

Commonwealth of Kentucky  
Department of Highways

A STUDY OF THE EFFECT OF BLENDED  
COARSE AGGREGATE ON AIR ENTRAINED CONCRETE

First Progress Report  
on  
Research Project C-23

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## INTRODUCTION

This research with combined coarse aggregates in cement concrete was initiated at the request of the Director of Design as a direct result of the condition study\* made by the Division of Design in 1945. In the report on this study it was shown that on the basis of averages pertaining to 80 projects with crushed limestone totalling about 395 miles in length, and 70 projects with Ohio River Gravel totalling approximately 410 miles in length, the service record for pavements with the river gravel was far inferior to that of pavements containing limestone coarse aggregate.

Specifically, the summary of data showed that pavements with the gravel had an average of seven times as many outside corner breaks, more than eight times as many inside corner breaks, and almost eleven times as many blow-ups per mile as the pavements with crushed limestone; furthermore, the average transverse crack and joint interval in the former was only about 0.6 as long as that in the latter.

Such rating was irrespective of age, design, subgrade conditions, separate sources of aggregates, and other factors which in the total analysis were considered individually but which could not be isolated as influences in combination with the coarse aggregates. Naturally, the effect of one or all of these factors could reduce the disparity in performance as related to aggregates alone, nevertheless, the contrast was so pronounced that some measures for obtaining parity of concrete with the different aggregates were considered desirable. As an absolute minimum, research to determine whether results of field observations would be reflected in laboratory tests was proposed. Accordingly, this project was established through an outline or working plan prepared on May 18, 1946.

Two corrective measures, air entrainment and blending of aggregates, were the primary bases upon which the research was founded. Results from many investigations - later summarized in a comprehensive report\*\* - had indicated that air entrainment had been beneficial to concrete in almost every experiment, and that the greatest improvement in quality of concrete had occurred when the coarse aggregates were inherently of lowest quality. Similarly, blending of aggregates as a means for off-setting detrimental properties of

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\* "A Summary of Experiments with Air Entrainment in Cement Concrete", Commonwealth of Kentucky, Department of Highways, Materials Research Laboratory, September, 1946.

\*\* Johnson, M.F., Neiser, A.O., and Bray, D.H.; "Report of Portland Cement Concrete Pavement Condition Study, 1945", Intra-departmental Report, Kentucky Department of Highways, March, 1946.

one of the components had been used successfully in other states, an outstanding example of this being in Kansas where aggregates are quite variable and satisfactory sources are far from evenly distributed throughout the state. (A copy of the Supplemental Specification developed in Kansas is appended to this report.)

Since air entrainment was due to become a standard in concrete for pavements, interest was centered on the possible benefits or detriments of combined aggregates and the proportions in which they should be combined in order to provide the best concrete within practicable limits of economy on actual construction jobs.

### MATERIALS

Initially the proposed research was limited to air entrained concrete containing separately aggregates from five locations along the Ohio River, each in combination with limestone of known good quality from one source. A few mixes with normal portland cement were included for comparative purposes, and one series with bank or glacial gravel from the vicinity of Cincinnati was added for the same reason. From that standpoint, the working outline has been adhered to rather closely to the extent that preparation of specimens for one (and by far the most comprehensive one) of six series of tests has been carried out and two groups of samples in this series have been tested to failure. About half the specimens for another series have been poured, cured, and started in durability tests.

Other minor changes that have been found necessary or desirable since the working outline was prepared are: (1) mixes with 80 percent limestone and 20 percent gravel discarded as being impractical; (2) mixes with 60 percent No. 3 stone changed to 50 percent No. 3 and 10 percent No. 6 stone to obtain a gradation within usual specifications; (3) substitution of a group of specimens with 100 percent stone and normal portland cement to replace those discarded in accordance with (1) above, and (4) storage of "stock" specimens for use in making length-change measurements during freezing and thawing rather than for final strength measurements as originally planned. Tests on these "stock" samples have not been started because equipment for making accurate measurements of length is not yet available.

