COMPACTION OF ASPHALT MIXTURES AND THE USE OF VIBRATORY ROLLERS

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PREFACE

This is the first in a series of reports that deal with a study of field compaction of asphalt mixtures. The objectives of this report are concerned with compaction theory and the use of vibratory rollers. Definitions of terms related to vibratory compaction are presented along with guidelines for operation.

This report was completed with the assistance of many people. Special appreciation is extended to Mr. Billy R. Neeley, Materials and Tests Engineer, D-9, for his helpful comments during preparation of this manuscript. In addition, appreciation is extended to Messrs. Paul E. Krugler, Irl E. Larrimore, Jr., and Robert L. Mikulin, who served as DHT contacts. Appreciation is also extended to the staff of the Center for Transportation Research who assisted with preparation of the manuscript.

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LIST OF REPORTS

Report No. 317-1, "Compaction of Asphalt Mixtures and the Use of Vibratory Rollers," by Thomas W. Kennedy, Freddy L. Roberts, Robert B. McGennis, and James N. Anagnos, summarizes a literature review concerned with compaction of asphalt mixtures and vibratory compaction, and presents suggested methods of operation of vibratory rollers.

ABSTRACT

This report summarizes an investigation of compaction of asphalt concrete and compaction using vibratory rollers. The primary objectives of the study were to clarify terminology associated with compaction and vibratory rollers and to suggest effective operational procedures for vibratory rollers.

A literature review was performed in order to gain an accurate understanding of the theory of compaction. The report lists factors affecting the compactibility of asphalt mixtures. In addition, a discussion of mixture problems that affect compaction is presented.

A portion of the literature review summarized in this report deals with the background and theory of vibratory compaction. A brief history of the development of vibratory compactors is presented along with current rollers marketed in the United States. Operational terms associated with vibratory rollers are presented and defined.

Manufacturers of vibratory rollers were contacted to obtain current vibratory roller specifications and recommended operating procedures. Based on this information, a set of operational guidelines is presented.

KEY WORDS: compaction, density, vibratory rollers, harsh mixtures, tender mixtures, rolling pattern.

SUMMARY

This report summarizes a study of compaction of asphalt mixtures and the use of vibratory rollers. The primary purpose of the study was to summarize and clarify concepts related to compacting and factors affecting compaction of asphalt mixtures and to develop guidelines for the proper use of vibratory rollers.

Based on the results of the investigation the resistance of asphalt mixtures to compaction, whether by static or dynamic means, can be characterized in terms of frictional resistance, initial resistance, and viscous resistance. Mixture compaction problems can usually be diagnosed in terms of these resistances. In addition, of critical importance is an understanding of the difference in meaning of the terms density and compaction. Density is a material property, whereas compaction is the process by which a certain level of density is achieved.

In the past, most of the vibratory roller difficulties encountered were the result of improper use of rollers (e.g., rollers designed for compacting soil) and/or improperly trained operators.

The results of the study indicate that technology and experience have advanced to such a degree that vibratory rollers can effectively be used to compact asphalt mixtures.

IMPLEMENTATION STATEMENT

The following recommendations are intended to serve as a quick guide concerned with the operation of vibratory rollers. Additional discussion is available in the text as indicated by the designated page numbers.

Amplitude - highest possible to achieve desired results but not high enough to damage mat, p 27, Fig 11 - p 28

Compaction time - cold, windy days less time available; hot, still days more time available; keep mixture temperature as high as possible, between 175 and 275°F, p 38, Table 3 - p 42

Direction of travel - vibrating drum closest to laydown machine; tiller (steering) drum away from laydown machine, p 26

Eccentric rotation - opposite of drum, p 29, Fig 12 - p 30

Frequency - operate at maximum rated frequency, p 27, Fig 10 - p 25

Impact spacing - usually between 1.5 and 1.2 inches which corresponds to 8 and 10 impacts per foot, p 27, Fig 10 - p 25

Longitudinal edges (confined) - as close as possible to curb and gutter; adjacent mat to be placed later use 6-inch overhang, p 33, Fig 15 - p 36

Longitudinal edges (unconfined) - thick lifts leave 6-inch gap; thin lifts use 6-inch overhang, p 33, Fig 16 - p 37

Longitudinal joints - overlap or pinch, p 33, Fig 14 - p 35

Operational mode (harsh mixtures) - breakdown in vibratory mode; finish in vibratory mode, p 29

Operational mode (normal mixtures) - breakdown in vibratory or combination mode; finish in vibratory mode, p 29

Operational mode (tender mixtures) - breakdown in combination or static mode; finish in combination mode, p 29

Roller speed - highest possible to obtain desired impact spacing and production but not to exceed 3.5 mph, p 27, Fig 10 - p 25

Rolling pattern - develop using a test strip, p 31, Fig 13 - p 34

Superelevated sections - low side to high side possibly with higher speed or no vibration, p 38, Fig 17 - p 39

Thin lifts - no vibration if over rigid base such as portland cement concrete, Fig 11 - p 28

TABLE OF CONTENTS

TABLE OF CONTENTS
(Continued)

DEFINITIONS

Ballast weight - additional weight of material added to increase the static weight and total applied force of the machine, p. 14

Cessation temperature - minimum temperature below which the asphalt viscosity is too high to facilitate adequate compaction, p. 41

Compaction - the process by which the asphalt mixture is compressed into a reduced volume, p. 2

Density - the unit weight of asphalt mixture which is dependent on degree of compaction and the amount and type of aggregate and asphalt, p. 2

Double amplitude - total peak-to-peak vertical movement of the drum during a complete cycle of vibration with the drum in a freely suspended condition, p. 18

Dynamic (impact) force - the force produced by the rotating eccentric located in the drum, p. 14

Effective drum width - the mat width divided by the number of lateral coverages to compact the surface once, p. 20

Frequency - the number of complete cycles of vibration (eccentric or drum) per minute, p. 18

Impact spacing - the distance the roller travels between dynamic impact forces being applied to the mixture, p. 18

Maximum theoretical density - refers to the density (unit weight) of a voidless mass of asphalt and aggregate in the appropriate mixture proportions, p. 5

Nominal amplitude - half of the double amplitude, p. 18

Relative density - ratio of field density to either a laboratory maximum density or the maximum theoretical density, p. 5

Sprung weight - portion of the frame weight which acts on the drum and is transmitted to the underlying layer through the drum suspension system

Static weight - the component of the total weight due to the frame and drum, p. 14

Total applied force (weight) - the sum of the dynamic (impact) force and the static weight which is applied to the asphalt mixture, p. 18

Unit force (static or centrifugal) - the applied force per unit width of the drum

Unsprung weight - the weight of the drum including its internal parts up to the shock absorbers on both sides of the drum

CHAPTER 1. INTRODUCTION

The purpose of compaction of asphalt mixtures is to produce a mixture that has satisfactory engineering properties such as stability, durability, fatigue resistance, and tensile strength (Ref 1). Compaction can be achieved using either static or dynamic compaction and either steel wheeled or pneumatic tired rollers. In this regard, there has been a growing emphasis on compaction of asphalt mixtures using vibratory (dynamic) methods because of the cost savings in both equipment and labor.

