Relationship Between Cement Content And Freeze-Thaw Loss of Soil-Cement Mixtures

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Although the freeze-thaw test was originally devised to measure the hardening effect of portland cement on soils, it has become useful as a reliable criterion for the determination of the durability of a soil-cement mixture. One great disadvantage of this test is the large amount of labor necessary to complete the freeze-thaw test. This paper attempts, by correlation analysis, to reduce the amount of testing required to conduct a reliable freeze-thaw evaluation of a soil-cement mixture.

A strong logarithmic relationship was found to exist between the cement content and the freeze-thaw loss of a soil-cement mixture. Two freeze-thaw tests will establish the logarithmic relationship for any soil type. From this relationship the cement content that will produce a satisfactory freeze-thaw loss could be accurately determined.

An analysis of the logarithmic relationships for all soils used in this investigation indicated a linear relationship between the slopes and intercepts of the relationships. Theoretically this would indicate a common point through which all relationships would pass. This was found applicable for A-1 through A-4 soils. For these soils one freeze-thaw test is sufficient to establish the logarithmic relationship and thereby determine the cement content required to produce a durable soil-cement mixture.

The slope of the logarithmic relationship was found to be independent of the number of cycles used to conduct the freeze-thaw test. A logarithmic relationship at a reduced number of cycles could be indicative of the possibility of reducing the number of cycles needed to conduct the freeze-thaw test with no loss in the significance of the test.

By the use of these relationships the labor involved in the conduct of the freeze-thaw test can be reduced. The accurate determination of the cement content required to produce a specified freeze-thaw loss will result in more economical mix design of soil-cement mixtures.

• THE cement content required to stabilize a soil adequately will usually determine the economic feasibility of cement stabilization. A soil-cement mixture can be considered to be adequately stabilized if it meets specified design criteria of strength and durability. There are several shortcut methods used to evaluate the required cement content; however, for major projects a complete series of detailed tests is

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usually necessary. These tests include compressive strength evaluation, wet-dry and freeze-thaw tests.

Compressive strength tests are usually supplementary to the wet-dry and freeze-thaw tests. An adequately hardened soil-cement mixture will increase in compressive strength with time of curing. Generally an increasing unconfined compressive strength of 300 psi or more at 7 days will pass the wet-dry and freeze-thaw tests satisfactorily (3).

The wet-dry and freeze-thaw tests are usually considered indicative of the durability of soil-cement mixtures. The wet-dry test produces high shrinkage stresses; the freeze-thaw test produces high expansive stresses. These tests were developed to introduce destructive forces which a soil alone could not withstand, but which a structural material would resist. Thus, they are more valuable in analyzing a soil-cement mixture as a structural material rather than as a criterion of durability. The adequacy of a soil-cement mixture as a structural material would also confirm its ability to withstand weathering (1).

The freeze-thaw test is generally the critical test in determining the required cement content except for mixtures containing relatively large amounts of silt and clay. For other mixtures than these, it is standard practice to mold only one wet-dry specimen at the median cement content, while a freeze-thaw specimen for each cement content investigated is usually molded (3). Thus the freeze-thaw test is the major test in evaluation of a soil-cement mixture, requiring considerable time and labor to conduct.

The freeze-thaw test is, by its nature, very subjective. Individual brushing techniques can cause a wide variance in the results of the test. A relationship between the cement content and the freeze-thaw loss would serve to reduce the error which is inherent in the test.

CEMENT FREEZE-THAW LOSS RELATIONSHIP

An investigation to develop a relationship between the cement content and the freeze-thaw loss of a soil-cement mixture was first considered. An excellent logarithmic relationship was observed using 172 sets of data taken from data sheets of the Portland Cement Association. Typical relationships for the soil types studied are shown in Figure 1. The r^2 correlation coefficients of the logarithmic relationships were evaluated by the IBM 650 digital computer. All r^2 correlation coefficients are extremely high (Appendix). Thus it appears that the cement content by weight can be related, to within good approximation, to the freeze-thaw loss of a soil-cement mixture by a logarithmic relationship.

The cement content by volume was also investigated. Good logarithmic relationships were also obtained; however, the cement content on a weight basis resulted in the best relationships. Although A-1 and A-5 soils were not investigated, it is believed that these would also follow a logarithmic relationship.

The logarithmic relationship is

$$\log C = A + B \log L \tag{1}$$

in which

C = cement content,
L = freeze-thaw loss,
A = intercept, and
B = slope.

Using this relationship, the cement content which will give the maximum allowable freeze-thaw loss can be chosen. Normally, soil-cement mixtures with at least three cement contents are tested. A logarithmic plot may be constructed with these data. The relationship will reduce the error caused by any possible outliers in the data, reducing the possibility of arriving at erroneous conclusions.

