Commonwealth of Kentucky
Department of Highways

A SUMMARY OF EXPERIMENTS

with

AIR ENTRAINMENT IN CEMENT CONCRETE

With notations on current practices in surrounding states and specifications and methods of control recommended for use in Kentucky

by

The Highway Materials Research Laboratory

Lexington

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INTRODUCTION

Field and laboratory experiments designed to show the merits of air-entrainment in cement concrete have been conducted by the Department of Highways since 1940. During that time six laboratory projects with many variables have been completed, and most of these were directly related to the four experimental roads which have been in service from four to six years. Collectively these experiments form a moderately comprehensive analysis of the features of air-entrainment, still there are many points which have not been fully covered either because of limitations in time and personnel or because of new developments which render some of the 1940 experiments obsolete in detail.

For example, in 1940 it was known that blended cements would accomplish air-entrainment provided one contained a so called entraining agent or the other was prepared with a grinding aid. At that time materials ranging from beef tallow to petroleum distillates (of uncertain grade) were used as a grinding aid, but in the interim new developments have brought about a more thorough standardization of the quality and quantity of materials used for this purpose. Similarly, other experiments (10) (15)* completed in 1944 and 1945 and dealing with Vinsol resin as an air-entraining agent "indicated clearly that the non-uniformity of results obtained by the use of flake Vinsol resin was due to the fact that air-entraining capacity of the Vinsol resin was developed only when the water-soluble alkalies present in portland cement were dissolved and reacted with the resin to form a resinate with sud-

* Numbers in parenthesis refer to the references at close of this report.

sing qualities". Because of variations in the alkali content of different cements, this led to new techniques such as the addition of a Vinsol rosin-sodium hydroxide-water solution (neutralized Vinsol rosin).

Thus, the absolute efficiency of cements and combinations of cements manufactured today cannot be judged by the performance of materials produced as recently as six years ago. This does not completely vitiate the results from older experiments but rather it merely modifies them, for the value derived from air-entrainment appears to lie in the amounts of air-entrained and not necessarily in the means by which it is entrained. Consequently, the object of immediate concern is an evaluation of cement concrete from the standpoint of beneficial or detrimental effects of trapped air.

With that in view, the results from all the complete experiments (one is in progress) have been summarized in this report and these have been supplemented by information from other states, the Highway Research Board, A.S.T.M., and similar sources in order to cover points not included in the field and laboratory research.. On the basis of all these data, conclusions have been drawn and recommendations made for future policies and specifications warranted by the data and desirable for future design.

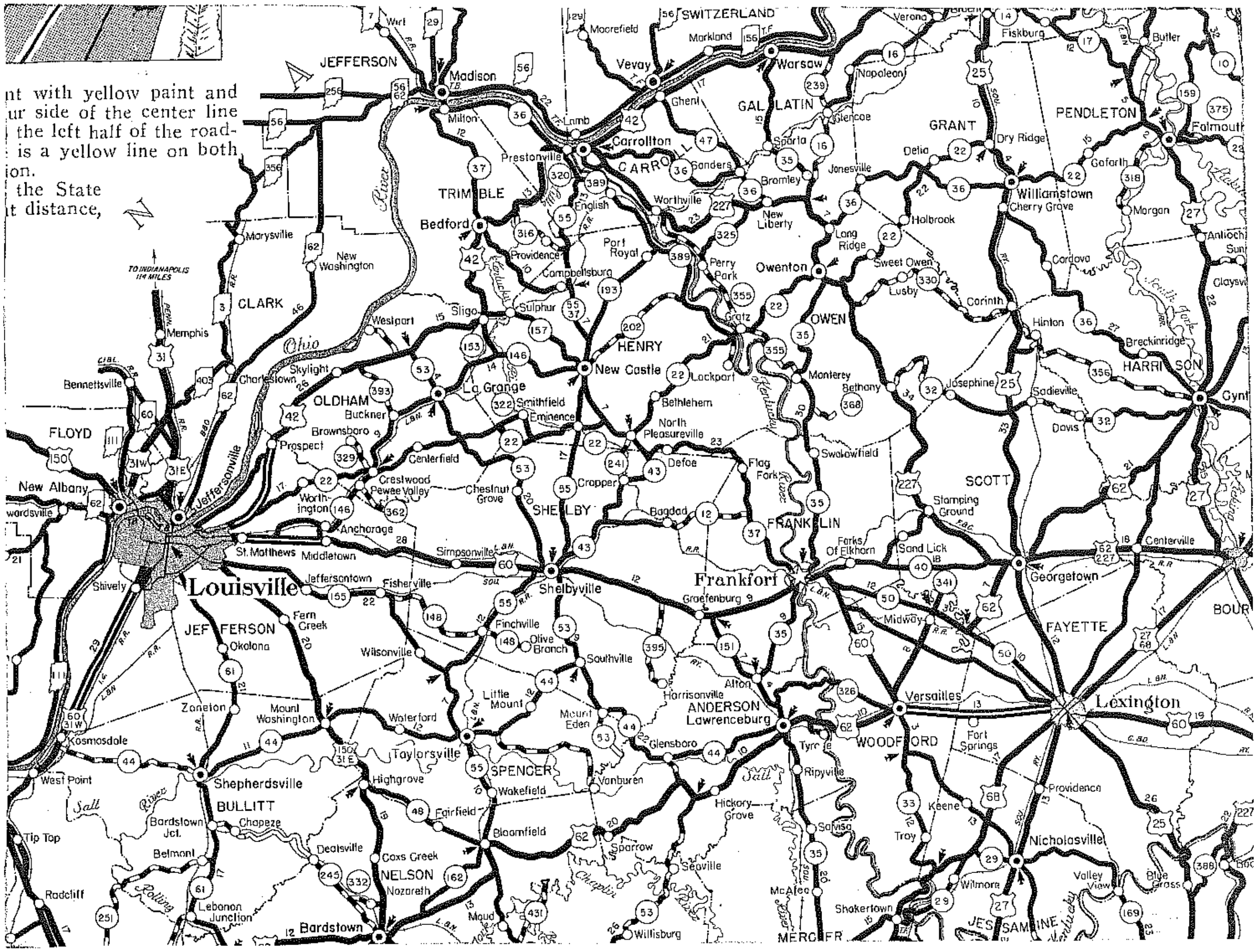
PROJECTS, MATERIALS, AND METHODS

Only two, the oldest and the most recent experiments with air-entrainment have not been reported to the Research Board heretofore. For details of those that have been described previously, reports by Collier (14)(17) should be reviewed. Otherwise, in this manuscript complete descriptions of materials and methods have been confined to the two experiments reported herein for the first time, and only cursory mention is made of the others. All are treated in accordance with their comparable features in the discussion of results.

Combined Field and Laboratory Projects

Each of the four experiments on field projects had a correlative group of laboratory tests. Three of these were of the type called "accelerated" in that artificial alternations of freezing and thawing were used, and the duration of tests never exceeded twenty-four months. In the fourth, all but two of eighteen sets of beams were placed on the roof of the laboratory for natural exposure. If carried through as originally planned, this experiment will continue for fourteen years.

<u>Project F.A. 79 D(2)S, Louisville-Elizabethtown Road.</u> The initial work with air-entrainment was applied to a one-lane addition to U.S. 31W and U.S. 60 in Hardin and Meade counties. This project, built in 1940, contained a number of variables in cements and air-entraining features, curing methods, and surface applications of a metallic hardener. These resulted in an abundance of tests made in five different laboratories. Since this project has not been



Code	Res. Proj.	Project Designation	Geologic Region	Soil Designation
A	C-1	FA 366 C(2)	Upper Ordovician-Cincinnatian (Eden and Cynthiana)	Eden-Fairmount
B	C-2	SN-FA 194E(3) F(3)L(2)	Devonian (Jeffersonville Ls), Silurian (Louisville Ls and Laurel Dolomite) and Pleistocene-Glacial Valley Fill	Hagerstown, Russellville, Crider; Wheeling, Sciotoville
C	–	FA 79 D(2)S	Mississippian-Meramec (Warsaw and St. Louis Groups) and Pleistocene-Glacial Valley Fill	Wheeling, Sciotoville, Westmoreland, Caneyville; Bedford, Cookesville, Baxter
D	C-3	FA 79 B(5)D(4)	Mississippian-Meramec (St. Louis Group)	Bedford, Cookeville, Baxter

Fig. 1 Locations and Descriptive Data for Field Experiments

reported before, a specific outline of data and a layout are included as Fig. 7 in Plate I following page 23. The reader should open this and have it before him for reference whenever the project is mentioned.

Both aggregates, crushed limestone (apparently about a standard size 36 with a maximum nominal size of two inches) and Ohio River sand were from single sources. Limestone was taken from a quarry alongside old Route U.S. 31W, and the sand came from the vicinity of Louisville. Vinsol resin when used was interground in the cement at the manufacturing plant. Specifications for the job required a weight loss of not less than four nor more than eight pounds per cubic foot.

In the laboratory tests, emphasis was placed on durability as determined by freezing and thawing and upon loss in strength caused by air-entrainment as well as by internal disintegration resulting from the temperature fluctuations. The intensity and duration of freezing and thawing cycles were different in all the laboratories thus making a direct comparison among the results impossible. However, trends in results were so definite that a valid basis for correlation was available. The Notes on Plate I adequately describe all materials and procedures.

Closely associated with this project were tests for the fatigue characteristics of different concrete mixes. This experiment - possibly the only one of its kind devoted to air-entrainment - was made specifically for the Kentucky Department of Highways by Purdue University and was reported (9) in 1943. A total of 280 beams were prepared with materials supplied by the Department of Highways. Aside from minor additions and a top limit of 3/4 inch coarse aggregate size, these materials were the same as those used on the field experimental road.

Among the cements and cement combinations were the following:

1. Normal portland.
2. A 5:1 blend of normal portland and natural.
3. A 5:1 blend of normal portland and natural with a grinding aid.
4. Portland with 0.034 percent Vinsol resin interground.
5. A 5:1 blend of portland with interground Vinsol resin and natural.
6. A 5:1 blend of portland with interground Vinsol resin and natural with grinding aid.

A cement factor of 1.5 was used, and coarse and fine aggregates were combined in proportions of 45 percent and 55 percent respectively.

Beam specimens for both fatigue and static loading were 4 x 6 x 30 inches with 4 x 4 x 12 inch reduced midsections. Holes for strain-gage plugs, approximately ten inches apart, were cast in the sides of the beams. A typical sample in place and ready for the fatigue test is shown in Fig. 2.

Prior to tests for fatigue, breaking strengths under static loads were determined by vertical end loadings. "Beams were clamped in a rigid vertical position in the fatigue machine [see Fig. 3] and supported a horizontal straining beam fastened in one position to the test specimens. Loads were applied to one end of the straining beam in increments of 10 lbs. _ _ _ until the beam fractured. The breaking load secured was used as a basis for fatigue loading.

