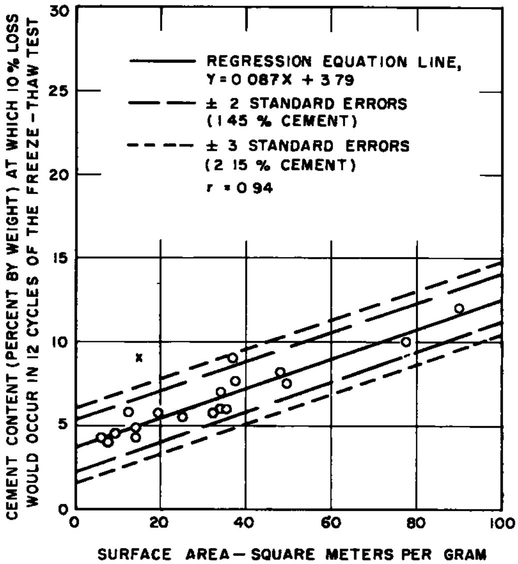

Figure 4A. Soils having less than 45 percent silt: cement content (by wt) at which 10 percent loss would occur in 12 cycles of the freeze-thaw test vs surface area.

Summarizing the results to this point, it has been shown that:

1. A definite though not very precise correlation exists between surface area and the cement requirement (percent cement by volume) actually recommended by the P.C.A. for this first group of plastic soils.

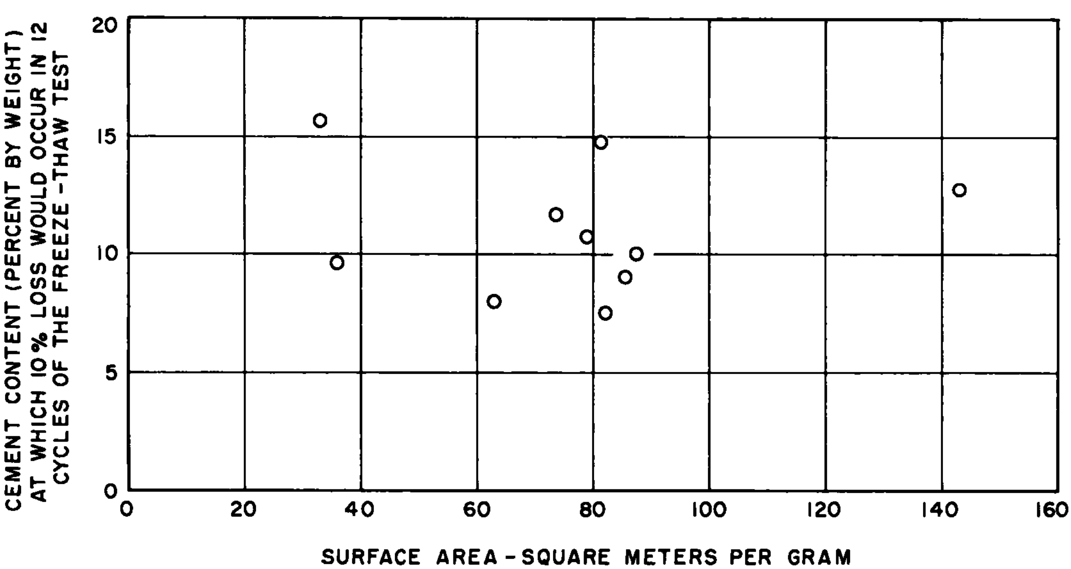

Figure 4B. Soils having 45 percent or more silt: cement content (by wt) at which 10 percent loss would occur in 12 cycles of the freeze-thaw test vs surface area.

