INVESTIGATION OF VIBRATORY METHOD OF FINISHING CONCRETE PAVEMENT IN ILLINOIS

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SYNOPSIS

This investigation was conducted to study the practicability of the vibratory method of placing concrete on a regular paving contract Mixtures of standard proportions placed by conventional methods were compared with two types of mixtures placed by vibration, in which the proportion of fine to coarse aggregate was adjusted to give the best results Both gravel and crushed stone coarse aggregates were used In one type mixture, designed for standard yield, a reduction in mixing water of about one-half gallon per bag of cement and a corresponding increase in strength were obtained In the other, in which the standard water-cement ratio was maintained, a saving in cement of about 10 per cent was obtained without reduction in strength The progress of the work was as satisfactory as with the conventional methods and the surface of the pavement showed no defects after one year The relative amounts of honeycomb in the slabs showed that the vibratory method is far superior to the Illinois Standard method in consolidating the concrete Concrete of one inch slump, which was about as dry as could be discharged and spread by the mixer bucket, was consolidated very satisfactorily around transverse metal joints, when installation bars to protect the copper seal or bituminous cap were used

This investigation takes up the practical application of the vibration method under field conditions Before presenting the data, however, it will be of advantage to consider briefly the results of a previous investigation in Illinois, because the investigation described herein may be considered, in a way, a continuation of the first one

INVESTIGATION OF 1932

In August, 1932, the Illinois Division of Highways constructed about one mile of pavement with one of the first vibratory finishing machines offered for use, with the object of making a thorough study of the merits of this method of placing and finishing concrete pavement Only a very brief account of this investigation can be given here, and for further information, a report entitled, "Vibratory Method of Finishing Concrete Pavements," issued November 15, 1933, should be consulted

Description of Finishing Machine The vibratory finishing machine used in the investigation of 1932 was essentially the standard double-screed equipment with screeds slightly different in design and provided with electrically driven vibrator units operating at about 3,600 impulses per minute Four vibrator units were placed on the front screed and two on the rear screed and the vibratory action was imparted to the concrete through the screeds while in motion

Mixtures Used The experimental pavement contained 114 individual sections, averaging about 45 ft in length, three different series of progressively changing concrete mixtures for both gravel and crushed stone coarse aggregate were used Expressing all quantities in amounts per bag of cement, the mixing water was the major variable in one series, the coarse aggregate in another, and the fine aggregate in another An idea of the range of mixtures used may be had from the fact that the quantity of cement per cubic yard of concrete ranged from 1 11 barrels to 1 58 barrels A sufficient number of mixtures were used to determine the maximum practical limits of the proportions of materials which could be handled by this machine and the proportions which appeared to be most suitable

The ability of the vibratory finishing machine to handle and consolidate even the harshest mixtures was found to be truly remarkable and satisfactory pavement was obtained from most, if not all, of the mixtures placed The most suitable mixtures, however, appeared to be those having a slump of about one-half inch which contained a ratio of sand to the total quantity of aggregates by absolute volumes in the vicinity of 32 per cent for gravel mixtures and 35 per cent for crushed stone mixtures

Surface Condition The only disconcerting thing about the investigation was that some surface scaling developed on many of the sections However, scaling occurred on several other pavements constructed that year and therefore it could not be said that the scaling which occurred on the experimental pavement was due to the vibratory method of compacting and finishing, although an excessive amount of manipulation was required to finish many of the sections This viewpoint appeared to be justified from the fact that no surface scaling occurred on the experimental pavements placed by other States with the same equipment

Conclusions Definite conclusions drawn from the investigation referred almost exclusively to the mixtures and the resulting concrete

It was fairly well established that concrete, though unworkable by ordinary means of placing, follows the same laws as concrete of ordinary workability when made plastic by vibration during the process of placing In other words, vibration imparts essentially no new property to the concrete and the water-cement and voids-cement ratio laws still hold good

The advantages of vibration from economic considerations were established It was found entirely feasible to produce concrete of higher strength than standard at about the same cost as standard by reduction of the amount of mixing water and adjusting the proportion of fine to coarse aggregate, also to produce concrete of standard strength at lower cost than standard by maintaining the same water-cement ratio and increasing the amounts of the aggregates in proper proportions

With reference to the first mentioned advantage, it was not determined definitely from the investigation how much increase in strength above that of the standard mixtures may be obtained by reducing the water-cement ratio With reference to the second mentioned advantage, however, a reduction of the amount of cement from that used in standard mixtures of about 15 per cent was obtained without sacrifice of strength Obviously it would also be possible to obtain some increase in strength and save cement at the same time.

It was realized at the time the investigation was under way that it had certain shortcomings and that the manner of conducting it precluded proper study of the practicability of the machine This was indicated by the statement in the conclusions "that the vibratory finishing machine should be further employed with mixtures suitable for it" The opportunity to do so, however, did not occur until September, 1936

INVESTIGATION OF 1936

The results of the investigation of 1932 were not in themselves considered sufficient justification for specifying this method for finishing concrete pavement

There was the question of surface scaling, and while it was never seriously believed that this was an inherent result of the vibratory method, there was still some possibility that it might be

The chief concern, however, was the fact that there was insufficient information as to the practicability of the equipment when operated under job conditions At any rate, it was felt that the equipment should be given a further test on a regular contract job using only mixtures which were strictly suitable for it

An investigation of this nature was undertaken in 1936 The United States Bureau of Public Roads was invited to cooperate and did so in permitting the work to be done on a Federal-aid section, assisting in planning the investigation, and furnishing some of the auxiliary testing equipment

A contract which was awarded during the fall of 1936 specified the use of a vibratory finishing machine and also the use of separated sizes of coarse aggregate The construction work was started so late in the season, however, that it was not only necessary to deal with conditions which always result from late construction, but also to rush construction operations This was at first thought to be unfortunate, but in reality it provided an excellent test of the practicability of the finishing machine In the case of some of the test data, however, the lateness of the season was a handicap, because of the inadequate and variable curing conditions which resulted from low temperatures

The experimental section was designated as Federal-aid Route 142, Federal aid Project 339, Section 34, Sangamon-Menard Counties It is located about 11 miles west of Springfield and extends 5½ miles in a northerly direction from its junction with State Bond Issue Route 125

OBJECT OF INVESTIGATION

In addition to proving or disproving the practicability of the vibratory equipment, another object of this investigation was to determine whether the concrete could be consolidated satisfactorily around all-metal air-chamber expansion joints and the all-metal contraction joints by the vibratory screed without damage to the joints, also to study the use of separated sizes of coarse aggregate, to study thoroughly the concrete obtained, and to make observations from time to time of the finished surface

DESCRIPTION OF FINISHING MACHINE

The finishing machine was a self-propelled unit designated for vibratory finishing It was equipped with reciprocating screeds, the forward one being 18 in wide and the rear screed 12 in wide

Three high frequency electric vibrators were mounted on the front screed, one in the center and one 5 ft from each end The rear screed carried no vibrator units

The bottom plate of the forward screed was curved upward and connected with the vertical plate, the radius of curvature being 2¼ in, thus forming a bull nose which crowded sufficient concrete under the screed to provide for the increased consolidation due to the vibration

A gasoline powered motor-generator unit was mounted on the finishing machine to provide power for the vibrators The frequency of vibration, as determined with a vibrating reed tachometer, ranged from 3,950 to 4,150 impulses per minute, the latter value being that obtained when the screed was resting on the forms and not in contact with the concrete When the screed was pushing a good sized load of concrete, the frequency of vibration ranged from 3,950 to 4,075 impulses per minute The finishing machine weighed about 1,000 lb more than the standard machine, its total weight being 10,700 lb.

Figure 1 is a view of the equipment in operation, showing the front screed and the vibrators.

While there was no essential difference in design of the machines used in the 1932 and 1936 investigations, it should be remembered, in any comparison of data between the two, that the finishing machine used in 1932 carried four vibrator units on the front screed and two on the rear, while that used in 1936 carried three vibrator units on the front screed and none on the rear.

