Influence of Vibrating Beams on Compaction of Concrete Surfacings

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• THE CHARACTERISTICS of vibrating beams for compacting concrete road and runway slabs by applying vibrations to the upper surface have been evolved largely from experience. Since there were few precise data on the relative importance of the several characteristics of the vibration, an experimental vibrating machine (*1*) (Fig. 1) was built at the Road Research Laboratory a few years ago and tests have been made to assess the effect of the following variables on the compaction of concrete:

1. The acceleration of the vibrating beam.
2. The amplitude of the vibrating beam.
3. The number of vibrations transmitted to the concrete as the machine passes over a point.
4. The weight of the beam.
5. The shape of the shoe fitted to the underside of the beam.

The frequency of vibration was not considered as a separate variable since it is included both in the acceleration of the vibrating beam and in the number of vibrations applied. When the machine was made it was also considered desirable to alter the direction and the waveform of the vibration, but up to the present only a vertical sinusoidal vibration has been used.

In addition to the tests to examine the effect of the characteristics of the vibration, the experimental machine has been used to examine the effect of the method of using the machine. The factors which were considered most likely to have the greatest influence on the depth of compaction, and which have been investigated up to the present time, are: (a) the workability of the concrete; (b) the thickness of the concrete; (c) the presence of reinforcement; and (d) the number of passes.

This paper gives a brief outline of the technique of the tests—details have been published elsewhere (*2*)—and summarizes the results.

TEST METHOD

For each test one or more slabs were laid, each about 18 ft long, 4 ft wide and generally about 18 in. deep, on a 6-in. thick base of compacted hoggin, (a naturally occurring mixture of gravel and sand containing sufficient clay to hold the mixture together when rolled) the base being thoroughly rolled to achieve as uniform a foundation as possible. The 18-ft length was necessary so that the first 8 ft could be used to allow the machine to reach a steady condition and the remaining 10 ft could be used for the test slab. The 4-ft width was thought to be sufficient to avoid the effects of the side forms, but not so wide that the mixing and placing of the concrete could not be carried out in the laboratory. The 18-in. depth was initially selected so that the slabs would not be compacted throughout their depth; but, as experience was gained, it was necessary to increase the depth of compaction up to 36 in.

The concrete had a cement content of 400 lb per sq yd, and the sand was 33 percent of the total aggregates. The water/cement ratio for the main series of tests was 0.52. Before any test was carried out, a preliminary test was made