TABLE 3

COMPARISON OF CEMENT REQUIREMENTS PREDICTED FROM SURFACE DATA WITH CEMENT REQUIREMENT FROM FREEZE-THAW TEST DATA

B. P. R. soil No.	AASHO classification	Surface area m²/g	Regression equation prediction of cement content at which 10 percent loss occurs % by wt	Corrections for soils where 7 percent or 14 percent loss is allowed % by wt	Corrected prediction of cement requirement % by wt	Corrected prediction of cement requirement % by vol	Cement requirement computed from freeze-thaw test data % by vol	Deviation of predicted from test cement requirement % by vol
			Category 1 - Plastic soils silt content less than 45%					
S-32044	A-2-4(0)	12.5	4.9	-0.7	4.2	4.9	5.7	-0.8
S-32045	A-6(7)	90	11.6	+2.0	13.6	13.1	13.2	-0.1
S-32046	A-6(2)	49.5	8.1	+2.0	10.1	10.6	10.4	+0.2
S-32053	A-2-6(1)	48	8.0	-	8.0	8.6	8.8	-0.2
S-32055	A-4(8)	37.5	7.1	-0.7	6.4	7.6	5.4	+2.2
S-32060	A-1-b(0)	14	5.0	-0.7	4.3	5.9	5.0	+0.9
S-32063	A-7-6(14)	77.5	10.5	+2.0	12.5	12.4	12.6	-0.2
S-32064	A-1-b(0)	75	4.4	-0.7	3.7	5.0	4.8	+0.2
S-32065	A-2-4(0)	25.5	6.0	-0.7	5.3	6.5	7.0	-0.5
S-32068	A-2-4(0)	28.5	6.3	-0.7	5.6	6.8	8.7	-1.9
S-32070	A-4(1)	19.5	5.5	-	5.5	6.6	6.8	-0.2
S-32071	A-4(4)	37.5	7.1	-	7.1	8.5	8.8	-0.3
S-32072	A-2-6(0)	14	5.0	-	5.0	6.4	6.3	+0.1
S-32976	A-2-4(0)	6	4.3	-0.7	3.6	4.8	4.8	0.0
S-32078	A-2-4(0)	20	5.5	-0.7	4.8	5.8	7.0	-1.2
S-32085	A-4(0)	32.5	6.6	-	6.6	7.7	6.8	+0.9
S-32576	A-6(6)	36	6.9	+2.0	8.9	9.5	9.5	0.0
S-32577	A-4(1)	34	6.8	-	6.8	7.7	6.8	+0.9
S-32578	A-2-4(0)	34	6.8	-0.7	6.1	7.3	7.2	+0.1
S-32579	A-4(0)	37	7.0	-	7.0	8.1	10.1	-2.0
S-32584	A-2-4(0)	9	4.6	-0.7	3.9	5.1	5.5	-0.4
S-32572[1]	A-2-4(0)	14.5	5.1	-0.7	4.4	5.6	10.4	-4.8[1]
			Category 2 - Plastic soils: silt content 45% or higher					
S-32047	A-6(9)	63	9.3	+2.0	11.3	11.4	9.7	+1.7
S-32051	A-4(8)	79	10.7	-	10.7	10.8	10.9	-0.1
S-32056	A-4(8)	36	6.9	-	6.9	7.7	10.5	-2.8
S-32062	A-7-6(11)	81	10.8	+2.0	12.8	11.7	13.7	-2.0
S-32075	A-4(8)	87.5	11.4	-	11.4	11.6	10.3	+1.3
S-32082	A-4(8)	82	10.9	-	10.9	11.4	8.1	+3.3
S-32083	A-4(8)	85.5	11.2	-	11.2	11.6	9.5	+2.1
S-32573	A-7-6(15)	143	16.2	+2.0	18.2	16.2	13.9	+2.3
S-32575	A-4(8)	33	6.7	-	6.7	7.1	15.0	-7.9
S-32583	A-4(8)	73.5	10.2	-	10.2	9.8	11.3	-1.5

[1] Deviant sample, this was discarded in computing the regression equation.

2. The correlation was greatly improved by using instead of the recommended cement requirement by volume, the cement content by weight at which an arbitrary figure of 10 percent loss would occur in 12 cycles of the freeze-thaw test. The computed regression equation permitted satisfactory predictions of this value to be made from the surface area.

3. A procedure was developed for correcting this cement factor to predict the cement content (by weight) at which 7 percent or 12 percent loss would occur, and by the use of a given formula involving the density of the soil-cement product, this prediction could be converted to a volume basis.

4. Predictions thus made were in reasonable agreement with cement requirements derived directly from the freeze-thaw test data, the correlation between the two sets of values being 0.87.

Another group (sample Nos. S-32572 through S-32584) of soils received after work on the first group had been completed, provided an opportunity to check the validity of these results. These samples are described in Table 1 as Group B, and cement requirement test data for them are listed in Table 2. After the surface areas were determined for these soils, predictions of cement requirement (by volume) were computed, using the regression equation derived for the soils of Group A and the additional procedure outlined above. A comparison of these predicted values with cement requirements computed directly from the freeze-thaw test data indicated good agreement for some of the samples but considerable deviations for certain others. Upon examination of the engineering test data for Group B, it was noted that all but one of the deviant samples were very high in silt content, silt being taken as that portion passing the 200-mesh sieve and coarser than 0.005 mm. When the data for the samples of Group A were re-examined, it was found that here also high silt content was associated with relatively poor agreement between predicted and test results. In particular, it was noted that the three soils it was necessary to discard from the previous correlation were high in silt content. For such soils, the cement requirement is evidently governed by some property or properties other than surface area.

