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Laboratory Freeze-Thaw Tests
of Portland Cement Treated Granular Bases

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INTRODUCTION

Cement requirements for soil-cement mixtures are controlled by freeze-thaw tests (ASTM D560-57) and wet-dry tests (ASTM D559-57). Since soil-cement is primarily used in bases, rather than surface courses where wearing ability is an important criteria, the validity of a test where the samples are stiff-wire-brushed after each cycle of freeze-thaw could be questioned.

A laboratory freeze-thaw test for cement treated granular base materials that will more nearly duplicate field conditions is compared to the ASTM D560-57 freeze-thaw test in this report. Also, a vibratory method of compaction is compared to the AASHO-ASTM standard compaction method for preparation of all freeze-thaw specimens.

MATERIALS

The crushed limestone materials used in this investigation have previously been described in detail (2, 3). A summary of their engineering properties is presented in Table 1. Hereafter the following designations are assigned: Bedford (B series); Garner (G series); and Gilmore City (H series). Type I portland cement was used in all specimens prepared and tested in this study.

SPECIMEN PREPARATION

Sufficient air-dried crushed limestone material to produce two Proctor size specimens, plus two 500 gram moisture content samples, was placed in a mixing bowl. Type I portland cement was added in the following dry weight proportions:

a. Five percent for B-5, G-5, and H-5 specimens.

b. Three percent for B-3, G-3, and H-3 specimens.

c. One percent for B-1, G-1, and H-1 specimens.

Table 1. Representative engineering properties of the crushed stone materials.

Freeze-thaw test designation series	Bedford B	Garner G	Gilmore H
Textural Composition, %			
Gravel (2.00 mm)	73.2	61.6	66.8
Sand (2.00 - 0.074 mm)	12.9	26.0	23.3
Silt (0.074 - 0.005 mm)	8.4	10.2	5.9
Clay (< 0.005 mm)	5.5	2.2	4.0
Colloids (< 0.001 mm)	1.7	1.4	0.9
Atterburg Limits, %			
Liquid limit, %	20.0	Non-Plastic	Non-Plastic
Plastic limit, %	18.0		
Plasticity index, %	2.0		
Standard AASHO-ASTM Density:			
Optimum moisture content, % dry soil weight	10.9	7.6	9.4
Dry density, pcf.	127.4	140.5	130.8
Specific Gravity of Minus			
No. 10 sieve fraction	2.73	2.73	2.76
Textural Classification	Gravelly	Sandy	Loam
AASHO Classification	A-1-6	A-1-a	A-1-a

The dry materials were thoroughly mixed by hand. Sufficient distilled water, as calculated from the optimum moisture content determined in accordance with ASTM designation D558-57 was then added to the sample which was again mixed by hand. The sample was covered with a damp cloth, allowed to stand for 5 minutes, and was then remixed. About 500 grams of the sample were removed for a moisture determination, weighed, and placed in an oven at a constant temperature of 105-110°C. Two Proctor size specimens were then molded, as described in the succeeding section, and about 500 grams of mix was used for a second moisture content sample. Moisture contents were thus calculated as the average of the two moisture samples.

COMPACTION

Two methods of compaction of the freeze-thaw test specimens were used in this study. The first was in accordance with ASTM designation D558-57, hereafter referred to as method A. Since all of the crushed stones used in this study passed a 3/4 inch U. S. standard sieve, it was not considered necessary to carry out the sample separation and re-proportioning process recommended in section 5 of the above ASTM method.

The second method of compaction, hereafter referred to as Method B, was accomplished in a Proctor size mold mounted on a Syntron Electric vibrator table. Following final mixing, a sufficient quantity of material to provide a 4.00 inch diameter by 4.585 inch high cylindrical specimen was weighed and placed in the mold in three equal layers, each layer being rodded 25 times with a 3/4 inch diameter tapered-end rod. A 25 lb. surcharge was placed on top of the sample and compaction was accomplished for a period of one minute at an amplitude of 0.705 mm (dial setting 50) and frequency of 3600 cycles per minute. The above values were selected as a result of previous compaction studies (4) as being the most desireable in terms of (a) little or no degradation of particle sizes, (b) little or no segregation of particles, and (c) extremely small loss of fines at tope or bottom of mold during vibration. Figure 1 illustrates compaction method B.

In compaction Method A, height of specimen was always 4.585 in., or the length of the Proctor cylinder. In compaction method B, the height was determined as the average of 4 readings taken on the top of the 25 lb. surcharge weight immediately after compaction and prior to removal from the specimen. An Ames dial mounted on a ring stand was calibrated in the following manner. The 25 lb. surcharge weight was placed eccentrically on the empty 4.585 in. long mold (i.e., without mold extension attached). The dial was adjusted to read 0.585 when resting on the surcharge weight. The surcharge weight was shifted to 4 different positions on the mold and the dial was adjusted to assure an average dial reading of 0.585 in. With this calibration the actual specimen length was 4.000 in. plus the dial reading. This method of length determination eliminated the effect of change in diameter and length which may occur during extrusion, handling, or curing processes. The method also eliminated the possibility of the spring on the Ames dial forcing the dial plunger into soft spots on the top surface of the specimen. In both methods of compaction the specimen was weighed in the mold. The tared weight of the mold was subtracted from the total weight to obtain the specimen weight.

CURING

After height and weight measurements were made, each specimen was extruded onto a flat metal plate and cured in the moist room at near 100%

relative humidity and 75 ± 2°F for 24 hours. Each specimen was then sealed in saran wrap and cured for an additional 6 days in the moist room.

All specimens used in this study were wrapped and cured as noted above, as it was found that specimens wrapped immediately after compaction, by either method, were deformed by the wrapping process. Deformed ends would be particularly objectional where any specimens were later tested in compression.

METHOD OF TEST

ASTM FREEZE-THAW TEST

Specimens compacted by both methods A and B were subjected to 12 cycles of freezing and thawing in accordance with ASTM designation D560-57 with the exception that no volume change measurements were made. Instead, the height of specimen was recorded after molding, curing, and each full cycle of freeze-thaw.

IOWA FREEZE-THAW TEST

The Iowa Freeze-Thaw Test was conducted in accordance with the methods developed by George and Davidson (5) with the following exceptions:

a. Proctor size specimens were used rather than 2.0 inch diameter by 2.0 inch height.

b. Compaction was as previously described in this report, using both methods A and B. The freeze-thaw test apparatus is illustrated in Figure 2. The reader is referred to reference No. 5 for a more detailed procedure of the Iowa test. Essentially, the test consists of freezing the specimens from the top, with free water, at about 35°F, available at the bottom.

The large thermos flask used in this study precludes the necessity of a heating element in the water. After 16 hours of freezing, it was found that the water below the specimen was about 36°F without the heating element being turned on. For more severe temperature gradations, or longer freezing cycles the heating element may be required and was thus included in the illustration, Figure 2.

After seven days moist curing, the specimens were removed from the moist room, weighed, measured, and a coating (about 1 mm thick) of quick drying resin-base paint was applied to the top surface of each specimen. After the top surfaces were dry, the specimens were placed in distilled water at 77°F for 24 hours. The height and weight of the specimens were again recorded. Each specimen was then placed in the plastic holder and height of specimen was measured to the nearest 0.001 inch at three previously marked locations. Specimen and holder were then placed in the vacuum flasks such that the bottom 1/2 inch of each specimen was in contact with distilled water at 35°F. The entire apparatus was placed in a freezer maintained at 18°F for a period of 16 hours which constituted one cycle of freezing. Following removal from the freezer, the plastic holder, with specimen, was removed from the vacuum flask and height of specimen was again measured as above. Comparison of the averages of height prior to and immediately following freezing was indicative of change in height of specimen. The holder, with specimen, was then returned to the vacuum flask and stored at 77°F for 8 hours, after which the height was again measured. This constituted one thaw cycle. Prior to each freeze cycle the water level of the flask was replenished, if needed. Ten full cycles of freezing and thawing were conducted.

During the freeze-thaw test, identical specimens remained immersed in distilled water. At the end of the ten freeze-thaw cycles both the control (immersed) specimens and the freeze-thaw specimens were tested in unconfined compression. The ratio of the average strength of the freeze-thaw specimens, P_f, to that of the control specimens, P_c, is the index of resistance to the effect of freezing, R_f.

Strength determinations on the low-cement content specimens were difficult to obtain due to excessive expansion during the freeze-thaw cycles. Following completion of all cycles, loss of portions of the specimens during their removal from the plastic holders was minimized as follows. A smooth metal plate was placed on top of the specimen while it was still in the container. Then, keeping one hand on the plate, the specimen and container were inverted with the other hand. The container was then removed from the specimen, and the specimen was tested in compression while still on the metal plate.

Loading rate during compression testing was 35 to 50 psi per minute. All portions of each specimen were retained for a moisture content determination immediately after the unconfined compression test.

A typical time-temperature chart for the Iowa Freeze-thaw test is shown in Figure 3. The chart was obtained from recorder tracings of thermocouples in the freezer, vacuum flask water, and molded into three locations within one of the test specimens.

RESULTS

COMPARISON OF COMPACTION METHODS

Table 2 summarizes the moisture-density values for two conditions; (a) as designed; and (b) as achieved by both methods of compaction. Design densities were determined from moisture-density plots of each of the nine series, run in accordance with ASTM Designation D558-57.

According to ASTM Designation D560-57, all acceptable freeze-thaw test specimens should be molded at moisture contents within 1.0 percent of optimum and 3.0 pcf of maximum dry density. This criteria was met with all specimens except the G series, Method A specimens and the H series, Method B specimens. With the latter, average densities were higher and moisture contents lower than as originally designed. Discontinuities of the former were with lower densities than as designed. In general, densities obtained with Method A were slightly lower, while densities obtained with Method B were slightly higher than initial design.

Prior research conducted under Project HR-99 of the Iowa Highway Research Board, indicated Bedford specimens compacted by method A had nearly seven percent reduction in gravel size fraction and about five percent increase in minus No. 200 sieve sizes (4). Similar Bedford specimens compacted by method B, indicated negligible change in all particle size fractions.

Reproducibility of densities by the two compaction methods used in the present study are of significant interest. Specimens compacted by method A showed an overall average standard deviation in density of 1.25 pcf and a coefficient of variation of 0.95 percent. Specimens compacted by method B, had an average standard deviation of 0.55 pcf in density and a coefficient of variation of 0.40 percent. A summary of these results is shown in Table 3. The vibratory compaction procedure yielded more uniform densities than did the standard drop-hammer process. In addition, the vibratory technique produced negligible amounts of degradation of particle sizes.

Table 2. Comparison of Average Values of Moisture Content and Density for each Compaction Method.

	Design		Compaction Method A		Compaction Method B	
Series Designation	Optimum Moisture Content, %	Maximum Dry Density, pcf	Average Moisture Content,[a] %	Average Dry Density,[a] pcf	Average Moisture Content,[b] %	Average Dry Density,[b] pcf
B-5	9.5	128.6	9.8	126.5	9.4	128.6
B-3	11.1	125.6	10.9	124.1	10.7	125.2
B-1	10.5	125.4	11.0	123.5	10.3	127.7
G-5	6.3	143.3	6.7	138.7	6.5	144.5
G-3	6.4	142.8	7.3	138.3	6.6	143.3
G-1	7.4	141.2	8.3	138.1	7.3	143.2
H-5	8.7	134.8	8.3	132.7	7.8	137.7
H-3	9.2	133.5	8.4	130.8	7.7	137.7
H-1	9.6	131.5	8.2	130.5	8.1	134.8

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[a] Each value noted is the average of 8 specimens.

[b] Each value noted is the average of 12 specimens.

Table 3. Standard Deviation and Coefficient of Variation of Densities of Specimens.

Series Designation	Compaction Method A[a]		Compaction Method B[b]	
	Standard Deviation, pcf	Coefficient of Variation, %	Standard Deviation, pcf	Coefficient of Variation, %
B-5	0.93	0.73	1.14	0.89
B-3	0.61	0.49	0.39	0.31
B-1	1.28	1.03	0.38	0.30
Bedford Ave.[c]	0.94	0.75	0.64	0.50
G-5	1.13	0.82	0.67	0.46
G-3	0.99	0.72	0.75	0.52
G-1	1.25	0.91	0.37	0.26
Garner Ave.[c]	1.12	0.81	0.60	0.41
H-5	1.04	0.78	0.29	0.21
H-3	2.65	2.03	0.36	0.26
H-1	1.35	1.03	0.56	0.42
Gilmore Ave.[c]	1.68	1.28	0.40	0.30
Overall Average	1.25	0.95	0.55	0.40

[a] Each value computed from a series of 8 specimens.

[b] Each value computed from a series of 12 specimens.

[c] Each value is average of the preceeding 3 standard deviations or coefficients of variation.

ASTM FREEZE-THAW TEST

Figures 5 through 10 and Table 4 present the basic data obtained from the ASTM freeze-thaw test conducted in this study. Each plotted point in the figures is the average of at least two specimen tests. Figure 4 shows representative specimens of each of the three treated stones following testing.

Brushing Loss

The Portland Cement Association (PCA) recommends that soil-cement brushing losses for A-1 AASHO classified soils, as used in this study, be not greater than 14.0 percent by dry soil weight following 12 cycles of freeze-thaw (6).

Table 4 presents the brushing loss data for each of the cement treated stones and compaction methods used. Design cement contents can be assigned only to the H series compacted by method A and the G series, method B These were the only series having brushing losses near the 14.0 percent specification. Additional specimens for the G series compacted by method A would have to be freeze-thaw tested at: (a) 2 percent cement to obtain a design cement content to the nearest 1 percent; or, (b) 1.5, 2.0 and 2.5 percent cement to obtain a design cement content to the nearest 0.5 percent. Likewise the B series, methods A and B, and the H series, method B, would have to be retested at 4.0 percent or 3.5, 4.0, and 4.5 percent cement contents, depending on whether design cement requirements are desired to the nearest 1.0 or 0.5 percent respectively.