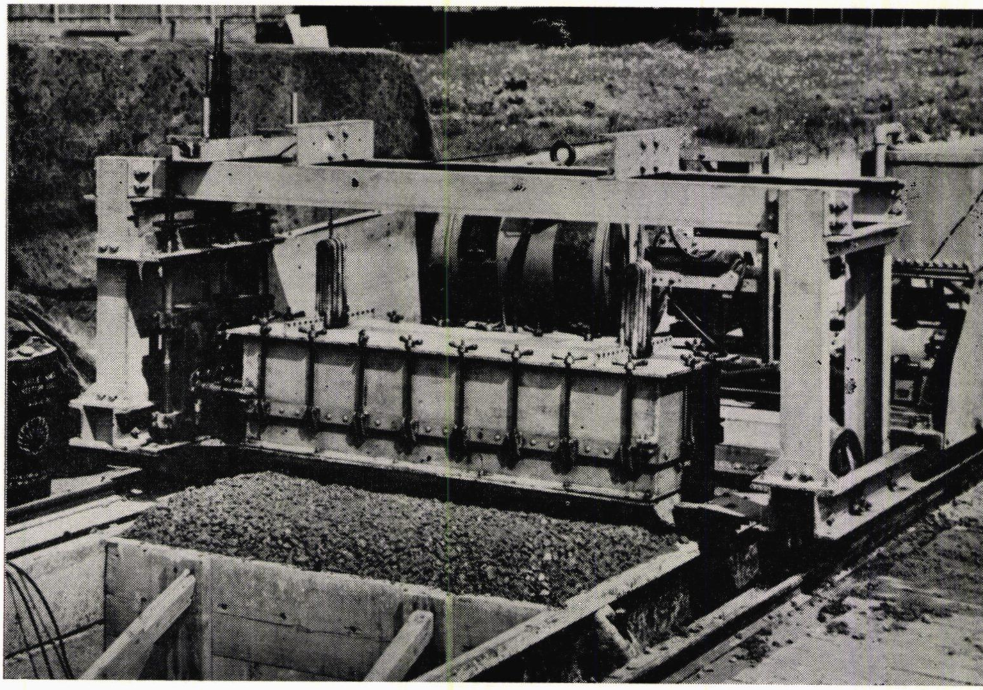


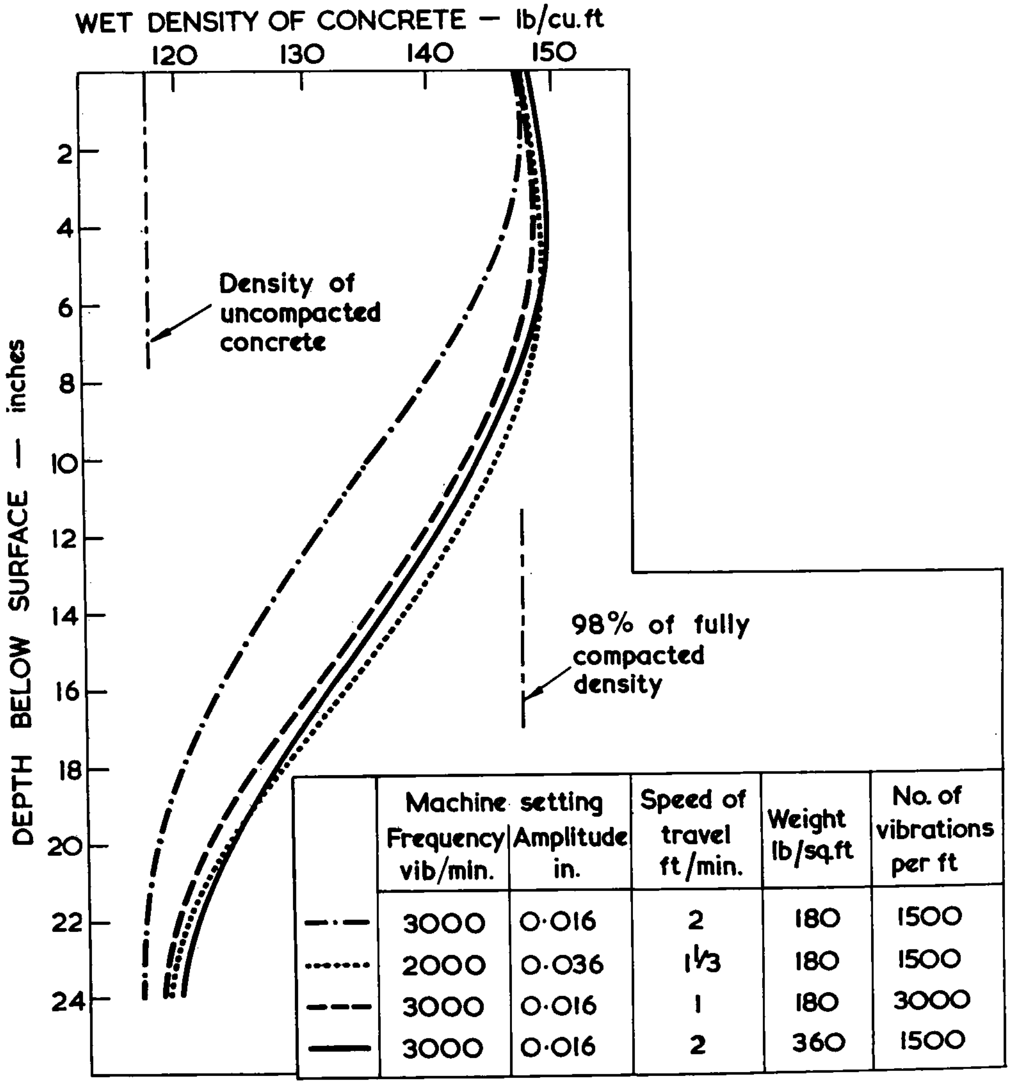
Figure 1. Experimental vibrating machine.

to determine the surcharge. The required surcharge was estimated, and then a slab was laid, the surcharge being increased steadily from about 1½ in. less than the estimated value to about 1½ in. more, in a length of 6 ft. This slab was compacted with the vibrating machine running at the frequency, amplitude, and speed of travel of the main test. Then, on the same day as the main test, materials from the same stock piles were used so that the surcharge estimate would be as accurate as possible. The point at which the beam started to rise was determined, and the nominal surcharge (that is, the height to which the concrete was spread above the rail on which the machine ran) for this point was used for the main test.

The density/depth gradient for the 10-ft test length was determined by the gamma-ray technique (*3*) as soon as the concrete had set sufficiently for the formwork to be removed. This technique is based on the fact that the absorption of gamma radiation by a material depends on the density of the material and the path length. Holes were drilled vertically into the slab at 1-ft intervals along the centerline and a radioactive source was lowered into each hole in turn, measurements being made of the intensity of radiation received by collimating tubes maintained horizontally in line with the source. Tests were made at vertical intervals of 1 in. throughout the thickness of the slab. Density/depth gradients were generally measured for each half of the slab at 10 transverse planes so that a very detailed survey of the variation of the density/depth gradient was obtained. In the first tests there was some scatter of the results, which was primarily caused by variations in the amount of precompaction given to the concrete by spreading from one side and restraint due to the method of driving the beam. Modifications were made to the equipment before the main tests were made; the scatter was then very small and it was possible to use the average density of the whole slab for studying the results.

EFFECT OF ACCELERATION OF VIBRATING BEAM AND SHAPE OF SHOE

Tests on vibrating tables have generally shown that the compaction of concrete is improved when the acceleration of the vibrating table is increased (*4*, *5*); therefore, the acceleration of the vibrating beam was one of the first of the variables to be studied. It was found, however, that varying the acceleration from 1 to 12 *g* had little or no effect on the compaction of the concrete, and it was decided to carry out most of the work with the beam having an acceleration of about 4 *g*, the acceleration of most commercial beams at the time. It was felt that by adhering to this accleration any improvements in compaction



	Machine setting: Frequency vib/min.	Machine setting: Amplitude in.	Speed of travel ft/min.	Weight lb/sq.ft	No. of vibrations per ft
—·—	3000	0·016	2	180	1500
·······	2000	0·036	1⅓	180	1500
— —	3000	0·016	1	180	3000
——	3000	0·016	2	360	1500

Figure 2. Effect of amplitude of vibration, number of vibrations transmitted, and weight of beam.

would be achieved without the change in design leading to undue wear of the moving parts and therefore to high maintenance costs.

