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MISSOURI COOPERATIVE HIGHWAY RESEARCH PROGRAM
REPORT 71-3

INVESTIGATION OF "D" CRACKING IN PCC PAVEMENTS

PHASE I

MISSOURI STATE HIGHWAY DEPARTMENT
FEDERAL HIGHWAY ADMINISTRATION

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INVESTIGATION OF "D" CRACKING IN PCC PAVEMENTS

LABORATORY PHASE I

Prepared by

MISSOURI STATE HIGHWAY DEPARTMENT
Division of Materials and Research

May 1971

in cooperation with

U. S. DEPARTMENT OF TRANSPORTATION
Federal Highway Administration

The opinions, findings, and conclusions expressed in this publication are not necessarily those of the Federal Highway Administration.

ABSTRACT

The physical properties of several coarse aggregates, chosen on the basis of their average bulk specific gravities from within the Bethany Falls limestone stratum, were found to correlate with the durability results of the laboratory concrete freeze and thaw test. However, the results were found to be more significant if the internal gravity gradation of each aggregate was considered. The resistance of a concrete to freeze and thaw was found to vary directly with the bulk specific gravity, bulk specific gravity (saturated surface dry), and bulk specific gravity (vacuum saturated surface dry). The resistance also varies indirectly with the absorption of the coarse aggregate used. Coarse aggregates with a bulk specific gravity (saturated surface dry) of 2.65 or less were found to contribute significantly to a decrease in the resistance of the concrete to freeze and thaw.

Other variables considered in this phase of the laboratory test program were sand contents, air contents, maximum size of coarse aggregates used, specific blends of high and low gravity coarse aggregates, and geographic location of the sources from which the aggregates were obtained.

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INTRODUCTION

The primary source of paving stone in the northwestern and west-central areas of the State of Missouri is the Bethany Falls limestone, a member of the Swope formation. Service records from many paving projects built in these areas have shown the concretes to have a low resistance to frost damage as evidenced by the occurrence of "D" cracking adjacent to the longitudinal and transverse joints.

The primary purpose of Laboratory Phase 1, to be covered in this report, of the "D" cracking investigation was to determine if the frost resistance of laboratory concrete specimens could be correlated with the physical properties of the coarse aggregates used. Laboratory Phase 2, now in progress, will consider the effects of different cement brands as related to the frost resistance of laboratory concrete specimens. Eventually, the results of both laboratory phases will be compared with actual field exposure records obtained from the Field Phase which was begun in 1967.

The coarse aggregates used in this phase of the investigation were chosen on the basis of their average bulk specific gravity. Detailed sampling of the stone within many ledges of many quarries in the geographical areas mentioned, showed a range of bulk specific gravity (saturated surface dry) of 2.54 through 2.68 which corresponds to a bulk specific gravity of approximately 2.47 through 2.65. Therefore, for this investigation, coarse aggregates were obtained to represent each of the following bulk specific

gravity groups; 2.68 to 2.64, 2.63 to 2.60, 2.59 to 2.56, 2.55 to 2.52, 2.51 to 2.48, and 2.47 to 2.44, from each of the geographical areas under consideration. Therefore, with the exception of the 2.51 to 2.48 group where only one sample was obtained, two samples were obtained for each gravity group.

The other variables included in this study were limited due to the laboratory's capacity for freezing concrete. These variables were air content at two levels (entrained and non-entrained), sand content at three levels, and maximum size coarse aggregate at two levels. High and low gravity aggregates were blended in different ratios to provide an additional variable.

A modified accelerated laboratory freeze and thaw test was used as the basis for testing the relative effects of each of the variables or combinations of variables to provide protection against freeze and thaw deterioration. An outdoor exposure test was included to provide, at some later date, a relative basis for comparison of the laboratory results with the actual field survey results.

This report presents the results of work completed under Laboratory Phase 1 and the conclusions which these results indicate. The methods of obtaining and preparing the materials, the physical and chemical test data obtained for each coarse aggregate, the mix design and batching information, the test procedures, and the petrographic analysis for each coarse aggregate are included in appendix form.

CONCLUSIONS

The laboratory tests completed under this phase of the "D" cracking investigation have provided excellent results for analysis of the frost resistance of various gravity coarse aggregates obtained from the Bethany Falls formation. Several other variables were included on an exploratory basis only and the results obtained, therefore, must necessarily be limited as must the corresponding conclusions.

A variable which was inadvertently and undesirably included in this test was a difference in the physical character of the limestone samples. This difference was first detected by the irregular trends produced by the results of the freeze and thaw test. The Division of Materials and Research was fortunate in having a trained petrographer on its staff at the time this problem was detected. Therefore, subsequent petrographic analysis of each of the stone samples indicated that although nine of the eleven aggregates were finely crystalline the two aggregates in question were primarily composed of oolites and pellets bound together by a calcite matrix. Even though the remaining nine aggregates did compare fairly well in their relative rate of failure, the petrographic analysis did show two of these aggregates to have undergone some degree of dolomitization, and would be classified as dolomitic limestones.

Specifically, from the results of the laboratory tests thus performed under this phase of the "D" cracking investigation, the following conclusions seem justified:

1. The rate of deterioration of the concrete beams increased as the average bulk specific gravity (saturated surface dry) of the coarse aggregate decreased.

2. The internal gravity gradation of the coarse aggregate must be considered as having some degree of influence on its frost resistance. A five term multiple linear relationship was derived which is only representative of the samples used in this phase of the investigation. This relationship shows the relative contribution of coarse aggregate particles having a bulk specific gravity (vacuum saturated surface dry) below 2.65 reduces the frost resistance of concrete.

3. The rate of deterioration based on the permanent dilation of the concrete specimens at the end point of the test was not significant because the specimens which failed all had ultimate dilations of 0.06 to 0.10 percent. However, the permanent dilations occurring at 10 cycles of freeze and thaw were found to be good indicators of the ultimate rate of deterioration.

4. The effects of the variation in sand content, for exploratory purposes only, were not absolutely conclusive; however, there is a trend that the higher sand content of 45 percent of the total aggregate fraction did appear to increase the resistance to frost action.

5. The entrainment of air in the concretes added significantly to the resistance to frost action. However, the actual difference in the number of freeze and thaw cycles at failure of the air and nonair-entrained specimens was small.

6. The effect of the 2 inch maximum size coarse aggregate was found to be more pronounced with the rapid-failing aggregate. The 2 inch gradation caused failure of the rapid-failing aggregate in approximately 2/3 of the time required for the 1 inch gradation, but made little difference with the slow-failing aggregate.

7. The results of blending high and low gravity aggregates did not fit the multiple linear equation derived for the individual samples as well as expected. In general, the results did show a decrease in a concrete's resistance to freeze and thaw when the percentage of low gravity stone is increased.

8. The outdoor exposure test has not had sufficient time to give any significant results at this time.

9. The geographical location from which these samples were obtained was intended only as a means of distributing the source of the samples to be taken. Therefore, comparison of the results of the two areas from the data contained herein and the fact that the samples were chosen on the basis of average bulk specific gravity would be highly misleading.

IMPLEMENTATION

Based on the increasing occurrence and seriousness of "D" cracking in many of the concrete pavements located in the northwestern and west-central districts of the State of Missouri, major changes were made in the mix design of the concrete. In addition, placement of a 4 mil polyethylene sheeting moisture barrier was required between the subbase and the pavement on Portland Cement Concrete Pavements to be built in these areas. This was set out in a special provision to apply in these areas after June 1967. To test the significance of these changes, laboratory and field investigations were also initiated in June 1967.

The conclusions from the laboratory investigation presented in this report indicate the modifications to the mix design specifically mentioned in the special provision were warranted. These modifications have caused the standard for acceptance of Bethany Falls limestone to increase and in some cases may not have been increased enough. Definite analysis of the benefit gained from the changes which were made will come from the Field Phase of this investigation which was initiated with the first projects built to compliance with the special provisions.

SCOPE

Eleven coarse aggregates, six from the northwestern and five from the west-central districts of the State of Missouri, Figure 1, were chosen for use in this laboratory phase of the Investigation of "D" Cracking. All of these aggregates were obtained from within the Bethany Falls member of the Swope formation. The variables introduced into this investigation for purposes of evaluating the freeze and thaw resistance of concrete with stones from this formation were:

A. Coarse aggregates with bulk specific gravities between 2.66 and 2.47.

B. Sand contents of 33, 37, and 45 percent of the total aggregate fraction with air entrained concretes and 36.3, 40.1, and 47.7 percent with nonair-entrained concretes.

C. Air-entrained and nonair-entrained concretes.

D. Maximum size coarse aggregate of 1 and 2 inches, necessitating the making of two sizes of concrete specimens of 3½ x 4½ x 16 inches and 6 x 6 x 20 inches respectively.

E. Specific blends of high and low gravity coarse aggregates.

F. Indoor freeze and thaw test with an outdoor natural exposure test, and

Figure 1 - Location of Sampling Sites.

G. Geographical location from which the coarse aggregates were obtained.

Specific details of the physical characteristics and petrographic descriptions of these coarse aggregates are shown in Appendix A and B, respectively of this report.

A total of 348, 3½ x 4½ x 16 inch beams and a total of 48, 6 x 6 x 20 inch beams were made and tested to establish the freeze and thaw resistance of the concretes with the above mentioned variables. The specific arrangement of the number and quantity of beams designed to accommodate all of these variables with our limited freezing and thawing facilities is given in Appendix C of this report.

The modified accelerated freeze and thaw test consisted of freezing the beams in air at 0°F once each week with storage in a saturated limewater solution at room temperature between cycles. The beams were terminated as their dynamic modulus of elasticity, "E", dropped below 70 percent of their 35-day value (30 percent loss) or at the end of 100 cycles. Complete details of the test procedures used in this phase are shown in Appendix D of this report.

PETROGRAPHIC ANALYSES

The coarse aggregates were obtained from within the same geologic formation; however, the sampling points were widely separated geographically. Various sampling points were necessary because all the stones having the proper average specific gravities satisfactory for including in the test could not be found in sufficient quantity at any one point.

Due to the wide geographic distribution a petrographic analysis was made to evaluate the relative composition and structure of each source. It has been mentioned in reports published recently by other organizations that petrographic analysis may assist greatly in the identification of frost susceptible aggregates. Unlike this investigation, however, most of these studies have dealt with different types of aggregates or mixtures of many types of aggregates such as those found in glacial or river deposits. All the coarse aggregates included in this investigation are of sedimentary origin within the same geological era, therefore, were expected to be similar in many aspects.

The data shown in Table 1, as a result of petrographic examination of each aggregate source, disproved the expectation of similarity between the sources. The first noticeable difference was that coarse aggregates 4 and 6 had undergone some degree of dolomitization. The dolomitic limestone designation means that there was a high percentage of rhombohedral-shaped crystals within these coarse aggregates. Apparently the

Table 1 - Petrographic Description of Coarse Aggregates After Crushing for Use in Concrete Specimens

Coarse Aggr.	Hardness(1) Range	Porosity	Thin Section Analyses(2)	Degree Rounding(4)
1	3.5 - 3.8	Low	Microcrystalline Fossiliferous Ls.	Angular
2	3.5	Moderate	Microcrystalline Fossiliferous Ls.	Angular
3	3.1	Moderate	Microcrystalline Fossiliferous Ls.	Angular
4	2.5 - 3.0	High	Finely Crystalline Dolomitic Ls.	Rounded
6	2.5 - 3.0	High	Finely Crystalline Dolomitic Ls.	Rounded
7	3.3	Moderate	Microcrystalline Fossiliferous Ls.	Angular
8	3.2 - 3.3	Low	Microcrystalline Fossiliferous Ls.	Angular
9	3.1 - 3.7	Moderate	Microcrystalline Ls.	Angular
10	3.0 - 4.0	High	Mixed Oolitic & Pelletal Ls.(3)	Angular
11	3.1	High	Microcrystalline Ls.	Sub-Rd.
12	3.8 - 4.0	High	Mixed Oolitic & Pelletal Ls.(3)	Sub-Angular

(1) Average of scratch tests by Mohs Scale, made on all sides of several aggregate particles for each coarse aggregate.
(2) Using terminology described by Folk, (II) p. 14.
(3) The oolites and pellets are bonded together with clear discrete interlocking crystals of calcite.
(4) Determined by comparison with index made by Geological Specialty Co. for Sand Gauge.

variations do not affect the relative freeze and thaw resistance in such a manner that it could be detected in this study because statistical evaluations including coarse aggregates 4 and 6 remained significant.

The second noticeable difference between the aggregates was the structures of coarse aggregates 10 and 12. These two stones were of slightly coarser texture than the other aggregates and were composed of oolites and pellets in a fine matrix of calcite and microspar. Apparently the deposition of these limestones occurred under different conditions than the other aggregates experienced. These two aggregates did not conform to the expected rate of failure for the gravity stone they represented. Two possibilities exist which may explain this deviation in performance. One is the compositional structure or the arrangement of compounds as described by the petrographic analyses, see Appendix B for specific descriptions. The other possibility is that the pore structure of the two aggregates may be significantly different when compared to the other aggregates. This difference can be shown by the data in Table 12, Appendix A, under the columns headed "Percent of Vacuum Saturated Absorption". These values are the percent absorption at two hours as compared to the absorptions obtained by vacuum saturation. Aggregates 10 and 12 did not gain water by absorption at a rate comparable to the other aggregates. Specific correlations derived by using aggregates 10 and 12 will be compared with the correlations omitting aggregates 10 and

12 in the discussion of the results in the remainder of this report.

Further basis for the implication that the Bethany Falls limestone is heterogenous in structure and composition are the columnar sections representing each quarry in the geographical areas under consideration and other published reports of investigations dealing with different properties of the Bethany Falls limestone. One such report was written by Charles Payton (I)* wherein he subdivides and reclassifies the Bethany Falls into nine different geologic facies. In his report each of these facies are well defined and reflect the variation in depositional environments under which the Bethany Falls strata was created.

The detailed petrographic descriptions and microphotographs of each of these coarse aggregates are shown in Appendix B.

*The Roman numeral in parenthesis refers to the reference listing at the end of this report.

PHYSICAL RELATIONSHIPS WITHIN THE AGGREGATES

The coarse aggregates used in this phase of the "D" cracking investigation were all obtained from within the same geological formation even though they were widely separated geographically. Generally, it should be reasonable to consider the basic physical properties of aggregate obtained from within the same geologic stratum to maintain some emperical relationships. In the previous discussion it was indicated that this was not true for the coarse aggregates included in this investigation. Therefore, further restrictions of the statement would be to require the aggregates to be within the same family grouping as described by Folk (II) and others. This restriction will become apparent as examination of the following data will be made by including or excluding the aggregates of different family groupings.

The relationship between the two-hour absorptions and the gravities of the coarse aggregates were examined by regression analysis. Figures 2 and 3 show the bulk specific gravity and bulk specific gravity (saturated surface dry) correlated with the two-hour absorption as calculated on a weight or volume basis. The respective coefficient of correlation for the regression lines are:

Figure 2: Two-hour Absorption (weight basis) vs.

Bulk Specific Gravity:	N = 11	r = 0.89
	N = 9	r = 0.97
Bulk Specific Gravity (SSD):	N = 11	r = 0.77
	N = 9	r = 0.93

Figure 2 - Relationship Between Bulk Specific Gravity and Bulk Specific Gravity (Saturated Surface Dry) With the Two-Hour Absorption. (Weight Basis)

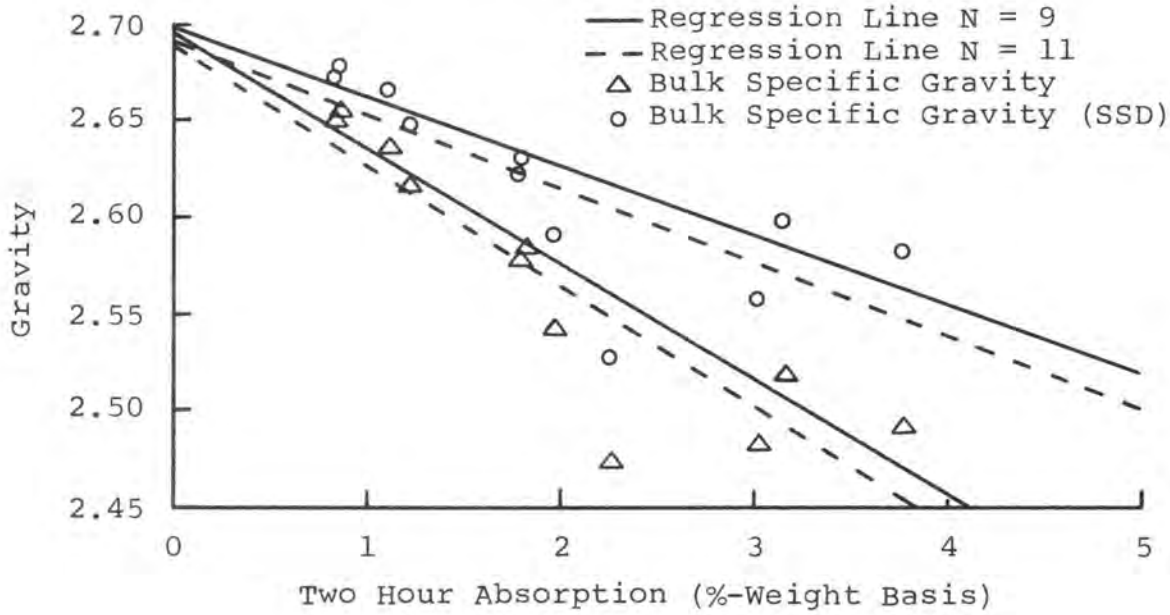


Figure 3 - Relationship Between Bulk Specific Gravity and Bulk Specific Gravity (Saturated Surface Dry) With the Two-Hour Absorption. (Volume Basis)

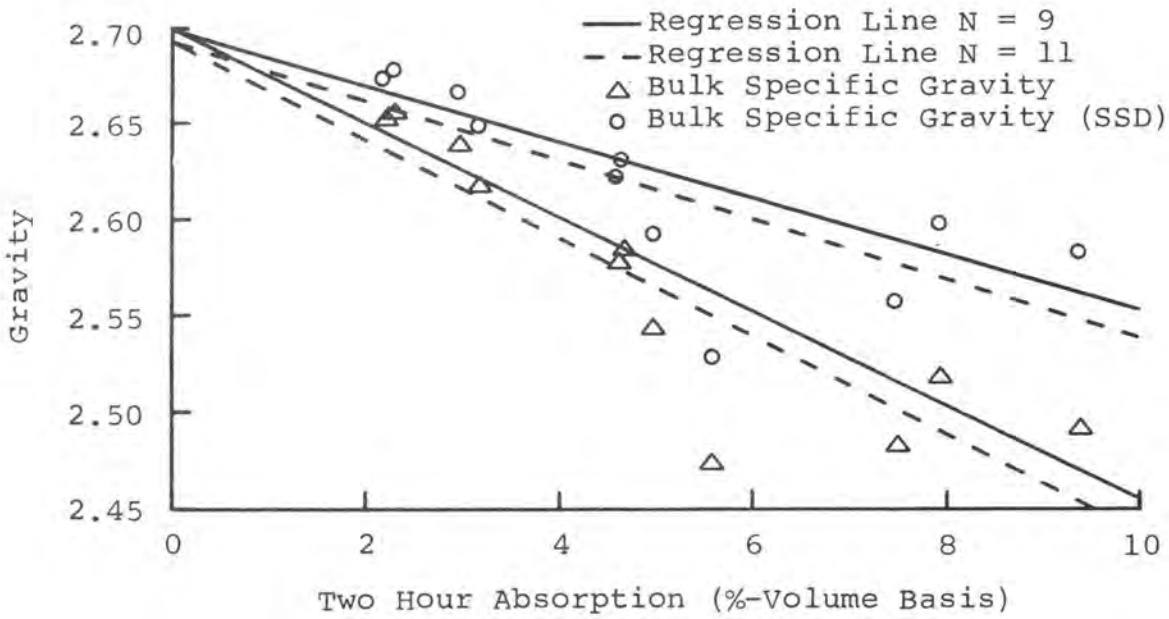


Figure 3: Two-Hour Absorption (volume basis) vs.

Bulk Specific Gravity:	N = 11	r = 0.89
	N = 9	r = 0.97
Bulk Specific Gravity (SSD):	N = 11	r = 0.76
	N = 9	r = 0.92

From these coefficients there appears to be little difference between the degree of the correlations obtained by using either of the two-hour absorption factors. However, there is a substantial difference between the correlation coefficients when coarse aggregates 10 and 12 are included in the analysis (N = 11).

The best correlation was obtained using the bulk specific gravity with either the two-hour absorption, by weight or volume basis, and only considering the nine fine-grained coarse aggregates.

The relationships between the results of the two-hour absorptions and the vacuum absorptions are shown in Figures 4 and 5. The effects of aggregates 10 and 12 are not as pronounced in these cases, however, the correlations are better where these two aggregates are omitted from the analyses.

The expressed differences in composition and the fact that coarse aggregates 10 and 12 do not correlate with the other aggregates, doubt must be placed as to whether it would be proper to evaluate all these aggregates together. However, the results of coarse aggregates 10 and 12 will be studied along with the other coarse aggregates by showing the difference they cause in correlation of the results.

Figure 4 - Relationship of the Two-Hour and Vacuum Absorptions of the Coarse Aggregates by Weight Basis.

