THE EFFECT OF GOOD VIBRATION ON THE DURABILITY OF CONCRETE PAVEMENT

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Because a noticeable difference in durability of concrete pavements in Colorado seems to be associated with differences in consolidation and void content of the concrete, an effort has been made to determine the relationship. Test sections were laid out on 2 pavements; one was composed of a fine-aggregate mix and one was composed of a coarse-aggregate mix. The paver used with the coarse-aggregate mix was equipped with a surface pan vibrator and 2 internal vibrators that could be spaced for any desired setting. The other test sections had internal vibration by vibrators having eccentrics with 4 different diameters and 3 different vibration speeds. In addition, the angle of the vibrators was changed, as was the height of the vibrator from the base of the slab. Paver speeds were also varied from 10 to 19 ft/min. After having been in place for only 4 months, little can be said about durability of the concrete, but much has been determined about consolidation and segregation of the particles. To acquire good consolidation, $1\frac{1}{4}$-in. slump concrete required considerable vibration. Proper amplitude, frequency, and spacing of vibrators will provide up to 100 percent consolidation of concrete pavements without segregation of the aggregate. The nuclear density device is a reliable indicator of the consolidation of freshly poured concrete pavement and, when used by a capable operator, may be used to check and control densities during construction.

•A COMPARISON of the performance of concrete pavements in Colorado to the effort during construction to vibrate the concrete will reveal a consistent relationship. Where the effort and cost were relatively high, the wearing surface has usually provided good, maintenance-free service. Where very little attention was given to consolidation of the fresh concrete, the ensuing years of heavy loads, studded-tire use, and freezing weather have left the surface badly abraded.

Figure 1 shows the results of a cursory investigation of concrete pavements in Colorado over which there has been considerable traffic in the past 10 years. The percentage of densification shown in the figure is based on core weights and rodded cylinder tests. No doubt factors other than vibration such as age, air entrainment, and water-cement ratio affect durability of concrete pavements, but densification appears to be one factor that we might improve by means of better specifications. At the present time, many specifications for the placement of concrete are vague in regard to consolidation.

PRESENT SPECIFICATIONS

The following wording of the standard Colorado specification for consolidation of pavements is typical of that used by many other construction agencies:

> Vibrators for full width vibration of concrete paving slabs may be either the surface pan type or the internal type with either immersed tube or multiple spuds. They may be attached to the spreader or the finishing machine, or may be mounted on a separate carriage. The frequency of the surface vibrators shall not be less than 3,500 impulses per minute and the frequency of the

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internal type shall not be less than 5,000 impulses per minute for tube vibrators and not less than 7,000 impulses per minute for spud vibrators.

Some doubt is created by other standard specifications such as those of the U. S. Corps of Engineers that state, "Vibrating equipment shall be of the internal type, and the number and power of each unit shall be adequate to properly consolidate all of the concrete. The amplitude of vibration shall be sufficient to produce satisfactory consolidation of the concrete with the vibrator spacing used." The main questions are, Will an effort to consolidate concrete pavements during construction consistently increase pavement durability? What realistic densification effort should be specified to acquire durable concrete pavement?

This project was started in an attempt to help answer these 2 questions. Interest from other agencies such as the Highway Research Board, the Corps of Engineers, The American Concrete Paving Association, and other state highway departments has been high, indicating that the problem is universal. The Federal Highway Administration approved our request for this study in April 1970 and made some very helpful suggestions involving procedure and items for investigation. Contractors and suppliers in the area readily agreed to provide equipment for the study.

LABORATORY FINDINGS

Two classes of concrete are commonly used for concrete pavements in Colorado. The coarse-aggregate mix (Class A) is made up of about 65 percent plus No. 4 particles, 35 percent sand, and 6 sacks/cu yd of cement. The fine-aggregate mix (Class AX) is made up of about 35 percent plus No. 4 particles, 65 percent sand, and 6½ to 7 sacks/cu yd of cement. The consolidation characteristics of the coarse-aggregate mix were investigated north of Denver on the 2-mile, 4-lane project I270-6(7). Consolidation studies on the fine-aggregate mix were made in northeastern Colorado on the 15-mile, 4-lane project I80S-2(20) and on the 23-mile, 2-lane project I70-5(21). The designed mixes for two of these projects were investigated in the laboratory prior to and during construction. Table 1 gives typical values determined in the laboratory with each mix.

An attempt was made to determine both the static pressure and the vibratory effort to consolidate both classes of concrete. The results shown in Figure 2 indicate that

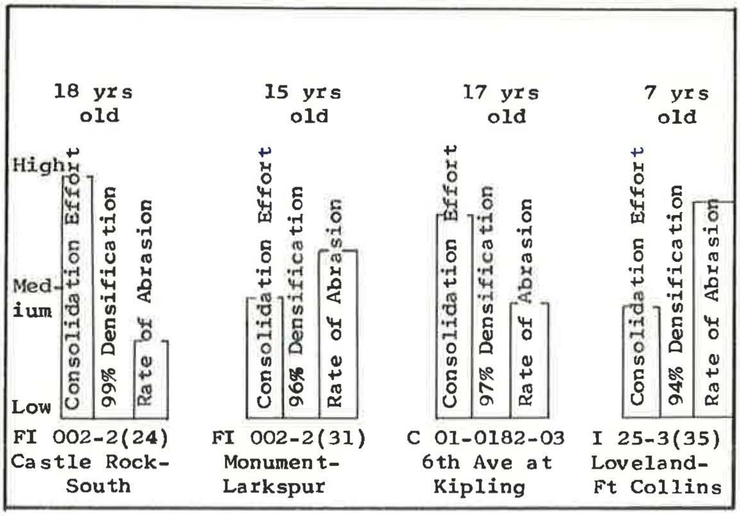

Figure 1. Consolidation effort indicated by extra work orders and close vibrator control.

TABLE 1

CHARACTERISTICS OF CONCRETE MIXES

Characteristic	Fine-Aggregate Mix on Project I80S	Coarse-Aggregate Mix on Project I270
Theoretical density air free, pcf	147.56	152.24
Theoretical density 4 percent air, pcf	141.66	146.15
Average rodded density, pcf	140	146
Average density of cylinders from field, pcf	138	145
Average density of beams from field, pcf	137	145
Swiss hammer readings, psi	2,800 to 3,300	3,400 to 4,100
Sonic modulus of elasticity, psi	1,185,700	1,356,700
Average 14-day beam strength, psi	450	450
Average 28-day cylinder strength, psi	4,470	4,480
Water-cement ratio	0.45	0.44

there is considerably more effort needed to consolidate 1-in. slump concrete than 2-in. slump concrete. Because both construction paving projects were scheduled to use 1- to 1½-in. slump concrete, it is easy to imagine that, unless there was good vibration on both projects, the number of voids (rat holes) would be large.

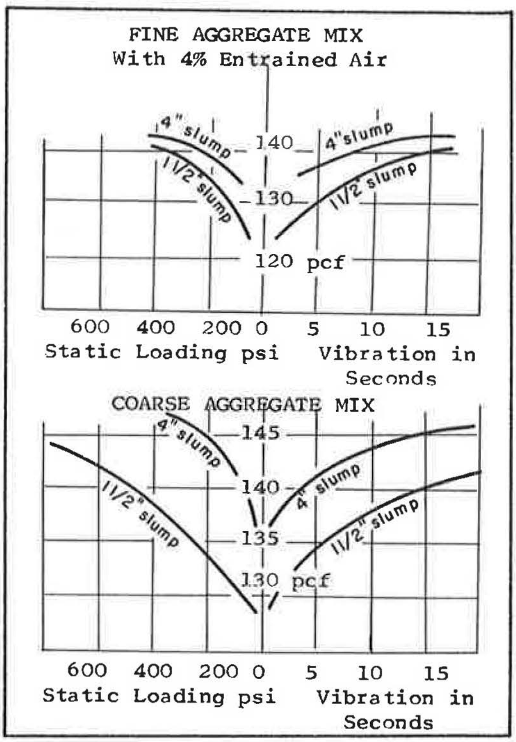

Figure 2. Effort necessary to consolidate stiff and plastic mixes as indicated by vibration in the laboratory and static loading.

From unvibrated samples of 1¼-in. slump concrete prepared in the laboratory, it appeared that 127 pcf might be the lower limit of density that we could ever expect in the field for the fine-aggregate mix. The oscillating screeds provide some consolidation, however, so a value of 130 to 132 pcf appeared to be a more realistic value to expect as a lower limit for density values of the fine-aggregate mix. The paver for the coarse-aggregate mix was a "form" type equipped with a vibrating pan. Internal vibrators were added to provide the needed information for this research. The relationship between density and void space is shown in Figure 3.

FIELD TEST LAYOUTS

With some knowledge derived from laboratory tests, it was possible to lay out a series of test sections on the paving projects that would provide information on consolidation by 4 different sizes of vibrators. These sections would also serve as durability test sections from 1970 until 1975 or longer, because both roadways would be serving about 8,000 vehicles per day. Data on the layout of the test sections and the variations in vibrators are given in Tables 2 and 3.

On project I80S where the fine-aggregate mix was used, the unaltered or "control" sections were usually in the passing lane next to the experimental driving lane.