"Fatiguing of beams was accomplished by employing a system of horizontal steel straining beams operating from a cam to produce

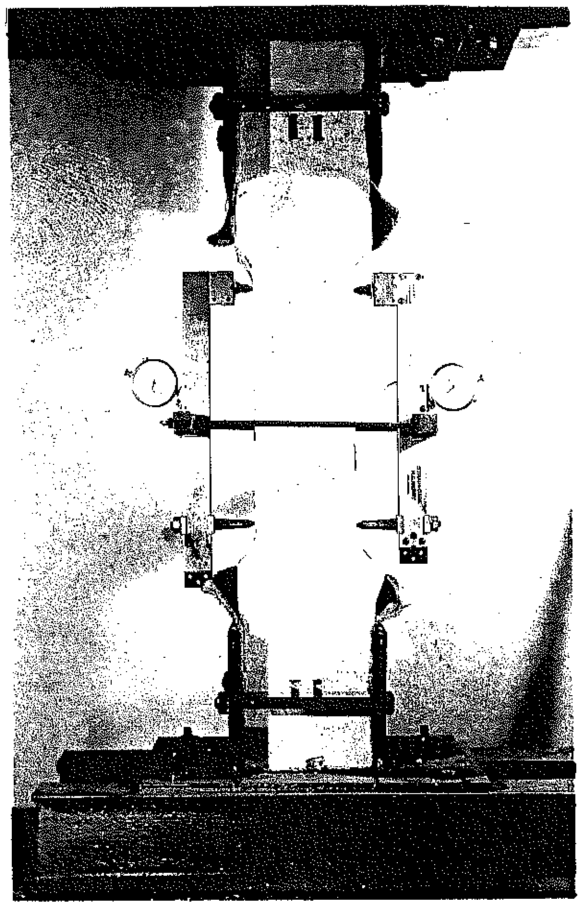


Fig. 2 Fatigue Specimen in Place with Strain Gages Mounted for Measurements of Deformation

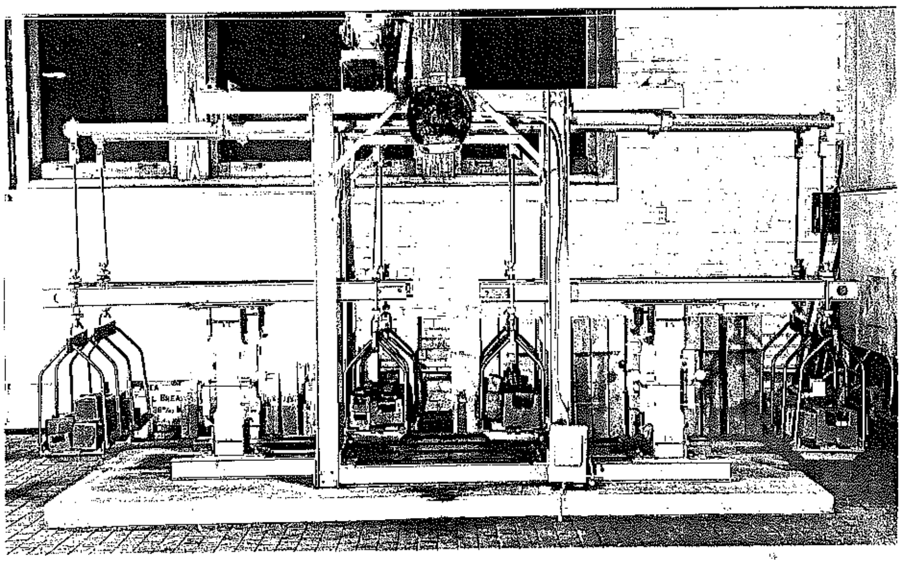


Fig. 3 Arrangement for Testing Concrete Under Fatigue Loads

reversed bending moments in the specimens. When a test specimen is clamped in the base of the frame and the movable steel straining beam is mounted at the top of the vertical test specimen, alternate tensile and compression stresses are induced in the faces of the beam in the plane of bending as the machine operates. The rate of load application was ten reversals per minute."

Initial loads were by series, with beams representing each concrete mix being started at 50, 55, 60, 65, 70, and 75 per cent of the static load for that mix. After approximately 100,000 reversals of stress at the initial load, the beams were subjected to an increase of 5 percent load and an additional 100,000 reversals. This was carried on until the specimens failed. Recordings of the measured deformations and the total number of stress reversals were made.

Project F.A. 366 C(2), Falmouth-Cynthiana Road. In 1941, a portion of one project on U.S. 27 in Harrison and Pendleton counties was used for ten experimental sections totalling 7.89 miles in length. Two coarse aggregates - crushed limestone and glacial [redacted] gravel - were combined individually with five cements or cement blends and treated materials as outlined in Table I. A total of 155 beams (5"x 6"x 20") were made on the job and tested for flexural strengths and durability in the laboratory. Details of this project were reported (14) in 1945.

Because of contrasting performance records for concrete pavements with different aggregates as revealed in a recent survey (19), and because of speculation regarding the possible merits of blended aggregates for improved performance, this project has some indirect significance. Also, located as it is in an extensive

TABLE I - COMPOSITION AND STATIONING OF SECTIONS IN PROJECT F.A. 366-C(2), FALMOUTH-CYNTHIANA ROAD.

Section No.	Cement Composition	Coarse Aggregate	Stationing
1	Portland with interground Vinsol resin.	Limestone	336+00 to 373+00
2	Blend (5:1) of portland with interground Vinsol resin and natural.	Limestone	373+00 to 424+06
3	Blend (5:1) of portland and natural with grinding aid.	Limestone	424+06 to 475+30
4	Blend (5:1) of portland and natural.	Limestone	475+30 to 521+20
5	Normal portland.	Limestone	521+20 to 555+66
6	Normal portland.	Gravel	555+66 to 567+10
7	Blend (5:1) of portland and natural.	Gravel	567+10 to 616 [redacted]+42
8	Blend (5:1) of portland with interground Vinsol resin and natural.	Gravel	612+42 to 710+43
9	Blend (5:1) of portland and natural with grinding aid.	Gravel	710+43 to 762+09
10	Portland with interground Vinsol resin.	Gravel	762+09 to 388+38

region where the well known Eden shale dominates topographic and soil conditions, the road has a subgrade factor which is extraneous to the immediate objective of experimentation and which must be watched for undue influence.

<u>Project SN-FA 194 E(3)F(3)L(2), Louisville-Cincinnati Road</u>. A third field project was started in 1941 as a two lane addition on U.S. 42 beginning at the Zachary Taylor monument in Jefferson county and extending 6.44 miles to a point about 1,000 feet inside Oldham county. Here a coarse aggregate from a quarry near the road was used throughout, but the project was divided into five sections. Cements and cement combinations were the same as those used in the Falmouth-Cynthiana Road. Table II is a brief outline of the project as it was previously reported (14) in 1945. Durability was the primary objective in these tests.

TABLE II - COMPOSITION AND STATIONING OF SECTIONS IN PROJECT SN-F.A. 194 E(3)F(3)L(2), LOUISVILLE-CINCINNATI ROAD

Section No.	Cement Composition	Stationing
1	Portland with interground Vinsol resin.	112+50 to 187+00
2	Blend (5:1) of portland with interground Vinsol resin and natural.	187+00 to 263+20
3	Blend (5:1) of portland and natural with grinding aid.	263+20 to 331+45
4	Blend (5:1) of portland and natural.	331+45 to 422+10
5	Normal portland.	422+10 to 458+00

<u>Project F.A. 79 B(5)D(4), Louisville-Elizabethtown Road</u>. A final test road for experiments with air entrainment was a third-lane

northbound addition on U.S. 31W in Hardin and Meade counties. The experimental portion began at station 30+00 and extended to station 266+00, all of which was in Hardin county. Only one type of cement, a 5:1 blend of portland and natural containing a grinding aid was used, and the aggregates were crushed limestone (maximum size, 2-1/2 inches) and sand combined on a 62 to 38 per cent basis.

Beams were poured on this job in May and June of 1941, but they were almost two years old before tests were started. Most of these samples were placed on the roof of the laboratory for exposure, and from that group representative samplings for annual tests have been made three times beginning in 1944. Original tests in 1943, as reported (14) previously, consisted of initial sonic modulus and flexural strength, as well as durability by alternations of freezing and thawing.

Laboratory Projects

Of three studies carried out entirely in the laboratory, one was concerned solely with volumetric and absorptive properties of the mix. That research was reported (14) as Project C-17 in 1945, and since it was only incidental to the objectives of this report it will not be given further consideration. In addition to the two remaining projects, some minor experiments related to an extensive study of blended aggregates (now in progress) have revealed some interesting and significant results.

<u>Research Project C-13</u>. In order to study the effect of air-entrainment on concrete containing an aggregate known to be of poor quality, Research Project C-13 was started in 1945 and com-

pleted and reported (17) only this year. Here a crushed limestone containing a high percentage of shale (not acceptable in present specifications) and having a large amount of clay in the limestone itself, was mixed with normal portland cement and also was treated with a 5:1 blend of portland cement and natural cement with a grinding aid. In addition, some samples were made with a modified aggregate prepared by crushing some of the original material and using the "dust" passing a No. 4 sieve in the amount of 15 percent. For a complete description of the materials and the procedures - particularly durability tests - the reader should review the report noted here.

Research Project C-16. One of the most elaborate of all experiments with air-entrainment was Laboratory Project C-16, started in 1945 and just completed within the past few days. The stated purpose of this work at the time it was initiated was to "determine the effect of various air-entraining agents on the strength and durability of concrete made with both high quality and low quality coarse aggregate".

Seventeen different mixes, all alike in basic design but differing in air-entraining materials and coarse aggregates, were made and tested for strength and durability. From the standpoint of agents for air-entrainment about the entire range of products commonly associated with this type of concrete were included; viz., pozzalith, Vinsol resin interground, Vinsol resin-sodium hydroxide solution, blend of portland and natural with a grinding aid, Darex, and an ordinary soap solution.

Coarse aggregates (No. 6 size) were crushed limestone from two sources one of which had an excellent service record and the other failing to meet specifications for concrete aggregate.

In addition, a third type was produced by crushing the low quality rock and recombining so that 15 percent of the total was "dust" finer than the No. 4 sieve size. A standard concrete sand was combined with each limestone aggregate in the ratio of 40 to 60 percent by weight. Table IV following page 44 is a summary of data pertaining to aggregates. There in column 5 headed "Coarse Aggregate", the No. 1 material was that which failed to pass specifications; No. 2 was an aggregate from the same source but containing 15 percent dust; and No. 3 was the material having an excellent service record.

Three of the air-entraining agents were interground in the cement and three were added during the mixing process. These were as follows:

1. Pozzalith added at the mixer at the rate of 3/4 pound per bag of portland cement.

2. Vinsol resin interground in portland cement.

3. Neutralized Vinsol resin solution added at the mixer in quantity of one quart per six bags of portland cement. This is equivalent to 0.007 percent Vinsol resin to cement by weight (solution prepared in proportions of 7.9 lbs. of flake Vinsol resin and 1.2 lbs. of commercial sodium-hydroxide to fifty gallons of water).

4. Blend of five parts portland to one part natural cement with a grinding aid.

5. Darex interground in portland cement.

6. Portland cement containing a soap solution prepared in the laboratory. The soap beads were completely dissolved in water and the solution added at the mixer in amounts such that 1/4 lb. of soap was combined with six bags of cement.

Samples for a test consisted of 6" x 12" cylinders, 3 x 5 x 20 inch beams and 12 x 12-1/2 x 1-1/2 inch slabs. Mixes were not redesigned for constant cement factor, rather the objective was to maintain a slump from three to four inches and a cement factor as close to 1.5 as possible. The weight per cubic foot of concrete coming from the mixer was carefully determined for every pour so that the actual cement factor, water-cement ratio and percentage of drop in weight could be determined.

All samples were removed from the molds after twenty-four hours and were stored in a moist room for a period of twenty-seven days. Then initial sonic moduli were determined for all beams after which those beams and all the cylinders were loaded in flecture and compression for initial strengths. The remaining beams and all the slabs were then subjected to freezing and thawing tests with the former being thawed at room temperature in water and the latter at room temperature in a 10 percent solution of calcium-chloride. Freezing temperatures were approximately -10°F.

Incidental Data, Measurements, and Tests

In conjunction with a study of combined coarse aggregates not particularly related to air-entrainment, it was convenient to make some evaluation of means for controlling air contents as obtained by the proposed Indiana method (see Appendix B). The percentages of air-entrained measured by this method were compared with those calculated from the drop-in-weight measured in accordance with A.S.T.M. designation C138-44. Also, some of the samples representing both air-entraining and non-air-entraining concrete, upon being broken for strength, were sampled at random for microscopic inspection to determine whether there were differences in characteristics of the exposed surface. Finally, to supplement all the data accumulated in field and laboratory experiments, contacts were made with states surrounding Kentucky to find out what policies were being used by these states and methods and specifications preferred for design and control of these concrete mixes. The information obtained from the several states is tabulated in Table III and discussed at appropriate points in the sections on Results and Recommendations.

RESULTS

With some reservations the results from six years of experimental work in Kentucky corroborate discoveries made elsewhere (18) during the same period of time. For example, the consensus of of investigators is that:

1. Air entrainment improves the resistance of concrete to freezing and thawing.

2. The compressive and flexural strengths of normal concrete are reduced by air entrainment, and in general this reduction is progressive with increases in the amount of air entrained.

3. There is little benefit derived from air entrainment when the air content is less than 3 per cent; similarly, when the air content is greater than 6 or 7 per cent durability is not increased appreciably yet strength is reduced improportionately.

4. A concrete mix with an air-entraining material is more workable, has less tendency toward segregation and bleeding, and is slightly more difficult to finish than normal concrete.

In general, these tests produced data that conform with prevailing conclusions. Where there is disagreement the cause can sometimes be attributed to results that are contradictory within themselves and hence subject to doubt. Differences in test conditions such as storage of specimens, variable cement contents, and limitations in the number of samples representing a given mix all have influence on the results. Where such variable factors exist and results are not accordant, conclusions must be drawn on the basis of prevailing trends with recognition but slight account given to the contradictory data.

Not all the contrasting situations are of this type. In some, the results from laboratory tests here are invariably different from those originating in other laboratories. One of these projects definitely showed a marked increase in the value of concrete with a so-called "inferior" coarse aggregate when air entrainment was used, yet one study in Missouri (8) led to conclusions that were just the opposite in effect.