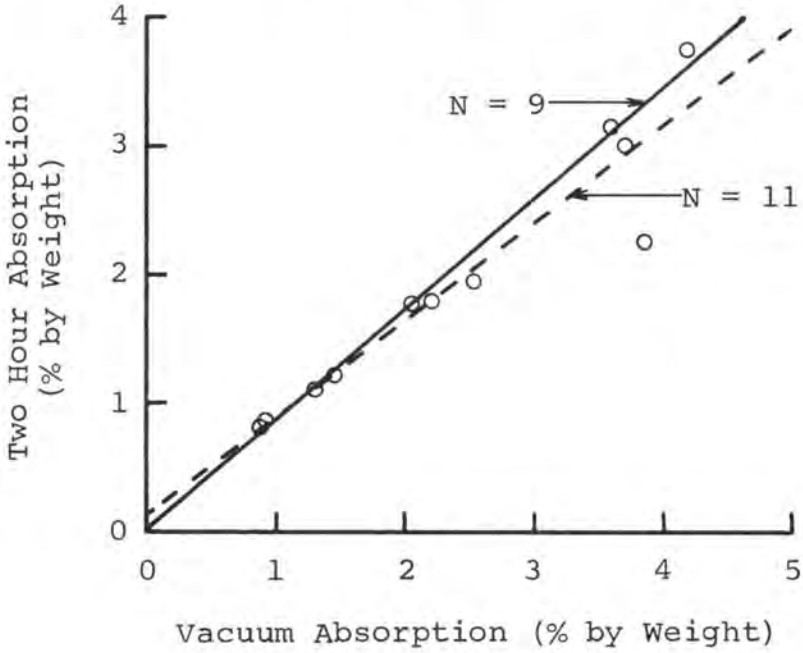
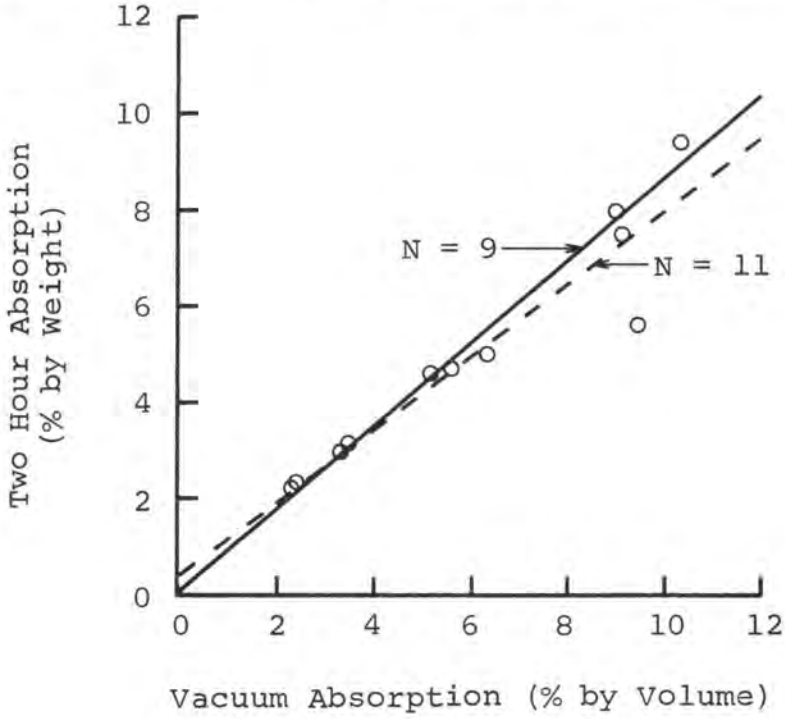


Figure 5 - Relationship of the Two-Hour and Vacuum Absorptions of the Coarse Aggregates by Volume Basis.



In so doing, the emphasis of this report will be placed on the fine-grained sublithographic limestone contained within the Bethany Falls ledges.

GRAVITY GRADATION ANALYSIS OF COARSE AGGREGATE

A heavy liquid separation was made on one sample of each of the coarse aggregates. The separation analysis was prompted by the noticeable variations in the gravities of the ledge samples.

The large variation in the distribution of different gravity material occurring by random sampling of each of the coarse aggregates is shown in Table 2. The first four aggregate samples to be separated were subdivided into six groups roughly representing the division points between the desired bulk specific gravities. Later the division points were changed to equal intervals of 0.025 bulk specific gravity units. A few of the values shown in Table 2 are representative of very small amounts of material and are relatively insignificant in contributing to the whole.

The bulk specific gravity and bulk specific gravity (vacuum saturated surface dry) for the material retained in each batching fraction are shown in Appendix D. The distribution of the material within each sample based on the gradation and bulk specific gravity (vacuum saturated surface dry) are shown in Figures 6 and 7. Even though the average bulk specific gravity of each coarse aggregate was within the specified group limits established for this investigation, a substantial range with variable amounts of high to low gravity materials was found in each aggregate sample.

Table 2 - Gradation of Coarse Aggregates by Heavy Liquid Separation

Coarse Aggr.	Percent by Dry Weight of Blended Sample(1)						
	+2.675	2.675 to 2.650	2.650 to 2.625	2.625 to 2.600	2.600 to 2.575	2.575 to 2.550	-2.550
1	27.036	58.061	10.456	2.208	1.182	0.519	0.538
2	5.033	49.890	31.274	11.231	0.344	1.038	1.190
2(2)	4.950	59.791	25.073	8.069	0.608	0.606	0.903
3	0.820	25.186	30.341	25.358	9.938	5.342	3.015
4	0.390	10.476	20.375	41.218	18.777	5.917	2.847
4(2)	0.657	9.077	20.463	44.278	19.748	4.031	1.746
6	0.005	0.436	1.557	78.492	1.783	13.833	3.894
11	- -	0.298	3.696	19.076	27.070	27.556	22.304
12	3.528	6.810	16.722	16.794	14.398	10.018	31.730

Coarse Aggr.	Percent by Dry Weight of Blended Sample(1) & (3)					
	+2.650	2.650 to 2.610	2.610 to 2.570	2.570 to 2.530	2.530 to 2.490	-2.490
7	95.385	4.132	0.483	- -	- -	- -
8	57.452	36.423	4.694	1.131	0.300	- -
9	15.846	48.152	29.070	6.058	0.664	0.210
10	16.898	18.944	33.510	22.643	6.303	1.702

(1) Blended Sample means the fractions 1" to 2", ½" to 1", and #4 to ½" blended to the ratios shown in Table 11.
(2) Note 2" max. size aggregate for this gradation analysis, Gradation A.
(3) These samples were run before the gravity groups were established as shown above.

Figure 6 - Distribution of Gravity Separated Coarse Aggregates Obtained from West-Central Missouri.

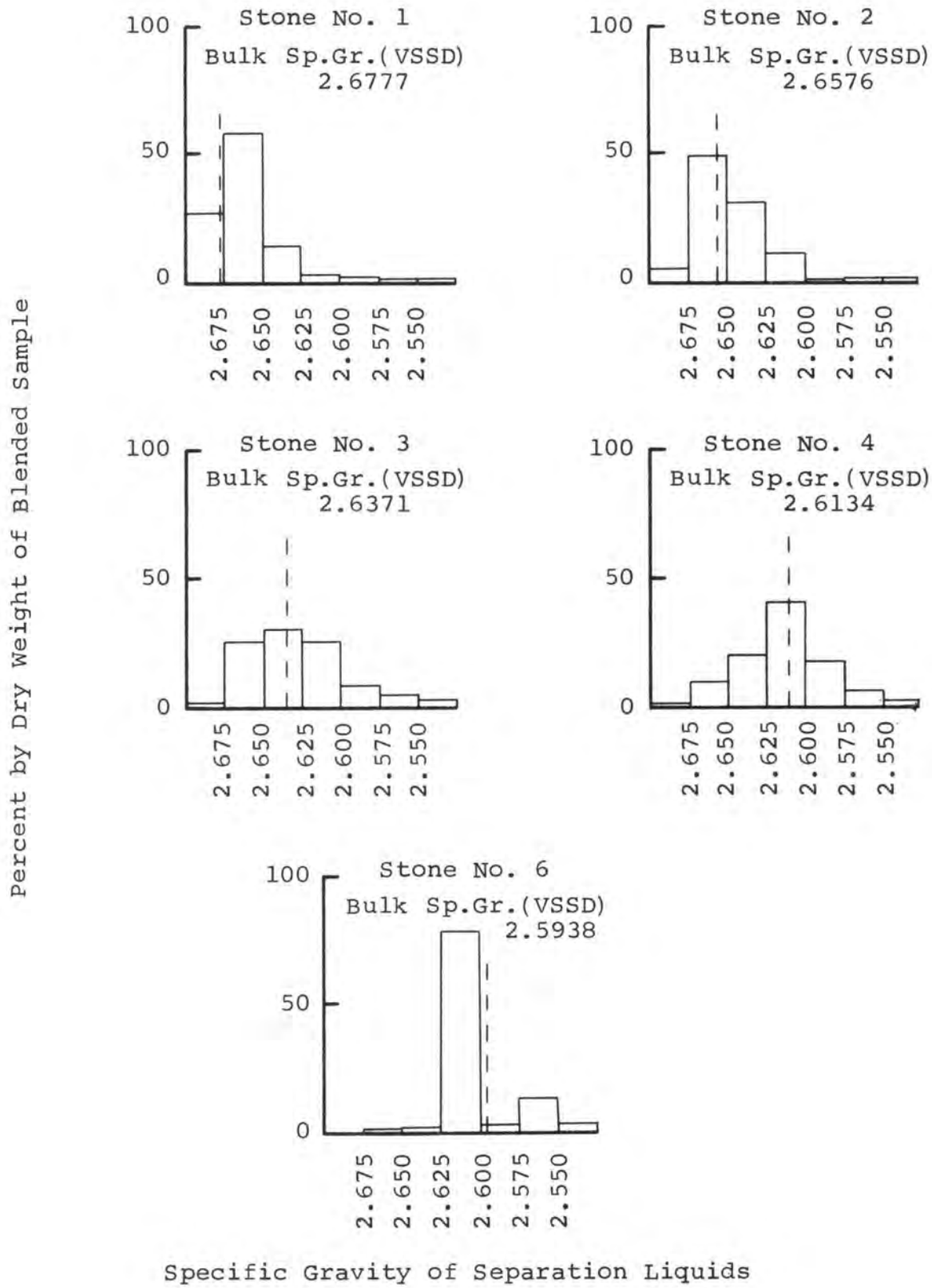
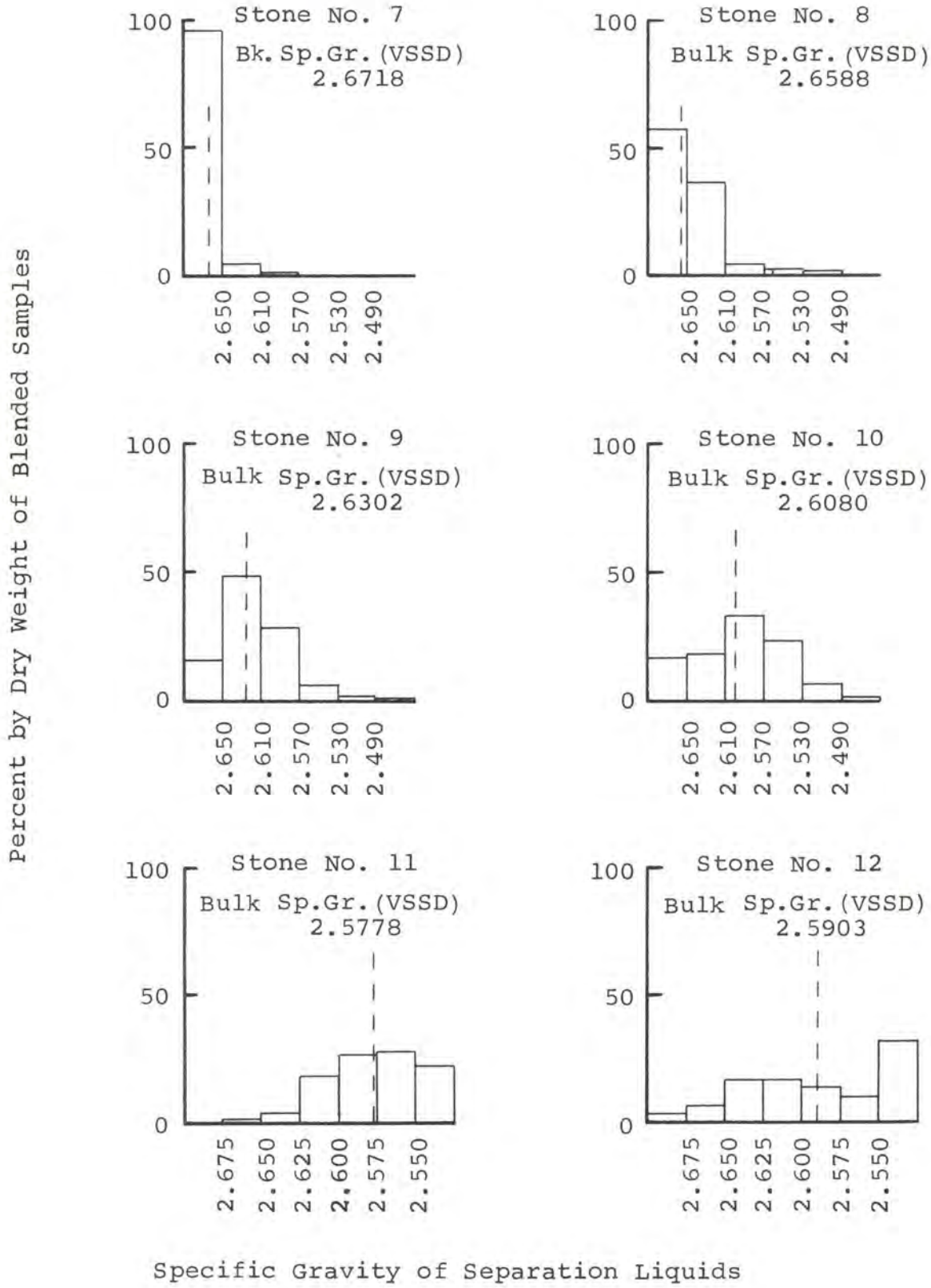


Figure 7 - Distribution of Gravity Separated Coarse Aggregates Obtained from Northwestern Missouri.



The multiple linear regression analysis was used to establish the relative contribution of each gravity fraction to resist frost damage. The data was regrouped into four bulk specific gravity (vacuum saturated surface dry) classifications of 2.57 or less, 2.58 to 2.61, 2.62 to 2.65, or greater than 2.65. The regression coefficients (b_0, b_1, b_2 . . b_n) thus derived gave a relative weight to the contribution of each variable (the quantity of material retained in each gravity classification) to the rate of freeze and thaw deterioration. The data and the equations derived therefrom are shown in Table 3. It was necessary at this point to prematurely inject data from the results of the freeze and thaw test in order to derive this relationship. It will suffice at this point to say that the "Durability Factor" (DF), as used in Table 3, is a parameter indicating the relative rate of failure of concrete beams subjected to the freeze and thaw test based on strength properties of the concrete beams. The two equations thus derived show the relative similarity of the nine fine-grained samples and the complete lack of similarity of coarse aggregates 10 and 12. The coefficients of multiple correlation for the two equations are 0.73 and 0.94 for N values of 11 and 9 respectively.

Interpretation of those equations gives a general relative relationship of the contribution of each group of coarse aggregate contained within the bulk specific gravity (vacuum saturated surface dry) limits as shown, to effectively increase or decrease the resistance of

Table 3 - Regression Analysis for Gravity Separated Samples of Each Coarse Aggregate.(1)

Coarse Aggr.	Percent by Dry Weight of Blended Sample 2.57 (A)	2.58-2.61 (B)	2.62-2.65 (C)	2.65 (D)	Durability Factor (DF)
1	1.0	2.3	11.6	85.1	85
2	2.2	6.0	36.9	54.9	45
3	8.4	22.6	43.0	26.0	22
4	8.7	39.4	41.0	10.9	18
6	17.8	41.0	40.8	0.4	18
7	0.0	0.5	4.1	95.4	94
8	1.4	4.7	36.4	57.5	86
9	6.9	29.1	48.2	15.8	37
10	30.6	33.5	19.0	16.9	91
11	49.9	36.6	13.2	0.3	11
12	41.8	22.8	25.1	10.3	96

The multiple linear regression analysis using all samples where N will equal 11 yields:

$$DF = -8.2223 + (1.5246)A - (0.4990)B + (0.5122)C + (1.0488)D$$

This equation has a coefficient of multiple correlation of $r = 0.73$.

The multiple linear regression analysis using only the nine samples, considered to be similar, yields:

$$DF = 55.9956 - (0.4158)A - (0.5547)B - (0.3234)C + (0.4104)D$$

This equation has a coefficient of multiple correlation of $r = 0.94$.

(1) Multiple linear regression analysis method shown in Rider (III).

laboratory concrete specimens to the accelerated freeze and thaw test. The relationship for N = 9 gives an indication as to what effects may be expected by increasing the percentage of the lower gravity stone in a concrete aggregate. More specifically, this relationship is only applicable to the type of limestone represented by the nine similar coarse aggregates used in this investigation.

The parameter described above will be used extensively in the discussion of the results and will tend to show freeze and thaw failure in a more realistic perspective rather than by the average bulk specific gravity only.

The vacuum absorption by weight and volume for each batching fraction are shown in Table 19, Appendix D.

RESULTS OF THE FREEZE AND THAW TEST

The results of this phase of the laboratory investigation are necessarily complex because of the many variables introduced to gain exploratory information as to their relative effects on the ability of concrete specimens to resist the Missouri freeze and thaw test. The following discussion of the results will be subdivided with each subdivision dealing with only one set of variables at a time. The results will be discussed in the same order in which the variables were introduced in the scope of this report.

The beams subjected to the freeze and thaw test were tested once each week for their change in length, weight, and sonic frequency. Tables 4, 5, and 6 summarize the average results of the measurements taken on each of the four replicate specimens for each mix design. The results shown in these tables will be used extensively throughout the following discussions.

A relative measure of the ability of laboratory concrete specimens to resist frost action, by application of a laboratory freeze and thaw test has been described in terms of a parameter labeled "Durability Factor", such as that explained in ASTM Designation C290-67 and C291-67. Even though our freeze and thaw method does not comply with either of the ASTM methods as described therein, the relative results obtained by using the durability factor formula should provide a valid analysis as long as they are not

Table 4 - Ultimate Permanent Dilation of Concrete Beams Subjected to the Freeze and Thaw Test.

Concrete Mix Design	Percent Gain in Length (1)					
	7 Days at 70°F			35 Days at 70°F		
	Top	Bottom	Avg.	Top	Bottom	Avg.
	3½ x 4½ x 16 inch Concrete Beams					
1-1AS	(2)	(2)	(2)	(2)	(2)	(2)
2-1AS	0.124	0.131	0.128	0.124	0.128	0.129
2-1BS	0.125	0.118	0.122	0.121	0.114	0.118
2-1CS	0.108	0.119	0.114	0.106	0.118	0.112
2-2DS	0.140	0.134	0.137	0.138	0.134	0.136
2-2ES	0.138	0.110	0.124	0.138	0.109	0.123
2-2FS	0.135	0.113	0.124	0.136	0.114	0.124
3-1AS	0.118	0.110	0.114	0.119	0.109	0.113
4-1AS	0.127	0.110	0.118	0.126	0.109	0.118
4-1BS	0.122	0.093	0.107	0.123	0.094	0.108
4-1CS	0.124	0.090	0.107	0.122	0.087	0.104
4-2DS	0.123	0.114	0.118	0.124	0.114	0.119
4-2ES	0.108	0.114	0.111	0.106	0.113	0.109
4-2FS	0.105	0.120	0.112	0.101	0.116	0.108
6-1AS	0.115	0.098	0.106	0.117	0.100	0.107
6-1BS	0.130	0.083	0.107	0.127	0.081	0.104
6-1CS	0.124	0.093	0.108	0.124	0.091	0.107
6-2DS	0.106	0.138	0.122	0.103	0.136	0.119
6-2ES	0.096	0.131	0.114	0.092	0.130	0.105
6-2FS	0.074	0.133	0.104	0.073	0.128	0.101
7-1AS	(2)	(2)	(2)	(2)	(2)	(2)
8-1AS	(2)	(2)	(2)	(2)	(2)	(2)
9-1AS	0.108	0.085	0.097	0.108	0.084	0.096
10-1AS	(2)	(2)	(2)	(2)	(2)	(2)
11-1AS	0.096	0.080	0.088	0.093	0.077	0.085
12-1AS	(2)	(2)	(2)	(2)	(2)	(2)
1&3-1AS	0.130	0.127	0.129	0.127	0.127	0.127
1&6-1AS	0.118	0.138	0.129	0.123	0.106	0.130
2&4-1AS	0.124	0.116	0.121	0.125	0.115	0.109
2&6-1AS	0.128	0.134	0.131	0.124	0.130	0.127
	6 x 6 x 20 inch Concrete Beams					
2-1AS	0.110	0.117	0.113	0.107	0.114	0.110
2-1AO	0.112	0.119	0.116	0.112	0.118	0.114
2-1CO	0.109	0.084	0.097	0.110	0.086	0.098
4-1AS	0.124	0.093	0.108	0.125	0.090	0.107
4-1AO	0.104	0.076	0.090	0.102	0.077	0.090
4-1CO	0.099	0.080	0.090	0.098	0.080	0.088

(1) Gain in length based on the length at either 7 days or 35 days as shown in the column headings.
(2) Data omitted because beams did not fail prior to the 100-cycle termination point.

Table 5 - Ultimate Change in Weight of Concrete Beams Subjected to the Freeze and Thaw Test.