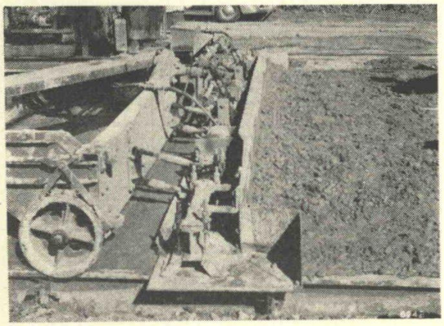

Figure 1. Finishing Machine in Operation. Showing Front Screed with Vibrators

DESCRIPTION OF PAVING PLANT

Outside of the different type finishing machine and an extra crane and bin, the equipment was the same as that regularly used on most paving jobs. A standard 1936 model 27-E paver was used.

MATERIALS

Gravel was used for one-half of the job and crushed stone for the other. The only other deviation from standard practice, was the requirement that the coarse aggregate should be furnished in two sizes, one ranging from 2 in. to 1 in. and the other from 1 in. to $\frac{1}{4}$ in. These sizes were recombined during the proportioning operations.

The physical properties of the aggregates are shown in Table 1. The cement used was a standard portland cement.

TABLE 1

COARSE AGGREGATE

Size	Passing sieve—per cent						Voids per cent	Sp. gr.
	2″	1½″	1″	¾″	½″	No.4		
Crushed Stone								
2″ to 1″....	100	61	10	2				
1″ to ¼″...			100	87	27	1		
Combined...	100	86	69	57	18	1	40.0	2.73
Gravel								
2″ to 1″.....	100	68	3	1				
1″ to ¼″...		100	98	67	30	1		
Combined...	100	87	60	41	18	1	37.5	2.70

FINE AGGREGATE

Passing sieve—per cent					Sp. gr.
No. 4	No. 8	No. 16	No. 50	No. 100	
98	77	62	8		2.65

CONCRETE MIXTURES

Standard Mixtures: Since the sources of materials had been used in pavement construction for a number of years, the proportions of the standard mixtures were well known, except as to the effect of two sizes of coarse aggregate. For this reason and also to obtain certain test data for comparison, short stretches of pavement were constructed with standard mixtures without the use of the vibrators, the finishing machine when used in this manner being considered equivalent to the standard reciprocating machine. A total of 1,196 ft. of this mixture was placed using gravel coarse aggregate and 1,709 feet using crushed stone coarse aggregate.

Mixtures of Yield Equal to Standard: In order to determine to what degree increased strength could be obtained without greater expenditure for materials, one mixture was designed to produce exactly the same yield as the standard mixture, the proportion of sand to coarse aggregate and the amount of mixing water, however, were reduced to obtain the mixture most suitable for the vibratory equipment A total of 6,264 ft of this mixture was placed using gravel coarse aggregate and 5,288 ft using crushed stone coarse aggregate

Mixtures of Strength Equal to Standard To determine the amount to which the yield could be increased, and thereby save cement, without reduction in strength, one mixture was designed to produce the same strength as the standard mixture, the amounts of the aggregates, however, were increased and the proportion of sand to coarse aggregate was adjusted to obtain the mixture most suitable for the equipment The water-cement ratio was kept essentially the same as in the standard mixture A total of 5,560 ft of this mixture was placed using gravel coarse aggregate and 6,964 ft using crushed stone coarse aggregate

Proportions In order to start the work with a minimum amount of experimentation the proportions believed to be about correct were estimated for each of the mixtures These were then adjusted until the most suitable proportions were obtained

Approximately correct proportions for the standard mixtures were known from previous experience In estimating the proportions for the mixtures to be placed by vibration, the data from the investigation of 1932 were used as a guide, taking into account the difference in the number of vibrator units used in the two investigations and assuming that somewhat greater plasticity would be necessary because of the metal joints around which the concrete had to be consolidated Table 2 shows the proportions originally estimated and those which were determined through experimentation to be best suited, these proportions were used for the greater part of the job

The proportions used were nearly the same as the estimated proportions, except in the case of the vibrated mixtures designed for standard strength, in which somewhat smaller amounts of coarse aggregate produced considerably more satisfactory mixtures Comparing the cement factors of the vibrated mixtures designed for standard strength with those of the standard mixtures, it is seen that the cement was reduced about 11 per cent for the gravel mixture and nearly 9 per cent for the crushed stone mixture, whereas a reduction of 12 per cent was assumed in the estimated proportions

The degree to which the use of separated sizes of coarse aggregate may have affected the yields obtained could not be studied effectively in this investigation Data relating to this are given in the Illinois Division of Highways', Bureau of Materials, report entitled, "A Study of the Segregation of Coarse Aggregate and the Use of Divided Coarse Aggregate for Its Prevention."

In general, 40 per cent of the larger size and 60 per cent of the smaller size, or the 40-60 combination, produced the best results for the gravel mixtures, while the 35-65 combination produced the best results for the crushed stone mixtures

That the use of separated sizes of coarse aggregate provides a desirable latitude in proportioning was clearly shown on one occasion when a 40-60 combination gravel mixture became unsatisfactory and a change was immediately made to a 30-70 combination Investigation showed that the difficulty was caused by segregated material from one of the stockpiles When the next shipment of aggregate arrived, the 30-70 combination became unsatisfactory and it was necessary to resume the 40-60 combination Had it not been for the separated sizes of coarse aggregate, the contractor would either have had to reduce the amount of coarse aggregate or place an unsuitable mixture for the period involved, possibly with an increase in the amount of mixing water

CONSTRUCTION PROCEDURE

An engineer was stationed at the plant to control the proportioning of the mixtures It was his duty to see that the correct amount of each material was measured for each batch and to determine the amount of water to be added at the mixer

Close coordination was necessary between the proportioning engineer and the engineer at the mixer and, since it was necessary for the proportioning engineer to be at the plant most of the time, an engineer from the Bureau of Materials was assigned to assist him at the beginning of the work and at such times thereafter as major changes in the mixtures were made, which necessitated some experimentation before the most desirable proportions of the materials were determined

For a description of the tests required and the duties of the proportioning engineer, reference should be made to the "Manual of Instructions for Proportioning Engineers," March, 1935

The materials were transported to the mixer in trucks having a capacity of two batches The cement required for each batch was placed on top of the aggregates and the bags were not dumped until just before the materials were emptied into the skip of the mixer Each batch contained the exact amount of materials for 29 7 cubic feet of mixed concrete and was mixed for 60 seconds after all of the materials were in the drum

The water measuring device on the mixer was calibrated before the beginning of the work and set to deliver the correct amount of water over a greater range than was to be used

In all respects, care was taken that no error should enter the investigational

TABLE 2

Item	Standard mixtures		Vibrated mixtures			
			Standard Yield		Standard strength	
	Gravel	Stone	Gravel	Stone	Gravel	Stone
Originally Estimated Proportions						
Cement (lb)	94	94	94	94	94	94
Sand (lb)	220	220	205	205	235	235
C A (lb)	369	346	394	371	462	434
Water (gal)	5 40	5 40	4 90	4 90	5 45	5 45
Yield (cu ft)	4 77	4 63	4 77	4 63	5 44	5 27
Cement Factor	1 415	1 458	1 415	1 458	1 241	1 281
Proportions Used						
Cement (lb)	94	94	94	94	94	94
Sand (lb)	220	220	205	205	235	235
C A (lb)	365	354	391	380	448	414
Water (gal)	5 42	5 52	4 92	5 12	5 42	5 55
Yield (cu ft)	4 75	4 66	4 73	4 67	5 34	5 11
Cement factor	1 421	1 448	1 427	1 445	1 264	1 321
Slump (in)	2 4	2 0	1 1	1 1	1 0	1 1

Note The cement factor is barrels of cement per cubic yard of concrete work from inefficiency in control of the proportioning