The various mixes and correlative results are summarized in Table I. Limestone from the Tyrone and Oregon formations mined in Lexington was used throughout, and both sand and river gravel came from a commercial source in Louisville which dredges above Louisville toward Carrollton. Glacial gravel and glacial sand excavated from a Miami River terrace near Cincinnati were obtained from a commercial plant with facilities for washing, grading, and otherwise treating the aggregates in accordance with requirements.

As purchased, the stone met grading requirements for No. 2 size (there being no No. 3 available at the time) and the river gravel met or very closely approximated the upper limits for No. 6 size, failing (if at all) only through a slightly excess amount of material near the 3/8 inch size. The glacial gravel was known to be far from requirements because at the time of procurement the only gravel being produced was of an Ohio classification similar to Kentucky No. 7. Likewise, the Ohio River sand as furnished did not meet requirements of Article 7.3.1, part D, of the 1945 specifications.

Where materials procured did not conform with requirements, crushing (in the case of stone), sieving, and recombining of the aggregates was necessary. Table II is a listing of percentages of fractional components and other physical test data pertaining to the different aggregates as they were used. Limestone for No. 3 classification was prepared by crushing all material larger than 2 inches in size, wasting everything smaller than 1 inch in size, and combining the remainder in the ratio of 45 percent retained and 55 percent passing the 1-1/2 inch sieve. For mixes with 80 percent or 100 percent limestone in the coarse aggregate, it was necessary to crush some of the stone to meet No. 6 specifications in order to maintain a practicable gradation. Final composite gradation varied with the different mixes because of variable characteristics of the coarse aggregates but more so because of necessary adjustments for entrained air. Initial designs approximated 36 percent sand in combination with 100 percent gravel, and 39 percent sand in combination with 100 percent limestone for mixes with normal portland cement. The minimum sand content, even with adjustments for air and combined coarse aggregates, was 35 percent.

The cement in every case was marketed by the producer as normal portland and was so labeled. This was purchased in sacks from a Lexington distributor, and no attempt was made to test it for conformance with specifications. In the mixes scheduled for air entrainment, a Vinsol Resin-sodium hydroxide-water solution was incorporated, the percentages of Vinsol Resin and sodium hydroxide by weight of cement being .007 and .001 respectively. This required a solution consisting of about one part combined Vinsol Resin and sodium hydroxide to 40 parts water.

### PROCEDURES

The procedures for these tests were essentially those usually followed for laboratory purposes. Customary designs for a six-bag mix calculated on a solid volume basis were followed, but since most of the mixes were scheduled for air entrainment, adjustments in design were necessary to compensate for increased yield. Maximum and minimum values for cement factor (1.46 to 1.53) and water-cement ratio (4.73 to 5.00) listed in Table I are ample evidence that reasonable

Table II. Characteristics of Coarse and Fine Aggregates as Used in Project C-23

	Passing	Retained on	No. 3 Stone	No. 6 Stone	No. 6 River Gravel	No. 6 Glacial Gravel	River Sand	Glacial Sand
Gradation Sieve Sizes - Square Openings	2"	1-1/2"	45.0					
	1-1/2"	1"	55.0	5.0	8.6	8.0		
	1"	3/4"		20.0	17.8	25.0		
	3/4"	1/2"		32.0	41.0	35.0		
	1/2"	3/8"		21.0	27.7	17.0		
	3/8"	No. 4		17.0	4.6	15.0		
	No. 4	No. 8		5.0	0.3		9.4	9.1
	No. 8	No. 16					13.5	24.1
	No. 16	No. 30					30.0	30.0
	No. 30	No. 50					43.6	29.3
	No. 50	No. 100					3.5	6.1
Physical Tests	Bulk Specific Gr. Saturated-Surface Dry		2.74	2.73	2.63	2.69	2.66	2.65
	L.A. Abrasion Loss (Pct.)			27.0 <sup>†</sup>	22.7	28.5		
	NaSO <sub>4</sub> Soundness (Pct. Loss)							
	Absorption (Pct.)		0.5	0.6	2.2	1.3	1.0	1.0

control was exercised and that the degree of variation in the mixes was estimated accurately. The design slump was within the limits of 1-1/2 to 2-1/2 inches, and the range of determined slumps was from 1-1/2 inches to 3-1/3 inches.

