242

TRANSPORTATION RESEARCH CIRCULAR

Number 242, April 1982
ISSN 0097-8515

Transportation Research Board, National Academy of Sciences, 2101 Constitution Avenue, N.W., Washington, DC 20418

STATE OF THE ART: VIBRATORY COMPACTION OF ASPHALT PAVEMENTS

modes

1 highway transportation
4 air transportation

subject areas

31 bituminous materials and mixes
33 construction
40 maintenance
41 construction and maintenance equipment

GROUP 2 - DESIGN AND CONSTRUCTION OF TRANSPORTATION FACILITIES

Roger V. LeClerc, Washington Department of Transportation, Chairman

SECTION F - CONSTRUCTION

David S. Gedney, De Leuw, Cather and Company, Chairman

COMMITTEE ON FLEXIBLE PAVEMENT CONSTRUCTION

Gerald S. Triplett, The Asphalt Institute, Chairman

Members

E. R. Brown
Donald E. Carey
William E. Gehman
Myron Geller
Charles S. Hughes
Richard C. Ingberg
Charles H. Jackson
Cyrus S. Layson
Edward T. Lynch
Duncan A. McCrae
Harry R. Marien
Milton F. Masters
James J. Murphy
Charles F. Potts
James A. Scherocman
Harrison S. Smith
Richard R. Stander
David G. Tunnicliff
Lansing Tuttle

William G. Gunderman, Transportation Research Board Staff

State of the Art: Vibratory Compaction of Asphalt Pavements

Vibratory rollers were first used to compact asphalt pavements more than ten years ago. However, until the last six or seven years, their use was relatively rare. For example, one 1972 publication states that up to that time knowledge of vibratory rollers in asphalt was insufficient to permit any kind of a definitive statement, and another reported no advantage resulting from vibratory rollers (1,2). The purpose of this report is to summarize the art of vibratory compaction and its successful development.

Early attempts at using vibratory rollers in asphalt paving were often unsatisfactory and when satisfactory, generally uneconomical. Unsatisfactory pavement density, or smoothness, or both were often obtained (3). When satisfactory results were achieved, the vibratory roller usually was substituted for a static roller in the conventional train, and as most specifications described the number of rollers required, the process was uneconomical because of the relatively high cost of the vibratory roller (4). The early vibratory rollers were designed to compact soil and granular bases, and it is not surprising that they were used improperly with asphalt (5). Furthermore, even if they had been designed for asphalt, there would still have been a transitional period of learning how to use them. The rare early successes appear to be fortuitous combinations of circumstances, job conditions and roller characteristics, which happend to work but could not be duplicated elsewhere.

Today, there are vibratory rollers designed for asphalt. Some are third or fourth-generation designs representing the benefits of experience. In addition, considerable know-how in their effective use has accumulated. Asphalt pavements can be compacted satisfactorily with vibratory rollers which replace enough static rollers to be economical. Often satisfactory vibratory compaction is accomplished with significantly fewer passes and shorter rolling time.

Perhaps the most important lesson that has been learned is that in order to use a vibratory roller effectively, the roller has to fit the circumstances of each job or part of a job. All vibratory rollers do not fit all jobs, but many vibratory rollers can be operated properly to fit many jobs.

Factors Influencing Compaction

Compaction of asphalt pavements is an extremely complex process involving many significant factors which have been thoroughly documented in the literature (1,6,7,8,9,10, 11,12,13). Most of these factors cannot be expressed quantitatively in relationship to compaction, and as a result, compaction has been accomplished by methods which have evolved through the years based on experience. Vibratory rollers do not eliminate any of these factors, and they do introduce significant new factors making an already complex process even more complex (14).

Important new factors introduced by vibratory rollers are explained by the following definitions (15,16):

Vibratory Roller. A roller with a rotating eccentric inside one or both rolls.

Frequency. The speed of rotation of the eccentric in hertz (usually expressed as vibrations per minute, vpm).

Amplitude. The total vertical motion of the roll caused by rotation of the eccentric in meters (usually expressed as inches). Sometimes called "actual double amplitude."