Concrete Mix Design	Percent Gain in Weight (1)	
	1 Day at 70°F	35 Days at 40°F
	$3\frac{1}{2}$ x $4\frac{1}{2}$ x 16 inch Concrete Beams	
1-1AS	(2)	(2)
2-1AS	1.09	0.42
2-1BS	1.04	0.40
2-1CS	1.08	0.50
2-2DS	0.79	0.23
2-2ES	0.77	0.27
2-2FS	0.79	0.24
3-1AS	0.95	0.44
4-1AS	1.10	0.42
4-1BS	0.98	0.30
4-1CS	0.91	0.28
4-2DS	0.91	0.31
4-2ES	0.88	0.27
4-2FS	0.92	0.28
6-1AS	1.03	0.33
6-1BS	1.03	0.30
6-1CS	1.02	0.28
6-2DS	0.83	0.25
6-2ES	0.85	0.24
6-2FS	0.78	0.19
7-1AS	(2)	(2)
8-1AS	(2)	(2)
9-1AS	1.05	0.37
10-1AS	(2)	(2)
11-1AS	1.06	0.40
12-1AS	(2)	(2)
1&3-1AS	1.06	0.42
1&6-1AS	1.00	0.38
2&4-1AS	1.01	0.40
2&6-1AS	0.99	0.41

(1) Gain in weight based on the weight at either 1 day or 35 days as shown in the column headings.
(2) Data omitted because beams did not fail prior to the 100-cycle termination point.

Table 6 - Ultimate Change in Sonic Frequency of Concrete Beams Subjected to the Freeze and Thaw Test.

Concrete Mix Design	Sonic Frequency (Cycles/Sec. at 40°F) 35 Days	End(1)	Loss in Sonic Frequency(2) (Percent)
	3½ x 4½ x 16 inch Concrete Beams		
1-1AS	(3)	(3)	(3)
2-1AS	2054	1704	31.2
2-1BS	2045	1686	32.0
2-1CS	2022	1672	31.6
2-2DS	2091	1726	31.9
2-2ES	2089	1736	30.9
2-2FS	2104	1739	31.7
3-1AS	2019	1656	32.7
4-1AS	1909	1571	32.2
4-1BS	1880	1536	33.2
4-1CS	1856	1534	31.7
4-2DS	1960	1602	33.2
4-2ES	1945	1602	32.1
4-2FS	1918	1566	33.3
6-1AS	1849	1516	32.7
6-1BS	1816	1494	32.4
6-1CS	1784	1459	33.2
6-2DS	1885	1551	32.3
6-2ES	1855	1518	33.0
6-2FS	1835	1504	32.8
7-1AS	(3)	(3)	(3)
8-1AS	(3)	(3)	(3)
9-1AS	2030	1676	31.8
10-1AS	(3)	(3)	(3)
11-1AS	1965	1599	33.8
12-1AS	(3)	(3)	(3)
1&3-1AS	2045	1662	33.8
1&6-1AS	2021	1675	31.3
2&4-1AS	1972	1625	32.2
2&6-1AS	2011	1664	31.6
	6 x 6 x 20 inch Concrete Beams		
2-1AS	2065	1698	32.4
2-1AO	2071	1714	31.6
2-1CO	2049	1701	31.0
4-1AS	1900	1565	32.2
4-1AO	1914	1565	33.1
4-1CO	1848	1526	31.7

(1) "End" signifies the average sonic frequency remaining in the beams at the date of termination from the freeze and thaw test.

(2) Calculated as percent difference in the squares of the frequencies at termination and the original 35-day frequency.

(3) Data omitted because beams did not fail prior to the 100-cycle termination point.

construed to mean or are not compared with durability factors derived by other test procedures.

The durability factors obtained by averaging the relative results for each of the four replicate specimens representing each mix design are shown in Table 7. These durability factors will be used quite extensively throughout the remainder of this report as a measure of the ability of each particular combination of variables to resist deterioration due to frost action as described by the various physical properties of the coarse aggregates and the concrete beams.

Coarse aggregates 10 and 12 were shown to be different in basic structure and grain texture by the petrographic analyses and were shown to influence the gravity separation analyses to an extent that they had to be eliminated from the multiple regression analysis to have a significant relationship. Apparently, there is a band of this type of pelletal-oolitic low gravity limestone within the Bethany Falls member of the Swope formation; however, to study the results of these coarse aggregates on an equal basis with the other nine coarse aggregates would be misleading. There is a need for a field survey to be made of the Bethany Falls strata to obtain more information about the relative percentage of each type of limestone present.

Table 7 - Durability Factors

Concrete Mix Design	Percent of Sonic Frequency Remaining at End of Tests	Cycles of Freeze and Thaw at Termination	Durability Factor (DF)
	3½ x 4½ x 16 inch Concrete Beams		
1-1AS	84.8	100.00	84.8
2-1AS	68.8	65.00	44.7
2-1BS	68.0	55.75	37.9
2-1CS	68.4	60.00	41.0
2-2DS	68.1	59.00	40.2
2-2ES	69.1	59.25	40.9
2-2FS	68.3	55.25	37.7
3-1AS	67.3	32.25	21.7
4-1AS	67.8	26.50	18.0
4-1BS	66.8	22.75	15.2
4-1CS	68.3	20.75	14.2
4-2DS	66.8	20.75	13.9
4-2ES	67.9	17.75	12.0
4-2FS	66.7	16.00	10.7
6-1AS	67.3	26.25	18.0
6-1BS	67.6	24.25	16.4
6-1CS	66.8	24.75	16.5
6-2DS	67.7	18.00	12.2
6-2ES	67.0	15.75	10.6
6-2FS	67.2	14.25	9.6
7-1AS	94.2	100.00	94.2
8-1AS	85.6	100.00	85.6
9-1AS	68.2	53.75	36.6
10-1AS	91.4	100.00	91.4
11-1AS	66.2	17.25	11.4
12-1AS	95.5	100.00	95.5
1&3-1AS	66.2	49.50	32.8
1&6-1AS	68.7	68.75	47.2
2&4-1AS	67.8	36.50	24.7
2&6-1AS	68.4	49.50	33.8
	6 x 6 x 20 inch Concrete Beams		
2-1AS	67.6	84.75	57.3
2-1AO	68.4	78.25	53.5
2-1CO	69.0	66.50	45.9
4-1AS	67.8	44.50	30.9
4-1AO	66.9	30.00	20.1
4-1CO	68.3	27.25	18.6

DISCUSSION OF RESULTS

VARIABLE A - COARSE AGGREGATES WITH BULK SPECIFIC GRAVITIES BETWEEN 2.66 and 2.47.

Variable A - Effects Measured by Sonic Frequency

The primary objective of this phase of this investigation was to study the relative rate of breakdown, as shown in Figure 8, which occurred in concrete specimens made with various coarse aggregates obtained from within the Bethany Falls ledges. To establish the existence of a true difference between the coarse aggregates, an analysis of variance was run on the durability factors as shown previously in Table 7 for the air-entrained 45 percent sand content (1AS) specimens. The analysis showed a significant difference in the rate of failure of the coarse aggregates due to the freeze and thaw test.

Two of the principal physical characteristics of a concrete aggregate are the various gravities and absorptions. The relationships of these parameters for the aggregates used in this test have already been established, therefore, by using either parameter, in our case the various gravities, an explanation of the rate of deterioration due to freeze and thaw may be sought. Figure 9 shows the relation of the bulk specific gravity of the coarse aggregates with the average durability factor of the concrete specimens subjected to the freezing and thawing test from

Figure 8 - Change in Sonic Frequency of the Concrete Specimens for Each Coarse Aggregate. (Based on the Sonic Frequency at 35 Days)

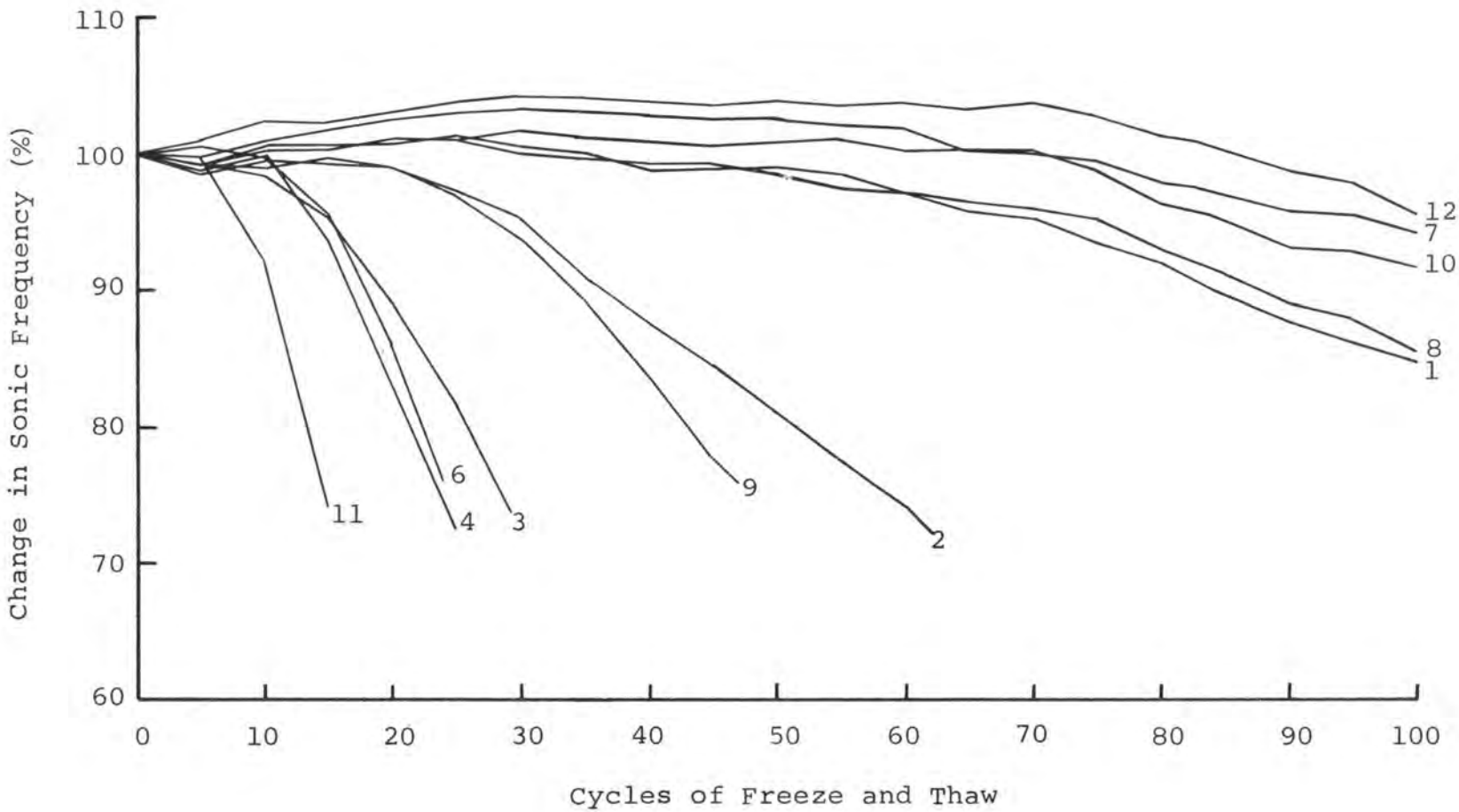
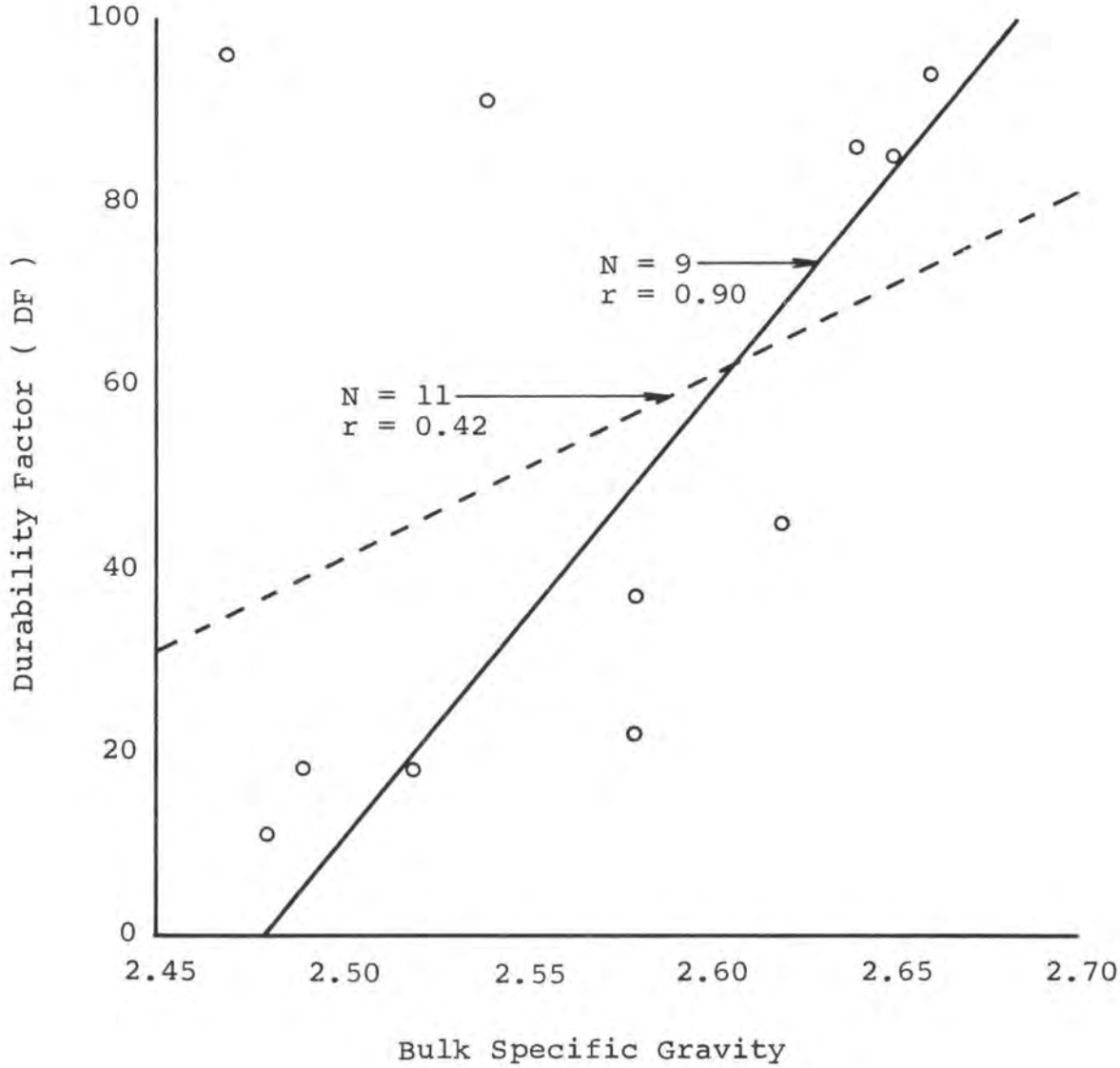


Figure 9 - Significance of Bulk Specific Gravity as an Indicator of Freeze and Thaw Durability.



data shown in Table 7 and Table 11, Appendix A. The relationship using only nine aggregates has a coefficient of correlation of 0.90 which is significant. The relationship for all eleven coarse aggregates has a coefficient of correlation of only 0.42 and is not considered statistically significant. The relationships between the durability factors and the bulk specific gravities (saturated surface dry), Table 11-Appendix A, and (vacuum saturated surface dry), Table 18-Appendix D, are shown in Figures 10 and 11 respectively. The correlation coefficients for these regression lines are:

Figure 10: Durability Factor vs.

Bulk Specific Gravity (SSD): $N = 11$ $r = 0.28$
$N = 9$ $r = 0.91$

Figure 11: Durability Factor vs.

Bulk Specific Gravity (VSSD): $N = 11$ $r = 0.43$
$N = 9$ $r = 0.86$

The relationships for the nine aggregates are significant but the relationships using all eleven aggregates are not significant.

The vacuum absorption analyses also show differences in the behavior of aggregates 10 and 12 as compared with the other nine aggregates. Checking the results shown in Tables 12, Appendix A, and 19, Appendix D, aggregates 10 and 12 do not have similar rates of absorption as the other aggregates and from Table 12, Appendix A, it was found that aggregates 10 and 12, especially aggregate 12, did not absorb water in the two-hour soak period in quantities

Figure 10 - Significance of Bulk Specific Gravity (Saturated Surface Dry) as an Indicator of Freeze and Thaw Durability.

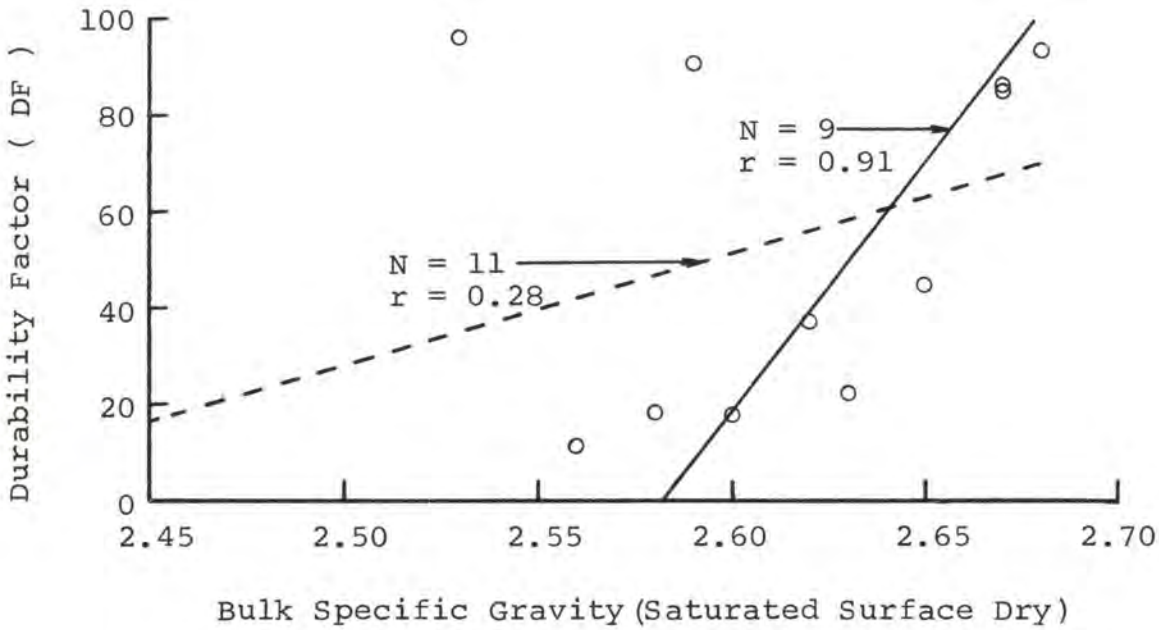
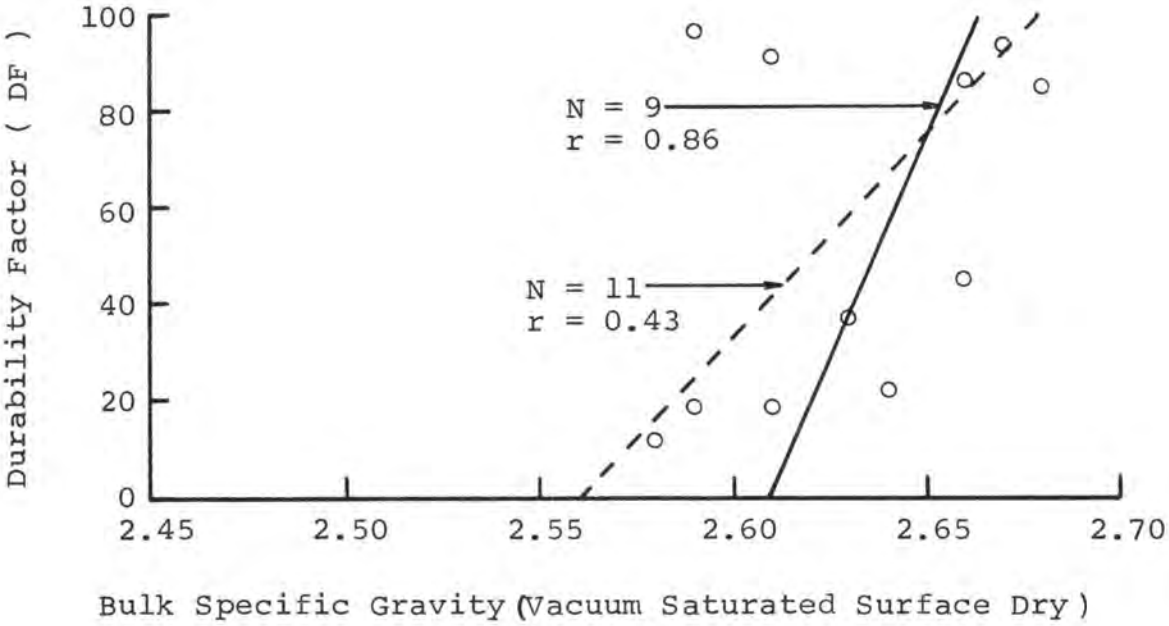


Figure 11 - Significance of Bulk Specific Gravity (Vacuum Saturated Surface Dry) as an Indicator of Freeze and Thaw Durability.



proportional to the other aggregates. This gives further indication that the properties and internal structure of these aggregates are not similar to the other nine aggregates.