Placing of Concrete The placing of concrete began September 24 and was finished November 18

The vibratory mixtures were mixed, deposited, and spread in the same manner as the standard mixtures, except for certain modifications introduced as the work progressed The mixer was operated outside of the forms except where it was impracticable to do so

It was found that the mixer operator, by pushing the bucket toward the end of the boom while the concrete was being discharged, could aid materially in spreading the relatively dry mixtures Also, the concrete could be spread across the centerline without materially affecting the longitudinal center joint and tie bars

This method of spreading was at first thought unsatisfactory because some of the larger particles of aggregate were separated from the batch when it was dumped and these tended to deposit themselves against the side forms and joints, but this was remedied by depositing concrete with shovels along the forms and joints in advance of spreading it with the bucket The best edges were obtained when the concrete was shoveled with a turning motion in such a manner that the concrete in direct contact with the shovel would come next to the side forms No spading was done along the side forms with the mixtures placed by vibration

In placing the standard mixtures, the contractor employed three puddlers to distribute and level the concrete and two side form spaders When the vibratory placing was started, the two form spaders were not needed, but it was soon found necessary to use them as puddlers, as three men could not handle the concrete, which was not only drier than the standard mixtures but also contained a considerably greater amount of coarse aggregate

The standard mixtures were of 2-in slump or slightly more, while the vibrated mixtures were of 1-in slump or slightly more The 1-in slump for the latter seemed to be about the lower limit, not only from consideration of proper placement around the transverse joints, but also because of the fact that concrete of lower slump could not be discharged properly from the mixer bucket

The mixtures designed for the same yield as the standard mixtures were somewhat sticky because of the relatively richer mortar A reduction of 0 5 gallon per bag of cement in mixing water was obtained for the gravel mixtures, and about 0 4 gallon per bag of cement for the crushed stone mixtures, which was expected to increase the strength over the standard mixtures

The mixtures designed for the same strength as standard mixtures were better suited for the equipment than those of standard yield because of less stickiness They were placed with about the same amount of mixing water per bag of cement as the standard mixtures and were expected to result in about the same strength The saving in cement, about 11 per cent for the gravel mixture and about 9 per cent for the crushed stone mixture on the basis of the amounts used in the standard mixtures is an item of considerable importance

The percentage of sand in the total absolute volumes of the aggregates provides an excellent comparison between the standard and vibrated mixtures For gravel and stone coarse aggregates, respectively, these percentages were for the standard mixtures, 38 0 and 39 0, for the vibrated mixtures designed for standard yield, 34 8 and 35 7, and for the vibrated mixtures designed for standard strength, 34 8 and 36 9

What has been said in regard to placing of the concrete applied particularly to the mixtures after they had been adjusted to produce the most satisfactory results, these being in general the gravel mixture of the 40-60 coarse aggregate combination and the crushed stone mixtures of the 35-65 coarse aggregate combination, the first figure referring to the percentage of the larger size and the last to the percentage of the smaller size coarse aggregate Some experimentation was made in the case of all of the mixtures before these combinations were adopted to see if some other combinations would give better results When such experimentation was made, the placing of the concrete did not always proceed as satisfactorily as described, though extreme limits in proportions were not attempted and all of the mixtures may be said to have been satisfactory for the equipment, and good results were in general obtained Such experimentation was confined to a minimum and does not represent much of the mileage constructed

The finishing machine made at least two trips over the freshly deposited concrete, but in some cases three trips were required The vibrators were used only during the first trip, during which the finishing machine was operated in low gear

The operations involved in finishing the surface were essentially the same as under standard practice, including the use of a longitudinal float, longhandled floats, belting and brooming Curing was accomplished by 24-hour wet burlap application and thereafter calcium chloride surface application or, when it was too cold for this method, by dry straw covering

The number of irregularities of the surface exceeding ⅛ in in 10 ft, found on the pavement where the vibratory action was employed, was no greater than found on that placed by standard methods The great majority of these were confined to the pavement placed with crushed stone mixtures, indicating that these were perhaps as a general rule slightly harsher than the gravel mixtures However, the crushed stone concrete happened to be placed at the more difficult places, such as on grades, in cuts, and on superelevated curves

Side Forms In general the subgrade was good, since the location followed an old road Side forms of 6-in base were used, but these apparently constituted a more or less definite limitation on the vibratory method of placing the concrete and might have been entirely unsatisfactory on a poor subgrade

Rocking of the side forms occurred to such a degree that it was considered impracticable to operate the finishing machine in second gear with the vibrators in action This, together with time consumed in stationary vibration at transverse joints, left only sufficient time for a second trip over the concrete with the finishing machine in second gear and the vibrators turned off, thus limiting the amount of vibration when keeping pace with the mixer However, under this procedure, no appreciable settlement of the forms was noted, provided they were correctly set and well tamped Under less favorable conditions, forms with wider base would undoubtedly be necessary, even in the case of minimum vibration

A mechanical form tamper was used on a part of the job A comparison, by means of precise levels taken on the forms, between hand tamping and mechanical tamping showed a great improvement resulting from the latter The settlement of the forms was small and regular where the mechanical tamper was used, while an irregular settlement occurred when the forms were tamped by hand Mechanical tamping also prevented the forms from rocking during operation of the finishing machine

Transverse Joints One feature of the present pavement design, the use of all-metal air-chamber expansion joints and all-metal sealed contraction joints, was from the beginning expected to cause some difficulty. These were spaced at 30-ft. intervals, every third joint being an expansion joint. The load transmission feature of these joints consisted of relatively short dowels through the joint working in sleeves provided with wing anchors set in the concrete. These load transmission units were spaced at 20-in. intervals along the joints.

The method of consolidating the concrete around these joints was developed through trial. Various methods were tried and, as soon as the concrete had set sufficiently, a joint was opened and the results examined. This was continued until a method of procedure was developed which insured thorough compaction of the concrete around the load transmission units and against the sides of the joints without collapse of the joints, infiltration of mortar, or damage to the copper seal. The method as finally developed and found entirely satisfactory was as follows:

Concrete was first forced directly under each load transmission unit by shovels. It was then shoveled against both sides of the joint up to the horizontal flange of the copper seal, taking care that no coarse aggregate particles were left on top of the copper seal flange. The best results were obtained when the concrete was shoveled against the joint with a turning motion of the shovel in such a manner that the concrete next to the blade of the shovel was deposited against the joint. Figure 2 shows the concrete deposited along the sides of an expansion joint.

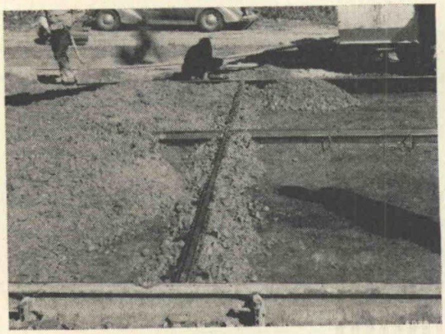

Figure 2. Concrete Deposited Along the Sides of an Expansion Joint

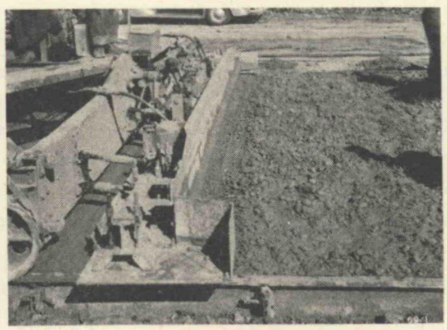

Figure 3. Front Screed of Finishing Machine in Position for Stationary Vibration at an Expansion Joint.

The front screed was stopped about 3 in. from the joint and permitted to vibrate for about one minute. It was then raised and set directly over the joint and stationary vibration was again applied for about one-half minute before proceeding into the next panel. Figure 3 shows the finishing machine in position for stationary vibration at an expansion joint.