For the first tests a shoe with a quarter-elliptical shape, the type most commonly used in practice, was used. However, it was found very difficult to maintain the vertical sinusoidal vibration when, for most of the time, only the rear edge of the shoe was in contact with the concrete, which was partly compacted in front of the beam. A rectangular shoe having its front edge rounded to 2-in. radius was tried. With this shoe it was much easier to maintain a pure sinusoidal vibration and, contrary to expectation, no considerable amount of concrete was "pushed off", but the concrete was compacted in front of the shoe to such a depth that the leading edge compressed it satisfactorily.

EFFECT OF AMPLITUDE AND NUMBER OF VIBRATIONS AND WEIGHT OF BEAM

The variation of density with depth in slabs compacted with constant acceleration and a rectangular shoe, but with varying amplitude, number of vibrations and weight of beam, is shown in Figure 2. With an amplitude of 0.016 in., a frequency of 3,000 vibrations per min, a beam weighing 180 lb per sq ft, traveling at about 2 ft per min, the concrete was well compacted (about 98 percent of the theoretical maximum value) only to a depth of about 2½ in. Below this the density decreased until, at a depth greater than 22 in., the concrete had not been compacted at all by the vibration. When the amplitude was increased to about 0.036 in. at a frequency of 2,000 vibrations per min, with the number of vibrations transmitted kept constant at 1,500 per ft of travel by reducing the speed of travel to about 1⅓ ft per min, the depth to which 98 percent of the theoretical maximum density was obtained was increased to about 8½ in. In the same way, if the amplitude and frequency were retained at 0.016 in. and 3,000 vibration per minute but the number of vibrations transmitted increased to 3,000 per ft by running the machine at about 1 ft per minute, the depth of good compaction was increased to about 6½ in. A similar increase (to 7½ in.) could also be obtained with the amplitude and number of vibrations remaining constant but with the weight of the beam increased to 360 lb per sq ft. Although the depths to which 98 percent of the theoretical maximum density could be achieved varied from 6½ to 8½ in., the shape of the curves obtained either by doubling the amplitude, doubling the number of vibrations transmitted to the concrete, or doubling the weight of the beam, were very similar. It seems, therefore, that similar increases in compaction can be obtained by proportional increases in any of these three factors, and the depth of compaction thus appears to be proportional to the work which the vibrating machine is capable of doing on the concrete.

Although there is a limitation to the ultimate amount of improvement in the depth of compaction which can be achieved, these results can be used to consider methods of improving the work done with existing machines. On many construction projects there is a temptation to increase the speed of travel of the vibrator in order to expedite the work. The results show, however, that this practice is likely to result in poorer compaction unless the vibrating machine is one with a large amplitude or a heavy beam. For internal vibrators there has been a tendency in recent years to increase the frequency of vibration, but this practice would obviously not lead to improved performance with a surface vibrating machine. If the acceleration of the beam is kept constant, to avoid increased wear on the bearings, but the number of vibrations per inch is increased by raising the frequency of vibration, the depth of compaction would again be reduced because the consequent reduction in amplitude will have a greater effect than the increase in the number of vibrations transmitted. The compaction of thick slabs or the more economical use of plant for compacting slabs of conventional thickness is, therefore, most likely to be achieved by increasing the amplitude of vibration or by increasing the weight of the vibrating beam.

EFFECT OF WORKABILITY OF CONCRETE AND REQUIRED SURCHARGE

When the effect of the characteristics of the vibration was being examined, a second series of tests was made in which the concrete had a lower workability. For this concrete the proportions of the solid materials were the same, but the water content was reduced to give a reduction in compacting factor of about 0.04. Also during these tests the proportion of the weight of the beam supported from the framework of the machine was measured by strain gages on links between the anti-vibration supports on the beam and the wire ropes connected to the framework. Thus, an estimate could

