Effect of Heavy Media Separation on Durability Of Concrete Made with Indiana Gravels

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Alternate freezing and thawing are among the most destructive of the natural weathering conditions to which concrete is subjected. Indiana pavements undergo a large number of freezing and thawing cycles each year, and in addition, several aggregates of questionable durability are found in the state. The Joint Highway Research Project at Purdue University has, therefore, done considerable research concerning the freezing and thawing of concrete.

In 1946, Woods, Sweet, and Shelburne (1) reported results of extensive field surveys of over 2,600 miles of rigid pavements constructed in Indiana prior to 1935. Statistical analysis of the data indicated that the field performance of the pavements was directly related to the source of coarse aggregate used. Further investigation revealed a relationship between the mineralogical composition of gravel coarse aggregate and pavement field performances (2).

It appeared evident that the aggregates which were shown to have poor field performance met, and still would meet, most of the commonly employed acceptance tests developed for specification purposes (3). This fact gave impetus to many laboratory research programs directed toward development of a test, the results of which could be correlated with field performance. Among these programs was a study by Sweet (4) in which he concluded that freezing and thawing tests could be used to differentiate coarse aggregates with poor field performance from those with good performance. He suggested that all coarse aggregates tested should be put into concrete after being vacuum saturated so that the moisture condition of the aggregates would be similar to the degree of saturation that may be encountered in a pavement.

Using Sweet's conclusions and recommendations, other research programs were conducted. Studies of the effect of freezing and thawing on air-entrained concrete using poor aggregates were conducted by Bugg (5) and Blackburn (6). Venters (7) found that the deleterious portions of the gravels have high absorption and a potentially high degree of saturation. He was able to separate the deleterious particles from the gravels by means of heavy liquid flotation. Commercial heavy media (or heavy liquid) separation methods now exist and have been applied successfully toward the improvement of certain gravels (8).

All of the studies mentioned have produced laboratory data which can be correlated with the field performance of aggregates, but in each, either all gravel or all crushed stone coarse aggregate was used. Indiana's present field practice, however, is to blend crushed stone (for the larger sizes of the coarse aggregate) with gravel. Also, the development of commercial heavy media separation methods makes worthy of consideration the more extensive use of these methods for the improvement of gravel aggregates. These two factors merited laboratory research and form the basis of this study.

● THE purpose of this study was to obtain laboratory freezing and thawing data that would indicate what effect, if any, the addition of crushed stone and the use of heavy media separation have on the durability of concrete made with gravel coarse aggregate.

In order to carry out this work, four gravels were chosen, representing the northern,

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middle, and southern parts of the state of Indiana. Three crushed limestones were selected to be used with these gravels on the basis of their use in field practice; i. e., a northern stone is used with a northern gravel, etc. The stone used with the northern gravel was a reef-type material from the Huntington limestone formation. Stone from this formation has a very high porosity but has shown relatively good performance in the past. One source of stone from the St. Genevieve formation was used with the other gravels since a large part of the limestone quarried in the central and south central parts of the state is from this formation. A third limestone from the Glen Dean formation was also used with one of the southern gravels because it is of unknown quality but in the future may be used extensively in the southern part of the state.

In the heavy media study, the larger sizes of gravel in the gravel-crushed stone combinations were separated at two different specific gravity levels. This was an attempt to apply a procedure that might prove to be commercially economical. If heavy media separation is to be economically feasible in Indiana, it would not be desirable to treat the entire gradation of the aggregate. In addition, other investigators have found that if the deleterious particles are eliminated from the larger sizes, considerable benefit will result (9, 13). The deleterious particles might then be crushed into smaller sizes, which would minimize their harmful effects.

To complete the study, six series of tests were conducted. Five different mix designs were included in each series. Batches of concrete for each of the five mix designs of each series were mixed on one day and then repeated on three other days. Three, 3- x 4- x 16-in. beams were made from each batch of concrete, resulting in sixty beams for each series. The results are based on freezing and thawing tests on a total of 360 beams.

Test Series and Mix Designs

The first test series was designed to bring out the influence of the size of deleterious particles on the durability of a concrete mix. The results from this series were used in designing the remainder of the experiment.