Regardless of the care exercised in keeping coarse aggregate particles off the top of the copper seal, it was impossible to prevent some such particles from being carried forward by the screeds and damaging the seal. In the past, installation bars of various designs had been used and other precautionary methods had been taken to protect the copper seal, but many were impracticable. The vibratory finishing machine still further complicated the problem of protecting the copper seal, because the action of the screed on any particle of coarse aggregate which lodged on top of the seal produced a hammering effect on the particle.

Installation bars for contraction joints were provided by the manufacturer; these gave adequate protection to the seal but were unsatisfactory from a structural standpoint. These bars had wide flanges and they could not be removed after the joint was installed without bending them because of the suction between the bar and the concrete. Furthermore, the space left over the joint was too wide and had to be partially filled.

With cooperation of the contractor, installation bars without flanges were made, which gave a little more clearance for the screed; these proved entirely satisfactory.

The copper seal of expansion joints was protected by premolded bituminous caps. These also suffered damage in the same manner as the copper seal of the contraction joints, though not to so great a degree, and it was decided to try installation bars for their protection.

The manufacturer of the joint submitted installation bars of $\frac{1}{8}$-in. material pressed into the form of a channel conforming exactly to the shape of the bituminous cap. These proved very effective for protection of the cap and for keeping it clean. The only objection was some disturbance of the concrete adjacent to the cap when the installation bar was removed from the expansion joint.

TEST SPECIMENS

The test specimens consisted of 6 by 6 by 30-in. beams and 6 by 12-in. cylinders cast from the concrete at the time of placing, $4\frac{1}{2}$-in. cores drilled from the completed pavement, and special test sections constructed from time to time as an integral part of the pavement and later removed for testing purposes.

Beams and Cylinders: Four beams and eight cylinders were made during each day's construction. When the standard method of placing was employed, the specimens were made by standard methods; and when the vibratory method of placing was employed, the specimens were vibrated for 15 sec. this period having been decided upon from preliminary laboratory tests.

The apparatus used for vibrating the test specimens consisted of a vibrator unit fastened to the bottom of a plank, which was suspended by straps from a trestle. On the top of the plank, provision was made for securely clamping either one beam mold or two cylinder molds. The current for operating the vibrator was obtained from the motor-generator unit on the finishing machine. Figure 4 is a view of the apparatus in operation.

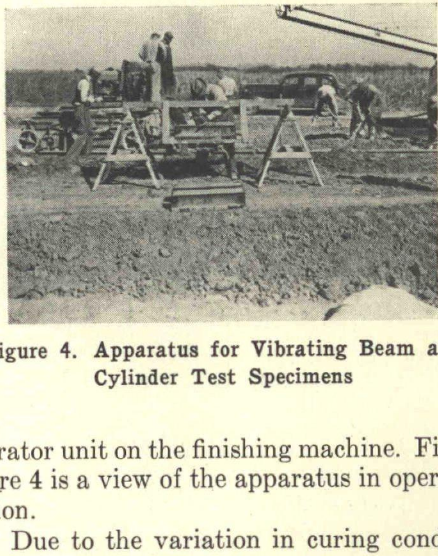

Figure 4. Apparatus for Vibrating Beam and Cylinder Test Specimens

Due to the variation in curing conditions anticipated in late fall construction, the beams and cylinders were transported to the laboratory at Springfield as soon as possible and cured in the moist room. They were from 30 to 36 hours old when this curing was started. They were tested at the ages of 3, 5, 7, 14 and 21 days. An exception to this procedure was made in the cases of the beam specimens from the special test sections which were cured alongside these special test sections and tested with them.

Cores: When the concrete had reached an average age of about 5 months, 144 cores were drilled from the pavement.

These were used for the purpose of studying the crushing strength of the concrete, its absorption, weight per cubic foot, specific gravity, degree of honeycomb, and resistance to alternate freezing and thawing.

Twenty four cores were drilled from each of the gravel and crushed stone mixtures considered the most satisfactory for the vibratory method of placing and also from the standard mixtures. They were taken from well distributed locations and about one-third of them were taken at what was considered the most critical points of the pavement; namely,

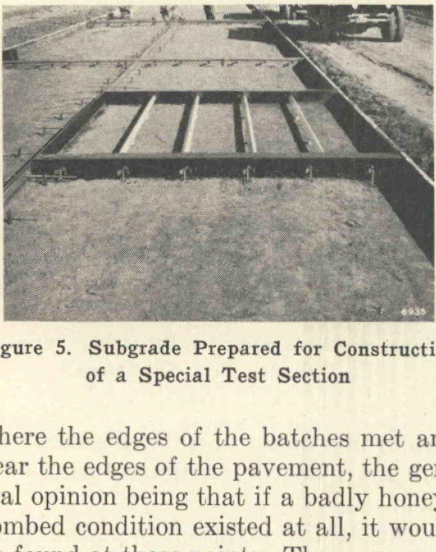

Figure 5. Subgrade Prepared for Construction of a Special Test Section

where the edges of the batches met and near the edges of the pavement, the general opinion being that if a badly honeycombed condition existed at all, it would be found at these points. The cores were tested when the concrete was about 8 months old.

Special Test Sections: In order to examine large samples of the slab and to obtain the flexural strength of the pavement slab itself, special test sections were constructed integrally with the pavement and removed at a later date for examination and tests. These special test sections were constructed and finished in the same manner as the pavement. They extended from the edge to the center of the pavement, were 9 ft. in a longtitudinal direction, and had a uniform thickness of $6\frac{1}{2}$ in. A section was constructed for approximately every 1,500 lineal feet of slab and they were located alternately to the right and left of the centerline. Figure 5 shows the subgrade prepared for the construction of one of the special test sections.

The sections were separated from the rest of the pavement by collapsible wooden headers and four 2 by 2-in. wooden separators were inserted between the headers to crack each section into five slabs, each 24 in. in width. It was thought that the concrete next to the wooden headers would possibly not be representative of the pavement, and provision was made for easy removal of 2 ft. from each end of each slab by making a row of $\frac{3}{4}$-in. holes across each special section 2 ft. from each header before the concrete had set. The ends of the slabs were removed later by means of plugs and feathers. U-bolts were set in each slab to facilitate handling. The arrangement was essentially the same as described in "Public Roads," Vol. 12, No. 6, page 147, August, 1931.

Each test section was placed with two batches from the same truck to eliminate possible variation. No special effort was made in consolidating the concrete beyond that received by the pavement proper, and concrete was not deposited by shovel against the side forms prior to depositing the batches. Three 6 by 6 by 30-in. beams were made from the concrete used in each test section to compare the flexural strength of the usual test specimens with that of the slab. They were kept with the test slabs and cured in the same manner as these until the time of testing.

Upon completion of the paving work, the special sections were removed from the pavement and the place occupied filled with concrete. After removal of the ends, the test slabs were taken to the laboratory, placed outside, and the edges banked with soil. It was thought desirable to let these slabs attain considerable age before testing to minimize the effect of the initial variable curing temperature, and they were not tested until they were about eight months old. Figure 6 shows a special test section ready for removal.

RESULTS OF TESTS

CONSTRUCTION PROGRESS

In connection with the question of the practicability of the vibratory finishing machine, a study of the construction progress on this job is of special interest.

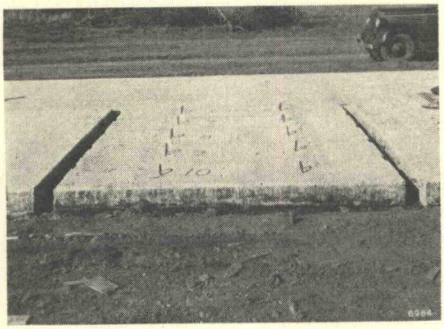

Figure 6. View of Special Test Section Ready for Removal

The average rates shown in Table 3 include all of the pavement laid, except that which could not be classed as representative, such as a wye intersection and one or two short stretches, including most of the pavement placed on the first day before the work was coordinated.