Currently, most state transportation agencies allow the use of vibratory compaction equipment. Much of the recent research has focused on the interaction and effects of vibratory compaction variables such as frequency, amplitude, etc. (Ref 2), and mixture and construction parameters such as gradation, aggregate characteristics, type and amount of asphalt, environmental conditions, lift thickness, and type of support.

The purpose of this report is to summarize information related to compaction of asphalt mixtures, vibratory compaction, and the characteristics of vibratory compaction, and to make recommendations related to the operation of vibratory compactors. While emphasis is placed on vibratory compaction, many of the basic principles are applicable to asphalt mixture compaction in general.

Chapter 2 contains a brief summary of compaction, density, and factors affecting compactibility. Chapter 3 summarizes information related to vibratory compactors and their operating characteristics. Chapter 4 contains guidelines for the use of vibratory compactors. A summary and recommendations are contained in Chapter 5.

CHAPTER 2. DENSITY AND COMPACTION

An asphalt mixture consists of aggregate, asphalt cement, and air voids (Fig 1). The primary purpose of compaction is to reduce the air voids, the reduction of which will increase the density of the mixture. Thus, density is a measure of the degree of compaction and the reduction of air voids and is often used as a field control.

DENSITY

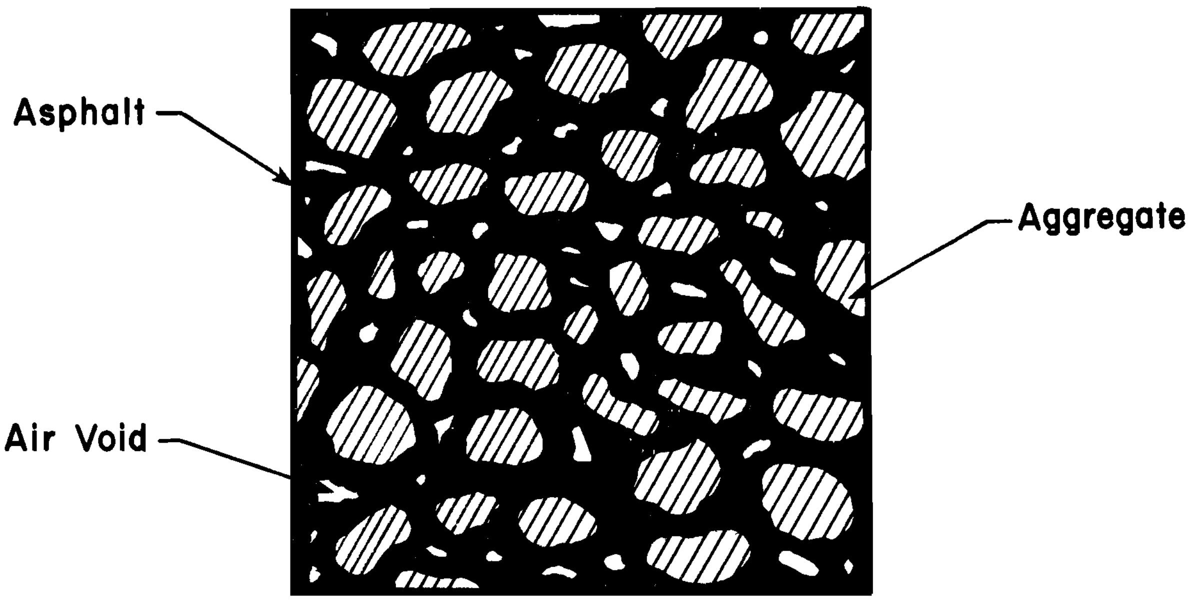
Density is the unit weight of an asphalt mixture which is dependent on the type and amount of asphalt and aggregate and the degree of compaction which affects the amount of air voids. Thus, density can be increased by filling the voids with asphalt; however, increased density should be achieved by compaction.

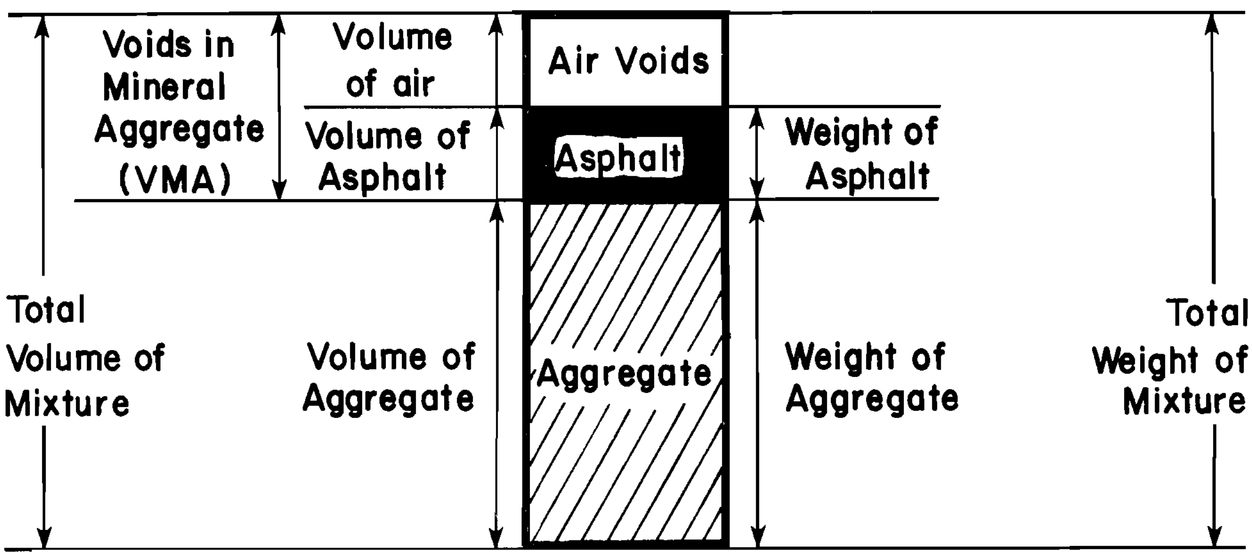
The Texas State Department of Highways and Public Transportation uses the following definitions (Ref 3): The percent density or percent compaction is the ratio of the actual bulk specific gravity of the compacted bituminous mixture specimen to the theoretical specific gravity of the combined aggregate and asphalt contained in the specimen expressed as a percentage. The percent of laboratory molded specimen density is the ratio of the actual bulk specific gravity of the field specimen to the average actual bulk specific gravity of laboratory molded specimens expressed as a percentage.