In series 1, a single coarse aggregate (a gravel of mediocre field performance) was subjected to heavy liquid separation to remove deleterious particles from different parts of the gradation. Five mixes were included which were separated as follows:

Mix A - No heavy media separation
Mix B - Separation used on 1 in. - ¾ in. fraction
Mix C - Separation used on 1 in. -½ in. fraction
Mix D - Separation used on 1 in. - ⅜ in. fraction
Mix E - Separation used on 1 in. - No. 4 fraction

A heavy liquid having a specific gravity of 2. 50 was used for all heavy media treatments in this series.

Five additional test series were made, each of which was identical in all respects except for the source of the coarse aggregate used. Again, five mix designs were used for each series and these were intended to determine the differences in durability among concretes made with gravel, stone, a combination of gravel and stone, and a combination of gravel and stone in which the gravel had been treated by heavy media techniques.

More specifically, the following five mix designs were used for Series 2 through 6:

Mix F - Gravel aggregate for the entire coarse aggregate gradation which ranged from a 1-in. top size to material retained on a No. 4 sieve.

Mix G - Crushed stone, subsequently to be combined with the gravel used in Mix F was used for the entire aggregate gradation in mix design G.

Mixes H, I, and J - These mixes utilized the stone of Mix G as 35 percent of the total coarse aggregate in the sizes ranging from the 1-in. top size to ½-in. The remaining 65 percent of the total aggregate was the gravel used in Mix F, ranging from a top size of ¾-in. to the No. 4 sieve. Mix designs I and J differed from H in that the ¾- to ½-in. portion of the gravel had been separated in a heavy liquid; i. e., the particles which floated were discarded and the materials which sank were incorporated in the mix. A heavy liquid having a specific gravity of 2.35 was used for Mix I and one having a specific gravity of 2.45 was used for Mix J.

The test series, mix designs, and coarse aggregate gradations are summarized in Table 1.

MATERIALS AND PROCEDURES

Mineralogic composition, field performance records, and the sources of the coarse

TABLE 1

SUMMARY OF TEST SERIES, MIX DESIGNS, AND COARSE AGGREGATE GRADATIONS

Mix Design	Description of Coarse Aggregate	Gradation of Coarse Aggregate % Total Coarse Agg Between Sieves 1"-¾"	¾"-½"	½"-⅜"	⅜"-No. 4
	Series 1				
A	gravel, no heavy media separation	25	25	25	25
B	gravel, 1"-¾" fraction separated at sp gr 2.50	25	0	0	0
	gravel, no heavy media separation	0	25	25	25
C	gravel, 1"-½" fraction separated at sp gr 2.50	25	25	0	0
	gravel, no heavy media separation	0	0	25	25
D	gravel, 1"-⅜" fraction separated at sp gr 2.50	25	25	25	0
	gravel, no heavy media separation	0	0	0	25
E	gravel, 1"-No. 4 fraction separated at sp gr 2.50	25	25	25	25
	Series 2 through 6[a]				
F	all gravel, no heavy media separation	25	25	25	25
G	all crushed stone	25	25	25	25
H	35% stone, 1"-½"	25	10	0	0
	65% gravel, ¾"-No. 4, no heavy media separation	0	15	25	25
I	35% stone, 1"-½"	25	10	0	0
	50% gravel, ½"-No. 4, no heavy media separation	0	0	25	25
	15% gravel, ¾"-½", separated at sp gr 2.35	0	15	0	0
J	35% stone, 1"-½"	25	10	0	0
	50% gravel, ½"-No. 4, no heavy	0	0	25	25
	15% gravel, ¾"-½", separated at sp gr 2.45	0	15	0	0

[a] Series 2 through 6 differed from each other in the source of the coarse aggregates used.