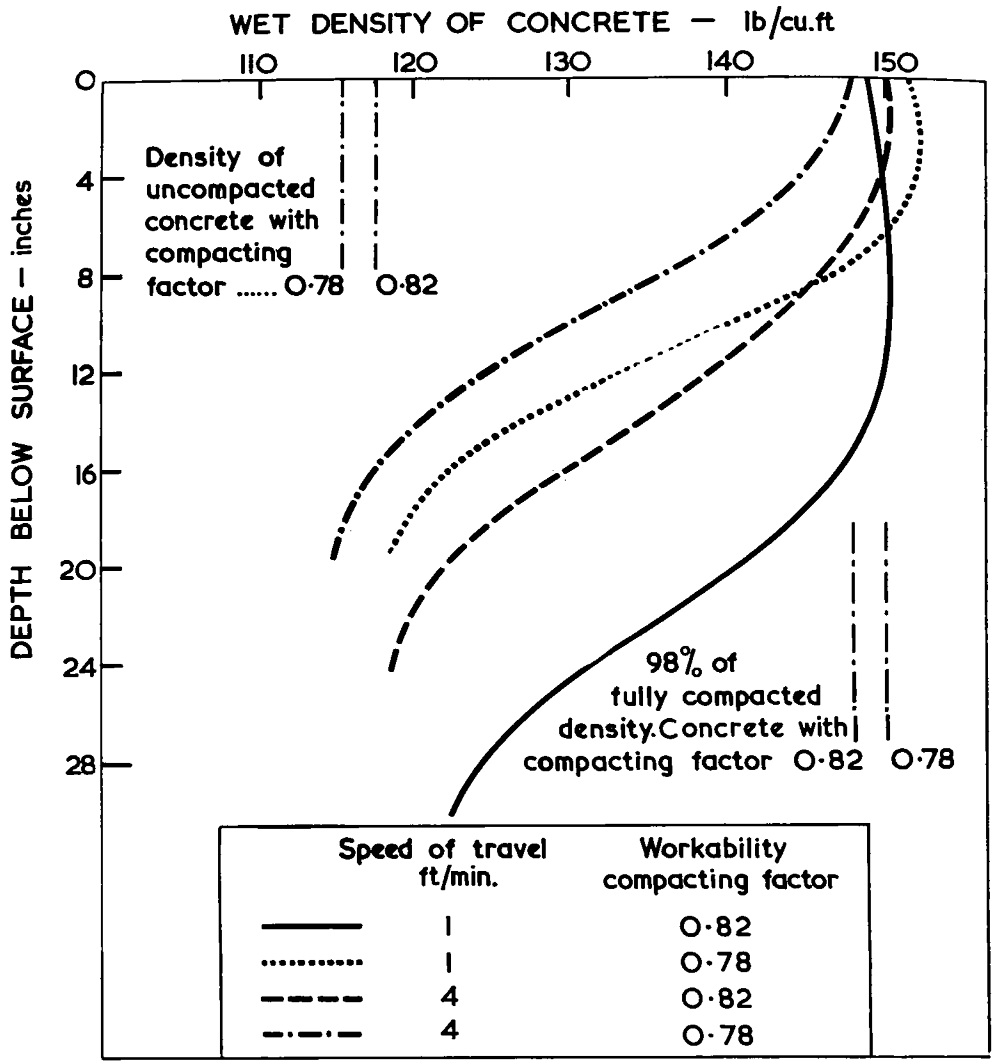


Figure 3. Effect of workability of concrete and speed of travel.

be made of the proportion of the weight of the beam which was supported by the concrete. For the driest mix, which had a compacting factor of 0.78, about 10 percent of the weight of the beam was supported by the concrete irrespective of variations in the characteristics of the vibration or the weight of the beam itself. With this mix, when the beam weighing 360 lb per sq ft was vibrated with an amplitude of 0.064 in. at a frequency of 1,500 vibrations per min, it was not possible to get full compaction even at the top of the slab when the machine was run forward at a speed of 4 ft per min (Fig. 3). When the speed of travel was reduced to 1 ft per min, however, good compaction (98 percent of the theoretical maximum) was achieved to a depth of about 6½ in. This was about the maximum depth of concrete of this workability which could be compacted however much the work which the machine was capable of doing was increased. With concrete of a higher workability having a compacting factor of about 0.82, the concrete supported about 7½ percent of the weight of the