COMPACTION

Compaction is the process by which the asphalt and aggregate are compressed into a reduced volume. Since asphalt cement and aggregate are relatively incompressible, compaction produces a reduction in air voids. In addition, the aggregate particles are forced closer together producing granular interlock which also depends on particle shape and texture of the aggregate and the type (grade) and temperature of the asphalt cement at the time of compaction.

Both aggregate interlock and air voids have a definite effect on the engineering properties of the compacted asphalt mixtures and generally it can be stated that these properties are improved by better compaction and reduced air voids (Fig 2).





$$\text{Density} = \frac{\text{Total Weight of Mixture}}{\text{Total Volume of Mixture}}$$

$$\%\ \text{Density} = (100)\,\frac{\text{Bulk Specific Gravity of Compacted Mixture}}{\text{Theoretical Specific Gravity of Mixture}}$$

Fig 1. Typical asphalt mixture containing asphalt, aggregate, and air voids.

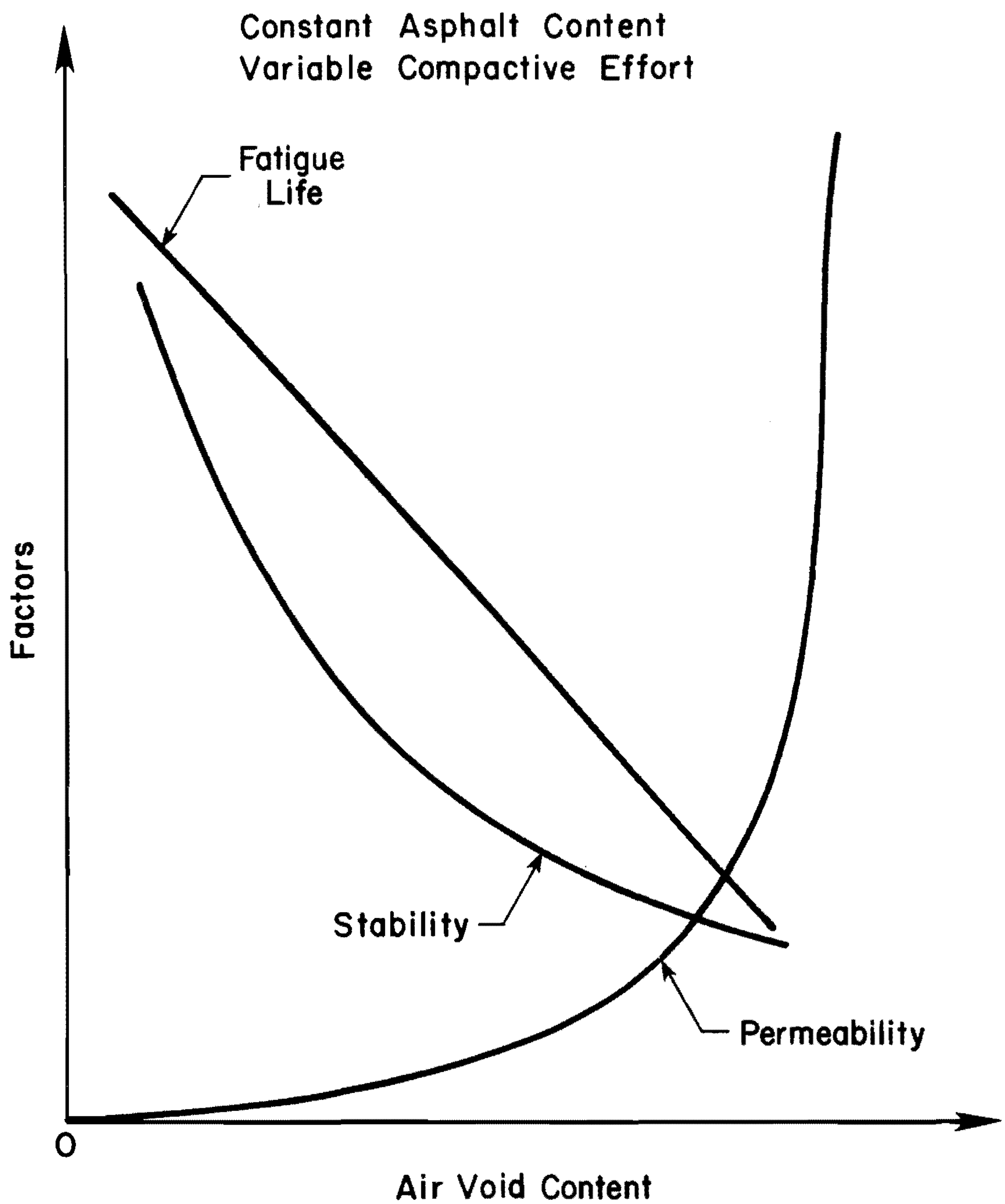


Fig 2. Illustration of relationships between mixture properties and air void content.

AIR VOIDS

Based on laboratory and field evaluations, it is recommended (Ref 4) that the air voids in the final mixture range between 3 and 5 percent. The minimum value is important to insure that expansion of the asphalt cement due to temperature rise or additional compaction under traffic does not overfill the voids producing flushing and instability. The reduction of voids can occur due to

(1) compaction during construction, or

(2) compaction under traffic.

Effort should be focused on the design of the mixture and compaction during construction to insure that the maximum degree of compaction occurs during construction.

FIELD CONTROL

Field control of compaction for constructed asphalt mixtures is normally obtained by measuring density by one of the following procedures:

(1) Measure density of sections taken from the roadway,

(2) Measure density of cores taken from the roadway, or

(3) Estimate density using correlated nuclear density gauges.

These densities are then compared with one of two standards:

(1) a percentage of the theoretical maximum density;

(2) a percentage of a laboratory compacted density obtained with a given compaction procedure.

Generally it is felt that control should be based on achieved density compared to the maximum theoretical density since this is a direct measure of air voids in the compacted mixture; however, there can be problems related to this method. Maximum theoretical density can be obtained using the weights and specific gravities of the aggregate components and asphalt cement assuming zero air voids. Difficulties have been experienced with these calculations due to problems associated with measuring the effective specific gravities. These problems are greater with porous aggregates which may absorb relatively large amounts of asphalt. It is recommended that the maximum theoretical density be obtained using the Rice Method (Ref 5) because no assumptions are made as to proportions or specific gravities of constituents.

FACTORS AFFECTING THE COMPACTIBILITY OF ASPHALT MIXTURES

The resistance to compaction (Ref 6) is composed of

(1) interparticle frictional resistance,

(2) initial resistance (cohesion), and

(3) viscous resistance (time-temperature).

Immediately following laydown hot bituminous mixtures are in a highly plastic state. While in this plastic state the void content of the mixture is reduced through compaction by reorienting the solid particles into a denser arrangement. The mixture resistance to compaction while in this plastic state is basically a function of asphalt and aggregate properties and their interactions. Most compaction problems encountered in the field can be explained in terms of these factors.

