SIMPLIFIED SOIL-CEMENT MIX DESIGN METHOD FOR ALBERTA SANDS

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Because the conventional procedures for soil-cement mix design are usually quite time-consuming, a simplified method utilizing both 7-day unconfined compressive strength and freeze-thaw loss is proposed. The method is based on an analysis of mix design data collected on more than 100 sources of sand found in Alberta and used for soil-cement base construction. Unconfined compressive strength and freeze-thaw loss at 7 days, tested according to local procedures, have been related to cement requirements for various sands by use of granulometric and density considerations. Least squares fit and linear regression methods have enabled charts to be prepared indicating cement requirements for desired levels of unconfined compressive strength and freeze-thaw losses for various density ranges. The charts developed are considered useful for initial selection of cement requirements for various sands or for adjustments during construction. Although the analysis has been based on local data, more widespread application may be possible.

•CONVENTIONAL laboratory techniques following AASHO, ASTM, or PCA procedures for the mix design of soil-cement are widely used all over the world. Those techniques are modified depending on the climatic conditions and other relevant factors of the locality. The large amount of mix design data accumulated and the experience gained through years with the use of soil-cement could make it possible to derive short-cut methods such as those proposed by PCA (1) or more recently by Kemahlioglu, Higgins, and Adam (2). These methods help in cutting down the normal testing time. Because the methods are derived from statistical analysis of the data of standard procedures, they could be expected to be fairly reliable for the particular local circumstances. The simplified method proposed in this paper is one such method.

Although construction of soil-cement bases was initiated in Alberta in 1953, only since 1959 has construction taken place on a larger scale. Between 1959 and 1968, about 800 two-lane miles of this type of pavement were built on the provincial highway system. Primarily the extensive use of soil-cement base construction in Alberta has been brought about by the depletion of available gravel sources used in standard base construction and the extension of highway surfacing into regions that are void of suitable gravels (3). Large deposits of sand, for use in place of gravel, are available throughout many parts of the province and the utilization of these sand deposits provides substantial savings in haul costs.

Conventional procedures of ASTM and AASHO for soil-cement mix design are generally used with certain modifications. Experience with the sandy soils in Alberta reveals that the wet-dry test does not govern the cement factor and, therefore, is not included in the design procedure. The freeze-thaw test is considered to be a governing criterion for cement content of soil-cement mixes. The effects of freeze-thaw on soil-cement specimens were compared by molding 2 sets of specimens at varying cement contents and at optimum moisture and maximum standard Proctor density. That is, 9 specimens were formed for "control" compressive strengths and were broken after 7 days of curing in ideal moist conditions. The remaining 9 specimens were subjected to 12 freeze-thaw cycles after 7 days of curing in ideal moist conditions. A freeze-thaw cycle was a period of 24 hours at a constant temperature of -10 F, during which the specimens were permitted to absorb water through the base they were set on, and a period of 23 hours at a temperature of 70 F and 100 percent humidity. The freeze-thaw specimens were brushed by means of a calibrated wire brush only after the final cycle (this is not in accordance with standard ASTM procedures). Generally, 2 to 3 percent of loss due to freezing was considered acceptable. The percentage of loss was computed by determining the quantity of material brushed from the specimens and calculating as a percentage of the dry weight of the specimen.

An extensive evaluation and testing program has been conducted by the Department of Highways and by the Alberta Cooperative Highway Research Program since inception of this type of construction within the province. Design data consisting of the sand source pit numbers, gradations, cement contents, compressive strengths (psi at 7 days, at 28 days, and after 7 days of freeze-thaw), average density (lb/ft^3), and freeze-thaw loss (percent) are available for each of the mix designs.

An analysis has been made of the design data of more than 100 sand sources so that design charts, could be prepared and used to estimate the cement requirements of any sand in the province for stabilization. Such charts permit realistic adjustments to the construction cement contents without much field testing (4). The analysis was made on granulometric and on density considerations.

GRANULOMETRIC CONSIDERATIONS

The grain size characteristics of the sands were determined with a sieve series in which the diameters of successively smaller sieve openings decreased by one-half. The relative surface area per unit weight of spherical particles having the same specific gravity varied inversely with the diameter of the particles. Therefore, the surface area per gram of sand retained within a given sieve interval of the sieve series may conveniently be assumed to be double that of the previous coarser sieve interval. The grading modulus was calculated from the sum of the products of the percentage of the weight retained in each sieve interval and the corresponding surface area factor, divided by 100.