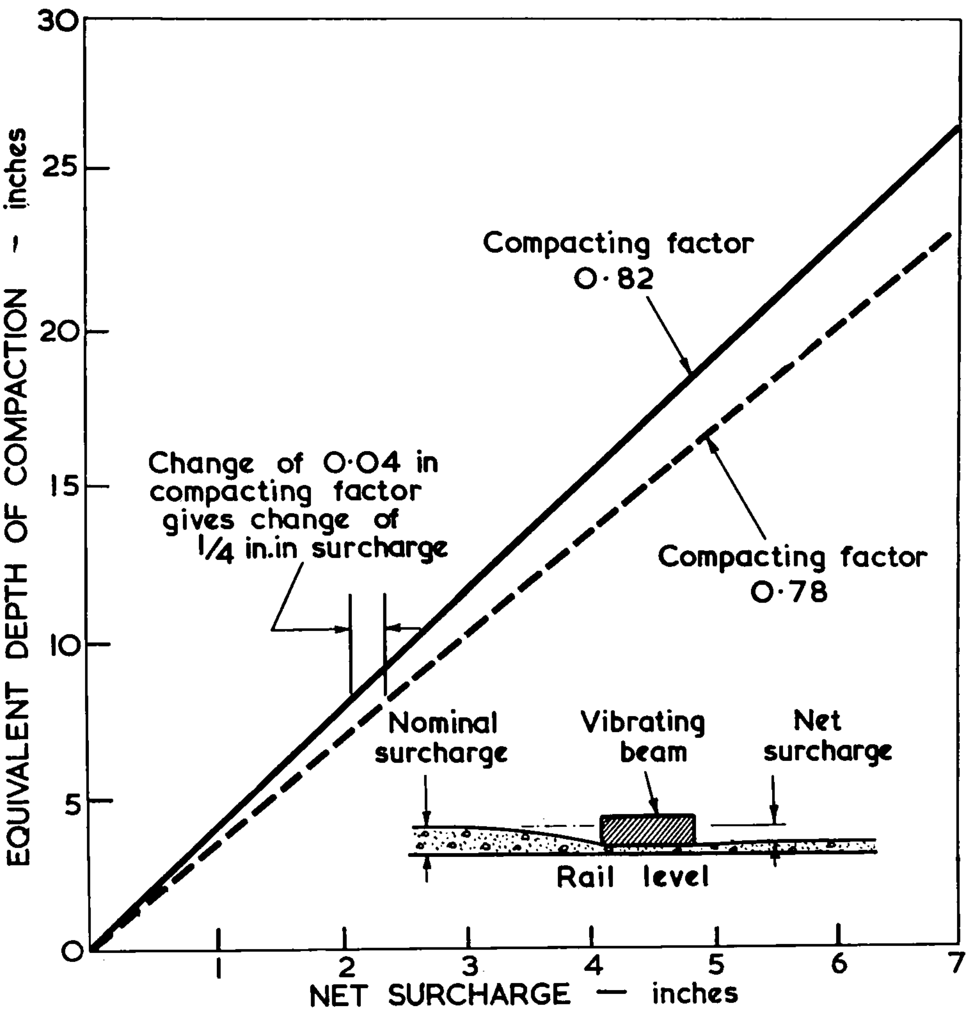


Figure 4. Effect of workability of concrete on surcharge required.

beam and the same beam running at a forward speed of travel of 4 ft per min achieved good compaction to about the same depth (about 6½ in.). Reducing the speed of travel to 1 ft per min, however, gave a much larger increase in the depth of compaction, which was about 16 in. With the more workable mix, therefore, much greater improvements were possible than with the very dry mix; although increasing the work which the machine was capable of doing would not give much increase in the depth of compaction above 16 in., some small increase might be possible. It seems probable, therefore, that even with machines modified to give improved performance it would not be desirable, except for very thin slabs, to use concrete of as low a workability as the mix with a compacting factor of 0.78. Mixes, however, with a compacting factor of about 0.82 should be perfectly satisfactory.

The nominal surcharge for each test was determined by a preliminary test. In practice, however, it was not easy to detect the exact point at which the rise of the beam commenced and it is possible that the results were also affected by small variations in the workability of the concrete, so that the estimated value of the nominal surcharge could only be regarded as approximate. Any small error was corrected by variations in the surge of the concrete behind the beam during compaction and the net surcharge was determined for each test, that is, the height to which the concrete was spread above the level of the concrete after compaction. The net surcharge was thus the nominal surcharge less the surge of the concrete behind the vibrating beam. For concrete of a given workability it was found that this net surcharge was linearly related to the depth of compaction achieved (Fig. 4). The relationship was determined for concretes with a compacting factor of 0.78 and of 0.82, and for a slab 8 in. thick a change in compacting factor of 0.04 would require a change in surcharge of about ¼ in. This emphasizes the importance of estimating the surcharge carefully if full compaction is to be achieved and of careful control of concrete quality in order to achieve uniform workability if full compaction is to be achieved at all points in the slab.

EFFECT OF THICKNESS OF SLAB

In some of the early tests, piezo-electric accelerometers were set at various depths in the concrete to record movements under the vibrating beam (*6*). Each accelerometer was equal in size and weight to the larger stones employed in making the concrete in order that they should not interfere with the vibration. The outputs from the accelerometers were fed into electronic equipment from which a photographic record of the vibration was made while the vibrating beam traveled along the concrete over the gages. In analyzing the records, measurements were made of the amplitude obtained at intervals of 1 in. of travel, and a diagram was plotted for each test showing for each gage depth the variation of amplitude of vibration with position of the beam. From this a diagram was produced showing the contours of amplitude of vibration in the concrete beneath the vibrator. These diagrams showed that there was considerable movement in the concrete in front of the beam and that the amplitude diminished with increasing depth below the surface and then increased slightly at the bottom of the slab. This increase in amplitude seemed to be due to reflection of vibration from the base and it seemed possible that the depth of compaction obtained in a very thick slab would be less than the thickness of slab which could just be fully compacted. Figure 5 shows the results of some of the tests on slabs of different thickness. With the vibrating beam traveling at 4 ft per min, the 18-in. thick slab was only fully compacted to a depth of about 3 in. and a similar depth of compaction was achieved in a 12-in. slab. When the slab thickness was reduced to 9 in., however, full compaction was achieved to the bottom of the slab. It is important, therefore, to use vibrating machines well