The standard gravel mixture was the first one placed and the 170 linear feet of pavement constructed with it which were considered entirely representative for a study of this nature; on the basis of this distance, the rate of 116.0 linear feet per hour was determined. The remaining rates shown in Table 3, however, were based on more than 90 per cent of the pavement laid with the representative mixes. The lowest rate occurred with the vibrated mixture designed for standard yield. Crushed stone concrete gave slightly lower rates than gravel concrete, although this may be partially accounted for by the fact that the crushed stone mixture, though possibly a little harsher than the gravel mixtures, were placed on the most difficult part of the pavement, containing features such as cuts, fills, and superelevated curves. The vibrated mixtures designed for standard yield were in general too sticky to give the best results. Those designed for standard strength are, from the standpoint of the rates shown, entirely on a par with standard mixtures.

TABLE 3

Mixture	Rate lin. ft. per hr.
Gravel Coarse Aggregate	
Standard	116.0
Vibrated—yield equal to standard	114.7
Vibrated—strength equal to standard	116.8
Crushed Stone Coarse Aggregate	
Standard	110.3
Vibrated—yield equal to standard	107.9
Vibrated—strength equal to standard	114.3

While the vibrated gravel mixture designed for standard strength showed the best average rate, the vibrated gravel mixture designed for standard yield showed the best average rate during a single day. With this mixture, using two $5\frac{1}{2}$-hour shifts, 1,320 linear feet at the average rate of 120 linear feet per hour, or 521 batches of concrete at the average rate of 47.36 batches per hour, were placed in one day. During a 6-hr. period on this same day, the production was as high as 130 linear feet per hour, or about two batches short of a perfect run based on a 62-sec. mixer period.

The average production for the entire job, excepting the wye intersection, was 112 linear feet per hour. The finishing machine was in general capable of handling all the concrete that possibly could be put through the mixer when operated as previously described herein

TESTS OF BEAMS AND CYLINDERS

In spite of the fact that the beam and cylinder specimens were cured in the laboratory moist room, the results obtained from the strength tests did not in all cases show the anticipated differences probably because of variable factors such as the weather conditions during the 30 to 36 hours that had to elapse before the specimens could be placed in the moist room, the initial temperature of the concrete, and the protection afforded the specimens during their early ages The construction work was started under almost summer conditions, later it became somewhat chilly at night, and after a time it became necessary to heat the mixing water, and finally it was necessary to use a heater on the mixer in addition to heating the mixing water Under these conditions, the erratic results shown in Table 4 might be expected

Rather than to try to make detailed correlation between strengths and initial condition of the mixtures, which at best would be more or less indefinite, it was decided to make strength comparisons only on the basis of the tests of the cores and slabs, which were actually a part of the pavement, and which were not tested until the concrete had attained an age at which it would be expected that the effect of the initial variable conditions would be minimized

TABLE 4

TESTS OF BEAMS AND CYLINDERS

Age in days	Number of Tests and Average Strengths in Pounds Per Square Inch											
	Gravel mixtures						Crushed stone mixtures					
	Standard		Yield-Std		Str -Std		Standard		Yield-Std		Str -Std	
	No	Str	No	Str	No	Str	No	Str	No	Str	No	Str
Flexural Strength												
3			6	549	4	570	2	546	4	545	6	459
5			6	661	6	651	2	614	8	707	4	660
7			12	729	10	736	4	747	10	757	16	772
14	12	777	14	868	10	786	8	888	12	863	16	895
21			10	913	12	962	2	776	8	916	12	868
Compressive Strength												
3			6	2576	4	2542	2	2162	4	1811	6	1868
5			6	3329	6	3042	2	3393	8	3398	4	3444
7			12	3752	10	3316	4	3963	10	4045	16	3746
14	12	4423	14	4793	10	4103	8	4847	12	4789	16	5025
21			10	5073	6	5084	2	5402	10	4988	12	4843

TESTS OF CORES

About half of the cores were used for strength tests, the other half were used for miscellaneous additional tests Table 5 shows the average specific gravity, percentage absorption, and weight per cubic foot of the concrete produced from the various mixtures These values are in most cases the average of six determinations

It is seen that almost identical results were obtained excepting the standard crushed stone mixture, which appears to be inferior to the rest Either the standard crushed stone mixture was improperly consolidated or the vibrated crushed stone mixtures were benefited sufficiently by vibration to increase the weight per cubic foot more than 2 lb

The strength results, for the sake of correlation with similar data, are shown in Table 6 It will be seen that the standard crushed stone mixture, so far as the tests of the cores are concerned, also showed somewhat inferior strength This will be discussed more fully in connection with the results obtained from tests of the special slabs

Few of the cores drilled showed any unusual degree of honeycomb Only 10 cores showed honeycomb worth mentioning, five each from gravel and crushed stone mixtures Four of these were from standard and six from vibrated mixtures Eight were taken from what was considered the most critical points of the slab, four of these being from standard mixtures and four from vibrated mixtures A few representative cores were sawed longitudinally into halves and the coarse aggregate was in general found to be well distributed in the mortar, leaving no greater degree of voids and air holes than found in the ordinary run of cores In short, the cores were of very excellent appearance, but it may be doubted whether this type specimen is of sufficient size to show clearly anything but severe degrees of honeycomb, especially as far as the bottom of the slab is concerned, as may be seen from the study of the special slabs

Eighteen representative cores were subjected to alternate freezing and thawing tests, consisting of freezing the specimens in the cold room over night under a temperature of 0° F and thawing them during the day in water at 70° F At the present time, after 60 cycles of freezing and thawing, only two specimens show any effects whatever from this test One core of the vibrated gravel mixture designed for standard yield, and one core of the vibrated crushed stone mixture designed for standard strength each show a minute crack, discernible only upon close inspection, which may not be of any particular significance These tests are nevertheless being continued until at least 100 cycles have been obtained

TABLE 5

Mixture	Specific gravity	Absorption, per cent	Weight per cubic ft -lb
Gravel Coarse Aggregate			
Standard	2 37	4 35	147 8
Vibrated—yield equal to standard	2 37	4 35	147 9
Vibrated—strength equal to standard	2 37	4 30	147 6
Crushed Stone Coarse Aggregate			
Standard	2 32	5 02	145 0
Vibrated—yield equal to standard	2 36	4 54	147 3
Vibrated—strength equal to standard	2 37	4 58	147 6

TESTS OF SLABS

The slabs were tested at ages ranging from 231 to 251 days, the average being slightly less than 8 months. They were tested for their flexural strengths and examined to determine the percentage of honeycomb both on the bottom and on the fractured surfaces produced in the strength test. A determination was also made of the percentage of broken coarse aggregate particles in the fracture.

Description of Apparatus and Methods: The apparatus for testing the special slabs was furnished by the United States Bureau of Public Roads. It consisted of a structural steel base frame supporting a transverse rocker bearing and a roller bearing, upon which the slabs were placed for testing. A vertical tension member was attached at the center of each side of this frame by easily removable pins. Fastened at the upper end of these tension members was a transverse steel beam against which the load was applied. The load was applied by means of a ball bearing rachet jack and distributed to the one-third points of the span by means of a structural frame. The load was measured with a micrometer dial by observing the deflection of a calibrated pair of heat treated steel beams inserted between the jack and the beam against which the load was applied. To insure that the roller and rocker bearings would work, metal bars were placed on top of them and molding plaster was used at all points of contact with the specimens to insure even bearings.

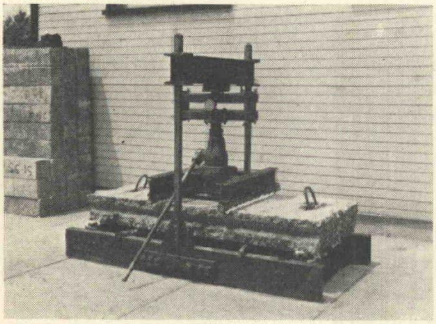

Figure 7. Slab Mounted in Apparatus Ready for Testing

Two weeks or more before testing, the slabs were soaked and thereafter kept wet by ponding water on the surface until the time of testing. They were loaded over the one-third points of a span of 54 in.