It is not possible to adequately graph soil-cement brushing losses versus percent cement and interpolate a design cement content due to the fact that end of test conditions are not equivalent. For example, if such a graph had been made of the data of Table 4, only one-half of the information could be plotted following 12 freeze-thaw cycles. The remaining 50% of the data shows 100% loss of specimens due to brushing, prior to 12 F-T cycles.

From the above considerations only, a range of design cement contents to the nearest 0.5% might be indicated as follows:

a. Bedford stone, 3.5 to 5% cement, for both compaction methods A and B.

b. Garner stone, 3 and 1.5 to 3% cement, compaction methods A and B, respectively.

c. Gilmore stone, 3.5 to 5 and 3% cement, compaction methods A and B, respectively.

It is apparent from Table 4 and the above considerations, that the method of compaction affects the quantity of cement needed to satisfy PCA mix design criteria for the Garner and Gilmore stones. Compaction method B indicated lower design cement contents than did compaction method A; part of this inconsistency may be due to the slight variations in densities of the mixes, noted previously (Table 2). It is possible also, that the variations may be due to increase of fines content by the drop-hammer method A, which would tend to increase the cement content needed for PCA durability, as well as reducing the number of cycles the one and three percent cement treated specimens were capable of withstanding.

Length Change

As previously noted, the volume change determinations of ASTM Designation D560-57 were not made. Studies by Packard and Chapman (7) have indicated that the volume change techniques specified in the standard ASTM freeze-thaw test are not a sensitive measure of deterioration of all cement-treated soils. Instead, precise length change measurements are considered to be a very sensitive and direct measure of deterioration (7).

Table 4. Relation of Soil-Cement Brushing Loss to Cement Content.

Series Designation	Compaction Method A		Compaction Method B	
	Soil-Cement Loss, %	Number F-T Cycles	Soil-Cement Loss, %	Number F-T Cycles
B-5	2.3	12	0.7	12
B-3	100	6	100	10
B-1	100	2	100	4
G-5	1.4	12	0.5	12
G-3	11.3	12	1.4	12
G-1	100	3	100	6
H-5	3.0	12	0.4	12
H-3	100	5	13.2	12
H-1	100	1	100	5

Because of the aforementioned studies, each specimen length was determined as the average length, to the nearest 0.001 inch, taken at three previously marked locations, immediately following the thaw cycle. Average length change was then expressed as a percentage of the cured average length of the specimen. Figures 5, 6, and 7 present the length change data for compaction method A, Bedford, Garner and Gilmore cement treated specimens respectively. It will be observed that the treated Bedford and Garner stones fluctuated through both length increase and decrease while the treated Gilmore specimens increased in length only. If it is assumed that a material is adequately stabilized by cement for resistance to freeze-thaw deterioration, length changes should be minimal. If cement content is insufficient, expansion should occur due to formation of ice lenses forcing the particles apart. If the cement content is greater than that required for freeze-thaw durability either (a) little or no length change will be noticed or (b) decrease in length will occur due to normal shrinkage during continued curing in a moist atmosphere. Though no standard criteria of length change versus design cement content has been established, it was felt that cement requirements based only on a minimization of length change might be assumed arbitrarily from the figures for comparative purposes only. Thus Figures 5, 6, and 7 indicate about 5% cement might be required for the Bedford stone, 3 to 5 % for Garner, and something in excess of 5% for the Gilmore stone. However, it is obvious that cement contents ascertained from such criteria can not be accepted as meeting good design requirements.

Figures 8, 9 and 10 present the length change data for compaction method B, Bedford, Garner and Gilmore cement treated specimens respectively. It may be noted that fluctuations of length change were not as evident as with compaction method A specimens. As based on the above considerations Figures 8, 9 and 10 indicate about 5% cement might be required for the Bedford stone, 3% for Garner, and 3 to 5% for the Gilmore stone.

IOWA FREEZE-THAW TEST

Figures 11 through 19 and Table 5 present the basic data obtained from the Iowa freeze-thaw test conducted in this study. Each point plotted in the figures is the average of at least two specimen tests.

Index of Resistance

As previously noted, the ratio of the average unconfined compressive strength of the freeze-thaw specimens, P_f, to that of the control specimens, P_c, is the index of resistance to the effect of freezing, R_f, in the Iowa freeze-thaw test. Tentative criteria for freeze-thaw durability by the Iowa test, as developed by George and Davidson (5). suggest a minimum P_f of 459 ± 41 psi, and R_f of 80%. Table 5 presents the major results of the Iowa test following the ten cycles of freeze-thaw. Each piece of data shown is the average of at least two specimen tests. Variation of the unconfined compressive strengths P_c and P_f due to materials, cement content, and compaction methods are obvious. In general the treated Garner stone shows the highest strength values while the Bedford is lowest. Also the vibratory compaction method B generally produced significantly higher strengths than the standard compaction method A and may be due in part to the higher densities of the method B specimens.

Values of P_f and R_f versus cement content are plotted in Figures 11, 12 and 13 for convenient selection of cement requirements as based on the above criteria of George and Davidson (5). Application of the criteria to the treated Bedford stone both indicate the same values of cement content; i.e., 4.5 and 4% for compaction methods A and B respectively. Slight differences of required cement content for compaction method A Garner specimens are noted for the

R_f and P_f criteria. Cement requirements for the Gilmore treated stone as based on P_f criteria indicate 4% and 2.5% for compaction methods A and B respectively while R_f criteria indicates 3% cement is required for both compaction methods.

Length Change

Figures 14, 15 and 16 present the length change data for compaction method A specimens, while Figures 17, 18 and 19 present similar data for compaction method B specimens. Specimen lengths were determined as the average length, to the nearest 0.001 inch, taken at three previously marked locations. Since the specimens were left in their plastic holders, accurate length measurements could be made after the freeze cycle as well as after the thaw cycle with negligible specimen disturbance. It will be observed that length change is dependent on (1) test condition of measurement, i.e., either after freezing or thawing, (2) percentage of cement, and (3) stone used. It is also observed that length changes in this test process show: (1) much less dependence on method of compaction than in the ASTM test process following thawing; (2) less fluctuation, i.e., positive and negative length change, than with the ASTM test specimens; and (3) larger length change values, particularly with the lower cement content specimens, indicating a potential severity of the test process through greater water attraction and absorption during freezing. Assuming criteria for adequate stabilization, as based on length change assumptions previously presented, Figures 14, 15 and 16 indicate about 5% cement required for the Bedford stone, 3% for the Garner and 5% for the Gilmore stone. Figure 17, 18 and 19 also indicate about5% cement required for the Bedford stone and 3% for the Garner and Gilmore stones. Graphs of the length change versus cement content following 10 full cycles of freeze-thaw in the Iowa test are shown in Figures 20, 21 and 22. Cement requirements, to the nearest 0.1 percent, as determined

Table 5. Results of Iowa Freeze-Thaw Test after Ten Cycles.

		Compaction Method A				Compaction Method B			
Series Designation	Cement Content, %	P_c, psi	P_f, psi	R_f, %	Length Change following freezing, %	P_c, psi	P_f, psi	R_f, %	Length Change following freezing, %
B-5	5	757	770	95	0.0	969	951	98	0.0
B-3	3	338	170	50	3.4	317	281	69	2.6
B-1	1	134	41	31	5.7	227	109	48	7.4
G-5	5	1640	1595	97	0.0	2210	2010	91	-0.2
G-3	3	845	815	96	-0.2	1100	993	90	-0.0
G-1	1	190	117	62	0.2	374	245	66	2.5
H-5	5	702	668	95	-0.1	1315	1190	90	0.1
H-3	3	280	231	83	1.1	813	660	81	0.3
H-1	1	86	50	58	2.2	227	97	43	2.8

from the index of resistance, R_f and unconfined compressive strength after freeze-thaw, P_f shown on Figures 11, 12 and 13 were transferred to Figures 20, 21, and 22. The corresponding length changes for the R_f and P_f criteria can be read from Figures 20, 21, and 22 and are summarized in Table 6. Based on this table, length changes exceeding 1.0 percent following the last freeze cycle or 0.5 percent following the last thaw cycle are suggested as maximum allowable expansions. If this criteria is applied to Figures 20, 21 and 22, the design cement contents, to the nearest 0.5 percent, based on excessive length change are as shown in Table 7. These design cement contents agree within 0.5 percent of those determined by the R_f and P_f durability criteria shown in Table 8.

COMPARISON OF FREEZE-THAW TESTS

Table 8 presents a comparison of cement contents obtained using the ASTM-PCA and Iowa test criteria for both methods of compaction. Of primary importance in this comparison are the cement contents obtained by criteria of PCA brushing loss, index of resistance, R_f and compressive strength after freezing, P_f. In general the Iowa test indicates a reduction in required cement content ranging from 0.0 to 1.5%. Variation of compaction method is most pronounced in the brushing loss test and least in the index to resistance criteria, indicating an element of validity of this test method regardless of the method of lab compaction and potentially of field compaction processes.

Graphs of ASTM brushing loss and length change versus percentage cement could not be made as all specimens did not withstand the full 12 freeze-thaw cycles. Therefore, interpolation of design cement content was not possible and cement contents shown in Table 8 are either expressed to the next highest cement content tested, or as a possible range.

The data for index of resistance, R_f, compressive strength after 10 freeze-thaw cycles, P_f, and length change in the Iowa Freeze-Thaw test could all be graphed and design cement contents interpolated from the graphs. This was possible since all specimens had similar completion of test conditions. That is, all specimens could be tested throughout the full 10 freeze-thaw cycles. The interpolated design cement contents are shown in Table 8 for the R_f and P_f criteria and in Table 7 for the length change criteria. Neither the ASTM nor Iowa Freeze-Thaw tests have a standardized procedure for selection of cement content based only on length change. The data presented does indicate that the length changes in the Iowa test were more consistent with less fluctuation and scatter. The easy method of interpolation of design cement contents in the Iowa Freeze-Thaw test may encourage the standardization of cement content design as based on length change.

Table 6. Maximum Allowable Percentage Length Change as Predicted from R_f and P_f criteria in the Iowa Freeze-Thaw Test.

	Following Thaw Cycle				Following Freeze Cycle			
Compaction Method	A		B		A		B	
Durability Criteria	R_f	P_f	R_f	P_f	R_f	P_f	R_f	P_f
Bedford	0.9	1.0	0.8	0.7	0.9	1.1	1.3	1.2
Garner	-0.1	-0.3	0.4	0.5	1.0	0.3	0.8	1.0
Gilmore	0.8	0.6	0.2	0.4	1.4	0.6	0.4	0.6

Table 7. Suggested Design Cement Contents Based on Interpolation of Length Change Data in the Iowa Freeze-Thaw Test.

	Following Thaw Cycle		Following Freeze Cycle	
Compaction Method	A	B	A	B
Bedford	5.0	4.5	4.5	4.0
Garner	1.0	2.0	2.0	2.0
Gilmore	4.5	2.0	3.5	2.0

Table 8. Comparison of Cement Contents Obtained with Each Durability Criteria, Freeze-Thaw Test Procedure, and Compaction Method.

	ASTM Freeze-Thaw Test				Iowa Freeze-Thaw Test					
Compaction Method	Brushing Loss		Length Change		Length Change		Index of Resistance		P_f	
	A	B	A	B	A	B	A	B	A	B
Bedford	3.5-5	3.5-5	5	5	5	5	4.5	4	4.5	4
Garner	3	1.5-3	3-5	3	3	3	1.5	2	2	2
Gilmore	3.5-5	3	>5	5	5	3	3	3	4	2.5