Aggregates were introduced into the mixer separately, and cement and water or Vinsol Resin-sodium hydroxide-water solution were added immediately. Mixing time was five minutes in all cases, but slumps were measured after about four minutes with the slump sample being returned to the mix and dispersed throughout it before the mixer was stopped. Air content determinations were then made by the gravimetric method (A.S.T.M. Designation: C-138-46) using a 1/2 cubic foot container. With mixes in Series II the results of these determinations were supplemented with tests for air content by the pressure method. Samples for the gravimetric test were returned to the mix and dispersed throughout it by three or four revolutions of the machine, but concrete used for pressure tests was, by necessity, wasted.

The pressure test referred to was basically the same as that developed by Klein and Walker and first described in June, 1946\*, however, equipment for the test was developed by the Minnesota Highway Department and was purchased from a commercial producer. For the test, the container 0.255 cubic feet in volume was filled in three layers, each rodded twenty-five times with a puddling rod, and the top portion of the device was clamped in place. After water had been brought to the top of the standpipe to eliminate air pockets, the level was dropped to zero point on the calibrated water gauge. Air pressure was then introduced by means of a hand pump, and readings on the water gauge corresponding to 8, 15, 20 and 30.5 pounds per square inch air gauge pressures were taken. Calibration scales for the water gauge were such that air contents could be read directly.

Because air unrelated to air entrainment was contained in the aggregates, it was necessary to make determinations for the coarse and fine aggregates in the combinations used, and deduct these values from the air contents determined for the concrete mixes. Thus far, in this research project, the air meter has been applied only to mixes with 100 percent glacial gravel for which air contained in the aggregates was found to be 0.4 percent, but similar measurements have been made for the river gravel (0.45 percent) and the limestone (0.35 percent) with further tests on combined materials scheduled in the near future.

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\* Klein, W.H. and Walker, Stanton, "A Method for Direct Measurement of Entrained Air in Concrete", Journal, A.S.T.M. V. 17, n. 6, June, 1946.

Cylindrical and beam specimens, 6" x 12" and 3" x 5" x 20" respectively, were prepared in accordance with the number scheduled to represent the mix. These were poured and rodded by procedures stipulated in A.S.T.M. Designation: C-192-44T except that the depth (5") of the beam molds was in a vertical rather than horizontal position because of the form of the molds. After twenty-four hours of curing in air with exposed surfaces covered by damp burlap, the samples were removed from the molds, given identification markings, and placed in the moist room.

Specimens were separated into two general classes: those cured for seven days and those cured for twenty-eight days. Within these classes the cylinders were divided into "control" and "stock" specimens, and beams were separated into "control", "stock", and "durability" samples. Treatment and use of the different specimens was as follows:

Control. These beams and cylinders were cured seven days or twenty-eight days as the case may be, and tested for strength at the close of that period. Cylinders were loaded in compression at a rate of 3000 pounds per minute (A.S.T.M. Designation: C-39-44) until failure occurred. Beams were weighed, tested for sonic modulus, loaded in flexure over a span of 18 inches at a rate of 150 pounds per square inch per minute (A.S.T.M. Designation: C-78-44).

Stock Specimens of this designation, both cylinders and beams, were prepared with the intention of storing them in the moist room throughout the time that durability specimens were in freezing and thawing, then testing them and correlative durability samples for strength simultaneously. After past performance of similar specimens in other projects had been reviewed, plans for stock specimens were altered. When equipment is made ready for such tests, the beams will be frozen at +10 F. and thawed in water at +40°F., and at regular intervals accurate measurements of length will be made along with measurements for sonic modulus. Also, the stress-strain relationships for the cylinders will be determined to see whether durability characteristics and resiliency are interrelated. The ages of these samples range from thirty-six to almost two hundred days at present, but all will be tested at a specified age dependent upon the age of specimens of the first mix at the time equipment is available.

Durability Beams for durability tests were cured seven days or twenty-eight days depending upon requirements. Following this, weight and sonic

determinations were made and the beams were immediately subjected to freezing in air for about eighteen hours at  $+10^{\circ}\text{F}$ . and thawing in water for approximately six hours at room temperature (probably  $65^{\circ}\text{F}$ . to  $85^{\circ}\text{F}$ .). At several stages (not specified nor equally spaced) during the durability tests, sonic measurements were made, and when the reduction in sonic modulus approximated 30 percent, the beams were taken from freezing and thawing, weighed, and tested in flexure as described for control specimens on page 5.