Aggregate Properties

The five aggregate properties which affect the resistance of the mixture are

(1) particle shape and texture,

(2) concentration of coarse aggregate,

(3) gradation,

(4) absorption, and

(5) soundness.

Particle shape and texture influence the overall resistance of the mixture in that angular, rough surface textured aggregates are more difficult to compact than are rounded, smooth aggregates.

Gradations with high concentrations of coarse aggregates produce mixtures that are difficult to compact. For the production of dense graded hot asphalt concrete mixtures, Goode and Lufsey (Ref 7) proposed that the aggregates be graded according to the equation

$$P = 100 \times \left(\frac{S}{M}\right)^{0.45}$$

where P = Percent passing the particular sieve;

S = Size of opening for a particular sieve in microns; and

M = Maximum size of aggregate in microns.

Gradation curves that cross back and forth over the maximum density line (Fig 3), especially in the region of the No. 30 to No. 80 sieve, tend to produce tender mixtures that displace excessively during compaction.

Adequate filler content (minus 200) is necessary for a mixture to develop enough cohesion, i.e., initial resistance, to be compacted effectively. Filler material acting with the asphalt tends to hold the larger sized material in place (Ref 8). If the filler content is too high, "gummy" mixtures are produced. Such mixtures are difficult to compact because of a tendency to be picked up by the roller. In addition, these mixtures tend to exhibit excessive lateral displacement. Insufficient filler may require additional asphalt to fill the voids. This results in thicker asphalt films and possible instability in the unconfined mixture during compaction.

Absorptive aggregates tend to increase the resistance of the mixture by reducing the thickness of the asphalt film on the surface of the aggregate. The net effect is a reduction of the lubricating effect of the asphalt making compaction more difficult (Ref 8).

Although soundness does not directly affect the resistance of the mixture to compaction, it does tend to affect the density achievable by a certain compaction procedure (Ref 8). Unsound aggregate may fracture under the dynamic loading of vibratory rollers. Any such fracturing will effectively change the gradation of the mixture, may reduce actual density, or may increase the susceptibility of the mixture to moisture damage.

Asphalt

Asphalt viscosity and its relationship to temperature are shown in Fig 4. The rate of change of viscosity with temperature, i.e., the slopes of the lines relate to the temperature susceptibility of the asphalt. It is important to note that for grading purposes two asphalts which have the same viscosity or penetration grade (Fig 4) may have significantly different viscosities at normal temperatures for compaction.

Since the viscosity of the asphalt affects the overall resistance of the mixture, knowledge of this behavior characteristic is vital for effective compaction of asphalt mixtures. As the mixture temperature decreases during compaction, the viscosity of the asphalt increases at a

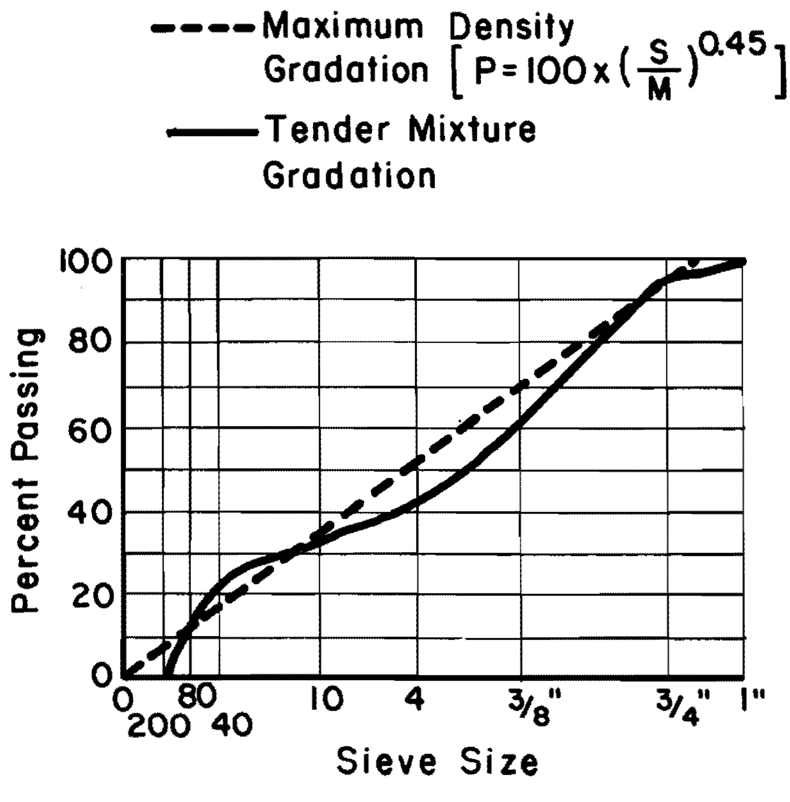


Fig 3. Gradation shown on a 0.45 log scale known to exhibit tenderness (Ref 7).

