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# VIBRATION STUDY FOR CONSOLIDATION OF PORTLAND CEMENT CONCRETE

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Interim Report
for
Iowa DOT
Research Project MLR-95-4

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Iowa Department of Transportation

# Vibration Study for Consolidation of Portland Cement Concrete

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# TABLE OF CONTENTS

Steffes, R.F., Tymkowicz, S.W.

## DISCLAIMER

**ABSTRACT**

The Iowa Department of Transportation has noticed an increase in the occurrence of excessively vibrated Portland Cement Concrete (PCC) pavements. The over consolidation of PCC pavements can be observed in several PCC pavement projects across the state of Iowa. It is also believed to be a factor in accelerating the premature deterioration of at least two pavements in Iowa. To address the problem of excessive vibration a research project was conducted in 1995 to document the vibratory practices of PCC slip form paving in Iowa and determine the effect of vibration on the air content of the pavement. The primary factors studied were paver speed, vibrator frequency, and air content relative to the location of the vibrator. The study concluded that the Iowa Department of Transportation specification of 5000 to 8000 vibrations per minute (vpm) for slip form pavers is effective for normal paver speeds observed on the three test paving projects. Excessive vibration was clearly identified on one project where a vibrator frequency was found to be 12000 vpm. When the paver speed was reduced to half the normal speed, hard air contents indicate that excessive vibration was beginning to occur in the localized area immediately surrounding the vibrator at a frequency of 8000 vpm. Also, the study gives indications that the radius of influence of the vibrators is smaller than many claim.

**KEY WORDS**

Air Content
Consolidation
Pavement
Portland Cement Concrete
Vibration

## INTRODUCTION

PCC pavements have provided good, durable highway surfaces for many years. When designed and constructed properly the expected service life will normally range from 25 to 40 years. In some cases a PCC paving project may suffer premature deterioration due to poor design, material qualities, construction operations or uncontrollable events.

One characteristic normally contributing to a long service life is the existence of a proper air void system in the PCC (*1*). An effective air void system will provide protection from freeze-thaw damage by reducing the pressures that develop during the freezing and thawing of moisture within the concrete. A second characteristic of quality concrete is the uniform dispersion of aggregate throughout the pavement. A nonuniform or segregated mix may initiate abnormal cracking during the hardening process. The cracking could be caused by differential drying shrinkage between zones of greater paste content and zones of greater aggregate content.

## BACKGROUND

Vibratory consolidation practices of PCC became an area of interest to the Iowa Department of Transportation when excessive vibration was identified as a factor in the premature deterioration of US Highway 20 in Webster County and Hamilton County (*2*). Deterioration of US 20 was initially noticed in May 1990. The deterioration was unexpected since the pavement sections were only three years old. The characteristics of the deterioration were similar to the staining and cracking associated with D-cracking. Investigators have identified the primary source of deterioration as either ettringite formation in the air voids or alkali-silica reactivity (*3,4*). Cores of

the pavement reveal many instances where the hardened concrete contains air contents of less than 3 percent, which accelerated the deterioration of the pavement (*2*). The probable cause of the low air content is believed to be excessive vibration during paving. Since this was the only known instance of excessive vibration, no additional studies about vibrator consolidation of slip form pavers were initially conducted.

A second cracking pattern began to emerge during the following years on the US 20 project. Longitudinal cracks spaced at about 0.6 m (2 ft) began to appear in the pavement (Figure 1). The transverse distance between the cracks is very similar to the spacing of the vibrators on the paver used for the project.

During this same time interval, a similar longitudinal cracking pattern was noticed on Interstate 80 in Dallas County (Figure 2). This roadway was also three years old when longitudinal cracking was first identified. These cracks were spaced at intervals that approximated the transverse spacing of vibrators. Cores taken from the longitudinal cracks indicated air contents of 3 percent in the top half of the core and 6 percent in the bottom half. The longitudinal cracking pattern and the reduced air content indicated the possibility of excessive vibration, since the vibrators were positioned near the top of the pavement.

In other areas in the state of Iowa, longitudinal trails can be observed in the surface of some PCC pavement projects. These trails run parallel to each other with a spacing similar to the spacing of vibrators on pavers (Figure 3). This longitudinal disconformity of the pavement was termed

vibrator trail. These vibrator trails were also observed in both the US 20 pavement and the I-80 pavement.

Vibrator trails are believed to be formed by the excessive vibration of concrete. The excessive vibration causes the paste content to increase in the localized area of the vibrator. This zone of increased paste allows the tines of the tining machine to penetrate deeper into the surface of the pavement, thus forming a longitudinal distortion of the pavement surface (Figure 4). Also, vibrator trails can be found below the surface when taking cores from the pavement. If the vibrator trail is slightly below the surface, it can become exposed by diamond grinding off the surface material during the removal of a bump (Figure 5,6). In this case the exposed surface has longitudinal bands where the pavement has reduced coarse aggregate due to excessive vibration.

## RESEARCH

As a result of these observations, a research project was initiated in 1995 to evaluate the practices of vibration during slip form PCC paving and to determine the effect of vibration on the air content of the pavement. The primary items studied for their effect on air content were vibrator frequency, paver speed, and transverse location relative to a vibrator. The research was conducted on three separate interstate paving projects. On each project a test section was paved where the paver speed was recorded and vibrator frequencies were set to known values. The transverse location of each vibrator was carefully measured, so the relative position of the vibrator to the location of a core would is known.

**Experiment Design**

The test sections were designed to have six divisions. The test sections were a matrix of two paver speeds and three vibrator frequencies. The speeds selected were the normal paver speed and a slow speed which was set at half the normal paver speed. Because the normal speed for the pavers was found to be 1.2 to 2.1 m (4 to 7 ft) per minute, the normal speed was set at 1.5 m (5 ft) per minute. The three vibrator frequencies were 5000, 6500, and 8000 vpm. This range was used because the Iowa Department of Transportation specifies that internal vibrators on slip form pavers must operate within the range of 5000 to 8000 vpm. This range was established to prevent the formation of vibrator trails and was based on preliminary work conducted during the summer of 1994.

A consecutive pair of vibrators was selected to be controlled at the indicated test frequency. This allowed cores to be taken in the vibrator trail and at the midpoint between the two controlled vibrators (Figure 7). The other vibrators on the paver were maintained at their normal operational frequency set by the contractor. The frequency of these vibrators was also recorded. In some instances this allowed a comparison between a vibrator set within specification and a vibrator that was found operating outside the specified range of 5000 to 8000 vpm.

Three cores were taken from both the vibrator trail and between the vibrator trails in each division. The cores were cut into thirds to determine the air content of the top, middle, and bottom portion of each core. Air content results were obtained through high pressure testing by Iowa Department of Transportation test method number Iowa 407-B. A vertical slice was taken

off each core prior to the high pressure air test for possible image analysis testing.

### General Information

Careful measurements were taken of the vibrator spacing, vibrator location relative to the edge of the pavement, and vibrator location relative to the pan of the paver. The brand and model of each vibrator was documented. In addition, mix design, weather conditions, type of paver, tilt of the vibrators relative to the pavement surface, type of base, pavement design thickness, and slump were recorded. These factors were held as constant as possible for each individual project.

## PCC CONSOLIDATION PRACTICES

The paving practices of each of the three contractors was observed prior to the construction of the test sections. The items most carefully observed during this time were the number and location of vibrators, the types of vibrators used, the operating frequency of the vibrators, and the speed of the paver. This allowed an opportunity to observe and compare the normal paving operations of the contractors (Table 1).