Nominal Amplitude. One-half of the theoretical vertical motion of the roll during one full revolution of the eccentric when the roll is vibrating on a medium such as a rubber tire.

$$A = \frac{wr}{m}$$

where: A = amplitude, meters
w = mass of eccentric, kg
r = radius of w, meters
m = mass of roll assembly including eccentric mechanism, kg

$$A = \frac{WR}{M}$$

where: A = amplitude, inches
W = mass of eccentric, lbs
R = radius of W, inches
M = mass of roll assembly including eccentric mechanism, lbs

Dynamic Force. The force caused by rotation of the eccentric in newtons (usually expressed as pounds-force).

$$DF = 39.5wrf^2$$

where: w = mass of eccentric, kg
r = radius of w, meters
f = frequency, Hz
39.5 = a dimensional constant

$$(DF = WRF^2/35235$$

where: DF = dynamic force, pounds-force
W = mass of eccentric, lbs
R = radius of W, in
F = frequency, vpm
35235 = a dimensional constant)

Total Applied Force. The sum of the dynamic force plus static working weight on the roll in newtons (usually expressed as pounds-force).

Unit Total Applied Force. Total applied force in newtons per meter of roll width (usually expressed as pounds-force per inch of roll width).

The definition of amplitude is an attempt at stating what the roll would do if it could. Actual up and down motion of the roll is, or should be, almost imperceptible because of the dampening effects of both the material being compacted and its underlying layers, which may or may not yield under the action of the roller. With respect to compaction, amplitude can be considered to be a measure of how hard the roll strikes the pavement each time the eccentric weight rotates. High amplitude means a heavy blow, and low amplitude means a light blow.

Total applied force of a vibratory roller is analogous to total applied force of a static roller. The difference between a static and vibratory roller is applied through vibration. This makes it possible to vary the total applied force making the vibratory roller more versatile and able to achieve satisfactory results under a wider variety of conditions.

Occasionally, total applied force has been defined the same as dynamic force is defined above. The two should not be confused. The static working weight of some vibratory rollers is comparable to the total applied force of some static rollers and must be considered to avoid overstressing the pavement. No vibratory roller compacts by vibration alone.

Although total applied force is an important concept that is useful in understanding vibratory rollers, its use for comparing rollers or specifying rollers is not recommended. A given dynamic force can be achieved by a wide variety of combinations of frequency and amplitude. In addition, the static working weight on the roll can be achieved with different ratios of sprung and unsprung masses. All of this may be applied through rolls of various diameters and widths, roll characteristics which are equally important for vibratory rollers as for static rollers. Therefore, a given level of total applied force developed by two distinctly different rollers would not necessarily produce the same compactive effect, nor a desirable compactive effect, on a specific pavement.

Another factor known to be important with vibratory rollers is travel speed (4,18,22). A relationship between frequency and travel speed has been observed. Knowledge on this point is entirely empirical, but it is known that the spacing between tamps of a vibrating roll can be too great at high speeds resulting in low density and roughness.

Some vibratory rollers offer other features not found on static rollers including wide rolls, drive in both rolls, and reversible eccentrics. Wide rolls are an obvious advantage on large jobs because they allow coverage of a given area with fewer passes. Drive in both rolls improves traction and reduces horizontal drag, resulting in increased vertical components of static weight; but it is not clear that this improves compaction. The direction of rotation of the eccentric affects propulsion of the roller but does not affect dynamic force. Certain combinations of eccentric and roll rotation would reduce horizontal drag and increase vertical components of static weight, but again, it is not clear that this improves compaction.

The important features of vibratory rollers which influence compaction are frequency, amplitude, and dynamic force which must be present in proper relationship to each other and to travel speed if the roller is to be used effectively.

Evaluating Compaction

To take advantage of the new factors associated with vibratory compaction, it is necessary to evaluate compaction quickly and accurately. In fact, indications are that vibratory rollers are most effective when used with methods and techniques developed in the field specifically for each job (4,13,17,18,19). The most advisable method of evaluating compaction is to measure roadway density. This can be done with cores, but usually test results from cores are delayed too much to be used effectively. The alternative is the nuclear density gauge which has proved to be useful in establishing the best way to adapt vibratory rollers to fit job conditions (13,17,22,23). If acceptance is based on cores, nuclear density can still be used to assure a high probability of success.