It isn't that these findings contradict completely those made in Missouri or elsewhere*; rather, they accentuate the importance of all constituents in a concrete mix and further emphasize the fact that local materials make local problems. In evaluating this type of concrete for use in Kentucky, preference must be given to features peculiar to local materials and not necessarily applicable to similar materials in other states.

Combined Field and Laboratory Projects

At their present ages, the experimental roads show little or no tangible evidence of differences among the several concrete mixes. Most of the apparent damage can without question be charged to abrasion by military traffic or to inequalities of subgrade support which caused pumping, breaking of the pavement, settlement with cracks, and even a serious side-hill fill slide**. For the most part, the slabs have not cracked to the extent of requiring maintenance except where pronounced breaks have developed from causes mentioned above. Thus, the most recent survey (19) showed that the recorded crack and joint interval was hardly different from the original joint spacing in all cases.

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* Note particularly a discussion by Wuerpel, Procedures, A.S.T.M., Vol. 43, page 1000, 1943.

** U.S. 27, Proj. F.A. 366 C(2), Falmouth-Cynthiana Road, About Sta. 511+00. Another is developing on the opposite side of the road at about Sta. 509+00.

This condition is about as expected. General experience has shown that aside from extremely active scaling usually attributed to methods of ice control, differences in durability characteristics seldom become manifest on the surface in less than eight or ten years. Possibly differences could have been found had cores been drilled or a new method of field sonic measurements been applied to the several pavements. Neither was practicable because of the priority status of construction work in the current program or because necessary equipment was not available. One or both will be tried in the fall or early next spring.

In lieu of these fundamental procedures for evaluating the concrete, several photographs were taken at different points on the separate projects. Pictures in Figs. 8 to 16 inclusive are representative of the group. Although very general in appearance, these photographs will serve as a record of present conditions for comparison with future shots taken from the same points. As such, their value will increase with time. For the present, significance can be given only to the laboratory test results and the few peculiar conditions noted on the roads when inspections were made.

Project F.A. 79 D(2)S, Louisville-Elizabethtown Road. A layout, tabulation of results, and graphs of data from experiments with concrete in the third-lane addition on U.S. 31W and U.S. 60 are given in Plate I. In addition, Plate II is a plot of results from fatigue tests made on mixes comparable with some of those placed in this project. The essence of notes taken during the inspection was:

1. Entire lane (experimental) abraded by military traffic. In some places, rod surface almost 50 percent removed by this abrasion. No noticeable differences in this characteristic in all the sections.

2. Pronounced subgrade difficulties in Sections 3, 4, 2A and 5. In effect, this means that the most trouble was confined to the rock cut on Muldraugh Hill and immediately adjacent areas. The portions on Ohio River Valley sediments and on upland soils where the grade was about at ground line were hardly affected.

3. All sections pitted to some extent. Indications that individual pieces of aggregate had broken down or had been removed.

4. Conditions throughout comparable with that of the two lanes built entirely with normal portland cement.

Important relatiomships resulting from laboratory tests are plotted in Plate I. The curves of Figs. 4 and 5 apply to beams tested in Laboratory No. 2 (see notes on Plate I), while Fig. 6 applies to cores tested in two other laboratories. The tabulation and bar graph apply to all sources of data. In Figs. 4, 5, and 6, the numbers in parenthesis at the end of each line refer to the section of the road represented by that line.

On the basis of either field condition or laboratory tests, the value of the red iron-oxide surface is hard to determine. Since beams and cylinders were poured on the job prior to the finishing operation, only those laboratory tests on cores were relevant to the red surface material. The curves in Fig. 6 on Plate I, which are results of these tests, show the cumulative percentage loss in weight with increasing alternations of freezing and thawing. Dashed lines represent results from tests in laboratory No. 4 while those that are solid refer to laboratory No. 3.

In this figure, the ordinate scale for percentage loss in weight was divided into two ranges, with the one representing tests in laboratory No. 3 being twice as great as the 0 to 35 representing tests in laboratory No. 4. This was more a matter of avoiding congestion of lines near the bottom of the diagram rather than designating any great differences in results from the two sources. Actually there is as much as 100 percent difference in the loss in weight for some mixes measured by the two test methods as early as 100 freezing and thawing cycles. The two methods of test, as outlined in the notes on Plate I, were:

Lab. No. 3. Cycle: 7 hours at 0° to -10°F. and 7 hours at 65° to 75°F. in 10 percent $CaCl_2$ solution.

Lab. No. 4. Cycle: 24 hours at -10°F. and 24 hours at 70°F. in water.

Cores for both laboratories were extracted simultaneously but there is a possibility that the samples were a little different in age when the tests were started.

If the red surface could have been of any consequence in these tests, evaluation must be made by comparison between Sections 3 and 3B; sections 4 and 6; and sections 5 and 7. A wide divergence between the performance of Sections 3 and 3B (both containing normal portland cement) is evident in results from both laboratories; on the other hand, the data for cores from Sections 4, 6, 5 and 7 are not so inconsistent with respect to either the sections or sources of data. In general, these losses of weight by cores from Sections 4 and 5 were slightly less than those for cores from Sections 6 and 7.

From this standpoint alone, it appears that some benefit was derived from the red surface of iron oxide and cement, and that the benefit was more pronounced for the mixes with normal portland cement than for those with air-entrainment. Obviously, in the laboratory freezing and thawing tests the red surface could give protection only to the tops of the cores - a negligible factor at best. Hence, if and when advantage was gained by use of the red surface it must have occurred in the setting or curing of the concrete before it was cored.

Results from durability tests on beam samples as plotted in Fig. 4 and Fig. 5 tend to discount possibilities of increased durability imparted by the red surface insofar as laboratory tests are concerned. Since the beam samples were poured on the job, the red surface was not involved in their characteristics, yet in all cases the samples representing Sections 4 and 5 were superior to those representing Sections 6 and 7. It is evident then, that concrete in sections having a red surface coating was more durable than similar concrete in sections without - but at least partially for reasons extraneous to the coating. Furthermore, the reduction in sonic modulus (Fig. 4) for Section 3B (portland cement without a coating) was not as great as for Section 3, a condition which further obscures the value of a red surface particularly since this is contrary to results from tests on cores as illustrated in Fig. 6.

A more distinct relationship brought forth in Plate I, and illustrated by Fig. 4, 5, and 6 and the Bar Graphs, is concerned with air-entrained versus non air-entrained concrete. With but one exception (cores from Section 1, see Fig. 6) the results showed that the mixes with normal portland were not as durable as those containing cements combined or treated. That one exception was a mix with air entrained in about the same amount as contained in concrete with normal portland. Thus, in all cases air-entrainment increased the durability over that for normal portland cement concrete mixes, yet some of the mixes with air-entrainment were not quite equal to one with practically no air-entrained (see lines for Section 1 in Figs. 4 and 5).

Still more definite is the fact that air-entrainment reduced the strength of the concrete if Section 3B containing normal portland is used as a basis for comparison. As shown by the tabulation and Bar Graph on Plate I, the mix in Section 4 had the least over-all strength reduction which on a strict percentage basis was less than the strength lost by samples from Section 3. Specimens suffering the greatest loss in strength from all standpoints were those representing Sections 2 and 7.

In fatigue tests, the results of which are charted by a Bar Graph in Plate II, differentiation of mixes and their respective properties was not so well defined. Without doubt, Group II (comparable with Section 1 in the experimental road) had the least over-all resistance to prolonged alternations of stress, yet it was slightly better than some of the other groups when the initial fatigue load was high and only a few alternations were carried through. Actually, only Group VI, which was not strictly analagous to any section on the road, was invariably superior to Group I (representing Section 3B) in fatigue resistance. However, Groups III, IV and V, which were mixes similar in composition to those in Sections 7, 6, and 2 on the experimental road, were sometimes superior and sometimes inferior to Group I depending upon the initial fatigue load applied.

As illustrated by average values of deformation and stress reversals plotted as dashed lines above the Bar Graph, Group III with a 5:1 blend of portland and natural and a grinding aid was highest, while Group II with a 5:1 blend of portland and natural without a grinding aid was lowest in fatigue resistance. Otherwise, Groups IV and VI were slightly above and Group V slightly below Group I in this respect.

In view of all these data taken collectively, the results from this experiment show the mixes with different cement composition

Fig. 8 Proj. FA 79 D(2)S, Louisville-Elizabethtown Road. Near view of the boundary between section 3 with normal portland cement and section 4 with portland cement and interground vinsol resin. The pavement in both sections was given a rod surface which has been abraded considerably by treads on military vehicles.

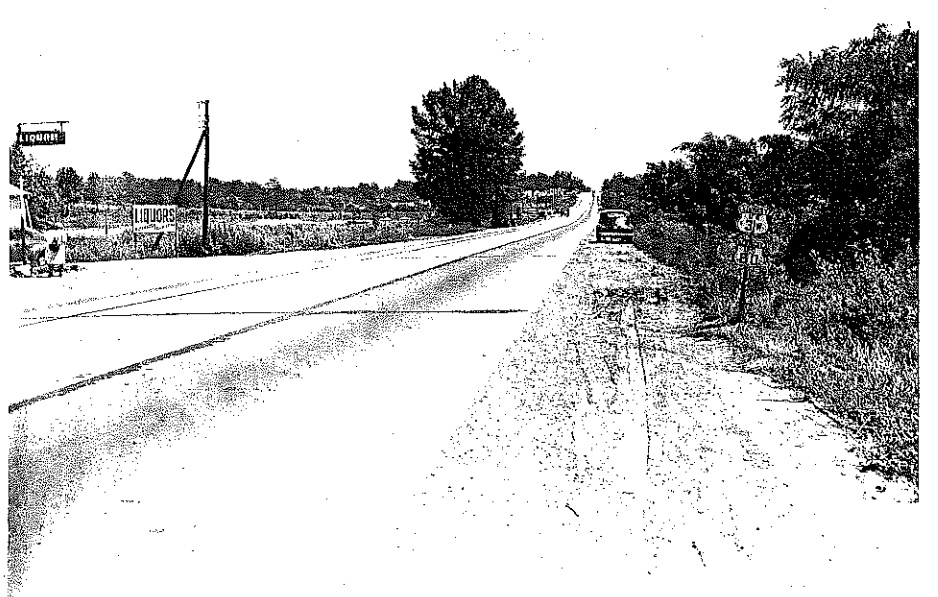

Fig. 9 Proj. FA 79 D(2)S. Louisville-Elizabethtown Road. Section 6 in the foreground contains portland cement with interground vinsol resin and section 7 in the distance has a 5:1 blend of normal portland with natural and a grinding aid. The juncture is about at the rear of the parked car on the right.

to be generally as follows:

1. Normal Portland (Sections 3 and 3B and Group I in fatigue). Extremely low durability, medium to high strengths; fatigue resistance about average.

2. Blend 5:1, normal portland and natural (Section 1, Group II in fatigue). Fair to poor durability; medium to little strength reduction; poor fatigue resistance; practically no air entrainment.

3. Blend 5:1, portland with interground Vinsol resin and natural (Section 2, Group V in fatigue). Fair durability; severe strength reduction; average fatigue resistance; satisfactory air entrainment.

4. Portland with interground Vinsol resin (Sections 4 and 6, Group IV in fatigue). Durability good to fair; medium to slight strength reduction; fatigue resistance above average; satisfactory air entrainment.

5. Blend 5:1, normal portland and natural with a grinding aid (Sections 5 and 7, Group III in fatigue). Durability good to fair; medium to great strength reduction; fatigue resistance high; satisfactory air entrainment.

Results from this project are compared with those from other projects in the summary beginning on page 54 and in Fig. 24 and Fig. 25 related to that summary.

Project F.A. 366-C(2) Falmouth-Cynthiana Road. In conjunction with discussions of results on the experimental road in Harrison and Pendleton Counties, reference to a previous report by Collier (14) is recommended. The data which formed the basis of Table VII in that report are listed by section and station numbers in Appendix C herein. Additional material drawn from daily reports and core drill records for the job has been incorporated primarily as a means for judging strength reductions and durability factors representative of construction intervals smaller than entire experimental sections.