### Vibrator Frequencies

Vibration readings were found to vary substantially on each of the pavers. A difference of 3000 vpm from the slowest vibrator frequency to the highest vibrator frequency was typical. The hydraulic control valves of individual vibrators commonly allowed a variation of several thousand vpm for valves at the same numeric setting. Vibration readings were often found to be outside the specified limits of 5000 to 8000 vpm. In most cases when the frequency was outside the

specification, the frequency was above the specified limit. In one instance a vibrator was found to be operating at 12000 vpm.

**Vibrator Positioning**

Inspection of the pavers revealed that, in most cases, the vibrators were positioned at the level of the paver's pan and in a horizontal position. However, some pavers had a large variation in the horizontal position of the vibrators. In one case the center of the vibrators ranged from 50 mm (2 in.) above the pan to 75 mm (3 in.) below the pan (Figure 8). In another case, a paver operator indicated the vibrators were at the pan level; however, evidence from cores showed the vibrators were as far as 125 mm (5 in.) below the pan. The change in position can occur from an inaccurate position indicator, sag due to oil leakage in the hydraulic system which holds the vibrators up, or loose bolts that hold an individual vibrator in position.

Placing the vibrators parallel to the pavement surface also minimizes the frontal area or cross sectional area of the vibrator. In this position the possibility of excessive vibration is increased since all the available energy from a vibrator is applied to a minimum cross sectional area of concrete.

**RESULTS**

The results of this research are based on two primary factors. The first was visual observation. The cores from the project were carefully inspected for consolidation and aggregate distribution. The second factor was hard air testing to determine the entrained air content of the concrete.

**Visual Observations of Co[illegible]**

Observations from PCC cores taken on and between the vibrator trails indicate the radius of effective consolidation from the vibrator may be smaller than many claim. The cores commonly show significant entrapped air within a 100 mm (4 in.) of the vibrator location. One noticeable case of this was on project B (Figure 9). The vibrator was positioned at the top of the slab. The test variables used in this case were slow paver speed, vibrator frequency of 8000 vpm, and on the vibrator trail. This test section had the condition of maximum consolidation energy for the project. The 3 cores taken from this test section show an area of aggregate separation approximately 25 mm (1 in.) below the top of the cores. This separation is starting to show the formation of a vibrator trail. However, this consolidation effort still is leaving entrapped air only 100 mm (4 in.) from the area of segregated concrete. Similarly, on project C where a vibrator was running at 12000 vpm entrapped air is located within 100 mm (4 in.) of areas of excessive vibration (Figure 10). In this case the vibrator was 125 mm (5 in.) below the pavement surface. A vibrator trail can be clearly seen passing through the core, yet entrapped air can be found in the bottom third of the cores taken in this vibrator trail.

Visual observations also revealed that the cores from the 5000 vpm test sections had significantly more entrapped air than the 6500 and 8000 vpm test sections, especially under the test conditions of normal paving speed. The impact of this increased entrapped air was not studied, but it appears that the frequency of a vibrator should not be below 5000 vpm to ensure adequate consolidation.

**High Pressure Air Testing**

High pressure hardened air testing was conducted on 182 cores taken from the three projects. The first project (A) had three separate test sections. Therefore, the test sections are designated as A-1, A-2, A-3, B, and C.

The results of the hardened air test show for the frequency range of 5000 to 8000 vpm and for a normal paver speed the air content of the concrete is not significantly reduced (Table 2). However, the hard air tests on project B and C for the condition of slow paver speed at 8000 vpm on the vibrator trail and in the top third of the core indicate that excessive vibration was starting to occur in the area immediately surrounding the vibrator (Figure 11). The average air content for this condition was near 5 percent for both projects.

The vibrator found to be operating at 12000 vpm on project C caused significant air loss in the concrete. From the cores, the location of the vibrator was estimated to be 125 mm (5 in,) below the surface of the pavement. Hard air tests indicate air contents of less than 2 percent for the middle portion of these cores (Figure 12). This indicates a severe case of over vibration. The bottom third of the cores had an average air content of 6 percent. Also, cores were taken midway between the vibrator operating at 12000 vpm and the vibrator positioned next to it , a distance of 215 mm (8.5 in.) transversely. These cores had air contents very similar to those taken at 5000 vpm and between the vibrators. The combination of the air content difference between the bottom and the middle of the core and the difference in air content from on to between the vibrators indicates that the vibrators' energy is concentrated in the few inches immediately

surrounding the vibrator.

The effect of moving a vibrator from the top of the slab to 100 mm (4 in.) below the top of the slab can be observed by comparing project A-2, vibrators at the top of the slab, and A-3, vibrators 100 mm (4 in.) below the top of the slab. The cores show a more uniformly consolidated pavement when the vibrators were 100 mm (4 in.) below the top of the slab (Figure 13).

## CONCLUSIONS

Excessive vibration of PCC can cause vibrator trails that have low air contents, but the specification of 5000 to 8000 vpm did prevent the formation of vibrator trails at normal paver speeds. However, at 8000 vpm the possibility of excessive vibration begins to increase as the paver speed decreases. Therefore, it is critical that the specification of 5000 to 8000 vpm be followed for paver speeds greater than 0.9 m (3 ft) per minute, and vibrator frequencies may need to be reduced if the progress of the paver is reduced below this speed. To ensure adherence to the specification, frequent vibrator checks with a tachometer should be performed, and it should not be assumed that the paver hydraulic control valve settings will give reliable results.

## FUTURE RESEARCH

To more uniformly consolidate the pavement slab and to reduce the occurrence of excessive vibration and loss of entrained air, the following areas need to be researched to determine their effect on pavement consolidation:

1) Tilting the vibrators at an angle of 10 to 20 from the horizontal plane of the pavement

surface to increase the area of influence of the vibrator.

2) The development of a maximum vibrator spacing to ensure that the slab is uniformly consolidated based on a study of set vibrator spacings.

3) The effect of larger vibrator diameters and increased amplitudes on the consolidation of PCC for slip form paving.

4) The influence of mix design on vibrator consolidation of PCC.

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3. V.J. Marks and W.G. Dubberke, "A Different Perspective for Investigation of PCC Pavement Deterioration," Interim Report for Iowa DOT Research Project HR-2074, Ames, Iowa, January 1995.

4. D. Stark, "Investigation of Pavement Cracking in US 20 and I-35, Central Iowa," Construction Technology Laboratories, Inc., Skokie, IL, September 1992.

**FIGURE CAPTIONS**

1. Longitudinal and joint cracking on US 20 in Webster County
2. Longitudinal crack on I-80 in Dallas County
3. Vibrator trail in pavement surface on US 65 in Polk County
4. Distortion of pavement surface in a vibrator trail
5. Longitudinal distortion in the surface of a diamond ground pavement
6. Aggregate separation in the vibrator trail in a diamond ground pavement
7. Location of cores relative to vibrator trails
8. Variation in elevation of vibrators
9. Cores from project B showing aggregate separation near the top
10. Cores from project C revealing a vibrator trail