TABLE 2

COARSE AGGREGATE DATA

Series	Material	Percent Absorption	Bulk Sp Gr	Field Performance History	Geologic Source
1	gravel 1	2.49	2.54	poor	Lower Wabash River terrace
	gravel 1, separated at sp gr 2.50	1.12	1.70	-	
2	gravel 2	4.01	2.38	bad	
	gravel 2, separated at sp gr 2.35	1.63	2.54	-	Dredged, lower Ohio River
	gravel 2, separated at sp gr 2.45	0.98	2.59	-	
	stone 1 (fine grained limestone from central Indiana)	0.70	2.68		St. Genevieve formations, Mississippian age
3	gravel 3	2.77	2.50	bad	
	gravel 3, separated at sp gr 2.35	1.54	2.56	-	Dredged, lower Ohio River
	gravel 3, separated at sp gr 2.45	-	2.59	-	
	stone 2 (coarse grained limestone from southern Indiana)	1.80	2.61	no record	Glen Dean formation, Mississippian age
4	gravel 4	1.51	2.68	good	
	gravel 4, separated at sp gr 2.35	1.01	2.73	-	Dredged, upper Ohio River
	gravel 4, separated at sp gr 2.45	0.98	2.74	-	
	stone 1	See Series 2			
5	gravel 5	2.36	2.60	fair	Glacial outwash, northcentral Indiana
	gravel 5, separated at sp gr 2.35	2.19	2.62	-	
	gravel 5, separated at sp gr 2.45	1.94	2.64	-	
	stone 3 (porous dolomitic reef rock, northcentral Indiana)	2.99	2.63	good	Huntington formation, Silurian age
6	gravel 6	2.82	2.57	poor	Lower Wabash River terrace
	gravel 6, separated at sp gr 2.35	1.85	2.63	-	
	gravel 6, separated at sp gr 2.45	1.51	2.65	-	
	stone 2	See Series 3			

TABLE 3

MINERALOGIC COMPOSITION OF GRAVEL COARSE AGGREGATES, PERCENT TOTAL WEIGHT

Test		Calcareous			Siliceous			Metamorphic	
Series		Limestone	Dolomite	Sandstone	Chert	Igneous	Other	Foliated	Non-Foliated
2	gravel 2	0.2	-	7.6	75.5	8.9	1.9	1.5	4.4
	gravel 2, sep at 2.35[a]	-	0.1	17.5	40.2	28.7	-	5.1	8.4
3	gravel 3	-	-	13.1	44.0	25.6	0.1	4.1	13.1
	gravel 3, sep at 2.35	0.3	-	18.5	34.4	30.4	-	8.5	7.9
4	gravel 4	9.8	12.8	10.7	10.6	42.9	0.4	6.3	6.5
	gravel 4, sep at 2.35	10.3	14.3	10.6	7.3	48.0	0.6	4.3	4.6
5	gravel 5	27.0	37.1	1.9	7.3	16.8	3.4	3.2	3.3
	gravel 5, sep at 2.35	30.8	38.7	2.2	7.2	13.7	1.6	2.7	3.1
6	gravel 6	17.2	27.4	3.4	20.8	21.0	2.6	3.1	4.5
	gravel 6, sep at 2.35	17.1	30.1	4.5	18.3	22.0	1.4	2.8	3.8
	gravel 6, sep at 2.45	12.9	37.0	2.9	14.6	23.4	0.9	3.7	4.6
	Composition of Materials That Floated on a Heavy Liquid of Sp Gr 2.35 and Were Discarded								
	gravel 2	-	-	9.6	89.8	-	0.6	-	-
	gravel 3	-	-	5.3	94.7	-	-	-	-
	gravel 4	-	-	12.6	83.8	-	3.6	-	-
	gravel 5	12.7	11.1	23.8	24.2	-	28.2	-	-

[a] Composition of the gravel after separation by heavy media at the indicated specific gravity.

aggregates used in this study are shown in Tables 2 and 3. A single fine aggregate sample from a river terrace deposit of glacial origin was used in all concrete mixes. This material met Indiana's specifications for concrete sand and had the following characteristics: F.M. - 3.13, bulk specific gravity - 2.61, absorption - 1.65 percent.

Type I portland cement from a single clinker batch was used for all mixes. Since only one cement lot was used, the cement characteristics do not affect the conclusions

TABLE 4

DURABILITY OF SERIES 1
(Gravel 1)

Durability Factors at 300 Cycles

Mix	Aggregate	Average D. F.
A	gravel 1	32.2
B	gravel 1, 1"-¾" size sep at sp gr 2.50	52.3
C	gravel 1, 1"-½" size sep at sp gr 2.50	80.4
D	gravel 1, 1"-⅜" size sep at sp gr 2.50	97.9
E	gravel 1, 1"-No. 4 size sep at sp gr 2.50	94.7

Difference in Average D. F.'s Between Mix Designs at 300 Cycles

Mix	Difference Average D. F.'s	Sig	Max and Min Difference Average D. F.'s
A and B	20.1		-
A and C	48.2	*[a]	25.3 - 71.1
A and D	65.7	*	42.8 - 88.6
A and E	62.5	*	39.6 - 85.4
B and C	28.1	*	5.2 - 51.0
B and D	45.6	*	22.7 - 68.5
B and E	42.4	*	19.5 - 65.3
C and D	17.5		-
C and E	14.3		-
D and E	3.2		-

[a] Asterisk indicates significance at the 5 percent level. Required difference for significance is 22.9.

and, therefore, are not included here. Darex, added at the mixer, was used as the air-entraining agent.