Another advantage of this relationship is the reduction of the necessary number of cement contents to be tested. An experienced tester could conduct the freeze-thaw test

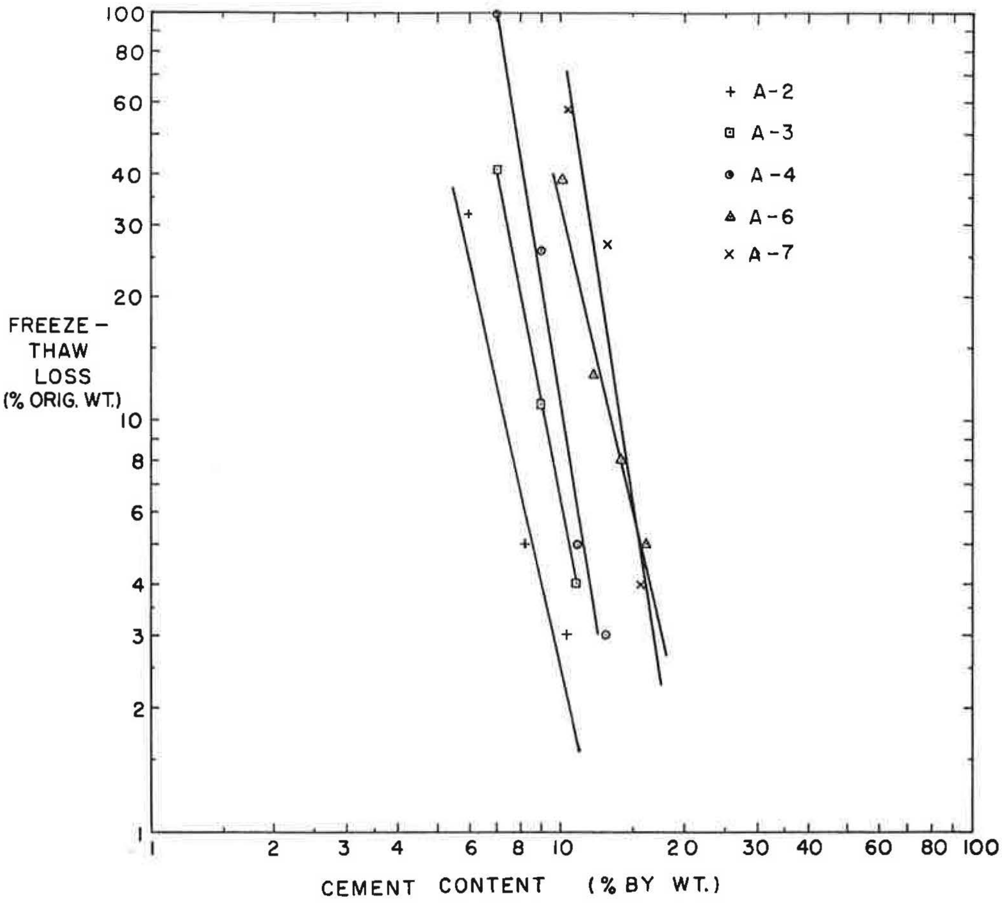

Figure 1. Relationship between the cement content and the freeze-thaw loss of soil-cement mixtures.

with 2 cement contents. A logarithmic plot connecting these points would establish the relationship. The cement content which will give the required freeze-thaw loss may then be determined. It is best to obtain data that will fall on either side of the specified freeze-thaw loss. An experienced tester should be able to choose cement contents which produce these results most of the time.

The ability to select the exact cement content to produce a specified freeze-thaw loss will result in more economical mix designs. Many soils have recommended cement contents which produce 2 percent freeze-thaw loss because the next lower cement content tested had a freeze-thaw loss greater than the allowable. The logarithmic relationship would indicate a cement content between these two. This intermediate cement content might be considered adequate for the particular soil-cement mixture.

All cement contents below the one that will produce 100 percent freeze-thaw loss will also indicate 100 percent loss. In the same manner, all cement contents greater than the one which will give little or no freeze-thaw loss will also produce no freeze-thaw loss. A relationship passing through 100 percent freeze-thaw loss and/or 0 percent loss might lead to erroneous conclusions. Therefore a relationship connecting points between these extremes is recommended.

SLOPE-INTERCEPT RELATIONSHIP

An analysis of the equations obtained for the cement freeze-thaw relationship was undertaken. A linear relationship was found to exist, approximately, between the slope (B) and the intercept (A) of the equations (Fig. 2). The granular soils tend to lie along the lower edge of the scatter diagram (i.e., parallel to the axis of scatter), with a transition to the fine-grained soils at the upper edge.