13 ~~11~~. Average percent hard air for projects B & C

12. Average percent hard air for project C

11 ~~13~~. Average percent hard air for projects A-2 & A-3

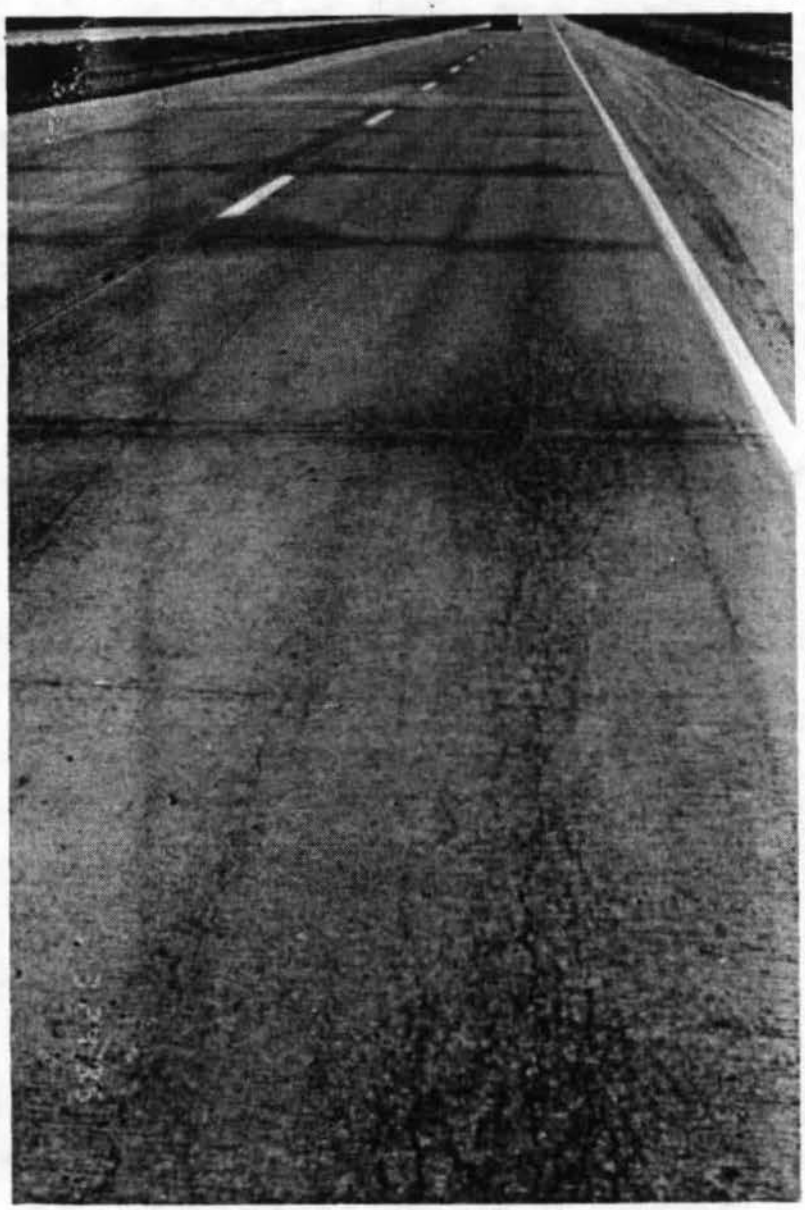

FIGURE 1 Longitudinal and joint cracking on US 20 in Webster County.

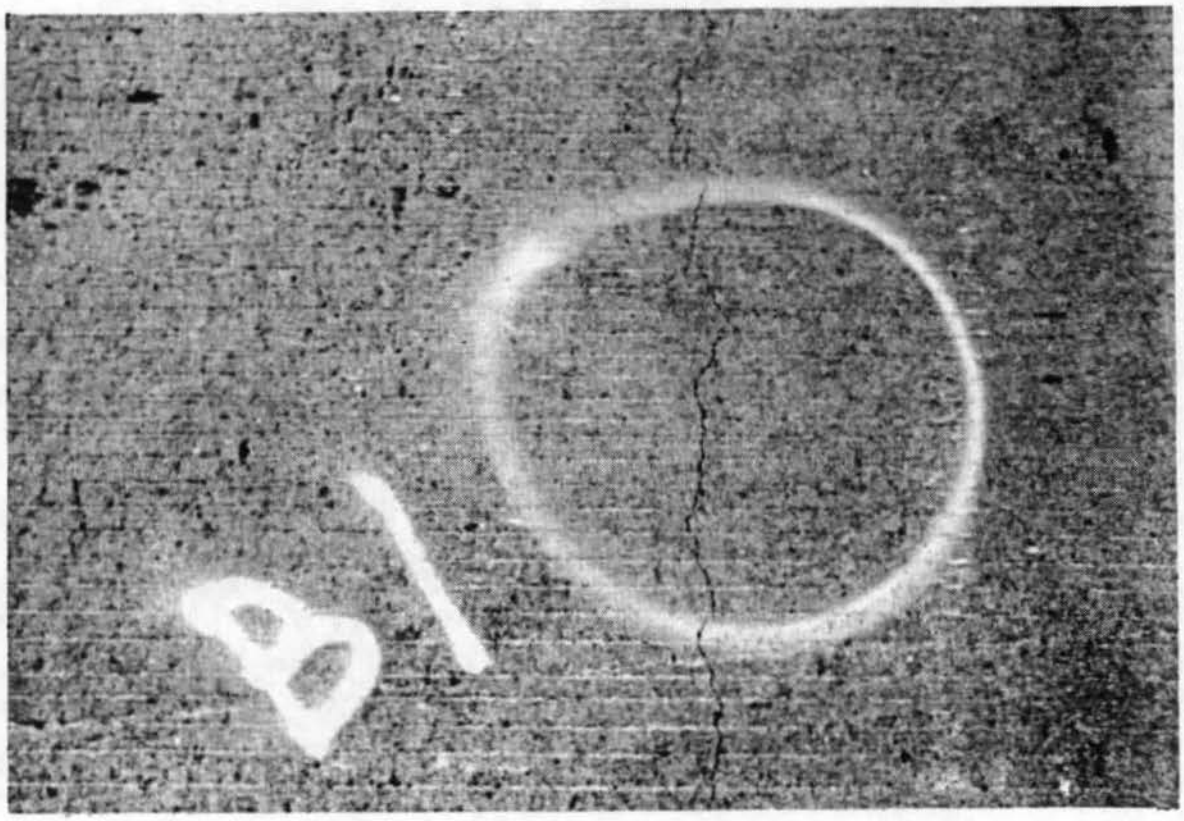


FIGURE 2 Longitudinal crack on I-80 in Dallas County.