Figure 7 shows a specimen mounted in the apparatus ready for testing.

The amount of honeycomb was determined by placing a 4-in. square wire mesh over the surface to be examined and measuring the amount for each square separately. When necessary, the 4-in. squares were subdivided into 2-in. squares. The amount of honeycomb was expressed in terms of the percentage of the total area.

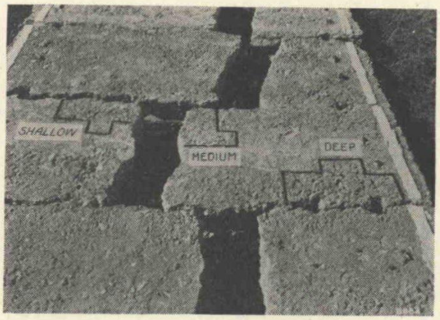

Figure 8. Slab Showing All Three Degrees of Honeycomb

The degree of honeycomb was classified as shallow, medium, and deep. While there was no distinct line of demarcation between these classes, the general rule was to classify any condition where the fine aggregate was not completely covered with cement paste as shallow honeycomb. If the fine aggregate particles and some of the coarse aggregate particles were not covered, the condition was classified as medium honeycomb. If the coarse aggregate particles were definitely not covered by the mortar, the condition was classified as deep honeycomb. Figure 8 shows a slab exhibiting all three degrees of honeycomb The percentage of broken aggregate in the fracture was estimated as closely as possible

Results of the Strength Tests Two special tests sections were constructed for each of the standard mixtures and four for each of the vibrated mixtures and since each special section was divided into five slabs, there were 10 individual tests performed on each standard mixture and 20 on each vibrated mixture Except in case of the first special section constructed, for which no beams were made, there were three 6 by 6 by 30-in beams made with each special section, making a total of three beams for the standard gravel mixture, six for the standard crushed stone mixture and twelve for each of the vibrated mixtures, but three beams of the crushed stone mixture designed for standard strength were lost before testing The average results of the tests of these specimens are shown in Table 6 together with the average compressive strengths of the cores, the latter being the average of twelve individual tests performed at the same age

There is fair agreement, in case of the gravel mixtures, between the strength values obtained for the standard mixture and those obtained for the vibrated mixture designed for standard strength Also, the vibrated mixture designed for standard yield, in which the amount of mixing water had been reduced by one-half gallon per bag of cement, shows on the average about 7 per cent higher strength than the standard strength mixtures, as far as the cores and slabs are concerned The companion beams, however, show discordant results in that the standard strength mixtures show slightly higher strengths

In case of the crushed stone mixtures, it appears that the standard mixture gave entirely too low compressive strength, while its flexural strength fell fairly well in line with that of the vibrated mixture designed for standard strength The vibrated mixture designed for standard yield, in which the amount of mixing water was reduced by 0 4 gallon per bag of cement, shows an undue gain in strength over the standard strength mixtures Even when the low core strength of the standard mixture is eliminated from the comparison, the gain is about 18 per cent on the basis of core and slab strength The companion beams again

TABLE 6
TESTS OF SLABS, CORES AND BEAMS

Mixture	Strength in P S I			
	Comp	Flexural		
	Cores	Slabs	Beams	Per cent diff
Gravel Coarse Aggregate				
Standard	5381	905	1157	27 9
Vibrated—yield equal to standard	5797	953	1066	11 9
Vibrated—strength equal to standard	5386	877	1133	29 2
Crushed Stone Coarse Aggregate				
Standard	4408	825	1016	23 1
Vibrated—yield equal to standard	6349	944	1075	13 9
Vibrated—strength equal to standard	5277	788	1018	29 1

show discordant results in that only about 6 per cent gain in strength over those of the standard strength mixtures was obtained

The reason for the low strength of the cores of the standard crushed stone mixture is difficult to explain, especially since the slab strengths did not show a similar tendency. The core strengths would have to average nearly 1,000 pounds higher to be on par with the other standard strength mixtures It will be recalled that the cores from this mixture employed in miscellaneous other tests showed lower specific gravity, higher absorption, and lower weight per cubic foot than the cores of any other mixture, which tends to be in agreement with the low core strengths, but which would scarcely be sufficient to cause the entire deficiency in strength

The beams made in connection with the slabs showed considerably higher strength than the slabs The reason for this lies primarily in the method of test The beams were tested by the so-called cantilever method which is in reality a simple beam test over a 16-in span with the load at the midpoint, restraint being reduced by means of a roller under each end During comparative tests (Report No 31-4, File No 354 0, issued March, 1929), the Illinois Division of Highways found that the one-third point loading gave about 82 per cent of the strength obtained by the midpoint loading using a 24-in span, or, in other words, the midpoint loading gave about 22 per cent higher strength than the one-third point loading In this case, because of the difference in span length between the slab and beam tests, the difference between the two methods would probably not be exactly the same Some of the difference, also, is no doubt due to the difference in thickness of the specimens, the slabs being 6½ in thick and the beams 6 in.

From Table 6, it is seen that the beam strengths for the standard strength mixtures are on the average 28 or 29 per cent higher than the slab strength, excepting the beams of the standard crushed stone mixture which showed a corresponding value of about 23 per cent The vibrated mixtures designed for standard yield, that is, the mixtures in which the water-cement ratio was reduced, showed much lower corresponding percentages, the average being about 13 per cent It would appear then that there is reasonably close agreement between the mixtures within each strength class, and that the beam test within comparable mixtures is a fairly uniform measure of the slab strength However, there appears to be an unreasonable difference in the percentages shown for the two classes of mixtures, and this statement is by no means conclusive

Results of Examination for Honeycomb The vibrated mixtures on the average showed much less honeycomb on the bottom of the slabs than the standard mixtures Honeycomb of any great consequence was not found in most of the slabs when the fracture was examined after testing There was in all instances a large percentage of broken aggregate in the fracture The average percentages for the mixtures are shown in Table 7

The highest percentage of honeycomb was found in the standard mixtures In the gravel mixture, one special section was very badly honeycombed, while the other was in fairly good condition with no deep honeycomb In the crushed stone mixture, both special sections were badly honeycombed

In the vibrated mixtures, conditions of honeycomb, when of any consequence, were generally found in the slabs cast next to the side forms This may be directly charged to the fact that the concrete was not shoveled against the side forms by hand as it was in the pavement proper. Some of the worst conditions found in the slabs, therefore, would in general not be found in the pavement and from this viewpoint the special sections cannot be said to be fully representative of the pavement

Without question, the special sections, however, show a true comparison between the results obtained with the various mixtures Undoubtedly a 2-in slump concrete is not nearly so satisfactory for the standard method of placing as is a 1-in slump concrete for the vibratory method. On the average, the percentage of honeycomb in the standard mixtures was from three to four times as great as that found in the vibrated mixtures

While by comparison the extent of honeycomb found in the vibrated mixtures was much less than that found in the standard mixtures, the appearance of the bottom of the vibrated slabs indicates that a single trip of the finishing machine with the vibrators operating is insufficient for the best results with 1-in slump concrete

It is firmly believed that the amount of honeycomb would have been negligible if there had been sufficient time available to make two trips with the finishing machine over the concrete with the vibrators in action An increase in slump of the concrete, however, would probably not have improved the consolidation since, while only a small range in consistency was employed in the investigation, it was shown that the vibration was not particularly effective on mixtures of 1½-in slump or greater

TABLE 7

Mixture	Broken aggregate in fracture, percent	Honeycomb—percentage of total area				
		In fracture	In bottom of slab			
			Shallow	Medium	Deep	Total
Gravel Coarse Aggregate						
Standard	90 3	0 4	10 9	12 9	3 4	27 1
Vibrated—yield equal to standard	84 1	0 2	4 8	2 7	2 2	9.7
Vibrated—strength equal to standard	83 0	2 9	1 8	3 7	4 3	9 8
Crushed Stone Coarse Aggregate						
Standard	82 5	2 2	6 3	22 7	5 4	34 4
Vibrated—yield equal to standard	86 5	1 5	1 2	1 4	2 7	5 3
Vibrated—strength equal to standard	81 8	2 7	2 0	6 9	2 5	11 4

SURFACE CONDITION AFTER ONE YEAR

A detailed examination of the pavement surface after nearly one year of service revealed few surface defects and no condition which could be classed as surface scaling There were two stretches where rain had fallen on the surface during construction, giving it somewhat different appearance from the rest, and a few locations where some of the surface may have dusted off, but even if this should be classed as scaling, there would perhaps not be ten or fifteen square feet of such in the entire 5½ miles constructed.