Consideration of strength and durability characteristics for the several mixes were hampered somewhat by the lack of accuracy and sometimes lack of data that could have marked influence on performance. Circumstances relative to any field construction are not conducive to

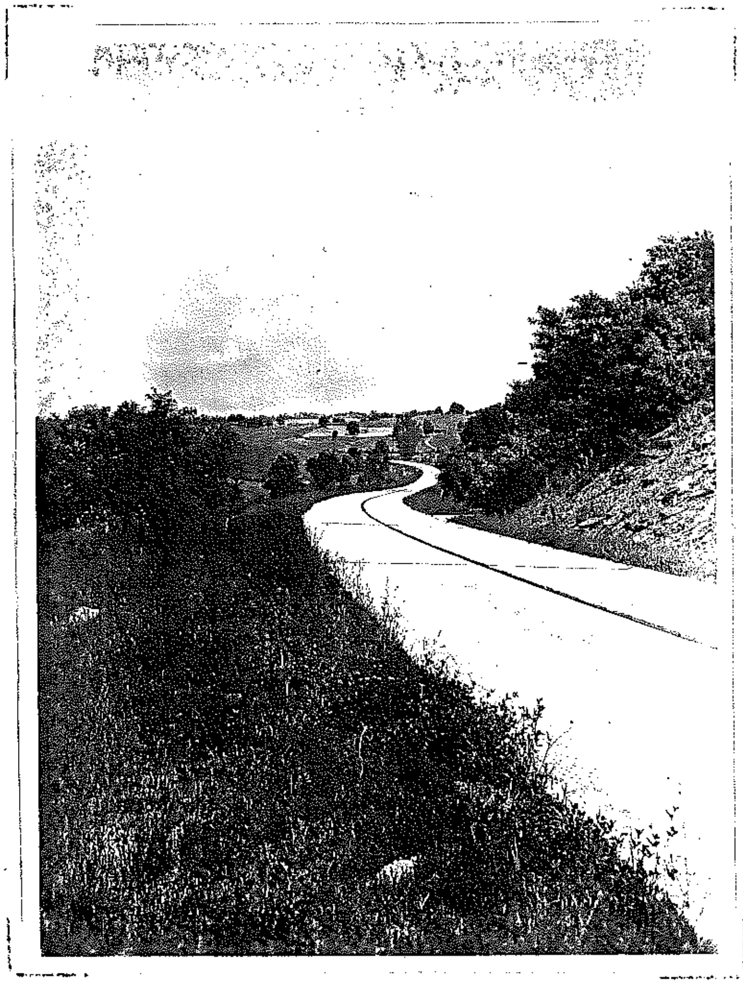

Fig. 10 Proj. FA-366 C(2), Falmouth-Cynthiana Road. View across the boundary between section 1 and section 2 (concrete in foreground contained portland cement with interground vinsol resin while that beyond the second joint had a 5:1 blend of portland and natural without grinding aid). Coarse Aggregate - crushed limestone.

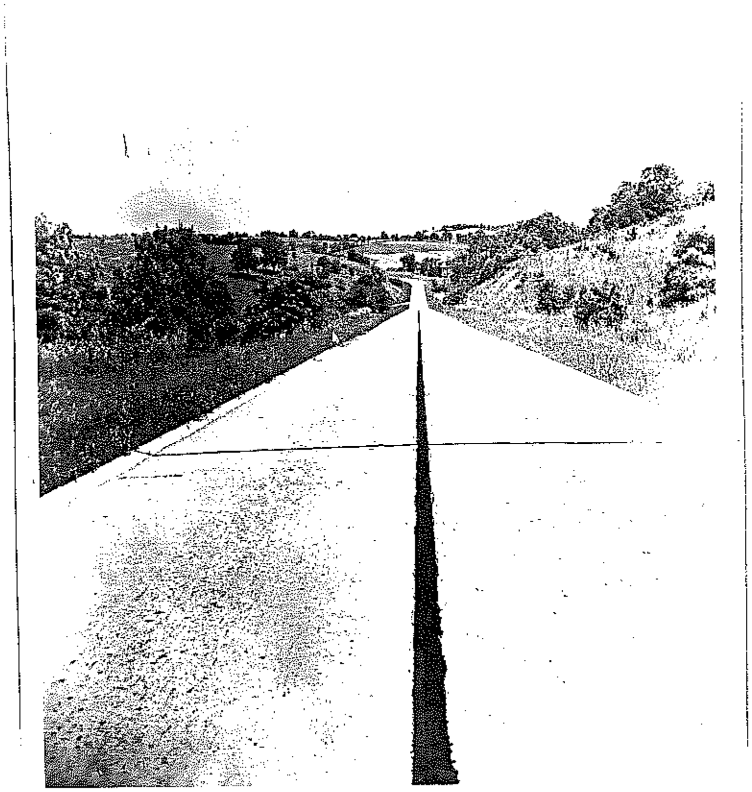

Fig. [redacted] 11 Proj. FA-366 C(2), Falmouth-Cynthiana Road. The flag at the edge of the pavement marks the joint where coarse aggregate was changed from crushed limestone to [redacted] glacial [redacted] gravel. Slabs with crushed limestone are 60 feet in length while those containing gravel are 30 feet long. Both sections contain normal portland cement.

precise measurements or careful handling of samples; similarly, on this project weight determinations were not always made at locations where samples were taken, hence estimates and interpolations were required. Finally, the pattern of variation in cement content, water cement ratio, and air content could be only estimated. The first was assumed to be constant at six sacks per yard, the second was known to vary in some manner that could not be determined (hence it was disregarded), and the last was calculated from weight measurements, a few of which indicated not only no air-entrained but a unit weight in excess of that possible as computed by theoretical solid volumes.

In contrast to thse restricting influences, the project had an outstanding feature in the dual coarse aggregates - bank gravel (glacial) from a source near the Ohio River and crushed limestone from the inner blue grass (lower Ordovician) region. These were used separately but each with all the combinations of cements.

Briefly, the field inspection produced more information concerning difficulties caused by slides and fill settlements with occasional cracking of the pavement rather than anything solely dependent upon the concrete. On the surface this pavement was in excellent condition, the most obvious damage being few minute cracks -such as shown in Fig. 14 - where settlement had occurred. Occasionally the surface was pitted probably as a result of pop-outs or removal of weak aggregate or mud. In the few areas of settlement, where slabs had been mudjacked, realignment was accomplished without causing apparent structural damage. Notwithstanding the favorable aspects, the general character of topography, soils, and rock exposures along this right of way clearly indicated that the pavement would have suffered much more damage had traffic been heavier - a factor quite aside from the merits of air-entrainment.

Fig. 12 Proj. FA-366 9(2), Falmouth-Cynthiana Road. Cracks such as those shown in this picture occurred at some points in the pavement, particularly in section 5. These were obviously locations where sub-grade support was not adequate, hence, they are not indicative of disintegration in the concrete itself. The cement in this case was normal portland and the coarse aggregate was crushed limestone (Station 544+50).

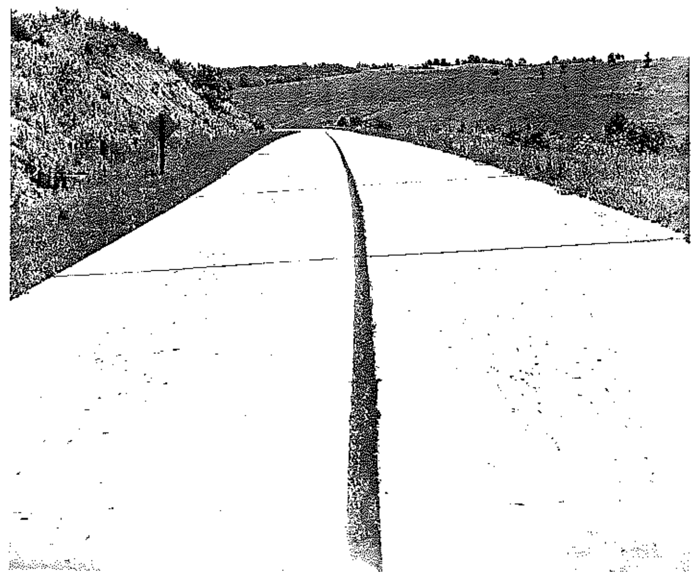

Fig. 13 Proj. FA-366 C(2), Falmouth-Cynthiana Road. Pavement in the foreground of this picture contains a blend of five parts portland cement with interground vinsol resin and one part natural cement (no grinding aid). Beyond the sign on the left, a blend of five parts portland and one part natural (no grinding aid) was used. Both sections contain gravel aggregate.

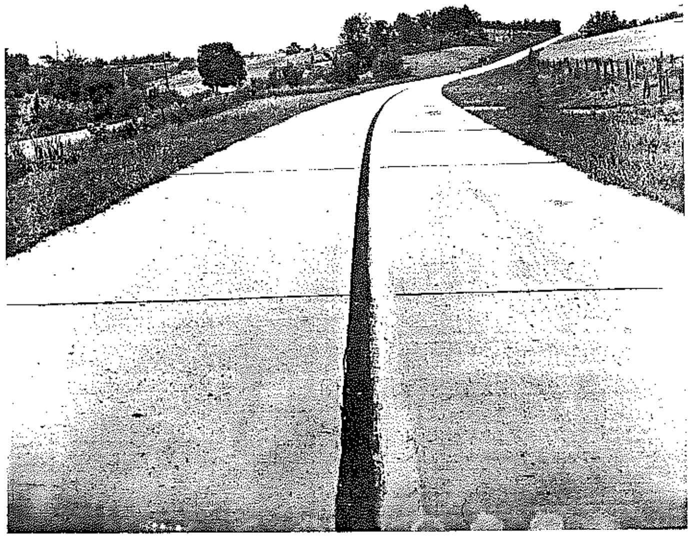

Fig. 14 Proj. FA-366 C(2), Falmouth-Cynthiana Road. The juncture between sections 9 and 10 occurs at the second joint from the bottom of the picture. Section 9 in the foreground contains a 5:1 blend of portland and natural cements (with grinding aid). Section 10 has portland cement with vinsol resin interground. Both have gravel coarse aggregate.

Laboratory tests on beam samples poured on this project again showed with little deviation that air-entraining concrete was more durable than normal portland cement concrete or any concrete containing a small percentage of air. However, the relationship between estimated percentages of air entrained and measured durability factors was not direct or consistent for mixes with either type of coarse aggregate; in fact, it was so erratic that only the trends were evident. This could be largely attributed to the inexactness of field weight determinations and consequent estimates of air content.

From the standpoint of strength reduction, these mixes were seriously affected by air entrainment, yet the actual strengths were very high regardless of the cement composition or percent air entrained. For example, among the samples from the Louisville-Elizabethtown Road, compressive strengths of cores ranged from 3100 to 4690 lbs. per sq. in. and 49 day moduli of rupture ran from 557 to 820 lbs. per sq. in. In contrast, the low and high values for average compressive strengths on this project were 5126 and 6770 lbs. per sq. in. respectively, while the average moduli of rupture for control varied from 787 to 1113 lbs. per sq. in. There are only two mitigating factors in favor of the tests representing the Louisville-Elizabethtown Road - specimens were younger and indicated air contents were higher than on the Falmouth-Cynthiana project.

There was some difference between the over-all results from tests on samples containing limestone aggregate and corresponding specimens containing gravel aggregate. Invariably, estimated percentages of entrained air were higher for mixes with limestone than for similar mixes with gravel; also, the two mixes with practically no air entrainment were definitely more durable and slightly stronger with gravel than with limestone aggregate. These two groups were the specimens containing normal portland cement and the 5:1 blend of portland and natural, neither of which had an estimated air content exceeding 1.4 percent. As a minimum they indicate (if the possible effects of cement brands and fine aggregates are considered negligible) that for these particular aggregates the gravel has more inherent durability than the stone when both are used in concrete. Further comparisons for relative durability values representing these and other mixes can be made readily through reference to Fig. 24 following page 58. This will be discussed in the summary of results.

General performance of the different mixes having varied cement composition as measured by these laboratory tests on beams and cores from this project was as follows:

1. Normal Portland (Sections 5 and 6). Durability low and strength high. Indicated rate of deterioration more than twice as great as any other mix with one exception. Slightly stronger and more durable with gravel than with limestone aggregate.

2. Blend 5:1, normal portland and natural (Sections 4 and 7). Extremely low durability with limestone and fair durability with gravel. Insignificant reduction in flexural strength and moderate reduction in compressive strength due to air entrainment. Estimated amount of air entrained slight but still about twice as great as that for mixes with normal portland.

3. Blend 5:1, portland with interground Vinsol resin and natural (Sections 2 and 8). Durability good with gravel and moderate with limestone. Moderate reduction in both flexural and compressive strength due to air entrainment. Relatively fair amount of air entrained.

4. Portland with interground Vinsol resin (Sections 1 and 10). Durability fair with gravel and moderate with limestone. Great reductions in flexural strength with gravel and compressive strength with limestone; negligible reduction in flexural strength with limestone. Estimated amount of air entrained lower than desired amount, yet higher than in all other mixes.