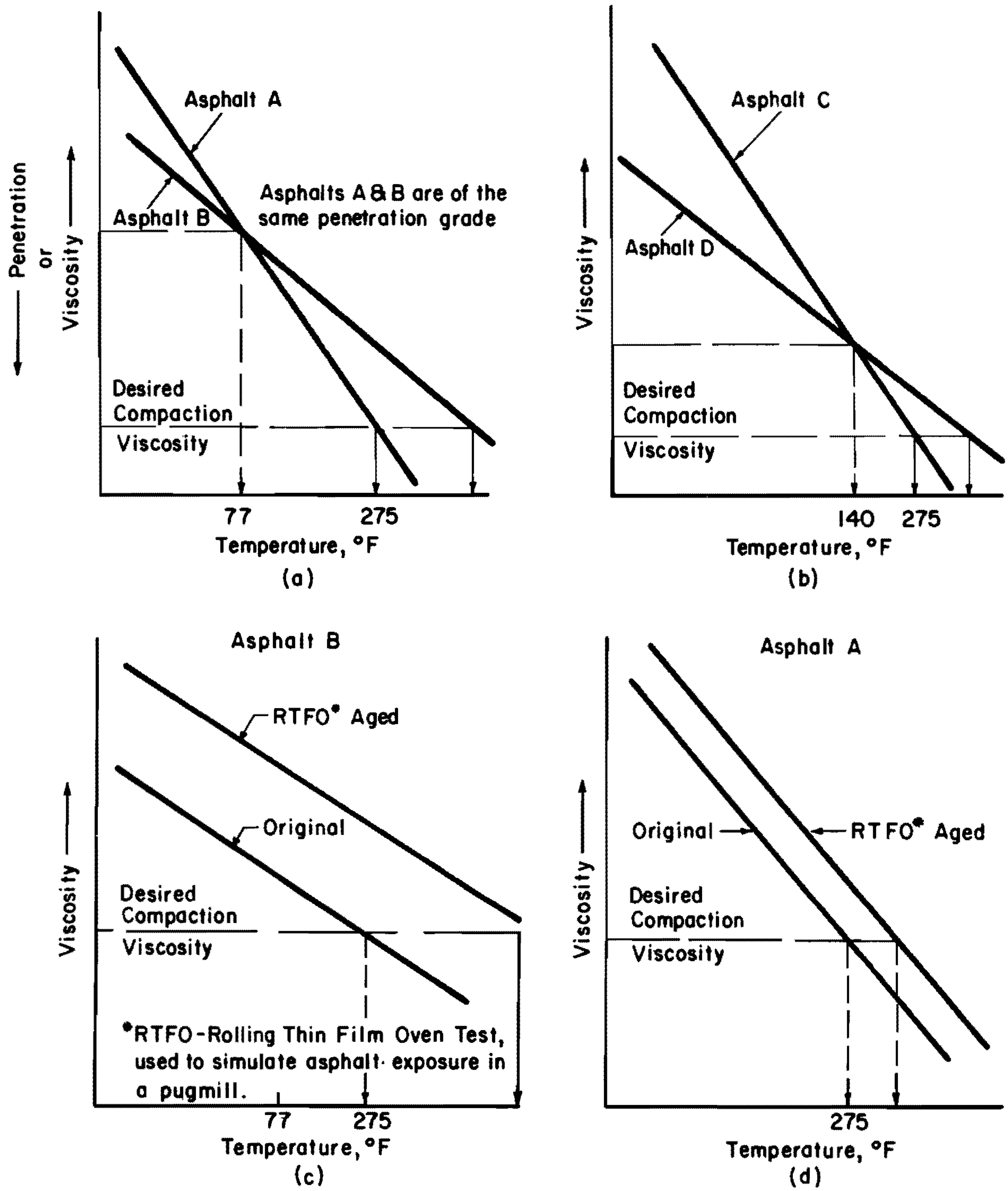


Fig 4. Temperature-viscosity relationships for asphalt.

rate determined by its temperature susceptibility. The net effect of this temperature drop is to increase the viscous resistance of the mixture to compaction. In addition, different asphalts will also harden more or less during mixing in the plant. This hardening can also be influenced by the type of plant (batch plants versus drum mix plants) and the method or temperature of operation.

The overall viscous resistance of the mixture is also a function of the asphalt content. Thinner asphalt film thicknesses produce mixtures that are more difficult to compact than mixtures with thicker asphalt films. Higher asphalt contents increase film thickness and can lubricate the mixture excessively, reduce the viscous resistance, and produce unstable mixtures. In addition, if the asphalt content becomes too high, the air voids become filled, the aggregate particles are forced apart, and the density is reduced.

OTHER TEMPERATURE RELATED FACTORS

Lift thickness affects the compaction process. Thick lifts maintain temperature above the cessation temperature because the larger mass of material holds heat longer than for thin lifts. Thicker lifts tend to protect the subgrade (Ref 8) allowing adequate compaction over yielding subgrades. Following placement of the thick lift other lifts may be placed and compacted more effectively because of the more effective resistance provided by the cold, thick base layer.

Weather conditions also affect the time available for compaction. Factors such as low ambient temperature, wind, and low base temperature are major contributors to cooling the mixture before adequate compaction can be achieved.

COMPACTION PROBLEMS AS RELATED TO ASPHALT MIXTURES

When problems occur in the compaction process they are likely to result because of either

(1) harsh mixtures or

(2) tender mixtures.

These two types of problems are discussed separately in terms of the previously mentioned mixture factors.

Harsh Mixtures

These mixtures are typically very stiff and difficult to compact. Because of this difficulty in compaction, harsh mixtures often have lower densities and higher void contents than normal mixtures. The most common causes of harshness are

(1) high coarse aggregate content,
(2) aggregate with rough surface texture,
(3) highly angular particles,
(4) gradation in which the maximum particle size is too large relative to compacted mat thickness,
(5) segregation, and
(6) low voids in the mineral aggregate.

If during the compaction process harsh mixture characteristics are detected, operations should cease until the cause(s) is determined and corrected.

Tender Mixtures

These are mixtures that have very low resistance to deformation by punching loads and scuff under horizontally-applied shearing loads after compaction has been completed. Tender mixtures display the following characteristics:

(1) mixture is difficult to roll without excessive lateral displacement;
(2) specified density cannot be achieved;
(3) pavement ruts after construction is complete;
(4) pavement is soft after compaction and will displace under the heel of a shoe;
(5) pavement shoves under traffic, sometimes months after construction;
(6) pavement slips under traffic, usually soon after construction;
(7) pavement scuffs under power steering or braking action; and
(8) pavement indents under a punching load.

In terms of the previously mentioned asphalt properties, the following are probable causes of mixture tenderness during compaction:

(1) too much medium-sized sand in the mixture, characterized by a hump in the gradation curve;
(2) insufficient fines;

(3) high asphalt film thickness;

(4) mixture temperature excessively high (greater than 300°F);

(5) viscosity of asphalt too low;

(6) smooth, rounded aggregate; and

(7) moisture in the mixture.

As with harsh mixtures, if mixture tenderness is detected during compaction, construction operations should cease until the cause(s) is determined and corrected. Usually, when tenderness is detected the tendency of roller operators is to delay rolling until the mat cools enough to support the weight of the roller. This is temporary and not the proper corrective action. Holding the rollers back on tender mixes instead of adjusting the mixture design can result in a poorly compacted pavement which, if excess asphalt is added, will flush the first summer under heavy traffic.

CHAPTER 3. VIBRATORY COMPACTION

HISTORY

The state of the art of vibratory compaction is the result of forty years of research, development, and field experience. Vibratory compaction techniques first gained acceptance as an efficient means of compacting unbound material such as soil, subbase, and base materials. The first large-scale project use of vibratory equipment occurred in Germany during Autobahn construction in the 1930s. Following World War II, equipment development occurred primarily in Europe; however, during the 1950s, various highway agencies in the United States began using vibratory rollers for subbase and base compaction, and by 1970 vibratory methods had significantly replaced static methods for compacting these materials.

Concurrent with the growing usage of vibratory rollers for compaction of unbound materials, several European countries began to use vibratory rollers to compact asphalt mixtures. Early reports indicated that the dynamic force imparted by these machines was too high for asphalt concrete construction. The early equipment had fixed vibration amplitudes and the only way to reduce the dynamic force was to reduce the frequency which increased the impact spacing. This required a decrease in roller speed which could not completely compensate for the reduced frequency and increased impact spacing. Therefore, design constraints on early rollers caused an objectionable washboard pattern in wearing courses. In about 1967, the first large tandem vibratory roller was introduced in the United States, and California and Ohio accepted it for construction work (Ref 9). Shortly thereafter other states began using these heavier and more sophisticated vibratory rollers.