The line which best represents this scatter diagram can be represented by

$$A + 1.118\ B = 0.62 \tag{2}$$

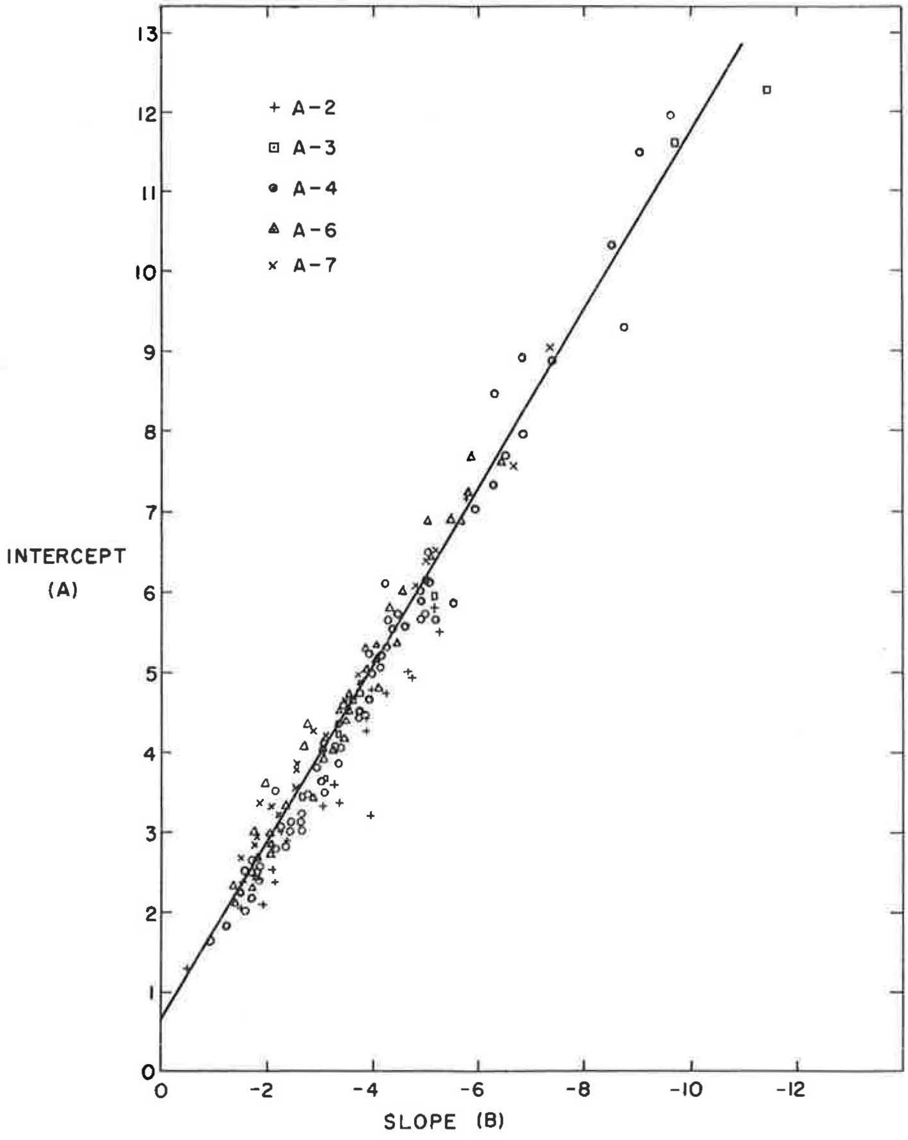

Figure 2. Relationship between slope and intercept of logarithmic cement-freeze-thaw relationships.

TABLE 1

THEORETICAL COMMON INTERSECTION OF LOGARITHMIC FREEZE-THAW RELATIONSHIPS BY SOIL TYPE

Soil Type	Common Intersection	
	Cement (%)	Freeze-Thaw Loss (%)
A-2	12.2	2.0
A-3	13.0	2.8
A-4	13.0	2.8
A-6	13.0	5.0
A-7	12.0	10.2

From this equation it can be seen that any point on the line (an individual cement freeze-thaw relationship) is equal to a constant; thus,

$$A_1 + 1.118\, B_1 = A_2 + 1.118\, B_2 = \ldots = A_n + 1.118\, B_n \qquad (3)$$

Theoretically this would indicate that all logarithmic cement freeze-thaw relationships would pass through a common point. This point is at C = 1.118 and L = 0.62. On the logarithmic scale: C = 12.5 percent cement and L = 4.2 percent freeze-thaw loss.

In Table 1, the common intersection increases in the percent freeze-thaw loss as the clay content increases. A soil-cement mixture requiring a cement content greater than the cement coordinate of the common intersection would have to assume a positive slope, making the relationship invalid. Therefore, the common intersection concept cannot be used with these soils. A-6 and A-7 soils have a usual cement requirement in the range of 9 to 16 percent (3). For the most part this common intersection would not be applicable for these soils. Therefore A-6 and A-7 soils were eliminated from this investigation.

A-2, A-3, and A-4 soils were then investigated to determine if this common intersection was applicable to the data. Inasmuch as the common intersections for these soil types are similar, an average intersection of C = 12.6 and L = 2.4 was assumed. Graphical analysis of the data indicated that the relationships passed through, or in the vicinity of, the intersection (Fig. 3).

Thus, with a common point through which all relationships of A-2, A-3, and A-4 soils pass established, only one freeze-thaw test is necessary to establish the relationship and select the required cement content to produce a durable soil-cement mixture. It is believed that A-1 soils will follow a similar relationship.

Analysis indicated that certain limitations should be placed on the data to obtain best results. The cement content of the freeze-thaw specimen should be below 9 percent cement. The freeze-thaw loss should fall below 50 percent soil loss and above the maximum allowable soil loss.

A comparison was made between the actual and predicted cement contents required to produce a durable soil-cement mixture (Appendix). For this investigation 10 percent freeze-thaw loss was considered the maximum allowable loss for all soil types. The actual cement content was determined by the logarithmic relationship using all data points. The predicted cement content was determined by the line from the data point in each set that had the lowest cement content, subject to the limitations, passed through the common intersection. The predicted values compare well with the actual cement content. Most predicted values are greater than the actual values, placing the prediction on the safe side. The actual and predicted cement contents compare favorably with those recommended by the PCA (Appendix).

A freeze-thaw test conducted with one cement content, subject to the prescribed limitations, would be sufficient to evaluate the required cement content properly. For any random soil it might be difficult to choose a cement content which would fall within the limitations; however, in the case of a soil series or soils where the cement content is approximately known, a cement content can be selected and the method used advantageously. For example, this method could be used in conjunction with the "shortcut test procedures for sandy soils" for major projects in order to determine better the required cement content. Although A-6 and A-7 soils were not investigated, this method might also be applicable for these soils which require low cement contents.