The heavy liquids were prepared by mixing carbon tetrachloride (specific gravity 1.58) and acetylene tetrabromide (specific gravity 2.97). The specific gravities of the mixtures were checked with a hydrometer.

The concrete mixes were designed by the B/B_0 method (14) which is essentially the same as the "Recommended Practice for Selecting Proportions for Concrete" published by the American Concrete Institute (15). All mixes were designed for six bags of cement per cubic yard of concrete, 4.5 percent air, a 3- to 4-in. slump, and to produce 0.5 cubic feet of concrete. Details of aggregate gradations used are shown in Table 1.

Absorption and bulk specific gravity values were determined for the coarse aggregates by means of vacuum saturation techniques. The fine aggregate was a commonly used sand for which data were available.

In making the specimens, trial mixes were used to establish the water and air-entraining agent requirements. The water-cement ratios and slumps of most of the mixes conformed to the specifications for paving concrete of the Indiana State Highway Department. The mixing was done in a 1.5 cubic foot tub-type mixer. Three 3- x 4- x 16-in. specimens were molded from each batch according to the procedure specified by ASTM designation C192-52T. After curing for one day in a humid atmosphere, the beams were removed from the molds and cured in water having a temperature of about 80 F for 13 days after which they were weighed and tested for their relative dynamic modulus of elasticity according to ASTM designations C215-52T and C290-52T. If space were available, sets of three beams were placed in the freezing and thawing apparatus. If not, the beams were placed in cold storage in a freezer where the ambient temperature was about -15 F. When space became available, the specimens, in sets of three, were transferred from cold storage to the freezing and thawing apparatus. An attempt was made to have all 15 specimens that were fabricated on the same day placed in the freezing and thawing apparatus following curing, or to have all of them placed in cold storage.

TABLE 5

DURABILITY OF SERIES 2
(Gravel 2 and Stone 1)

Durability Factors at 100 Cycles

Mix	Aggregate	Average D. F.
F	gravel 2	5.7
G	stone 1	94.7
H	gravel 2 and stone 1	19.4
I	same as H except sep at sp gr 2.35	33.4
J	same as H except sep at sp gr 2.45	37.6

Difference in Average D. F.'s Between Mix Designs at 100 Cycles

Mix	Average D. F.'s	Sig	Max and Min Difference Average D. F.'s
F and H	13.7	*[a]	2.2 - 25.3
F and I	27.7	*	16.2 - 39.2
F and J	31.9	*	20.4 - 43.4
H and I	14.0	*	2.4 - 25.5
H and J	18.2	*	6.7 - 29.7
I and J	4.2		-
J and G	57.1	*	45.6 - 68.6

[a] Asterisk indicates significance at the 5 percent level. Required difference for significance is 11.5.

It was assumed that the results were not affected by the length of time that the beams were stored. This procedure facilitated convenient scheduling of sets of three beams in the testing program.

The freezing and thawing cycle corresponded to ASTM designation C291-52T, rapid freezing in air and thawing in water. The concrete specimens were exposed to approximately seven cycles per day through the use of automatic equipment. In this equipment, the air temperature was reduced to 0 F in about one hour of the freezing cycle and within 2½ hours the centers of the beams also reached 0 F. At this time, the thaw water was circulated and the ambient temperature quickly rose to 40 F. The centers of the specimens reached 40 F within 30 minutes. After 35 minutes elapsed, the water was pumped out and then the freezing cycle began again.

Periodically, weight and dynamic modulus of elasticity determinations were made on the specimens. A specimen was removed from the test program when it reached a point where its relative dynamic modulus of elasticity was 50 percent or less. In addition, the test program was ended at 300 cycles of freezing and thawing for all except series 3.

A durability factor described by Stanton Walker (16) was used as a measure of relative durability among the various types of concrete used. This factor was calculated for the test results at 100 cycles and at 200 and 300 cycles where applicable. Analysis of variance was used to detect differences in the durability performance of the mix designs.