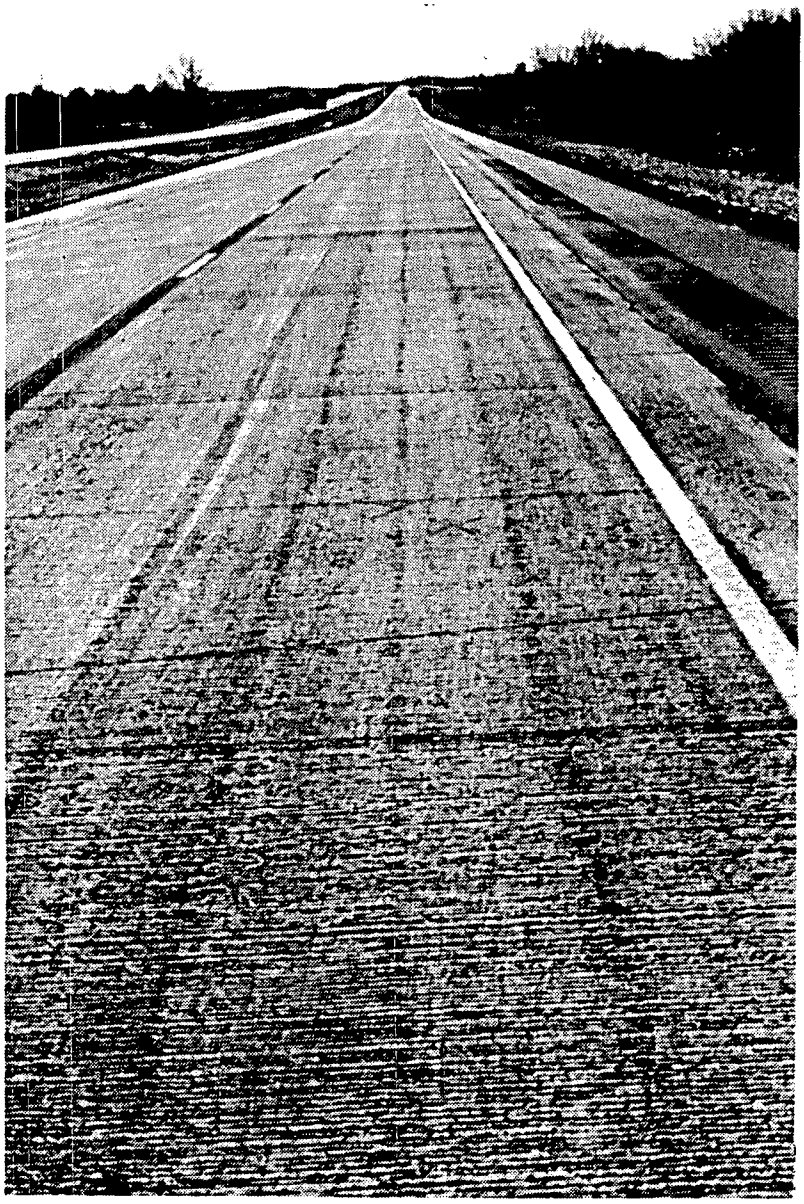

FIGURE 3 Vibrator trail in pavement surface on US 65 in Polk County.

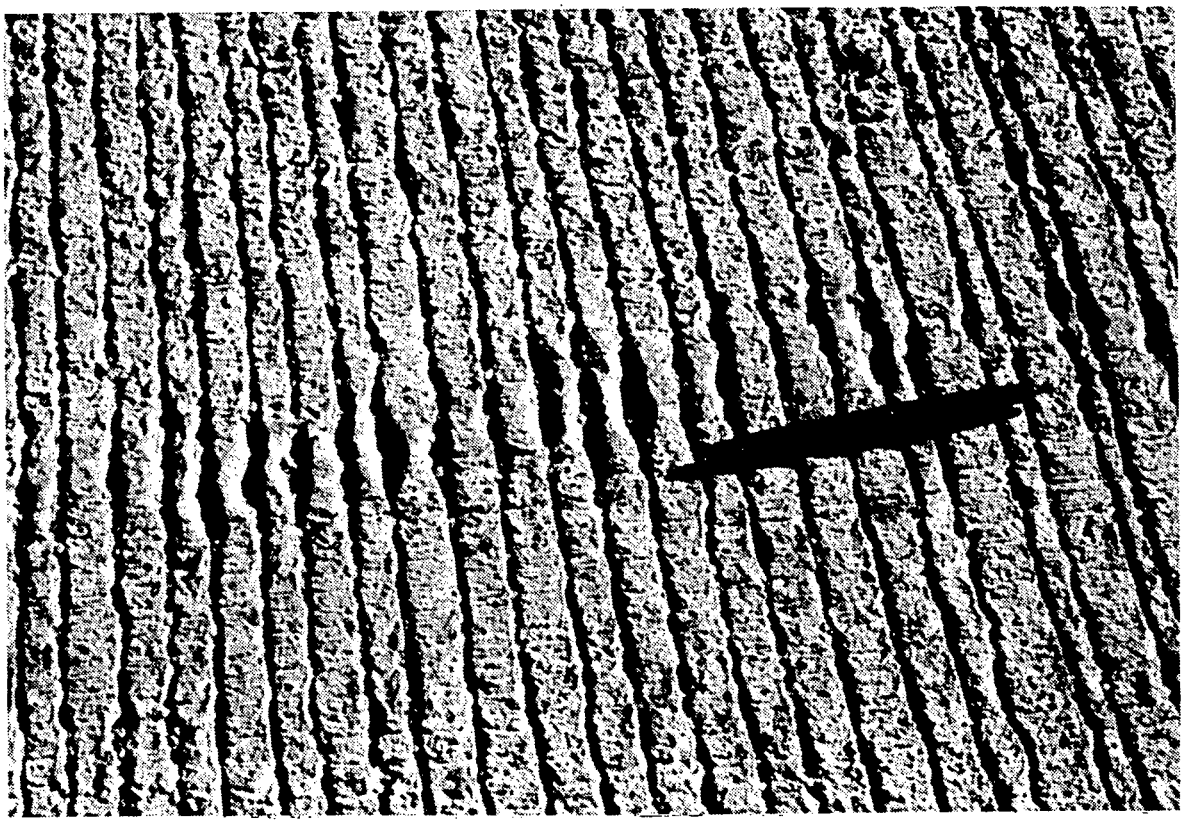

FIGURE 4 Distortion of pavement surface in a vibrator trail.

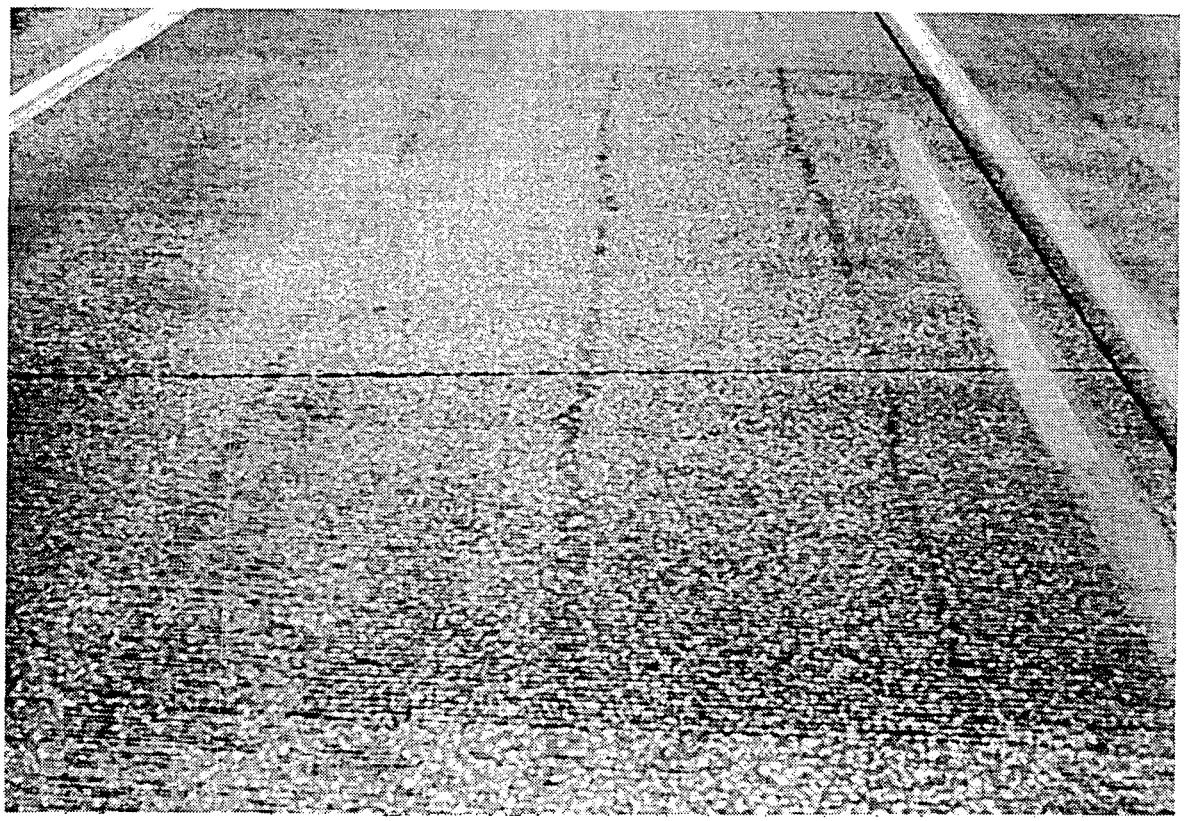

FIGURE 5 Longitudinal distortion in the surface of a diamond ground pavement.