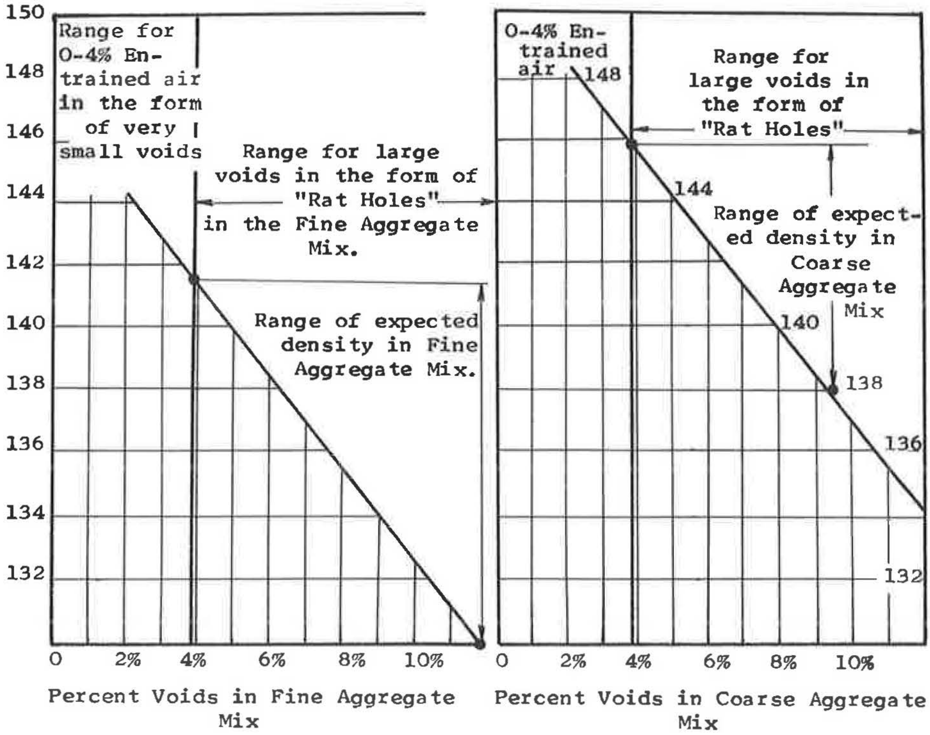

Figure 3. Relationship between density and percentage of voids for the fine-aggregate and the coarse-aggregate mixes.

TABLE 2

LAYOUT OF TEST SECTIONS FOR FINE-AGGREGATE MIX ON PROJECT I80S

Paver Speed (ft/min)	Amplitude of Vibration (eccentric diameter in in.)	Approximate Spacing Between Vibrators (in.)	Angle of Vibrator (deg)	Height of Vibrator From Base (in.)	rpm of Vibrator	Section	Station	Typical Density (pcf) Over Vibrators	Typical Density (pcf) Between Vibrators
13	1⅞	24	0	—[a]	9,000	12[b]	4994+35-4997+65	137	134
			0	5	9,000	13[b]	4997+65-5000+50	137	133
			30	—[a]	9,000	14[b]	5000+50-5003+50	137	133
			30	—[a]	10,800	5	4940+00-4913+50	139	136
	1⅝	15	0	—[a]	9,000	8	4961+50-4968+75	135	134
			0	—[a]	10,800	9	4970+50-4978+02	138	136
			0	5	9,000	7	4949+25-4958+40	135	135
			0	5	10,800	6	4940+00-4948+50	137	136
			30	—[a]	9,000	11	4987+50-4994+35	134	133
			30	—[a]	10,800	10	4978+75-4986+50	138	136
	1 7/16	12	0	—[a]	9,000	16	5013+50-5018+50	135	133
			0	—[a]	10,800	15	5008-50-5013+50	137	135
			0	5[c]	9,000	17	5024+50-5032+00	135	133
			0	5[c]	10,800	18	5032+00-5038+50	137	135
			0	5[c]	10,800	19	5040+50-5042+50	136	134
			30	—[a]	9,000	21	5049+50-5057+00	135	134
			30	—[a]	10,800	20	5042+50-5049+50	138	136
	1¼	9	0	—[a]	9,000	23	5088+50-5095+50	134	133
			0	—[a]	10,800	22	5081+50-5088+50	136	135
			0	5	9,000	24	5095+50-5100+50	134	133
			0	5	10,800	25	5100+50-5107+50	136	135
			30	—[a]	9,000	27	5114+50-5122+00	134	133
			30	—[a]	10,800	26	5107+50-5114+50	135	133
10	1⅞	12	30	5	10,800	1	4874+54-4880+40	140	136
19	1⅞	12	30	5	10,800	2	4880+60-4887+68	139	135
13	1⅞	12	30	5	10,800	3	4888+00-4894+42	140	135
16	1⅞	12	30	5	10,800	4	4894+60-4901+50	139	135

[a]Midway between base and top of surcharge. [b]Passing lane; all other test sections in driving lane. [c]Fast power speed.

TABLE 3

LAYOUT OF TEST SECTIONS FOR COURSE-AGGREGATE MIX ON PROJECT I270

Amplitude of Vibration (eccentric diameter in in.)	Spacing Between Vibrators (in.)	rpm of Vibrator (in air)	Section	Station	Typical Density (pcf)	
					Over Vibrators	Between Vibrators
1⅞	12	7,000	16	95+50-97+00	144	144
		9,000	17	100+50-102+00	145	145
		11,000	18	104+00-105+50	146	146
	18	7,000	15	94+50-95+50	144	143
		9,000	14	93+50-94+50	145	144
		11,000	13	91+27-93+50	146	144
	24	7,000	10	85+10-85+96	143	140
		9,000	11	85+96-87+43	144	141
		11,000	12	90+27-92+27	145	143
1⅝	12	7,000	3	72+00-73+50	143	141
		9,000	2	70+60-72+00	144	143
		11,000	1	68+20-70+60	145	144
	18	7,000	4	73+60-75+50	143	141
		9,000	5	75+50-77+50	144	141
		11,000	6	77+50-78+40	144	141
	24	7,000	9	81+50-83+50	143	138
		9,000	8	80+50-81+50	144	139
		11,000	7	78+40-80+50	144	140
	30	11,000	X	83+63-84+60	144	139
1$\frac{7}{16}$	12	7,000	22	109+75-111+00	142	140
		9,000	23	111+00-112+25	143	140
		11,000	19	106+00-107+30	144	143
	18	7,000	21	108+50-109+75	143	140
		9,000	24	114+50-116+00	144	141
		11,000	20	107+30-108+50	145	142
	24	7,000	27	118+00-119+00	143	140
		9,000	25	116+00-117+00	144	140
		11,000	26	117+00-118+00	145	141
1¼	12	7,000	28	119+70-121+00	142	141
		9,000	29	121+00-122+00	143	142
		11,000	33	133+00-134+00	144	143
	18	7,000	36	136+50-137+50	141	140
		9,000	35	135+25-136+50	142	141
		11,000	34	134+20-135+25	143	142
	24	7,000	31	124+00-125+50	141	139
		9,000	30	122+85-124+00	142	140
		11,000	32	125+50-127+00	143	141

Occasionally the passing lane became the experimental lane and the driving lane was designated as the control section. The base course for this project was a 4-in., 3 percent SS-K emulsified asphalt-treated sand. The paver and vibrator mounting are shown in Figures 4 and 5.

On project I270 where the paver was equipped with a surface pan vibrator operating at 4,100 rpm, only 2 internal vibrators were used for each test section because the large auxiliary 189-cycle, 15-kw generator for the vibrator used on project I80S was not available. A smaller auxiliary 5-kw generator was used for the 2 vibrators. One internal vibrator was mounted 32 in. from the edge of the driving lane shoulder, and the other was positioned 12, 18, or 24 in. from the first vibrator for different test sections. The remainder of the 24-ft roadway became the control section, although there were many control sections placed between test sections as well. The base course was a 4-in. layer of crushed gravel and sand. The form

Figure 4. Paver used on project I80S with 15-kw, 180-cycle generator on right front leg of paver.

paver and vibrator are shown in Figures 6 and 7.

The vibrators on both pavers were changed at the end of the day so that the changeover to different eccentrics would not interfere with the contractor's operation. The rpm of the vibrator (frequency) and the angle could be changed while the pavers were in motion. Inspectors measured speed of the paver every 15 min or whenever there appeared to be a change. There were occasional "stops" due to the paver or haul truck slowdown. All such irregularities were documented as to location so that future coring and testing would not be affected by them.

Figure 5. Internal vibrator mounted on paver.

In addition to the regular tests for control of the construction, special tests recommended by the Federal Highway Administration officials were performed for segregation of particles, density, air content, and pressure around the vibrators. Selection of the sample for the particle size analyses was made in the finished pavement by pushing a 21-in. diameter cylinder (bottomless garbage bucket) into the mix and scooping out the top third, middle third, and bottom third of the concrete into separate containers for separate tests.

Probably the most valuable information was obtained with the nuclear device that was used to measure density of the concrete immediately after placing. A means was devised for opening a small hole in the pavement and inserting the probe in a very exact manner. Within 3 min after the pavement was placed, a wet-density value could be determined. Figure 8 shows the use of the nuclear tester on project I80S. Figure 9 shows the use of the open-end cylinder for sampling fresh concrete for the particle size tests to determine segregation of the aggregate.

FIELD TEST RESULTS

Test results from this study will be in the process of development for several years. This is particularly true for durability tests that will require thousands and even millions of vehicle traverses to tell the complete story. However, much information about consolidation has already come to light. Average densities determined for the test sections are given in Tables 2 and 3. From the available data on field consolidation, it

Figure 6. Form paver used on project I270 with machine used to insert plastic transverse weakened-plane joint and with bridge for burlap drag.

Figure 7. Internal vibrator mounted on paver and "wake" developed as vibrator passes through 1½-in. slump concrete.

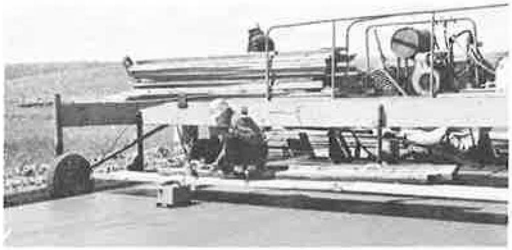

Figure 8. Nuclear test being taken in fresh concrete to determine density immediately after laydown.

Figure 9. Sampling procedure for particle size analysis.

appears the the density limits predicted from laboratory tests are quite applicable. There were densities as low as 127 pcf and as high as 140 pcf from cores and nuclear readings in the fine-aggregate mix.

On project I270 where the coarse-aggregate mix was used, the typical density pattern from the cores and nuclear readings was supplemented by density values from beams sawed out of the pavement. The coarse-aggregate mix varied in density from 138 to 146 pcf. Low densities were accompanied by a high percentage of rat holes. Soon after coring operations began, testers found the need for a procedure to measure the bulk specific gravity rather than the specific gravity obtained by the usual procedure of weighing cores in air and in water and basing the density on the difference between these 2 values. Bulk specific gravity was finally determined by sawing the ends off the cores as squarely as possible. The density was then based on the weight in air and a volume calculated from the height and the diameter. Some of the samples had 5 or 6 percent air voids in addition to the entrained air and this procedure became necessary even though it required more time to perform.