RESULTS AND DISCUSSION

In this section, the results are presented and discussed for each test series. The graphs (Figures 1 through 6) represent the average performance of each series. When the average is calculated from 12 beams (the original number of specimens for each mix design), a solid line is used on the graph and this continues to the point where one or more beams failed. Following this, the curve is completed by using a broken line to connect this point with one more point which represents the average number of cycles at which freezing and thawing was discontinued on the beams, and the average relative E value at the time or removal of the beams from test. These final points are usually close to 50 percent relative E, since that was the criterion of failure.

TABLE 6

DURABILITY OF SERIES 3
(Gravel 3 and Stone 2)

	Durability Factors at 100 Cycles	
Mix	Aggregate	Average D. F.
F	gravel 3	8.6
G	stone 2	78.4
H	gravel 3 and stone 2	15.1
I	same as C except sep at sp gr 2.35	19.8
J	same as C except sep at sp gr 2.45	40.4

Tables 4 through 9 present information concerning differences between the mix designs of the various test series. The average durability factors and the results of the statistical analyses obtained after 100, 200, or 300 cycles of freezing and thawing are presented for each series. The information derived from the statistical analyses is presented in the form of limits, within which the differences of the average durability factors of the two mix designs may be expected to fall at least 95 percent of the time. These limits are listed only for those comparisons that indicated a significant difference at the 5 percent level.

Series 1

Series 1 was undertaken to obtain some basic information concerning the effect of particle size and heavy media treatment on concrete durability. A graphical summary of the freezing and thawing data is shown in Figure 1 where percent relative dynamic modulus of elasticity is plotted against cycles of freezing and thawing. In this series, the lightweight constituents of the gravel were progressively removed by heavy media separation at a specific gravity of 2.50, starting with the larger sizes and proceeding to the smaller.

In general, Figure 1 indicates that the larger particles of deleterious materials are more harmful to concrete durability than the smaller. This is borne out by the comparisons of durability factors shown in Table 4. At the top of the table is listed the average durability factor for each mix. Differences between mix averages were tested for significance and the results of this analysis are listed in the lower portion of Table 5. Significant differences were found between mix designs A and C, and between designs B and C, but none between C and D or E.

These results and the graphical presentation indicate that in this case, the removal

TABLE 7

DURABILITY OF SERIES 4
(Gravel 4 and Stone 1)

	Durability Factors at 200 Cycles	
Mix	Aggregate	Average D. F.
F	gravel 4	79.3
G	stone 1	94.3
H	gravel 4 and stone 1	89.6
I	same as H except sep at sp gr 2.35	87.6
J	same as H except sep at sp gr 2.45	88.6

Difference in Average D. F.'s Between Mix Designs at 200 Cycles

Mix	Difference Average D. F.'s	Sig	Max and Min Difference Average D. F.'s
F and H	10.3	*[a]	4.9 - 15.7
F and I	8.3	*	2.9 - 13.7
F and J	9.3	*	3.9 - 14.7
H and I	2.0		-
H and J	1.0		-
I and J	1.0		-

[a] Asterisk indicates significance at the 5 percent level. Required difference for significance is 5.4.

TABLE 8

DURABILITY OF SERIES 5
(Gravel 5 and Stone 3)

Durability Factors at 200 Cycles

Mix	Aggregate	Average D. F.
F	gravel 5	39.0
G	stone 3	88.8
H	gravel 5 and stone 3	61.5
I	same as H except sep at sp gr 2.35	69.6
J	same as H except sep at sp gr 2.45	69.8

Difference in Average D. F.'s Between Mix Designs at 200 Cycles

Mix	Difference Average D. F.'s	Sig	Max and Min Difference Average D. F.'s
F and H	22.5	*[a]	9.0 - 36.0
F and I	30.6	*	17.1 - 44.1
F and J	30.8	*	13.3 - 44.3
H and I	8.1		-
H and J	8.3		-
I and J	0.2		-
J and G	19.0	*	5.5 - 12.5

[a] Asterisk indicates significance at the 5 percent level. Required difference for significance is 13.5.

of lightweight particles of sizes smaller than ⅜-in. will not add to the durability of the concrete. Most strongly indicated is the importance of the removal of deleterious particles down to the ½-in. size. Further work along these lines would seem to be warranted.

Series 2

The results of the tests in Series 2 (gravel 2, stone 1) are shown in Figure 2 and Table 5.