CONCLUSIONS

From the data and discussion presented herein, the following conclusions may be drawn

1 The investigation proved that the vibratory method of placing concrete pavement is practical as far as equip-

ment is concerned No mechanical difficulty of any consequence was encountered with the finishing machine, no enlargement of the construction force was necessary, and no additionad equipment was required, with exception of the extra crane and bin needed to handle the separated sizes of coarse aggregate

2 The investigation proved that the vibratory method of placing pavement is practical from the standpoint of progress of the work, an average rate of production of 112 linear feet per hour being maintained for the entire job under late season construction conditions During the most favorable conditions, the rate was higher and often approached closely all that the mixer could handle and still maintain the required mixing period

3 The concrete mixtures used with the vibratory finishing machine were as easily placed and finished as the standard mixtures were with the conventional equipment

4 It was clearly demonstrated that the use of separated sizes of coarse aggregate furnishes a desirable latitude in control of the mixtures

5 It was found that the amount of mixing water used in standard mixtures may be reduced by about one-half gallon per bag of cement, when the mixture is redesigned for use with vibratory equipment by taking out some of the fine aggregate and adding a sufficient amount of coarse aggregate to produce the same yield The increase in strength resulting from this varied considerably between the gravel and crushed stone mixtures and between the various types of test specimens

6 It was found that when the amount of water per bag of cement used in standard mixtures was maintained and the mixture redesigned for use with the vibratory equipment by adding fine and coarse aggregate in proper amounts, a reduction of around 10 per cent in cement content may be obtained without reduction in the strength of the concrete

7 The mixtures were best suited for the vibratory equipment when the amount of sand in the gravel mixtures was about 35 per cent of the total amount of aggregates by absolute volumes and 36 or 37 per cent in the crushed stone mixtures

8 The lower limit of the slump of the mixtures suitable for the vibratory equipment was about 1 in, this limitation, however, being in a large measure due to the transverse joints and the design of the mixer bucket

9 Concrete of 1-in slump may be consolidated very satisfactorily around transverse metal joints by the vibratory finishing machine Installation bars to protect the copper seal or bituminous cap of the joints are necessary

10 The 1-in slump concrete was about as dry as could be satisfactorily discharged and spread by the mixer bucket Possibly some change in design of the mixer bucket would be advantageous where the vibratory type of finishing machine is used

11 Satisfactory edges were obtained without spading when concrete was deposited by shovels along the forms prior to the depositing and spreading of the batches

12 Heavier forms than used on this job would be necessary

13 The amount of honeycomb present in the concrete placed by standard and vibratory methods showed that the vibratory method is far superior to the standard method in consolidating the concrete A 2-in slump concrete placed by the standard method does not give nearly so satisfactory results as a 1-in slump concrete placed by the vibratory method However, a single trip of the finishing machine with the vibrators in action is not believed to be sufficient for best results

14 It is indicated that the standard flexural test of beam specimens used by the Illinois Division of Highways as a

field test gives results which are a fairly uniform measure of the actual slab strength within any certain strength class of the concrete

15 An examination of the pavement surface nearly one year after the construction revealed few surface defects of any kind and no surface scaling

16 Any variation in results between the investigations of 1932 and 1936 is largely due to the difference in the number of vibrator units employed with the finishing machine, and in the limitation as to slump of the concrete imposed by the presence of transverse joints in the 1936 investigation If special test sections had been constructed in connection with the investigation of 1932, thus permitting an examination of the bottoms of the slabs, some of the conclusions drawn from this investigation might have been modified

DISCUSSION ON VIBRATION OF PAVEMENT CONCRETE

Mr Bert Myers, *Iowa State Highway Commission* The work covered by this study is a part of a paving project 7 646 miles long built August 26 to October 22, 1937 The test results reported cover approximately one mile of pavement placed by the Jackson Tube in single day's runs alternated with runs of similar length placed in accordance with the 1937 Standard Specifications of the Iowa State Highway Commission For the sake of brevity the two will be referred to as "Vibrated Concrete" and "Standard Concrete"

The report of the Wisconsin Highway Commission describes the Jackson Vibratory Paving Tube The Iowa Standard Specifications require that all concrete within 18 in of all joints, including the center joint shall be consolidated by means of an internal vibrator The "internal vibrator" used on the standard concrete was a Mall vibrator This tool was not used in the concrete placed with the Jackson Tube

The special provisions requiring the use of the Jackson Tube provided that in the sections to be consolidated by means of the vibratory tube the proportions should be those which would produce concrete with a satisfactory degree of workability for this method of placement, with the provision that the water-cement ratio should not be greater than the average used in concrete placed in the standard manner and that the quantity of cement per cubic yard of concrete should not be less than 1 6 bbl

The dry weight proportions used in the two kinds of concrete were as given in Table 1

The composition of a unit volume of fresh concrete was determined on one 300 ft section of each kind of concrete by observing carefully the quantities of all the materials used and measuring the space filled by taking cross sections of the pavement slab Cross sections were taken at intervals of 10 ft with measurements at one foot intervals across the pavement

The compositions of unit volumes of concrete as thus determined are given in Table 2

Fifty cores were drilled from each kind of concrete A summary of the results of density tests made by weighing in water and weighing in air after being thoroughly soaked in water at laboratory temperature is given in Table 3

The mean deviation from the average of these density determinations expressed as percentage of the average is as follows:

	Percent
Standard Concrete	0.55
Vibrated Concrete .	0 45

One possible explanation for the fact that there was greater variation in the density of standard concrete than in vibrated concrete is that perhaps some of the cores from the standard concrete were taken from areas that had been affected by the Mall vibrator, while others were taken from areas not so affected.

Of the 50 cores drilled from each kind of pavement one-half were sawed in half lengthwise to be examined for evidence of "honey comb" or porosity Two of the cores from the standard concrete showed honey comb extending about one inch up from the bottom of the slab for about half their diameter One of the cores from the vibrated concrete showed similar honey comb A visual examination of the sawed surfaces of the half cores does not show any appreciable difference between the two kinds of concrete as to quantity, size or distribution of pore spaces A more thorough study of this point will be made later

Table 4 gives a summary of the results of compressive strength tests on the 25 cores from each kind of concrete at age 60 days

TABLE 1

	Standard concrete	Vibrated concrete
Cement	1 0 lb	1 0 lb
Sand (sp. gr 2 65)	1 946 lb	2 165 lb
Stone (sp gr 2 58)	2 842 lb	3 162 lb
Water (average)	0 436 lb	0 426 lb
Cement per cu yd	1 71 bbl	1 60 bbl

TABLE 2

	Standard concrete	Vibrated concrete
Cement	0 1226	0 1128
Sand	0 2827	0 2893
Stone	0 4242	0 4340
Water	0 1606	0 1537
Air	0 0099	0 0102
Total	1 0000	1 0000

Total voids	0 1705	0 1639
Total solids	0 8295	0 8361
Void-cement ratio	0 667 cu ft per bag	0 691 cu ft per bag
Water-cement ratio	0 629 cu ft per bag	0 643 cu ft per bag
Weight per cu ft	149 08 lb	149 39 lb

The mean deviation from the average is as follows

Standard Concrete	525 lb
	= 7.8 percent of average
Vibrated Concrete	374 lb
	= 5.5 percent of average

The evidence presented shows little difference in the quality of the concrete as affected by the difference in the method of placing In fact the differences in average density and strength are so slight as to be considered identical. The vibrated concrete is slightly the more uniform in both strength and density.