Larnach (5) has shown that the unconfined compressive strengths developed by a sand stabilized with portland cement may be defined by Feret's strength law:

$$S = A(C/V)^N$$

where S is the unconfined compressive strength psi, A is essentially the strength of the cement but is influenced by material and packing, C is the absolute volume of cement, V is the absolute volume of voids in the sand, and N is a constant depending on material and geometrical factors. Hutchinson (6) attempted a graphical model of shear strength development and based it on triaxial tests carried out on 11 sands. His analysis indicated that the factor N was related to the grading modulus GM by the relationship $N = 3.373 - 1.131 \log_{10} GM$, and the factor A, presumably dependent also on cement type and curing environment, was related by $A = 1{,}054 N^{2.341}$.

In this study the representative soil-cement design data from 100 sand sources were arranged into various groups of grading modulus at a regular interval of 5. In these data, the unconfined compressive strengths developed by each sand at 7 days can be defined by Feret's equation that was fitted to the experimental data for each sand according to the least squares criterion. The values obtained for A and N did not seem to have any trend with respect to the grading modulus of the sand.

The compressive strength values at 7 days and the corresponding C/V values of all sands lying in a grading modulus range were fitted by the least squares criterion, and the A and N values for groups together with correlation coefficients are given in Table 1. Even now, careful examination of the tabulated values shows that the values of neither N nor A indicated any definite trend with respect to the grading modulus. However, by least squares fit, the values of A and N were related by $A = 3{,}626 N^{2.82}$ with a correlation coefficient of 0.9736. Contrary to what was reported by Hutchinson, N and GM were not related at all.

The erratic behavior of A and N with respect to the grading modulus may be explained as follows: In Feret's strength law, A is defined as essentially the strength of the cement but as being influenced by the material and packing. Grading modulus, obviously, does not reflect either of these characteristics. N is said to be a constant depending on material and geometrical factors. It is doubtful whether the grading modulus takes care of the geometrical factors like shape, surface texture, and so on. Therefore, the granulometric properties of the sands, as defined in terms of the grading modulus, are not satisfactory. The grading modulus is not a clear reflection even of the grading of a material because of the weightage factors given for the different sieves. According to the definition, grading modulus is highly susceptible to the percentage of materials passing sieves No. 50, No. 100, and No. 200 inasmuch as the weightage factors for those sieves are high. A low grading modulus may only mean coarse aggregate, and a high GM may mean more of finer fractions. A well-graded material will have an intermediate value of GM. Two different materials having the same GM may not have the same grading. Therefore, GM that is not truly representative of the gradation cannot be a satisfactory criterion for assessing the development of unconfined compressive strength of soil-cement mixtures.

DENSITY CONSIDERATIONS

Housel (7), Catton (8), Felt (9), and many other investigators have shown that maximum density of soil-cement is a significant factor in the design and performance of soil-cement construction, and it is also generally accepted that a densely compacted material has necessarily high compressive strength. Housel further stated that the consistent relation between density and mechanical analysis is yet another important factor. Variation in texture and grading is quite accurately reflected in the compacted density that gives a measure of the total void content in the mix. The variation in the density can be assessed from a comparison between the ideal gradings and the actual grading, and this is facilitated by the BPR gradation chart (10). (Numerous plots have been prepared and are included in another report (4) but not in this paper.) The BPR chart enables the plotting of the gradations of the different sands and provides at the same time a comparison with the theoretical maximum density grading corresponding to the particular maximum size of the particle of the sand under consideration. The sands that have their gradations farther away from the maximum density line result in low densities; those that lie nearest give high densities. These plots clarify further the fact that the grading modulus does not reflect either the grading or the density.

With the thought that, rather than the GM, the density obtainable with a particular sand would be a more reliable reflection of the grading, we regrouped the soil-cement data on the basis of density ranges.