In this series, gravel coarse aggregate from a source on the lower Ohio River was employed. Pavements constructed with this gravel have not performed well. For the past several years, crushed stone from the same geologic formation as stone 1 has been used in combination with this gravel and these tests attempted to measure what improvement in durability might be expected from this combination over the gravel alone.

The results in Figure 2 and in Table 5 indicate that the concrete made with the gravel-

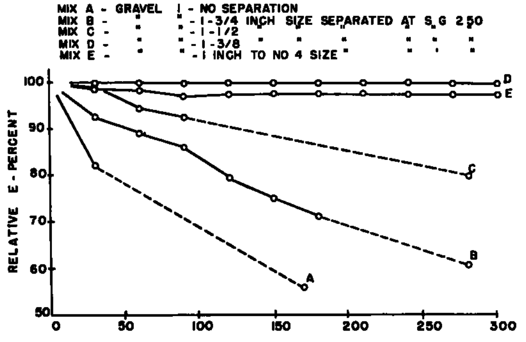

Figure 1. Summary of freezing and thawing data - Series 1.

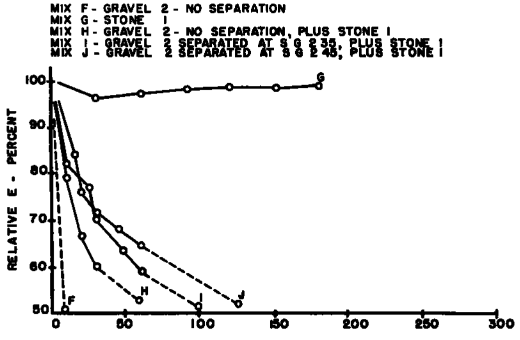

Figure 2. Summary of freezing and thawing data - Series 2.

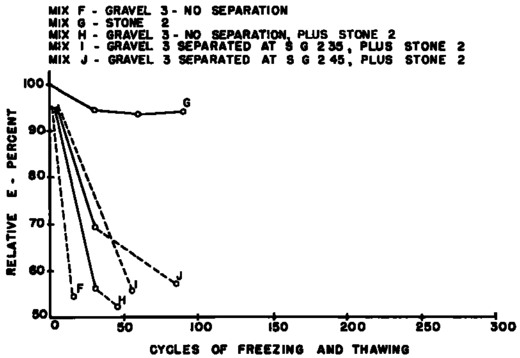

Figure 3. Summary of freezing and thawing data - Series 3.

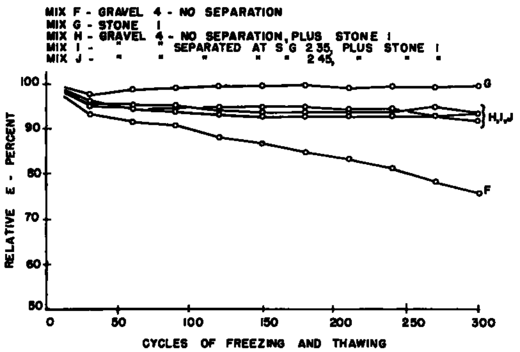

Figure 4. Summary of freezing and thawing data - Series 4.

crushed stone combination of design H is considerably more resistant to alternate freezing and thawing than that made with gravel alone. The difference might be even greater than indicated, because the durability of the gravel concrete was almost too low to measure with any degree of accuracy.

The removal of low specific gravity particles from the ¾- to ½-in. size of gravel in the gravel-crushed stone combination further aided concrete durability. The improvement of designs I and J over design F was almost twice that of design H over design F (Table 5), indicating an advantage gained by heavy media separation. However, as the heavy media separation levels used in this study lowered the chert content of the gravel from 70 percent of total untreated gravel to 40 percent for the treated gravel, it is obvious that a large portion of the ¾- to ½-in. fraction was removed in this process. With the larger sizes of the aggregate already sufficiently scarce to make necessary the use of crushed stone in their place, the amount of improvement in durability would have to

TABLE 9

DURABILITY OF SERIES 6
(Gravel 6 and Stone 2)

Durability Factors at 100 Cycles

Mix	Aggregate	Average D. F.
F	gravel 6	54.0
G	stone 2	88.0
H	gravel 6 and stone 2	71.6
I	same as H except sep at sp gr 2.35	73.3
J	same as H except sep at sp gr 2.45	75.0

Difference in Average D. F.'s Between Mix Designs at 100 Cycles

Mix	Average D. F.'s	Sig	Max and Min Difference Average D. F.'s
F and G	34.0	*[a]	24.8 - 43.2
F and H	17.6	*	8.4 - 26.8
F and I	19.3	*	10.1 - 28.5
F and J	21.0	*	11.8 - 30.2
H and I	1.7		
H and J	2.7		
I and J	1.7		
J and G	13.0	*	3.8 - 22.2

[a] Asterisk indicates significance of the 5 percent level. Required difference for significance is 9.2.

be considerable to make heavy media separation warranted in this case.