During the early 1970s tandem rollers were introduced with variable amplitude and higher frequency ranges for both drums than previously available. Development of these more sophisticated rollers coupled with extensive use of the nuclear density gauge made establishing roller patterns easier and helped facilitate more acceptable compaction results (Ref 2).

VIBRATORY ROLLER TYPES

The Construction Industry Manufacturers Association (CIMA) has identified (Fig 5) the following five types of vibratory rollers that are or have been marketed in the United States (Ref 10):

(1) single drum - rigid frame,

(2) single drum - articulated frame,

(3) double drum - rigid frame,

(4) double drum - single articulated frame, and

(5) double drum - double articulated frame.

Most rollers used for compaction of asphalt mixtures are contained in groups 2 and 4. Table 1 summarizes the types of rollers marketed by the various manufacturers.

OPERATIONAL CHARACTERISTICS OF VIBRATORY ROLLERS

Vibratory rollers have two components of compactive force which provide energy for the compaction process:

(1) static weight and

(2) dynamic (impact) force.

The <u>static weight</u> component is composed of the frame and drum weight. The static weight can be increased with the addition of ballast material. Ballast material is usually water and the amount required is a function of desired compactive effort.

The <u>dynamic (impact) force</u>, which is exerted through the drum, is produced by a rotating eccentric located in the drum (Fig 6). As the eccentric rotates about the shaft, a dynamic force is produced which is directly proportional to the mass, the square of the rotational velocity, and the length of the eccentric radius. In order to keep the drum pressed against the material to be compacted, the eccentric is designed so that the ratio of the weight of the drum to the weight of the frame is within a certain range (Ref 11). If the drum is relatively heavy compared to the frame, a large eccentric produces forces that will tend to bounce the frame up and down. A rubber element usually separates the drum from the frame in order to minimize frame vibration.

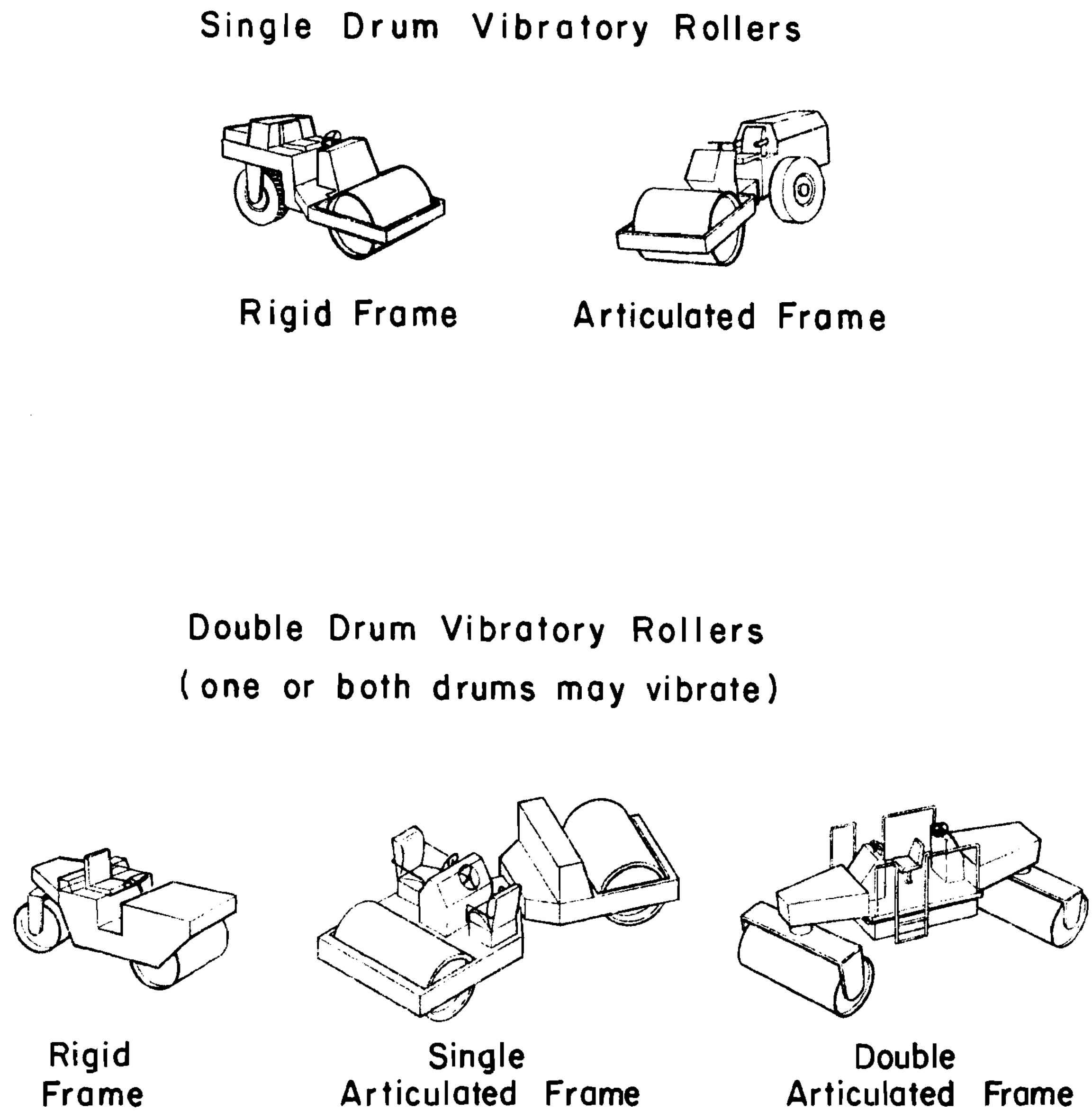


Fig 5. Representative vibratory roller types commonly encountered in asphalt mixture compaction (Ref 10).