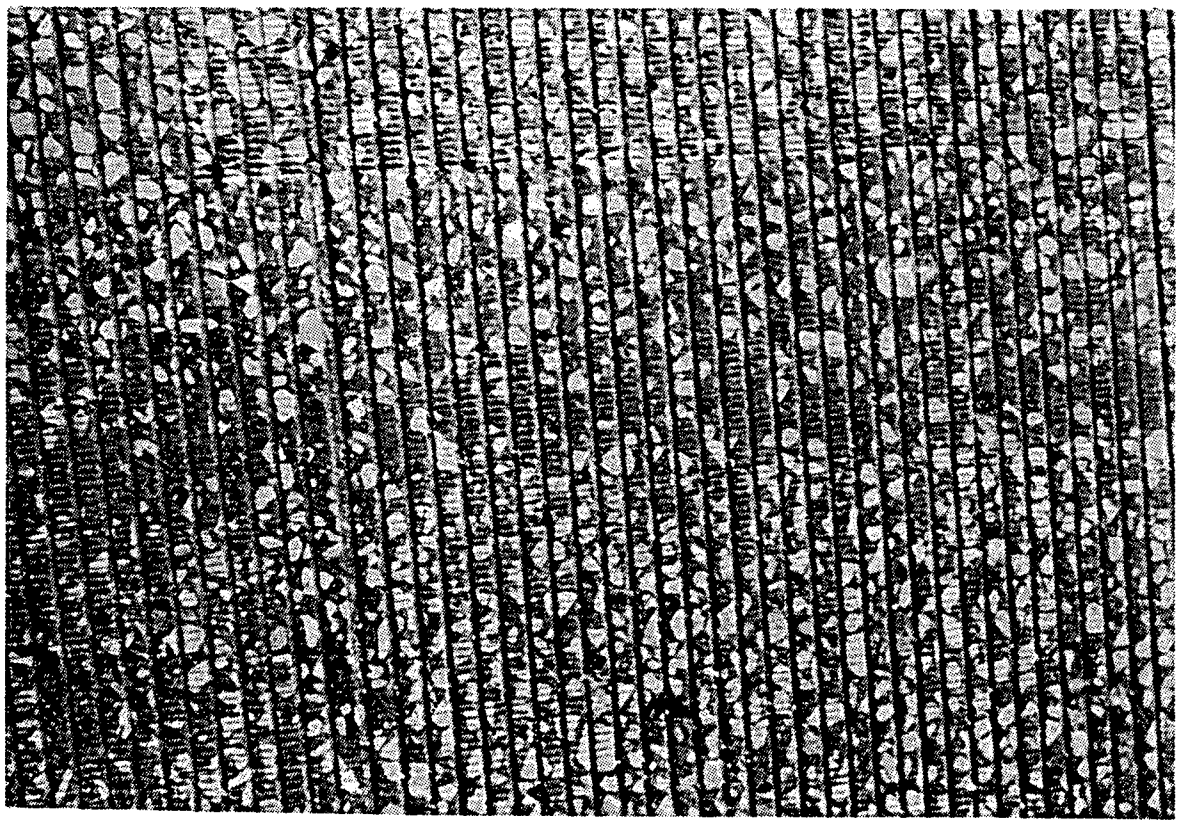

FIGURE 6 Aggregate separation in the vibrator trail in a diamond ground pavement.

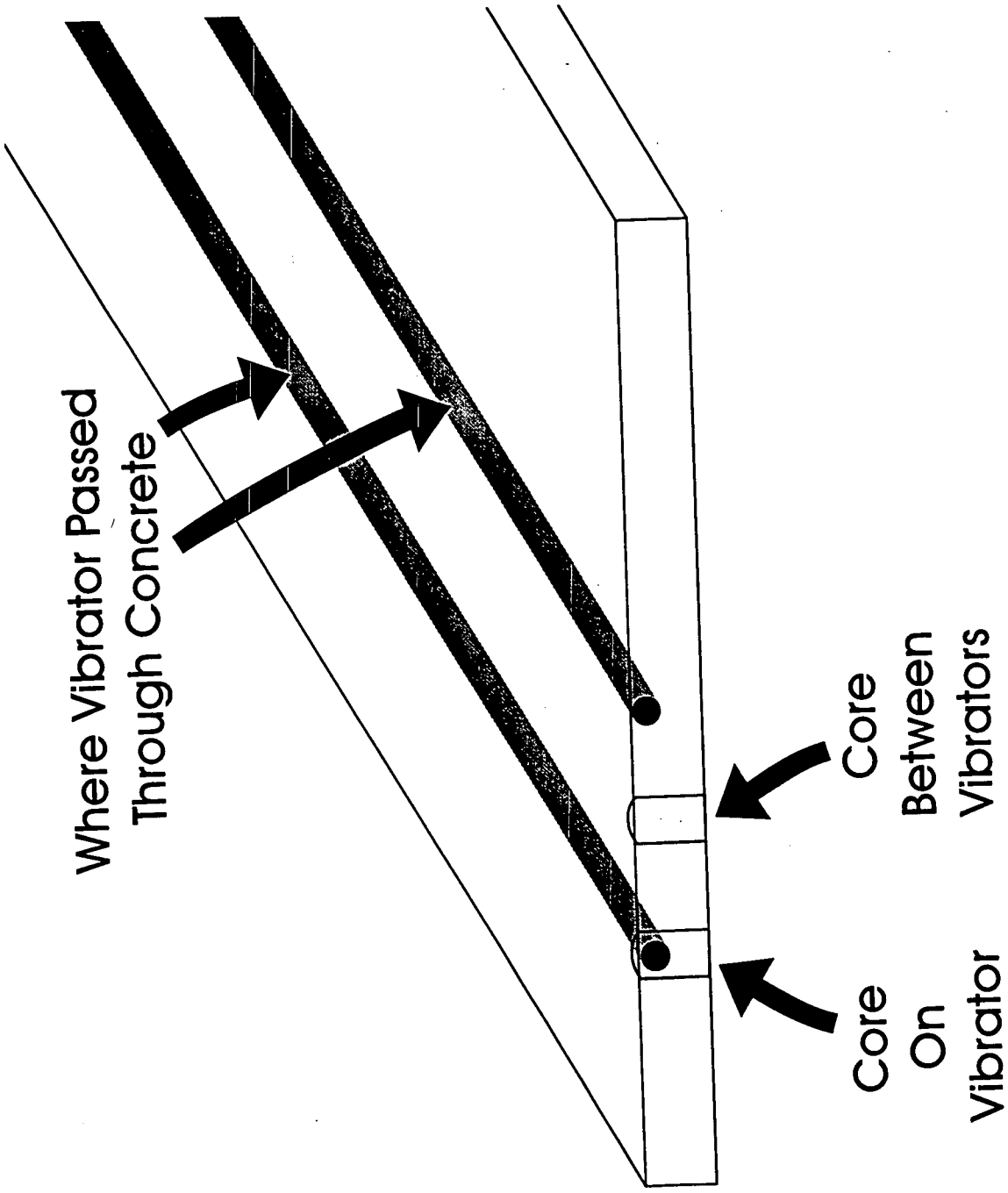


FIGURE 7 Location of cores relative to vibrator trails.