Tests for sonic modulus consisted of placing the beams on rubber supports, the centers of which were about 4.5 inches (0.224 L) from the ends of the beam. The beams were then vibrated by regulated electrical impulses, the objective being to determine the natural frequencies of the specimens which are indirect measures of their soundness or structural integrity. The process at best is only a relative measure of the true physical characteristics of the concrete; yet, trends in progression of sonic modulus readings are useful and fairly authentic indicators of the deterioration taking place within specimens subjected to freezing and thawing.

## RESULTS

At this stage in the investigation, judgment of the several mixes must be principally dependent upon trends in sonic moduli readings as affected by continued freezing and thawing, since most of the durability specimens have not yet reached the point of failure in freezing and thawing tests, hence, cannot be tested in flexure for more reliable durability indexes. Initial strength determinations, being only indirectly if at all related to lasting qualities of the concrete, are of secondary value.

As indicated in Table I, three groups of specimens, two containing 100 percent Ohio River gravel in the coarse aggregate and one containing 20 percent limestone, have failed in the durability tests. The least durable of these (containing regular portland cement; 1.6 percent air entrained) failed in approximately 50 cycles; thus, even at this early stage it is definite that at least six other groups of samples were more resistant to freezing and thawing. Similarly, samples in Group B completed 96 and 114 cycles (for twenty-eight day and seven day specimens) and these too have been exceeded by two other mixes from the standpoint of durability. Finally, samples in Group C were removed from the durability tests very recently (January 23) after completing 131 and 114 cycles. Otherwise, the only bases for comparison among the mixes lies in the sonic determinations.

Relationships between sonic modulus values, and the number of freezing and thawing cycles are plotted in Fig. 1 for samples cured seven days, and in Fig. 2 for samples cured



twenty-eight days. As pointed out in the discussion of procedures, the numerical value of the moduli are not necessarily authentic measures of physical qualities of the concrete, but trends in sonic readings as affected by increasing length of exposure to freezing and thawing are reliable indicators of deterioration actually occurring in the concrete.

The curves in Fig. 1 are good illustrations of this. Initial sonic readings for samples in Group A and Group B were 5.47 and 5.04, the inference being that the former mix was considerably better than the latter. Tests on corresponding control specimens did not bear this out, however, because the average initial modulus of rupture was 600 pounds per square inch for both mixes (see Table I), and average initial compressive strengths were 3767 pounds per square inch for Group A and 3613 pounds per square inch for Group B. Some reduction in strength would be expected for Specimens B as compared with Specimens A simply because of the lower air content in the latter, but the contrast was not as great as indicated by sonic values alone.

In contrast, the reaction of sonic modulus values to progressive exposure of the beams did reflect rates of deterioration as determined from the average percentage reduction in modulus of rupture per 100 cycles. These rates of deterioration, hereafter referred to as durability indexes, for Groups A and B were (see listings in Table I):

Group A - modulus of rupture reduced 74.7 percent in 54 cycles, or 138.3 percent per 100 cycles.

Group B - modulus of rupture reduced 76.0 percent in 114 cycles, or 66.5 percent per 100 cycles.

Likewise, the equivalent average rate of reduction in sonic modulus for each of the groups was:

Group A - 29.7 percent reduction in 46 cycles (last reading at 54 cycles discounted because of increase) or 64.5 percent per 100 cycles.

Group B - 28 percent reduction in 114 cycles or 24.5 percent per 100 cycles.

Direct comparison between these sets of figures is not quite valid because of indicated variations in the relationship of sonic modulus and cycles of freezing and thawing - as evidenced by the curves in Fig. 1; still, the ratio of values for Group A versus Group B was about 2.1 for the rate of reduction in sonic modulus and approximately 2.4 for the durability index. Thus, it could be said that concrete with 100 percent Ohio River gravel coarse aggregate and 5.2 percent air entrained was from two to two and one-half times as resistant to freezing and thawing as was concrete with the same aggregate but only 1.6 percent air entrained.