Relation Between Unconfined Compressive Strength and C/V Values

The 7-day unconfined compressive strength values and the corresponding C/V values of all sands lying in a density range were fitted by least squares criterion, and the A and N values for groups together with the correlation coefficients are given in Table 2. In 5 groups out of the 7 density groups the value of N has a definite trend with respect to density, whereas in 2 groups it is erratic. A term defined as the logarithm of mean density has been used to relate N to density. For the 5 groups, a relation of the form $N = 8.26 \log_{10} (\text{mean density}) - 15.59$ could be established with a correlation coefficient of 0.9750, a standard error of 0.0436, and a modified standard error of 0.0563. The 5 pairs of values of A and N were related by least squares criterion that resulted in the equation $A = 3{,}672\ N^{2.77}$ with a correlation coefficient of 0.9798, a standard error of 1,066, and a modified standard error of 1,376. These 2 relationships were combined to prepare a graphical model (Fig. 1) relating the unconfined compressive strengths to values of C/V for various densities.

Table 1. Unconfined compressive strength and C/V values based on grading modulus.

Group	GM Range	Sand Source Numbers in Group	Group Values		Number of Data Points	Coefficient of Correlation
			N	A		
1	7.6 to 12.5	23, 121, 123, 159, 77, 46	1.060	3,511	18	0.6383
2	12.6 to 17.5	61, 107, 55, 80, 103, 29, 122, 125	1.376	6,277	24	0.6253
3	17.6 to 22.5	101, 89, 203, 64, 62, 99, 106, 69	1.637	14,668	29	0.8599
4	22.6 to 27.5	49, 91, 160, 32, 114, 35, 120	2.302	43,987	21	0.8014
5	27.6 to 32.5	96, 22, 119, 124, 118, 78, 116, 72, 100, 141, 82	1.644	15,282	36	0.9605
6	32.6 to 37.5	47, 63, 93, 95, 108, 145, 53, 71, 41, 75, 102, 204, 28, 143, 140	1.339	7,186	50	0.8540
7	37.6 to 42.5	81, 43, 110, 115, 92, 60, 166, 87, 147, 67, 88, 83, 57, 74, 76	1.398	9,116	46	0.8814
8	42.6 to 47.5	48, 34, 207, 79, 56, 149, 54, 36, 84, 65, 50, 112	1.596	14,932	41	0.9630
9	47.6 to 52.5	70, 94, 33, 90, 104, 44	1.276	6,379	25	0.8879
10	52.6 to 57.5	109, 113, 86, 105, 66	1.099	4,713	17	0.8553
11	57.6 to 62.5	68, 45, 155, 30, 42	1.488	9,753	16	0.9744
12	62.6 to 67.5	97	0.8450	2,618	3	0.9929
13	67.6 to 72.5	167, 209, 152, 206	0.8670	3,261	13	0.9137
14	72.6 to 77.5	40, 117, 39	1.223	6,719	10	0.9337
15	77.6 to 82.5	98, 85	1.143	4,920	6	0.9796
16	92.6 to 97.5	38	1.667	20,112	3	0.9999

Table 2. Unconfined compressive strength and C/V values based on density.

Group	Density Range	Sand Source Numbers in Group	Group Values		Log Mean Density	Number of Data Points	Coefficient of Correlation
			N	A			
1	101 to 105	54, 95, 167	0.9870	3,858	2.0128	11	0.8902
2	106 to 110	33, 38, 40, 57, 85, 94, 105, 155, 206	1.2260	6,341	2.0334	31	0.9060
3	111 to 115	28, 30, 32, 35, 36, 39, 42, 44, 50, 53, 77, 86, 89, 91, 97, 98, 104, 106, 113, 117, 143, 152, 204, 207	1.4350	8,582	2.0531	75	0.6989
4	116 to 120	23, 34, 43, 45, 48, 49, 60, 63, 64, 65, 67, 68, 69, 71, 72, 74, 75, 76, 79, 80, 81, 88, 90, 92, 99, 102, 103, 118, 119, 124, 140, 141, 145, 147, 160, 209	1.5660	11,663	2.0719	122	0.8176
5	121 to 125	29, 46, 47, 55, 61, 66, 70, 83, 84, 87, 93, 96, 100, 109, 110, 112, 114, 115, 116, 120, 166	1.1670	5,112	2.0899	71	0.6894
6	126 to 130	22, 56, 62, 78, 82, 101, 159	1.7830	21,579	2.1072	23	0.9809
7	131 to 135	41, 107, 108, 121, 122, 123, 125, 203	1.3790	10,163	2.1239	25	0.9327