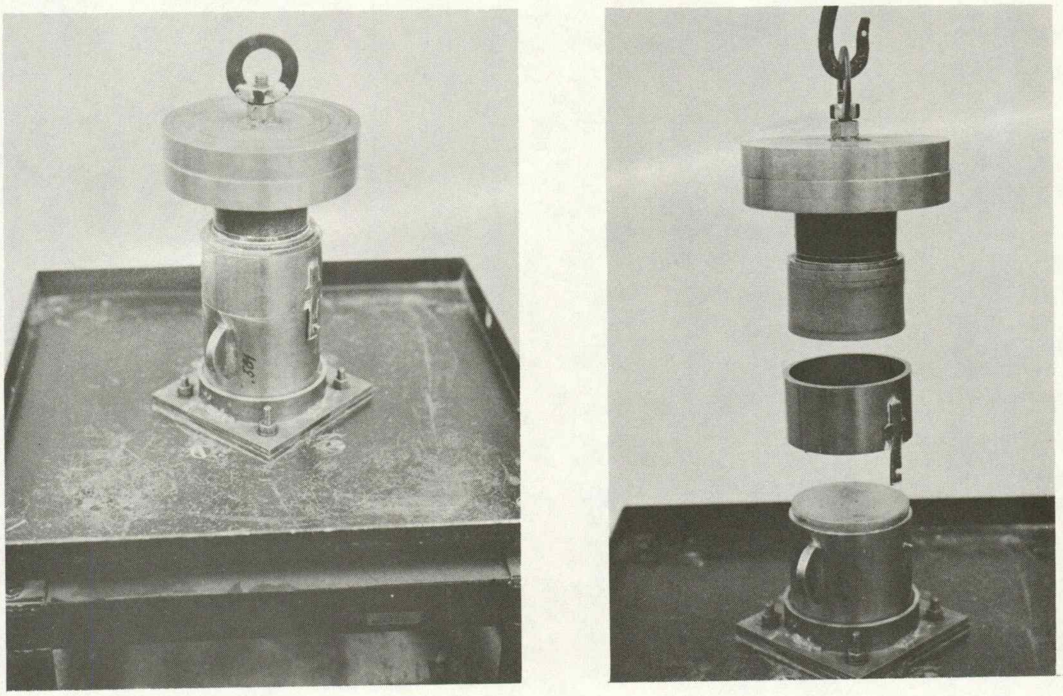


Figure 1. Vibratory Compaction Apparatus

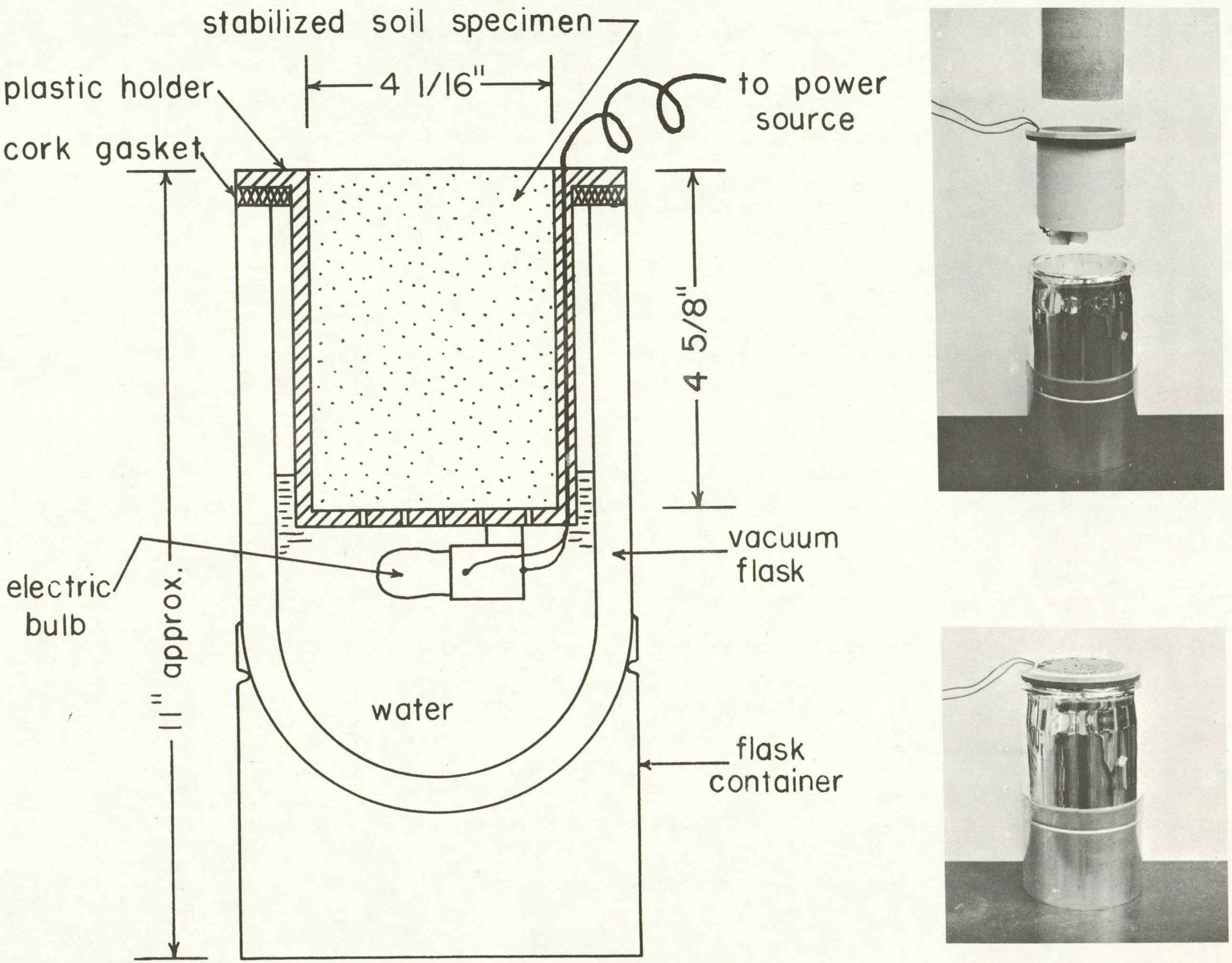
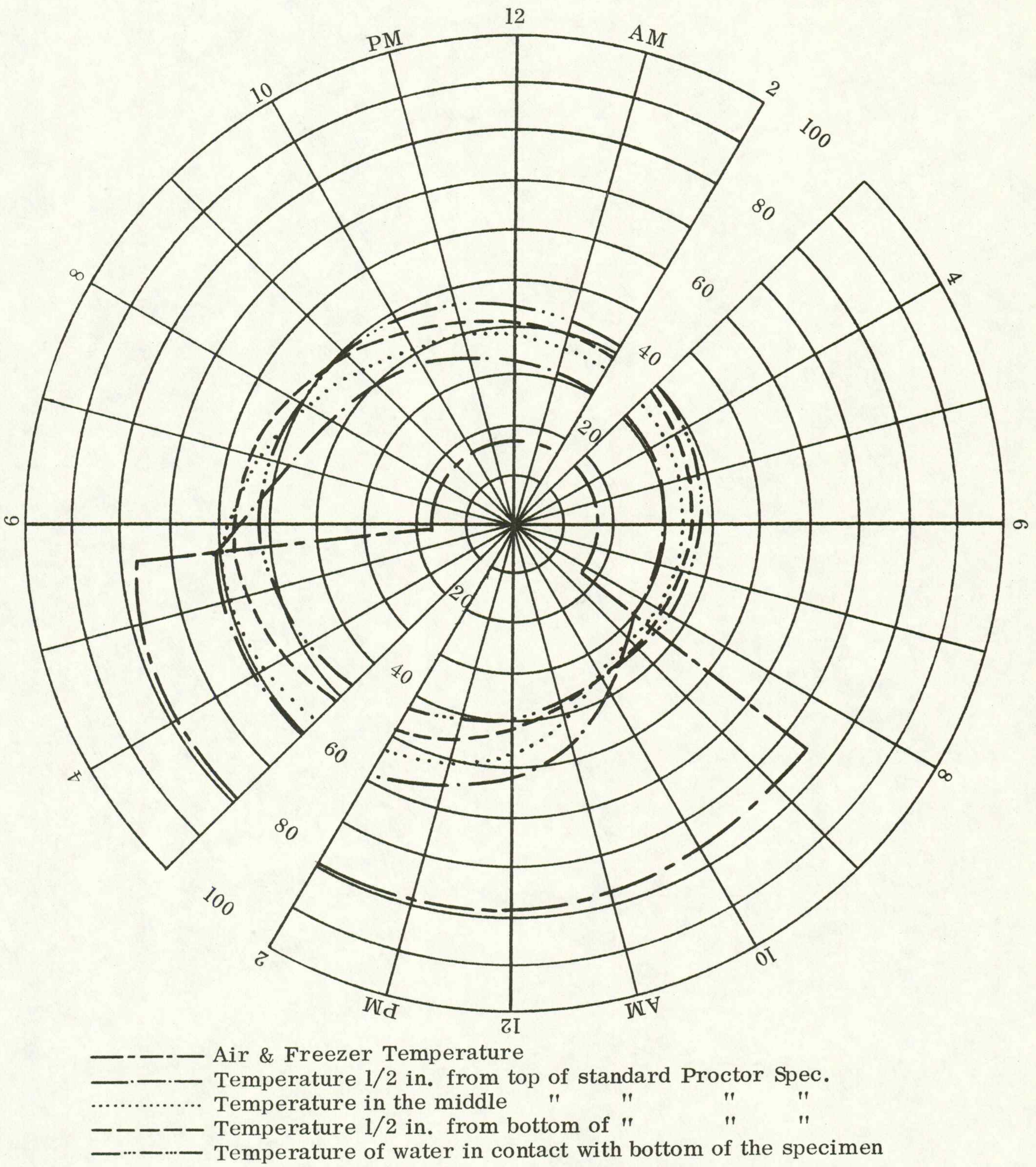


Figure 2. Iowa Freeze-Thaw Test Apparatus



Note: Specimen was in thermos bottle throughout cycle.

Fig. 3. Iowa Freeze-Thaw Test

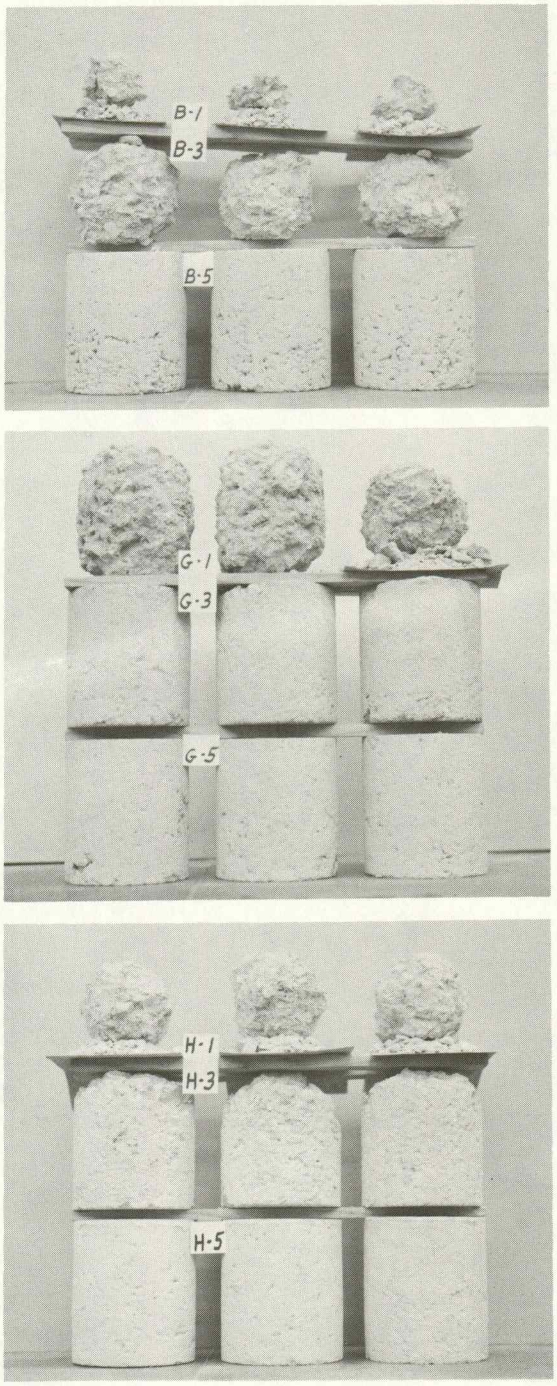


Figure 4. ASTM Freeze-Thaw Test Specimens

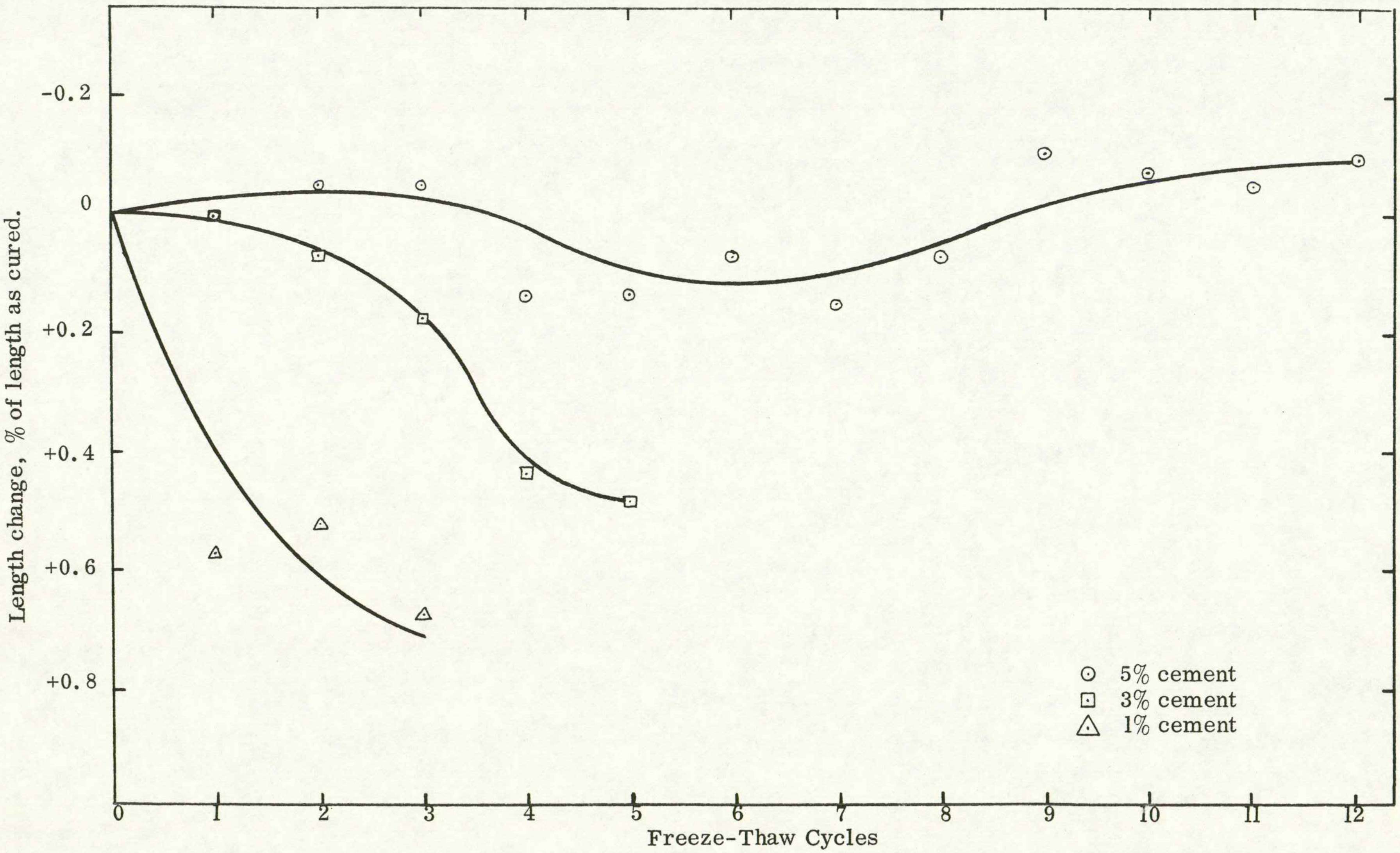


Figure 5. Relationship of percentage length change of specimens to number of ASTM freeze-thaw cycles for various cement treatments of Bedford stone. Compaction Method A.