The significance of the relationships derived with the nine similar aggregates appears to be conclusive that as the various gravities decrease, the durability factor or the ability of the concrete specimens to resist frost damage also decreases. The best correlation appears to be with the bulk specific gravity (saturated surface dry). The whole story, however, is not presented within these correlations; because, as shown in Figures 6 and 7, the distribution of the various gravity stones within each coarse aggregate may change from sample to sample and may cause different results. It must be stipulated at this point that the results and correlations shown in this report only pertain to these particular samples and their related gravity distributions. Realizing there are numerous other distributions possible that would yield the same or similar average gravities as shown for each of these coarse aggregates, we can not necessarily judge their behavior when subjected to the freeze and thaw test on the basis of the data presented herein.

To establish a parameter to estimate the relative durability of each of these coarse aggregates with specific consideration for the distribution of the various gravity materials and the actual rate of deterioration due to the

laboratory freeze and thaw analysis a multiple linear relationship was derived in Table 3 using the concrete durability factors. This relationship has a correlation coefficient of 0.94; however, it only pertains to the nine similar coarse aggregates. Emphasis should be placed on the importance of gravity gradation within the samples, due to the fact that the multiple linear equation derived does predict, to a fairly high degree of accuracy, the relative rate of breakdown of laboratory specimens made with the respective aggregates.

The correlations discussed in this section show the gravities of the coarse aggregates, as a whole, to be predictive of frost susceptibility with the best relationship derived from the bulk specific gravity (saturated surface dry). This relationship can be enhanced by taking into consideration the gravity gradation within the coarse aggregates. However, the significant relationships thus derived are only valid for the particular type of fine-grained limestone studied within this investigation.

Variable A - Effects Measured by Permanent Dilation

Prior to each freeze and immediately after each thaw period, the permanent dilation or contraction of each concrete specimen was measured while the specimens were at 40°F. The gauge points were placed at 10 inch centers on the top and bottom of the specimens as molded. The results recorded in Table 4 are the average of the top and bottom measurements

for four replicate specimens representing each mix design.

It has been stated that dilation is a good measure of freeze and thaw resistance of laboratory concrete specimens. As shown in Figure 12, the total accumulated dilation at the established termination point of the test will generally lie above 0.06 percent change in length, but is not selective between the more rapid or the slower failing concretes. The average rate of failure does not appear to influence the ultimate permanent dilations of the test specimens.

The rate at which the permanent dilations increase, especially over the first 10 cycles, does appear to give some indication as to the ordering of the failure of the specimens. Comparing the slope of a straight line passing through the origin and the accumulated permanent dilation after 10 cycles of freeze and thaw with the durability factors gives the relationship shown in Figure 13. This relationship apparently estimates, to a very good degree, the durability factor which may be expected from each set of beams, even for those containing coarse aggregates 10 and 12. Figure 13 gives an indication that failure at a very early age is eminent with slope values above 1.5×10^{-4} and that relatively no failures would be expected in 100 cycles of freeze and thaw for slope values of 0.5×10^{-4} or less. The slope values lying between these two values apparently represent a zone of transition from the rapid to slow failures. The curve which apparently is

Figure 12 - Accumulated Permanent Dilation of Concrete Specimens Subjected to the Freeze and Thaw Test.

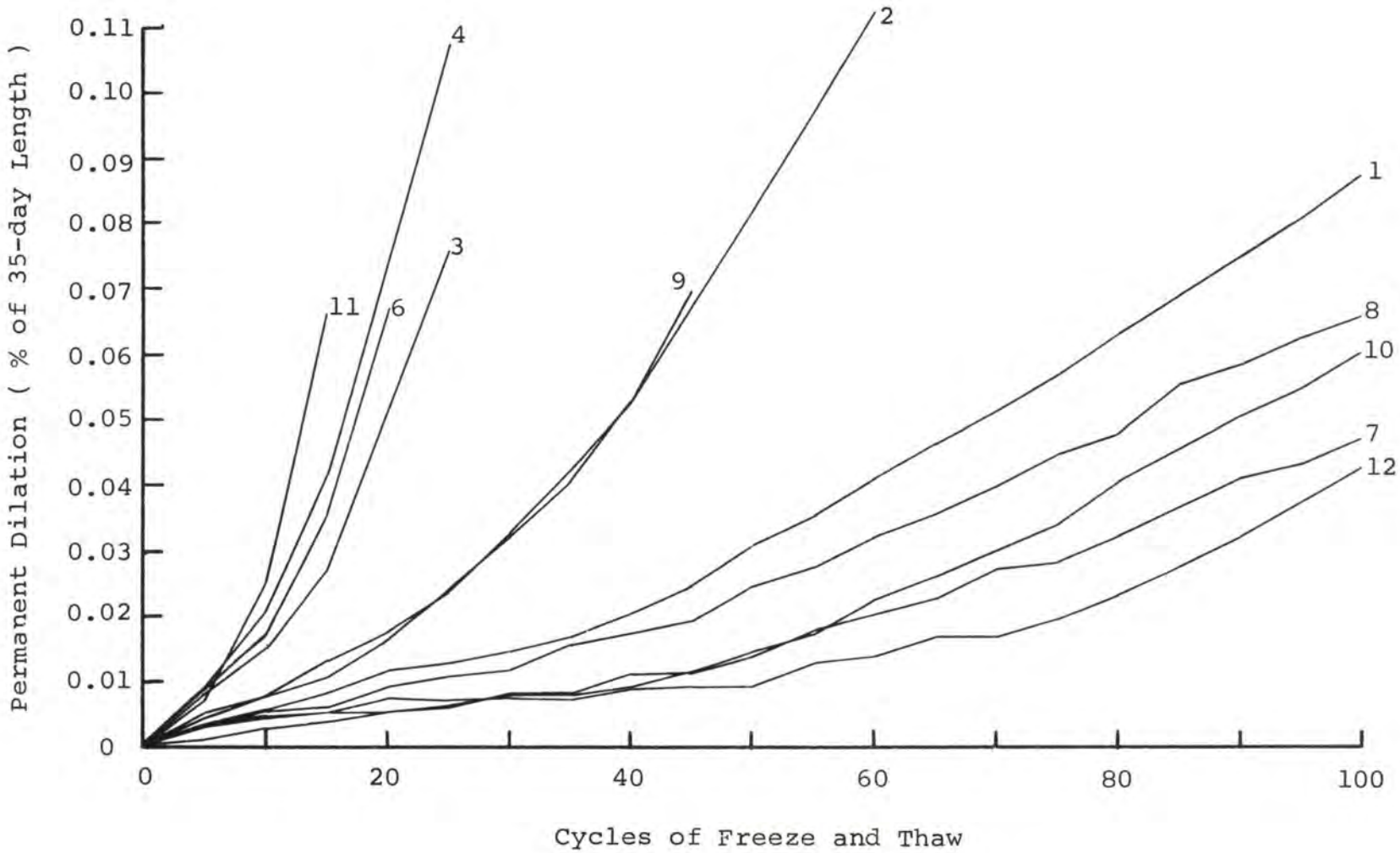
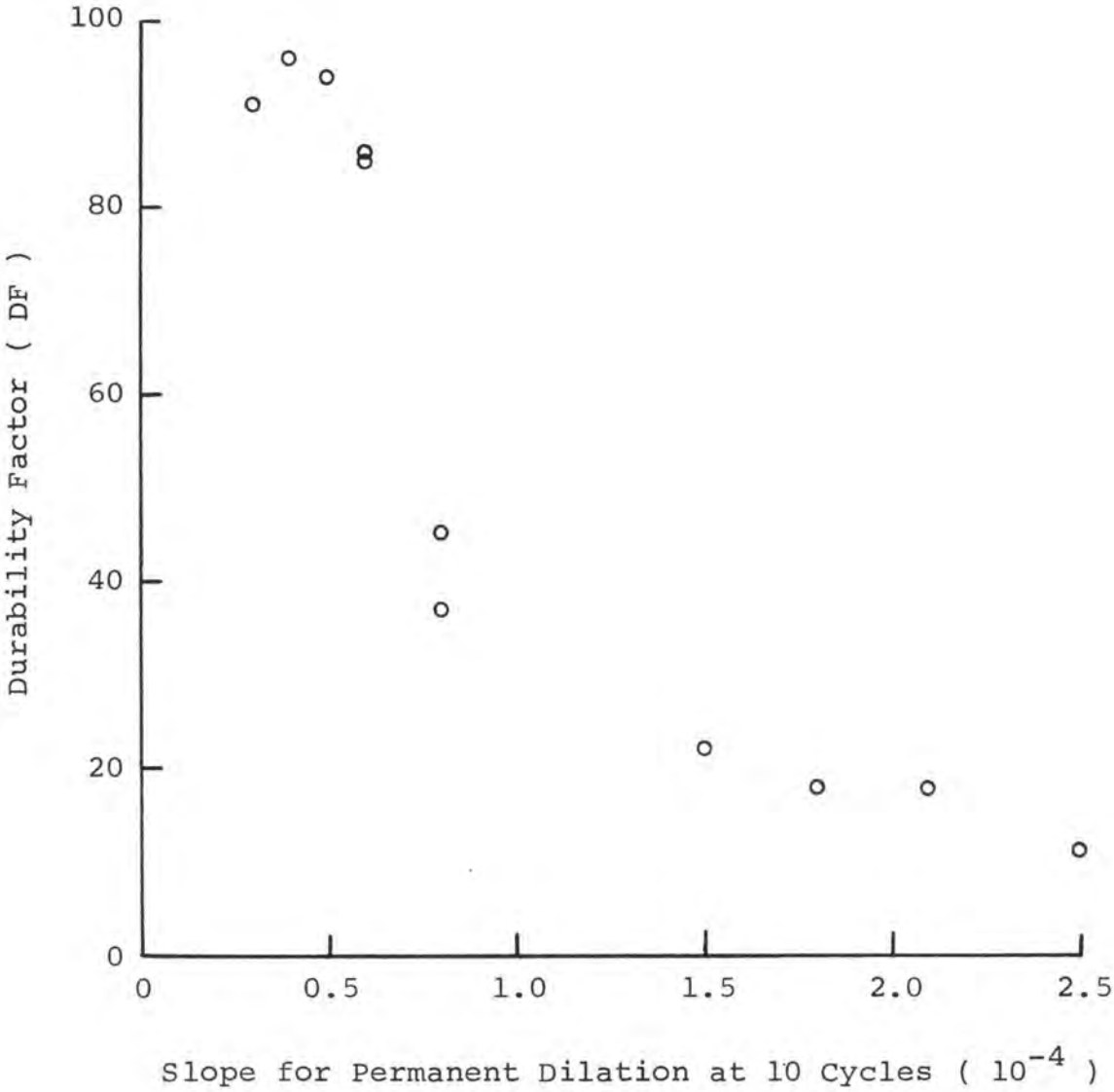


Figure 13 - Significance of the 10-Cycle Slope for the Permanent Dilation as an Indicator of Freeze and Thaw Durability.



beginning to take shape as shown in Figure 13 is at best only an estimate due to the limited data available. Refinement of this relationship is also desired because the apparent difference in durability of concrete from 50 to 100 as measured by the durability factors is influenced by a slope difference of only 0.25×10^{-4} which amounts to a length change of only 0.00025 inch for a 10 inch gauge length.

Variable A - Effects Measured by Weight Change

The change in weight data, presented in Table 5, representing concrete specimens which have been handled and transported to and from the storage facilities once each week for a period of approximately two years must reflect the losses due to slight chipping of the edges and corners of the specimens. Therefore, to use such weights to predict a gain or loss in moisture would be erroneous. However, a weight record was kept and as shown in Table 5, a normal average weight gain for the air-entrained, 45 percent sand specimens (1AS), of approximately 0.3 to 0.4 percent was realized. This gain was based on each specimen's weight at 35 days; however, the weight change during the 35-day curing period shows a total gain of approximately 1.0 percent. The total accumulated weight at termination of the specimens seems to make little difference to the rate of failure of the specimens.

Variable A - Effects Measured by Flexural Strength Loss

The flexural strength loss of each specimen was determined by averaging a set of four control beams broken after 35 days of curing and comparing this average with the strength of the specimens broken after the thawing cycle at which they reached a 30 percent loss in modulus of elasticity. The average loss in flexural strength, expressed as modulus of rupture, of the four freeze and thaw specimens as compared to the four control specimens for the 14 and 7 inch spans with centerpoint loading (ASTM C293-68) are shown in Table 8.

The loss in flexural strengths of the different beam groups appear to be relatively similar, however, previous studies (IV) have indicated the flexural strengths to be sensitive to air content, curing, and coarse aggregate type. The air-entrained (1AS) concretes generally lost from 56 to 67 percent of their flexural strength based on the 14 inch span and lost from 53 to 64 percent of the 7 inch span. The nonair-entrained (2DS) concretes generally lost from 48 to 60 percent of their flexural strength based on the 14 inch span and lost from 50 to 55 percent on the 7 inch span. The slow-failing aggregate (2) had the highest loss in flexural strength on the 14 inch span. However, no definite relationships were established.

Table 8 - Flexural Strengths of Control Beams and Beams Subjected to the Freeze and Thaw Test

Concrete Mix Design	Control Beams Average 35 Day Flexural Strengths 14" Span	Control Beams Average 35 Day Flexural Strengths 7" Span	F & T Beams Avg. Strength at Termination 14"Span	F & T Beams Avg. Strength at Termination 7"Span	Percent Loss in Flexural Strength 14"Span	Percent Loss in Flexural Strength 7"Span
1-1AS	976	1066	(1)	(1)	(1)	(1)
2-1AS	988	1066	380	463	61.5	56.6
2-1BS	1052	1138	358	476	66.0	58.2
2-1CS	1006	1096	407	510	59.5	53.5
2-2DS	1081	1162	439	500	59.4	57.0
2-2ES	1064	1175	435	557	59.1	52.7
2-2FS	1089	1196	450	498	58.7	58.4
3-1AS	1021	1079	448	504	56.2	53.3
4-1AS	885	1000	360	393	59.3	59.1
4-1BS	967	1025	413	447	57.3	56.4
4-1CS	903	1005	389	464	56.9	53.8
4-2DS	1013	1047	472	472	53.4	54.9
4-2ES	1011	1098	460	544	54.5	50.5
4-2FS	1016	1103	510	514	49.8	53.4
6-1AS	860	940	360	420	58.2	55.2
6-1BS	847	940	376	390	55.7	58.4
6-1CS	848	890	346	383	59.3	57.0
6-2DS	895	956	462	483	48.4	49.5
6-2ES	896	1023	428	498	52.2	51.3
6-2FS	885	919	417	484	52.8	47.3
7-1AS	1020	1088	(1)	(1)	(1)	(1)
8-1AS	1045	1105	(1)	(1)	(1)	(1)
9-1AS	976	1068	391	383	59.9	64.2
10-1AS	964	1080	(1)	(1)	(1)	(1)
11-1AS	990	1057	324	468	67.3	55.7
12-1AS	1004	1104	(1)	(1)	(1)	(1)
1&3-1AS	994	1043	430	398	56.8	61.8
1&6-1AS	942	1058	353	435	62.6	58.9
2&4-1AS	956	1033	417	492	56.4	52.4
2&6-1AS	976	1014	386	482	60.4	52.4
	18"Span		18"Span		18"Span	
2-1AS	946		428		54.8	
2-1AO	912		337		63.1	
2-1CO	875		434		50.4	
4-1AS	815		445		45.4	
4-1AO	813		384		52.8	
4-1CO	892		391		56.2	

(1) Data omitted because beams did not fail prior to the 100-cycle termination point.

VARIABLES B & C - SAND CONTENTS OF 33, 37, and 45 PERCENT; AIR AND NONAIR-ENTRAINED

The objective of this exploratory phase of this investigation was to study the relative change in a concrete's ability to resist frost action by changes in the sand content. The reasons for including the change in air content were:

1) To study its effects on resistance to frost action, and
2) To study the effects of the prolonged soak period between freezing cycles of the air and nonair-entrained concretes.

For this test, only three of the coarse aggregates, 2, 4, and 6, were used with each of the following mix designs:

Concrete Mix Designs	Air Content	Sand Content
1AS	5.5% ± 1.5%	45.0%
1BS	"	37.0%
1CS	"	33.0%
2DS	Nonair-Ent.	47.7%
2ES	"	40.1%
2FS	"	36.3%

The cement factor, as shown in Table 17, Appendix D, remained relatively constant; however, the water requirement did vary slightly, due to the air contents.

The discussion of the variation in sand and air contents will be presented at the same time because changes

made to either of these quantities dictated changes to the other. As air-entrainment was omitted the sand was increased to take up the volume difference so that the absolute volume of the coarse aggregate would remain constant.

Variables B & C - Effects Measured by Sonic Frequency

The significance of the rate of breakdown shown in Figures 14a, b, c, and 15a, b, and c, between each of the mix designs expressed above was determined by statistical deviation of means as described by Rider, p. 89, (III). This method of analysis was used because more specific relationships between each of these mix designs were desired rather than a general overall indication.

The significance of the effects of the sand contents on the rate of failure of the beams in each mix design, as calculated with respect to each coarse aggregate and each air content, are shown in Parts a and b of Table 9. The results obtained with coarse aggregate 2, a slow-failing aggregate by our freeze and thaw test, are difficult to justify. One possibility would be that an optimum value may exist and that not enough or too much sand may have significant effects on a concrete's ability to resist freeze and thaw damage. Coarse aggregate 4, a rapid-failing aggregate, does appear to be beneficiated by the higher sand contents. Coarse aggregate 6, also a rapid-failing aggregate with the lowest bulk specific gravity of the three, does not appear to be beneficiated with any adjustment in sand content.

Figure 14 - Change in Sonic Frequency of Each Set of Replicate Air-Entrained Beams With Sand Content as a Variable.

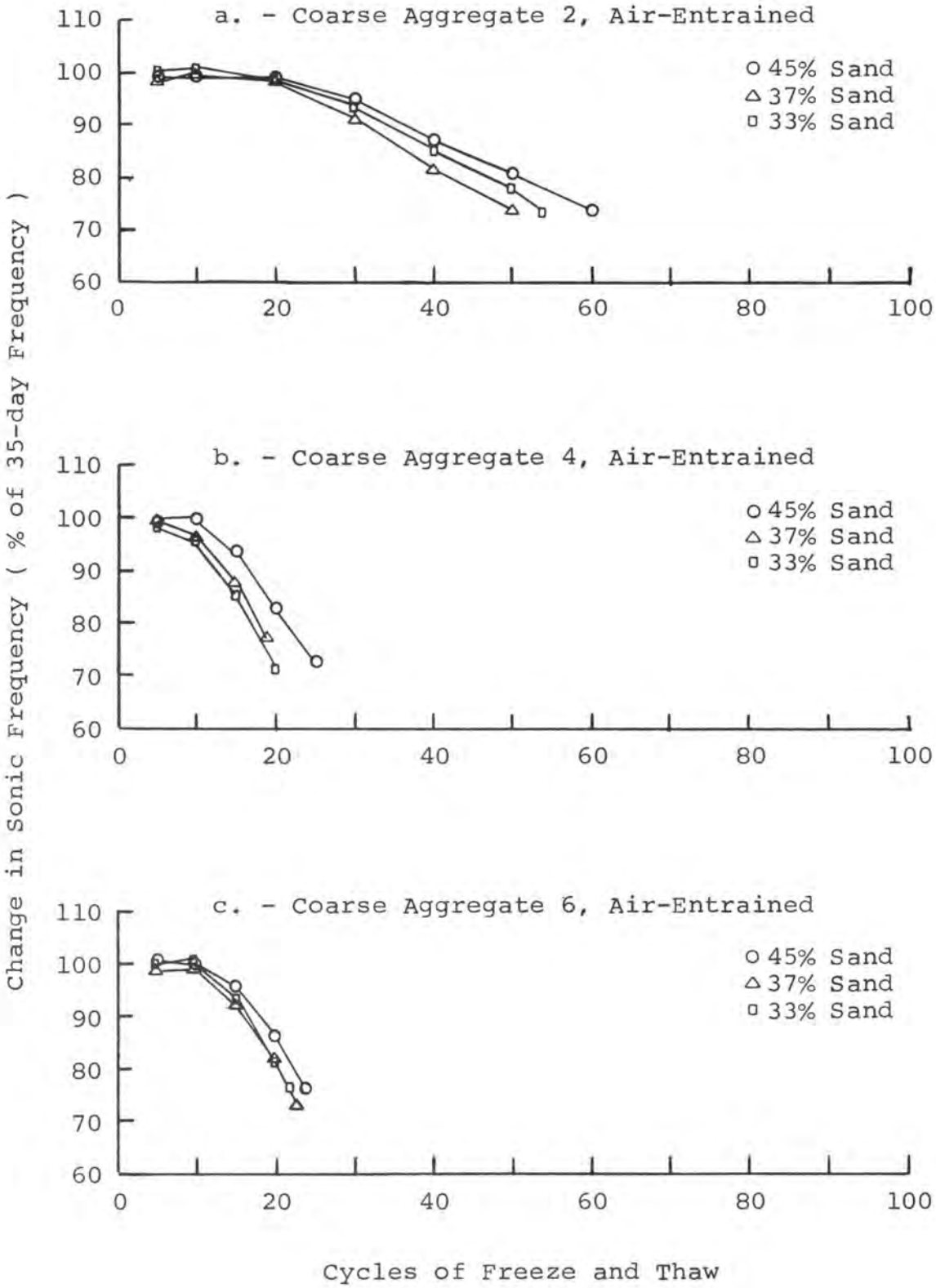


Figure 15 - Change in Sonic Frequency of Each Set of Replicate Nonair-Entrained Beams With Sand Content as a Variable.