In order to verify this premise, the data of both groups of soils taken together were divided into two categories on the basis of silt content. Upon examination of the data, an appropriate dividing line appeared to be at a silt content of 45 percent. The correlation between surface area and the cement content (by weight) at which 10 percent

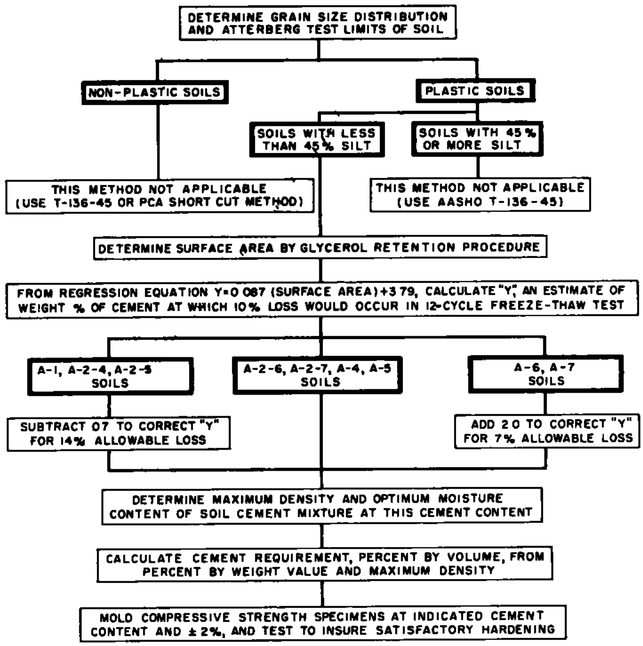

Figure 5. Flow sheet: short-cut method, using surface area to determine cement requirement of plastic soils containing less than 45 percent silt.

loss occurred in the freeze-thaw test was recomputed separately for each category. The category (22 samples) with silt content under 45 percent showed a high degree of correlation (correlation coefficient r = 0.94) similar to that previously determined for the first batch alone. One deviant sample (No. 32572) did not fit the correlation, and since it was considerably more than three standard errors from the regression equation line, it was discarded. This sample is discussed later in the report. On the other hand, the category consisting of soils with silt contents of 45 percent or higher, showed essentially zero correlation (correlation coefficient r = -0.03). The data of the two categories of samples are plotted separately in Figures 4A and 4B. The striking difference in correlation coefficients demonstrates clearly that the two sets of samples represent different populations; for the soils of lower silt content the cement requirement is essentially a function of surface area, as has previously been determined; but for soils of higher silt content there is little relation between the two.

The regression equation was then calculated for the soils of low silt content. It differs only slightly from the corresponding equation previously calculated for Group A samples alone. The new equation is: cement content (by weight) at which 10 percent loss occurs = 0.087 (surface area) + 3.79. The equation and the previously described procedure were then used to predict the values of cement requirement for these soils. These predictions are compared in the upper part of Table 3 with the cement requirements derived from the freeze-thaw test data. Agreement between the two sets of values is good (correlation coefficient r = 0.92, standard error of estimate = 0.9 percent cement), again with the exception of sample No. S-32572 previously noted as being a deviant sample. Neglecting this sample, the average deviation between predicted and test cement requirements was only 0.6 percent cement. Among the remaining 21 soils, six were classified in the highly plastic AASHO groups A-2-6, A-2-7, A-6 and A-7. For all six, predictions were within 0.2 percent cement of the test value.

The clay minerals present in the various samples were identified by x-ray diffraction techniques. The clay fractions were nearly all mixtures of two or more clay minerals, including among them montmorillonite, illite, kaolinite, chlorite, and vermiculite. Most contained at least a detectable amount of montmorillonite, and several were almost pure montmorillonite. None of the clays was principally illite or principally kaolinite, although several consisted largely of a chlorite-like clay mineral. From the evidence available, it seems that, in general, the cement reqirement is influenced by the surface area itself, without regard to the specific type of clay mineral from which the surface area is derived.

No definite explanation has been found for the behavior of sample No. S-32572 (point labeled x, Figure 4A), previously noted as strongly deviating from the regression equation line. The actual cement requirement is much higher than the predicted value. X-ray diffraction examination indicated that this soil consists primarily of finely divided calcium carbonate (caliche), much of it in the clay size-range. Further study is needed to determine the effect of this type of material on the cement requirement.

From the results obtained, a procedure for predicting cement requirements of plastic soils of less than 45 percent silt content was formulated. This is diagramed in Figure 5. For soils to which it can be applied, the procedure eliminates the time-consuming freeze-thaw tests. It would still be necessary, however, to prepare small specimens at and near the predicted cement requirement, and test them for compressive strength (or by other suitable means) to insure that adequate hardening was actually taking place. Furthermore, the predicted cement content should be modified by appropriate engineering judgment, to compensate for factors such as difficulty of adequate mixing in the field, and possible local variations in the soil materials.