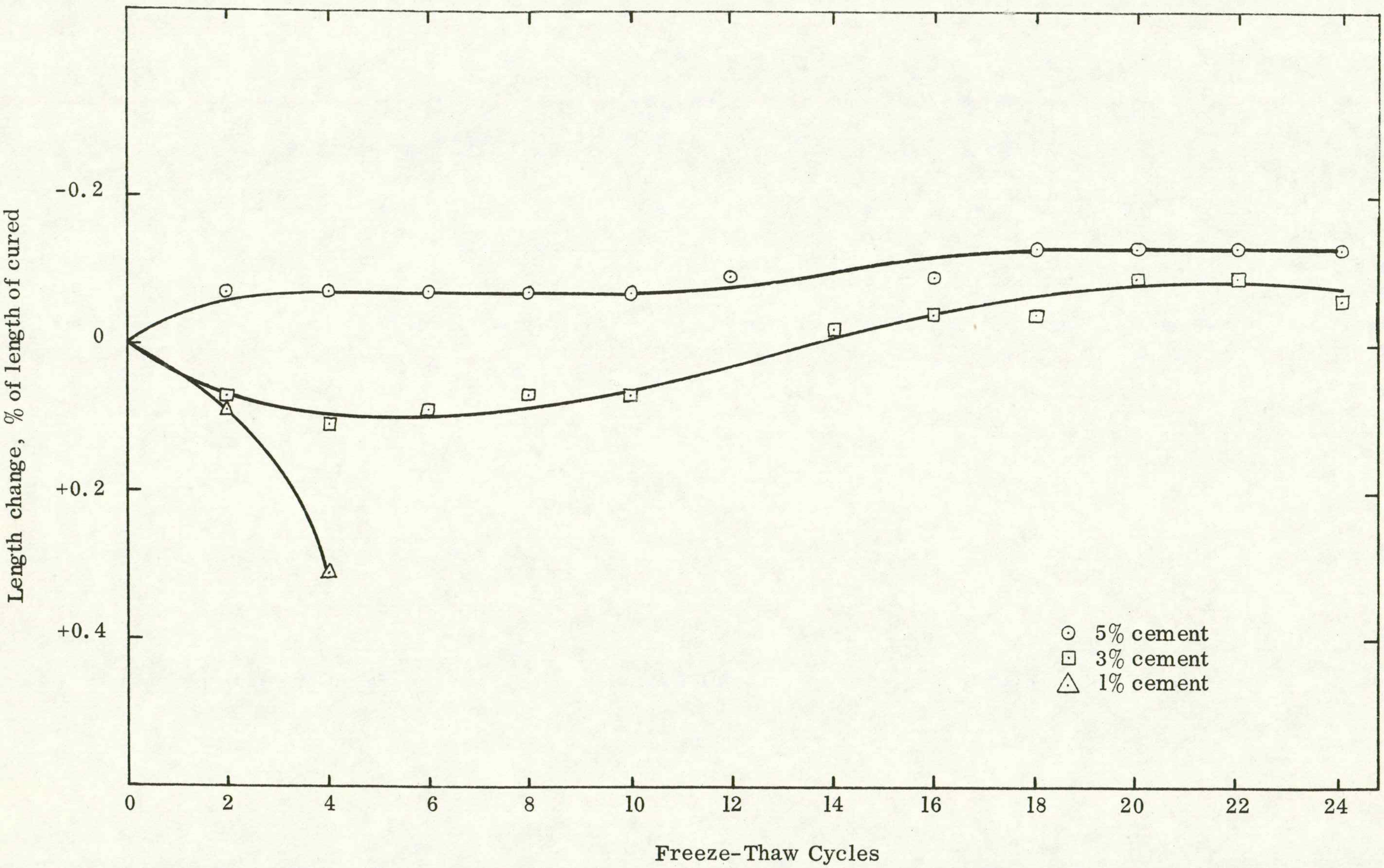


Figure 6. Relationship of percentage length change of specimens to number of ASTM freeze-thaw cycles for various cement treatments of Garner stone compaction Method A.

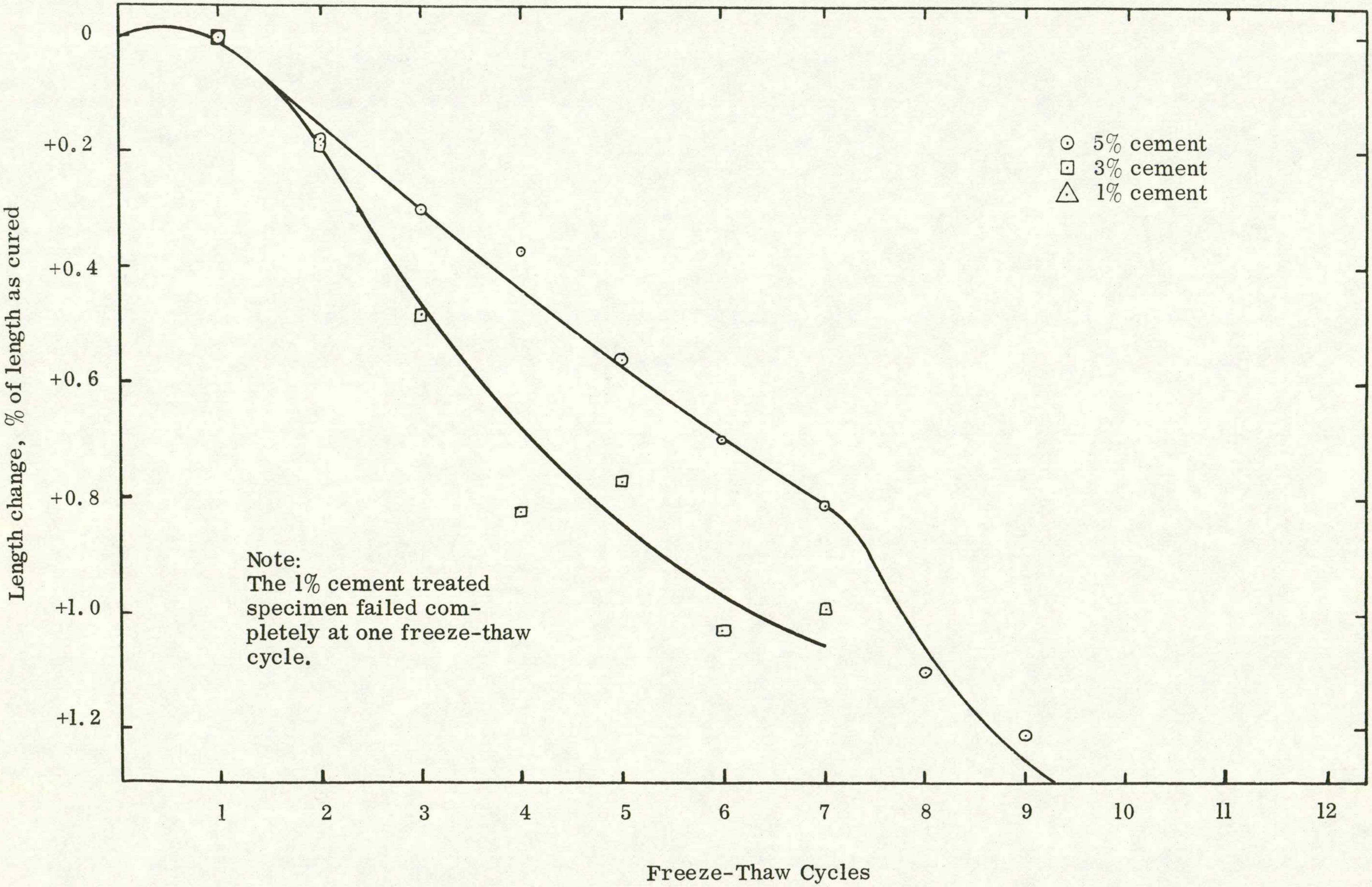


Figure 7. Relationship of percentage length change of specimens to number of ASTM freeze-thaw cycles for various cement treatment of Gilmore stone. Compaction Method A.

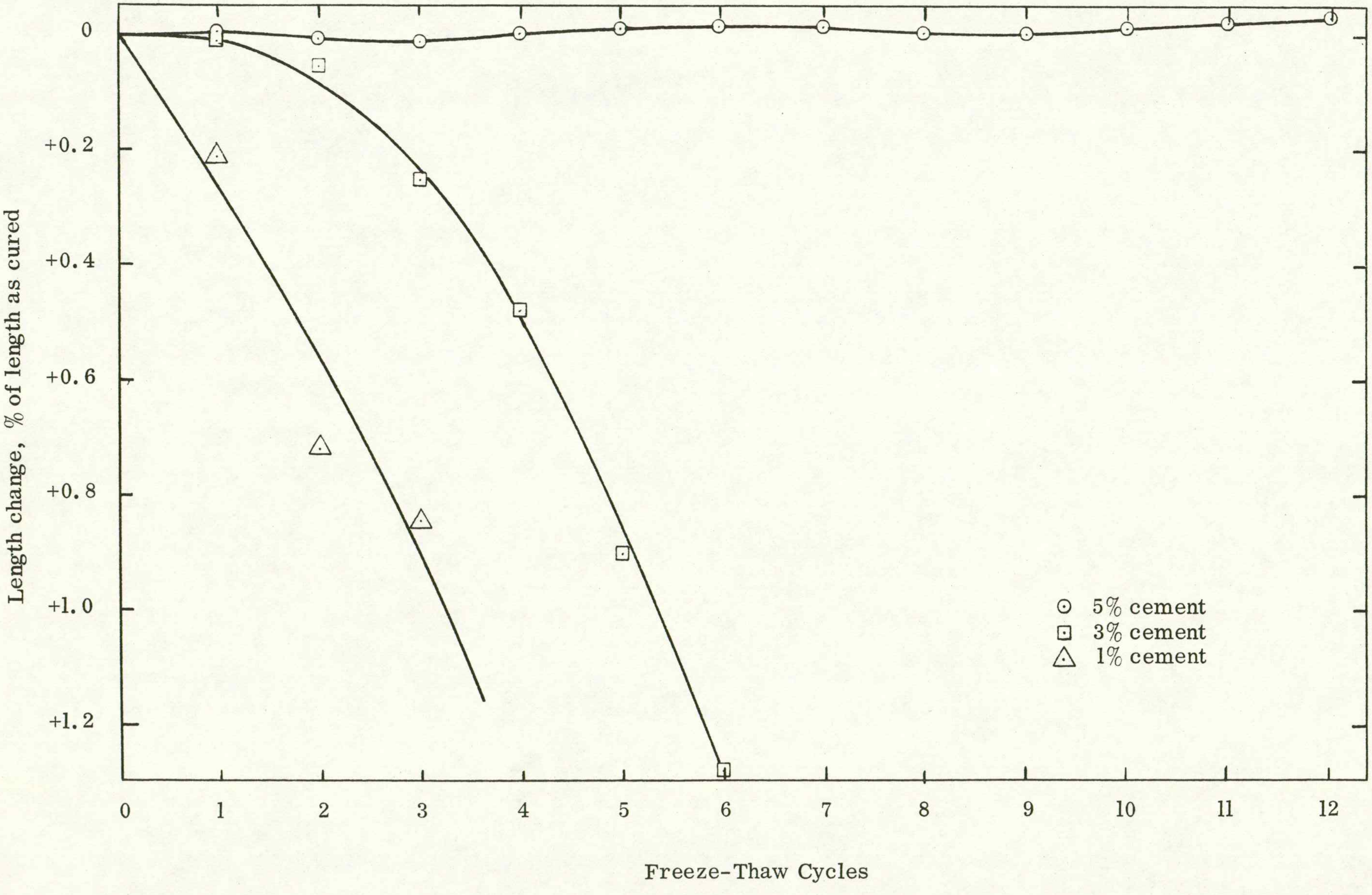


Figure 8. Relationship of percentage length change of specimens to number of ASTM freeze-thaw cycles for various cement treatments of Bedford stone. Compaction Method B.