Density achieved with vibratory rollers is comparable to density achieved with static rollers. Reliable data, based on sampling plans in which each portion of the pavement has the same chance of being sampled as any other portion, show that static rollers produce an average roadway density on surface courses of 96 percent of 50-blow Marshall density or 92 percent of maximum theoretical density with a standard deviation of 1.5 or more (8,9,14,20,21). Average density and standard deviation of base courses are usually somewhat higher. Data for vibratory rollers show higher average density and less variability in some cases and the contrary in other cases (4,13,17,22).

Attempting to produce significantly higher average density often leads to decompaction and may create undesirable roughness. Everything that compaction should accomplish can be destroyed. Decompaction on breakdown is easily recognized when the mat begins to crack and shove. After breakdown there may be no visible evidence of decompaction. Nuclear density measurements are very helpful in determining when decompaction begins and rolling should stop. They can also help to establish a different roller pattern which may result in higher density without decompaction.

Vibratory Roller Operation

Although operating a vibratory roller is no different than operating a static roller in some respects, experience has shown that certain vibratory roller techniques, which are different, should be used (3,4,16,18,24). In addition, in order to use a vibratory roller correctly to satisfy job conditions, decisions may be required concerning whether or not to use vibration and in which roll or rolls, what frequency and amplitude to use, and at what rolling speed. If the proper techniques are to be used and the correct decisions made, it is essential that operators and all others with responsibility for compaction be well trained in the use of vibratory rollers (3,4,17,18,22,25).

Reversing. Whenever a vibratory roller stops or stops to reverse direction, the vibration must be turned off; otherwise, a depression begins to form under the vibrating roll. Most vibratory rollers are equipped with an automatic shut-off to eliminate this, but some are not and must be shut off by the operator.

Basic Rolling Pattern. To be most effective, vibratory rollers operate toward the laydown machine parallel to the edge of the mat and then reverse along the same path. The adjacent pass then proceeds in the same manner, in and out on the same path, with a minimum lap onto the first pass. A lap of about six inches is usually enough. With 84 inch rolls, a vibratory roller can cover a twelve-foot lane in two passes.

Longitudinal Joints. The basic rolling pattern with a lap of about six inches onto the previously compacted lane produces very satisfactory longitudinal joints. The practice of "pinching" the joint, often used with static rollers, where most of the roll is on the previously compacted lane with a six inch lap onto the uncompacted mat, is ineffective with vibratory rollers because the vibrating roll simply chatters on the compacted lane and accomplishes nothing at the joint (3).

Other procedures have been found to be satisfactory at least under certain circumstances (4,22,24). These include "pinching" the joint using a vibratory roller without vibration (22).

Turning. Most vibratory rollers do not have segmented rolls. Sharp turns on warm mats result in scuffing and displacement and must be avoided. Sharp turns are usually unnecessary because of the basic rolling pattern for vibratory rollers.

Mode of Operation. Vibratory rollers can operate without vibration, known as static mode, or with vibration, known as vibratory mode. Tandem vibratory rollers offer more options with vibratory mode available in either or both rolls. Compaction is most effective when mode is selected to fit the job conditions present for each pass. Generally, the maximum total applied force that does not result in decompaction should be used. Job conditions continually change while compaction is in progress because the mat becomes stronger and more stable as density increases and temperature decreases.

Some examples of compaction using a tandem vibratory roller including mode of operation selected to fit job conditions follow:

1. On a very stable mix, initial breakdown may be accomplished with both rolls vibrating. The same mode would be used for all subsequent passes.

2. On a relatively unstable mix, the initial breakdown pass may have to be with both rolls static, in and out. Occasionally, if the mix is very unstable, or perhaps very hot, more than one static pass may be required before vibration can be applied. When vibration is applied on subsequent passes, it can be changed for each pass as necessary to achieve the maximum increase in density without decompaction. Some examples of combinations of modes include:

a. In static, out with one role vibrating.
b. In and out with one role vibrating.
c. In with one role vibrating, out with both vibrating.

When selecting mode, it should be remembered that the rear roll with respect to the direction of travel works on a mat slightly more dense and stable than the mat under the forward roll. The forward roll produces a large increase in density but with more risk of decompaction.