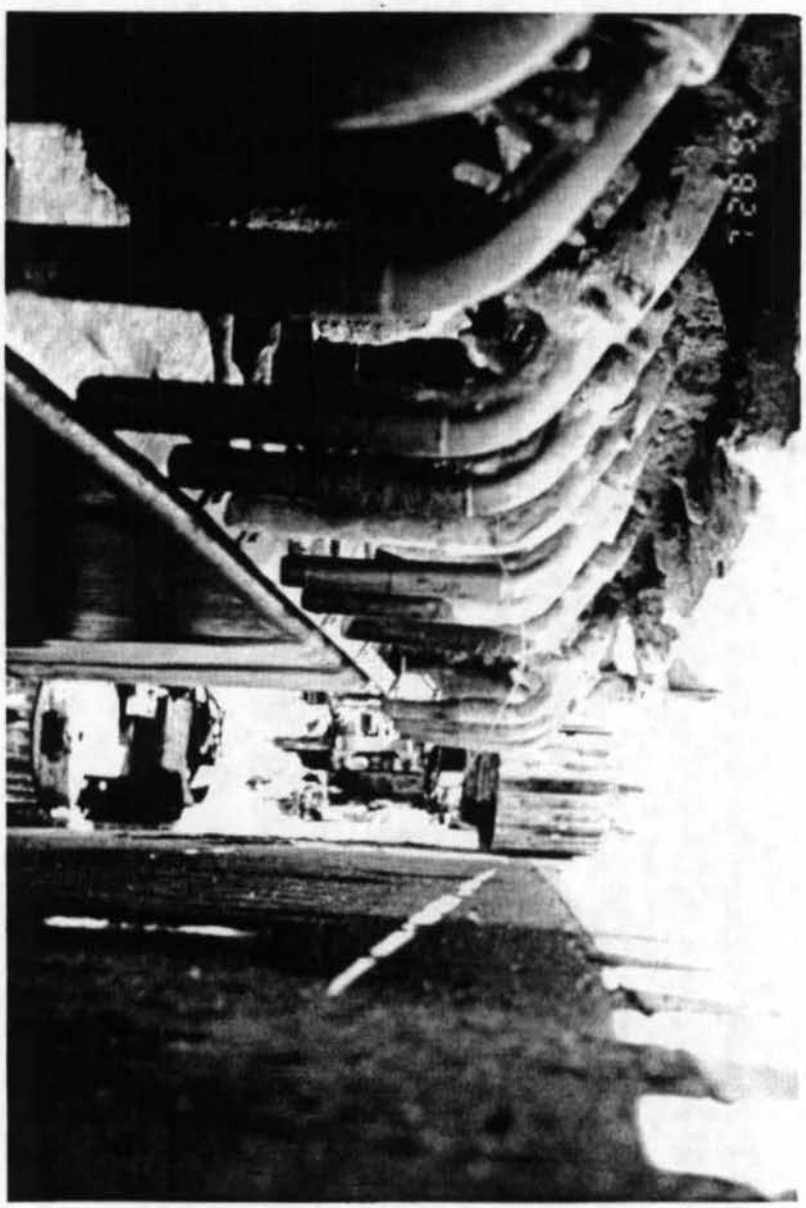

FIGURE 8 Variation in elevation of vibrators on a slip form paver.

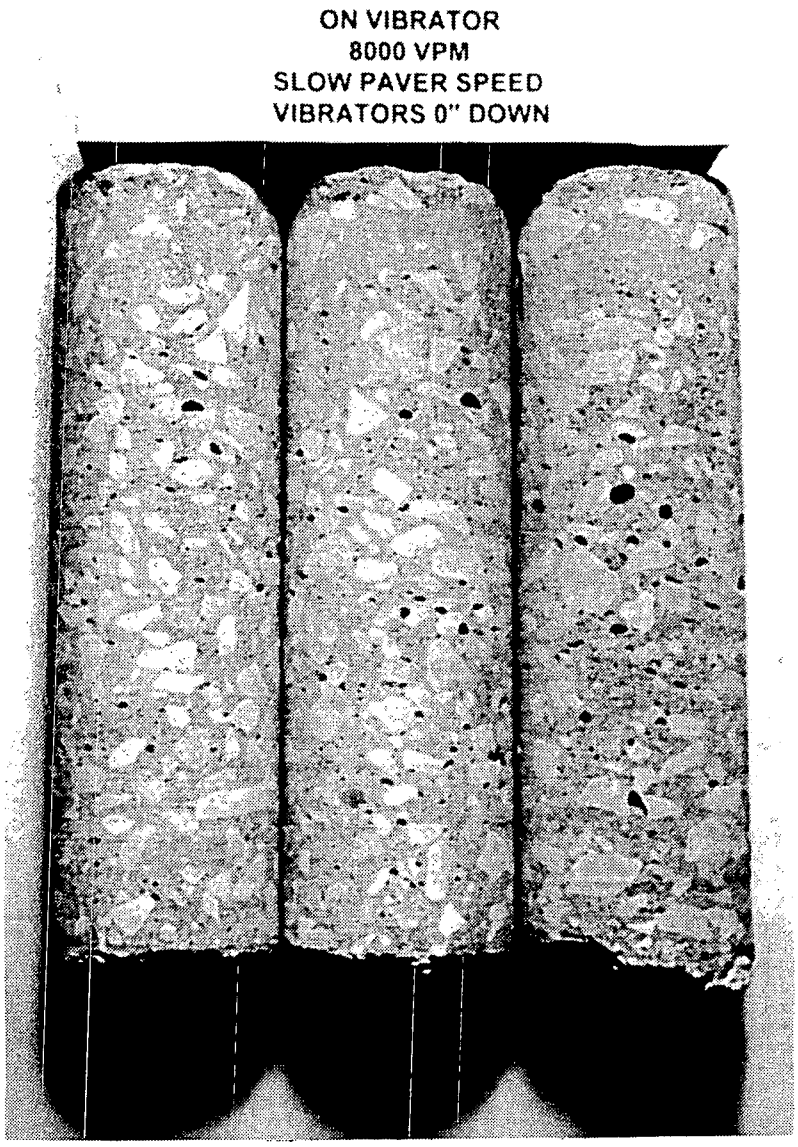


FIGURE 9 Cores from project B showing aggregate separation near their top.

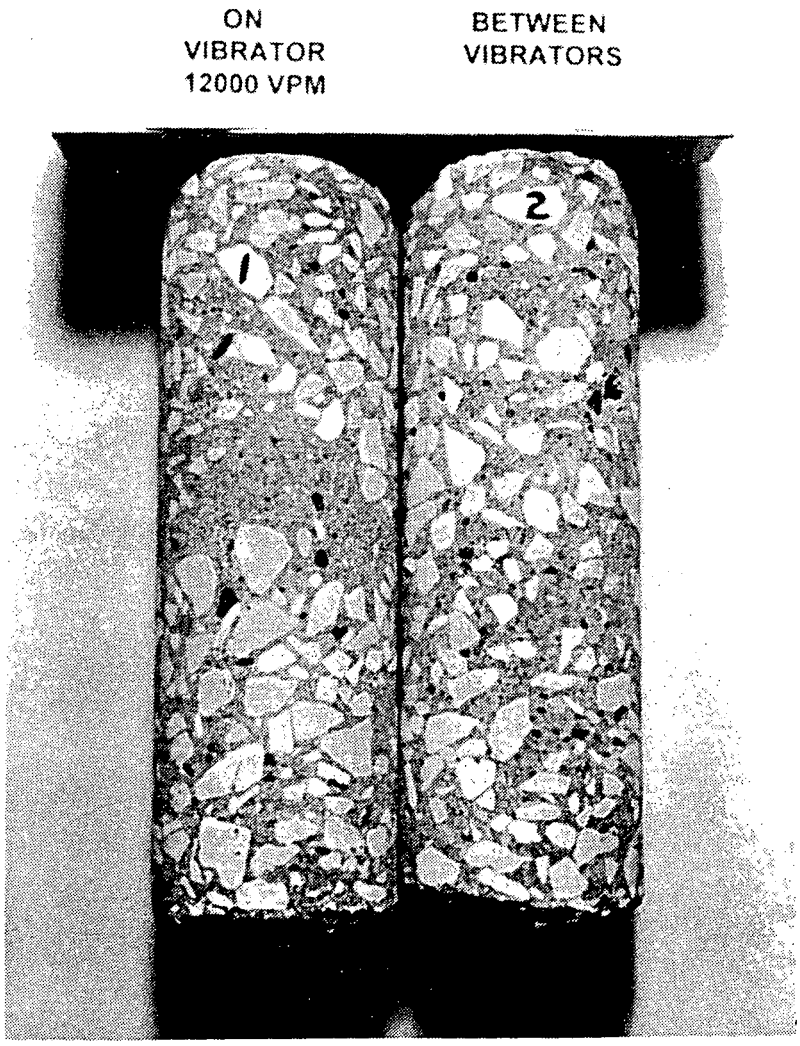


FIGURE 10 Cores from project C revealing aggregate segregation in a vibrator trail.