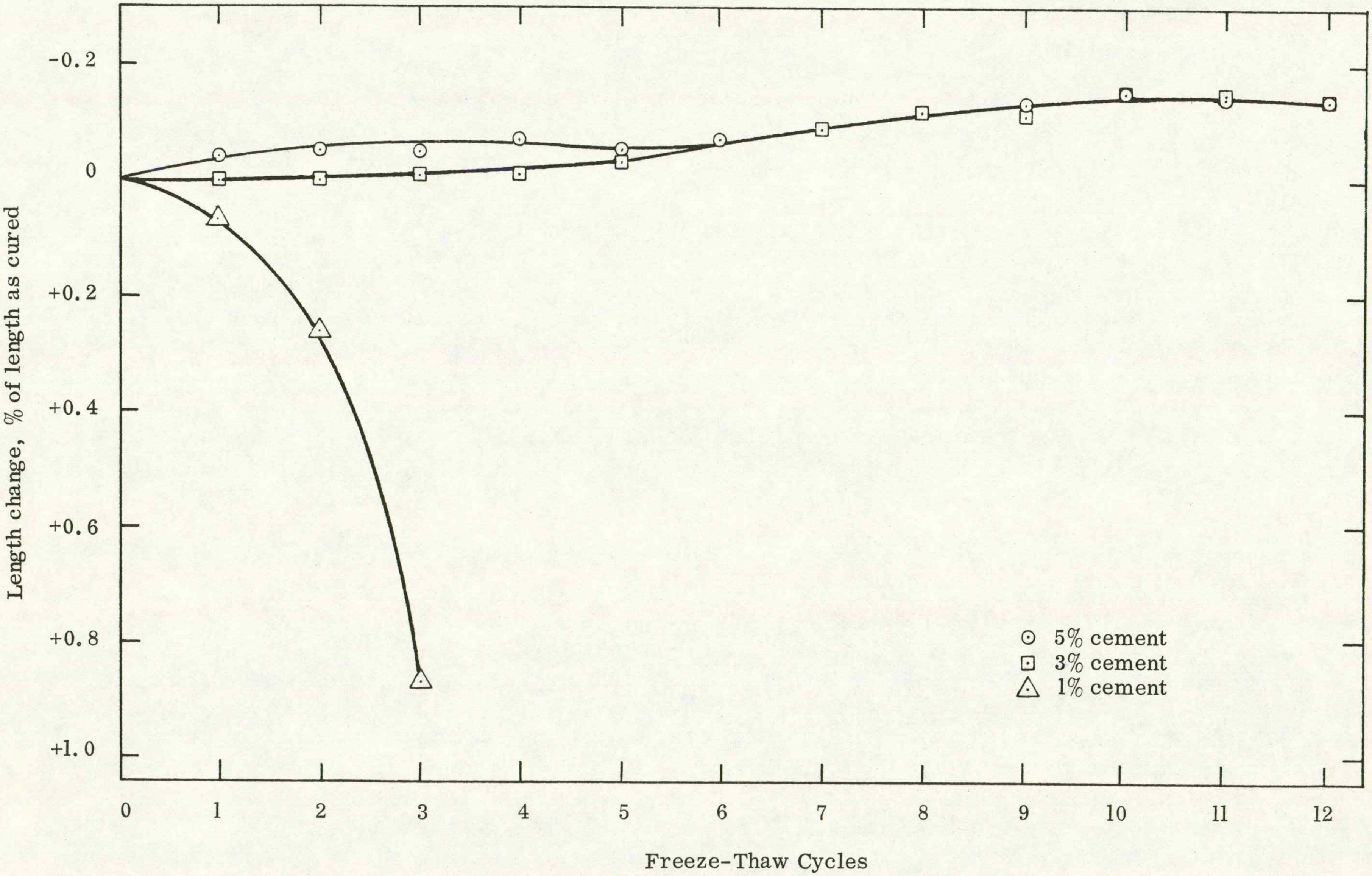


Figure 9. Relationship of percentage length change of specimens to number of ASTM freeze-thaw cycles for various cement treatments of Garner stone. Compaction Method B.

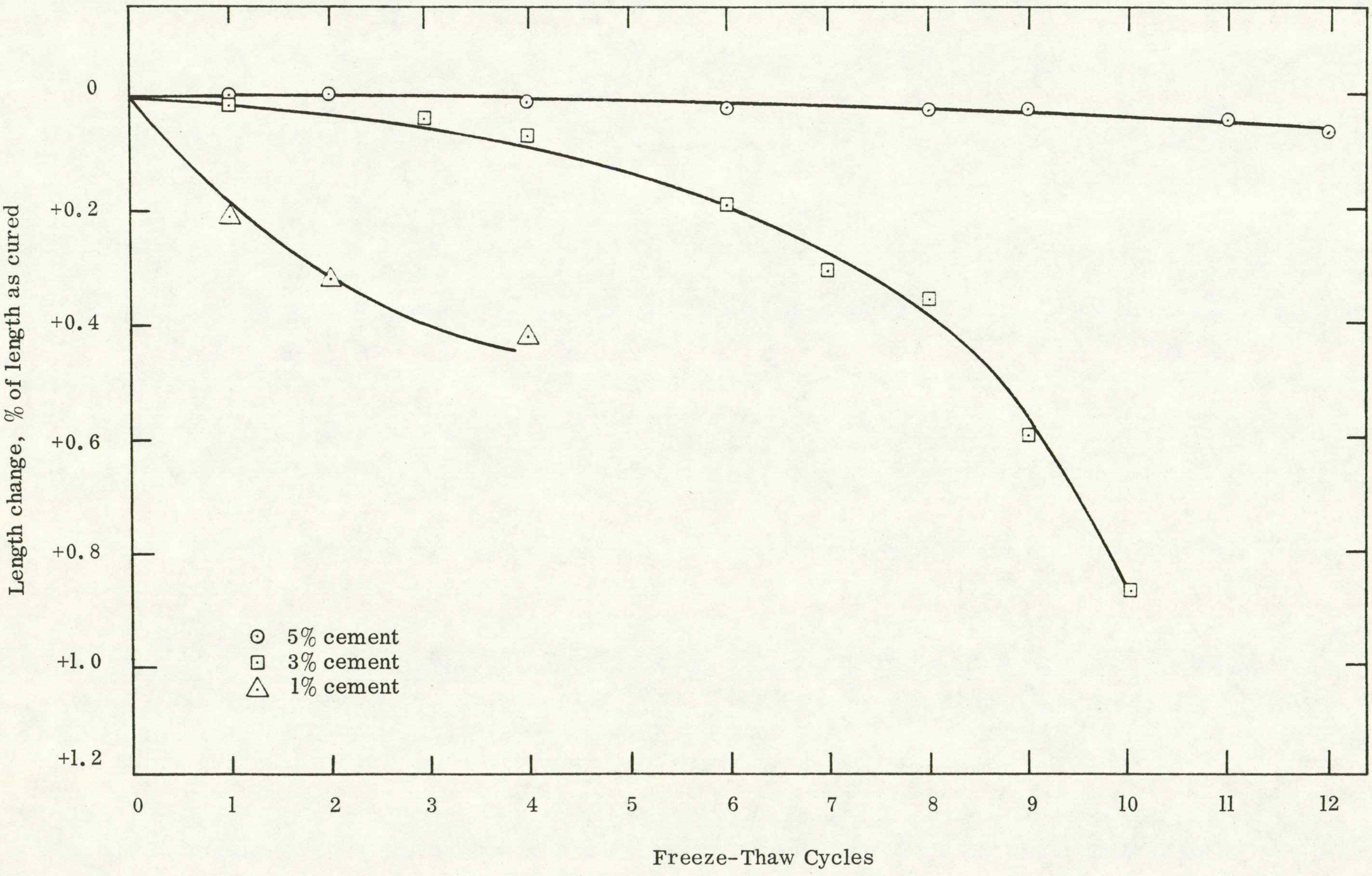


Figure 10. Relationship of percentage length change of specimens to number of ASTM feeze-thaw cycles for various cement treatments of Gilmore stone. Compaction Method B.

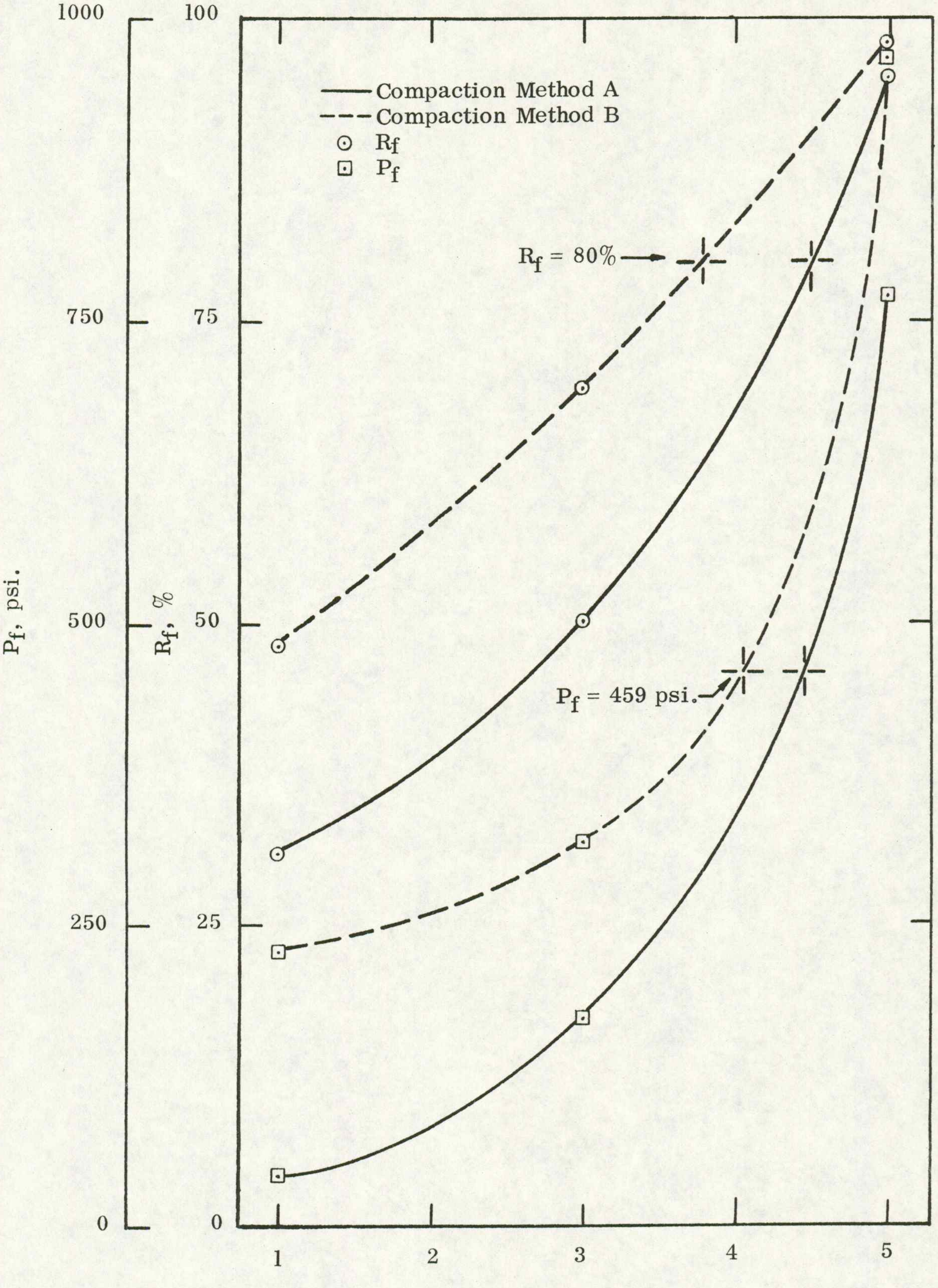


Figure 11. Relationship of cement content to index of resistance to freezing, R_f, and unconfined compressives strength, P_f, of Bedford freeze-thaw test specimen for compaction methods A and B.

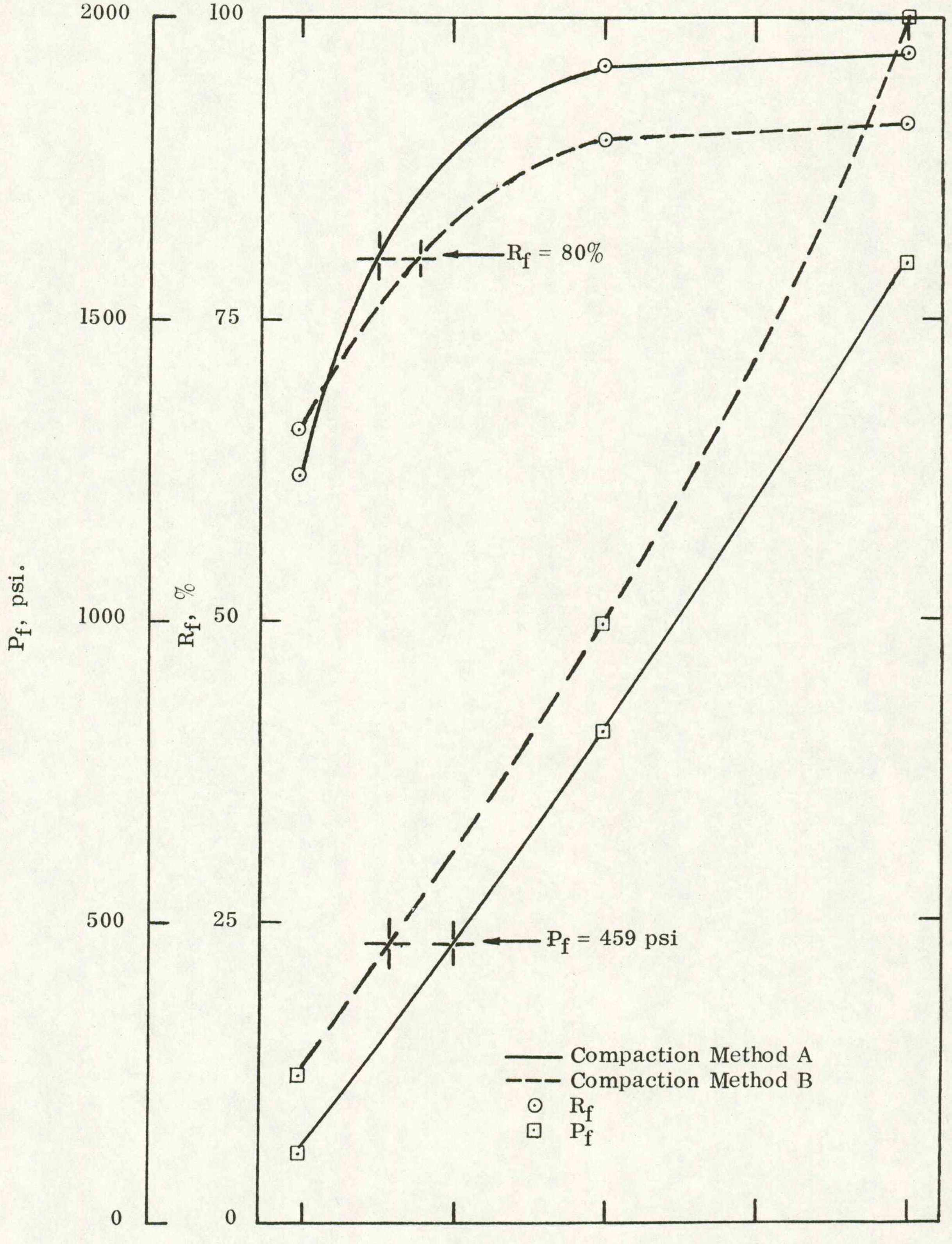


Figure 12. Relationship of cement content to index of resistance to freezing, R_f, and unconfined compressive strength, P_f, of Garner freeze-thaw test specimens for compaction methods A and B.