It is recognized that these findings are based on only a limited number of samples, and are not necessarily applicable to all soils. For example, other workers have reported that certain types of soil organic matter strongly influence the cement requirement; although a number of the soils in this study were moderately high in organic matter, there was no evidence of appreciable effects on cement requirement. With a larger group of samples, soils containing such deleterious organic matter might have been encountered.

CONCLUSIONS

The following conclusions are drawn from this investigation:

1. For soils of measurable plasticity, a definite correlation exists between surface area, as measured by the glycerol retention procedure, and cement requirement (percent by volume) calculated from loss data of the freeze-thaw durability test and amended by other engineering considerations. However, this correlation is not sufficiently close to permit adequate predictions to be made directyly from the surface area values. The weakness of this correlation is considered to be due to such factors as:

   a. The surface area is expressed on a weight basis in contrast to the volume basis of the cement requirement.

   b. The different standards of allowable losses in the freeze-thaw test, 7, 10 or 14 percent, depending on the AASHO classification of the sample.

   c. The use of a certain amount of engineering judgment in deriving practical recommendations for field use from the freeze-thaw data.

   d. The rounding of the cement requirement to the nearest half-percent.

   e. The presence in the group of samples studied of several soils high in silt content. Such soils have been shown to have cement requirements which do not correlate with surface area.

2. A very strong correlation is obtained when soils of higher than 45 percent silt are excluded from consideration, and the cement factor in the correlation is taken as the actual cement content by weight at which a 10 percent loss occurs in the freeze-thaw test, no allowance being made for AASHO class differences. The regression equation $y = 0.087$ (surface area) $+ 3.79$ can be employed to derive accurate predic-

tions of this cement factor from measurements of surface area by the glycerol retention method.

3. A suitable prediction of the conventional cement requirement, in percent by volume, can then be made by the following procedure:

a. Modifying if necessary the cement factor predicted by the regression equatiin be adding 2.0 percent cement to adjust to the basis of a 7 percent allowable loss in the freeze-thaw test, or by subtracting 0.7 percent to adjust to the basis of an allowable loss of 14 percent.

b. Converting the modified value to a percent by volume basis using the density of the soil-cement mixture.

In a comparison of cement requirement values obtained by test with values obtained by the use of this procedure, the average deviation for the group of samples used in this study was 0.6 percent cement by volume, and considerably less than this for the more highly plastic soils of the group.

4. Admittedly, these results were obtained from a restricted number of samples and the procedure should be checked further with a wider and more representative selection of soils. Furthermore, use of the surface area determination to predict cement requirements should be accompanied by compressive strength or other tests on small specimens made at and near the predicted cement requirement.

Appendix

Statistical Terms

The statistical terms employed in this study are as follows:

Correlation coefficient (r): A term which indicates the degree of association or relation between the measured values of one property and the corresponding measured values of another property, for a specified group of samples. This term varies from 1.0, indicating that a perfect functional relation exists and that one property could be predicted with absolute accuracy from knowledge of the other, to zero, which indicates a complete lack of relation between the two properties. If the relation is direct, i.e. if one property increases with increase in the other, the correlation coefficient is positive; if the relation is inverse, i.e., one property decreases with increase in the other, the correlation coefficient is negative. Generally, a correlation coefficient above 0.9 is required for the correlation to be good enough to permit predictions of one value from the other with a reasonable degree of accuracy.

Statistical Significance Level of Correlation Coefficient

This is a measure of the probability that so large a correlation coefficient as has been computed from the data could arise by pure chance sampling from a population in which there is in fact no correlation. A 0.1 percent or even a 1 percent significance level indicates that a correlation almost certainly does exist.

Regression equation: If a linear correlation exists between two properties of a group of samples, and a plot is made of property "Y" vs property "X" for all samples of the group, an array of scattered points results. A straight line may be drawn through the scattered points in such a way that it best fits the data, using as the criterion of "best fit" that the sum of the squares of the deviations of all of the points from the line is at a minimum. The equation of this line is called the regression equation, and its use permits the best estimate of values of property "Y" to be made from measured values of property "X".

Standard error of estimate (Sy): This is a measurement of deviation or degree of scatter of the points around the regression equation line. It has the same dimensions as the dependent variable, Y, and it provides an estimate of the uncertainty of the prediction of Y from X by means of the regression equation. If the normal distribution of errors hold, 19 out of 20 samples should fall within two standard errors of the regression equation line, and 997 out 1,000 within three standard errors.

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