3. On mixes of average stability, initial breakdown passes using a combination of modes is often best. Subsequent passes can usually be made in vibratory mode.

When satisfactory density has been achieved, finish rolling to iron out roller marks may be accomplished most effectively in static mode on all types of mixtures.

Single-roll vibratory rollers can combine modes in a similar manner but usually require about twice as many passes to achieve the same result.

Frequency-Amplitude. To be effective, frequency and amplitude must be selected to satisfy job conditions so that total applied force is high enough to produce the required density efficiently, but low enough to avoid decompaction. On most vibratory rollers, either frequency or amplitude, or both, can be changed by the operator. Exactly how to set frequency and amplitude cannot be stated, but general guidelines are available:

1. Thick lifts - when lifts are more than 50.8 mm (two in.) thick, high amplitude and low frequency may be best. A heavy blow is needed to transmit force throughout a relatively large mass but at a low frequency to avoid decompaction caused by too much total applied force.

2. Thin lifts - usually low amplitude and high frequency should be used when lift thickness is 50.8 mm (two in.) or less. High amplitude should be avoided because a heavy blow will transmit through the mat into underlying layers. If the underlying layers are weak, they yield, resulting in decompaction and roughness on the surface. If the underlying layers do not yield, the blow reflects back to the surface with the same result, decompaction and roughness, and

perhaps roll chatter. High frequency is needed to provide enough total applied force and blows close enough to result in a smooth surface.

Because a variety of frequency and amplitude controls are available from different roller manufacturers, all vibratory rollers cannot follow these guidelines exactly. Fixed amplitude with variable frequency can be satisfactory on both thick and thin lifts but could be inefficient or unsatisfactory in some cases. Variable amplitude and fixed frequency can be satisfactory on both thick and thin lifts provided that the frequency is high enough for thin lifts. This combination may be effective on certain thick lifts only with the judicious use of static mode. Some rollers offer both variable frequency and variable amplitude. The question then arises as to what is high and what is low. The highest amplitude and lowest frequency would not necessarily be best for some thick lifts, and in fact, these extremes may be best only for certain unusual cases. Similarily, the lowest amplitude and highest frequency would not necessarily be best for some thin lifts.

Lift thickness should not be the only consideration in the selection of frequency and amplitude. Total applied force is a function of both. When either one or both can be varied, it is possible to set total applied force, perhaps for each pass, so that combined with mode selection the resulting compaction best fits the job conditions.

Frequency-Speed. The travel speed of a vibratory roller that can be used effectively is related to frequency of vibration. If travel speed is too high, total applied force per unit area of mat is too low and satisfactory density, if it can be achieved at all, requires too many passes. In addition, rough surface courses are produced. Two empirical rules for controlling roller speed have been developed:

The first rule is that travel speed should be controlled so that the linear distance between blows of the vibratory mechanism is equal to the depth of the mat. For example, a frequency of 40 Hz (2400 vpm) working on a 38.1 mm (1.5 in.) mat should have a space of 38.1 mm (1.5 in.) between blows. Roller speed would be 40 x 38.1 = 1524 mm/s (2400 x 1.5 = 3600 in./minute, about 3.4 mph). This rule does not establish a practical maximum speed for thick lifts. If the above example were for a 101.6 mm (4 in.) mat, roller speed would be 4064 mm/s (about 9 mph). Experience suggests that travel speed should not exceed 3 mph $\pm$, and the indication is that this rule may provide practical travel speeds up to 3 mph but should not be applied when mat thickness results in higher speeds.

The second rule, developed in thin overlay work, is that blows should be spaced 25.4 mm (one in.) apart regardless of mat thickness. Roller speed in the above example would be 40 x 25.4 = 1016 mm/s (2400 in./minute, about 2.3 mph). Indications are that this rule provides a practical roller speed for thin lifts, but it may not establish the maximum speed that could produce acceptable results.