The strength values are higher for low density than for high density groups for the same value of C/V, up to C/V values of 0.14 to 0.15. For C/V values beyond 0.15, the higher the density is, the greater is the compressive strength for the same value of C/V. The trend is more and more distinct with increasing values of C/V. This can be explained by the fact that the factor C/V takes care of both cement content and density of a soil-cement mixture. The percentage of cement content is higher in low density groups than in high density groups at the same value of C/V and, hence, the strength is higher. (The variation in the density with cement is assumed to be negligible in this connection.)

Relation Between Unconfined Compressive Strength and Cement Content

In the previous analysis, it is clear that C/V covers the 2 variables in a soil-cement mix, namely, cement content and density. Because all the data had been grouped by density ranges, a study of the direct relationship of strength to the cement content seemed appropiate. Coefficients were computed by linear regression for the relation between 7-day unconfined compressive strength and the cement content and are given in Table 3. A design chart was prepared (Fig. 2) that relates the unconfined compressive strength with the cement content for various density ranges. For low density ranges, particularly from 100 to 115 lb/ft^3, the increase in strength with increase of cement content is not significant, whereas the variation is more significant for density ranges from 115 to 125 lb/ft^3. In the high density range of 125 to 135 lb/ft^3 the increase in strength for any increase in cement content is highly significant.

Relation Between Freeze-Thaw Loss and Cement Content

Experience with the sandy soils used in Alberta has caused the freeze-thaw test to be a governing criterion for cement content of soil-cement mixes (3). Circeo, Davidson, and David (11) reported that a strong logarithmic relationship was found to exist between the cement content and the freeze-thaw loss of a soil-cement mixture. By correlation, they established that 2 freeze-thaw tests would reveal the logarithmic relationship for any soil type. The data for cement content by weight and freeze-thaw losses for each density range were analyzed by correlation analysis and are given in Table 4. From this analysis, a chart was developed (Fig. 3) relating the cement content and freeze-thaw losses for the different density ranges so that the cement content needed for a specified freeze-thaw loss for any sand producing a particular density could be read. The variation in cement requirements for density ranges from 101 to 125 lb/ft^3 is not very significant.

CEMENT CONTENT REQUIREMENTS OF VARIOUS SANDS

The Portland Cement Association has suggested that a study of the strength data is of particular value in the selection of cement contents for investigation. The Associations handbook states, "generally, a soil-cement mixture having a compressive strength that is approximately 300 $lb/in.^2$ or more at 7 days, and is increasing, will pass the wet-dry and freeze-thaw tests satisfactorily" (1). Later research shows that strength requirements may vary from 300 to 800 psi for acceptable durability; however, the cement content for the 300 psi has been determined for comparison purposes.

Dacyszyn (3) stated that generally 2 to 3 percent of freeze-thaw loss is acceptable for soil-cement mix design. Based on these 2 criteria, the cement requirements of the sands analyzed have been taken from charts shown in Figures 2 and 3 and are given in Table 5. The actual recommended average cement contents have also been extracted from designs of the Department of Highways of Alberta (DHA) and are tabulated for comparison. It is observed that the cement requirement from the consideration of freeze-thaw loss is usually more than that needed to produce an unconfined compressive strength of 300 psi at 7 days. The recommended cement contents of the DHA are found to be quite in agreement with those suggested by the charts except in one density range, 131 to 135 lb/ft^3. This was probably due to the fact that the DHA recommendation was for

Figure 1. Strength versus C/V values for different densities.

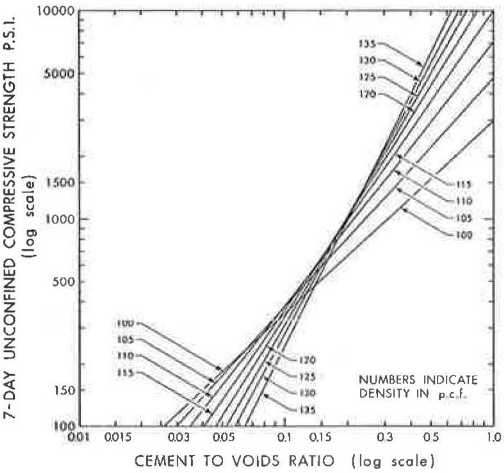

Figure 2. Strength versus cement content for different densities.