Probably the most striking relationship demonstrated in Fig. 1 and Fig. 2 is the tendency for increases in the sonic moduli of specimens containing 60 percent or more of limestone coarse aggregate and cured seven days (see Fig. 1). This relationship holds up to about 50 cycles of freezing and thawing. In contrast, like specimens cured twenty-eight days (see Fig. 2) did not increase in sonic moduli during the initial phases of the durability tests, but rather decreased at a comparatively slow rate. The most plausible and most reasonable explanation for this is the tendency for concrete cured but seven days to gain in strength and integrity because of hydration of cement while the samples were immersed during the thawing periods, and that the damage caused by freezing and thawing was more than counter-balanced by increased soundness gained through this hydration.

Because the relationships shown in Fig. 1 and Fig. 2 are difficult to follow and at the same time analyze for effects of aggregate combinations, air entrainment, and other factors, Fig. 3 has been prepared by extrapolation of data from curves in Figs. 1 and 2, as a means for differentiating groups of specimens in accordance with the percentage of limestone in the coarse aggregate. Results for specimens cured seven days are plotted above and those for specimens cured twenty-eight days are plotted below the horizontal center line. Colors represent different total cycles of freezing and thawing completed, and symbols (solid or cross hatched bars) distinguish between mixes with and without air entrainment\*. Only the results for tests in Series I (concrete with Ohio River gravel or limestone or both combined) are plotted because tests on samples in Series II when glacial gravel was represented had not been carried to an appreciable length at the time these data were prepared.

On the basis of all information compiled to date and presented in Fig. 1, Fig. 2, Fig. 3, Table I, and Plate I, the following results are apparent or indicated at this stage of the investigation:

Durability; effect of air entrainment. In every case where tests have extended past 50 cycles of freezing and thawing and where samples both with and without appreciable air were represented, the entrained air has prolonged the life of the concrete or - in instances where specimens have not yet failed in durability tests - has inhibited the rate of decrease in sonic modulus to the extent that longer life for the air entrained concrete can be predicted with assurance. As pointed out previously (page 7), the durability indexes (average percentage reduction in modulus of rupture per 100 cycles) for concrete with only river gravel in the coarse aggregate

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\* This is an approximation, for actually some mixes with cement labeled normal portland had relatively high air contents (see Table I).

were reduced to less than 50 percent of their former value by air entrainment thus indicating that the usable life of the concrete could be more than doubled under these conditions.

Trends in sonic moduli for concrete containing 40 percent limestone in the coarse aggregate (see Figs. 1, 2 and 3) indicate that the difference in final durability indexes will not be as great as 100 percent, thus implying that the life of concrete containing this aggregate combination could not be doubled simply with air entrainment under these conditions. This relationship, however, could be modified by the fact that the mix with regular portland cement in this case had 2.3 percent air entrained whereas that mentioned above (100 percent river gravel) contained only 1.6 percent air; likewise the air content in mixes containing Vinsol Resin was higher (5.2 percent) with the all-gravel concrete than with the concrete containing 40 percent limestone (4.7 percent). Both of these factors would tend to accentuate differences in durability for the mixes containing no limestone and minimize differences for those with 40 percent limestone.

For those mixes with 100 percent limestone coarse aggregate, the performance of concrete with normal portland cement is exceeding that of concrete with air entrainment. However, these samples have not been exposed long enough to permit a great amount of deterioration to occur. Tests made in other research projects would substantiate a prediction that these specimens will complete at least 300 cycles of freezing and thawing so the 40 to 60 cycles of exposure thus far in these tests could hardly be indicative of the effect that will be obtained eventually. On a comparative basis, however, it is significant that beams with all river gravel coarse aggregate and normal portland cement did not withstand more than 54 cycles.

In summary then, it is evident that air entrainment was beneficial and that it could be expected to increase the durability of some mixes as much as 100 percent, depending upon the aggregates contained in the mixes. Also, results from these tests corroborated those from previous experiments - insofar as limited exposures at this stage will permit analyses - to the effect that air entrainment was more beneficial to the inherently poor (non-durable) mixes than to the inherently durable mixes.