Superelevation. Vibratory rollers work on normal crown and long-radius curves with low superelevation without difficulty. On curves with high superelevation, the roller tends to work itself toward the low side. It can be steered around sharp curves but may, and often does, produce unsatisfactory results. Better results may be achieved by operating at a higher speed, or by operating in static mode. Either way, more passes will be needed to produce the same density. There is no way of knowing in advance whether or not a curtain curve requires a special technique.

Mix Temperature. The old rule, roll as close behind laydown as possible while the mat is hot, is equally applicable to vibratory rollers and static rollers. Frequently, vibratory rollers can operate at higher mix temperatures because of their ability to adjust total applied force to fit job conditions. As a result, it is possible to achieve required density with fewer vibratory roller passes.

Field Experience. When vibratory rollers are used properly to fit job conditions, numerous field studies and actual full-scale projects have shown that specified density and smoothness can be achieved (4,5,13,17,18,22,23). These same cases also show that vibratory compaction is completed with fewer passes than are necessary with a conventional roller train. Fewer passes require less rolling time and offer the potential of a more economical and less risky process.

Specifying Vibratory Compaction

A variety of specifications has been developed by state and other agencies both to allow and to restrict vibratory compaction (3,25). Control strips and end-result density, which apply the same requirements to all rollers whether vibratory or static, are the most popular (25). This approach allows the use of a vibratory roller if the roller can be operated to satisfy job conditions and offers the potential of optimizing rolling techniques. Prequalification of vibratory rollers is used by a number of agencies (23,25). Prequalification can be used with control strips or end results, and offers the advantage of avoiding costly mistakes by eliminating rollers which cannot produce. A variety of vibratory roller characteristics is required by a number of agencies (25). These requirements are a form of prequalification and offer the same advantage. Unfortunately, there is little agreement with respect to which characteristics need to be required and how the requirements should be stated.

The art of specifying vibratory compaction of asphalt pavements is, perhaps, less advanced than the art of vibratory compaction itself. Three approaches to specifications, each with its own advantages, are noted above. There is, at this time, no basis for claiming that one is better than another.

Problem Areas

A number of problems with vibratory compaction of asphalt pavement have been reported (3,4,5,13,-17,22,23,25). Many of these can be eliminated simply by using vibratory rollers of recent design (5). Most of the remainder, although not problems which can be anticipated, can be eliminated in the field when they occur by applying practices already noted in this report. Three problems remain.

First, well trained personnel are needed to use vibratory compaction properly (3,4,17,18,22,23). Well trained roller operators are not necessarily well trained vibratory roller operators. These operators, as well as all inspectors and supervisors, need to be thoroughly trained in vibratory compaction. When all understand how to use vibratory compaction properly and work together as a team, the maximum benefits from vibratory compaction are most likely to be realized.

Second, some interested parties have expected too much from vibratory compaction (14,25). Because of the multitude of factors influencing compaction, a significantly higher average density and lower standard deviation resulting from a single new factor, vibration, is unlikely (14). For the same reason, the rate of production (tons compacted per hour) by a vibratory roller cannot be expected to exceed that of a conventional roller train in all cases. A single new factor, vibration, in a very complex process, is not going to solve or eliminate all compaction problems and certainly not all asphalt paving problems. Realistic, rather than high, expectations can be satisfied.

Third, measuring the density of thin lifts has proven to be a problem regardless of the type of roller used. Both nuclear and core densities present problems that are inherent in the testing procedure. One solution is to use the nuclear gauge to obtain relative density at a point while compaction is in progress. When density peaks, compaction ceases. This procedure requires continuous monitoring, but it assures maximum density under field conditions, even though the maximum obtained may not comply with specifications for other work.

Conclusions

Static rollers have been compacting asphalt pavements satisfactorily for more than one hundred years. Vibratory rollers represent the only fundamental change in the process that has ever occurred. Vibratory rollers introduce two basic new elements. One is the vibration itself, and the other is the ability to change the character of the vibration rapidly enough to satisfy changing job conditions. To take advantage of the new process, new techniques and methods must be learned. When a vibratory roller is used properly to match job conditions, it can produce satisfactory results quickly and economically.