Series 3

Series 3 is similar to Series 2 in that gravel 3 was actually obtained from the same plant as gravel 2 but was dredged from a different location in the river. However, stone 2 is one which does not have any record of field performance but which is being considered for use with this particular gravel in the future.

The results of the tests performed in Series 3 are shown in Figure 3 and in Table 6.

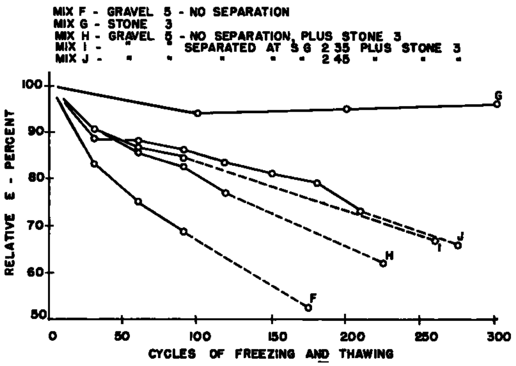

Figure 5. Summary of freezing and thawing data - Series 5.

In this series, the gravel-crushed stone combination (Mix H) produced results similar to those produced by Mix H in Series 2. The somewhat lesser durability of stone 2 might have been a factor accounting for the the slightly lower durability of Mix H in Series 3. However, to counterbalance this, gravel 3 had 44 percent chert compared to over 70 percent chert for gravel 2.

Table 6 shows the average durability factors for the five mixes in Series 3. The analysis of variance was not performed on this series because of lack of homogeneity of the variances and therefore no statement may be made regarding the significance of differences in these means. However, the data appear to be similar to those already discussed in Series 2.

Series 4

Gravel 4 is a material that is dredged from the Ohio River at a point near the southeastern corner of Indiana. Pavements in which this aggregate has been used have good performance records. As was the case for the material used in Series 2, crushed stone from the same geologic formation as stone 1 is often used with gravel 4.

The untreated gravel contained only 10 percent chert, and reference to the graph in Figure 4 and to Table 7 shows this gravel to be durable. The untreated gravel concrete had a durability factor of 79. 3 at 200 cycles of freezing and thawing. When combined with crushed stone, an increase in durability factor to 89. 6 is obtained. Heavy media treatment of this gravel reduced the chert content from 10 to 7 percent but no significant increase in durability was found over that obtained for Mix H, the untreated gravel-stone combination. This is brought out by the comparisons of durability factors shown in the lower half of Table 7.

Series 5

A gravel from a glacial outwash area in north central Indiana was studied in Series 5. This aggregate itself has a fair field performance record. It is used in combination with a crushed stone from a coral reef of Silurian Age, similar to several outcrops which occur across northern Indiana. Although the stone has a high porosity, the voids are large enough so that the aggregate is a durable one, yielding good performance in concrete pavements subjected to freezing and thawing.

The results of the tests made on the five mix designs of Series 5 are presented in Figure 5 and in Table 8. Figure 5 shows that, with the exception of Mix G, the plain stone mix, specimens began to fail between 100 and 150 cycles. The graph also indicates improvement in durability by the substitution of stone for some of the gravel (Mix F versus Mix H) and reference to Table 8 shows that this increase is significant. At 200 cycles of freezing and thawing Mix F had a durability factor of 39. 0 compared to 61. 5 for Mix H. Further comparisons show no difference between Mix H and Mixes I and J, the mixes in which the gravel had been treated. This may be explained by reference to Table 3 in which it can be seen that heavy media treatment made essentially no

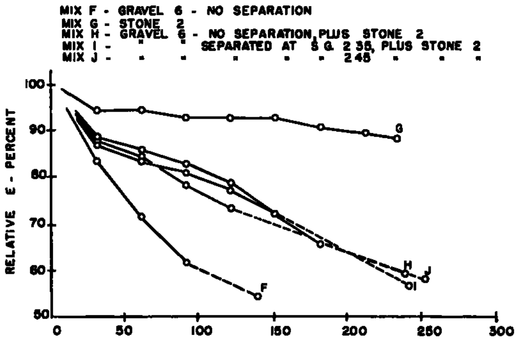

Figure 6. Summary of freezing and thawing data - Series 6.

change in the mineralogical composition of this gravel. Benefits from heavy media treatments are not indicated in this case.