Even after everyone was satisfied that the procedure for determining density from the cores was giving accurate results, it was apparent that the density data were not going to present a perfect pattern. Computer outputs showed rather poor correlation of density with vibrator effort, and standard deviation values were high. The trouble appeared to be associated with erratic slump values during construction. Apparently slump was one of the most important variables in the study, and no special significance had been attached to it in tests on project I80S or project I270. Data had been recorded for slump values throughout the tests, but neither of the 2 test sites had test sections with variables and controlled slump values.

By chance, paving on project I70-5(21) in eastern Colorado between Seibert and Bethune was about to start when the need was realized for more data on slump. The aggregate for this project was similar to that for project I80S and so was the designed mix. A conference with representatives of the Federal Highway Administration resulted in approval for the establishment of the additional experimental sections just south of Vona (Table 4). A discussion of this project follows.

TABLE 4

FIELD TESTS ON PROJECT I70 FOR THE EFFECT OF SLUMP ON CONSOLIDATION

Station	Slump (in.)	Density (pcf) at Distance From Vibrator			
		0 in.	6 in.	12 in.	18 in.
1958+50-1957+75	2¼	140	138.5	137.5	135.5
1956+85-1956+38	1	139	138	136	134
1954+45-1954+00	3	139	138	136	133
1953+85-1953+80	½	138	136.5	134.5	132
1950+18-1950+00	1½	140	138.3	137	135.2
1949+82-1949+52	4	133.5	132	131	130
1948+05-1947+93	½	138	136.5	134.5	132

ANALYSIS OF DATA

Effect of Slump on Density

Laboratory tests on the coarse-aggregate mix and on the fine-aggregate mix showed that, for a particular vibrator effort, the final density depended very much on the slump or consistency of the mix. The tests were made in molds 6 in. wide, 5 in. deep, and 48 in. long in order that a small vibrator with a $^3/_4$-in. eccentric and 5,500 rpm frequency might be pulled through the mix at approximately 10 fps. The results are shown in Figure 10.

The density appears to increase approximately 2 pcf as the slump increases from $^1/_2$ to 2 in., but it shows a gradual decrease thereafter because the specific gravity of water is about a third of the specific gravity of cement and aggregate. The flexure strength on the beams made from these mixes showed that, although the $^1/_2$- and 1-in. slump concrete contained large air voids, it was stronger than the concrete made with 3- and 4-in. slump concrete.

Field tests to determine the effect of slump on consolidation were performed on project I70 by using a paver equipped with 11 internal vibrators spaced as follows from the north edge to the south edge of the pavement: 0.5, 2.5, 2.7, 2.4, 2.6, 2.5, 2.0, 0.9, 2.2, 2.5, and 0.6 ft.

The densities given in Table 4 for the different mixes indicate the increase in consolidation that may be expected with 2-in. slump concrete as compared with less than 1-in. slump concrete. The laboratory and field tests agree quite well that slump values in the 2-in. range allow the vibrators to develop densities approximately 2 pcf higher than would be developed with the low slump of $^1/_2$ in. or with the high slump of 4 in.

Figure 11 shows a summation of the findings from field tests with the $1^7/_8$-in diameter eccentric on projects I80S and I270 after appropriate allowance is made for slump. The estimated level of compaction achieved by each type of vibration is also shown.

Effect of Vibrator Angle and Height

Vibrators were arranged on all the pavers so that their angles could be changed from 0 deg, or horizontal, to 30 deg during paving operations. No difference in consolidation of the concrete could be attributed to this change of angle so long as the entire vibrator was within the plastic concrete. When the height was varied far enough to withdraw the vibrator from the concrete mix, there was a noticeable loss of consolidation effort imparted to the concrete. There was also a noticeable gain in frequency, as the vibrator

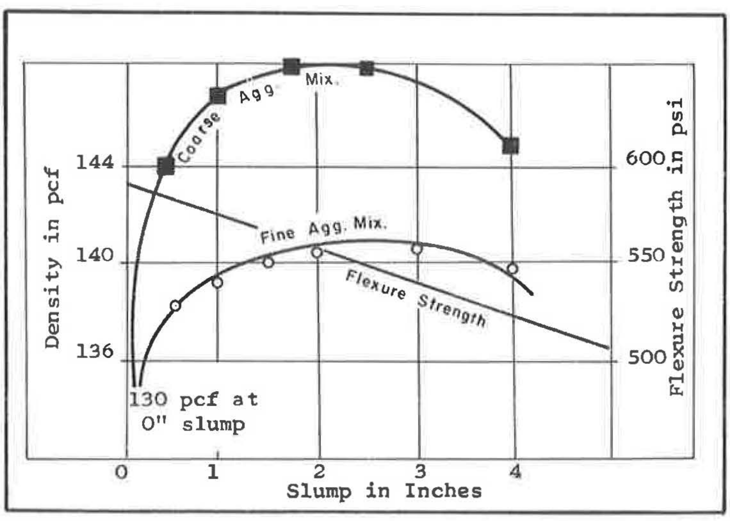

Figure 10. Results of laboratory tests.

was pulled out of the mix, indicating that the vibrator was not working against so much back pressure and, hence, was doing less work.

Some paver operators insist that a slight angle of the vibrator assists in "packing" the mortar in. No special tests were performed to affirm or refute this contention because the regular series of tests showed no advantage in placing the vibrators at an angle.

The tests on this project seem to indicate that a horizontal vibrator (or one only slightly tipped), placed at the midpoint of the slab height, is in optimum position for consolidation of the plastic concrete.

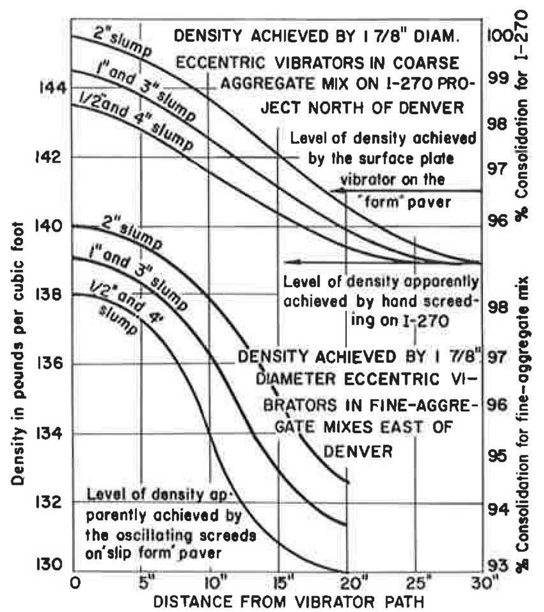

Figure 11. Relationship between density and distance from vibrator path for fine-aggregate and coarse-aggregate mixes.

Effect of Paver Speed on Density

The variation of density was checked with paver speed by operating the paver on project I80S as near as possible at constant speeds of 10, 13, 16, and 19 ft/min with the 1⅞-in. diameter vibrators operating at 9,600 rpm in the mix and 10,800 rpm in air. Uncontrollable variations caused by changes in slump and base course preparation resulted in considerable scatter of points. There was only the slight indication of loss in density with increased speed shown by test sections 1, 2, 3, and 4 (Table 2).

With a difference of only 1 pcf (and this directly over the vibrator path) between the 19-ft/min speed and the 10-ft/min speed, it would have to be agreed that paver speed between these ranges resulted in very little variation in consolidation of the concrete with the big paver and the large high frequency vibrators.

Effect of Amplitude and Frequency on Density

According to the theory and research, the amplitude and the rpm of vibration determine the force or pressure that the vibrator is able to impart to the concrete. For the vibrators used, the relationship is shown in Figure 12. At 10,800 rpm (the normal

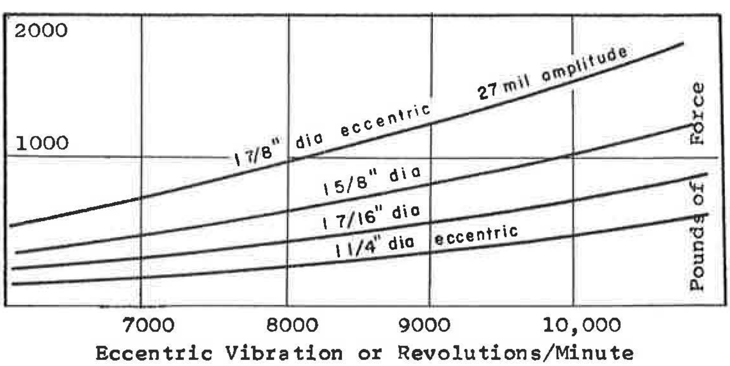

Figure 12. Force imparted by vibrators used on test sections of projects I80S and I270.

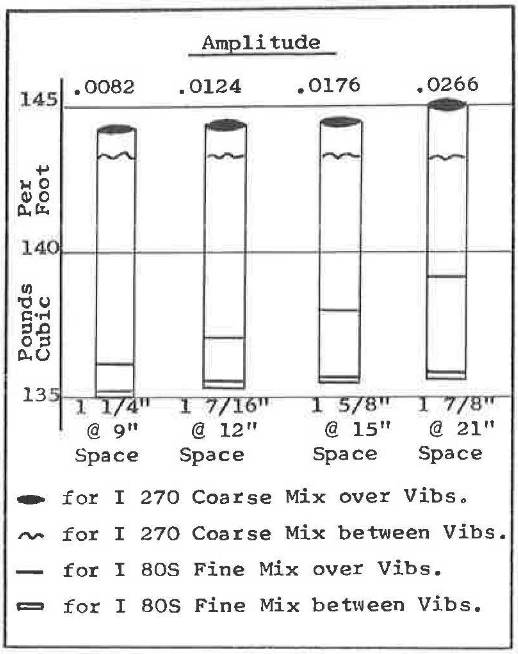

Figure 13. Variation of density with amplitude of vibration for different eccentrics.