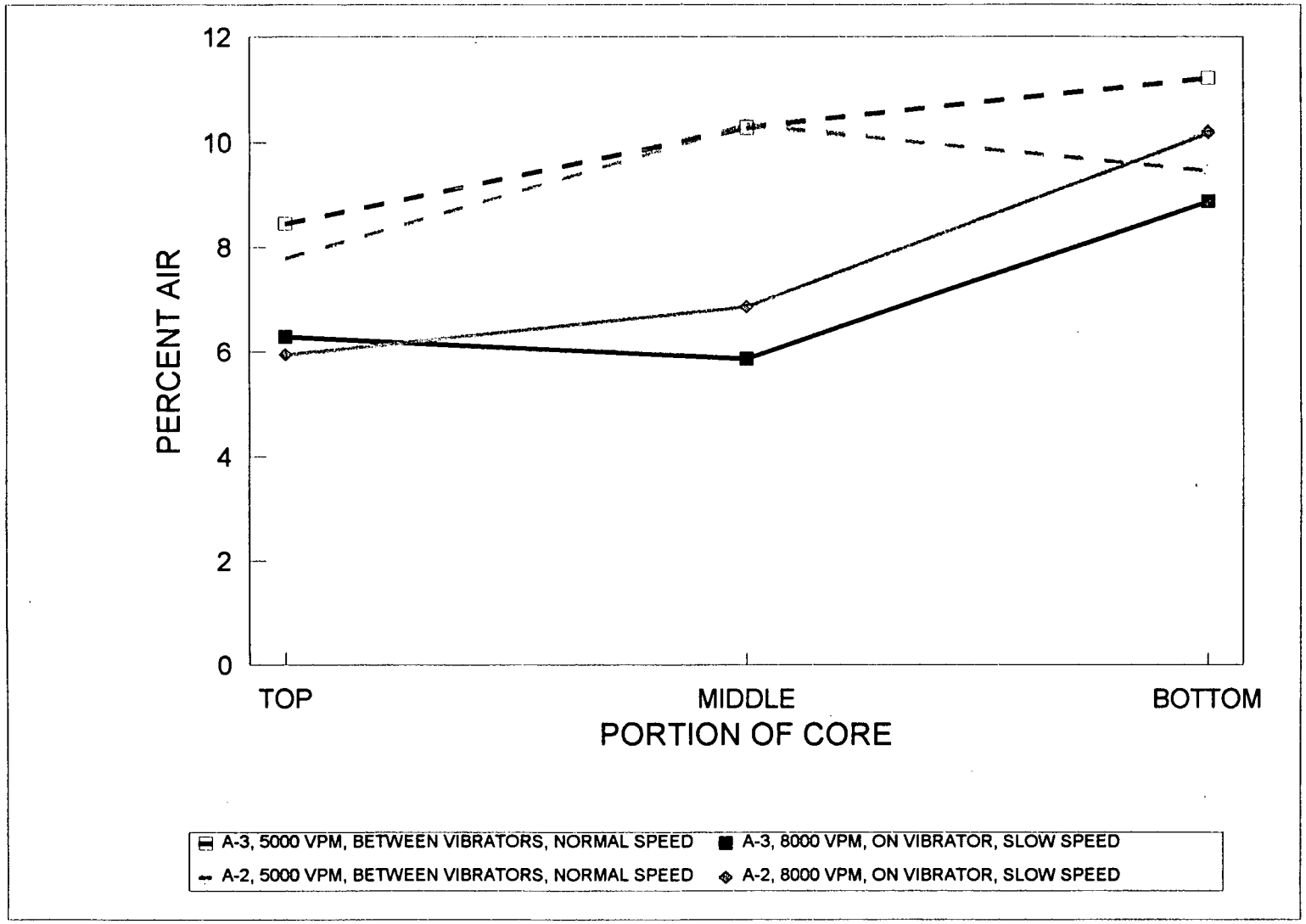


FIGURE 11 Average percent hard air for projects A-2 & A-3

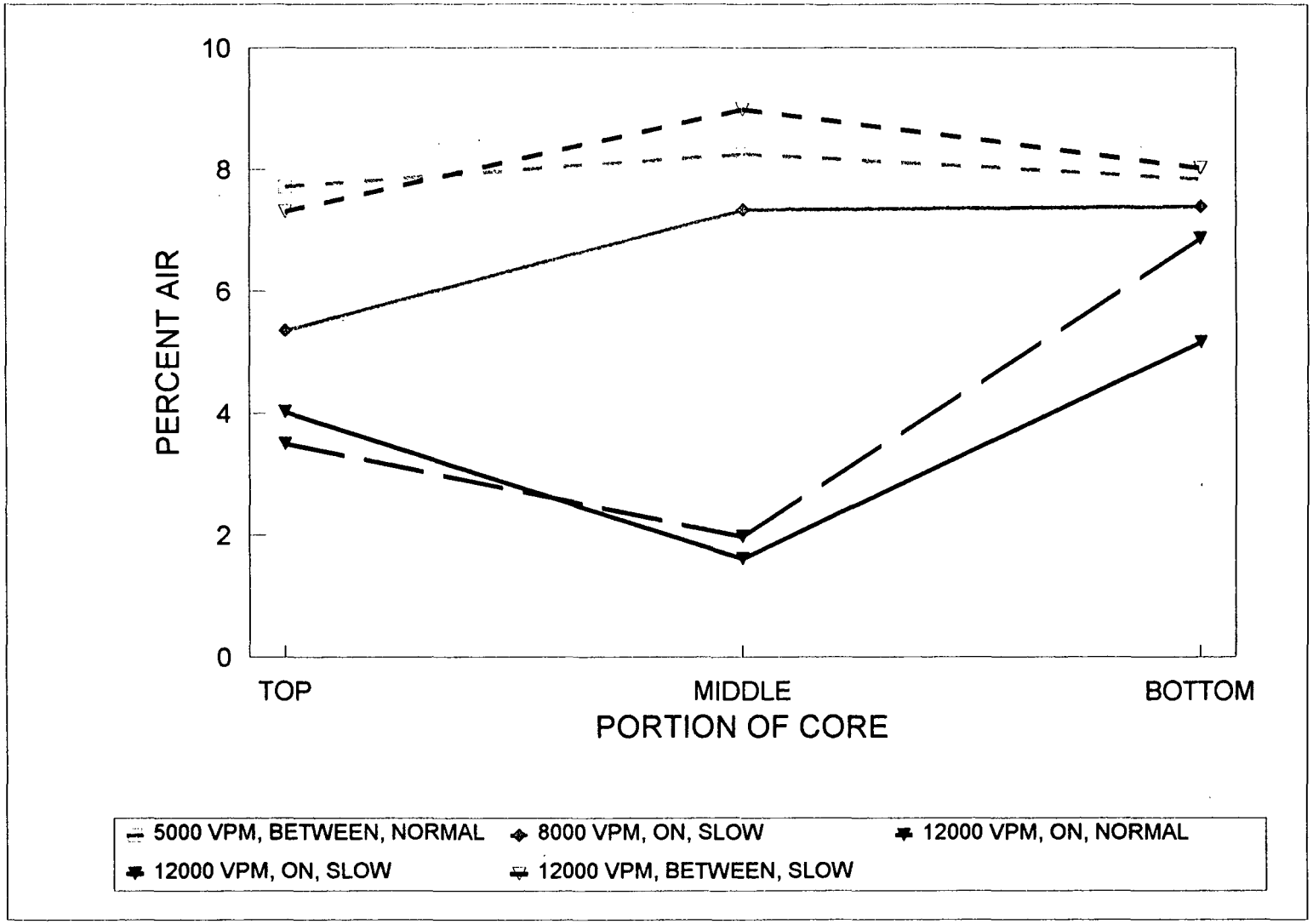


FIGURE 12 Average percent hard air for project C.