Series 6

Gravel 6 is a Wabash River terrace gravel found near the western border of Indiana. Its field performance record is poor. In Series 6, this gravel was tested alone and in combination with stone 2.

Figure 6 and Table 9 report the results from this test series. It can be seen that the addition of stone caused a marked increase in durability of the concrete. The average durability factor at 100 cycles increased from 54. 0 for the gravel alone (Mix F) to 71. 6 for the gravel-stone combination (Mix H). This trend also continues beyond 100 cycles.

No significant difference was found between the gravel-stone mixture and the two mixes in which the gravel had been treated by heavy media separation, even though the chert content was reduced from 20 percent to 14 percent by heavy media treatment at a specific gravity level of 2. 45.

Variability in the Results

Alternate freezing and thawing tests of concrete made with gravel aggregates are difficult to evaluate. Failure of an individual specimen is brought about by the presence of a sufficient number of deleterious particles. In a single concrete mix there are a given number of these particles, and there are an infinite number of combinations in which these particles may be distributed in the beams. If one beam receives most of the particles, a large specimen variance results. This would be of little importance if the average durability remained valid, but this is not always the case.

Concrete made with gravel 2 had such a large percentage of lightweight chert particles that no specimen to specimen variance resulted. For all four mixes of design F in Series 2, each specimen received enough deleterious material to produce rapid deterioration. Series 5 on the other hand, evinced the most specimen to specimen variance, because with only a limited quantity of deleterious particles, no one beam received exactly its share.

In many instances, one day of mixing produced specimens with durability of a different magnitude than those produced on a second day. Efficiency of vacuum saturation, atmospheric temperature, skill of labor, and many other factors may influence day to day variance. Also, a single mix is a sample from a larger one, and like the specimens can have a shortage or a surplus of the influential aggregate particles.

By including all the variables to be studied in the mixing program on a single day, and repeating the same program on several other days, differences between the variables can be detected without the day to day variation having a significant effect. The problem of the specimen to specimen variance is not so easily solved. In order to use available statistical methods, this variance must at least be uniform. In Series 2, 3, and 5, the data from two of the five mix designs had very low variances, while the other three had uniformly high variances. This meant that the three designs with high variances could be analyzed alone and later be included with the two designs of low variance for the comparisons. This, however, involves the sacrifice of some reliable data whereas if the specimen variance could be controlled, more reliable results would be available.

CONCLUSIONS

The alternate freezing and thawing test in the hands of an experienced engineer, familiar with economics, geography, and the aggregates of the state, could enable him to do a satisfactory job in passing or rejecting an aggregate to be used for construction work. The result of this work indicates that in the future these subjective requirements may not be necessary. Freezing and thawing testing can be used to detect differences between two kinds of concrete. Freezing and thawing tests can be used to benefit both the aggregate producer and the consumer. Poor aggregates must be used when other aggregates are not available, but they must be improved to be of acceptable quality. Each economic aspect must be examined, including better drainage facilities for pavements built with poor aggregates.

Finally, heavy media separation techniques could be exhaustively studied as a promising means of improving a poor quality gravel aggregate. Definite information is needed concerning the effect of deleterious particle size in concrete pavements. If treatment of the larger aggregate particles from a gravel source is not feasible because of their shortage, more extensive use should be made of combining durable crushed stone with the gravel. If it is shown that smaller particles are not deleterious, the expense of using only small size particles might be investigated. This may open up the possibility of crushing all of the larger particles into smaller ones, eliminating waste of material.

Specific conclusions of this study are:

1. Concrete made with the crushed stone-gravel combinations resulted in significant improvement in durability over that made with the gravel aggregate alone.
2. Concrete made with the crushed stone-gravel combinations, where the gravel used had poor field performance, was significantly improved with the heavy media treatments.
3. The durability results of concrete made with gravel aggregates alone compared favorably with the field performance of the aggregates.
4. Results of Series 1 indicated that further improvement of gravel aggregates was not obtained by heavy media treatment of particle sizes of $^3/_8$-in. or smaller.

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