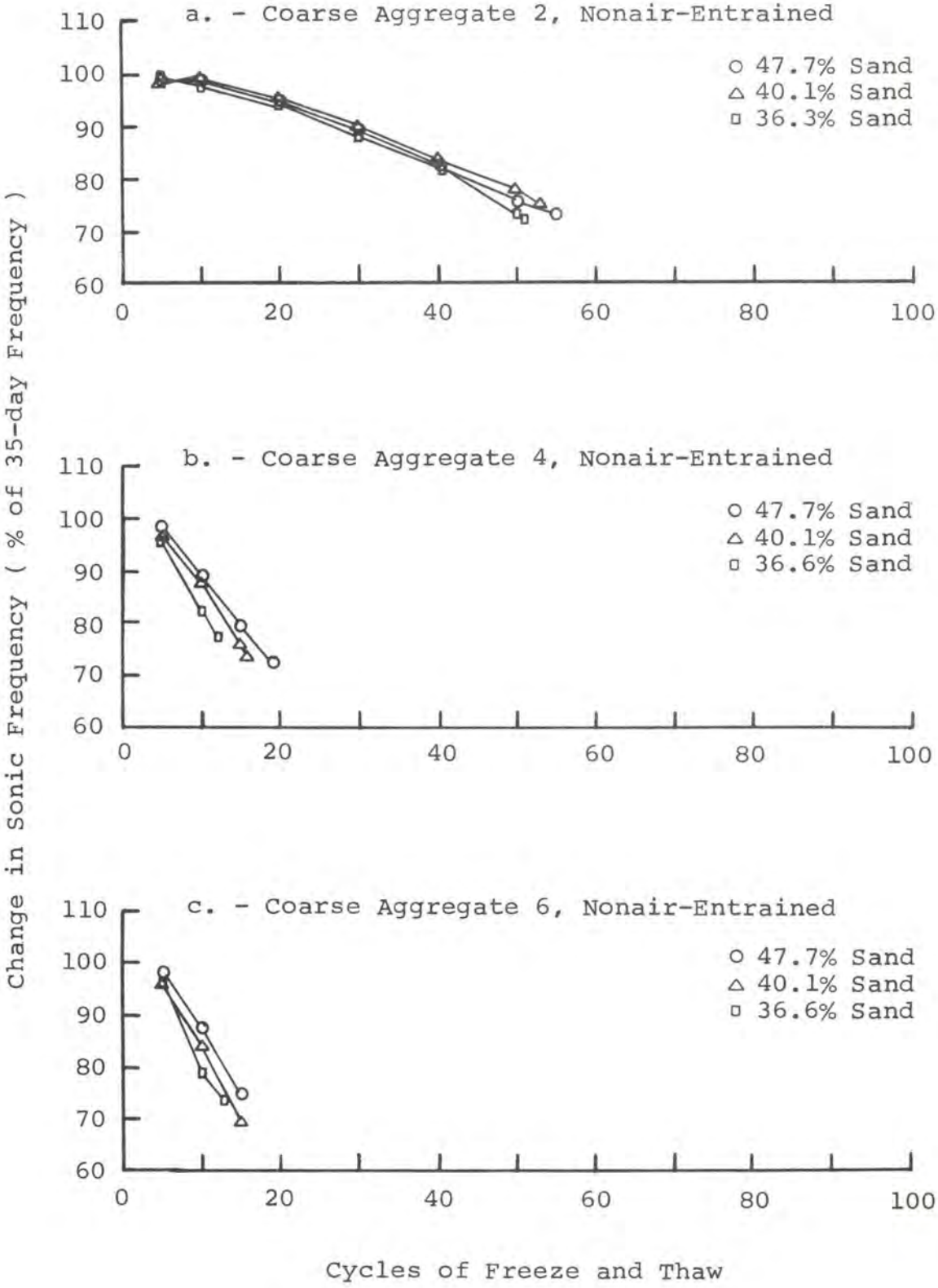


Table 9 - Significance of Relationships Between Sand and Air Contents.

Conditions are: below 5% = significant,
below 1% = highly significant

a. Relation of Various Sand Contents for Air-Entrained Concrete.

Coarse Aggregate	Sand Contents 45.0% vs. 33.0%	45.0% vs. 37.0%	37.0% vs. 33.0%
2	Not Signif.	Highly Signif.	Not Signif.
4	Highly Signif.	Not Signif.	Not Signif.
6	Not Signif.	Not Signif.	Not Signif.

b. Relation of Various Sand Contents for Nonair-Entrained Concrete.

Coarse Aggregate	Sand Contents 47.7% vs. 36.3%	47.7% vs. 40.1%	40.1% vs. 36.3%
2	Not Signif.	Not Signif.	Not Signif.
4	Signif.	Signif.	Not Signif.
6	Signif.	Not Signif.	Not Signif.

c. Relation of Air or Nonair-Entrainment for Similar Sand Contents.

Coarse Aggregate	Sand Contents 45.0% vs. 47.7%	37.0% vs. 40.1%	33.0% vs. 36.3%
2	Signif.	Not Signif.	Not Signif.
4	Highly Signif.	Signif.	Signif.
6	Highly Signif.	Highly Signif.	Highly Signif.

The durability results of the air-entrained and nonair-entrained concretes seem to indicate that in general the slow-failing aggregates may be only slightly receptive to changes in sand contents up to an optimum value. The rapid-failing aggregates of the higher bulk specific gravity ranges may be beneficiated if the larger sand contents are used, however, the rapid-failing aggregates of the lower bulk specific gravity ranges do not appear to be beneficiated in any case when used in air-entrained concretes and only slightly beneficiated when used in nonair-entrained concretes.

Increasing the sand content from 33 to 45 percent was definitely not detrimental to the concrete specimens in this test. The ultimate failure of the specimens made with the same coarse aggregate were so close together as far as number of freeze and thaw cycles required to reach a 30 percent loss in modulus of elasticity, that the only real measure of the effects of the change in sand content will be service records obtained from the new concrete pavements built under the field phase of this investigation.

The correlations shown in Part c of Table 9 are for the air-entrained and nonair-entrained concrete specimens with aggregates 2, 4, and 6. The small change in sand content of only approximately 3 percent should have little effect on the results based on the previous discussion. The effect of air-entrainment with the slow-failing aggregate, 2, was found to be insignificant except at the highest sand contents. The rapid-failing aggregates, 4 and 6, are beneficiated in

all cases by the addition of entrained air, especially with the higher sand contents for aggregate 4 and for all sand contents with the low gravity aggregate 6.

Variables B & C - Effects Measured by Permanent Dilation

The average accumulative permanent dilations of the four replicate specimens for each mix design are shown in Figures 16a, b, c, and 17a, b, and c. The results show relatively little difference between the various sand contents within each coarse aggregate or between the air-entrained or nonair-entrained concrete specimens. These results generally mirror the results of the loss in sonic frequency previously discussed.

Adjustments in the sand content or air content seem to have slight effect on the ultimate permanent dilation of the concrete specimens. The only difference distinguishable is the rate of length change of the air-entrained and nonair-entrained specimens. As shown in these figures, the nonair-entrained specimens have a higher rate of change in length during the early cycles of the test, however, the rate of change (slope of the curves) becomes more nearly the same as the test progresses.

Variables B & C Effects Measured by Weight Change

With reference to the weight data shown in Table 5 the following is evident:

1. Based on the initial weight at one day the ultimate

Figure 16 - Accumulated Dilation of Air-Entrained Concrete Specimens Subjected to the Freeze and Thaw Test.

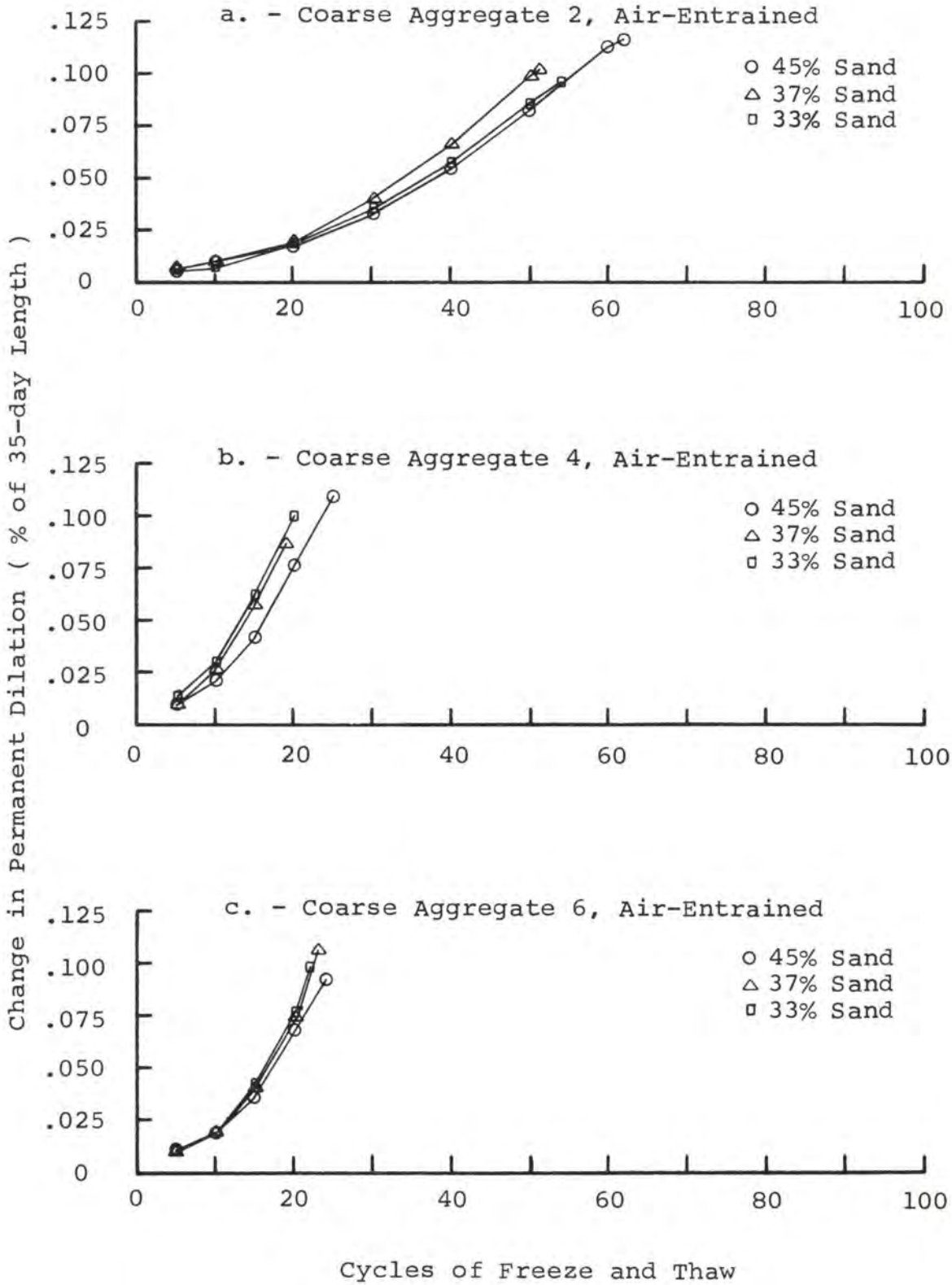
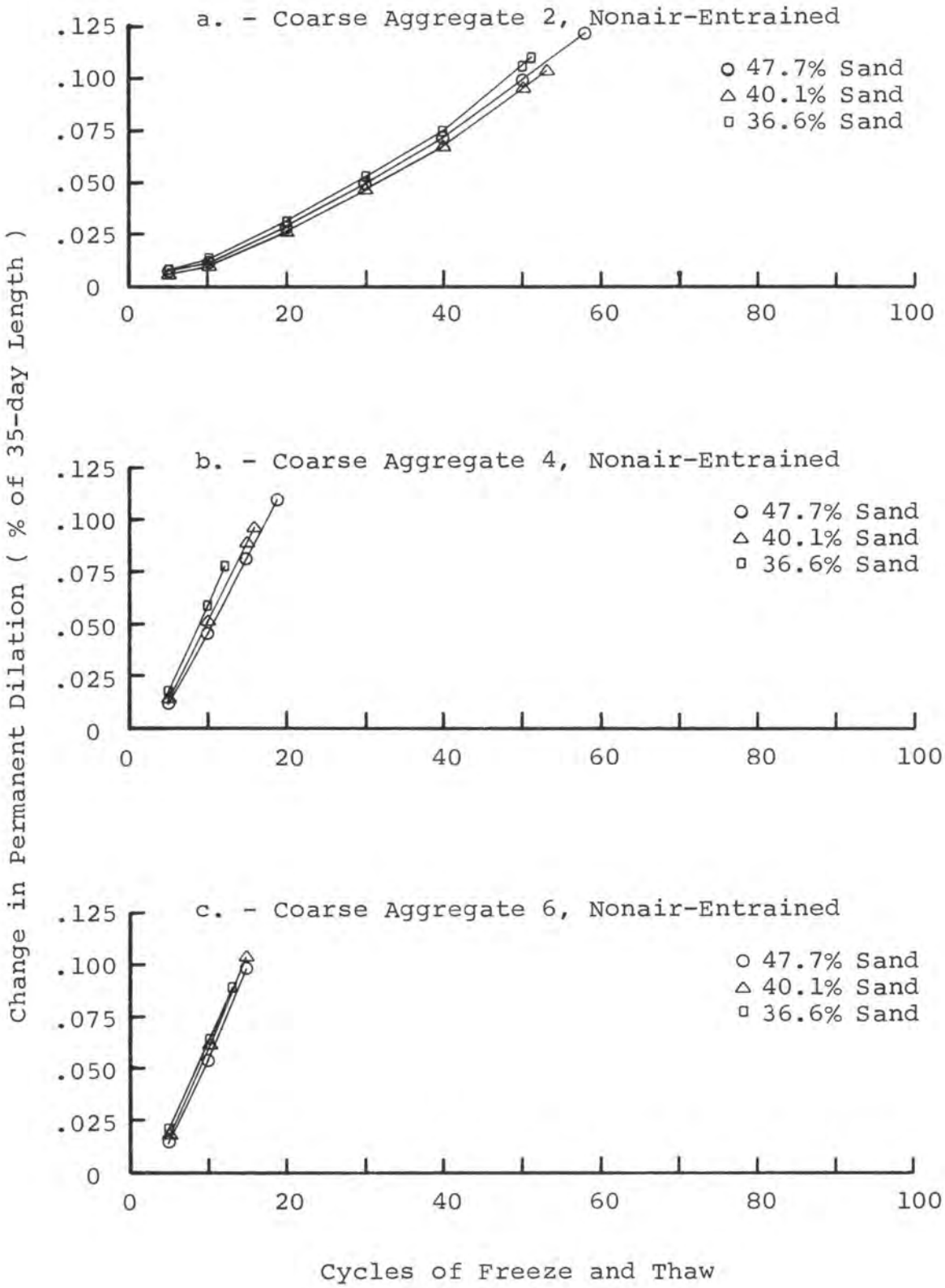


Figure 17 - Accumulated Dilation of Nonair-Entrained Concrete Specimens Subjected to the Freeze and Thaw Test.



weight gain for the air-entrained concrete was, on the average, 19 percent greater than the ultimate weight gain for the nonair-entrained concretes.

2. Based on the weight at 35 days the ultimate gain of the air entrained concretes was, on the average, 27 percent greater.

This indicates that generally all the specimens gained weight at a more rapid rate during the curing period than during the test period after 35 days of age. However, at the point of termination, the air-entrained specimens generally showed total weight changes approximately 20 percent greater than the nonair-entrained specimens. The effects of the sand contents on the relative gain in weight did not yield any significant relationship.

Variables B & C - Effects Measured by Flexural Strengths

The initial 35-day flexural strengths expressed as the modulus of rupture, of the air-entrained control specimens, as shown in Table 8, were on the average approximately 7 percent lower than the nonair-entrained specimens. The average loss of flexural strength irregardless of the sand content at the termination point of the specimens is shown below:

Coarse Aggregate	Average Loss Air	Average Loss Non-air	Difference
2	62.3%	59.1%	5%
4	57.8%	52.6%	9%
6	57.5%	51.1%	11%

This data indicates the air-entrained specimens had higher loss in flexural strength by the percentages shown. However,

the loss with respect to aggregate type indicates that the higher gravity slow-failing aggregate had the largest net loss in flexural strength. The effects of the sand contents on the loss in flexural strengths did not yield any significant relationship.

VARIABLE D - MAXIMUM SIZE COARSE AGGREGATE

The variation in coarse aggregate size from the 1 inch maximum to a 2 inch maximum necessitated a change in specimen size from the 3½ x 4½ x 16 inch beam to a 6 x 6 x 20 inch beam. Only coarse aggregates 2 and 4 were used in this analysis.

The various gravities and absorptions of the two gradations of each of the two coarse aggregates are very nearly the same as shown in Tables 11 and 12, Appendix A. The gravity gradation of aggregate 2 was changed somewhat over the 2.60 and 2.675 gravity range as shown in Table 2 while that for aggregate 4 remained similar. However, the combined gravities and absorptions remained similar for both aggregates as shown in Tables 18 and 19, Appendix D.

Incorporated into this analysis along with aggregate size was a change in sand content from 45 to 33 percent as shown in Table 16, Appendix C. The characteristics of the concrete mix designs are shown in Table 17, Appendix C. The only point of noticeable difference between the concretes is the slightly lower water to cement ratios shown for the concretes having 33 percent sand contents.

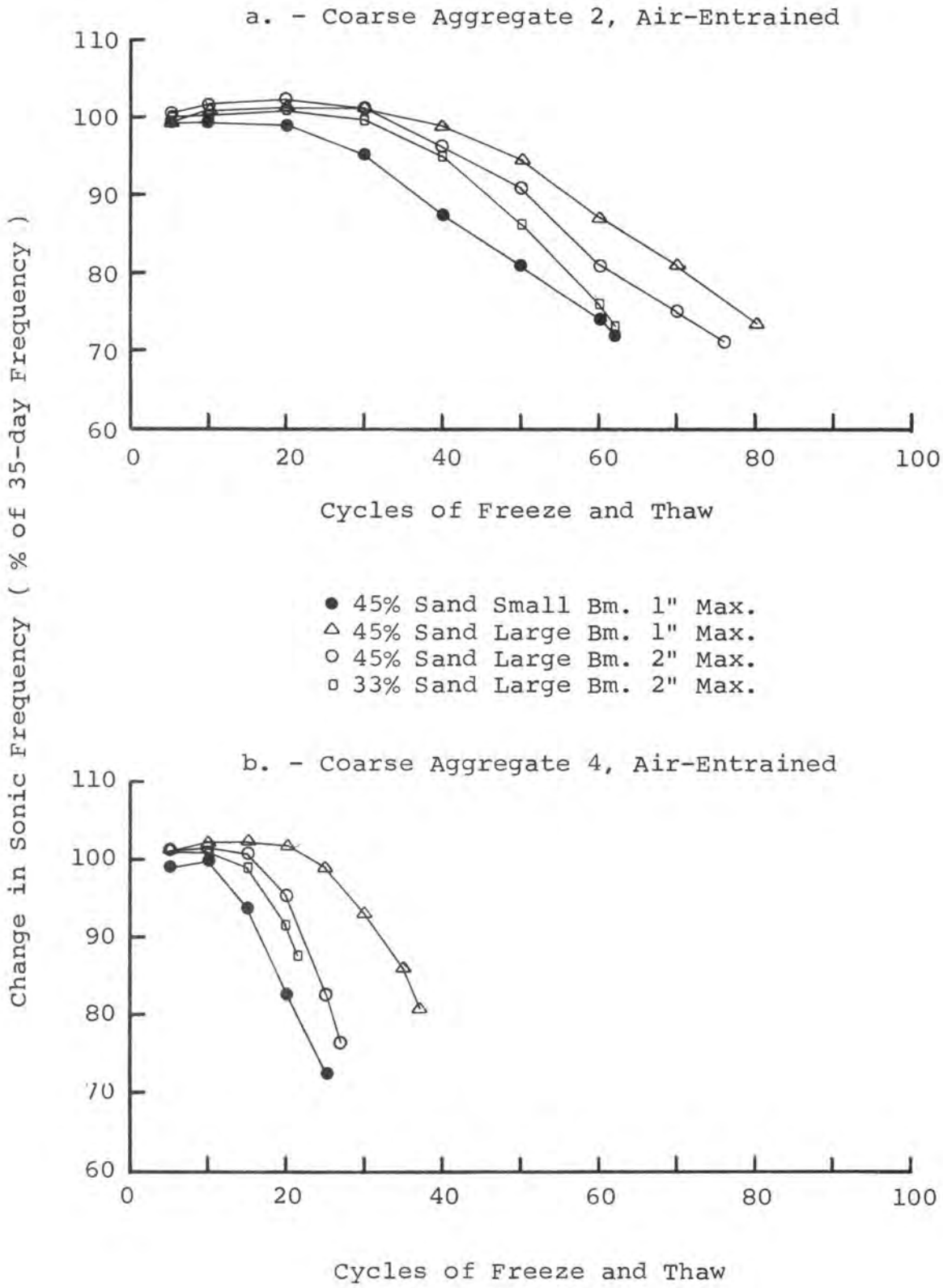
Variable D - Effects Measured by Sonic Frequency

The necessity of having two specimen sizes, caused the cross sectional areas to differ from 15.75 to 36 square inches or an increase of 128 percent. Therefore, it was realized that some difference in the freeze and thaw results should be expected between the two beam sizes. As shown in Figures 18a and b, the smaller beams failed at a more rapid rate. Specimen size appears to effect the rate of failure of the rapid-failing aggregate more than the slow-failing aggregate. This is shown by comparing the beams made with aggregates 2 and 4, 45 percent sand, air-entrained, and 1 inch maximum coarse aggregate; where the durability factors are 44.7 vs. 57.3 for coarse aggregate 2 small and large beams respectively and 18.0 vs. 30.2 for coarse aggregate 4 small and large beams respectively.