5. Blend 5:1, normal portland and natural with a grinding aid (Sections 3 and 9). Durability excellent (measured increase in soundness or integrity of concrete despite freezing and thawing) with gravel and good with limestone. Great reductions in flexural and compressive strengths in all cases. Air entrainment mediocre.

As will be shown in a later summary the general trend of results indicates that these mixes were superior to similar mixes used on the Louisville-Elizabethtown Road but were inferior to those placed in the experimental sections of the Louisville-Cincinnati Road.

<u>Project SN-FA 194 E(2)F(3)L(2) Louisville-Cincinnati Road.</u> In many respects the fundamental features of concrete on the Louisville-Cincinnati experimental road were similar to those on the Falmouth-Cynthiana project. For example, limitations in data necessitated an assumption of a constant cement factor of 1.5; no regard for possible variations in water-cement ratio; and approximate calculations of air entrained based on weight measurements some of which were excessive. Similarly, there is a strong possibility that subgrade conditions were of great influence, but this time in favor of prolonged service.

By calculation the air contents for this concrete were very low, the highest being 3.1 percent and the great majority being lower than 2.5 percent. Nevertheless, all mixes in this project were very durable as determined by laboratory freezing and thawing tests, for even the least durable (containing normal portland cement) was equal or superior to the majority of those in the other experimental roads. This characteristic can be best attributed to either or both the quality of coarse aggregate - since that was the principle variable from the other projects - and the subgrade conditions which probably promoted durability through drainage (assumed so since two companion lanes built earlier with a different coarse aggregate and all normal portland cement are in excellent condition).

As a result of the excellent pavement performance, there were no notes made during the inspection other than to record the outstanding condition that was evident.

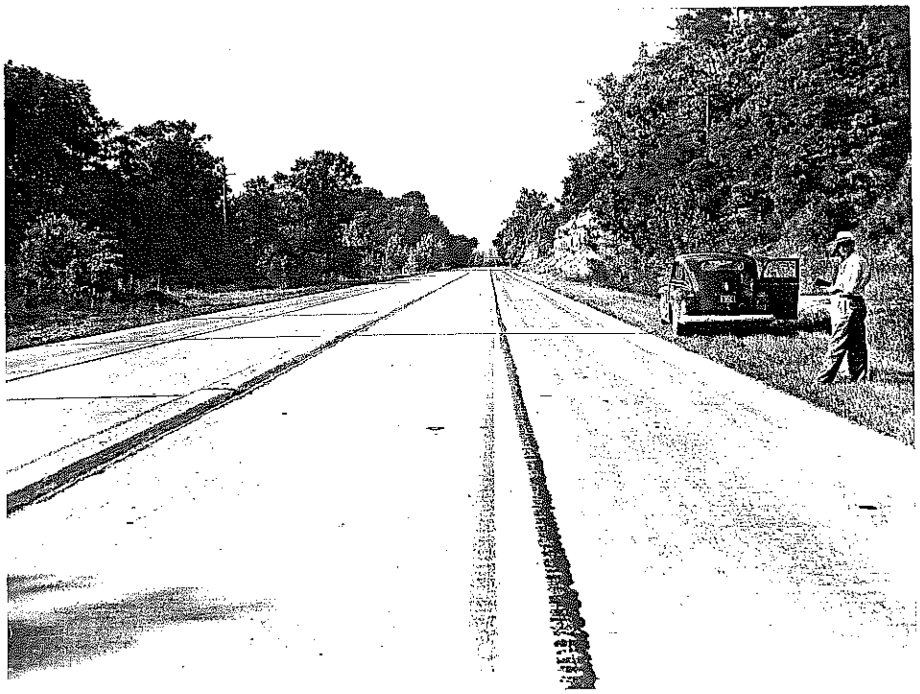

Fig. 15 Proj. SN-FA 194 E(3). Louisville-Cincinnati Road. View at the junction between sections 2 and 3. A 5:1 blend of portland cement with vinsol resin interground and a natural cement was used in the pavement in foreground and a 5:1 blend of portland cement with natural cement (containing a grinding aid) was used in pavement beyond the joint opposite the parked car. Experimental sections apply only to the two lanes on the right.

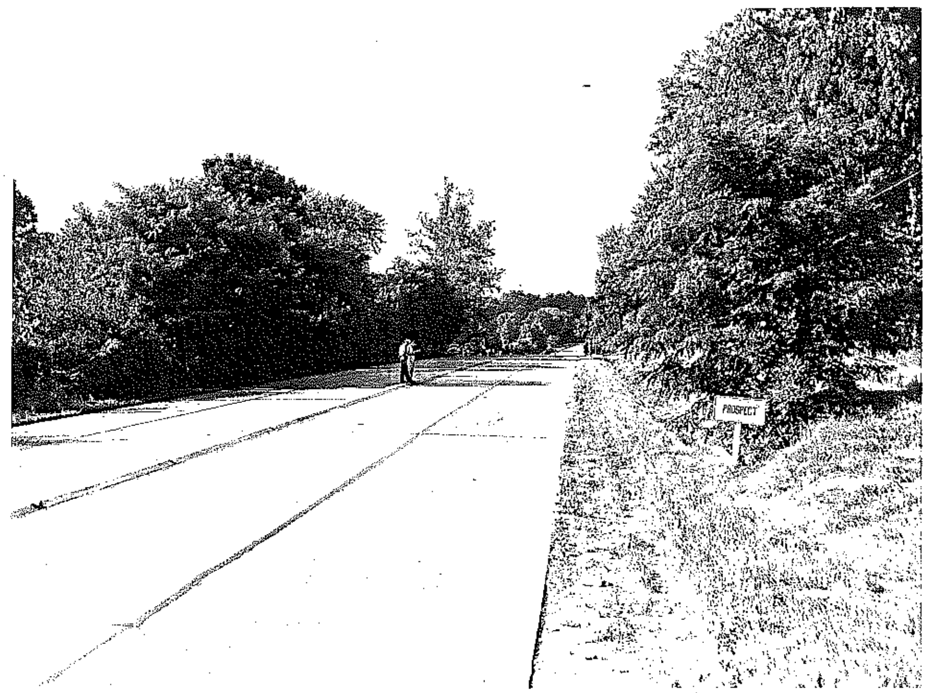

Fig. 1b Proj. SN-FA 194 E(3), Louisville-Cincinnati Road. Pavement in foreground contains a 5:1 blend of portland cement and natural cement without grinding aid, while that beyond the point where men are standing on the dividing strip contains normal portland cement.

Although the durability of all mixes was exceptional, there was enough difference in results of laboratory freezing and thawing tests to show that the reduction in durability index in beams containing normal portland cement was at least two times and approximately as much as ten times as great as the loss for beams with other cements and cement combinations (measured by change in modulus of rupture). All mixes averaged 430 or more cycles with a maximum reduction in modulus of rupture of 61.6 percent or 14.3 percent per 100 cycles. In contrast, the mix with portland cement and limestone aggregate on the Falmouth-Cynthiana Road averaged only 117 cycles with 63.7 percent reduction in modulus of rupture or 54.4 percent per 100 cycles.

In further contrast with the concrete on the Falmouth-Cynthiana Road (for which high strengths despite great strength reductions were noted on page 33), the average flexural strengths were from 0.4 to 24.0 percent higher than those of corresponding mixes on the Falmouth-Cynthiana Road. Low and high values here were 1054 and 1233 lbs. per sq. in. respectively, while on the Falmouth-Cynthiana Road they were 862 and 1087 lbs. per sq. in. for mixes with limestone aggregate or 787 and 1113 lbs. per sq. in. for mixes with gravel aggregate. Compressive strengths of cores ranged from 15 percent lower to about 16 percent higher than those for similar mixes with limestone on the Falmouth-Cynthiana project. The lowest average strength, 5760 lbs. per sq. in. for the mixes with normal portland cement, was determined as an average for five samples and thus should be reliable.

Because of the superlative combination of durability and strength characteristic of all mixes in this project, distinctive qualities for the various groups could hardly be extracted from the data. Generally, among themselves and not comparative with mixes in other projects, they were as follows:

1. Normal portland (Section 5). Poor durability; high flexural strength, low compressive strength.

2. Blend 5:1, normal portland and natural (Section 4). Fair durability; exceptionally high flexural strength (no reduction), considerable reduction in compressive strength.

3. Blend 5:1, portland with interground Vinsol resin and natural (Section 2). Durability good; considerable reduction in flexural strength, increase in compressive strength.

4. Portland with interground Vinsol resin (Section 1). Excellent durability; moderate reduction in flexural strength, increase in compressive strength.

5. Blend 5:1 normal portland and natural with a grinding aid (Section 3). Fair durability; considerable decrease in flexural strength; moderate decrease in compressive strength.

While the subgrade factor may be of great importance in the actual life of the pavement, this could have no bearing on samples prepared in the field but tested in the laboratory. As such, the laboratory data emphasize the importance of constituents other than cement in these concrete mixes, and serve as a reminder that air-entrainment (important though it is) may in many instances be subordinate to proper selection of component materials such as coarse aggregate.

Project F.A. 79 B(5)D(4), Louisville-Elizabethtown Road. In brief, the long-time exposure on samples poured during the construction of this road demonstrates that simple exposure on the roof of the laboratory was not comparable with accelerated tests nor with exposure in the road itself. However, it could possibly be representative of actual exposure in structures.

Initial tests in 1943 resulted in an average modulus of rupture for control specimens (not exposed to freezing and thawing) of 921 lbs. per sq. in., while the average modulus for corresponding samples subjected to 160 cycles of freezing and thawing (accelerated in air and water) was 379 lbs. per sq. in. - a reduction in strength of 58.9 percent or 36.8 percent per 100 cycles. Following that, a set of four samples was tested each year for the past three years, with the following results:

Year tested	Years of exposure	Modulus of rupture lbs. per sq. in.	Percent change in modulus
1944	1	859	- 6.7
1945	2	863	- 6.3
1946	3	1062	+15.3

all samples having been exposed on the roof of the laboratory with all faces exposed and free drainage.

The change in modulus for samples tested in 1946 appears to be unreasonably abrupt and hence open to question despite the fact that four samples taken at random were tested to provide an average. Nevertheless, it is hardly conceivable that there could have been an appreciable reduction in strength had any other or all samples been tested and the results averaged.

If about 55 cycles of natural freezing and thawing had occurred during each of the three years as indicated by temperature records (see Appendix A), then about 165 cycles of this exposure caused relative little or no damage to the concrete whereas 160 cycles of accelerated testing reduced the strength 58.9 percent. Naturally less rigorous exposure and consequent deterioration of the beams would result from on-the-roof storage as compared with thawing in a water bath, yet the actual environment for a pavement slab would certainly be somewhere between the two extremes.

In view of these results and conditions, it is proposed that the remaining samples for this experiment be divided so that half are embedded in a soil-filled container with only one of the beam surfaces open to air, while the other half are exposed as in the past. Thereby, a comparison can be made between the two methods and conclusions drawn regarding the efficacy of each type of exposure.

Laboratory Projects

Direct comparisons between results of tests on samples prepared in the field versus those made in the laboratory are hardly feasible despite uniformity of techniques applied in freezing and thawing exposure and fairly definite relationships attendant to loading tests on beams. For all beam specimens poured in the field on experimental jobs, center loading was used whereas all laboratory beams were tested with third-point loading. This situation alone does not prevent direct comparisons because laboratory tests (Research Project C-11, reported in December, 1943) have shown that the actual developed stress obtained by third-point loading is approximately 0.8 that determined by center loading.

It is a combination of other minor but indeterminate factors that makes the relative value of the different beams indefinite. Samples poured on the construction projects were not stored in an atmosphere of constant moisture and temperature as were the laboratory specimens; the former were always much older than the latter when freezing and thawing tests were started; field samples were immersed in water for seven days preceding the first freeze while laboratory samples were taken from the moist room and subjected to freezing and thawing without an interim for absorption; and the care and control given to field samples was without doubt inferior to that given to the laboratory samples.

None of these relationships has a particular bearing on the relative merits of air entrainment, but any or all could have considerable influence on the validity of direct comparisons between the two types of samples. Should such a comparison be desirable, as it may be in an evaluation of aggregate variables, probably the results of tests on laboratory samples should be modified to compensate for the advantageous treatment given those specimens.

Research Project C-13. As noted in the description of this project on pages 12 and 13, both normal portland and the 5:1 blend of portland and natural with a grinding aid were applied to an "inferior" coarse aggregate with two gradations. Percentages of air entrained, as calculated by the gravimetric method (A.S.T.M. Designation: C 138-44), were not high. See tabulation on page 43. The fine aggregate, aside from cases where 15 percent stone passed the No. 4, was Ohio River sand throughout.