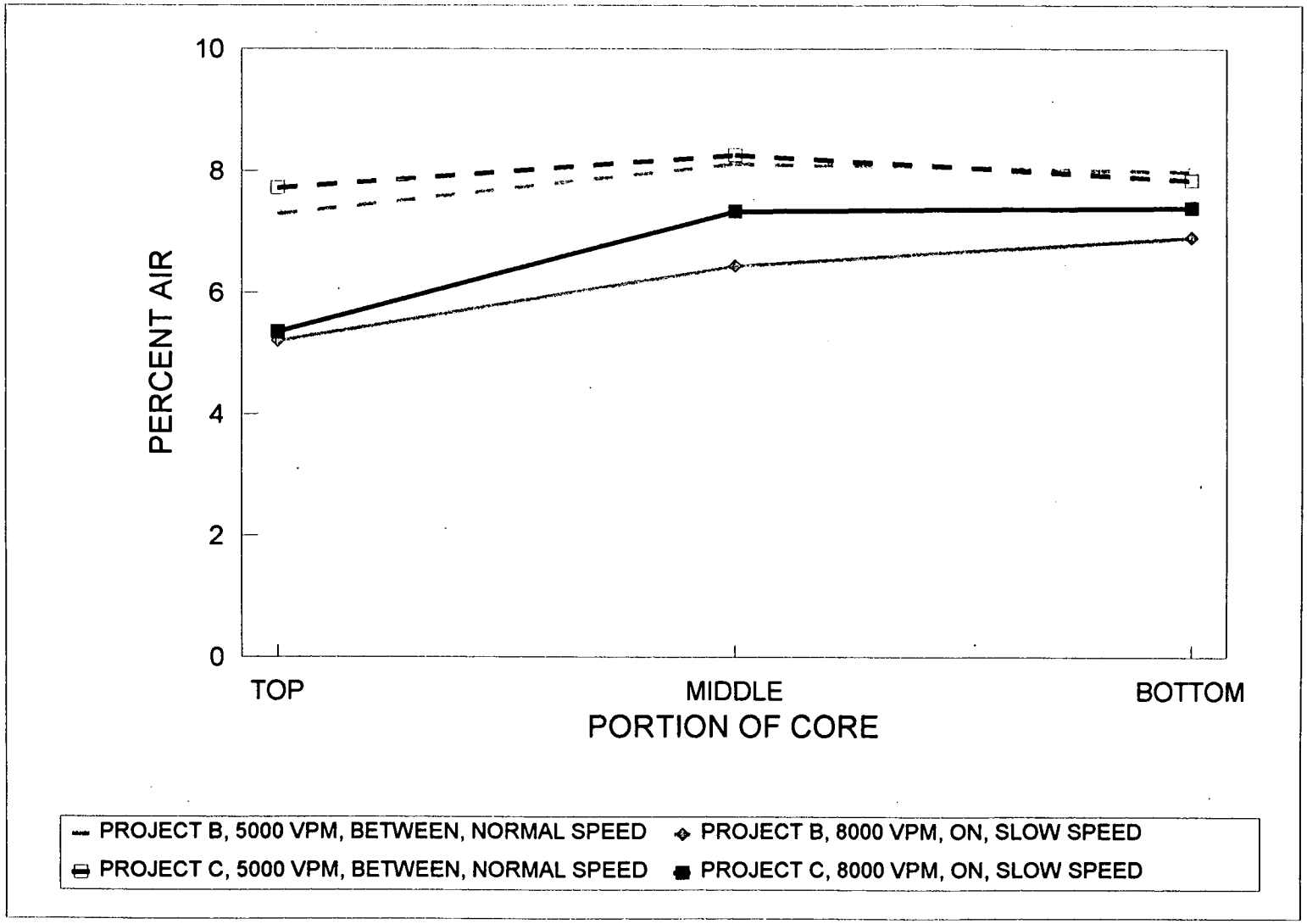


FIGURE 13 Average percent hard air for Projects B & C.

**TABLE TITLES**

1. Paver and Project Data

2. Average Hard Air Results for Minimum and Maximum Consolidation Effort on Each Project

**TABLE 1**
**Paver and Project Data**

| Project | A-1 | A-2 | A-3 | B | C |
|---|---|---|---|---|---|
| Number of vibrators | 22 | 22 | 22 | 17 | 15 |
| Maximum spacing between vibrators (mm) | 460 | 460 | 460 | 660 | 740 |
| Minimum spacing between vibrators (mm) | 230 | 230 | 230 | 360 | 360 |
| Spacing between test vibrators (mm) | 410 | 410 | 380 | 660 | 360 |
| Vibrator centrifugal force at 10,000 vpm (N) | 7870 | 7870 | 7870 | 5560 | 7870 |
| Vibrator elevation below paver pan (mm) | 0 | 0 | 100 | 0 | 0 |
| Design thickness of pavement (mm) | 300 | 300 | 300 | 300 | 300 |
| Design width of pavement (m) | 7.9 | 7.9 | 7.9 | 7.9 | 7.9 |
| Iowa mix design number | C-3WR-C20 | C-3WR-C20 | C-3WR-C20 | C-4WR-C20 | C-3WR-C20 |

**TABLE 2**
**Average Hard Air Results for Minimum and Maximum Consolidation Effort on Each Project**

| Project | Vibrator Frequency | Location Relative to Vibrators | Paver Speed | Average Percent Air in Cores | | |
|---|---|---|---|---|---|---|
| | | | | Top | Middle | Bottom |
| A-1 | 5000 | Between | Normal | 9.2 | 10.7 | 10.7 |
| A-1 | 8000 | On | Normal | 8.4 | 9.2 | 9.9 |
| A-2 | 5000 | Between | Normal | 7.9 | 10.3 | 9.5 |
| A-2 | 8000 | On | Slow | 6.5 | 7.2 | 10.8 |
| A-3 | 5000 | Between | Normal | 8.5 | 10.3 | 11.2 |
| A-3 | 8000 | On | Slow | 6.3 | 5.9 | 8.9 |
| B | 5000 | Between | Normal | 7.3 | 8.1 | 8.0 |
| B | 8000 | On | Slow | 5.2 | 6.4 | 6.9 |
| C | 5000 | Between | Normal | 7.7 | 8.3 | 7.9 |
| C | 8000 | On | Slow | 5.4 | 7.3 | 7.4 |
| C | 12000 | Between | Slow | 7.3 | 9.0 | 8.0 |
| C | 12000 | On | Slow | 4.0 | 1.6 | 5.2 |
| C | 12000 | On | Normal | 3.5 | 2.0 | 6.9 |