Durability; effect of coarse aggregate proportions. Without doubt, the addition of limestone into the coarse aggregate improved the durability of the concrete, but at this stage there is no definite evidence that improvement was proportional with the percentage of limestone. It can be definitely stated that substitution of limestone for river gravel in any amount up to 40 percent will increase the durability, and reason, as well as test data from other experiments strongly indicate that greater amounts of limestone would produce results equally good or better. The extent of improvement is still indefinite.

Final results obtained through breaking of beams after completion of the freezing and thawing tests are available for only three groups of samples. By way of contrast between the two groups with air entrainment (see results for Group B and Group C in Table I), the one with no limestone cured seven days completed 114 cycles and had an average percentage reduction in modulus of rupture per 100 cycles (durability index) of 66.5, while corresponding samples for Group C in which the coarse aggregate was made up with 20 percent limestone had a durability index of 44.5. This represents an improvement of about 50 percent in durability due to the addition of 20 percent limestone to the aggregate, and that despite the fact that the percentage air in samples with 20 percent limestone was only 3.9 percent while that in the air entrained concrete with no limestone was 5.2 percent.

The difference between samples of Group A (having no limestone and no air entrainment) and Group C (with 20 percent limestone and air entrainment) was, of course, much greater. Durability indexes for these groups, 138.3 and 44.5 respectively, signify that a normal concrete with all river gravel aggregate could be made three times as resistant to freezing and thawing by substituting 20 percent limestone in the coarse aggregate and adding air entrainment.

At this stage there are indications that even greater improvement can be accomplished with 40 percent limestone in the coarse aggregate, but this trend is still indefinite. Certainly, there is no assurance in the data that this additional 20 percent limestone will provide an additional increase of 50 percent in durability, as was the case when the first 20 percent limestone was added. Actually, in order to estimate probable results when the durability tests have been completed, three of six "twenty-eight day" samples of the mix with 40 percent limestone and air entrainment (Group D) and one of four "twenty-eight day" samples without air entrainment (Group E) were removed prematurely. Results from these tests are entered in Table I with proper notations that they will not necessarily represent the mixes in final analyses.

Results from the one sample for Group E indicated that all samples of that mix had failed or were near failure at 84 cycles with a reduction in modulus of rupture of 69.3 percent - resulting in a durability index of 82.5. The difference between this index and that for samples with normal portland and no limestone (Group A) indicates that the addition of 40 percent limestone irrespective of air entrainment can just about double the life of the concrete, but that it can not accomplish quite so much as air entrainment without the addition of limestone (see results for Group B, Table I).

On the other hand, the results from two "twenty-eight day" specimens in Group D, in which air entrainment was included with the 40 percent limestone, gave a durability index of 42.7 at 111 cycles. These samples have not approached the point of

failure, but at this stage the durability index does not contrast with the index for corresponding mixes without air entrainment as much as was the case for mixes with no limestone in the coarse aggregate. For mixes with 40 percent limestone the indexes suggest that the life of concrete could be extended only about 93 percent by the addition of air, whereas when the aggregate contained no limestone the indicated improvement was about 135 percent. This, of course, tends to substantiate other results to the effect that air entrainment is most beneficial to mixes with the poorest aggregate.

It is significant that relative durability indexes for air entrained concrete cured twenty-eight days and containing 0, 20, and 40 percent limestone in the coarse aggregate were as follows:

<u>Percentage limestone</u>	<u>Percentage Air</u>	<u>Durability Indexes</u>
0	5.2	72.5
20	3.9	56.6
40	4.7	42.7

If the disparity among percentages of air entrained are disregarded, the relation between percentage of limestone and durability index is almost directly proportional, as illustrated by Fig. 4.