Initial strengths on control specimens were relatively low but losses in strength due to air entrainment were generally small or even a gain in strength occurred. On beams 5 x 6 inches in cross section - which approximated the dimensions of beams poured on the experimental road projects - average initial moduli of rupture for the two mixes with coarse aggregates No. 1 and No. 2 and normal portland cement were 613 and 690 lbs. per sq. in. respectively, while corresponding mixes with air entrained had flexural strengths of 653 and 547 lbs. per sq. in. respectively.

These beams were tested by third-point loading whereas the field beams were tested with center loading; hence, if the equalizing formula (stress third-point loading = 0.8 stress center loading) is applied, the strengths of these beams with normal portland are almost equal to those for beams from Section 3B on the Louisville-Elizabethtown Road as tabulated on Plate I. Furthermore, the beams with blended cements tested in this experiment had adjusted strengths greater than those representing similar mixes in Section 7 of the Louisville-Eliza-

Bethtown experimental road. The fact that percentages of air entrained on the field project were from about one to more than two percent higher than on the laboratory project should not be overlooked as an influence favorable to the laboratory beams.

In opposition to the losses in strength approximating six percent*, there were distinct increases in the durability of the concrete when air was entrained. In fact, for three of the four groups of specimens containing the cement blend the strengths after 500 cycles of freezing and thawing were from 5 to 18 percent higher than those for corresponding control specimens. In other words, freezing and thawing improved the quality of the concrete containing this "inferior" coarse aggregate when the concrete had a considerable amount of air entrained.

Contrary to this, the mixes with normal portland cement lost from 6 to 87 percent strength after exposure to freezing and thawing from 256 to 500 cycles. The corresponding rates of deterioration (reduction in strength per 100 cycles) were from 1.8 to 27.8 percent per 100 cycles. In summary, the relationships of average durability factors is as tabulated below:

Limestone Aggregate	Cement	Percent Air	Durability Factor: Percent change in Modulus of Rupture per 100 cycles	
			5 x 6 beams	3 x 5 beams
100 percent retained on No. 4	Normal portland	0.6	-1.8	-25.4
	Blend	3.9	+3.7	+ 1.3
85 percent retained on No. 4	Normal portland	0.1	-27.8	-26.7
	Blend	2.2	+ 0.9	- 5.2

*Actually, tests on 5x6 inch beams indicated that air entrainment caused an increase in strength of 6.5 percent for samples with 100 percent limestone larger than the No. 4 sieve. On the other hand, 3x5 inch beams indicated a reduction of 22.2 percent for samples with 85 percent limestone retained on the No. 4. There is no reason to discard these results as being erroneous, yet it is probable that they were extreme and not representative.

Reference should be made to Table II of a former report by Collier (17) for details of variations among samples in the separate groups.

Despite pronounced variations in these results, there can be little doubt that the air-entrained concrete was far superior to the normal concrete. So far as the two gradations of aggregate were concerned, the addition of crushed limestone fines in the mix was not beneficial but rather slightly detrimental. Since this limestone was known to be of poor quality and not acceptable under existing specifications, the possibilities of using air entrainment to produce better concrete where the aggregates are questionable are greatly enhanced if these results are a valid indicator.

<u>Research Project C-16</u>. With its variety of air entraining materials, calculated air contents, and aggregate combinations, Research Project C-16 provided a broader basis for estimating the benefits and detriments of air entrainment than did any previous experiment. Even here, where laboratory control was available, there were some indicated deficiencies which must be abolished if a scientific design and production of air entraining concrete is to be accomplished consistently.

Outstanding among these deficiencies was the percentage of air calculated from the measured (actual) and calculated (theoretical) weights of green concrete. As listed in Table IV, those percentages of entrained air ranged from 1.56 to 7.40, both of which are extraordinary. Although there is no conclusive reason for condemning determinations of air content in normal portland cement concrete that are invariably above 1.5 percent, there is reason to question the efficacy of methods for making the determinations when the usual air content is less than one percent. This is particularly so when the personnel and equipment involved are good and reliable.

TABLE V - ADJUSTED STRENGTHS AND CALCULATED REDUCTIONS IN STRENGTHS FOR MIXES IN RESEARCH PROJECT C-16

Group	Series	Cement Composition	Pct. Air	Adjusted Strength		Percent Reduction in Strength		F&T Cycles Completed	Pct. Reduction in Modulus of Rupture	
				Compressive	Flexural	Compressive	Flexural		Total	Per 100 cycles
1.	(A)	Normal portland	1.56	5430	910	-	-	237	75.8	32.0
	(C)	Portland with HP-7	7.40	4750	825	12.5	9.3	383	66.3	17.3
	(E)	Portland and Vinsol resin - NaOH Solution	3.85	4820	817	11.2	10.2	493	53.8	10.9
	(G)	Portland with inter-ground Vinsol resin	2.40	5350	998	1.5	+ 9.7	225	75.1	33.4
	(I)	Blend - Portland and natural with G.A.	5.8	3940	732	27.4	19.5	412	60.3	14.6
2.	(B)	Normal portland	1.65	4640	851	-	-	500	31.2	6.3
	(D)	Portland with HP-7	7.37	4270	809	8.0	4.9	500	42.6	8.5
	(F)	Portland and Vinsol resin - NaOH Solution	4.51	4170	761	10.0	10.6	-	-	-
	(H)	Portland with inter-ground Vinsol resin	2.11	4810	822	3.6	3.4	413	61.4	14.9
	(J)	Blend - Portland and natural with G.A.	5.98	3450	744	25.4	12.6	489	55.2	11.3
3.	(K)	Normal portland	1.87	4260	779	-	-	487	23.7	4.4
	(L)	Portland with HP-7	6.67	4020	734	13.3	13.7	487	26.3	5.4
	(M)	Portland and Vinsol resin - NaOH Solution	4.59	4350	835	6.2	1.9	485	29.1	6.0
	(N)	Portland with inter-ground Vinsol resin	2.28	5170	912	+11.4	+ 7.2	485	32.5	6.7
	(P)	Blend - Portland and natural with G. A.	6.52	3620	656	22.0	22.9	483	18.7	3.9
	(Q)	Portland with inter-ground Darex	4.20	4610	748	0.6	12.1	443	27.7	6.3
	(R)	Normal Portland and Soap Solution	6.77	3180	559	31.7	34.3	411	17.4	4.2

In a manner somewhat similar to this critical feature, the data show that the properties of air entraining concrete varied when mixes were not adjusted for air resulting in under-run on the cement content. In this experiment the nearest approximation to a six bag mix was one with 5.98 bags and the most remote was 5.58 bags. Accordingly, the strengths varied greatly and undoubtedly durability suffered also. In all comparative strength relationships such as those listed in Table V or plotted in the summary chart Fig. 25, the strengths were adjusted proportionately so that the comparative strength was one estimated for the mix if it had a cement content of six sacks per yard. For example, the mix for series B (Table IV) had a cement content of 5.78 bags per cubic yard and an actual compressive strength of 4453 lbs. per sq. in., hence, the adjusted comparative strength was (6.0/5.78) x 4453 = 4630 lbs. per sq. in.

Results of these tests brought out marked effects of the three aggregate combinations* on concrete durability and strength. Those mixes containing the acceptable (No. 3) aggregate were consistently more durable than corresponding mixes with either of the other aggregates. In addition, the beams containing the unacceptable limestone with 15 percent fines had a better record than the beams with the same stone having 100 percent retained on the No. 4 sieve.

Contrary to trends in other projects, there was no pronounced inferiority of concrete with normal portland cement insofar as durability was concerned. Actually, in each of the three groups of mixes there was always some combination which had a greater reduction in modulus of rupture per 100 cycles than did the correlative mix ...

*See pp. 13-14. In Table IV these are referred to as aggregates No. 1 (limestone which was not acceptable under existing specifications), No. 2 (limestone from the same source as No. 1 but having 15 percent fines passing the No. 4 sieve), and No. 3 (limestone acceptable under specifications and having a good service record). Fine aggregate was river sand throughout.

with normal portland. The numer of cycles alone was not indicative of durability unless the cycles completed totaled less than 400. The reason for this is that some samples were made later than others and hence at any given time had not been exposed as long to freezing and thawing. Since the experiment was arbitrarily stopped within the past month in order that results could be included in this report, some beams which were carried for slightly more than 400 cycles might have completed 500 cycles had the test been continued.

Once again, the relationship between percentage of air entrained and durability value was not consistent, thus indicating that there was some difference in the efficiency of different materials for accomplishing durability irregardless of the amount of air trapped. In a brief form, the durability indexes (percentage reduction in modulus of rupture per 100 cycles) as well as adjusted strengths and strength reductions due to air entrainment are summarized in Table V. Further and more distinct comparisons of durability factors can be made through reference to the bar graph of Fig. 24.

From almost every standpoint, the group of mixes having the poorest durability record (those containing aggregate No. 1) had the best record so far as initial compressive and flexural strengths were concerned. Compressive strengths for samples containing aggregate No. 1 were from 10.1 to 14.5 percent higher than those for corresponding samples containing aggregate No. 2 and from 3.4 to 21.6 percent higher than those for samples with aggregate No. 3 (the only aggregate acceptable under specifications). Similarly, flexural strengths for mixes with aggregate No. 1 were from 1.6 percent lower to 17.6 percent higher than those representing mixes with aggregate No. 2 and from 2.2 percent lower to 14.4 percent higher than those where aggregate No. 3 was used. The specific relationships among these strengths as they varied with cement composition were:

Cement Composition	Pctg. Decrease or Increase from Strength of Corresponding Samples with Aggregate No. 1			
	Compressive Strength		Flexural Strength	
	Agg. No. 2	Agg. No. 3	Agg. No. 2	Agg. No. 3
Normal portland	-14.5	-21.6	- 5.6	-14.4
Portland with HP-7	-10.1	-15.4	- 1.9	-11.0
Portland with Vinsol resin - NaOH Solution	-13.5	- 9.7	- 6.9	+ 2.2
Portland with Vinsol resin interground	-10.1	- 3.4	-17.6	- 8.6
Blend - Portland and natural with G. A.	-12.4	- 8.1	+ 1.6	-10.4

Actually, the adjusted flexural strengths of these samples - adjusted for the relationship between third-point and center-point loading - indicated that the quality of mixes with aggregate No. 1 was somewhere between those for comparable mixes with limestone used on the Louisville-Cincinnati Road and the Falmouth-Cynthiana Road; compressive strengths gave about the same indication when the cement was portland with interground Vinsol resin. Also, allowances must be made for air contents which in this project were generally much higher than in any of the field projects.

From the standpoint of durability, Fig. 24 shows that the resistance of samples with aggregate No. 3 approached that of samples from the Louisville-Cincinnati Road, but that the mixes with aggregates No. 1 and No. 2 were much poorer in quality although in some instances better than similar mixes poured in the Falmouth-Cynthiana Road. With regard to the several compositions of cement, the variations in mixes were about as follows:

1. Normal Portland. Durability low with aggregate No. 1 but good with aggregate No. 2 and No. 3. Strength high with aggregate No. 1 and moderate with aggregates No. 2 and No. 3. Calculated percentage of air entrained higher than normally expected.

2. Portland with HP-7. Durability fair with aggregate No. 1 and good with aggregates No. 2 and No. 3. Fair reduction in strength with aggregate No. 2 and moderate reduction with aggregates No. 1 and No. 3. Percentage of air entrained higher than amount usually permissible.

3. Portland with neutralized Vinsol resin. Durability moderate with aggregate No. 1 and good with aggregate No. 3 (no results with aggregate No. 2). Moderate reductions in strength with aggregates No. 1 and No. 2, slight reduction with aggregate No. 3. Percentage of air entrained - good.

4. Portland with interground Vinsol resin. Durability low with aggregate No. 1, moderate with aggregate No. 2, and good with aggregate No. 3. Slight reductions to marked increases in strength for all cases. Percentages of air entrained low - below the amount usually permissible.

5. Blend 5:1, normal portland and natural with a grinding aid. Durability moderate with aggregates No. 1 and No. 2 and excellent with aggregate No. 3. Reductions in strength extreme in all cases. Air entrainment high - in all cases, at or near the upper limit usually specified.

6. Portland with interground Darex. Durability good, strength reduction slight to moderate. Percentage of air entrained - good. (Used only with aggregate No. 3).

7. Portland with a soap solution. Durability good bordering on excellent. Strength reduction excessive. Percentage of air entrained high - above permissible upper limit. (Used only with aggregate No. 3).