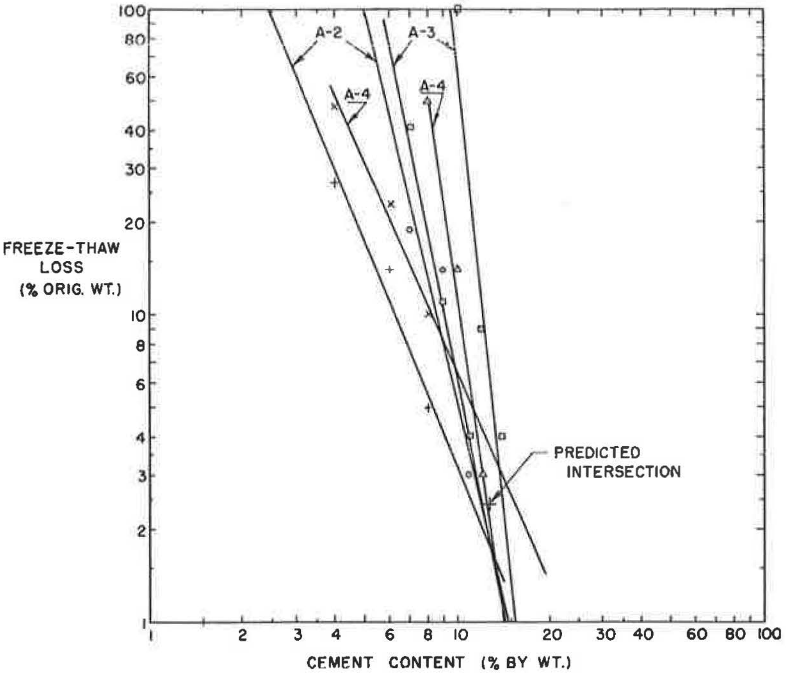

Figure 3. Ability of logarithmic cement freeze-thaw relationships of granular soil-cement mixtures to pass through the common intersection.

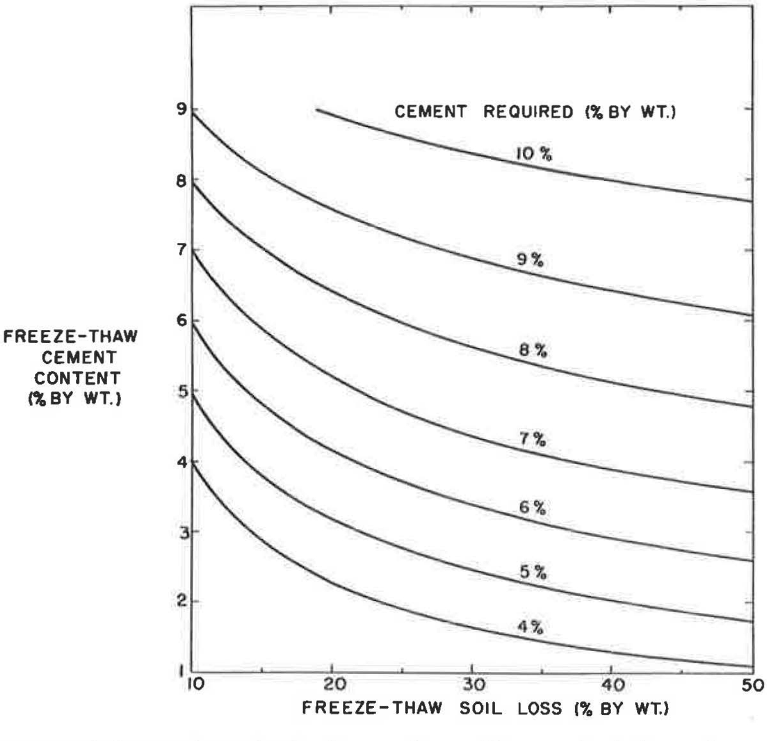

Figure 4. Recommended cement content of granular soil-cement mixtures by common intersection method.