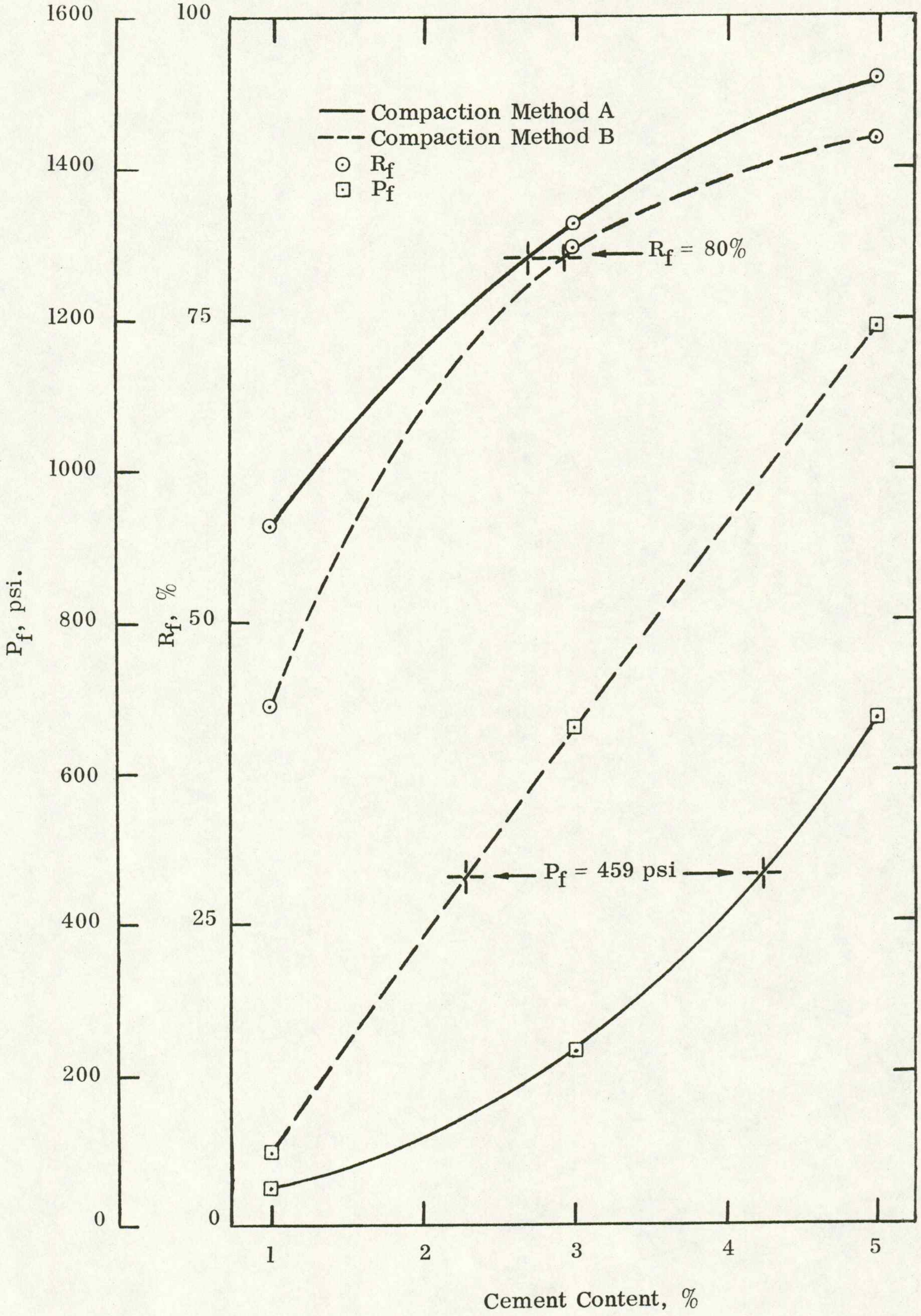


Figure 13. Relationship of cement content to index of resistance to freezing, R_f, and unconfined compressive strength, P_f, of Gilmore freeze-thaw test specimens for compaction methods A and B.

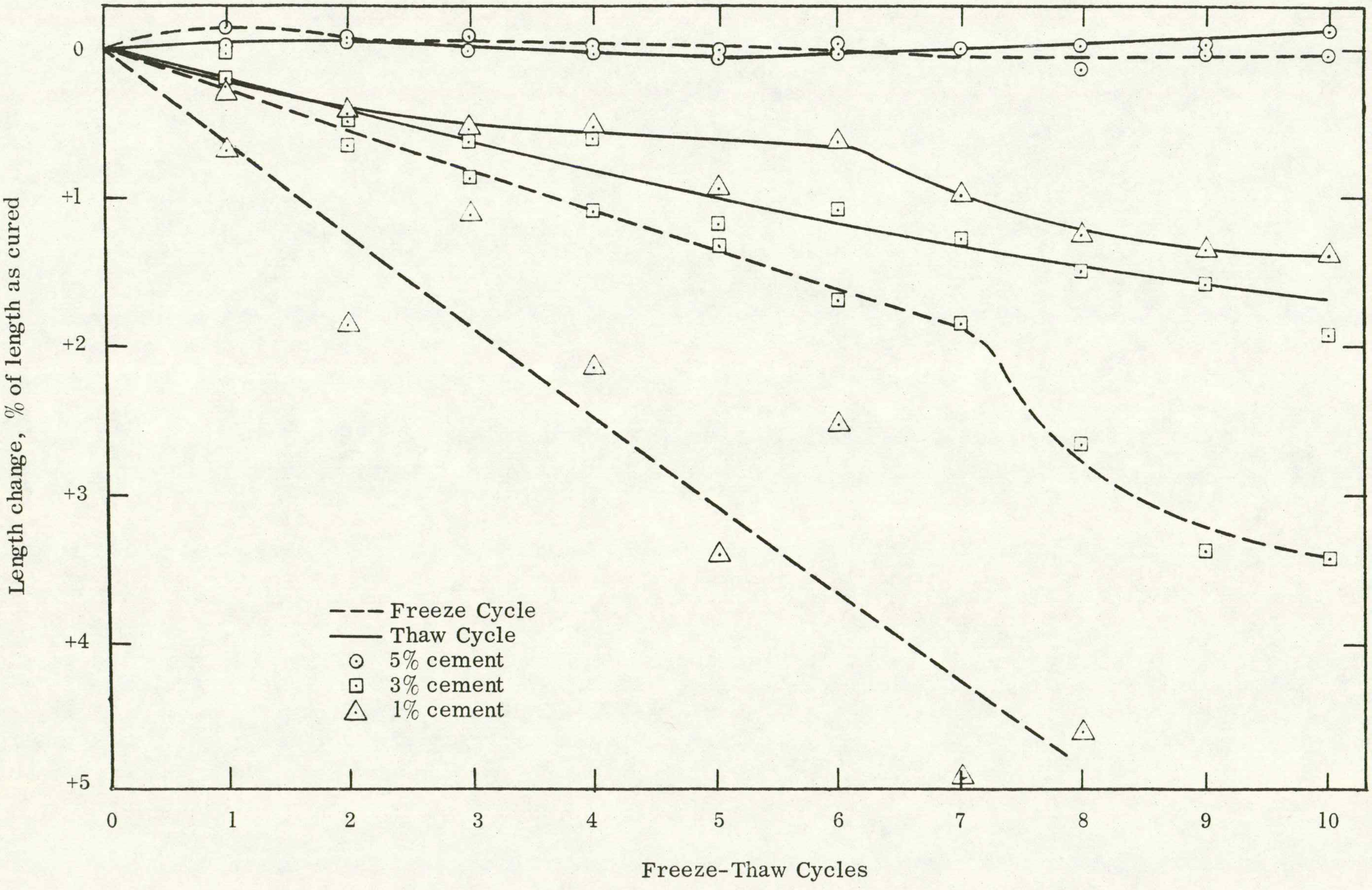


Figure 14. Relationship of percentage length change of specimens to number of Iowa freeze-thaw cycles for various cement treatments of Bedford stone. Compaction Method A.

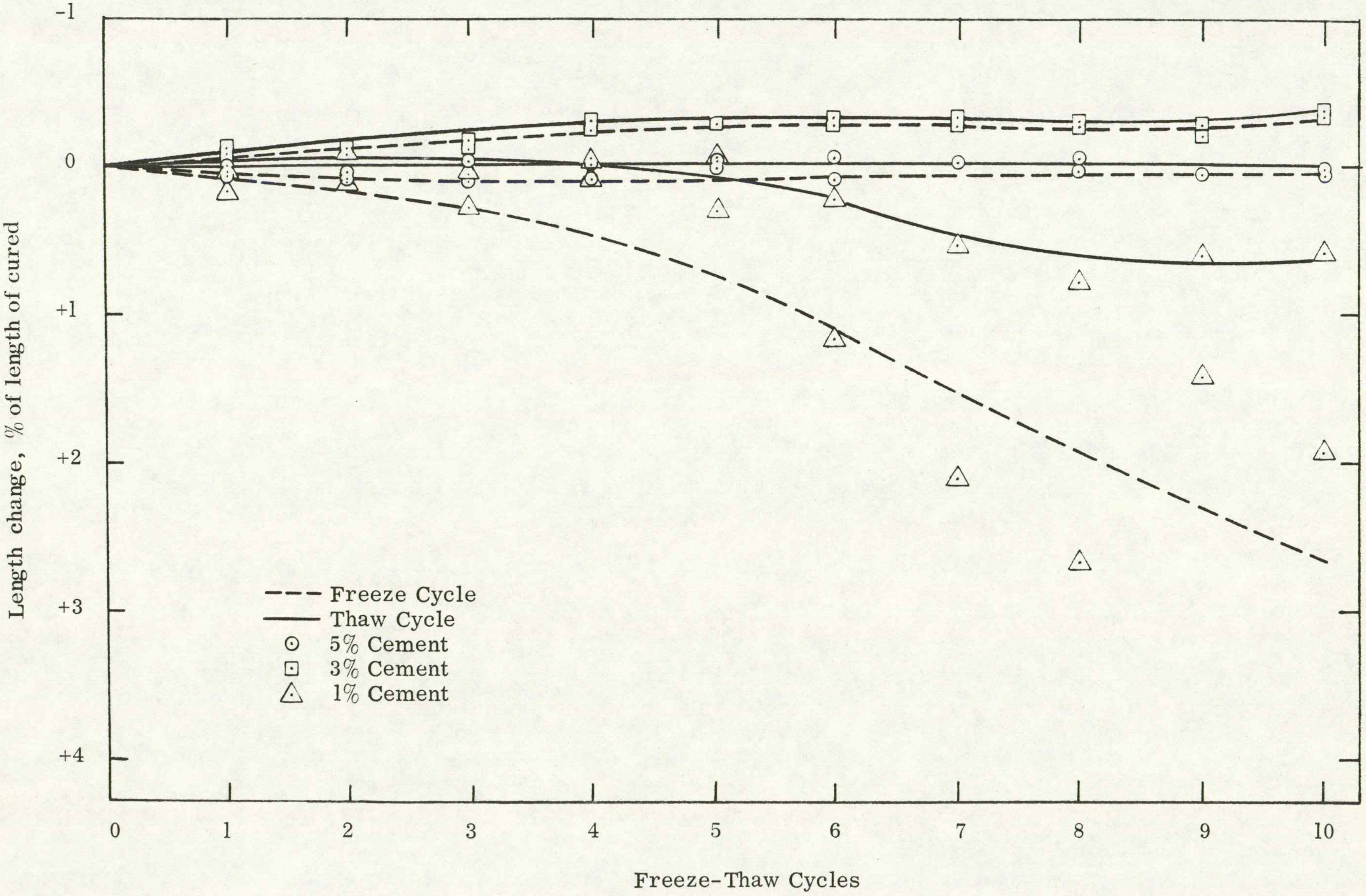


Figure 15. Relationship of percentage length change of specimen to number of Iowa freeze-thaw cycles for various cement treatments of Garner stone. Compaction Method A.