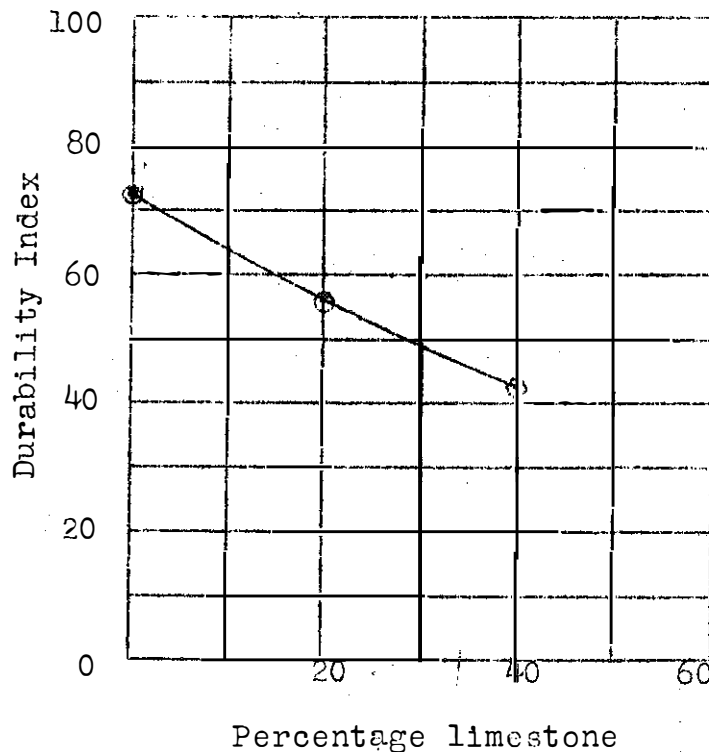


Fig. 4. Relationship Between Durability Index and Percentage Limestone for Specimen with Air Entrainment Cured Twenty-eight Days.

Thus, according to this preliminary group of data, the benefit derived from combining limestone and Ohio River gravel in air entrained concrete approaches but does not reach direct proportionality with the percentage of limestone in the mix (or with the ratio in which the aggregates are combined) at least up to the point where 40 percent of the aggregate is limestone.

For any mixes with limestone content greater than 40 percent the data are so limited that comparisons or predictions would be essentially speculative. Similarly, nothing with regard to specimens with glacial gravel prepared for this research project can be evident at this stage. It is possible, however, to make comparisons with mixes containing glacial gravel, as well as some with other aggregates, tested in previous research projects. Table III is a summary of such data. There it is shown by durability indexes with no allowances for differences in sizes of samples, type or length of curing, and methods of loading, that:

1. Mixes with 100 percent limestone tested in Project C-16 were about seven times as durable as similar mixes with 40 percent limestone (from the same source) and twelve times as durable as mixes containing no limestone and tested in this project.
2. Mixes with glacial gravel and no air entrainment prepared on the Falmouth-Cynthiana Road were about equal to mixes with air entrainment and 40 percent limestone as prepared in this project. Those with glacial gravel and air entrainment were about two and one-half times as durable as mixes with 40 percent limestone and air entrainment in this project. Naturally, sizes of specimens and other influences could modify these relationships to some extent, but what that modification would be cannot be estimated with any degree of accuracy.

Durability; effect of curing time. For the most part, the trend in sonic moduli as plotted in Fig. 3, and the few durability indexes listed in Table I, indicate that specimens cured 28 days are more vulnerable to freezing and thawing than are specimens cured 7 days. Irrespective of the reason for this, it is probable that the "28 day" samples are more representative of concrete as it would be in field construction projects.

Initial Strength; effect of aggregates and air entrainment. Strengths for control specimens were so variable that any specific relationships that might have existed for compressive strengths were obscured by contradictions in flexural strengths, and vice versa. In general, both flexural and compressive strength were lower for specimens with either 100 percent river gravel or 100 percent limestone than they were for specimens with aggregates combined in the ratio of 40 percent limestone and 60 percent gravel. Also, the mixes with river gravel were usually a slight amount stronger than those with limestone.

TABLE III. Comparative Strength and Durability Characteristics of Concrete Containing Different Coarse Aggregates.