References

1. Committee of Flexible Pavement Construction, "State of the Art: Compaction of Asphalt Pavements," Highway Research Board, Special Report 131, 1972.
2. Santoro, R.R., K.C. Afferton, and J.A. Walz, "Stanhope Study of Compaction Methods for Bituminous Stabilized Base," Highway Research Board, Highway Research Record 385, 1972.
3. Hughes, C.S., "Vibratory Compaction of Bituminous Concrete - Where Does It Stand?," Proceedings, Association of Asphalt Paving Technologists, Vol. 46, 1977.
4. Dellert, R.B., "Vibratory Compaction of Thin Lift Asphalt Resurfacing," Proceedings, Association of Asphalt Paving Technologists, Vol. 46, 1977.
5. Geller, M., "Summarizing the Development of Vibratory Roller Applications for Compacting Bituminous Mixes in the USA," Proceedings, Association of Asphalt Paving Technologists, Vol. 46, 1977.
6. Marker, Vaughn, "Introduction - Compaction of Asphalt Concrete," Proceedings, Association of Asphalt Paving Technologists, Vol. 36, 1967.
7. Parker, C.F., "Steel-Tired Rollers," Highway Research Board, Bulletin 146, 1959.
8. Graham, M.D., W.C. Burnett, J.J. Thomas, and W.C. Dixon, "Pavement Density-What Influences It," Proceedings, Association of Asphalt Paving Technologists, Vol. 34, 1965.
9. Serafin, P.J. and L.L. Kole, "Comparative Studies of Pneumatic Tire Rolling," Proceedings, Association of Asphalt Paving Technologists, Vol. 31, 1962.
10. Kari, W.J., "Mix Properties as They Influence Compaction," Proceedings, Association of Asphalt Paving Technologists, Vol. 36, 1967.
11. Fromm, H.J. and W.A. Phang, "The Compaction of Asphalt Concrete on the Road," Proceedings, Association of Asphalt Paving Technologists, Vol. 35, 1966.
12. Tegler, P.A. and B.J. Dempsey, "A Method of Predicting Compaction Time for Hot-Mix Bituminous Concrete," Proceedings, Association of Asphalt Paving Technologists, Vol. 42, 1973.
13. White, T.D., "Airfield Compaction Update-1977," Proceedings, Association of Asphalt Paving Technologists, Vol. 46, 1977.
14. Tunnicliff, D.G., "Introduction - Vibratory Compaction," Proceedings, Association of Asphalt Paving Technologists, Vol. 46, 1977.
15. Cosbey, H., "Asphalt Compaction by Vibratory Roller," Proceedings, Association of Asphalt Paving Technologists, Vol. 46, 1977.
16. Bituminous and Aggregate Equipment Bureau and Light Equipment Manufacturers Bureau, "Construction Industry Vibratory Roller Handbook," Construction Industry Manufacturers Association, 1978.
17. Noel, R.B., "Compacting Heavy Duty Highway Pavements," Proceedings, Association of Asphalt Paving Technologists, Vol. 46, 1977.
18. Vizi, L., F.A. Hanson, and C. Jonker, "Vibratory Roller Compaction of Asphalt Pavements in the Netherlands," Proceedings, Association of Asphalt Paving Technologists, Vol. 46, 1977.
19. Machet, J. and G. Morel, "Vibratory Compaction of Bituminous Mixes in France," Proceedings, Association of Asphalt Paving Technologists, Vol. 46, 1977.
20. Granley, E.C., "Variations in Bituminous Construction," Public Roads, Vol. 35, No. 9, August 1969.
21. Huculak, N.A., "Quality Control of Asphalt Pavement Construction," Proceedings, Association of Asphalt Paving Technologists, Vol. 37, 1968.
22. Nittinger, R.J., "Vibratory Compaction of Asphalt Concrete," Transportation Research Board, Transportation Research Record 659, 1977.
23. Cechetini, J.A. and G.B. Sherman, "Vibratory Compaction of Asphalt Concrete Pavements," Proceedings, Association of Asphalt Paving Technologists, Vol. 43, 1974.
24. Maner, A.W., "Vibratory Compaction of Asphalt Paving Mixtures," The Asphalt Institute, ES-2, 1978.
25. Hughes, C.S., "Questionnaire on Vibratory Compaction of Bituminous Concrete, Transportation Research Board, unpublished report to Committee A2F02, January 1980.