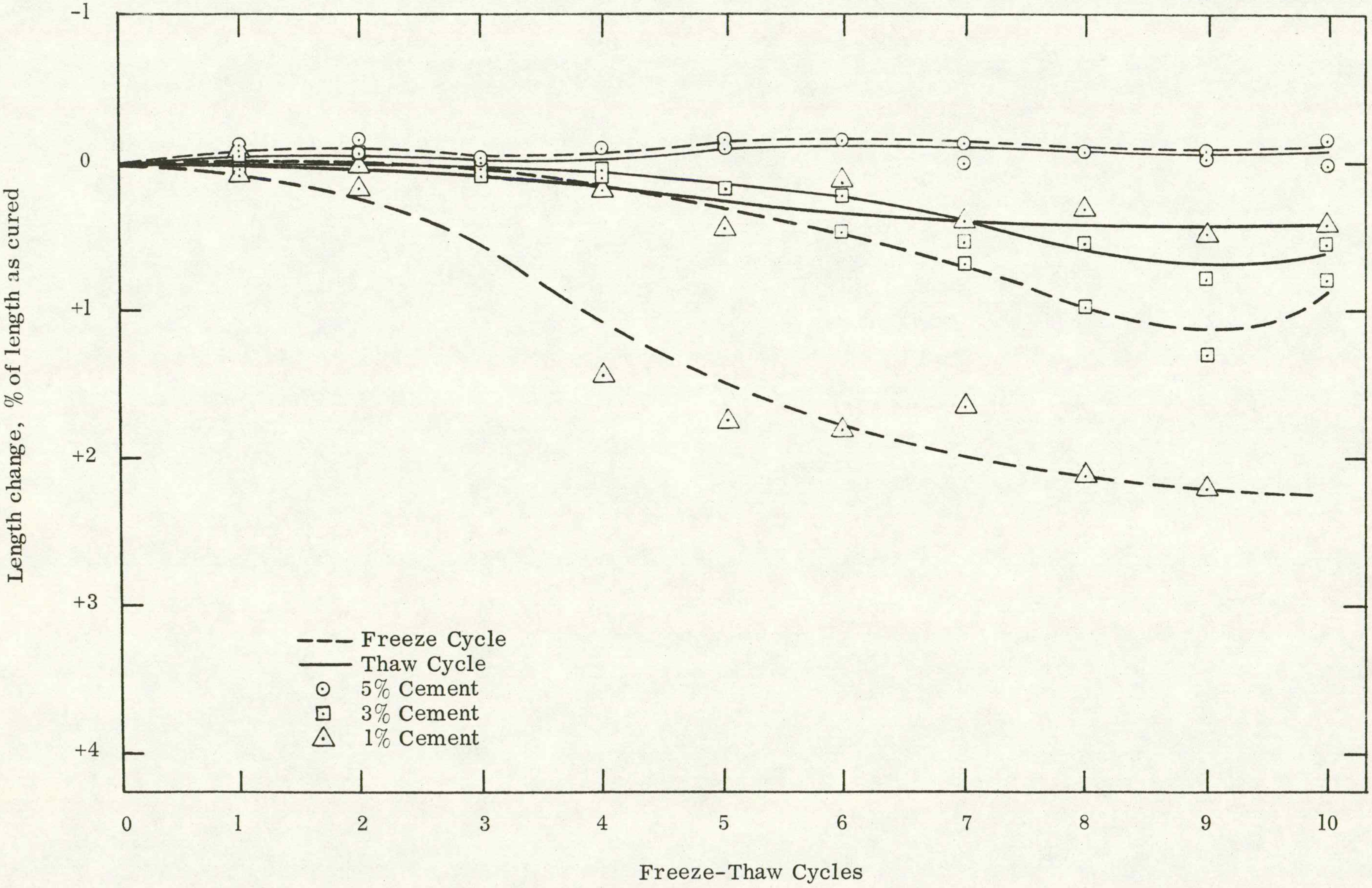


Figure 16. Relationship of percentage length change of specimen to number of Iowa freeze-thaw cycles for various cement treatments of Gilmore stone. Compaction Method A.

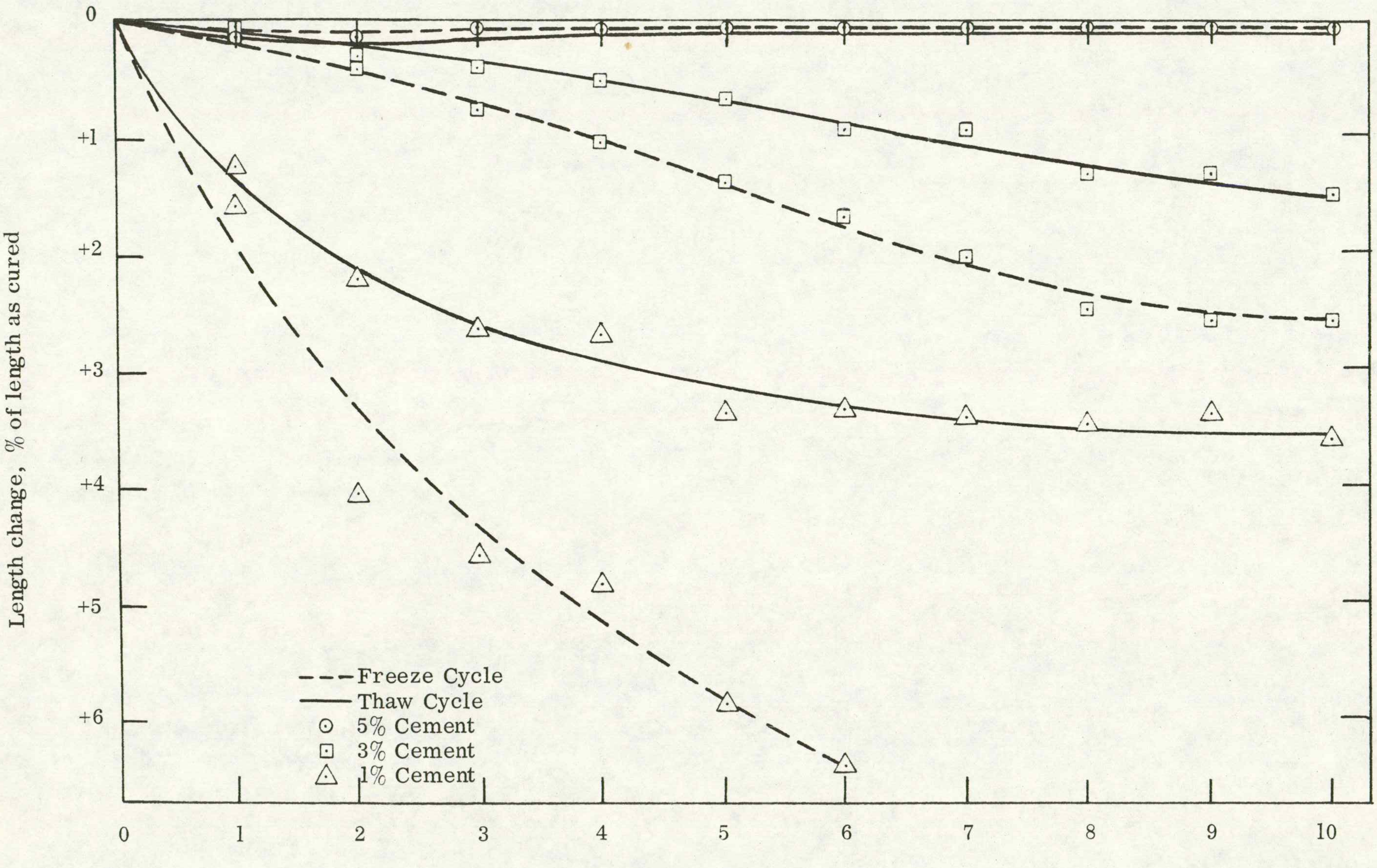


Figure 17. Relationship of percentage length change of specimens to number of Iowa freeze-thaw cycles for various cement treatments of Bedford stone. Compaction Method B.

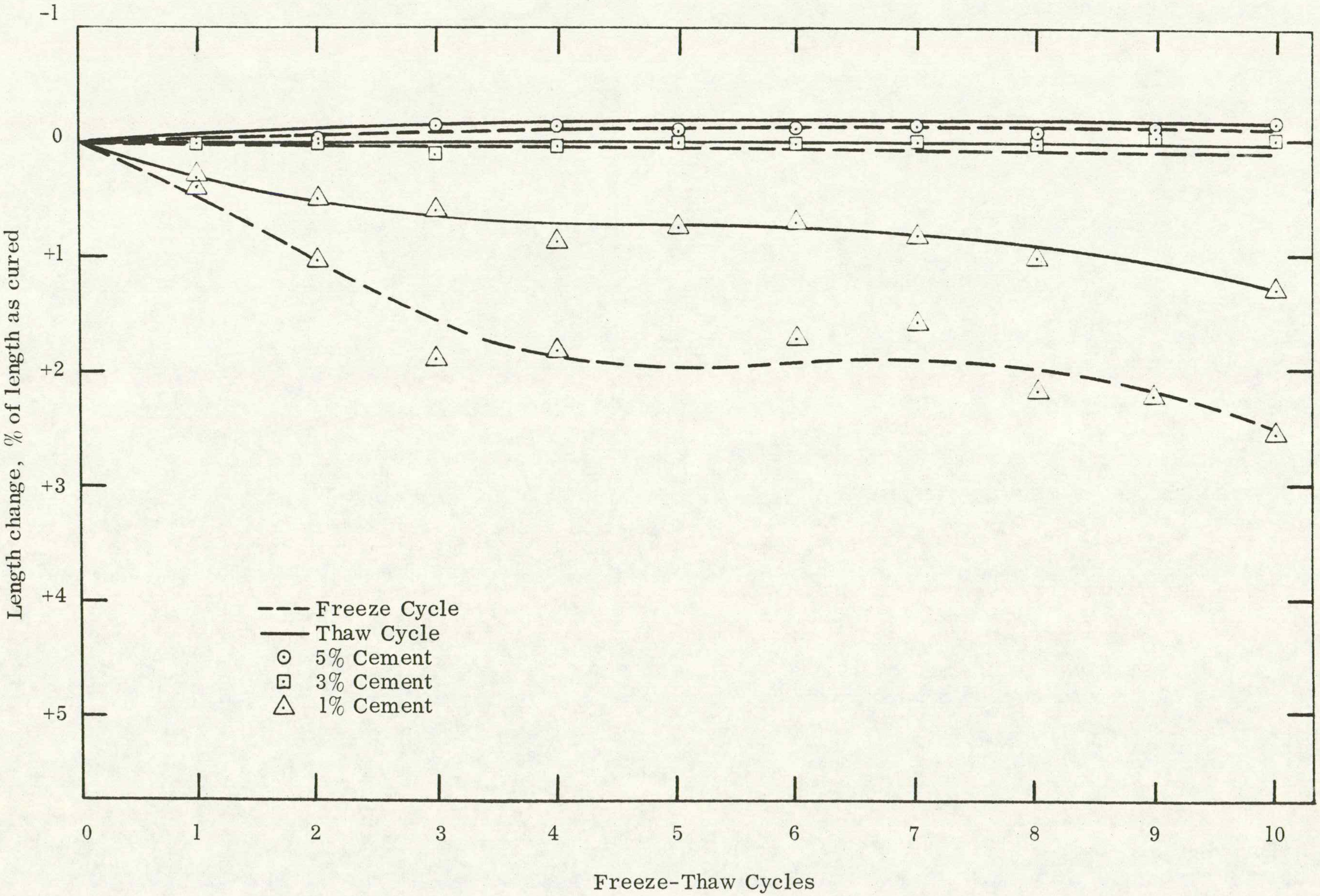


Figure 18. Relationship of percentage length change of specimens to number of Iowa freeze-thaw cycles for various cement treatments of Garner stone. Compaction Method B.

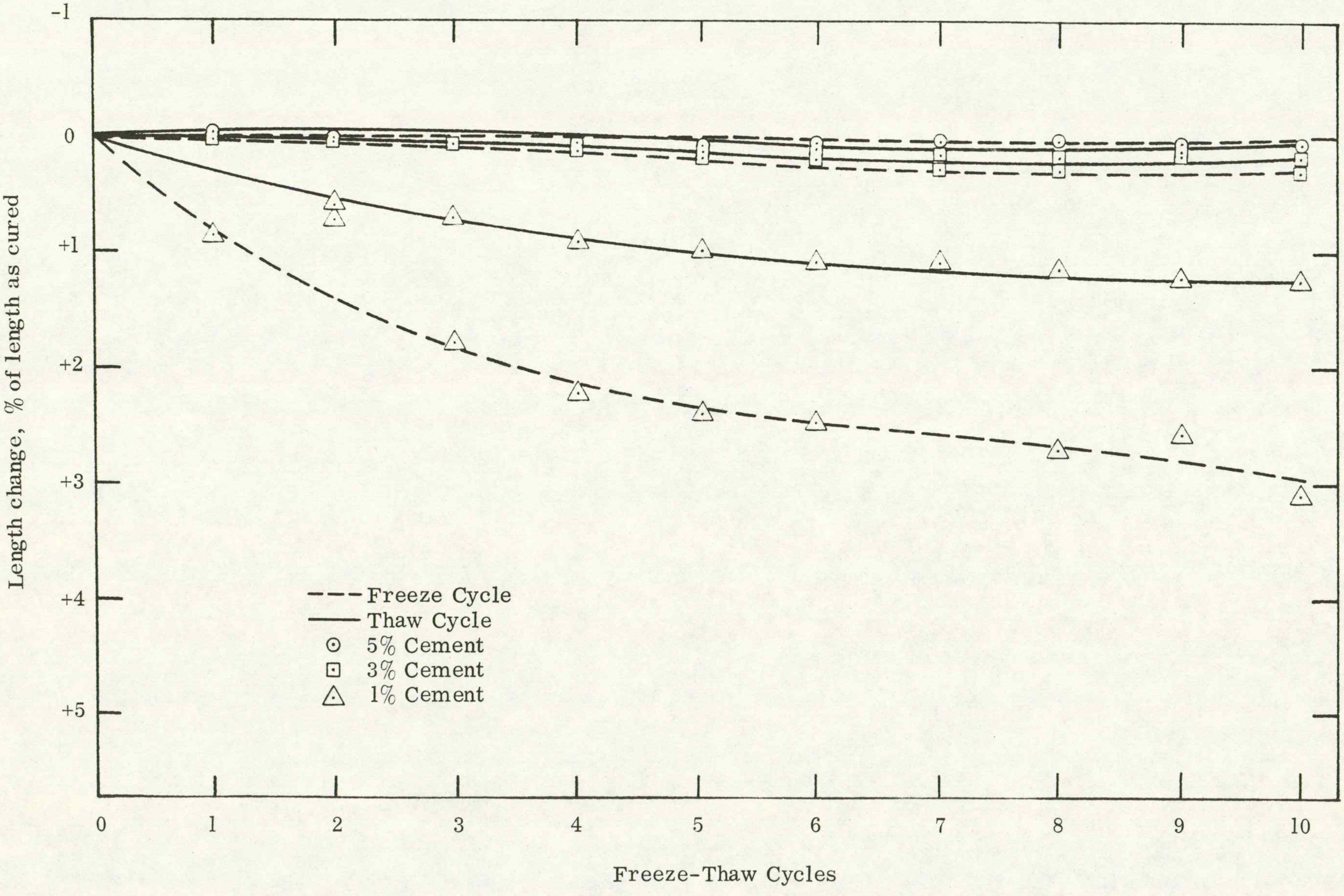


Figure 19. Relationship of percentage length change of specimens to number of Iowa freeze-thaw cycles for various cement treatments of Gilmore stone. Compaction Method B.