The vibrated concrete required 0 11 bbl less cement, 0 0252 tons more sand, and 0 0369 tons more coarse aggregate per cubic yard than the standard concrete

It was noted that placing by means of the vibratory tube required one less man on the crew than was required when the concrete was placed in the standard manner Assuming that cement cost $2 00 per bbl., sand $1 00 per ton, coarse aggregate $1 50 per ton, labor $0 50 per hour, the contractor placed 50 cu yd of concrete per hour and disregarding the difference in equipment costs for the two kinds of vibrators required the vibrated concrete cost $0 15 less per cubic yard than the standard concrete

It should be noted that no attempt was made to determine the harshest or driest mixture that could be placed by means of the vibratory tube The slump of the standard concrete was about 1½ in while that of the vibrated concrete was about ¾ in Both mixtures were easily handled by the methods used

TABLE 3

	Standard concrete			Vibrated concrete		
	Max	Min	Ave	Max	Min	Ave
Density (grams per cc)	2 420	2 358	2 390	2 429	2 365	2 402
Weight per cu ft , lb	151 01	147 14	149 11	151 57	147 58	149 88
Percent of average	101 27	98 68		101 12	98 46	

TABLE 4

	Standard concrete			Vibrated concrete		
	Max	Min	Ave	Max	Min	Ave
Strength, lb per sq in	8140	5210	6751	7620	5740	6806
Percent of average	121	77		112	84	

Mr R B Gage, *New Jersey Highway Department* I was certainly very much interested in the papers which were presented regarding vibration, and I can see no reasons to doubt that they correctly present the value of vibrating concrete used in pavements Mr Jackson, however, I believe was conservative in his estimate of about ten percent increase in compressive strength According to our data we have more than that Unfortunately, the conclusions are all based on compressive strength, but there are other factors than compressive strength that should be considered as indicative of the benefits to be thus secured

We might be eaten up by a lion, or killed by a wolf, but the chances of our thus being eaten or killed are so remote that no one thinks of such a death, yet a microscopic bug comes along and the first thing you know he has you, and you are soon down and out The same is also true of concrete We might have plenty of voids in the bottom of a concrete pavement, but usually they are large, and what damage they have done or can do is practically none We have had voids in the bottom of pavements, and made studies of a lot of them, but the voids have never caused a failure.

However, get a little porous concrete in a pavement and the bugs soon get to work and the first thing you know you will need a new pavement Surface waters will be absorbed if the concrete does not have a certain density Where water can get into a concrete pavement. it can easily get out when conditions are reversed, and every time it goes in and out it does a certain amount of damage, and the concrete sooner or later goes to pieces

With concrete constructed from a pure quartz sand and trap rock, there is nothing in it to be attacked by surface waters, except the cement Both the rock and the concrete sand are durable, yet the concrete goes to pieces The cement has been decomposed—why? The factor we are most interested in is that the life of concrete depends upon its density If we get density, the concrete is going to last, but if we do not, it is going to pieces Cement is only a hydrated silicate or silicates, and it should not be expected to be immune from attack If you will look through the list of the hydrated silicates you will soon discover there is not one that is stable These silicates are soon decomposed, and the residues are oxides These apparently are the only compounds that are stable Since cement is composed of hydrated silicates, we should protect them as much as possible, so that they will not be decomposed by water If the concrete does not have the desired density, the cement or silicates will not be protected, and that is the chief cause of decomposition, with ultimate failure of the concrete

Our experience with concrete pavements has been that if we get the desired compressive strength, we are safe in assuming that we have the desired density, and that we are going to get a durable pavement Generally we have, but how high that compressive strength should be to be perfectly safe, nobody knows We have never yet had a concrete pavement too strong, or too good

Since we revised the portland cement specifications we have added 500 to 1000 lb per sq in to the compressive strength of the concrete at 28-days, the average now being about 6500 lb per sq in The workability of the concrete has also increased, the sheen coating of mixing water on the finished pavements has likewise disappeared, and scaling is practically negligible, compared to what it once was

In New Jersey we have a definite record of where certain cements, sands and coarse aggregates were used with which concrete was secured which has not developed defects in from six to eight years, but in other cases, similar pavements have cracked, peeled and scaled, and are ready to be resurfaced or rebuilt Yet everything was identical in each case, with the exception of the construction methods

We have sand pits and trap rock quarries which have been working for 30 years, so that we know that we have the same materials that produced desirable pavements in one case, and bad pavements in another The only thing that has killed the one, has been the use of excess mixing water With the stronger pavements we are now building, we have had very little, if any scaling, but the methods of construction discussed her today have not been used I am thoroughly convinced that the water-cement ratio is not the thing to use in building pavements If strengths are to be used as a guide in constructing a pavement, why not use enough cement to give the compressive strength required? An engineer when preparing a contract, should know how much cement he wants to use, and should see that it goes into the pavement

With the vibrolithic method of constructing concrete pavements, 200 to 300 lb more coarse aggregate can be used than otherwise, and still a nice surface finish can be secured With an increase in the coarse aggregate, the quantity of cement in the pavement is automatically reduced, but this does not affect to any extent, the composition of the mortar, which, according to our data, is the vital factor The more cement the mortar contains within certain limits, the longer the concrete is going to resist decomposition Our records show that such is the case Why should we monkey with another theory, reducing the cement content to a point where we are not sure the durability of the concrete will not be affected

During the past seven years we have not made a change in the composition or method of fabricating concrete pavements We use a definite quantity of coarse aggregate per bag of cement, and if we find the cement is not working in a desirable manner, we go into the field and find out what the trouble is, and correct it Some of these pavements are now seven years old, yet in some cases the broom marks have not worn off In one particular case, there is not a single transverse crack or broken corner, or one square foot of peeling These results indicate that the methods we are using are producing pavements that will certainly give the service desired and anticipated

Mr A A Levison, *Blaw-Knox Company* It is interesting to note the development of vibratory equipment as used in France, which was so well described by Professor Crandell, compared with the development of similar equipment in this country It is quite evident that the equipment used for vibratory concrete pavements in France, and I believe that this applies to other foreign countries, does a much more violent and powerful job than the types of equipment that have been used in this country.

I might say that those interested in the manufacture and development of equipment for vibrating concrete for paving work are going to be somewhat perplexed, as to whether to develop equipment that will give the utmost or the ultimate results from the standpoint of improving the density and strength of concrete through the vibratory method, or whether to stop short of that goal and "tickle" the concrete partially to obtain partial results from the vibratory method I, for one, would be very happy to receive suggestions from any of the members here, or especially those that have had experience with the vibratory method of building concrete pavements,—such suggestions would help clear the atmosphere as to the amount of vibration and, incidentally, the type of equipment as affected by the amount of vibration that is desired

In connection with equipment for the vibratory method of building concrete slabs, I think I not only speak for the Company I work for in that connection, but also for others who are developing, planning and thinking in terms of equipment to be used for the vibratory method

Prof C H Scholer, *Kansas State College* I was very happy to learn that the French have adopted the practice of ramming concrete Most of our ideas and efforts run in cycles When we first started we placed concrete of low mortar content, with but little water, by means of ramming Gradually we added more water, and with the advent of mechanical mixing and transporting, went to the extremes of very wet and fluid concrete We are now slowly returning to the drier types It seems to me that a pavement is an ideal place in which to try out rammed concrete, and I hope that some of our manufacturers develop equipment which may be used in placing dry concrete on our highways