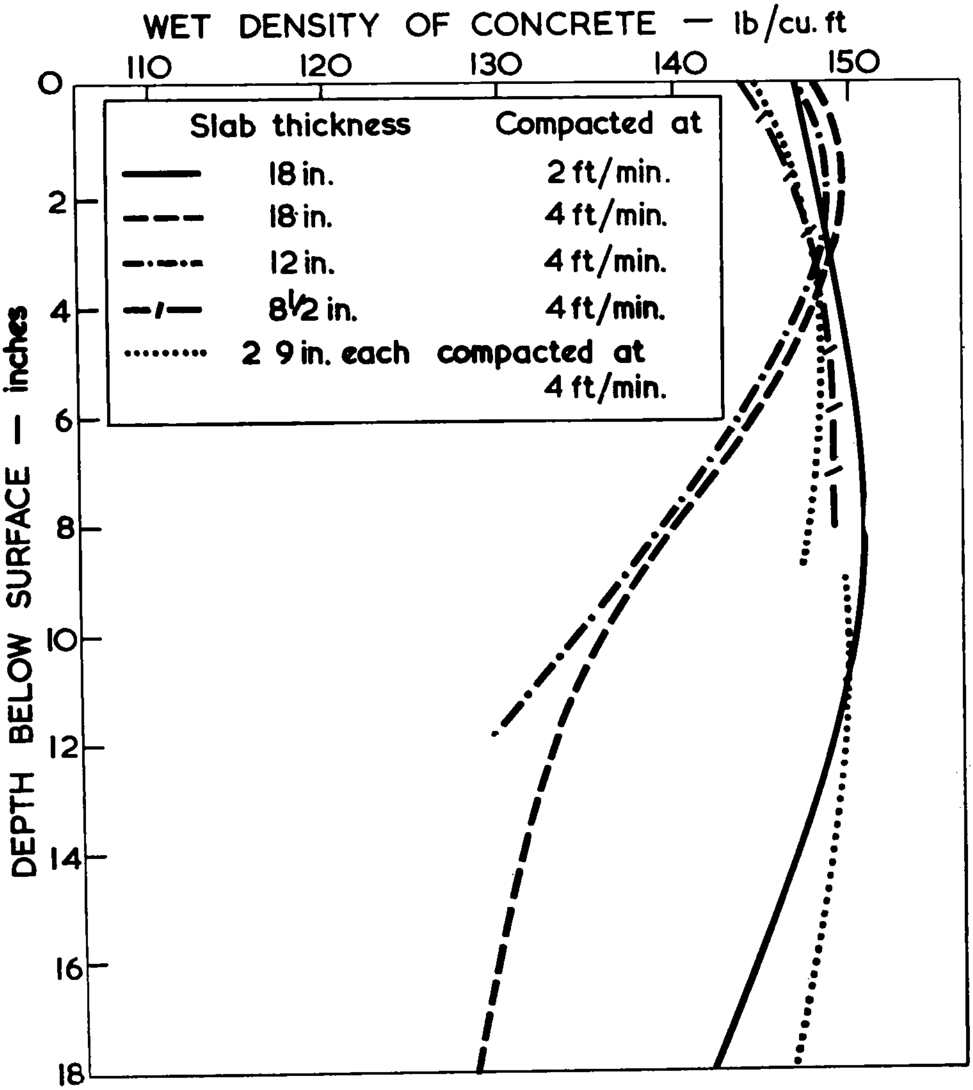


Figure 5. Effect of thickness of slab.

within their capacity or to alter the concrete so that full compaction can just be achieved. If the machine is not powerful enough to achieve compaction to the bottom of the slab, poor compaction will be obtained in large areas near the bottom, and not only below the depth to which full compaction would have been achieved in the thinner slab.

These tests were extended to examine the effect of compacting the concrete in two courses and it was found that unless the bottom course was fully compacted compaction of the top course was similar to that in a very thick slab. When the bottom course was fully compacted (Fig. 4), however, the top course was also fully compacted when its thickness was equal to that which could be fully compacted as a single slab. Unless a very dry concrete is being used, there seems to be little value in two-course compaction. With concrete of a compacting factor of 0.82 it was possible to achieve almost equal compaction of a 18-in. thick slab in one pass, if the machine was run at half the speed required to achieve full compaction of each of two 9-in. slabs. Two-course compaction would, therefore, be of value only if very dry mixes were considered necessary.

EFFECT OF REINFORCEMENT

Examination of cores taken from a large number of public roads over a period of about two years suggested that