TABLE 1. TYPES OF VIBRATORY ROLLERS AVAILABLE

Roller Manufacturer	Single Drum Rigid Frame	Single Drum Articulated	Double Drum Single Articulated	Double Drum Double Articulated	Double Drum Rigid Frame	Single Drum Walk Behind
Bomag			6		1	
Ingersoll-Rand		1	3			1
Galion		2	1			
Rexnord		2	2			
Bros			3			
Fergueson		1	1			
Hyster	4		1			
Cedar Rapids				2		
Roscoe		1	1		3	
Dynapac		3	4		1	
Raygo		2	2	1		
Tampo		1	3		1	

Numbers indicate number of models marketed as of September 1, 1982

Time for 1 Cycle	=	T, sec
Frequency 1/T	=	n, Hz, i.e., cycles per second
(Nominal) Amplitude	=	a, in
Weight of Eccentric	=	W, lb
Eccentric Moment	=	$W \times r$, in-lb
Centrifugal Force	=	$W \times r \times 4 \times \pi^2 \times n^2$, lb

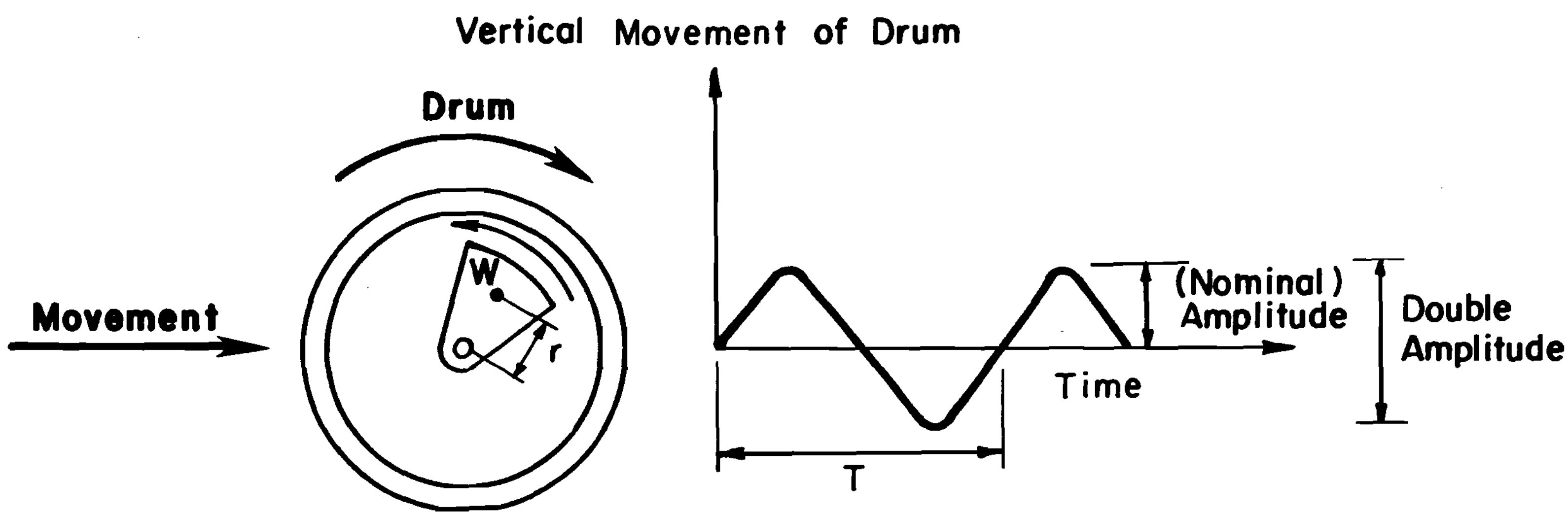


Fig 6. Mechanics of the rotating eccentric.

Total Applied Force

The total applied force is the sum of the static weight and dynamic (impact) force. A more meaningful comparison of rollers (Ref 10) can be made by using the unit force, i.e., the static weight plus dynamic (impact) force per linear inch of drum at a stated frequency.

The total applied force or total force per unit width of drum (unit force) is resisted by the layer being compacted. The resistance is a function of the mixture stability consisting of aggregate interlock and cohesion of the asphalt cement. For compaction to occur the total applied force must exceed the mixture's resistance or stability. This resistance is a function of compaction, temperature, degree of confinement, base resistance, and mixture characteristics which were previously discussed, p 6.

Amplitude

Amplitude is a measure of the total applied force. Double amplitude is the total peak-to-peak vertical movement of the drum during a complete cycle of vibration with the drum in a freely suspended condition, which is dependent upon the drum weight, configuration of the eccentric, and the elasticity of the material being compacted. The nominal amplitude is half of the double amplitude. Actually, the perceptible vertical distance the drum moves is likely to be small due to the damping effects of both the layer being compacted as well as underlying layers. Typical values of nominal amplitude range from 0.25 to 1.00 mm.

Amplitude changes are caused by changes in the configuration of the eccentric, which in turn alter the radius of rotation. As the radius of rotation increases, the resulting amplitude increases which produces larger dynamic forces.

Frequency and Impact Spacing

Frequency is the number of complete cycles of the vibrating mechanism per minute or the speed at which the eccentric rotates. The range of frequency is 1500-3000 vpm with a more common range of 2000-2400 vpm (Ref 12). Impact spacing, which is dependent upon frequency and roller speed, is the distance the roller travels between dynamic force pulses (Fig 7). A small impact spacing is usually desirable when compacting asphalt mixtures since this will ensure a smooth riding surface.

$$\text{Impact Spacing (I)} = \frac{\text{Roller Speed, fps}}{\text{Frequency, Hz}}$$

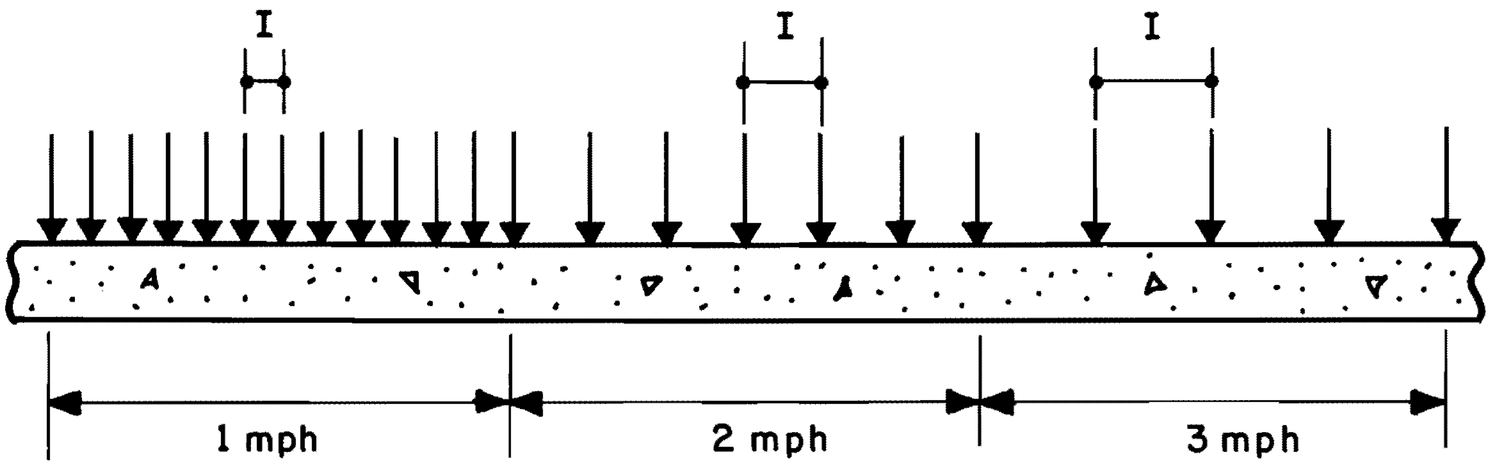


Fig 7. Effect of roller speed on impact spacing.