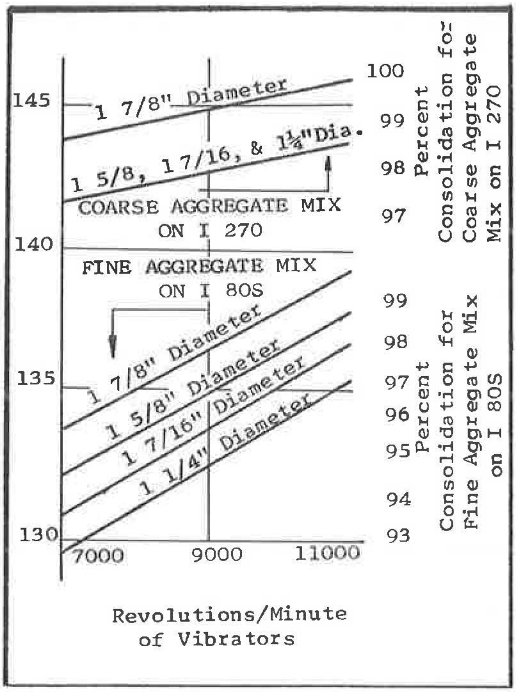

Figure 14. Variation of density with frequency of vibration.

vibration in air for the internal vibrators used on this research project), the densities developed over the vibrator path and between vibrators were as shown in Figure 13. The same vibrators run at different frequencies showed a relationship of vibration rate with density as shown in Figure 14.

From these relationships, it might be concluded that there is a gradual increase in density with an increase in either amplitude, frequency, or both. Not indicated by the data but possibly true is the fact that low slump grouts react most effectively to frequencies between 7,000 and 15,000 per minute. It is easy to imagine that, if the frequency and amplitude were too high, there would be a loss of vibrator-grout contact. What is desired is the proper number of "differential pushes" in rapid succession to effectively liquidize a stiff mix that has large entrapped air voids. Under liquid conditions, the air bubbles rise to the surface and are expelled, leaving a strong (because it has a low water-cement ratio) well-consolidated mass that should be durable.

The graphs show that the 1⅞-in. diameter eccentric vibrated at 10,800 vibrations per minute in air and 9,600 rpm and in the mix will consolidate both types of concrete close to 100 percent of the laboratory rodded density value. The other eccentrics vibrated at somewhat lower speeds are not quite so effective, even when spaced closer together.

Effect of Vibration on Strength

Figures 15 and 16 show the typical appearance of 700 cores taken and photographed for this study. In general, the fine-aggregate mix from project I80S showed the greater percentage of large air voids. However, in the case of both the fine-aggregate mix and the coarse-aggregate mix from project I270, there were fewer voids in the cores taken in the path of the vibrator than between the vibrator paths. In fact, many of the 2-in. diameter cores taken between vibrator paths on project I80S broke during the drilling operation. Others must have been badly fractured because some of them showed

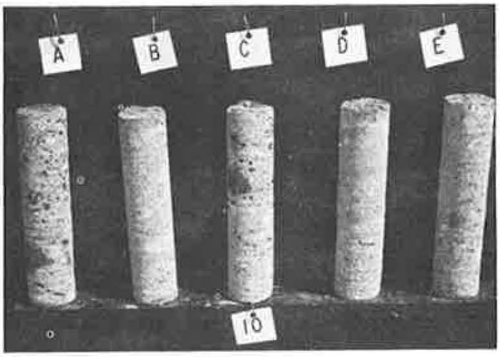

Figure 15. Cores from section 10 on project I80S where fine-aggregate mix was used (cores B and D were taken over path of vibrator, and cores A, C, and E were taken between paths of 1⅝-in. diameter eccentric vibrator).

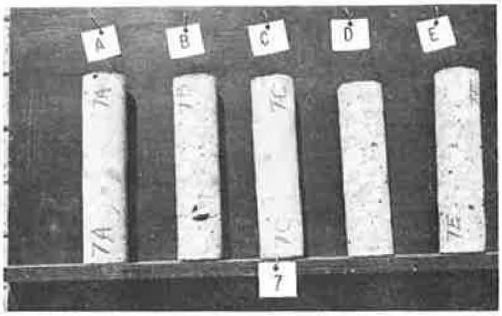

Figure 16. Cores from section 7 on project I270 where coarse-aggregate mix was used (cores A and C were taken over path of vibrator, and cores B, D, and E were taken between paths of 1⅝-in. diameter eccentric vibrator).

exceptionally low strength values when tested in the laboratory. In most cases, these low values were included in the data analysis because they generally reflect the overall strength of the pavement.

Compression test data are shown in Figures 17, 18, 19, and 20. Average values of 2-in. diameter cores 4 in. long show that the concrete in the path of the vibrators is on the average 10 percent stronger than concrete found between the paths of the vibrators on project I270 where the paver

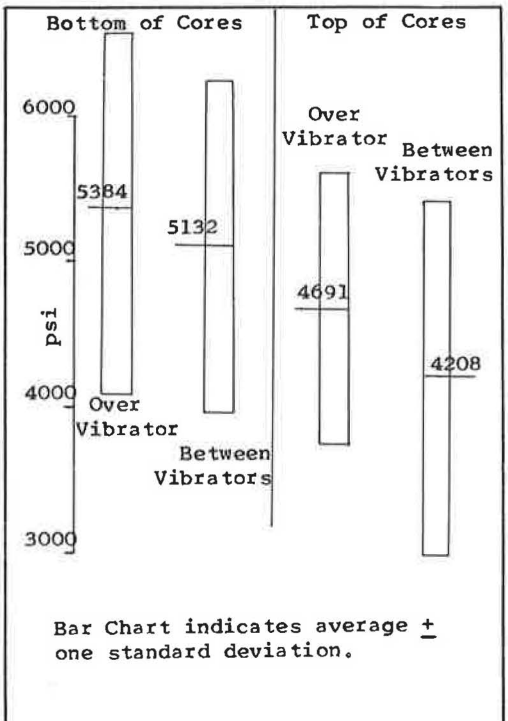

Figure 17. Comparison of compressive strength for top and bottom of concrete cores over and between vibrator paths on I270.

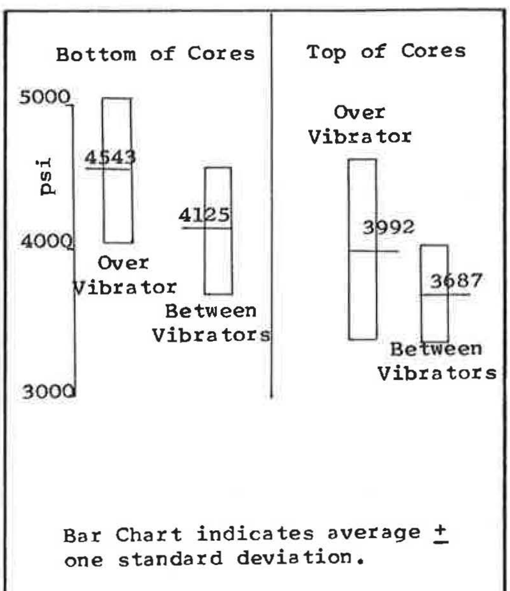

Figure 18. Comparison of compressive strength for top and bottom of concrete cores over and between vibrator paths on project I80S.

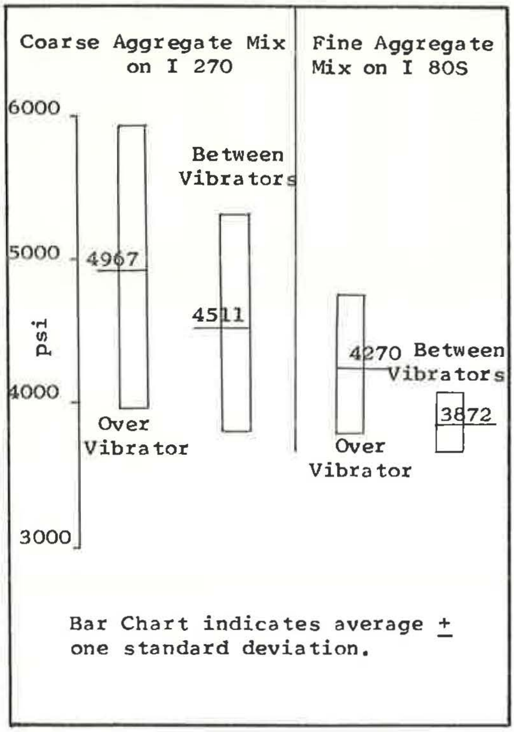

Figure 19. Comparison of compressive strength for concrete cores over and between vibrator on projects I270 and I80S.

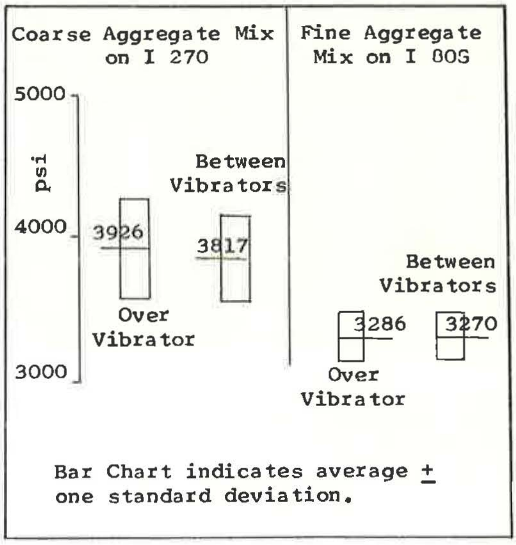

Figure 20. Comparison of compressive strength as indicated by Swiss hammer.

was equipped with a surface pan vibrator or on project I80S where only the internal vibrators provided the consolidation. The bottom 4 in. of the 8-in. slab appears to be slightly stronger than the top 4 in. (Figs. 17 and 18).

The Swiss hammer tests show lower strength values than the regular compressive tests for possibly 2 reasons: (a) They were taken when the concrete was only 28 days old, whereas the cores were broken when the concrete was 5 months old, and (b) the correlation between Swiss hammer readings and this particular concrete mix was not necessarily perfect. The general correlation supplied by the manufacturer was used to convert Swiss hammer readings to psi readings, and experience has shown this correlation to be a general one that does not apply to all mixes. However, the Swiss hammer readings do show that the concrete in the path of the vibrators is slightly stronger than the concrete between the vibrator paths. The standard deviation for Swiss hammer readings is certainly lower, indicating that the range of variance in readings is less on this nondestructive test than on the regular compression test.