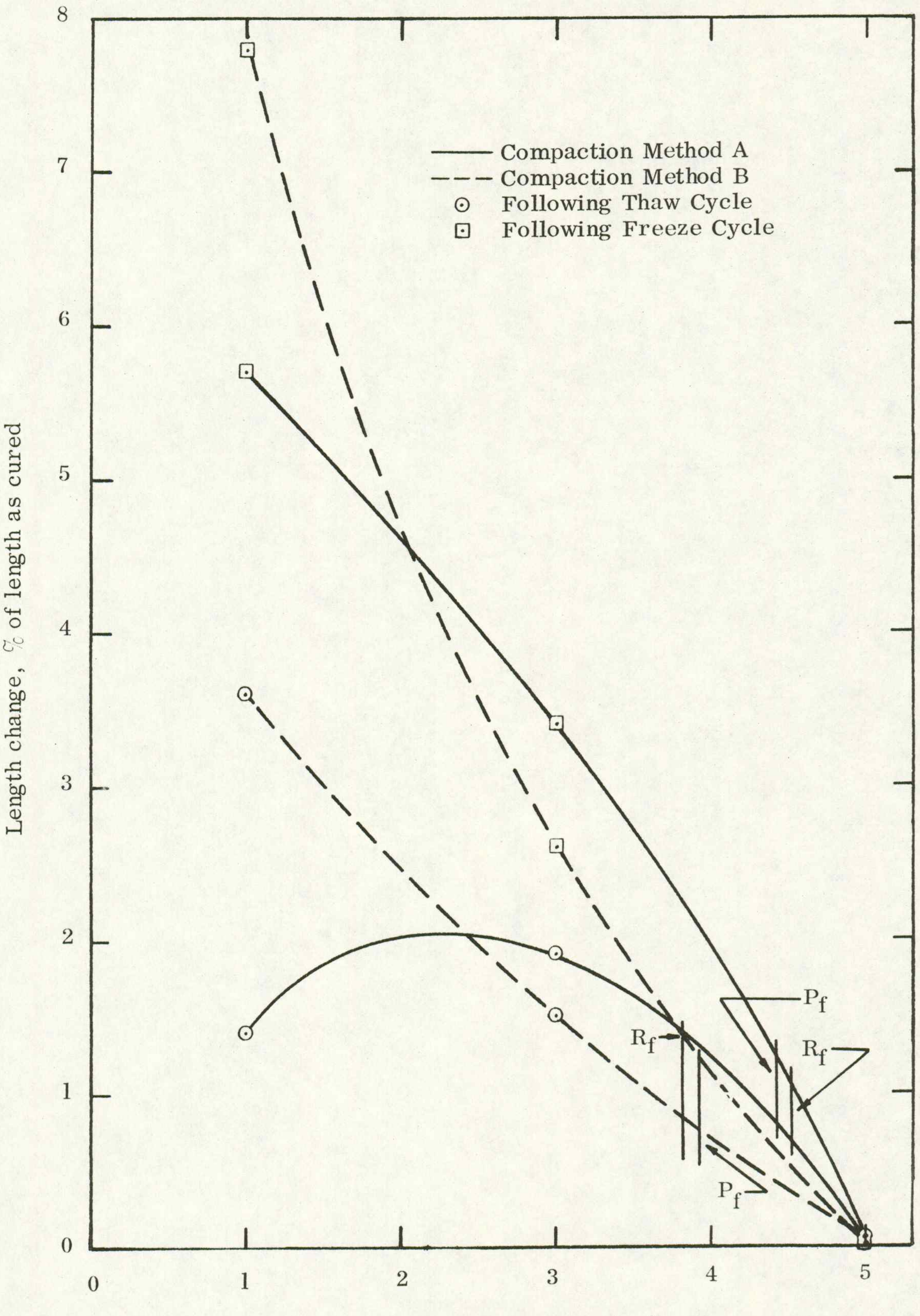


Figure 20. Relationship of cement content to percentage length change of Bedford test specimens following 10 Iowa freeze-thaw cycles.

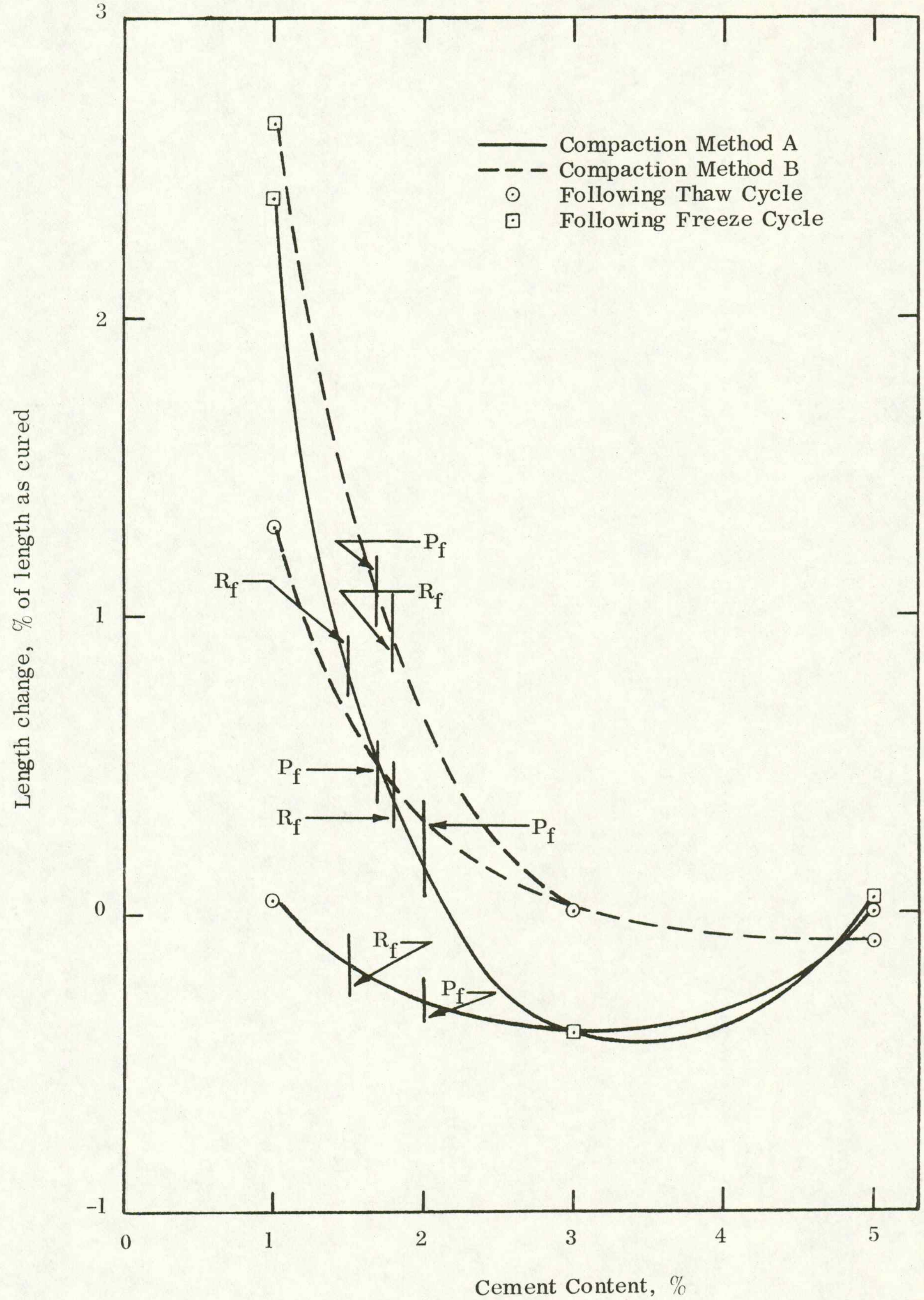


Figure 21. Relationship of cement content to percentage length change of Garner test specimens following 10 Iowa freeze-thaw cycles.

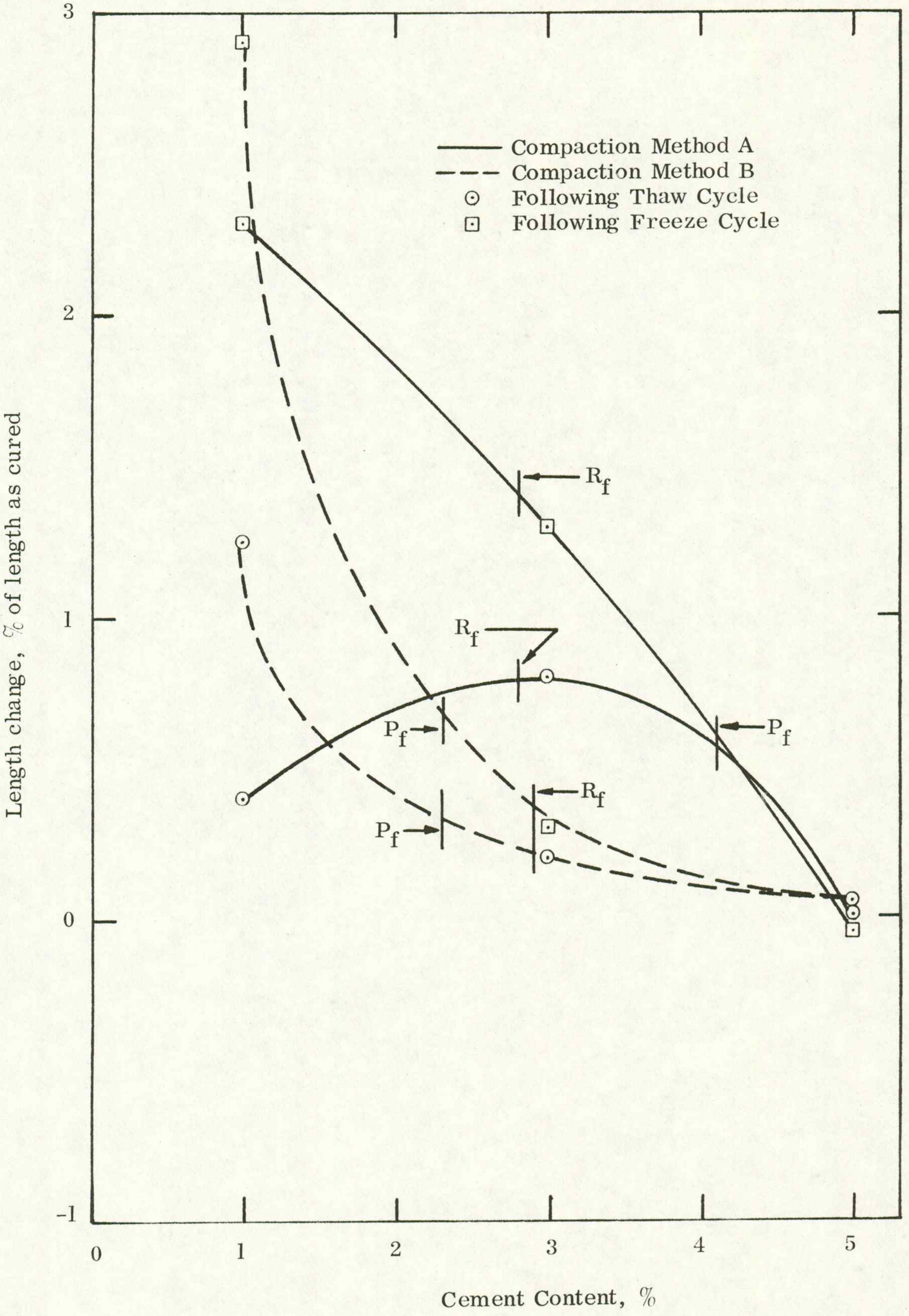


Figure 22. Relationship of cement content to percentage length change of Gilmore test specimens following 10 Iowa freeze-thaw cycles.

CONCLUSIONS

1. Relatively small additions of Type I Portland cement can increase the durability and compressive strength, and decrease the potential volume change upon freezing of compacted crushed stone bases in Iowa.

2. The vibratory method of compaction yields more consistent laboratory densities than does the ASTM compaction method. In addition the vibratory process is less time consuming, and produces less degradation of the particles during compaction.

3. The Iowa freeze-thaw test is easier to conduct and more nearly duplicates actual field conditions of freezing and thawing than does the ASTM test.

4. The Iowa freeze-thaw test allows considerations of strength and length change as well as durability of cement treated granular base materials.

5. The Iowa freeze-thaw test facilitates obtaining a design cement requirement by a simple plot of index of resistance to freezing, R_f, and unconfined compressive strength after test, P_f, versus cement content. The ASTM method often requires additional molding and testing of specimens to pinpoint the design cement content since no convenient method of interpolation is apparent.

6. Cement content by measurement of length change in the Iowa test, appears to be more suitable (probably due to less actual handling of the specimens), and more closely associated with other criteria in the test, than does the length change measurements of the ASTM specimens with the brushing loss test.

7. Accurate length measurements after the freeze cycle can be obtained in the Iowa Freeze-Thaw test but, due to the recommended procedure, can not be obtained in the ASTM Freeze-Thaw test.

8. Percentage of length change of the Iowa test specimens is generally greater than that of the ASTM specimens, and may be indicative of the severity of the test process through greater water attraction and absorption during freezing.

9. Comparison of cement contents by PCA brushing loss and Iowa P_f, indicated variations of 0.5 to 1.0% cement. Comparison of brushing loss and R_f indicated variations of 0.5 to 2.0% cement. In each comparison, the Iowa criteria indicated less cement content was required.

10. The vibratory compaction method usually indicated a slightly lower design cement content than did the ASTM compaction method.

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