Incidental Data, Measurements, and Tests

Determinations of air content made incidental to the primary investigations of air entrainment were too abbreviated to be conclusive. These consisted of laboratory measurements related to Research Project C-22 (A Study of Combined Coarse Aggregates In Concrete) and to the materials now being used on the Lexington-Nicholasville Road, Project

TABLE VI - CALCULATED AND MEASURED WEIGHTS AND AIR CONTENTS FOR REPRESENTATIVE CONCRETE USED IN LABORATORY PROJECT C-22 AND IN THE LEXINGTON-NICHOLASVILLE ROAD

Project	Designation	Cement	Actual Wt. of Concrete lb/cu. ft.	Wt. of Solid Concrete on Air Free Basis		Air Content		
				Calculated (Gravimetric)	Measured (Indiana)	Gravimetric	Indiana	Pressure
Lab. Proj. C-22 Study of Combined Aggregates	I-C	Portland with neutralized Vinsol resin	147.30 147.00 148.22	153.25 153.72 153.72	152.63 153.23 153.64	3.88 4.37 3.58	3.44 4.07 3.53	
	I-D	Portland with neutralized Vinsol resin	147.60 148.00 147.00	154.54 154.54 154.54	155.77 159.17* 154.66	4.49 4.00 4.62	5.24 7.04 4.95	
	I-E	Normal portland	150.1 150.80 150.6	154.17 154.20 154.17	155.40 155.90 156.00	2.60 2.20 2.7	3.40 3.30 3.5	
Proj. F 524 (1)-1; S.P. 34-124 Lexington-Nicholasville Road	Laboratory**	Normal portland	154.80 154.60 153.60 153.60		155.2 155.1 155.3 154.9		0.26 0.32 1.09 0.84	
		Portland with interground Vinsol resin	150.40 150.40 149.30 150.40		155.9 155.8 156.0 157.7		3.53 3.47 4.29 4.63	
	Field	Portland with interground Vinsol resin	150.0 149.6 148.6	155.10 155.10 155.10		3.3 3.5 4.2		3.2 4.0 4.2

* Obvious error in weighing
** Determinations made in Research Laboratory by Testing Laboratory Staff

F 524(1)-1, S.P. 23-124. The objective of the tests was to compare results of air content measurements by the gravimetric method (A.S.T.M. Designation C 138-44) with those by the volumetric or Indiana method (see Appendix B), and the pressure method, and thus estimate the feasibility of specifying and controlling air-entraining concrete by air contents rather than drop in weight.

The first group of tests, as listed in Table VI, included sets of three specimens from each of three series having different coarse aggregate combinations and representing each of the two cements - normal portland and portland with a neutralized Vinsol resin solution added. From any given batch, determination of theoretical weight of concrete computed on an air free basis and of the actual weight of an equal volume of the concrete were made and the resultant air content figured. Material from the same batch was also tested by the Indiana method, and the two resultant air contents compared.

In a similar manner, determinations with the volumetric procedure were made in the Research Laboratory by the Testing Laboratory staff preparatory to the pouring of concrete on the Lexington-Nicholasville Road, and during a day's pour on this job pressure measurements by a representative of the Portland Cement Association and gravimetric determination by the Research Laboratory were made simultaneously. Here normal portland and portland with interground Vinsol resin were used with one coarse aggregate.

Although there was seldom a great difference between air contents determined by gravimetric versus volumetric methods, the computations showed that results of the Indiana method could vary considerably unless weight measurements were precise. In fact, calculations from tests on materials for the Lexington-Nicholasville Road revealed that at one point - weighing of the concrete sample prior to inundation - an error of about 0.3 percent could make a difference of about 0.8 percent in the computed air content. Ordinarily, the sample would weigh about 30 to 35 pounds, hence an error of approximately 0.1 pound in weighing would be sufficient to vary the air content beyond permissible limits, especially if specifications and control were placed on that basis. Such precision on 100 pound scales is practicable when weighing is done in the laboratory, but whether it can be accomplished consistently in the field is questionable.

With no more than reasonable care given to weight measurements, the results of three gravimetric tests made simultaneously with pressure tests on the Lexington-Nicholasville Road were gratifying. Maximum discrepancy was 0.5 percent in air content which, considering the scales used, was reasonable. By the same token, the pressure apparatus gave promising results at least from the standpoint of corresponding with those obtained by the new method now required in specifications.

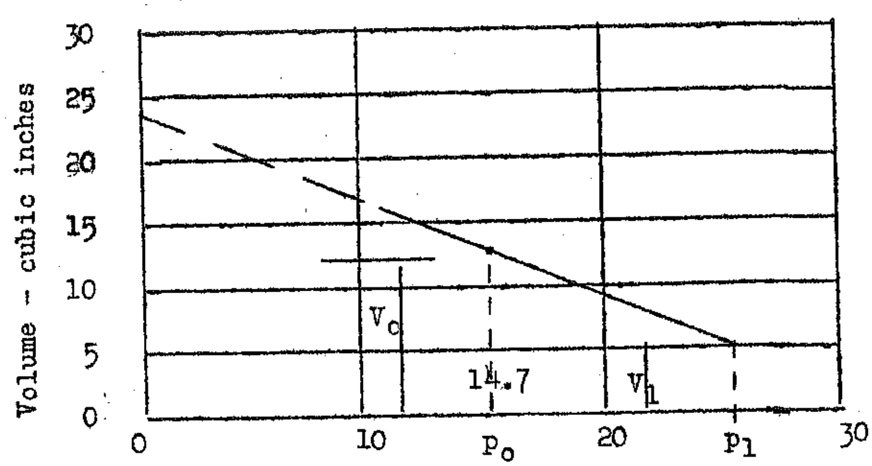

Fig. 17 Illustrative Diagram of Theoretical Pressure-Volume Relationships Pertaining to Air Entrapped in Concrete

The pressure method utlizes that property of gases whereby at any given temperature the volume varies inversely with the pressure. Since all components of a concrete mix (except the air entrapped) are incompressible or practically so, theoretically a group of pressure-volume relationships could be made from which the volume corresponding to zero pressure could be extrapolated. A hypothetical solution is depicted in Fig. 17.

where p_1 represents the pressure applied in the test (p_0 is atmospheric pressure) and V_1 represents the volume of air corresponding to p_1. The initial volume of air at atmospheric pressure, V_0, is the value which is of interest. Actually, the reading on the water column in the apparatus represents differential volume displacement, V_1-V_0, but since the volume of concrete tested is constant, the gauge may be calibrated so that not only V_0 can be represented but actually the air content on a percentage basis can be read directly from the gauge. No specific gravities or other properties need be known, and the volume of concrete in the pressure vessel can vary considerably without seriously affecting the result. Hence, the test need not require skilled or extremely competent personnel.

Other auxiliary data pertinent to this analysis but extraneous to these projects were accidentally discovered through microscopic study of small samples broken from beams poured for laboratory project C-22. There different concrete mixes were made and are now being investigated principally from the standpoint of combined coarse aggregates although both air-entraining and non air-entraining cements are involved. Samples were taken from a set of beams representing one design mix but poured from three or four different batches, these beams being control samples broken at twenty-eight days and not exposed to freezing and thawing.

Four different sets were sampled. Cement and aggregates represented in the sets were as follows:

A. Normal portland cement with 100 percent gravel (No. 6) coarse aggregate.

B. Portland and Vinsol rosin-NaOH solution with 100 percent gravel coarse aggregate.

C. Portland and Vinsol resin-NaOH solution with 20 percent limestone (No. 3) and 80 percent gravel (No. 6).

D. Portland and Vinsol resin-NaOH solution with 40 percent limestone and 60 percent gravel.

The samples - broken from the beams with a hammer - were about the size of a nickel or quarter dollar coin. There was no selective sampling with regard to either the beams taken or the samples observed, for each group was represented by at least twenty of the small chips. A picture of the microscope - camera arrangement used for this study is shown in Fig. 18.

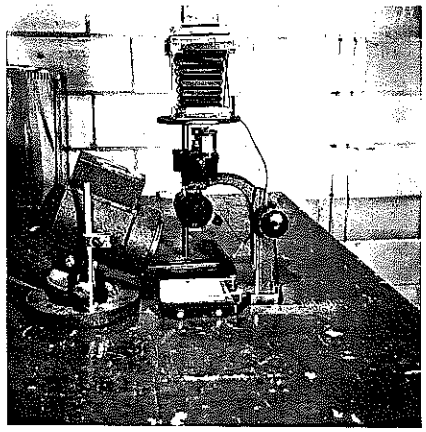

Fig. 18- Arrangement of microscope and camera for making the photographs on Plate III. The concrete specimen can be seen in dim outline on the white plate at the base of the microscope.

Plate III contains photomicrographs of three representative photographs from each of the four sets, and a scale is included as well. Magnification in all cases is approximately ten diameters, hence, the scale in Fig. 20, where each division unmagnified was 1/16 inch, can be applied directly to the other enlargements.

Fig. 19, comprising three photographs of samples from Group A, shows that the concrete with normal portland cement had few voids discernible under this magnification, whereas the air-entrained concrete of Groups B, C, and D, represented by Figs. 21, 22, and 23, had numerous voids of varying size. If not evident in these photographs, it was certainly evident in the actual microscopic views of the samples that these were not cavities from which particles of aggregate had been pulled as the samples were broken from the beams.

Some significance can be given to these photomicrographs in that they give a new and better description of possible distribution of air than has been presented heretofore. The prevailing conception is that air is dispersed in extremely minute - almost infinitesimal - bubbles throughout fresh concrete; perhaps this is partially correct but not entirely so, if the evidence contained in Plate III is moderately representative of all air-entraining and normal concrete. Also, these patterns and the voids observed thereon, may provide an answer to reduced strengths in air-entraining concrete - reduction in strength being dependent upon reduction in effective cross section.

Summary

Throughout the discussion of results thus far, individual analyses have been made for each experiment; comparisons among similar features in different projects have been noted; and, most important of all, limitations as well as applications of the data have been emphasized. To bring this mass of observations and numerical results into sharp focus through an abbreviated form, several of the important relationships unencumbered by qualifying statements and conditions are listed below.

Graphical illustrations of relative durability characteristics in Fig. 24, actual average strengths in Fig. 25, and strength reduction characteristics in Fig. 26, should facilitate correlation as will the notations calling attention to certain pages where features in question have been discussed more fully. Hence, the reader is referred to the expanded discussions which preceded this summary when and where detailed explanations are of interest.

Within the limits imposed by test conditions, the essence of results from these several experiments was:

1. Outward appearances of the field experimental sections were so uniform that differences among the sections or even among the separate projects could not be detected with certainty. Probably this was due to the fact that none of these projects was more than six years old - an insufficient length of time for durability characteristics to become apparent.

2. With but two exceptions, concrete containing normal portland cement was not as durable as correlative mixes having cements of an air-entraining nature (see Fig. 24). Often but not always, the mixes containing a 5:1 blend of portland and natural without a grinding aid were also inferior in durability characteristics. This could be expected, since the percentage air entrained in this type of mix was seldom much greater and often less than that in corresponding mixes with normal portland cement.

3. Relative efficiency of different mixtures for entraining air and promoting durability varied considerably throughout the different projects (see Fig. 24). Summaries applicable to the separate experiments should be consulted (pages 23, 34, 39 and 48) for general descriptions of those variations.

4. In the majority of cases, air entrainment caused a decrease in the strength of concrete; i.e. concrete with an air-entraining cement or with an appreciable amount of air entrained was weaker than concrete with normal portland cement, all other constituents being the same (see Fig. 25). Where increases in strength were indicated, there was a possibility but no definite evidence that samples with normal portland cement were inordinately weak.

5. The relationship between calculated or estimated air content and reduction in strength was not constant (see Fig. 26). However, there was a persistent tendency on the part of some materials to cause greater strength reductions than did others. Outstanding in this respect was the blend 5:1 of portland and natural with the grinding aids incorporated in cement for these experiments.

6. If values of permissible strength reductions set forth in Highway Research Board, <u>Current Road Problems</u>, Bulletin No. 13 (18, p.9), are used as a criterion, most of the mixes in these projects were satisfactory even when air contents were greater than six percent (see Figs. 25 and 26).

7. On the basis of average values of deformation and number of stress reversals withstood, the fatigue resistance of samples with a 5:1 blend of portland and natural with a grinding aid was highest and that of the 5:1 blend of portland and natural was lowest of all mixes tested in conjunction with Project FA 79 D(2)S, Louisville-Elizabethtown Road. Actually, only the one mix containing a 5:1 blend of portland with interground Vinsol resin and natural with a grinding aid had more fatigue resistance than the concrete with normal portland for all conditions of loading. (See Plate II and page 23).