Swiss hammer readings have shown very good correlation with performance of concrete pavements in Colorado. Figure 21 shows typical correlation and average core strength values from 3 projects that have been observed closely for cracking and abrasion by studded tires. It is interesting to note that Swiss hammer readings from 3 cores taken over paths of "dead" or nonoperating vibrators on project I80S showed values of 20, 22, and 24, which would correspond to psi values of 1,800, 2,000, and 2,400.

Data on the strength of beams cut from project I270 are given in Table 5 and indicate that the coarse-aggregate mix developed almost the same flexure strength with surface vibration as it did with a combination of surface vibration and internal vibration. The average strength of the beams tested with the top surface in tension is 10 percent higher than the average strength found when the beams were tested with the bottom side in tension. This fact may indicate a gain in strength due to additional surface vibration.

Figure 22 shows the gain in flexure strength as the density is increased from 144 to 146 pcf for beams taken from project I270. Based on limited data (24 flexure tests), flexure tests on project I270 indicate that there is a small increase in strength with an

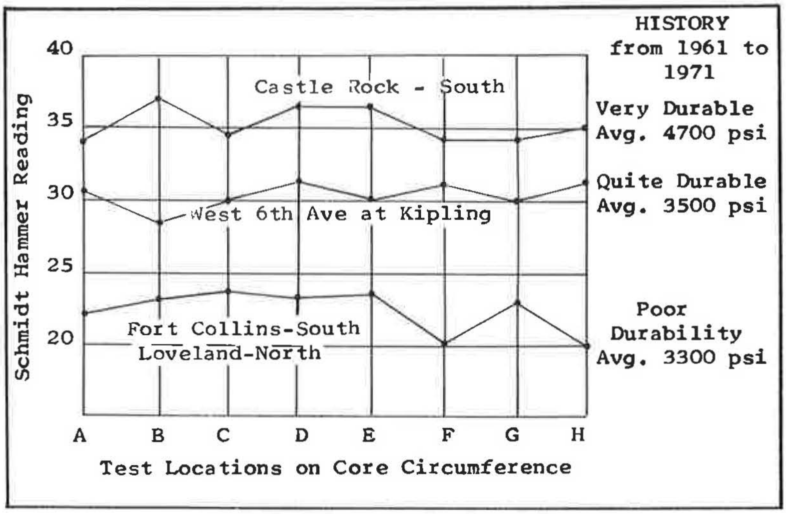

Figure 21. Swiss hammer test results.

TABLE 5

FLEXURE STRENGTH OF COURSE-AGGREGATE MIX ON PROJECT I270

Diameter of Eccentric (in.)	Distance From Internal Vibrator (in.)	Flexure Strength (psi) Surface Side up	Bottom Side up	Per ASTM C78	Density (pcf)
1¼	0 to 8	605	760	567	145
	8 to 16	707	787	553	145
	16 to 24	619	683	498	144
	24 to 32	673	713	639	144
1⅞	0 to 8	713	702	582	146
	8 to 16	623	743	633	146
	16 to 24	679	702	668	145
	24 to 32	598	638	538	144

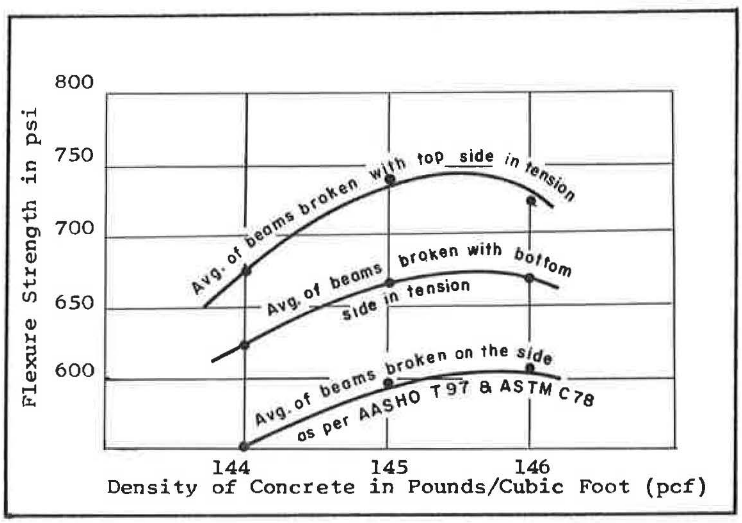

Figure 22. Flexure strength of coarse-aggregate mix from project I270.

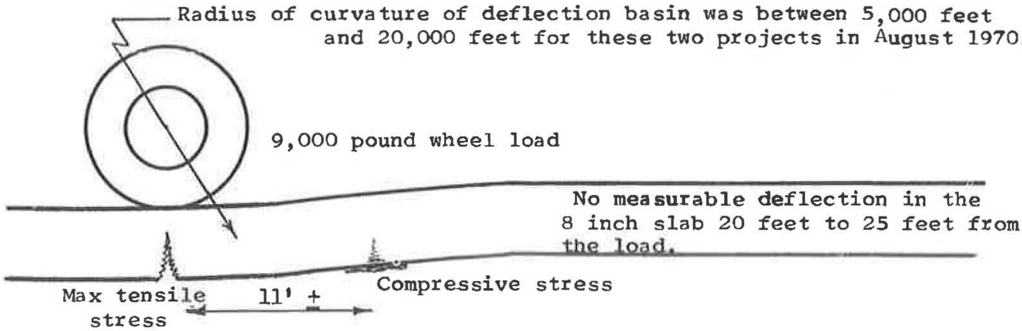

Figure 23. Texas basin beam tests on projects I80S and I270.

increase in density if all other factors remain steady. However, when surface vibration is provided as well as internal vibration, there is very little indication that the internal vibration has contributed much to an increase in strength.

A nondestructive field test, which was hoped would provide some information about the benefits of vibration, was the Texas basin beam evaluation for deflection of the test sections. The test is performed by the use of a 9,000-lb wheel load and a special beam with a deflection dial reading to $\frac{1}{10,000}$ in. (Fig. 23). Limited use of this deflection measuring system in Colorado had shown that it has reasonably good correlation with concrete pavement performance. The summary of findings is given in Table 6. When the test sections were only a month old, they did not show much effect of the different types of vibration. The radius of curvature of the deflection basin under the 9,000-lb wheel load is generally large (9,000 to 20,000 ft), and the induced stresses are quite low at the bottom of the slab. This information may be of more help in future evaluations than it appears to be at this time.

In summarizing the results of the strength tests, the point should be made that there seemed to be a greater indication of effect of vibration in the appearance and density of the cores than in the strength values. In other words, the overall average of the strength tests indicate only a small advantage in good vibration. From visual observation, there would seem to be a significant advantage in good vibration. This fact is not hard for testers and field engineers to understand after years of observing breaks on "ratty" cylinders made of low-slump concrete. It is very common for a porous cylinder made from a dry mix to show greater compressive strength than for a cylinder made from higher slump concrete that was vibrated down into a well-consolidated mass. There was some variation in factors such as slump, entrained air content, and subbase support on these 2 research projects during construction. The question that follows is whether durability will finally be associated more with strength, density, entrained air content, appearance, or with some other variable that is not apparent at this time.

Effect of Vibration on Pulse Velocity Readings

Field tests of the speed of an acoustic wave through concrete has been a method of evaluating the quality of concrete for many years. There are several reliable ways of producing a "pulse" and measuring the velocity, but one of the most recently developed instruments is the microseismic timer. This instrument was rented for an evaluation of test sections prepared for this study.

The instrument consists of a sliding drop hammer that produces a start pulse for the timer. When the elastic wave front in the concrete reaches the microseismic transducer (phonograph needle pickup), a stop signal is produced. The elapsed time is then indicated to the nearest millionth of a second by lamps on the timer panel.

Readings were made near the locations from which the cores were taken. There was a large scatter of points in the correlation between wave velocity density and distance

TABLE 6

AVERAGE VALUES FROM TEXAS BASIN BEAM TESTS MADE MIDWAY BETWEEN TRANSVERSE JOINTS ON PROJECTS I80S AND I270

Project	Section	Eccentric Diameter (in.)	rpm of Vibrator	Minimum Radius of Curve (ft)	Maximum Stress (psi) at Bottom of Slab: Tensile	Maximum Stress (psi) at Bottom of Slab: Compressive
I80S	1	1 7/8	10,800	15,154	84	15
	2	1 7/8	10,800	10,856	118	22
	3	1 7/8	10,800	13,892	91	15
	4	1 7/8	10,800	14,000	95	15
	5	1 7/8	10,800	13,988	94	15
	6	1 5/8	10,800	14,746	90	22
	7	1 5/8	9,000	12,365	103	15
	8	1 5/8	9,000	15,912	80	20
	9	1 5/8	10,800	14,522	88	38
	10	1 5/8	10,800	10,856	118	27
	11	1 5/8	9,000	16,670	76	50
	12	1 7/8	9,000	18,754	68	22
	13	1 7/8	9,000	14,746	87	19
	14	1 7/8	9,000	17,596	72	20
	15	1 7/16	10,800	15,912	80	19
	16	1 7/16	9,000	15,281	84	15
	17	1 7/16	9,000	15,154	84	22
	18	1 7/16	10,800	12,823	99	22
	19	1 7/16	10,800	13,352	95	22
	20	1 7/16	10,800	17,596	72	15
	21	1 7/16	9,000	15,281	84	23
	22	1 1/4	10,800	13,530	96	30
	23	1 1/4	9,000	15,281	84	22
	24	1 1/4	9,000	16,670	76	23
	25	1 1/4	10,800	23,814	53	15
	26	1 1/4	10,800	16,207	81	15
	27	1 1/4	9,000	18,546	76	15
I270	1	1 5/8	10,800	12,823	99	30
	2	1 5/8	9,000	11,907	106	23
	3	1 5/8	7,000	11,907	106	8
	4	1 5/8	7,000	9,261	137	31
	5	1 5/8	9,000	9,806	130	76
	6	1 5/8	10,800	8,774	145	31
	7	1 5/8	10,800	9,806	130	61
	8	1 5/8	9,000	8,335	152	84
	9	1 5/8	7,000	8,335	152	84
	X	1 5/8	10,800	9,261	137	46
	10	1 7/8	7,000	10,419	122	31
	11	1 7/8	9,000	10,419	122	31
	12	1 7/8	10,800	15,154	84	15
	13	1 7/8	10,800	12,823	99	15
	14	1 7/8	9,000	13,892	91	22
	15	1 7/8	7,000	5,557	228	23
	16	1 7/8	7,000	7,577	168	15
	17	1 7/8	9,000	10,419	122	15
	18	1 7/8	10,800	12,823	99	23
	19	1 7/16	10,800	11,907	107	15
	20	1 7/16	10,800	13,892	91	23
	21	1 7/16	7,000	11,907	107	15
	22	1 7/16	7,000	18,522	69	23
	23	1 7/16	9,000	13,892	91	31
	24	1 7/16	9,000	11,907	107	23
	25	1 7/16	9,000	18,522	69	23
	26	1 7/16	10,800	16,670	76	15
	27	1 7/16	7,000	15,154	84	15
	28	1 1/4	7,000	16,670	76	15
	29	1 1/4	9,000	18,522	69	15
	30	1 1/4	9,000	18,522	69	38
	31	1 1/4	7,000	13,892	91	15
	32	1 1/4	10,800	10,419	122	23
	33	1 1/4	10,800	13,892	91	15
	34	1 1/4	10,800	15,154	84	15
	35	1 1/4	9,000	16,670	76	15
	36	1 1/4	7,000	20,838	61	15