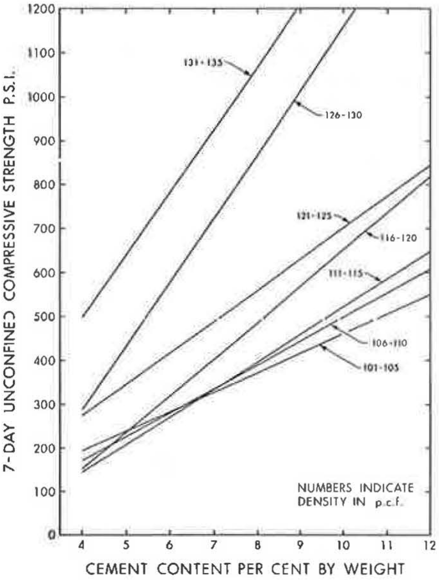

Table 3. Unconfined compressive strength and cement content based on density.

Group	Density Range (lb/ft^3)	Sand Source Numbers in Group	Slope	Intercept	Number of Data Points	Coefficient of Correlation	Coefficient of Determination	Standard Error of Estimate
1	101 to 105	54, 95, 167	44.64	14.19	11	0.8855	0.7830	56.38
2	106 to 110	33, 38, 40, 57, 85, 94, 105, 155, 206	54.93	-48.58	31	0.9187	0.8420	51.65
3	111 to 115	28, 30, 32, 35, 36, 39, 42, 44, 50, 53, 77, 86, 89, 91, 97, 98, 104, 106, 113, 117, 143, 152, 204, 207	62.72	-103.03	75	0.7174	0.5140	118.28
4	116 to 120	23, 34, 43, 45, 48, 49, 60, 63, 64, 65, 67, 68, 69, 71, 72, 74, 75, 76, 79, 80, 81, 88, 90, 99, 102, 103, 118, 119, 124, 140, 141, 145, 147, 149, 160, 209	83.78	-184.46	122	0.8019	0.6430	130.74
5	121 to 125	29, 46, 47, 55, 61, 66, 70, 83, 84, 87, 93, 96, 100, 109, 110, 112, 114, 115, 116, 120, 166	71.83	-14.78	71	0.7174	0.5140	147.03
6	126 to 130	22, 56, 62, 78, 82, 101, 159	145.93	-295.37	23	0.9885	0.9760	49.64
7	131 to 135	41, 107, 108, 121, 122, 123, 125, 203	143.06	-72.54	25	0.8202	0.6720	191.22

Table 4. Freeze-thaw loss and cement content based on density.

Group	Density Range (lb/ft³)	Sand Source Numbers in Group	Slope B	Intercept A	Number of Data Points	Coefficient of Correlation	Coefficient of Determination	Standard Error of Estimate	
								Log C	Cement Content
1	101 to 105	54, 95, 167	-0.2070	0.9430	10	-0.9636	0.9285	0.0360	1.086
2	106 to 110	38, 40, 57, 85, 94, 105, 155, 206	-0.1687	0.9675	27	-0.7758	0.6018	0.0779	1.196
3	111 to 115	28, 30, 32, 35, 36, 39, 42, 44, 50, 53, 77, 86, 89, 91, 97, 98, 104, 106, 113, 117, 143, 152, 204, 207	-0.1951	0.9585	70	-0.8610	0.7413	0.0497	1.121
4	116 to 120	23, 34, 43, 45, 48, 49, 60, 63, 64, 65, 67, 68, 69, 71, 72, 74, 75, 76, 79, 80, 81, 88, 90, 92, 99, 102, 103, 118, 119, 124, 140, 141, 145, 147, 149, 160, 209	-0.2031	0.9148	116	-0.8539	0.7291	0.0619	1.153
5	121 to 125	29, 46, 47, 55, 61, 66, 70, 83, 84, 87, 93, 96, 100, 109, 110, 112, 114, 115, 116, 120, 166	-0.1881	0.8918	66	-0.8237	0.6784	0.0730	1.183
6	126 to 130	22, 56, 62, 78, 82, 101, 159	-0.2561	0.8002	23	-0.8936	0.7985	0.0705	1.176
7	131 to 135	41, 107, 108, 121, 122, 123, 125, 203	-0.2552	0.7487	23	-0.8036	0.6457	0.1139	1.300

Figure 3. Freeze-thaw loss versus cement content for different densities.