The difference in the effects of the 1 inch maximum aggregate over the 2 inch maximum aggregate appears to be less for the slow-failing aggregates than for the rapid-failing aggregates. A decrease in the durability factors, as shown in Table 7 between the 6 x 6 inch specimens with the 1 and 2 inch maximum aggregates and 45 percent sand, was only 6.6 percent for the slow-failing and a decrease of 33.4 percent for the rapid-failing aggregates respectively. Apparently, the effects of reducing the maximum size coarse aggregate are more pronounced with the rapid-failing aggregates and make little difference with the slow-failing aggregates.

The effects of sand contents of 45 and 33 percent of

Figure 18 - Change in Sonic Frequency of the Small and Large Beams.



the 6 x 6 inch specimens with 2 inch maximum size coarse aggregate appear to be less effective for the rapid-failing aggregates than for the slow-failing aggregates. The difference in the average durability factors for these specimens indicate that 33 percent sand causes a reduction in durability factors of 14.2 and 7.4 percent for the slow and rapid-failing aggregates respectively.

This information, to a limited degree, gives some indication that:

1. The larger specimen size effects the relative rate of failure of rapid-failing aggregate by increasing its resistance to freeze and thaw.
2. The maximum size coarse aggregate effects the relative rate of failure of the rapid-failing aggregate by decreasing its resistance to freeze and thaw.
3. Increasing the sand content from 33 to 45 percent effects the relative rate of failure of the slow-failing aggregate by increasing its resistance to freeze and thaw.

Variable D - Effects Measured by Permanent Dilation

The permanent accumulative dilations occuring in the 6 x 6 inch specimens are shown in Figures 19a and b. In most cases the initial rate of dilation is less than that shown for the 3½ x 4½ inch specimens; however, as the specimens approach failure, the rate of dilation becomes similar to that shown for the smaller specimens. The one exception

being aggregate 2 which did show a slight decline in rate of dilation as it approached failure, as shown in Figure 12.

The data shown in Figures 19a and b, indicate that for the slow-failing aggregate, 2, the ultimate permanent dilation of the 6 x 6 inch specimens are nearly the same as the dilations of the smaller specimen, whereas the rapid-failing aggregate, 4, the ultimate permanent dilation of the 6 x 6 inch specimens are approximately 50 percent less than that of the smaller specimens.

This data tends to indicate that the rate of dilation is different for the two specimen sizes used in the test. The ultimate permanent dilation for the slow-failing aggregate is nearly the same regardless of specimen size. The ultimate permanent dilation for the rapid-failing aggregate in the 6 x 6 inch specimens is approximately 50 percent that of the ultimate permanent dilation of the 3½ x 4½ inch specimens.

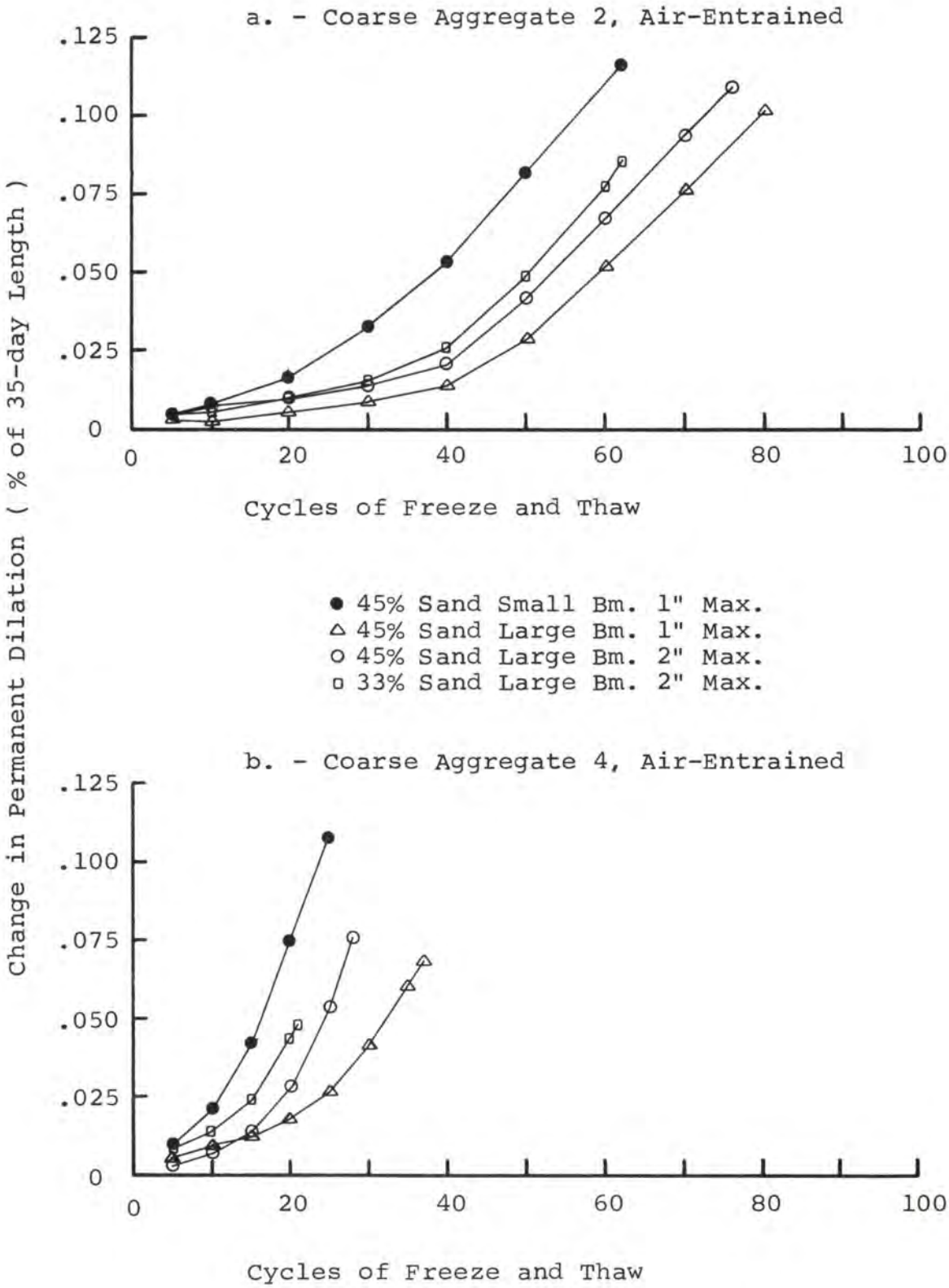
Variable D - Effects Measured by Weight Change

The weight of the 6 x 6 inch specimens was not recorded.

Variable D - Effects Measured by Flexural Strength Loss

The flexural strength test for the 6 x 6 inch specimens required a span of 18 inches rather than the 14 inches used for the smaller specimens with center point loading. Generally, the 6 x 6 inch specimens showed more retention

Figure 19 - Accumulated Dilation for Each of the Coarse Aggregates in the Small and Large Beams.



in flexural strength at the termination point of the test, however, this comparison can only be made between the 1A specimens using the 1 inch maximum size aggregate. The slow-failing and rapid-failing aggregates, 2 and 4, used in the 6 x 6 inch specimens showed a 17.4 and 34.2 percent greater retention in flexural strengths respectively. Apparently the rapid-failing aggregates are beneficiated to a greater extent by the increase in specimen size.

The change in sand contents from 45 to 33 percent with the 2 inch maximum size stone caused variable results between the two aggregates as shown in Table 8. With coarse aggregate 2, the 45 percent sand showed the greatest loss; whereas, with coarse aggregate 4, the 33 percent sand showed the greatest loss. The slow-failing aggregate, 2, seems to be most affected by the increased aggregate size and also the increased sand content. The data may be interpreted to mean that there does exist a possibility that beneficiation measured applicable to either of the aggregates (a slow-failing or a rapid-failing aggregate) may cause adverse conditions to exist for the other aggregate; however, as these are exploratory indications only, further testing would be necessary to determine the extent of this possibility.

VARIABLE E - BLENDS OF HIGH AND LOW GRAVITY COARSE AGGREGATES.

Realization that the stone within a geologic formation as defined in Missouri is capable of being highly

variable in physical and chemical properties, an exploratory study of the combined effects of several of the aggregates used in this investigation was included. The combinations were so arranged, as shown below, that the combined gravities of any two aggregates would approach the gravity of one of the test aggregates.

Concrete Design	Mix Ratio	Estimated Bulk Sp.Gr.(SSD) by Calc.	Comparable Mix Design	Comparable Aggregate's Bulk Sp.Gr.(SSD)
1&3-1AS	50:50	2.6518	2-1AS	2.6492
1&6-1AS	80:20	2.6548	2-1AS	2.6492
2&4-1AS	50:50	2.6236	3-1AS	2.6312
2&6-1AS	75:25	2.6329	3-1AS	2.6312

The properties of these mixtures were derived by mathematically weighted ratios of the properties of the individual aggregates which were mixed together.

Variable E - Effects Measured by Sonic Frequency

The concrete mix for this study was air-entrained to allow for comparison with the aggregates shown above. The characteristics of the concretes shown in Table 17, Appendix C, were consistent with those shown for the comparative aggregates except for a slight decrease in flexural strength for the 2&4-1AS and 2&6-1AS mix designs.

The durability factors as shown in Table 7 for the individual aggregates and the mixtures are reprinted on the following page for comparative purposes.

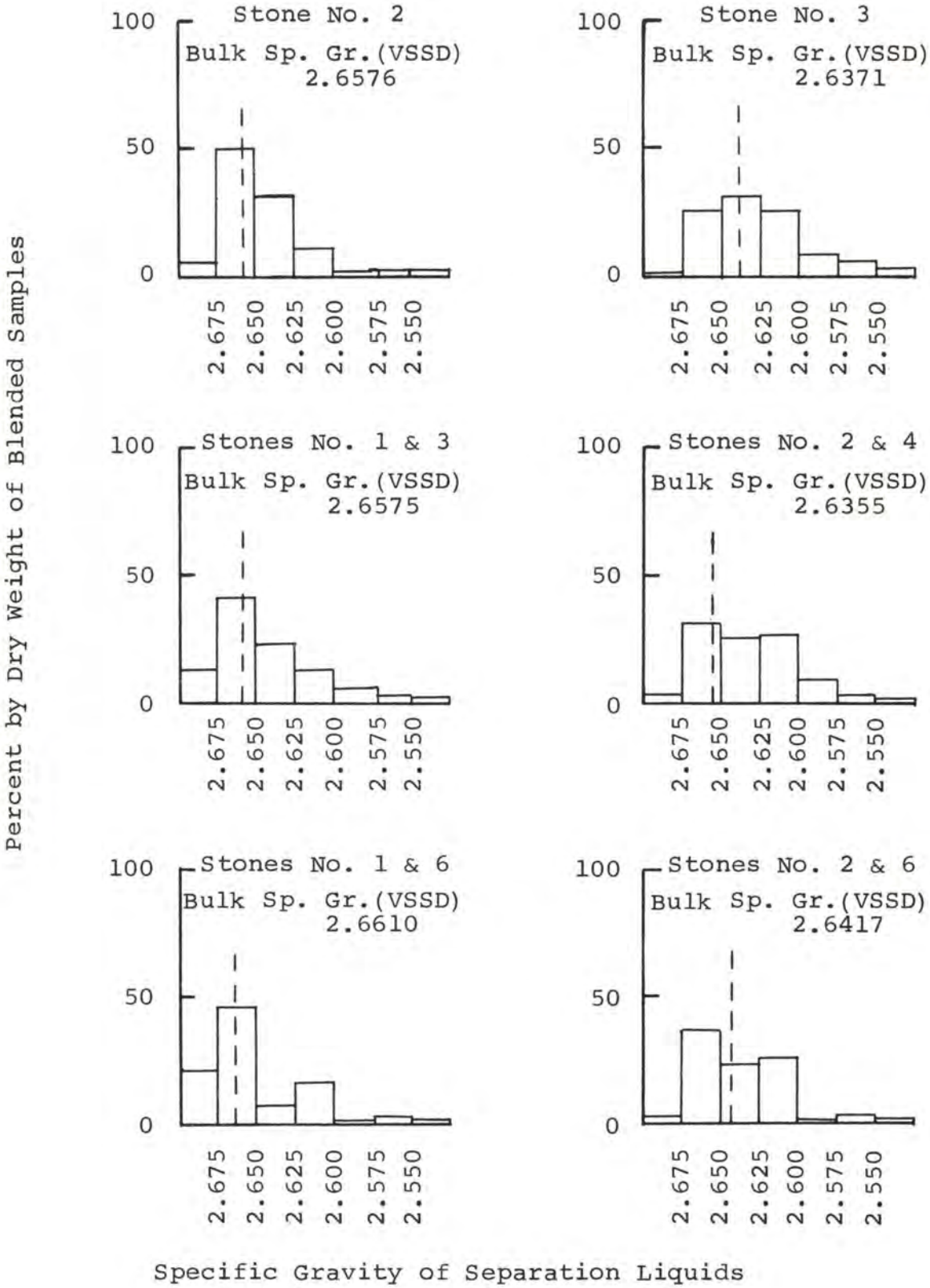
The durability factors for the mixtures appear to be higher in most cases than the aggregate of comparable

Coarse Aggregate	Durability Factor	fy
2	44.7	62.4
1&3	32.8	61.2
1&6	47.2	71.0
3	21.7	36.7
2&4	24.7	42.0
2&6	33.8	50.0

gravity, however, as mentioned earlier in the analysis of the coarse aggregates, the gravity gradation of these mixtures may not be similar to that of the single aggregate. The gravity gradation charts for the aggregate mixtures and comparable test aggregates are shown in Figure 20. These charts give an idea of the possible variations in gravity gradation that may be incurred within a very small range in bulk specific gravity (vacuum saturated surface dry). Applying the gravity gradation analysis data for the aggregate mixtures to the multiple linear equation derived in the proceeding sections, the empirical estimate (fy) of the durability factor of each aggregate mixture may be calculated with results as shown in the above tabulation.

The fact that the five-term equation derived in Table 3 does not adequately describe the relative durability of the concrete specimens made with these mixtures of coarse aggregates indicates that more sampling would be necessary to establish any confidence in the relationship, however, the relatively small error in this present relationship does indicate the possibility that such a relationship may exist.

Figure 20 - Distribution of Gravity Separated Mixed Coarse Aggregates.



Variable E - Effects Measured by Permanent Dilation

The accumulated permanent dilations of the concrete specimens with the aggregate mixtures are shown in Figure 21. These curves show a grouping tendency based on similar durability factors as shown in the previous tabulation on Page 63. There is, however, no correlation with aggregate type, various gravities, or other characteristics previously discussed to explain this grouping tendency.

The rate of permanent dilation during the early part of the test appears to be a good indication of the specimen's ability to resist frost action. Comparing the 10 cycle slope values as shown below for the specimens having mixed aggregates with those shown in Figure 13 for the individual aggregates, indicates that

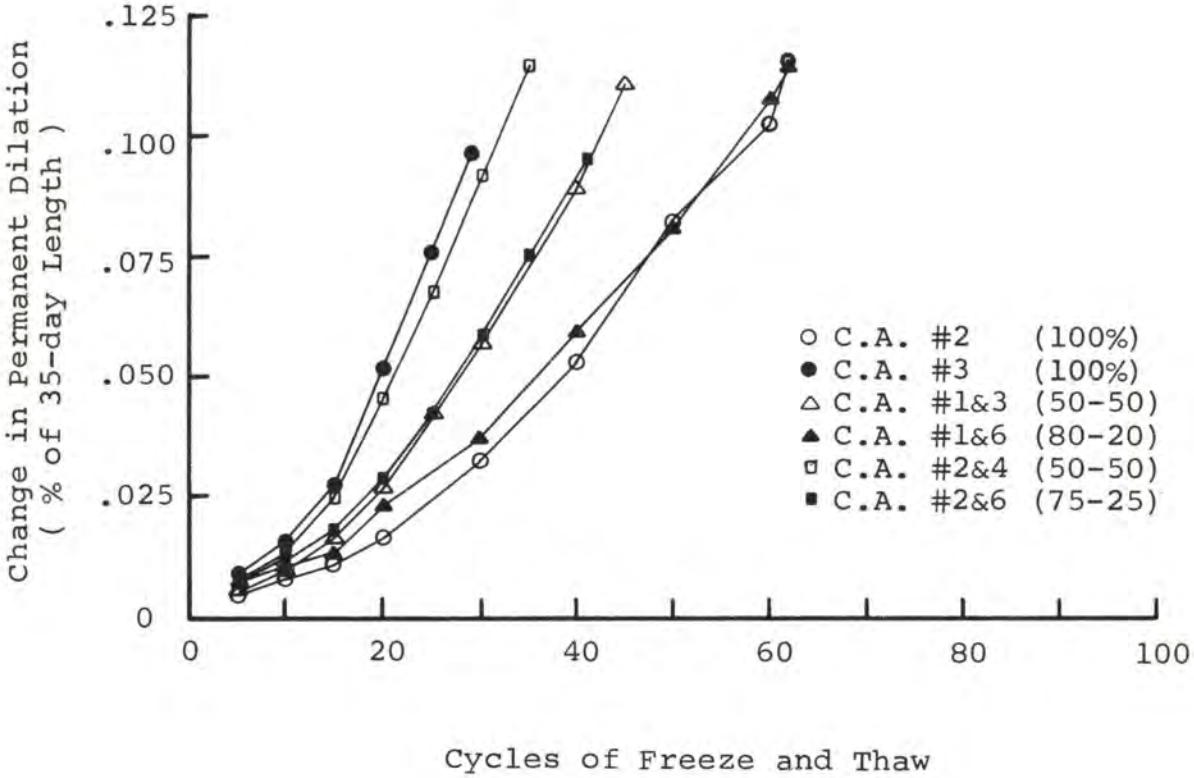
Coarse Aggregate	10 Cycle Slope (10^{-4})
2	.8
1&3	.9
1&6	1.1
3	1.5
2&4	1.3
2&6	1.1

the 10-cycle slope value may be a good parameter to estimate the rate of failure based on the durability factors obtained from Figure 13. Further study of this specific relationship with an increased number of samples may prove worthwhile.

Variable E - Effects Measured by Weight Change

The average change in weight shown in Table 5 of the concrete specimens with the mixed aggregates do not show any appreciable deviation from that shown for the comparable

Figure 21 - Accumulated Dilation of Air-Entrained Concrete Specimens With Mixtures of Coarse Aggregates.



specimens made with the individual reference aggregates.

Variable E - Effects Measured by Flexural Strength Loss

The average loss in flexural strength shown in Table 8 of the concrete specimens with the mixed aggregates does not show any appreciable deviation from the flexural strength loss shown for the comparable specimens made with the individual reference aggregates. However, the aggregate mixtures with aggregate 6 as one of the sources show approximately 5 and 4 percent greater reduction in flexural strength than the comparable mixtures made with the higher gravity aggregates.

VARIABLE F - OUTDOOR EXPOSURE TEST

The beams to be subjected to the outdoor exposure test were placed in the permanent outdoor sand bed, as described by Axon et al. (V), during the months of October and November, 1967. As the recorded information to date only covers a period of 4 years exposure and there being no relative basis upon which to discuss these results, presentation of this data will be delayed until the final report covering the laboratory and field results is published.

VARIABLE G - GEOGRAPHICAL LOCATION

For purposes of covering the largest areas possible it was stipulated that one sample of each gravity classification would be obtained from each of the two geographical areas most involved with this problem.

Coarse aggregates 1 through 4 and 6 were obtained from the west-central area and aggregates 7 through 12 were obtained from the northwestern area of the State of Missouri. Comparison of these aggregates will be limited as shown in the following abbreviated table:

West-central area	vs.	Northwest area
Coarse Aggr. 1	:	Coarse Aggr. 7
Coarse Aggr. 2	:	Coarse Aggr. 8
Coarse Aggr. 3	:	Coarse Aggr. 9
Coarse Aggr. 4 (Dolomitic)	:	Coarse Aggr. 10 (Pelletal)
Coarse Aggr. 5 Not obtained	:	Coarse Aggr. 11
Coarse Aggr. 6 (Dolomitic)	:	Coarse Aggr. 12 (Pelletal)

Omitting the groups where the character of the aggregates are different or there is an absence of data, the comparisons must be limited to the three highest gravity groups.

Comparison of the relative rate of failure of these coarse aggregates, as shown previously in Figure 8, shows the aggregates from the west-central area to have the highest rate of failure. However, the complicating factor underlying this comparison is the fact that these aggregates were chosen for use in this test on the basis of their average bulk specific gravity and do not represent the relative abundance of or absence of particular gravity stones. No attempt was made to determine the relative abundance of any

one gravity group nor was there any attempt to determine the durability of a quarry-produced sample. Therefore, a statement regarding durability with respect to geographical location on the basis of the data presented herein would be very misleading and possibly incorrect without further knowledge of the actual quantities of the various materials that are present within the two areas under consideration.

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APPENDIX A

MATERIALS

Fine Aggregate:

The fine aggregate used in this phase of the laboratory testing was a Missouri River sand having the Physical properties shown in Table 10. This sand was in an air dry condition when used. Two fractions of sand were used for batching; #16 to 3/8 and -#16, blended at 22.8 and 77.2 percent respectively.