from the vibrator. This was probably due to variation in factors such as air content, slump, and surface finish. Figure 24 shows the correlation between wave velocity and vibrator location. Wave velocities may be slightly higher for the fine-aggregate mix on project I80S than for the coarse-aggregate mix on project I270 because project I80S concrete was 3 months older when tested and contained a half sack of cement more than the mix for project I270.

Figure 25 shows the correlation between modulus of elasticity within the range of a vibrator and completely beyond the range of vibrator. Young's modulus of elasticity was computed from the following:

$$E = \frac{\text{density } (1 + 0.3)(1 - 0.6)\text{vel}^2}{32.2(1 - 0.3)}$$

where 0.3 was used for the value of Poisson's ratio.

Although individual microseismic tests seem to indicate very little about the value of consolidation, overall averages of microseismic data seem to indicate some advantage in good vibration. It is very doubtful that the microseismic instrument could be used as a means of control for consolidation of concrete pavements in the field.

Effect of Vibration on the Modulus of Elasticity

ASTM Test C 215 was used to determine Young's modulus of elasticity. The testing consists of the use of an amplified variable frequency audio oscillator connected to a

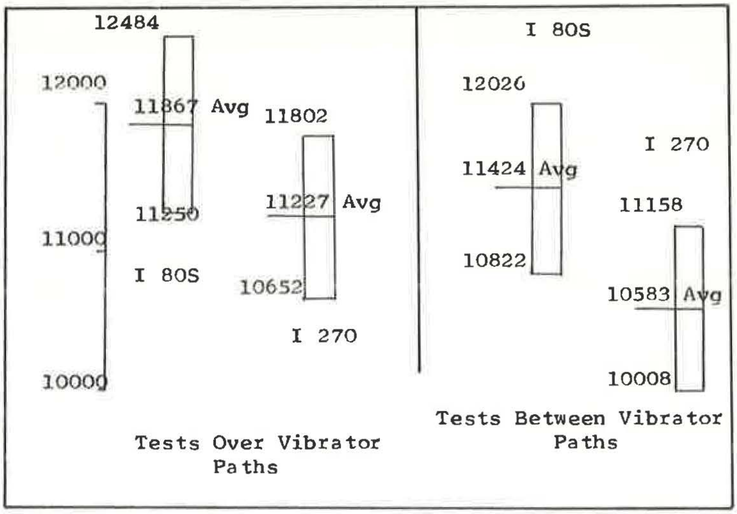

Figure 24. Impact elastic wave velocities for projects I270 and I80S.

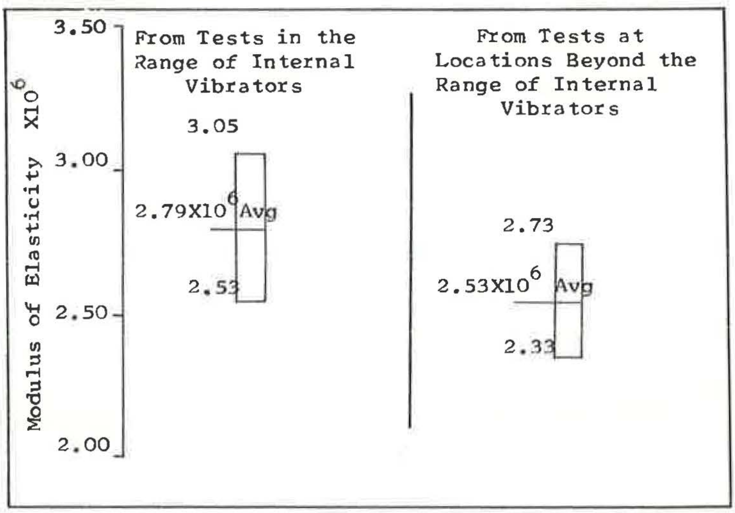

Figure 25. Modulus of elasticity values from project I270 (computed from pulse velocity device).

driving unit (modified audio speaker) that is fashioned to vibrate a concrete specimen. By adjusting the frequency of the oscillator and observing the reaction of the concrete specimen, as the vibrations are picked up with a phonograph cartridge and oscillograph, a frequency may be found that brings the specimen into resonance. A formula relating the frequency, weight, length, and diameter is then used to determine Young's dynamic modulus of elasticity. The presence of unsound material or invisible cracks is quickly detectable with this apparatus, and all cores taken for this study were tested to help classify and identify cores that were typical of certain areas. Figures 26 and 27 show the findings in regard to vibrator operations.

For both the fine-aggregate mix and the coarse-aggregate mix, modulus of elasticity values were greater for the concrete over the paths of the vibrator than for the concrete between the vibrators. Figure 27 shows that, for pavement sections on project I270

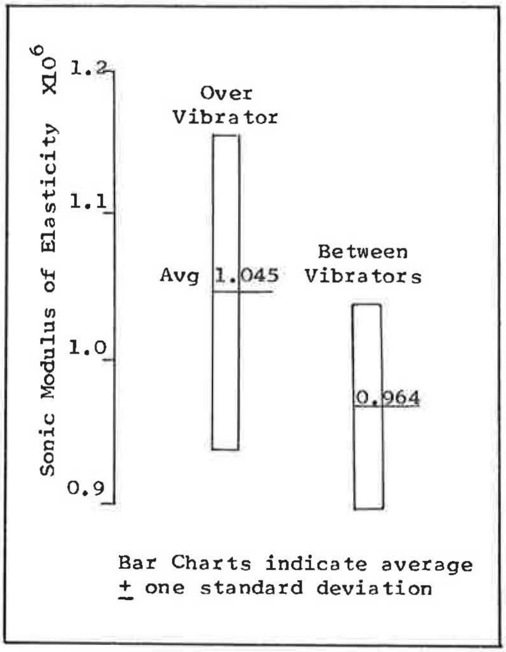

Figure 26. Sonic modulus of elasticity on cores from the fine-aggregate mix on project I80S.

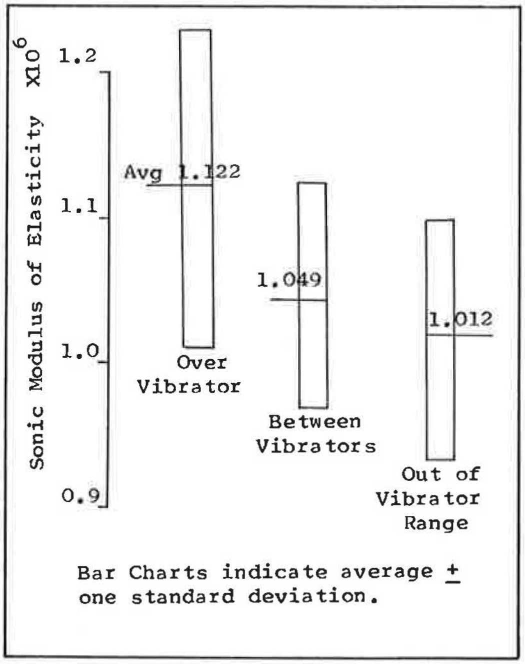

Figure 27. Sonic modulus of elasticity on cores from the coarse-aggregate mix on project I270.

(coarse-aggregate mix) where only surface pan vibration had been provided, the average modulus of elasticity was even less than it was between internal vibrators.

Effect of Vibration on Segregation

One of the main concerns of this study was to either confirm or invalidate the theory that heavy vibration causes segregation of the aggregate particles. This study has shown that it takes a great deal of vibration to cause segregation of particles in an 8-in. layer of concrete having only $1\frac{1}{4}$-in. slump. There was no visual indication of segregation of particles around any of the vibrated concrete that was placed on these 2 projects.

Sieve analyses of plus No. 4 aggregate on samples tested in the laboratory are given in Table 7. The data are too limited for the application of statistical analysis, but there is only a slight evidence of segregation on the coarse-aggregate mix. There is really none on the fine-aggregate mix.

Effect of Vibration on Entrained Air Content

It is generally agreed that heavy vibration will tend to expel all sizes of air voids in a concrete mix including the very small ones that are purposely implanted by means of additives to improve the freeze-thaw durability. Although a thorough study of the loss of this entrained air by vibration could be, and has been, the object of extensive research in that field alone, there is a possibility that some information along this line could be gathered from this study because of the control in the variation of amplitudes, frequencies, and paver speeds on the test sections.

The facilities for the measurement of pore size and number are available at the laboratories of a cement company in Colorado. Officials of that company readily agreed to perform tests necessary to determine entrained air content on cores from various test sections as well as cores from pavements with durable and nondurable service records in Colorado.