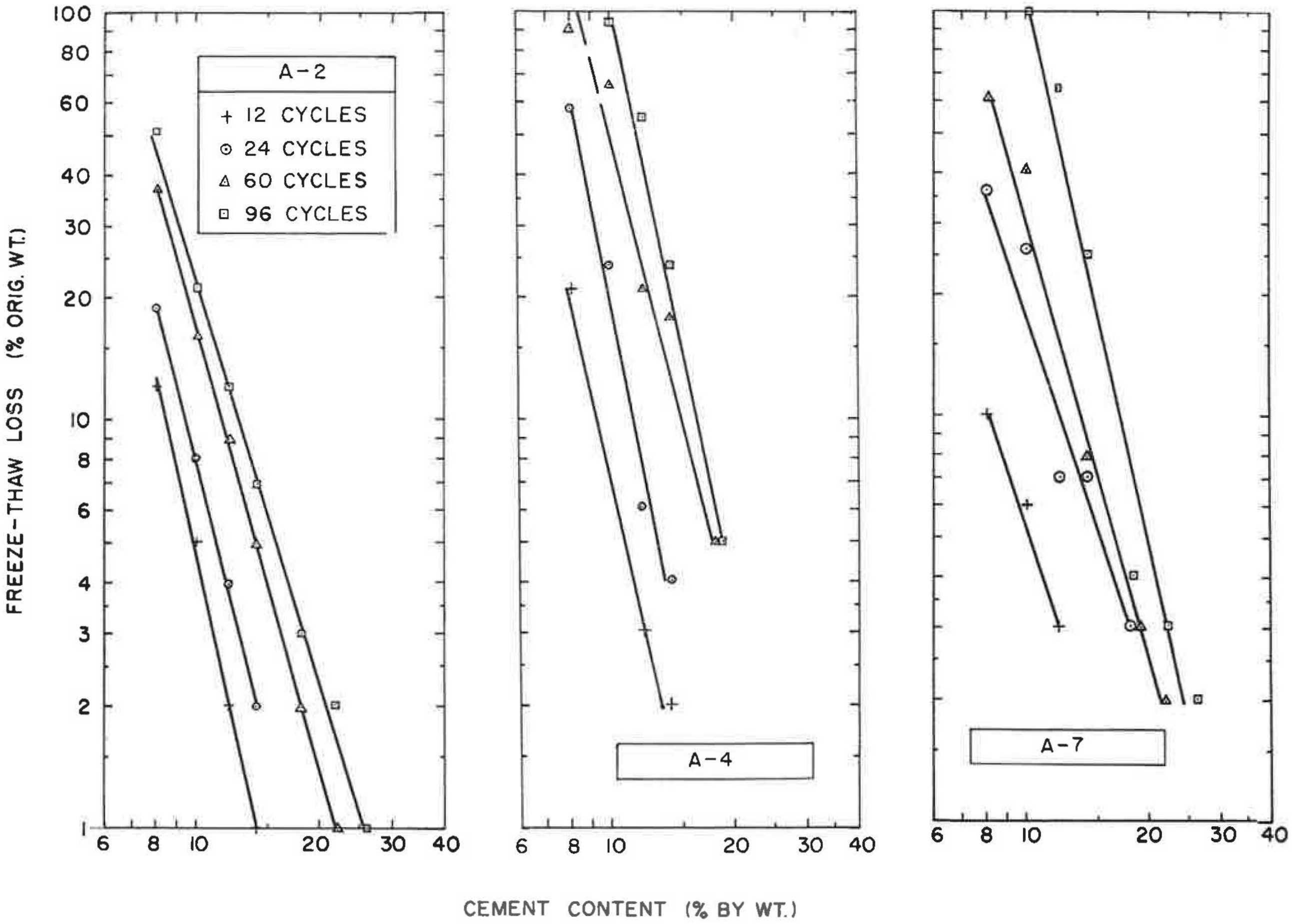

Figure 5. Effect of number of freeze-thaw cycles on logarithmic cement freeze-thaw relationship.

Figure 4 shows the selection of the required cement content with one freeze-thaw specimen at 10 percent freeze-thaw loss. Similar graphs can be constructed for other allowable losses. Safety factors are easily incorporated.

INFLUENCE OF NUMBER OF FREEZE-THAW CYCLES ON LOGARITHMIC RELATIONSHIP

An extensive investigation was undertaken by Felt (2) to observe the influence of cement content on freeze-thaw loss. Freeze-thaw tests from 12 to 96 cycles were conducted. These data were investigated to observe the influence of the number of freeze-thaw cycles on the logarithmic relationship.

The freeze-thaw test conducted at greater than 12 cycles will also produce an excellent cement freeze-thaw logarithmic relationship (Fig. 5). It seems that, as a first approximation, the relationships of each soil can be considered parallel, indicating that the slope of the logarithmic relationship is independent of the number of cycles used to conduct the freeze-thaw test.

The specifications for maximum allowable loss are 14 percent for A-2 soils, 10 percent for A-4 soils, and 7 percent for A-7 soils after 12 freeze-thaw cycles (3). It