8. More outstanding and more definite than any of the data regarding the effect of entrained air were the indicated effects of coarse aggregates. Contrasts in durability characteristics were so great (see Fig. 24) that the least durable mix in at least two instances was more than twice as resistant to freezing and thawing than the most durable mix in another project. Among these relationships were:

a. Crushed limestone used on the Louisville-Cincinnati Road had an excellent record from the standpoint of both durability and strength (See Figs. 24 and 25 and page 38).

b. Crushed limestone from Source 2 in Laboratory Project C-16 was excellent from the standpoint of durability but fair from the standpoint of strength. (See Fig. 24, Fig. 25, and pages 45 and 47).

c. The gravel used on the Falmouth-Cynthiana Road was inherently more durable in this concrete than was the limestone used on the same project, even though air entrainment provided more protection for the mixes with limestone. (See Fig. 24 and page 34).

d. Limestone used on the Louisville-Elizabethtown Road, Project FA 79 D(2)S, had a poor record from the standpoint of both durability and strength. (See Fig. 24 and Fig. 25).

9. While air entrainment in the majority of cases was definitely beneficial to concrete containing indicated good or fair coarse aggregate (less beneficial for the good than for the fair), much more benefit was derived by the concrete with known poor aggregate. In laboratory project C-13, the strength of beams after exposure to freezing and thawing was much reduced when normal portland cement was used, but when beams with similar aggregates and air-entraining cements were tested the strengths increased after exposure to freezing and thawing (see page 43). This phenomenon was observed in only one other instance; that of the mixes on the Falmouth-Cynthiana Road containing gravel coarse aggregate and a 5:1 blend of portland and natural with a grinding aid (see Fig. 24, Appendix C, and page 34).

10. Beams of air-entraining concrete stored on the roof of the laboraotory with all faces exposed suffered little or none from the attendant freezing and thawing. Strengths of a set of beams tested for 160 cycles of laboratory freezing and thawing were greatly reduced, whereas corresponding samples exposed for about 165 cycles or three years (see Appendix A) on the roof were practically unaffected (see page 40).

11. Calculations of air content by the methods ordinarily used were dubious particularly when made in the field. Although the few

tests made indicated that reasonably comparable results could be obtained by the gravimetric (A.S.T.M. Designation C 138-44) and the volumetric or Indiana methods (see Appendix B), the potentiality for errors with the latter was shown to be great especially in field determinations (see page 50 and Table VI). Limited tests using the pressure method gave results that corresponded well with those obtained by the gravimetric method.

12. Contrary to the usual conception of air entrainment in "minute disconnected bubbles", at least a portion of the trapped air in specimens from Laboratory Project C-22 was in a form such that resulting voids could be readily seen under a microscope with about ten diameters enlargement. (See Plate III).

13. An average of about 55 freezing and thawing cycles occur per year in the central and eastern portion of Kentucky. (See Appendix A).

CONCLUSIONS AND RECOMMENDATIONS

The principal advantage ordinarily attributed to air entrainment is the improvement in durability characteristics of concrete brought about by the entrapped air. Without doubt, this can be accomplished in most if not all cases, if durability is judged as resistance to freezing and thawing by laboratory methods. From the standpoint of actual field exposure evidence is not so conclusive; however, if the premise upon which laboratory tests are based is applied to the field there are reasons to believe that direct correlation is valid. Despite the fact that general weather conditions in Kentucky are moderate, precipitation is far above average for states in this latitude and temperatures fluctuate often and over a broad range throughout an average winter. These, combined with soils (which often inhibit drainage and thus retain moisture to intensify the effects of freezing) prevailing in this state, constitute vigorous exposure for pavement slabs. That being the case, air entrainment in concrete pavements is desirable and advantageous from the standpoint of durability alone.

There are other factors which favor concrete with air entrained. Although not revealed numerically or graphically in the data of this report, pouring of concrete on construction projects and in the laboratory as well, showed that the material was more workable and far less subject to segregation and bleeding than was normal concrete. Also, not only does it permit but it demands finishing within a short time after placement, a feature which could have two advantages: All operations on a job are condensed thus facilitating supervision and inspection; and, in the fall when the rate of evaporation is low and time is usually critical, normal pouring can be extended later in the day eliminating a great allowance for time lag in finishing.

In addition to these, air entrainment improves the quality of concrete containing a low-grade coarse aggregate in at least some cases. Evidently this isn't universally true, but on the other hand there is no evidence that or any reason why air entrainment should be detrimental in concrete with aggregate of this type unless it be the reduction of a strength which would not be high at best. If increased durability more than compensates for loss in strength, it seems possible that where necessity dictates unfavorable aggregates may be used to make favorable concrete; or conversely, when an inferior aggregate becomes mixed with one of better quality (as they often do from even the best of sources and under ordinary conditions), air entrainment offers a protection or insurance against detrimental effects of the inferior material.

The outstanding disadvantage of air entrainment is the reduction in strength (over that of normal concrete) which almost invariably results. This is accentuated by difficulties in adjusting the mix for entrapped air which as it varies causes variable cement and water contents. Thus, control is more important and more difficult with air entrainment than without. Also, a portion of the finishing operation is complicated by this type of mix because the concrete tears under the screeds of a machine; yet, the total amount of work required for finishing is reduced by air entrainment.

About the only possibility of overcoming the detriments of variable air contents which necessitate adjustment of the mix is to make many determinations to keep the best control possible.

Even so, the proportions of ingredients cannot be kept as constant in air entraining concrete as in normal concrete. In conjunction with this, constant control and adjustment of the mix may lessen the amount of strength reduction by keeping the cement content and water-cement ratio at or near the proper levels. Probably reductions in initial strength would generally occur even with the best of control, but this would become of little consequence after the pavement had been exposed for a few years, at which time the superior durability of the air-entrained concrete would become manifest as a strength higher than that of normal concrete under similar conditions. Thus, the concrete with air entrainment would have the greater strength at a time when strength is probably of most importance.

In view of these conditions, it is recommended that air-entrainment be specified for all future pavements of cement concrete built in all parts of the state. Futhermore, bridge decks and railings as well as other portions of structures exposed in a similar way should always have the protection afforded by air entrainment. Critical situations are pier and abutment caps and wing walls or retaining walls, all of which in existing structures have shown the results of detrimental exposure. Practical accomplishment of this, if air entrainment is not used for all structural concrete, may require pouring the major portion of an installation with normal portland-cement concrete, with the top two or three feet being finished with concrete containing an air-entraining agent added at the mixer.

Actually, the ordinary objection to air-entrainment in all structural concrete - reductions in strength or lack of accurate control over strength - is invalidated by the data of this report. Without doubt, it has been shown that materials other than the cements can have more influence on strength than the cement or anything added to it for the purpose of entraining air. Thus, the strengths of normal concrete containing one coarse aggregate may be (and were actually shown to be) far below those of concrete containing another coarse aggregate and having air-entrainment that caused a large percentage reduction in strength. In other words, some aggregate constituents can be much more important than cement in actually providing a strength acceptable in structural concrete. Since the mere fact that no air entrainment is included does not assure a high strength, since the strength of even the poorer mixes is almost invariably far above that acceptable for design, and since air entrainment does improve workability and thus facilitates placement of concrete in the forms, this type of concrete should be seriously considered even in parts of structures where durability has appeared to be unimportant heretofore.

Because of the variations in materials and proportions of materials usually attendant to air entrainment, specified limits in air contents are preferable to specified limits for drop-in-weight. Weights of concrete with normal portland cement are far from constant when measured in the field or in the laboratory for that matter, hence there is no absolute or unchanging basis upon which to calculate drop-in-weight. Furthermore, both the improved durability and reduction in strength are dependent upon entrainment of air, so it is important to specify acceptable maximum and minimum air contents and require that they be met.

The range usually considered best for durability without excessive strength reduction is from 3 to 6 percent air entrapped. Without particularly controverting these stipulations, the results of this group of tests suggested that in some situations an air content above 6 percent would not cause too much reduction in strength, whereas in other cases an air content as low as 2-1/2 percent would result in an inordinate strength loss. In contrast, there were many instances where favorable durability characteristics were obtained although the calculated amounts of air entrained were less than 3 percent. These discordant features indicate that different combinations of materials are suited to different limits on air content, but the data provide no valid basis for establihsing limits applicable to different materials nor do they provide definite means for revising the general limits ordinarily applied at present. That being the case, it is recommended that air contents between 3 and 6 percent by volume be considered acceptable.

Practicable specifications and control on this basis are dependent upon a reliable procedure for determining the volume of air entrapped. The volumetric or Indiana method is inadequate, but the gravimetric method (A.S.T.M. Designation: C 138-44) gives reasonable accuracy if care is taken in making the measurements. However, any procedure which is dependent upon physical properties of the constituents and which cannot adapt itself to the vicissitudes of batching that are always considerable on a construction job, will never be free from errors of some consequence. Therefore, the gravimetric method is recommended only for tentative use to be replaced by the pressure method if the latter is found to be accurate under all conditions.

One of the most important factors requiring attention is cement with the air-entraining material interground. At present, A.S.T.M. Designation: C 185-46T for measuring the air content of port land -cement mortar is a controlling feature in some states but in others failure to pass this test does not constitute basis for rejection. Essentially, a test with the Burmister flow trough specified by this Designation is a test for consistency of the mortar, at which consistency a determination of air content is made on a gravimetric basis. The latter part of this procedure is indirect and of questionable value, and it too should be replaced by the pressure method provided that method is found to give invariable results that can be checked by air contents in concrete made with the cements tested. There is no basis for judging the consistency measure at this time.

In addition to the air-entraining materials already permitted in the 1945 Standard Specifications, provision should be made to include others which have been or will be found satisfactory. For example, in laboratory project C-16, portland cement containing a material designated commercially as Darex interground was used in a series of tests and the resultant durability and efficiency of air entrainment were good yet the strength reduction was only slight to moderate. Use of the material as an admixture at the mixer has been reported unfavorably elsewhere.

Likewise, in the same laboratory project, mixes containing portland cement with HP-7 added at the mixer had good durability characteristics with no more than a moderate amount of strength reduction. This was so, despite the fact that the calculated percentage of air entrained was greater than 7 percent. On the basis of these records, it is recommended that Darex be accepted in the specifications as an interground material, and that HP-7 be accepted as an admix. Other materials should be given equal consideration but only after thorough investigation through research procedures.

Finally, the value of all research and all specifications and tests formulated through intensive study and consideration by division heads and their assistants will be largely wasted unless personnel charged with their application are thoroughly familiar with the properties of air entraining concrete and methods for its control. To accomplish this, it is proposed that a two or three day course in instruction and study be given at the Research Laboratory during the coming winter months. A suggested group to attend this includes district materials engineers, resident engineers who may be conducting projects of this type, technical inspectors or assistants who would be assigned to such work, and any others who may have a responsible part in carrying out the operations of control on the job. Instruction as such would be kept at a minimum, and little emphasis would be placed on the theoretical. Rather, most of the time would be given to demonstrations supplemented by operations of mixing, testing for weight and air content, and similar procedures in which all could participate.

As a minimum, the articles in the 1945 Standard Specifications affected by these recommended changes are:

4.1.6	Treated Portland Cement Concrete
4.1.7	Portland Cement - Natural Cement Blend Concrete
4.1.8	Portland Cement - Vinsol Resin Solution Concrete
7.1.4	Treated Portland Cement
7.1.5	Natural Cement
7.42.2	Vinsol Resin Solution

All these provisions are influenced by one of more of the recommendations which briefly and in review propose that:

1. Air entrained concrete be specified for all future pavements, bridge decks and railings, and other parts of structures that may suffer serious exposure. This

should apply throughout the state.

2. Specified air contents from 3 to 6 percent replace the 3 to 6 pound drop-in-weight set forth in the 1945 Standard Specifications.

3. The gravimetric method (A.S.T.M. Designation: C 138-44) be used only as a temporary expedient for determining air contents until the pressure method or some method not dependent upon physical properties of aggregates and not influenced by other variables can be firmly established.

4. Specifications for acceptance of air-entraining cements be made more rigid through elimination of at least a portion of the provisions of A.S.T.M. Designation: C 185-46T, and substitution of the pressure method or a known reliable method for arriving at the air content that can be expected in concrete made with the cement tested. Further research will be necessary to adapt a new method to the determination of air-entraining value of cements.

5. Darex as an interground material and HP-7 as an admix be included in the specifications as done with Vinsol resin in all the articles of 1945 Standard Specifications listed on page 65. In effect, this means a change in part from A.S.T.M. Designation C 175-42T to C 175-46 (See reference 18, p. 15), with additions included as well. The merits of other materials should be proved through research before being admitted to similar status.

6. A two or three day course of instruction and study be given for personnel who will be largely responsible for the application of specifications and tests to field construction, that course to be held at the Research Laboratory during the coming winter months.

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