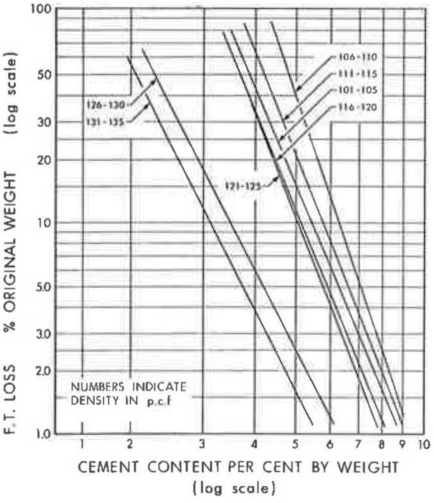

Table 5. Recommended cement content requirements.

Group	Density Range (lb/ft³)	300-psi, 7-Day Compressive Strength	2 to 3 Percent Freeze-Thaw Loss	Average DHA Design
1	101 to 105	6.5	7.0 to 7.7	8.67
2	106 to 110	6.5	7.8 to 8.3	8.2
3	111 to 115	6.5	7.3 to 8.0	8.03
4	116 to 120	5.65	6.6 to 7.2	6.92
5	121 to 125	4.2	6.4 to 6.9	6.41
6	126 to 130	4.1	4.8 to 5.3	5.3
7	131 to 135	under 4	4.3 to 4.75	3.72

cement-treated bases in which case the specification would be less rigorous.

The densities used in the development of the charts are laboratory densities, and, because the cement contents suggested by the charts are based on these, they will be valid only in case the field densities are almost the same as laboratory densities; otherwise, the cement contents have to be adjusted to the density attained.

USE OF THE CHARTS AND THEIR LIMITATIONS

For any particular sand, if the laboratory density can be determined, the cement content required for a specified permissible freeze-thaw loss can be determined from the chart shown in Figure 3. The unconfined compressive strength that is expected to be developed can be read out from the chart shown in Figure 2 at the cement content indicated earlier. Thus, the charts could enable realistic adjustments to the construction cement contents without much field testing in the event of major changes in grading developing.

Although the analysis has been based on actual mix design data of the Department of Highways of Alberta and can be considered to be a reliable guide for quick field adjustments, it has certain limitations. Anderegg (12), in discussing the factors affecting the development of compressive strength, stated that the amount of cement hydrated, the properties of the aggregate including especially the surface condition, the workability of the mix, and the keying effect of the large particles are all factors important in the order cited. Felt (9) stated that sandy soils, too, may react differently with cement depending on their chemical makeup and surface chemical properties. Another important factor that has pronounced influence on the physical properties of soil-cement mixtures is the water added. Because some of these factors could not be considered in the analysis, the charts developed have their limitations.

CONCLUSIONS

The following conclusions have been drawn from this study:

1. The grading modulus of a sand is not a reliable criterion for the design of soil-cement mixes;
2. The sand density attainable provides a useful parameter for estimating the cement requirements for various sands;
3. The BPR gradation chart gives a comparative assessment of the density attainable with a particular sand, when the gradation of the sand is plotted on the chart;
4. The charts developed from the analysis contained in this paper are useful for quick adjustments of the construction cement contents without much field testing, are particularly useful for the Alberta sands, and may have general application even for other areas if similar charts are developed; and
5. The use of this method results in a decrease in testing time to about 2 days, which is only the time needed for the Proctor density tests on the sand concerned.

ACKNOWLEDGMENTS

This paper is based on soil-cement mix design data collected for a project of the Alberta Cooperative Highway Research Program sponsored by the Department of Highways of Alberta, the Research Council of Alberta, and the Department of Civil Engineering of the University of Alberta. Special acknowledgment is due B. P. Shields for his helpful suggestions and for making data available for analysis.

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