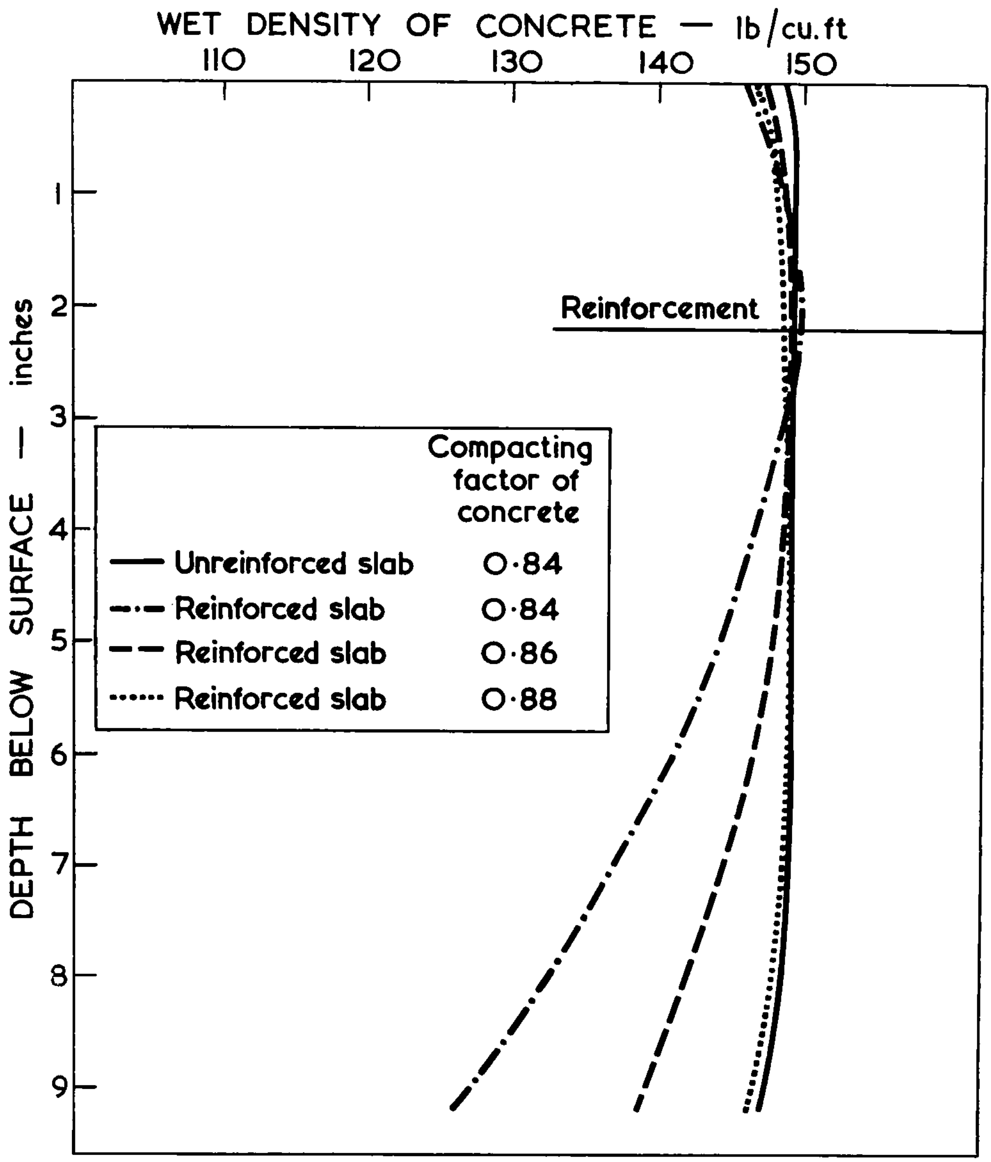


Figure 6. Effect of reinforcement.

the compaction of unreinforced concrete was generally good but that only about 50 percent of cores taken from 8- to 9-in. thick slabs of reinforced concrete were fully compacted to the bottom. This suggested that the presence of reinforcement in the slab was having some effect on the compaction, and a series of tests was made in which reinforcement of varying weights was placed in concrete in which aggregates of different maximum sizes were included. These tests showed that irrespective of the weight of reinforcement used (vary-