Coarse Aggregate:

To the extent possible, coarse aggregates were to be obtained having bulk specific gravities within each of the following categories; 2.68 to 2.64, 2.63 to 2.60, 2.59 to 2.56, 2.55 to 2.52, 2.51 to 2.48, and 2.47 to 2.44. Due to the high variability in the bulk specific gravity of ledge stone, and the scarcity of some material, a sample representing each of the desired gravity ranges could not be obtained.

The coarse aggregate was obtained from the field in boulder form of approximately 5 to 15-pound size. Preliminary bulk specific gravity (saturated surface dry), after 30 minutes soaking, was obtained on each boulder. The boulders were then shipped to the laboratory for processing. Crushing was done with a jaw-type crusher.

Two fractions of coarse aggregate were used for batching; #4 to 1/2" and 1/2" to 1", except for the special mixes having an additional 1" to 2" size fraction, as shown

in Table 11. The other mix design variables such as air and sand contents used in this study are shown in Table 16.

The bulk specific gravity and bulk specific gravity (saturated surface dry) after 2 hours soaking for the individual fractions and blends of the coarse aggregates are shown in Table 11. Note that the terms "blend" and "blended" are used to denote the combining of the two or three fractions together by the ratios shown. The term "combined" could not be used here because it is used to denote the combining of aggregates from each gravity group of the gravity separation analysis by weighted percentages. The vacuum absorptions and two-hour absorptions by weight and volume are shown in Table 12. The chemical analysis of each coarse aggregate is shown in Table 13.

The alcohol freeze-thaw test results and the deleterious material determinations for each coarse aggregate are shown in Table 14.

The deleterious material consists of the shaly rock, cap shale + 20 percent, and extremely soft and/or porous rock. Specifically each of these terms is defined as follows:

"Shaly Rock - A rock is generally contaminated with shale to a high degree. Color may vary but the rock usually has a dull gray appearance and is reasonably uniform in appearance. Also may occur in the form of numerous shale lines or seams closely spaced

throughout the particle, thus giving a laminated or streaked appearance.

"Cap + 20% - A rock particle with a line of demarcation of a layer or 'cap' of shale or shaly rock which usually occurs on one face, but may be found on two faces; in either case the summation of the percent of 'caps' should exceed 20% of the volume of the rock particle.

"Extremely Soft and/or Porous Rock - A rock which can be readily broken with the fingers. In some cases, due to the size or shape of the rock, it cannot be broken, however, small areas can be spalled or chipped off with the fingers. Porosity or high absorption may be detected by rapid disappearance of surface water or by breaking rock in half and observing the depth of penetration of moisture."

Cement

Normal portland cement was obtained from a source which had been used extensively in prior years for many of the paving projects in the geographical areas under consideration. The physical and chemical properties of this cement are shown in Table 15.

Air-Entraining Agent:

A vinsol resin solution was used as an air-entraining agent for the concretes. The formulation was as follows:

45.5 grams of vinsol resin

6.8 grams of NaOH

Plus sufficient distilled water to make 2000 ml.

Mixing Water:

Tap water at room temperature was used. A quantity of water sufficient for an entire day's run was drawn and allowed to set for at least 2 hours prior to being used.

Table 10 - Properties of Fine Aggregate

Gradation:

Percentages passing:

3/8"	sieve	100.00
No. 4	sieve	97.54
No. 20	sieve	62.92
No. 50	sieve	11.04
No. 100	sieve	1.24

Bulk Specific Gravity	2.60
Bulk Specific Gravity (SSD)	2.61
Apparent Specific Gravity	2.63
Absorption, percent (30 min.)	0.4
(24 hours)	0.4

NOTE: Generally the moisture content of sand as used was 0.18 percent.

Table 11 - Bulk Specific Gravity and Bulk Specific Gravity (Saturated Surface Dry) of Coarse Aggregates. (Each value shown is average of two tests)

Coarse Aggr.	Bulk Specific Gravity					Bulk Specific Gravity (SSD) (1)			
	1" to 2"	½" to 1"	#4 to ½"	Blended(2)	Blend(3)	1" to 2"	½" to 1"	#4 to ½"	Blended(2)
1	--	2.6578	2.6436	2.6507	0.0:50.0:50.0	--	2.6771	2.6679	2.6725
2	--	2.6253	2.6082	2.6174	0.0:54.0:46.0	--	2.6534	2.6442	2.6492
2(4)	2.6232	2.6253	2.6082	2.6194	42.5:28.5:29.0	2.6520	2.6534	2.6442	2.6501
3	--	2.5905	2.5791	2.5848	0.0:50.0:50.0	--	2.6323	2.6301	2.6312
4	--	2.5287	2.5090	2.5188	0.0:50.0:50.0	--	2.6032	2.5928	2.5980
4(4)	2.5216	2.5287	2.5090	2.5200	40.0:30.0:30.0	2.6046	2.6302	2.5928	2.6006
6	--	2.4993	2.4815	2.4901	0.0:48.5:51.5	--	2.5886	2.5794	2.5839
7	--	2.6665	2.6445	2.6555	0.0:50.0:50.0	--	2.6846	2.6719	2.6782
8	--	2.6426	2.6312	2.6369	0.0:50.0:50.0	--	2.6694	2.6630	2.6662
9	--	2.5798	2.5746	2.5772	0.0:50.0:50.0	--	2.6233	2.6227	2.6230
10	--	2.5507	2.5337	2.5422	0.0:50.0:50.0	--	2.5972	2.5868	2.5920
11	--	2.4914	2.4747	2.4830	0.0:50.0:50.0	--	2.5618	2.5539	2.5578
12	--	2.4760	2.4690	2.4725	0.0:50.0:50.0	--	2.5284	2.5278	2.5281

(1) Aggregate soaked for 2 hours, but not oven-dried prior to soaking.
(2) Blended means the gravity of the fractions blended to the ratios shown.
(3) Percentages shown are for the 1" to 2", ½" to 1", and #4 to ½" fractions respectively.
(4) Note 2" max. size aggregate for this gradation, Gradation A.

Table 12 - Two-Hour Absorptions of Coarse Aggregates
(Each value shown is average of two tests)

Coarse Aggr.	2 Hour Absorption (% by Wt.) 1" to 2"	½" to 1"	#4 to ½"	Blended(1)	Percent of Vac. Sat. Abs. (by Wt.)	2 Hour Absorption (% by Vol.) 1" to 2"	½" to 1"	#4 to ½"	Blended(1)	Percent of Vac. Sat. Abs. (by Vol.)
1	--	0.73	0.92	0.82	73.18	--	1.93	2.43	2.18	95.19
2	--	1.07	1.38	1.21	84.02	--	2.80	3.60	3.17	84.75
2(2)	1.09	1.07	1.38	1.17	84.78	2.88	2.80	3.60	3.07	85.04
3	--	1.62	1.98	1.80	81.81	--	4.18	5.10	4.64	82.70
4	--	2.95	3.35	3.15	87.74	--	7.45	8.39	7.92	87.80
4(2)	3.30	2.95	3.35	3.21	86.99	8.30	7.45	8.39	8.07	87.05
6	--	3.58	3.94	3.76	89.95	--	8.93	9.79	9.37	90.35
7	--	0.68	1.02	0.85	94.44	--	1.82	2.72	2.27	94.97
8	--	1.01	1.20	1.10	85.27	--	2.67	3.17	2.92	87.16
9	--	1.69	1.87	1.78	86.82	--	4.35	4.82	4.58	87.57
10	--	1.82	2.10	1.96	77.47	--	4.65	5.31	4.98	78.30
11	--	2.82	3.20	3.01	81.13	--	7.03	7.92	7.48	81.48
12	--	2.12	2.38	2.25	58.13	--	5.25	5.89	5.57	58.63

(1) Blended means weighted ratio of fractions by percentage blend, as shown in Table 11.
(2) Note 2" max. size aggregate for this gradation, Gradation A.

Table 13 - Chemical Analyses of Coarse Aggregates(1)

Coarse Aggr.	Chemical Analyses by Wet Method (Percent)										
	Loss on Ignition	Insol. Matter	Silicon Dioxide	Iron Oxide	Aluminum Oxide	Calcium Oxide	Magnesium Oxide	Sulfur Trioxide	Total Sulfur	Sodium Oxide	Potassium Oxide
1	42.9	0.2	1.7	0.4	0.8	53.9	0.3	0	0	0.02	0.02
2	42.6	0.1	2.2	0.9	0.7	52.5	1.0	0	0	0.05	0.03
2(2)	42.8	0	1.8	0.9	0.5	52.7	1.0	0	0	0.02	0.02
3	42.0	0.2	3.5	1.0	1.0	50.4	1.7	0	0	0.02	0.04
4	40.6	0.5	5.9	1.8	2.1	44.7	4.5	0	0	0.02	0.05
6	37.9	0.9	10.8	2.4	4.0	38.3	6.1	0	0	0.03	0.10
7	42.9	0	1.6	0.4	0.8	54.0	0.3	0	0	0.02	0.03
8	42.2	0.2	3.1	0.6	1.0	52.9	0.5	0	0	0.03	0.04
9	41.4	0	4.2	0.4	1.3	52.1	0.4	0	0	0.03	0.04
10	42.0	0.2	3.1	0.5	0.8	53.0	0.4	0	0	0.02	0.04
11	41.8	0.2	3.7	0.7	0.9	51.9	0.9	0	0	0.02	0.04
12	42.3	0	2.7	2.1	0.8	50.0	2.2	0	0	0.02	0.03

(1) Samples were blended to ratios shown in Table 11.
(2) Chemical Analysis of a recrushed sample because of lack of original -½" fraction.

Table 14 - Alcohol Freeze-Thaw and Deleterious Material Determinations for Coarse Aggregates

Coarse Aggr.	Alcohol Freeze-Thaw Test (Blended Sample) (1) Soundness Rating	Deleterious Material (1) Per Aggregate Fraction 1" to 2"	½" to 1"	#4 to ½"	Blended (2)
1	Some unsoundness	--	0.3	0.2	0.25
2	Some unsoundness	--	1.2	1.3	1.25
2(3)	Some unsoundness	1.2	1.2	1.3	1.23
3	Some unsoundness	--	1.0	1.7	1.35
4	Unsound	--	3.9	5.7	4.80
4(3)		1.4	3.9	5.7	3.44
6	Unsound	--	3.8	5.5	4.68
7	Some unsoundness	--	0.4	0.3	0.35
8	Some unsoundness	--	1.0	1.2	1.10
9	Some unsoundness	--	0.5	1.4	0.95
10	Some unsoundness	--	0.7	1.0	0.85
11	Some unsoundness	--	0.2	0.2	0.20
12	Some unsoundness	--	0	0	0

(1) Deleterious material is shown as a percent by weight of the coarse aggregate.
(2) Blended means the fractions 1" to 2", ½" to 1", and #4 to ½" blended to the ratios shown in Table 11.
(3) Note 2" max. size aggregate for this determination, Gradation A.

Table 15 - Properties of Cement

Physical

Normal Consistency, percent	23.8
Soundness, Autoclave	0.03
Initial Set (Hrs. & Min.)	3:20
Final Set (Hrs. & Min.)	5:25
Tensile Strength, avg. psi	
3 days	370
7 days	457
Specific Surface, Blaine	3225
Specific Gravity	3.17

Chemical

Percent SiO_2 (Silica)	21.5
" CaO (Calcium Oxide)	64.5
" MgO (Magnesium Oxide)	1.5
" Fe_2O_3 (Iron Oxide)	3.2
" Al_2O_3 (Aluminum Oxide)	5.2
" SO_3 (Sulfur Trioxide)	1.8
" Insoluble Residue	0.14
" Loss on Ignition	1.06
" Na_2O (Sodium Oxide)	0.21
" K_2O (Potassium Oxide)	0.32
" C_3S (Tricalcium Silicate)	54.5
" C_2S (Diacalcium Silicate)	20.6
" C_3A (Tricalcium Silicate)	8.4
" Total Alkali as Na_2O Equiv.	0.42

APPENDIX B

PETROGRAPHIC ANALYSES

The following petrographic descriptions are based on terminology given by Folk (II) and Pettijohn (VI). Microphotographs of each coarse aggregate in thin sections are shown in Figures 22, 23 and 24.

Coarse Aggregate 1:

Microcrystalline calcitic limestone, well indurated, tan to gray mottling; numerous small areas of coarsely crystalline calcite; fossiliferous. After crushing process this limestone occurs as angular fragments with considerable internal cracking.

Coarse Aggregate 2:

Microcrystalline calcitic limestone, well indurated, tan to dark gray mottling, fossiliferous, shale partings were observed on some particles along with styolite zones. After crushing process this limestone occurs as angular fragments with considerable internal cracking.

Coarse Aggregate 3:

Microcrystalline calcitic limestone, well indurated, tan to light gray mottling, a few areas of gray mottling, some areas of coarsely crystalline calcite, fossiliferous. After crushing process this limestone occurs as angular fragments with considerable internal cracking.

Coarse Aggregate 4:

Finely crystalline dolomitic limestone loosely indurated, tan to light gray, fossiliferous; some particles are

finely laminated. After crushing process this aggregate occurs as rounded fragments with a moderate amount of internal cracking. Photo shows a thin section stained with Alizan Red-S.

Coarse Aggregate 6:

Finely crystalline dolomitic limestone, loosely indurated, tan to light gray; finely laminated; fossiliferous. After crushing process this aggregate occurs as round fragments with a slight amount of internal cracking. Photo shows a thin section stained with Alizan Red-S.

Coarse Aggregate 7:

Microcrystalline calcitic limestone, well indurated, light gray; numerous small areas of coarsely crystalline calcite; fossiliferous. After crushing process this limestone occurs as angular fragments with a slight amount of internal cracking.

Coarse Aggregate 8:

Microcrystalline calcitic limestone, well indurated, light gray, some small areas of coarsely crystalline calcite, fossiliferous. After crushing process this limestone occurs as angular fragments with minor amount of internal fractures.

Coarse Aggregate 9:

Microcrystalline calcitic limestone, well indurated, tan to dark gray mottling; nonfossiliferous. After crushing process this limestone occurs as angular fragments with a minor amount of internal fractures.

Coarse Aggregate 10:

Mixed oolitic and pelletal limestone, white to light gray, well indurated, most oolids and pellets have been replaced by polycrystalline dolomite, fossiliferous with iron stains. After crushing process this limestone occurs as angular fragments with a slight amount of internal cracking. Photo shows a thin section stained with Alizan Red-S.

Coarse Aggregate 11:

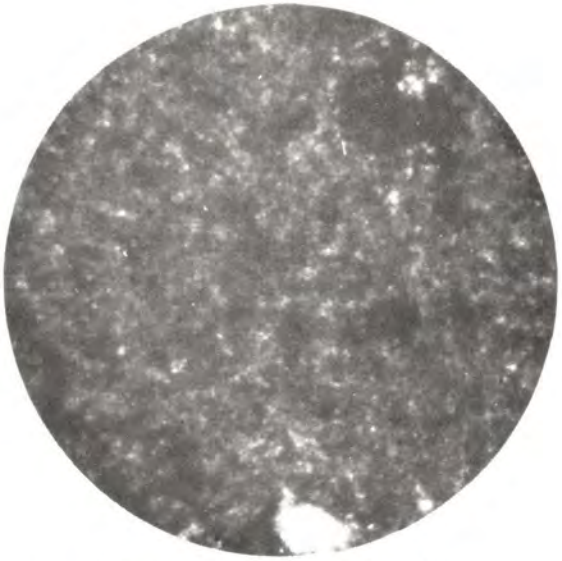
Microcrystalline calcitic limestone, well indurated, tan to light gray; nonfossiliferous. After crushing process this limestone occurs as subrounded fragments with a slight amount of internal cracking.

Coarse Aggregate 12:

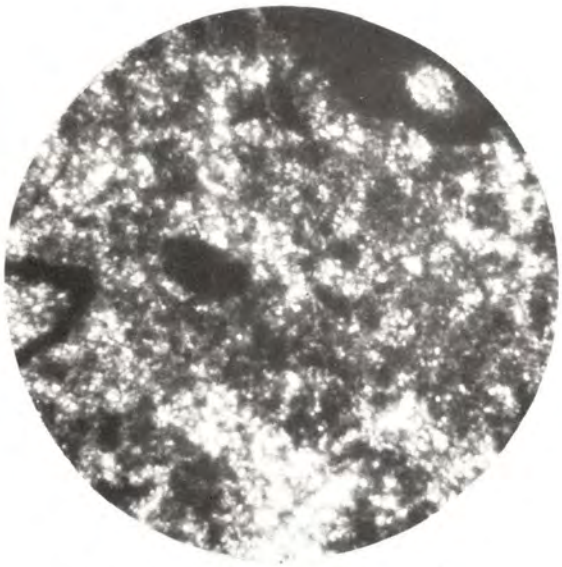
Mixed oolitic and pelletal limestone, light gray, well indurated with sparry calcite, microspar, and microcrystalline calcite, and a small percentage of oolids and pellets have been replaced by polycrystalline dolomite, fossiliferous. After crushing process this limestone occurs as angular fragments with a slight amount of internal cracking.

Figure 22 - Microphotographs of Coarse Aggregates.

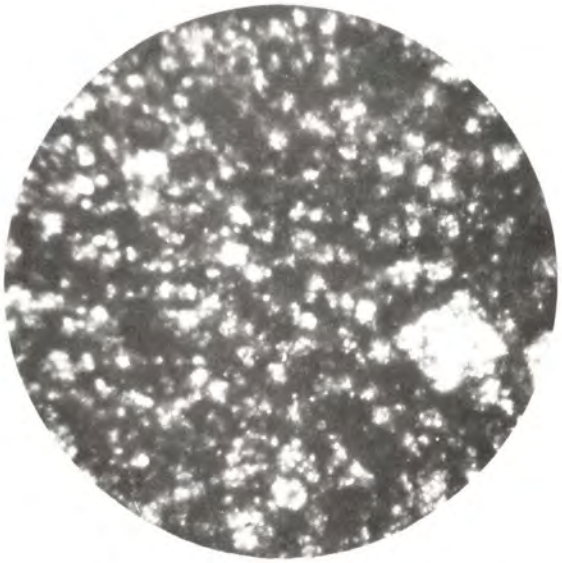
Coarse Aggregate 1



Coarse Aggregate 2

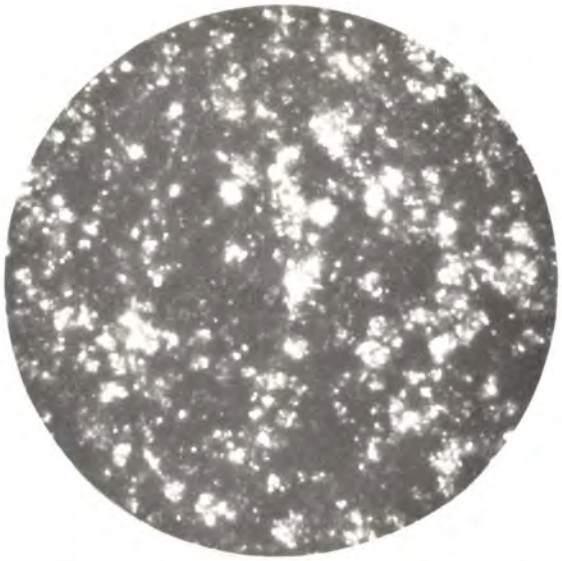


Coarse Aggregate 3

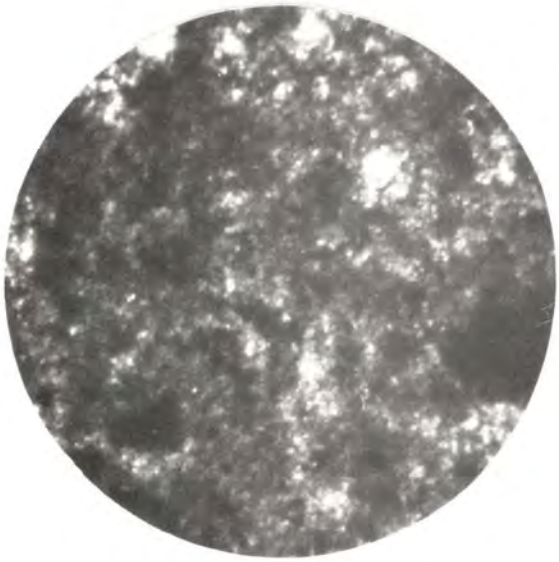


Coarse Aggregate 4
(Stained)

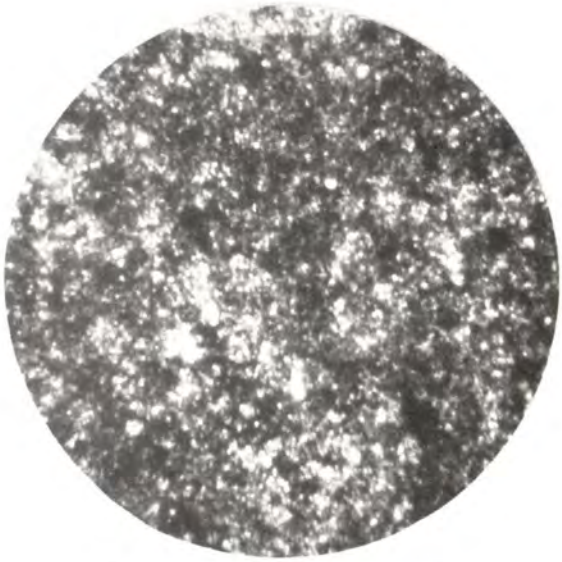
Figure 23 - Microphotographs of Coarse Aggregates.