Project	Coarse Aggregate	Cement	Air Cont.	F. & T. Cycles Completed	Modulus of Rupture		Compressive Strength	Durability Index		Strength Factor	
					Control	F. & T.		% Reduction in Mod. of rupture		% Reduction	
								Total	per 100 cycles	Mod. of Rupture	Compr. Strength
Laboratory C-23	Ohio River Gravel	Port.	1.6	42	742	202	5264	71.2	169.5	-	-
		Port. & V.R.S.	5.2	96	674	206	4385	69.5	72.5	9.1	16.7
	Ohio River Gravel & 20% Ls.	Port. & V.R.S.	3.9	114	618	219	4002	64.6	56.6	-	-
		Port. & V.R.S.	2.3	84*	646	216*	4238	69.3*	82.5*	-	-
Laboratory C-16	100 Percent Limestone	Port. & V.R.S.	4.7	111**	730	384**	4657	47.4**	42.7**	+28.5**	+9.9**
		Port.	1.9	487	779	592	4260	23.7	4.4	-	-
		Port. & V.R.S.	4.6	485	835	576	4350	29.1	6.0	1.9	6.2
FA366C(2) Falmouth-Cynthiana Road	Glacial Gravel	Port. & V.R.	2.3	485	912	612	5170	32.5	6.7	+7.2	+11.4
		Port.	0.3	187	1113	165	-	85.2	45.6	-	-
	100 Percent Limestone	Port. & V.R.	2.7	300	787	352	5478	55.3	18.4	29.3	-
		Port.	0.8	117	1087	395	6770	63.7	54.4	-	-
		Port. & V.R.	3.3	461	1085	548	5230	49.5	10.7	0.2	22.7

Note: Samples representing Proj. C-16 and Proj. C-23 were 3"x5"x20" beams and 6"x12" cylinders cured 28 days and loaded at the third points over an 18" span.

Samples representing FA-366 C(2) were 5"x6"x20" beams poured on the job, having no moist room curing, and loaded at the center over an 18" span.

V.R.S. denotes Vinsol Resin-sodium hydroxide-water solution.

V.R. denotes interground Vinsol Resin.

Strength reductions are based on strength of corresponding mixes with portland cement.

\*Interim results obtained by test on 1 of 4 specimens; remaining 3 not yet removed from durability test.

\*\*Interim results for 2 of 6 specimens; remaining 4 not yet removed from durability tests.

Finally, there was little or no general difference between mixes with river gravel and corresponding mixes with glacial gravel.

In the majority of cases air entrainment caused reductions in strength which were seldom very great when the aggregates were river gravel and limestone combined or separate, but more pronounced reductions were evident in the concrete with glacial gravel.

### CONCLUSIONS

Insofar as progress of the experiment and uncertainties in the results will permit, the following are concluded subject to revision when more progress is reported or when the experiment is completed.

1. The substitution of any amount of limestone for Ohio River Gravel in the coarse aggregate will increase the durability of concrete made with that aggregate. This, of course, is confined to river gravel from the vicinity of Louisville, and more so to the limestone used in this project. Any limestone of equal quality (as shown by service records) would probably be equally satisfactory.

2. Entrainment of air, in the neighborhood of 5 percent, will improve the concrete by more than 100 percent in its resistance to freezing and thawing.

3. With a substitution of 20 percent limestone in the aggregate, durability of the concrete with air entrainment can be increased by about 30 to 50 percent (depending upon curing conditions, etc.) in addition to that accomplished by air entrainment alone.

4. Substitution of 40 percent limestone in the aggregate will make the concrete more durable than with 20 percent limestone, but the amount of gain in durability is not quite directly proportional to limestone content. Thus far, data indicate that durability can be increased by at least 25 percent over that accomplished by substituting 20 percent limestone.

5. The addition of 40 percent limestone with no air entrainment will prolong the life of the concrete almost as much as the addition of air entrainment and no limestone.

6. While air entrainment alone will more than double the life of concrete with 100 percent river gravel, it will not accomplish as much improvement in concrete containing 40 percent limestone in the aggregate. This is in accordance with data from other experiments to the effect that the greatest amount of benefit from air entrainment is derived by the concrete with aggregates of poorest quality.



7. Based on comparisons between data from this experiment and those from other projects, mixes with glacial gravel and no air entrainment are almost as durable as those with 60 percent river gravel and 40 percent limestone containing air entrainment. When air entrainment is added, concrete with glacial gravel is about 2-1/2 times as durable as like concrete with 40 percent limestone as tested in this project.

8. Results of Los Angeles Abrasion tests, as listed in Table II, were poor indicators of the relative durability qualities of concrete containing the aggregates. Absorption and specific gravity values could be correlated with results of durability tests at least in a general way.