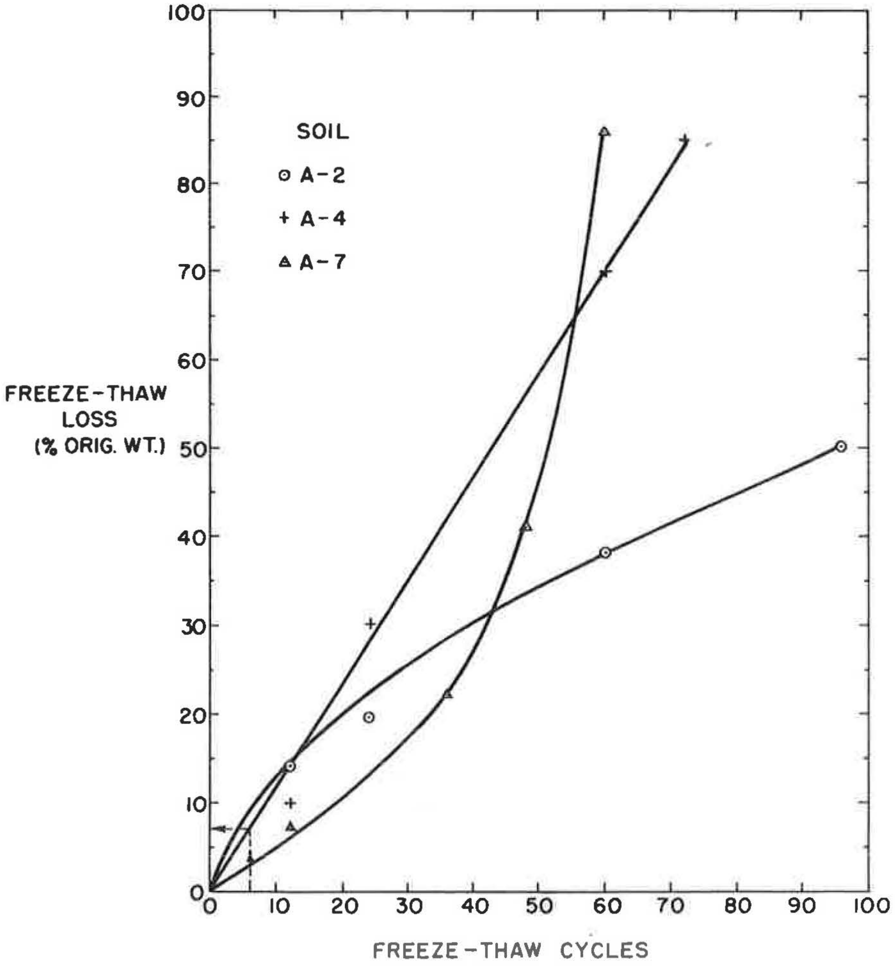

Figure 6. Effect of number of freeze-thaw cycles on maximum allowable freeze-thaw loss.

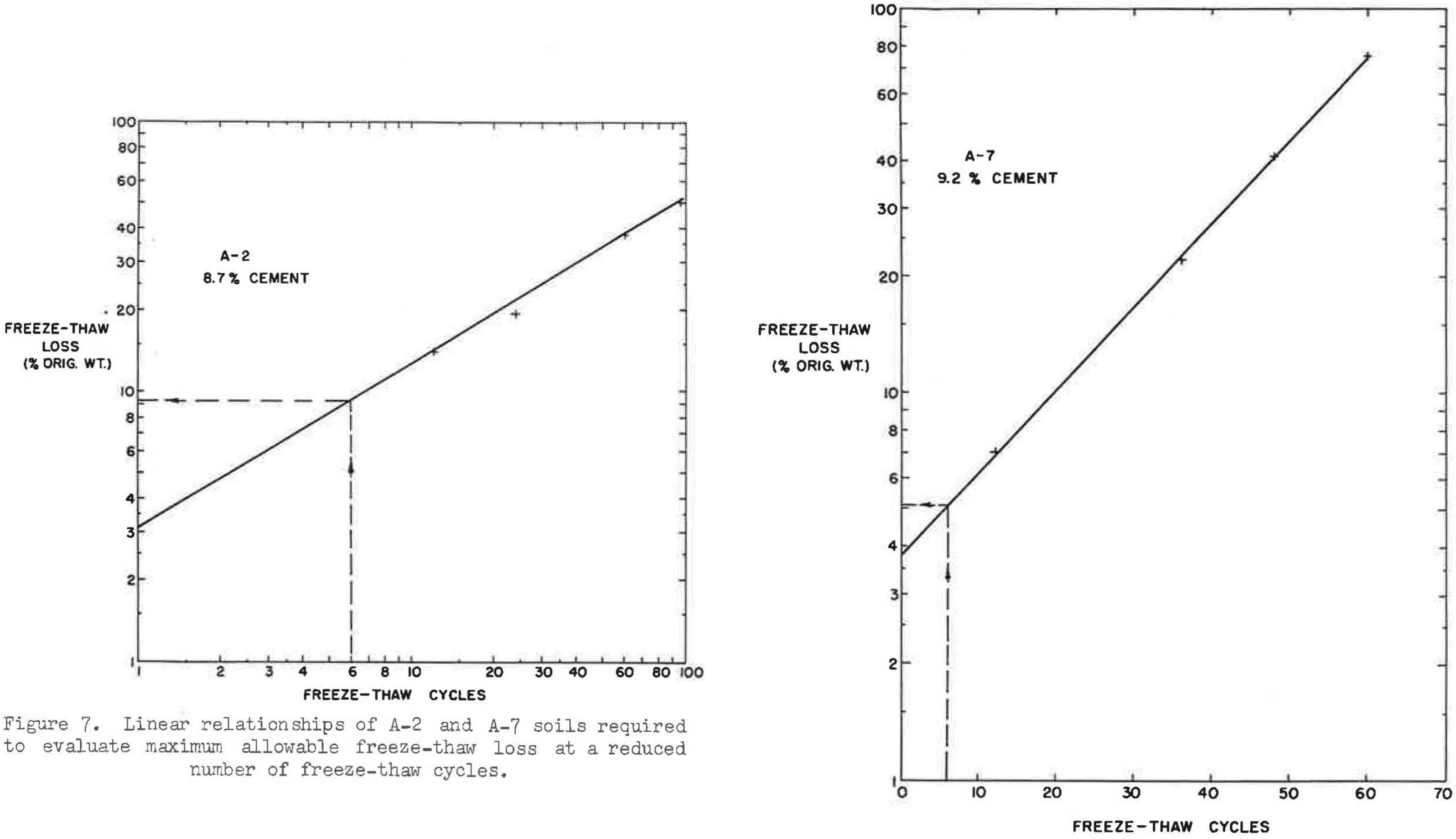

Figure 7. Linear relationships of A-2 and A-7 soils required to evaluate maximum allowable freeze-thaw loss at a reduced number of freeze-thaw cycles.

is apparent that the specifications for maximum freeze-thaw loss can be altered as the number of cycles are varied. For example, in the case of the A-2 soil, 14 percent freeze-thaw loss indicates a cement content of 7.9 percent cement. This cement content corresponds to 50 percent loss at 96 cycles. Thus if 96 cycles were used as the criterion in the freeze-thaw test, 50 percent loss would be considered the maximum allowable freeze-thaw loss.