The results of a preliminary group of these tests will be available during the winter of 1970-1971. If it appears at that time that future efforts will be rewarding, a request

TABLE 7

SIEVE ANALYSIS OF NO. 4 AGGREGATE CORES FROM PROJECTS I270 AND I80S

Project	Portion of Core	Station	Sieve (percent passing) 1 In.	¾ In.	½ In.	⅜ In.
I270	Top 2.5 in.	76	76	51	25	14
		105	75	48	25	14
		115	72	49	24	12
		125	75	49	23	13
	Middle 2.5 in.	76	79	51	23	12
		105	74	47	23	12
		115	68	47	22	12
		125	75	47	23	12
	Bottom 2.5 in.	76	72	42	17	8
		105	69	44	20	12
		115	69	44	22	12
		125	74	47	20	11
I80S	Top 2.5 in.	4911	98	80	51	35
		4948	100	88	57	38
		4988	100	88	57	41
		4881	100	84	56	39
		5011	100	81	54	39
		5024	100	87	56	40
		5085	100	83	55	41
		5118	100	78	53	39
	Middle 2.5 in.	4911	100	82	50	35
		4948	100	86	54	37
		4988	100	85	50	37
		4881	100	84	49	35
		5011	100	85	54	38
		5024	100	86	55	38
		5085	100	86	59	43
		5118	100	84	55	41
	Bottom 2.5 in.	4911	100	83	51	33
		4948	100	85	55	37
		4988	100	84	49	35
		4881	100	84	51	35
		5011	100	82	52	37
		5024	100	85	57	40
		5085	100	84	51	38
		5118	100	83	55	39

for assistance in further work along that line will be made. At this time, records of field tests for entrained air at the test sections have been assembled for comparison with results on a limited number of core samples. The work that has been completed so far indicates that heavy vibration does not reduce the entrained air content to any appreciable extent.

Effect of Vibration on Pressure in the Grout

As a means of investigating the pressure in the mortar beneath the pavement surface on this project, a simple pressure measuring device was constructed with a rubber tip and glass tubing for readings of pressure in inches of water. The tests confirmed the findings of Ore and Straughan (1), U. S. Bureau of Reclamation engineers, that good vibration merely transforms a nonfluid mixture into a mixture that may become fluid enough to allow the behavior or effects of hydrostatic pressure. In other words, with this rather simple instrument, it was possible to detect the hydrostatic pressure of 0.66 psi (8 in. of concrete) in the immediate vicinity of an operating vibrator, but not when the vibrator was turned off or when it was several feet away from the sensor. The application of a new ⅟₁₆-in. diameter pressure cell, now being produced by a technical industry in California, may make it possible to more accurately determine pressure between vibrators and grout. Work along this line is under way in a cooperative effort.

Effect of Vibration on the Durability of the Concrete

An accurate evaluation of the effect of vibration on the durability of the concrete pavements placed for this study will depend on several years of observation. However, an attempt was made to predict the outcome by use of ASTM Test C 418 that makes use of a standard sandblast apparatus. After the surface of the concrete is exposed to the sandblast, a determination is made of the volume of the abraded material per square centimeter of surface area.

The Colorado Department of Highways had no previous experience with this abrasion test, and correlation of the results with actual pavement surface durability appears to be meager. However, technicians had no trouble performing the test approximately 400 times on surfaces of cores of the fine-aggregate mix on project I80S and the coarse-aggregate mix on project I270.

Results of the tests are shown in Figures 28 and 29. The fine-aggregate mix on project I80S showed very uniform abrasion coefficients of approximately 0.21 on concrete throughout the slabs, without apparent effect of the internal vibrators. Concrete in the bottom 4 in. of the slabs appeared to be slightly more durable than the concrete in the top 4 in.

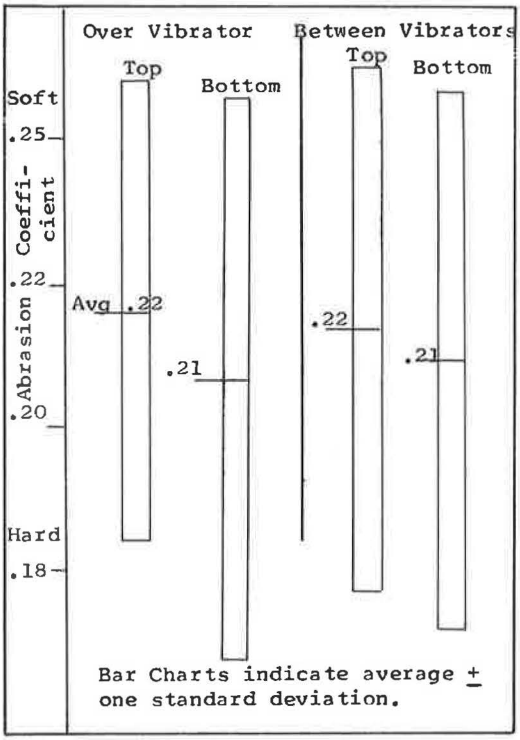

Figure 28. Abrasion coefficients for top 4 in. and bottom 4 in. on project I80S.

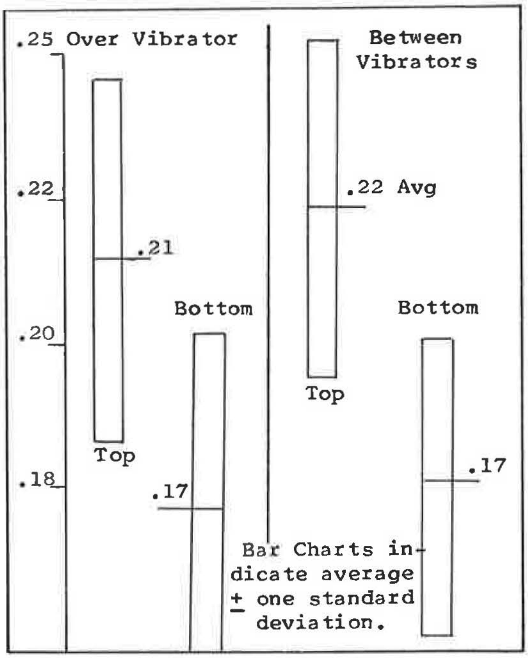

Figure 29. Abrasion coefficients for top 4 in. and bottom 4 in. on project I270.

A possible explanation for the increased hardness of the bottom of the 8-in. slabs from the coarse-aggregate mix on project I270 is that the vibration allowed the coarse aggregate to settle. It is a fact that, for both paving projects, the aggregate is more resistant to abrasion than is the mortar. However, the gradation tests taken separately at the upper third, middle third, and lower third of the slabs showed that only 2 percent less aggregate passed the $^3/_8$-in. sieve for the bottom third than for the top third of the slab, and so this does not back up the above explanation. Another possible explanation might be the ideal curing condition of the bottom of the slab as opposed to the top. However, project I80S did not show such a difference between tops and bottoms, and the curing on that project should have been similar to the curing on project I270.

On greatest concern is the fact that, although abrasion coefficients generally averaged 0.21 to 0.22 for interior surfaces of the concrete, the exposed or roadway surfaces generally averaged 0.40, which indicates much softer concrete. If the sandblast test is truly indicative of resistance to wear, the top $^1/_4$ to $^3/_8$ in. of the pavement is considerably softer than the interior. Future work on this project will be to investigate more thoroughly vibration effects on the wearing surface of the test sections.

Effect of Vibrator Spacing

A general summary of the results of various vibrator spacings is shown in Figure 11. Data for the coarse-aggregate mix were obtained from project I270 during August 1970, and data for the fine-aggregate mix were obtained from project I80S in June 1970 and I70 in October 1970.

Because of the surface plate vibrator attached to the coarse-aggregate paver (and perhaps the characteristics of coarse-aggregate mixes in general), the loss in density with increasing distance from the vibrator paths was greater for the fine-aggregate mix than for the coarse-aggregate mix. The loss in density for the first 6-in. distance is only about 1 pcf, but from the 6-in. to the 12-in. distance the loss is about 2 pcf for the fine-aggregate mix.

The research work on this project seems to show that, when the $1^7/_8$-in. eccentric (0.0266-in. amplitude) vibrators were run at 10,800 rpm and spaced 22 to 24 in. apart, the coarse-aggregate mix was adequately consolidated. On the other hand, the slump had to be very closely controlled between $1\frac{1}{2}$ and 2 in. for the same vibrator setup to obtain 97 percent compaction on the fine-aggregate mix. Similar findings for the $1^5/_8$-in. diameter (0.0176-in. amplitude), $1^7/_{16}$-in. diameter (0.0124-in. amplitude), and $1\frac{1}{4}$-in. diameter (0.0086-in. amplitude) were harder to assess because those vibrators were not used on project I70. However, the data given in Tables 2 and 3 show that at 10,800 rpm a 15-in. spacing is quite satisfactory for $1^5/_8$-in. vibrators, 11-in. spacing for $1^7/_{16}$-in. vibrators, and 8-in. spacing would be adequate for $1\frac{1}{4}$-in. diameter eccentric vibrators.

VALUE OF NUCLEAR TESTING EQUIPMENT FOR RAPID TESTS ON CONSOLIDATION

Although primarily designed for density tests on subgrades, bases, and hot-asphaltic concrete, the nuclear device proved to be a very effective instrument for measuring the density of plastic portland cement concrete immediately behind the paver. It was calibrated in the Denver laboratory by using specially prepared concrete blocks of various density, but the device had never been used in the field for density control of concrete paving.

The operator worked from a small movable bridge between the paver and the burlap drag. His order of procedure was as follows:

1. Measure from the edge of the concrete to find the exact location for the test;
2. Place a small wooden jig on the fresh concrete surface so that the dowel on the jig makes a clean vertical hole 8 in. deep and $^3/_4$ in. in diameter (the size of the probe on the nuclear device);
3. Remove the jig and replace it with the nuclear device by inserting the probe in the prepared hole;
4. Turn on the device with the timer set for 1 min;
5. Take the reading at the end of 1 min, compare it with the previously prepared calibration curve, and calculate the density; and
6. Fill the hole with a pat of concrete and trowel it over slightly (the burlap drag will completely obscure the marks left by the device).