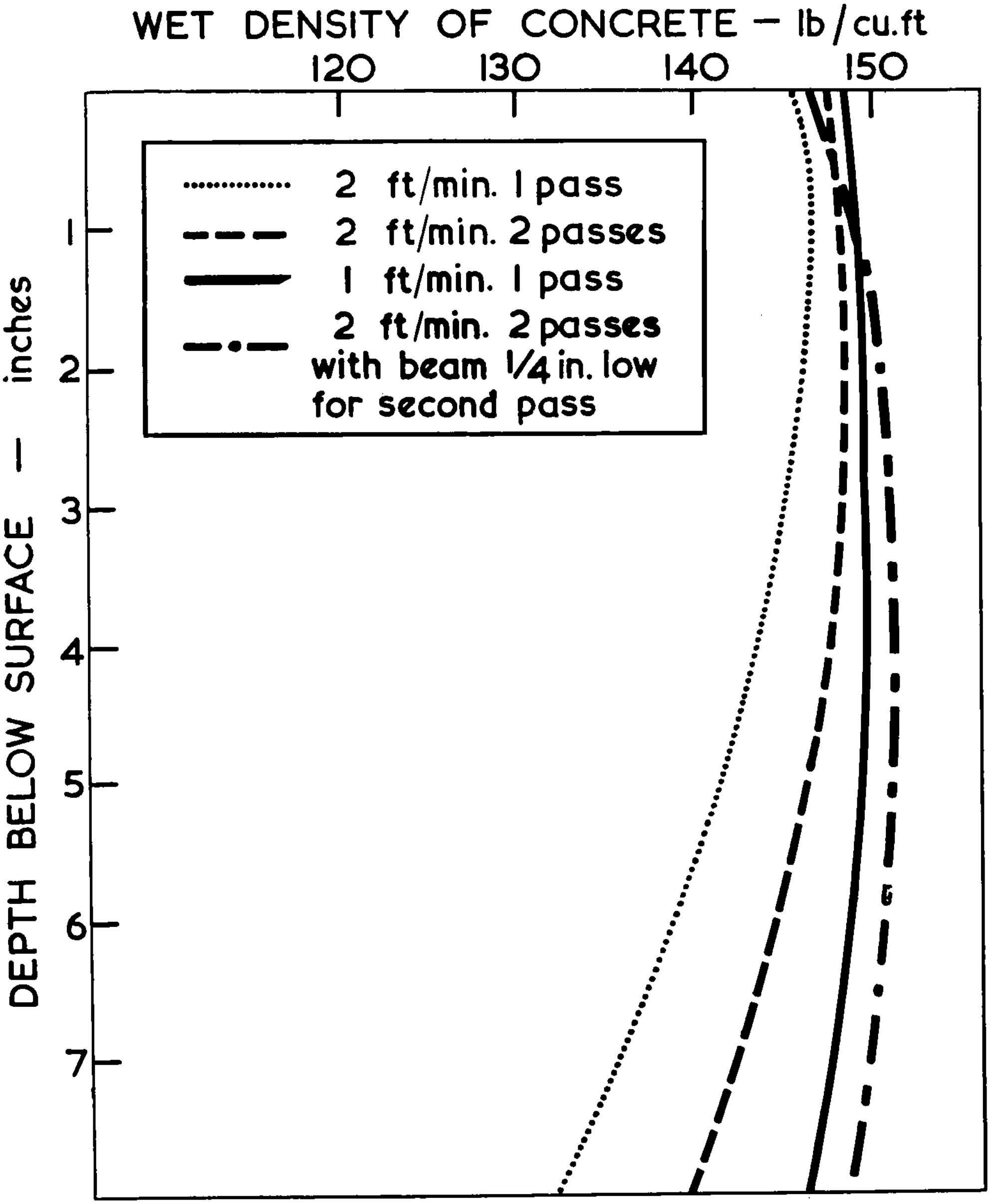


Figure 7. Effect of a second pass.

ing from 5 to 12 lb per sq yd), or the spacing of the bars (3 to 6 in.), or the maximum size of the aggregate (¾ to 1½ in.), the thickness of slab which could be fully compacted was reduced from about 9 to about 7 in. by the presence of a layer of reinforcement about 2 in. from the top. When an attempt was made to compact a 9-in. slab containing the reinforcement, it was found (Fig. 6) that the density of the concrete started to fall off immediately below the reinforcement and that there was poor compaction near the bottom of the slab. To obtain compaction similar to that obtained in an unreinforced slab, it was necessary to increase the workability of the concrete, the compacting factor being increased by about 0.04 in order to get the same depth of compaction. This increase in workability could be obtained either by increasing the water content or by increasing the cement content of the mix. If, however, it was necessary to use the same mix in a reinforced as in an unreinforced slab, it was found that with a similar machine it would be necessary to halve the forward speed of travel to achieve the same depth of compaction.

EFFECT OF NUMBER OF PASSES

In practice it is also common to attempt to get improved compaction by making a second pass with the vibrating machine. A series of tests was made to compare the depth of compaction achieved with the machine moving forward at 1 ft per min with that obtained with the machine making two passes at a forward speed of 2 ft per min for each pass. When the height of the beam was not altered, the compaction obtained with two passes, although better than that obtained with one pass at the same speed, was less than that obtained with a single pass at half the speed (Fig. 7). To obtain equally good compaction when two passes were made it was necessary to lower the vibrating beam by about ¼ in. for the second pass in order to increase the contact pressure between the vibrating beam and the concrete, thus enabling the beam to do sufficient work to compact the concrete at the bottom of the slab. There is no practical advantage to be gained in using more than one pass of the vibrating machine.

SUMMARY

Since 1945 the Road Research Laboratory has been carrying out a fundamental investigation into the factors affecting the efficiency of vibrating machines for compacting concrete. For this work an experimental machine was made which enabled the characteristics of the vibration to be altered, and tests have been made to examine the effect of the acceleration and amplitude of the vibration, the number of vibrations transmitted as the beam goes over a particular point in the concrete, the weight of the beam, and the shape of the shoe fitted to it. In addition, the experimental machine has been used to examine the effect of the method of using the vibrating machine.

The results of these tests, which are summarized in this paper, have shown that the amplitude of vibration, the number of vibrations transmitted and the weight of the vibrating beam, are the most important factors in relation to the compaction of the concrete. These factors are of equal importance, the increase in the depth of compaction which can be achieved being the same when either the amplitude, the number of vibrations or the weight is doubled. This suggests that the compaction of thick slabs or the more economical use of plant for compacting slabs of conventional thickness is most likely to be achieved by increasing the amplitude of vibration or the weight of the beam.

The depth of compaction is also related to the workability of the concrete. For concrete of a given workability there seem to be a maximum depth to which it can be compacted irrespective of changes in the characteristics of the vibration, and it does not appear desira-

ble to use mixes of lower workability than those which would have a compacting factor of about 0.82. Careful estimation of the surcharge and good control of concrete quality are necessary if full compaction is to be achieved at all points in the slab. The depth of compaction is reduced if the concrete slab is too thick for the machine to achieve full compaction to the bottom, and by the presence of reinforcement. It is important to use vibrating machines well within their capacity since if the machine is not quite capable of achieving full compaction to the bottom of the slab there will be large areas of poor compaction. When reinforcement is used the workability of the concrete must be increased or the speed of travel must be reduced compared with that necessary for unreinforced work. There is no advantage in using two passes in place of one in order to speed up the operations.

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