Figure 6 plots the maximum freeze-thaw loss permitted as the number of cycles of the 3 soils are varied. There is transition in the shape of the curves from the sandy to clayey soils. The A-4 soil assumes a linear relationship; the A-2 soil becomes linear on a logarithmic scale; the A-7 soil becomes linear on a semilogarithmic scale (Fig. 7).

By the use of these linear relationships it should be possible to choose a maximum freeze-thaw loss at any number of cycles. This assumes that the relationship is valid at less than 12 cycles. This would be advantageous in developing a method to conduct the freeze-thaw test at a reduced number of cycles. For example, at 6 cycles of freeze-thaw the cement content for the A-2 soil could be evaluated at 9 percent freeze-thaw loss. In the same way the A-4 and A-7 cement contents could be evaluated at 7 percent and 5 percent freeze-thaw loss, respectively.

This reduction in the number of cycles would reduce by 50 percent the time required to conduct the test. A minimum number of cycles required to produce significant results could be determined. Further investigation is necessary to evaluate this theory properly for all soils.

CONCLUSIONS

This investigation indicates that the freeze-thaw loss of soil-cement mixtures follows certain approximately predictable paths. An approximate logarithmic relationship was found to exist between the cement content and the freeze-thaw loss of a soil-cement mixture. This relationship is useful for determining, approximately, the cement content which will produce the allowable freeze-thaw loss. Freeze-thaw tests with two cement contents will establish the relationship. When more than two cement contents are used, the relationship will obviate any outliers that might exist in the data, reducing the error inherent in this type of subjective testing.

The logarithmic relationships for A-2, A-3, and A-4 soil-cement mixtures were found, approximately, to intersect at a common point. It is conjectured that all granular soil-cement mixtures follow this rule. This can be of great value when properly applied. A granular soil for which the cement content (below 10 percent) is approximately known would require a freeze-thaw test with one cement content to establish the relationship and determine, to within reasonable approximation, the required cement content.

The slope of the logarithmic relationship was found independent of the number of freeze-thaw cycles. This introduces the possibility of conducting the freeze-thaw test at a reduced number of cycles.

By the use of the above methods the time and labor involved in the conduct of the freeze-thaw test can be greatly reduced, though a detailed analysis of the precision to be expected from these methods has not been conducted. The accurate determination of the cement content required to produce a specified freeze-thaw loss will result in more economical mix design of soil-cement mixtures.

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Appendix

Soil Type	r^2 Correlation Coefficient[a]	Cement Content (% by weight)		
		Actual[b]	Predicted[b]	PCA[c]
A-2	0.990	5.0	5.0	6.0
	0.999			
	0.981	6.8	8.0	7.1
	0.999	8.7	8.9	8.2
	0.950	7.6	8.3	7.0
	0.811	12.0	10.7	12.0
	0.999	6.2	6.3	6.1
	0.944	5.9	6.6	6.1
	0.793			
	0.953	7.8	7.8	7.8
	0.798			
	0.823	9.0	8.5	9.3
	0.916			
	0.998	7.8	7.5	7.4
	0.975			
	0.896			
	0.994	4.5	4.8	5.0
	0.986	3.8	5.0	4.6
	0.950	6.5	6.4	6.3
	0.996	5.1	5.9	5.4
A-3	0.992	7.3	7.5	7.9
	0.996	8.0	8.4	9.8
	0.987	9.7	10.5	10.6
	0.951			
	0.999	9.2	9.4	9.3
	0.947			
	0.999			
A-4	0.999	8.7	8.8	9.0
	0.949			
	0.846	6.8	7.5	8.7
	0.976	9.0	8.5	9.2
	0.975			
	0.907	9.9	10.0	10.3
	0.971			
	0.908			
	0.987	10.4	10.2	10.8
	0.982			
	0.945	7.2	7.2	7.6
	0.950			
	0.987			
	0.938	9.7	9.9	10.5
	0.937	7.5	8.3	8.1
	0.972			
	0.910			
	0.829	9.7	8.4	8.8
	0.948			
	0.878	7.4	8.6	8.3
	0.924			
	0.978			
	0.923	6.9	7.3	8.2
	0.905	9.6	9.8	10.5
	0.905	8.2	8.1	9.3
	0.882			
	0.978			
	0.913			
	0.806	11.2	10.0	11.9
	0.965			
A-4	0.866			
	0.900			
	0.979			
	0.997			
	0.874			
	0.868			
	0.908	10.0	9.5	11.0
	0.934			
	0.875			
	0.965			
	0.999	9.3	9.5	10.7
	0.932			
	0.950	5.9	5.6	6.1
	0.959			
	0.983	7.6	7.4	8.1
	0.806	10.6	10.8	12.1
	0.994			
	0.894	9.1	9.4	9.8
	0.963			
	0.938	8.7	8.5	9.0
	0.946	8.8	10.1	10.1
	0.934			
	0.994	12.2	10.5	12.6
	0.990	10.0	9.6	10.2
	0.980	10.3	10.3	10.8
	0.962	8.2	8.2	9.0
	0.998	10.2	9.4	10.3
	0.974			
	0.893	8.3	8.6	9.0
	0.993	8.0	7.8	9.3
	0.963	7.7	7.5	7.6
	0.978	7.2	6.6	7.6
	0.891			
	0.873	7.0	6.8	7.6
	0.992			
	0.928			
	0.878	6.5	7.2	6.8
	0.982	8.2	7.4	8.1
	0.998			
	0.806			
	0.897			
	0.986			
	0.977	6.8	6.2	7.2
	0.968	7.2	7.2	7.2
A-6	0.997			
	0.991			
	0.953			
	0.999			
	0.940			
	0.998			
	0.991			
	0.993			
	0.965			
	0.907			
	0.969			
	0.943			
	0.928			
A-6	0.998			
	0.974			
	0.990			
	0.991			
	0.973			
	0.997			
	0.992			
	0.985			
	0.948			
	0.977			
	0.999			
	0.995			
	0.831			
	0.896			
	0.994			
	0.997			
	0.986			
	0.999			
	0.914			
	0.880			
	0.997			
	0.948			
	0.998			
	0.999			
	0.910			
	0.888			
	0.992			
	0.988			
	0.958			
	0.820			
	0.931			
	0.915			
	0.889			
A-7	0.997			
	0.860			
	0.955			
	0.909			
	0.886			
	0.969			
	0.979			
	0.961			
	0.998			
	0.999			
	0.879			
	0.937			
	0.922			
	0.932			
	0.937			
	0.972			
	0.927			
	0.983			
	0.979			
	0.959			
	0.999			
	0.909			
	0.993			