The test results given in Table 8 show almost as many high readings as low readings, indicating that the results are only slightly skewed to the left. The nuclear readings were overall 0.37 lb lighter than the average of all the readings. The operator was forced to take readings for this study with great haste, because of the desire to interfere with the contractor's operations as little as possible. Obviously a set of 3 readings at each location and an average of these readings would have resulted in values with a smaller standard deviation than the overall average of 1.3 pcf determined for this study. Actually, considering the variable slump and characteristics of the aggregates under field conditions, it is very possible that the density of the concrete actually varied within the range of 1 to 2 pcf from place to place within the test section.

The excellent performance of the nuclear device suggests the possibility of its use to control consolidation during construction of concrete pavements in the future. If, for instance, on some project a certain minimum density should be established, it would be well within the ability of a trained technician to determine, within 3 min of laydown, the density of the concrete. If changes in vibratory energy or placement were necessary, the need could be expressed before the paver had moved more than 100 ft.

An acceptance specification based on nuclear density relative to laboratory density appears to be practical. Under this type of specification, it would not be necessary to specify construction equipment and procedure for vibration of the concrete.

TABLE 8

RESULTS OF NUCLEAR DENSITY TESTS

Fine Aggregate on Project I80S						Fine Aggregate on Project I70		Coarse Aggregate on Project I270					
Mean[a]	Nuclear	Mean	Nuclear	Mean	Nuclear	Mean	Nuclear	Mean	Nuclear	Mean	Nuclear	Mean	Nuclear
140	140 (0)	139	139 (0)	138	137 (-1)	136	136 (0)	145	145 (0)	146	146 (0)	143	146 (+3)
139	138 (-1)	139	139 (0)	138	138 (0)	137	137 (0)	145	144 (-1)	144	144 (0)		
140	139 (-1)	139	139 (-2)	138	138 (0)	137	138 (+1)	144	145 (+1)			142	143 (+1)
136	131 (-5)	136	136 (0)	138	138 (0)	137	136 (-1)	144	143 (-1)	145	146 (+1)		
		136	133 (-3)	136	136 (0)	137	137 (0)	144	143 (-1)	144	142 (-2)	143	144 (+1)
139	139 (0)			136	135 (-1)	136	136 (0)					142	143 (+1)
135	135 (0)	138	135 (-3)					141	143 (+2)	144	143 (-1)		
139	139 (0)	138	138 (0)	135	135 (0)					143	140 (-3)	142	142 (0)
139	138 (-1)	138	139 (+1)	134	134 (0)			143	143 (0)			140	139 (-1)
135	132 (-3)	136	136 (0)	134	135 (+1)			143	144 (+1)	144	142 (-2)		
		136	133 (-3)	135	132 (-3)			143	143 (0)	144	141 (-3)	141	140 (-1)
140	140 (0)	136	138 (+2)	134	135 (+1)			141	141 (0)			139	139 (0)
140	139 (-1)									145	144 (-1)		
135	133 (-2)	133	132 (-1)	136	136 (0)			144	143 (-1)	145	145 (0)	143	143 (0)
135	135 (0)	133	133 (0)	136	138 (+2)							141	143 (+2)
135	133 (-2)	133	134 (+1)	135	136 (+1)			144	141 (-3)	146	146 (0)		
		132	132 (0)	135	136 (+1)			140	141 (+1)	146	142 (-4)	144	142 (-2)
139	138 (-3)	134	134 (-3)										
139	138 (-1)	134	131 (-3)	134	134 (0)			140	138 (-2)	144	144 (0)	143	142 (-1)
135	132 (-3)			134	134 (0)			140	140 (0)	144	144 (0)	142	141 (-1)
135	133 (-2)	137	137 (0)	133	135 (+2)			140	140 (0)				
		137	138 (+1)	133	134 (+1)					145	145 (0)	142	141 (-1)
139	138 (-1)	134	134 (0)					143	142 (-1)	145	146 (+1)	141	141 (0)
136	134 (-2)			134	136 (+2)								
136	132 (-4)	137	135 (-2)	133	134 (+1)			143	141 (-2)	143	144 (+1)	140	138 (-2)
136	134 (-2)	133	133 (0)	133	131 (-2)			138	139 (+1)	140	140 (0)		
		133	132 (-1)										
137	138 (+2)			136	137 (+1)			144	144 (0)	142	141 (-1)		
136	136 (0)	133	133 (0)	135	135 (0)			139	141 (+2)	140	139 (-1)		
136	136 (0)	133	133 (0)	136	135 (-1)			144	145 (+1)				
137	139 (+2)	133	133 (0)	135	137 (+2)					143	142 (-1)		
								140	142 (+2)	143	142 (-1)		
135	136 (+1)	137	137 (0)	135	134 (-1)			140	142 (+2)				
135	137 (+2)			133	131 (-2)					144	144 (0)		
135	135 (0)	135	135 (0)	135	135 (0)			144	144 (0)	144	144 (0)		
135	135 (0)	133	133 (0)	135	135 (0)			141	141 (0)				
135	134 (-1)	133	134 (+1)	133	132 (-1)					144	144 (0)		
135	135 (0)	133	133 (0)					145	146 (+1)				
				134	134 (0)					145	146 (+1)		
135	134 (-1)	135	135 (0)	133	134 (+1)					141	141 (0)		
135	133 (-2)	133	134 (+1)	134	134 (+2)								
134	134 (0)			134	132 (-2)								
134	133 (-1)	137	138 (+1)										
134	133 (-1)	135	135 (0)										
134	133 (-1)	135	134 (-1)										
		136	138 (+2)										

Note: Standard deviation = 1.45 pcf for project I80S; 0.57 pcf for project I70; 1.34 pcf for project I270; 1.3 pcf overall.

[a]Density of an area within a test section as indicated by the average of core samples, beam samples, and nuclear test results.

CONCLUSIONS

Two of the paving projects used to provide test sections for vibration studies were completed in October 1970 and opened to traffic. Snowstorms began less than a week after the sections were opened, and the number of vehicles with studded tires was estimated at 25 percent by November 1970. Some indication of the durability of each test section may be evident by the spring of 1971.

Meanwhile, the study has provided the following general conclusions:

1. A new construction specification for pavement consolidation is needed. Cores from pavements with poor abrasion records show high void contents, and their density is less than 97 percent of laboratory rodded density.

2. Good consistent consolidation (97 percent relative consolidation or more) requires considerable vibratory effort when concrete pavements are placed with less than a 2-in.

slump. However, concrete with less than a 2-in. slump is stronger than concrete with more than a 2-in. slump, and it is usually preferred when slip-form pavers are used.

3. Good surface plate vibrators operating at or above 4,000 vibrations per minute plus some internal vibration may effectively consolidate coarse-aggregate mixes for 8-in. thick pavement if the slump is between 1½ and 2½ in.

4. Internal vibrators with 1⅞-in. eccentrics turning 10,800 rpm in air and spaced 24 in. or less will effectively consolidate concrete for 8-in. thick pavements if the slump is between 1½ and 2½ in. Concrete with a slump less than 1 in. can entrap enough large air voids to reduce the relative consolidation below 97 percent.

5. The angle and height of internal vibrators are not critical if the entire vibrator is submerged. The vibrators used on this project appeared to provide the best consolidation when they were in a horizontal position midway between the base and the top of the surcharge.

6. Internal vibrators with 1⅞-in. eccentrics operating at 10,800 rpm in air at 24-in. spacing (or less) in 8-in. thick pavement may be moved at speeds up to 19 ft/min by the paver and still provide acceptable consolidation.

7. Reductions in amplitude below the 1⅞-in. eccentric size do not affect consolidation as much as reduction in rpm below the frequency of 10,800 rpm in air. The internal vibrator with a 1⅞-in. eccentric turning at 10,800 rpm in air appeared to be a very satisfactory size for 2-ft spacing. Internal vibrators with smaller eccentrics and lower vibrator rates should be spaced closer together to obtain at least 97 percent consolidation in 1½- to 2½-in. slump concrete.

8. "Dead" vibrators will leave low density areas, especially in low slump concrete.

9. Tests on cores indicate that the compressive strength of concrete pavements is as much as 10 percent lower between vibrator paths than it is over vibrator paths. Strength of the concrete on both of the observed projects was well above the minimum requirements, however.

10. Modulus of elasticity readings determined by sonic and pulse wave velocity tests show that the soundness of concrete is improved by good vibration.

11. Segregation of aggregate particles in concrete pavement mixes is not a matter of concern for the low slump concrete now being used in form paving or with slip-form pavers. Cores taken from all test sections showed no evidence of segregation and only a very slight evidence of settlement of coarse particles under heavy vibration.

12. The nuclear testing device is an invaluable aid in the control of consolidation immediately after concrete pavement is placed. The device shows good reliability and will provide density values within 3 min after laydown.

SUMMARY

One of the factors affecting the performance of concrete pavement appears to be the consolidation of the plastic mix by the paving machine. This study is an attempt to determine how strength and durability of pavements are affected by factors such as the speed of the paver, the type, height, angle, frequency, and amplitude of the vibrators, and the type of aggregate in the mix.

Seventy test sections at 3 different test sites were established in eastern Colorado with these variations in consolidation. Because it will take many winter seasons and millions of studded-tire traverses to really determine durability of each test section, it may be 5 or 10 years before the final results are available. However, tests for density, soundness by impact wave velocity, sonic modulus of elasticity, segregation, entrained air retention, strength, and deflection have been completed.

The results indicate that low slump concrete (usually used with slip-form pavers) requires considerable vibration effort to liquidize the mix and allow the escape of air bubbles. However, the proper combination of vibratory amplitude, frequency, and slump will secure the 97 percent of rodded density that seems necessary to obtain sound, durable concrete. This consolidation effort will not seriously reduce the entrained air content or cause segregation of the aggregate particles.

One of the most significant by-products of the study was the development of a procedure to measure density of the plastic mix immediately after laydown by means of a direct transmission type of nuclear gage. With the use of this nondestructive testing device, reliable pavement density values may be obtained before the paver has traveled more than 100 ft from the sampled area.

REFERENCE

1. Ore, E. L., and Straughan, J. J. Effect of Cement Hydration on Concrete Form Pressure. ACI Jour., Feb. 1968.