Coarse Aggregate 6 (Stained)

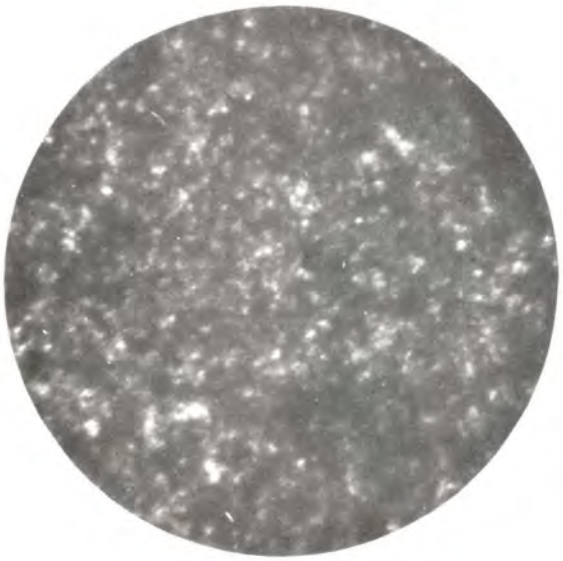


Coarse Aggregate 7



Coarse Aggregate 8

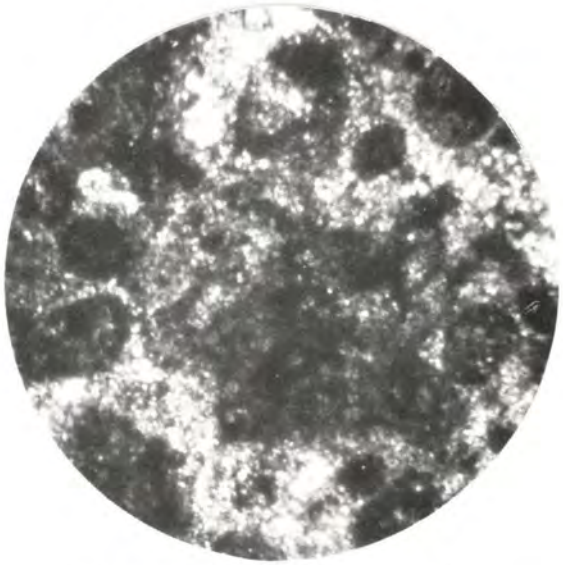
Figure 24 - Microphotographs of Coarse Aggregates.



Coarse Aggregate 9

Coarse Aggregate 10
(Stained)

Coarse Aggregate 11



Coarse Aggregate 12

APPENDIX C

MIX DESIGN AND BATCHING

The number and distribution of concrete specimens necessary to evaluate each variable in this phase of the laboratory testing is shown in Table 16. Due to the character and arrangement of the variables, the following mix designs and modifications were necessary.

Concrete:	Air-Entrained	Nonair-Entrained
Cement Factor:	1.53 bbls/cu. yd.	1.53 bbls/cu.yd.
Water/Cement ratio:	0.67	0.73
Air Content:	5.5 ± 1.5%	Normal
Total Aggr. Fraction:	68.51%	72.05%
Coarse Aggr./Total Aggr.:	55.0,63.0 or 67.0%	52.3,59.9 or 63.7%
Fine Aggr./Total Aggr.:	45.0,37.0 or 33.0%	47.7,40.1 or 36.3%

The concrete was batched in either 0.4848, 0.9168 or 1.4006 cubic foot size for the three small beams, two large beams, or three small and two large beams respectively, as shown in Table 16. For each combination of variables, four comparable batches were necessary to fabricate the required number of specimens. The 34 separate batch designs were randomized into four groups, representing four mixing days per week, then randomized within each group, representing each daily mixing schedule. Each of the four groups were used on either a Monday, Tuesday, Wednesday, or a Thursday of four consedutive weeks.

The fine aggregate was batched in an air-dry state. Allowance in the calculated weight of water required for the mix design was made to provide for the two-hour absorption of the fine aggregate at the time it was used. The coarse aggregates were soaked for 2 hours in water at room

temperature before batching.

The concrete was mixed in a Lancaster SW laboratory mixer. The coarse aggregate, cement and sand were dry mixed for one minute, then water and the air-entraining agent were added and mixed another three minutes. Immediately after mixing, slump and air content determinations were made. The material used in these tests was then remixed by hand with the remainder of the batch and the required number of beams molded.

Molding of the beams was accomplished in the following manner. The 3½ x 4½ x 16 inch beams were molded by placing two lifts and rodding each 50 times with a 5/8" bullet-pointed rod, spaded lightly around the edges, tapped lightly to settle the concrete, struck off with a metal bar, and finished with a wooden float. The 6 x 6 x 20 inch beams were molded in a similar manner except the two layers were rodded 75 times each.

Stainless steel strain gauge plugs were molded into the top and bottom of all beams that were to be subjected to the freeze and thaw test or outdoor exposure. Plugs were made from stainless steel rod 3/8 inch in diameter cut to 3/4 inch in length. The cylindrical surface of the plugs were roughened by machining a spiral groove to aid in bonding. A 1/16 inch hole approximately 3/16 inch deep was drilled in each plug and all burrs removed by very slight hand reaming.

Table 16 - Distribution of Concrete Specimens and Mix Characteristics for Variables Considered.

Concrete Mix Design	Air Ent.	Sand Cont. (%)	Max. Aggr. Size (in)	No. of beams/batch $3\frac{1}{2} \times 4\frac{1}{2} \times 16$	No. of beams/batch $6 \times 6 \times 20$	Total Beam Distribution(1) Control	Total Beam Distribution(1) F & T	Total Beam Distribution(1) Outdoor
1-1AS	Yes	45.0	1	3	--	4	4	4
2-1AS	Yes	45.0	1	3	2	4(4)	4(4)	4
2-1BS	Yes	37.0	1	3	--	4	4	4
2-1CS	Yes	33.0	1	3	--	4	4	4
2-1AO	Yes	45.0	2	--	2	(4)	(4)	--
2-1CO	Yes	33.0	2	--	2	(4)	(4)	--
2-2DS	No	47.7	1	3	--	4	4	4
2-2ES	No	40.1	1	3	--	4	4	4
2-2FS	No	36.3	1	3	--	4	4	4
3-1AS	Yes	45.0	1	2	--	4	4	--
4-1AS	Yes	45.0	1	3	2	4(4)	4(4)	4
4-1BS	Yes	37.0	1	3	--	4	4	4
4-1CS	Yes	33.0	1	3	--	4	4	4
4-1AO	Yes	45.0	2	--	2	(4)	(4)	--
4-1CO	Yes	33.0	2	--	2	(4)	(4)	--
4-2DS	No	47.7	1	3	--	4	4	4
4-2ES	No	40.1	1	3	--	4	4	4
4-2FS	No	36.3	1	3	--	4	4	4
6-1AS	Yes	45.0	1	3	--	4	4	4
6-1BS	Yes	37.0	1	3	--	4	4	4
6-1CS	Yes	33.0	1	3	--	4	4	4
6-2DS	No	47.7	1	3	--	4	4	4
6-2ES	No	40.1	1	3	--	4	4	4
6-2FS	No	36.3	1	3	--	4	4	4
7-1AS	Yes	45.0	1	3	--	4	4	4
8-1AS	Yes	45.0	1	3	--	4	4	4
9-1AS	Yes	45.0	1	2	--	4	4	4
10-1AS	Yes	45.0	1	3	--	4	4	4
11-1AS	Yes	45.0	1	2	--	4	4	4
12-1AS	Yes	45.0	1	3	--	4	4	4
1&3-1AS	Yes	45.0	1	3	--	4	4	4
1&6-1AS	Yes	45.0	1	3	--	4	4	4
2&4-1AS	Yes	45.0	1	3	--	4	4	4
2&6-1AS	Yes	45.0	1	3	--	4	4	4
					Totals	144	144	108

(1) Plain numbers indicate the number of $3\frac{1}{2} \times 4\frac{1}{2} \times 16$ inch specimens and the numbers in parenthesis indicate the number of 6 x 6 x 20 inch specimens per variables shown.

CURING

Immediately after fabrication, the concrete beams were placed in a moist room controlled at approximately 73°F and 95 percent relative humidity. The following day the molds were removed and the concrete beams were weighed in air and water and initial length measurements taken. Thereafter, the beams were handled as follows:

Control Beams: The 144 control beams to be broken in flexure were kept in the moist room on shelves until seven days old, then were stored in limewater at room temperature until they were broken in flexure at 35 days.

Freeze and Thaw Beams: The 144 freeze and thaw beams were kept in the moist room on shelves until seven days old, then were stored permanently in limewater at room temperature until the beginning of the freeze and thaw test at 35 days. The beams were removed once a week for approximately 20 hours of freeze and thaw testing.

Outdoor Exposure Beams: The remaining 108 beams for outdoor exposure were kept in the moist room on shelves until seven days old, then were placed in special wooden forms in the outdoor exposure test area.

CONCRETE BEAM IDENTIFICATION

To properly identify each individual concrete beam the following abbreviated identification was used:

For Example: 6-1AS

The numbers preceeding the hyphen indicate the coarse aggregate incorporated into the particular mix design.

Following the hyphen:

Column 1 - indicates air-entrained (1) or nonair-entrained (2) mix design.

Column 2 - indicates the sand content as a function of total aggregate fraction, were:

A = 45%
B = 37%
C = 33%
D = 47.7%
E = 40.1%
F = 36.3%

Column 3 - indicates the gradation of the coarse aggregate being 1 inch maximum (S) or 2 inch maximum (0).

For the properties of any beam identification code, refer to Table 17.

RESULTS OF TESTS ON FRESH CONCRETE AND CONTROL BEAMS

The cement factor, water-cement ratio, slump, and air content of the fresh concrete immediately after batching are shown in Table 17.

The results of the flexural tests from the control beams are shown in Table 8. One break on each of the 14 inch and 7 inch spans were made on the smaller (3½ x 4½ x 16 inch) beams and only one break on an 18 inch span was possible on the larger (6 x 6 x 20 inch) beams.

It is interesting to note, by observation of Table 17, that the cement factors and water-to-cement ratios were fairly consistent for all concrete mixtures of similar design. The slump and air contents were within the specified limits. However, the flexural strength results indicate that for the three aggregates 2, 4, and 6 the strength of the nonair-entrained concrete beams was approximately 6, 10, and 5 percent larger respectively at the 14 inch break and approximately 7, 7, and 5 percent larger respectively at the 7 inch break than were air-entrained concrete beams.

The deviation between the flexural strengths of the 3½ x 4½ x 16 inch concrete beams; taking the air and nonair-entrained groups separately for aggregates 2, 4, and 6; made with various sand contents is very small. Therefore, the effects of a change in sand content of approximately 12 percent on the flexural strengths of these laboratory specimens was relatively insignificant. The flexural strengths of the 6 x 6 x 20 inch concrete beams were not consistent

with this. The flexural strengths of the concrete beams with coarse aggregate 2 were similar; however, the concrete beams with coarse aggregate 4 did show an appreciable increase in flexural strength with a reduction in sand content from 45 to 33 percent.

Table 17 - Characteristics of Fresh Concretes
(All values are the average of four determinations)

Concrete Mix Design	Sand Cont. (%)	Cement Factor (Avg.)	W/C Ratio (Avg.)	Slump (Inches)	Air Cont. (%) Fresh
			3½ x 4½ x 16 inch beams		
1-1AS	45.0	1.54	0.64	3.25	5.3
2-1AS	45.0	1.54	0.62	2.47	5.7
2-1BS	37.0	1.56	0.63	2.98	4.7
2-1CS	33.0	1.56	0.62	2.50	4.8
2-2DS	47.7	1.53	0.72	2.47	0.8
2-2ES	40.1	1.54	0.71	2.69	0.2
2-2FS	36.3	1.55	0.70	2.50	0.1
3-1AS	45.0	1.55	0.63	2.38	5.0
4-1AS	45.0	1.54	0.63	2.94	5.9
4-1BS	37.0	1.58	0.63	2.66	4.6
4-1CS	33.0	1.55	0.64	2.56	4.7
4-2DS	47.7	1.53	0.72	2.41	0.8
4-2ES	40.1	1.54	0.70	2.31	0.5
4-2FS	36.3	1.54	0.71	2.31	0
6-1AS	45.0	1.55	0.63	2.56	5.3
6-1BS	37.0	1.56	0.63	2.72	4.8
6-1CS	33.0	1.56	0.62	2.34	4.7
6-2DS	47.7	1.53	0.71	2.17	0.9
6-2ES	40.1	1.54	0.70	2.78	0.4
6-2FS	36.3	1.55	0.69	2.16	0.2
7-1AS	45.0	1.55	0.63	2.84	5.9
8-1AS	45.0	1.54	0.63	3.09	5.7
9-1AS	45.0	1.55	0.63	2.56	5.1
10-1AS	45.0	1.55	0.63	2.53	5.2
11-1AS	45.0	1.55	0.62	2.60	5.0
12-1AS	45.0	1.55	0.62	2.84	5.4
1&3-1AS	45.0	1.55	0.63	2.53	4.9
1&6-1AS	45.0	1.55	0.64	2.68	5.0
2&4-1AS	45.0	1.54	0.64	2.56	5.3
2&6-1AS	45.0	1.56	0.64	2.00	4.6
			6 x 6 x 20 inch beams		
2-1AS	45.0	1.54	0.62	2.47	5.7
2-1AO	45.0	1.55	0.61	3.09	5.5
2-1CO	33.0	1.56	0.59	3.12	5.5
4-1AS	45.0	1.54	0.63	2.94	5.9
4-1AO	45.0	1.55	0.61	2.44	5.3
4-1CO	33.0	1.57	0.60	2.90	4.6

APPENDIX D

FREEZING AND THAWING TEST PROCEDURE

The Missouri accelerated laboratory freezing and thawing test is a modification of the method described by T. C. Powers in his paper "Basic Considerations Pertaining to Freeze and Thaw Tests" (VII). Under the Missouri procedure the concrete beams are cooled to 40°F in a water bath prior to being placed in the freezer. The concrete beams are frozen in air, the temperature of which is maintained at 0°F. A typical freeze and thaw cycle consisted of approximately 16½ hours of freeze (overnight) and 2 hours thaw. With this procedure only one freeze and thaw cycle was obtained per week per specimen. Storage of the specimens between cycles was at room temperature completely submerged in a saturated limewater solution.

The results of the freezing and thawing test were recorded by the change in length, weight, and fundamental sonic frequency when measuring the dynamic modulus of elasticity for each individual concrete beam before and after each freeze and thaw cycle. The change in length was measured by a Whittemore strain gauge (10" span) to the nearest 0.001 inch on both the top and bottom of each concrete beam. The change in weight was measured to the nearest gram on a laboratory Toledo balance. Due to handling the concrete beams over a period of 100 weeks, some chipping of the corners and edges was inevitable. Where possible, proper notation was made when large chips and excessive

changes in weight occurred. The change in dynamic modulus was measured electronically by the use of a frequency probe and pickup system.

The data obtained for the change in length, weight, and sonic frequency are shown in Tables 4, 5, and 6 respectively. Each value is the average results obtained from four replicate concrete specimens unless otherwise noted.

DESCRIPTION OF THE LABORATORY HEAVY LIQUID SEPARATION PROCEDURE

For the laboratory gravity separation, two liquids were combined by different ratios (by volume), to yield the desired gravity of each separation media. The liquids used were:

1. Acetylene Tetrabromide (Specific Gravity = 2.93)
2. Carbon Tetrachloride (Specific Gravity = 1.58),

and were combined by the following relationship:

$$A = \left[Bx + (100-x)C\right] \div 100$$

Where: A = Desired specific gravity of separation media
B = Specific Gravity of acetylene tetrabromide
C = Specific gravity of carbon tetrachloride
x = Percent by volume

Thus the percent by volume of each of the liquids may be calculated.

Example: Desired specific gravity of separation media is 2.40. Assuming Liquid B has a specific gravity of 2.93, and Liquid C has a specific gravity of 1.58,

Then: Substituting into the above equation:

$$2.40 = \left[\frac{(2.93)x + (100-x)1.58}{100}\right]$$

$$2.40 = 2.93x + 158 - 1.58x \text{ or}$$

$$x = \frac{82}{1.35} = 60.74\% \text{ and}$$

$$100-x = 39.26\%$$

This means the two liquids should be combined volumetrically by 60.74 percent acetylene tetrabromide and 39.26 percent carbon tetrachloride to obtain the desired 2.40 gravity liquid.

Operating Procedure:

During the laboratory heavy liquid separation, approximately two gallons of each of the desired gravity liquids were mixed and placed in 16-quart stainless steel pails. The sample to be tested, which had already been vacuum saturated and allowed to set under water for three days at room temperature, was surface dried and placed in a 13-quart stainless steel pail, the bottom of which had been perforated with 1/8 inch holes. The pail containing the sample was lowered into the pail containing the lowest gravity liquid first, thoroughly stirred and all floating particles removed with a small screen. The pail containing the sink fraction of the sample was then removed from the liquid, shaken to remove the excess liquid on the stone particles and placed in the pail containing the next higher gravity liquid. This operational procedure was repeated until the sample had been separated in all liquids.

Due to the more rapid evaporation of the carbon tetrachloride, the gravities of the liquids tended to increase during the test. Therefore, by starting the separation in the lowest gravity liquid, the carry-over of lighter gravity liquid from pail to pail tends to offset the evaporation of the carbon tetrachloride and maintain the desired accuracy in gravity of the liquids. Prior to testing each sample, the gravity of each liquid was checked with hydrometers and the necessary adjustments made.

As each floating portion of the stone was removed

from the heavy liquid it was washed in carbon tetrachloride, a commercial alcohol (solox) and tap water, respectively, and stored under tap water in suitable closed containers until weighed.

The bulk specific gravity and bulk specific gravity (vacuum saturated surface dry) and the vacuum absorptions by weight and volume for the gravity gradation samples are shown in Tables 18 and 19, respectively.

Table 18 - Bulk Specific Gravity and Bulk Specific Gravity (Vacuum Saturated Surface Dry) of the Gravity-Separated Coarse Aggregates. (One value per each fraction shown)

Coarse Aggr.	Bulk Specific Gravity 1" to 2"	½" to 1"	#4 to ½"	Blended(1)	Blend(2)	Bulk Specific Gravity (V.S.S.D.) 1" to 2"	½" to 1"	#4 to ½"	Blended(1)
1	--	2.6548	2.6538	2.6543	0.0:50.0:50.0	--	2.6782	2.6772	2.6777
2	--	2.6238	2.6162	2.6203	0.0:54.0:46.0	--	2.6610	2.6537	2.6576
2(3)	2.6356	2.6238	2.6162	2.6266	42.5:28.5:29.0	2.6700	2.6610	2.6537	2.6627
3	--	2.5881	2.5739	2.5810	0.0:50.0:50.0	--	2.6416	2.6327	2.6371
4	--	2.5319	2.5146	2.5233	0.0:50.0:50.0	--	2.6192	2.6076	2.6134
4(3)	2.5204	2.5319	2.5146	2.5221	40.0:30.0:30.0	2.6167	2.6192	2.6076	2.6147
6	--	2.4972	2.4833	2.4900	0.0:48.5:51.5	--	2.6010	2.5870	2.5938
7	--	2.6607	2.6352	2.6480	0.0:50.0:50.0	--	2.6811	2.6626	2.6718
8	--	2.6355	2.6151	2.6253	0.0:50.0:50.0	--	2.6644	2.6532	2.6588
9	--	2.5842	2.5718	2.5780	0.0:50.0:50.0	--	2.6332	2.6272	2.6302
10	--	2.5620	2.5268	2.5444	0.0:50.0:50.0	--	2.6206	2.5954	2.6080
11	--	2.4928	2.4794	2.4861	0.0:50.0:50.0	--	2.5811	2.5746	2.5578
12	--	2.5000	2.4906	2.4953	0.0:50.0:50.0	--	2.5939	2.5866	2.5903

(1) Blended means the gravity of the fractions blended to the ratios shown.
(2) Percentages shown are for the 1" to 2", ½" to 1", and #4 to ½" fractions respectively.
(3) Note 2" max. size aggregate for this gradation, Gradation A.

Table 19 - Vacuum Absorptions of Coarse Aggregates
(One value per each fraction shown)

Coarse Aggr.	Vacuum Absorption (% by Wt.)				Vacuum Absorption (% by Vol.)			
	1' to 2"	½" to 1"	#4 to ½"	Blended(1)	1" to 2"	½" to 1"	#4 to ½"	Blended(1)
1	--	0.895	0.859	0.877	--	2.347	2.225	2.286
2	--	1.435	1.450	1.442	--	3.737	3.755	3.745
2(2)	1.306	1.435	1.450	1.385	3.430	3.737	3.755	3.612
3	--	2.084	2.318	2.201	--	5.337	5.885	5.611
4	--	3.467	3.719	3.593	--	8.742	9.299	9.020
4(2)	3.826	3.467	3.719	3.686	9.634	8.742	9.299	9.266
6	--	4.180	4.185	4.183	--	10.376	10.366	10.371
7	--	0.766	1.042	0.904	--	2.038	2.742	2.390
8	--	1.100	1.471	1.286	--	2.891	3.814	3.352
9	--	1.908	2.191	2.050	--	4.913	5.548	4.230
10	--	2.316	2.745	2.530	--	5.866	6.858	6.362
11	--	3.556	3.860	3.708	--	8.837	9.527	9.182
12	--	3.822	3.919	3.870	--	9.392	9.600	9.496

(1) Blended means weighted ratio of fractions by percent blend, as shown in Table 18.
(2) Note 2" max. size aggregate for this gradation, Gradation A.

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