Supplement

A further investigation (4) into the possibility of reducing the number of cycles required to conduct the freeze-thaw test has recently been concluded. The results are generally in agreement with those observed in the paper.

To investigate the applicability of these relationships below 12 cycles, data on 4 soils from a recent PCA study (5) were used. These soils were classified as A-1-b(0), A-4(5), A-4(8) and A-6(10). Freeze-thaw loss at 2, 4, 6, 8, 10 and 12 cycles of testing was evaluated. Either 4 or 5 cement contents were used for each soil.

A graphical analysis indicated that excellent logarithmic cement freeze-thaw relationships exist between 6 and 12 cycles. Below 6 cycles the freeze-thaw loss was almost negligible and relationships were poor. The A-1-b and A-4 soils produced parallel relationships, whereas the slope of the A-6 soil increased directly with the number of cycles. A statistical analysis of the data of Felt (2) indicated similar results. The existence of the logarithmic relationship between 6 and 12 cycles of freeze-thaw testing would indicate that interpretable results are possible at a reduced number of cycles.

The reduction in the number of cycles was further investigated with data supplied by R. G. Packard, Portland Cement Association. Seventy-three sets of data representing most soil types were investigated. Logarithmic relationships at 6 and 12 cycles were determined; the cement content at the specified 12-cycle freeze-thaw loss was chosen, and this cement content was used to evaluate the freeze-thaw loss which would result from 6 cycles of testing. The freeze-thaw loss at 6 cycles corresponding to the required cement content at the specified 12-cycle freeze-thaw was evaluated, and is shown with the standard deviation at 6 cycles in Table 2.

The standard deviations observed are due to both the 6 cycle and 12 cycle logarithmic relationships. Thus, the standard deviation caused by imprecision of the 6-cycle interpolation is less than that in Table 2. The table is an evaluation of the required 6-cycle loss predicted from a knowledge of the 12-cycle loss. However, due to the parallelism observed in the relationships of the granular soils, the predicted standard deviation of the loss at 12 cycles from a knowledge of the 6-cycle loss would be the same on the logarithmic scale. Therefore, the coefficient of variation (the relative standard deviation) of 12 cycles of freeze-thaw testing predicted from 6 cycles would be the same as the coefficient of variation of 6 cycles of freeze-thaw testing predicted from 12 cycles.

These soils have been grouped according to their allowable freeze-thaw loss at 12 cycles (i.e., at 14 percent, 10 percent, and 7 percent). The results (Table 3) indicate that at 6 cycles a reduced freeze-thaw loss is obtained which is fairly consistent for each soil group. Thus, it is evident that 6 cycles of testing might produce interpretable and reproducible results from which a valid criterion can be established.

TABLE 2
AVERAGE FREEZE-THAW LOSS AFTER 6 CYCLES OF TESTING NECESSARY TO PRODUCE THE REQUIRED CEMENT CONTENT OF INDIVIDUAL SOIL TYPES

Soil Type	No. of Soils Tested	Freeze-Thaw Loss (% orig. wt.)	
		Avg.	Std. Dev.
A-1	7	6.4	2.2
A-2	14	6.5	1.8
A-3	5	5.0	1.1
A-4	22	3.3	1.2
A-6	13	3.2	0.9
A-7	12	2.3	1.2

TABLE 3
AVERAGE FREEZE-THAW LOSS AFTER 6 CYCLES OF TESTING NECESSARY TO PRODUCE THE REQUIRED CEMENT CONTENT OF FREEZE-THAW SOIL GROUPS

Soil Type	No. of Soils Tested	Freeze-Thaw Loss (% orig. wt.)	
		Avg.	Std. Dev.
A-1, A-2, A-3	26	6.0	1.7
A-4	22	3.3	1.2
A-6, A-7	25	2.8	1.0

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