The impact spacing can be calculated by dividing the roller speed by the frequency:

$$\text{Impact spacing} = \frac{\text{roller speed (ft/sec)}}{\text{frequency (vib/sec)}}$$

Impact spacing is sometimes reported in impacts per foot traveled.

NUMBER OF PASSES AND WIDTH OF DRUMS

Of primary consideration when selecting a roller type is the number and width of the drums. Both directly affect the ability to maximize production. A double drum vibratory roller can usually produce density in fewer passes than a single drum roller, and a wider drum can compact larger surface areas per pass.

The following formula can be used to calculate roller coverage (Ref 13):

$$C = \frac{VWE}{n}$$

$$C = 58.64 \frac{VWE}{n}$$

where

C = coverage,

V = roller speed, mph,

W = effective drum width = $\frac{w}{p}$, ft.,

w = mat width, ft.,

p = number of passes to compact the surface once,

E = efficiency,

n = number of coverages required to achieve density, and

58.64 = dimensional constant.

Table 2 summarizes the effective drum widths for various mat widths. Thus, a 72-inch drum can complete one coverage of an 11-foot mat in just two passes with the minimum required 6-inch overlap. A lane wider than 11 feet will require either additional passes with the 72-inch drum or a roller with a wider drum (Fig 8). An 84-inch drum can produce one coverage of an 11- to 13-foot mat in just two passes. Three passes are required for both the 72- and 84-inch drums for mats between 13 and 16 feet wide.

Efficiency, E , takes into account the time lost during reversals, moving to adjacent pass, etc. No guidelines are listed in the technical

TABLE 2. EFFECTIVE DRUM WIDTHS FOR VARIOUS MAT AND DRUM WIDTHS

Mat Width, ft	Effective Drum Width*, ft	
	72-in Drum	84-in Drum
10	5	5
11	5.5	5.5
12	4	6
13	4.33	6.5
14	4.67	4.67
15	4.67	4.67
16	4.67	4.67

*For use in coverage formula

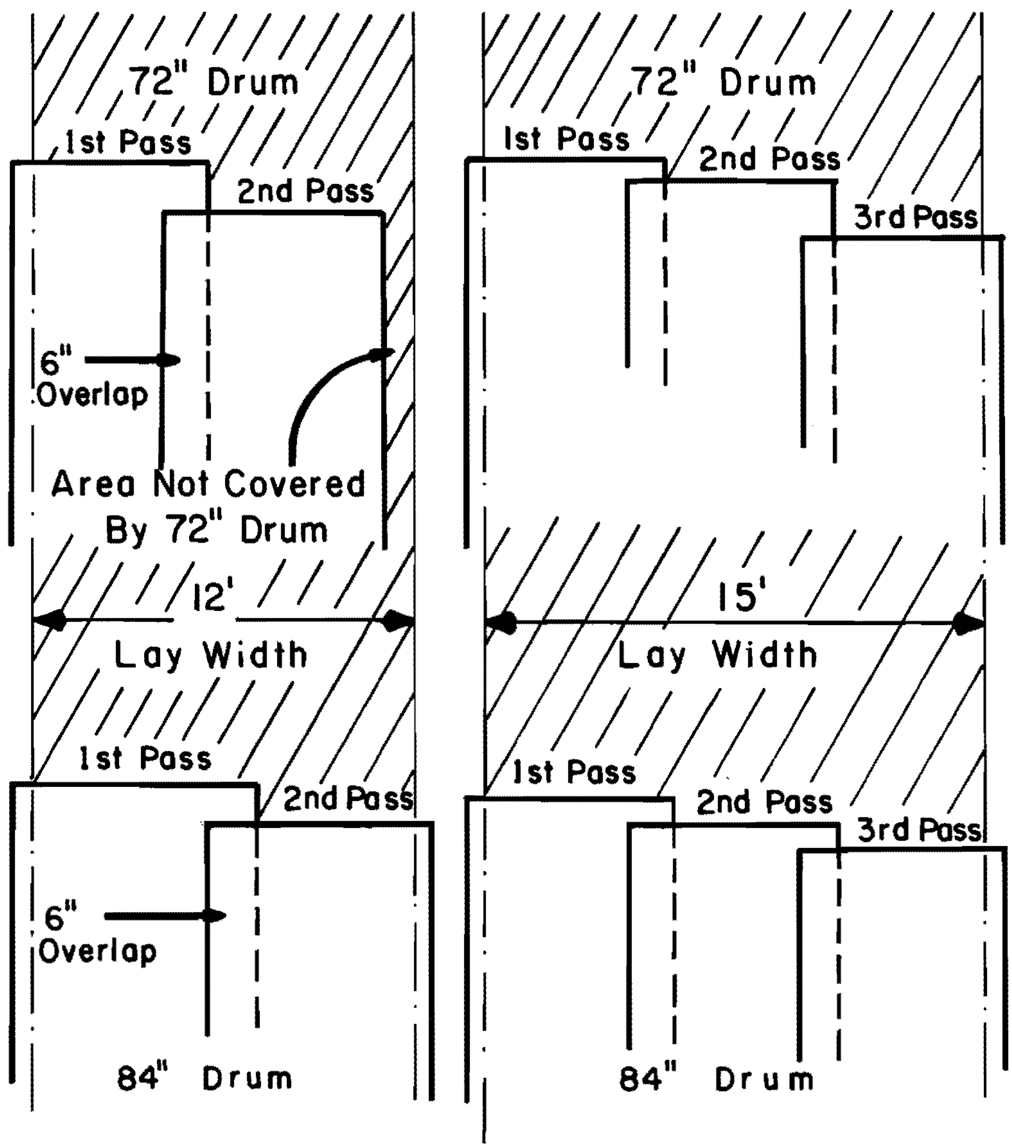


Fig 8. Areas covered by a 72-inch versus 84-inch drum (Ref 13).

literature; however, manufacturers most often suggest 80 to 90 percent as efficiency values suitable for use in the coverage formula (Refs 11 and 13).

ROLLER SPEED

Roller speed affects the attainment of density, the ability to meet production requirements, and the spacing of the impact. Higher roller speeds allow less compactive effort to be imparted to a given area of mat, thus producing a lower density for a particular number of coverages (Fig 9). If, on the other hand, roller speed is reduced too much, higher density is achieved but production requirements may not be met. In addition to density and production constraints, the roller speed interacts with the selected frequency to produce a certain impact spacing. Generally, the best roller speed is one that is low enough to impart compactive effort sufficient to attain density, high enough to meet production requirements, and one that produces an acceptable impact spacing at the selected frequency.

The evaluation of the effect of roller speed on these parameters should be considered (1) during the development of the rolling pattern for density, (2) using the coverage formula for production, and (3) using Fig 10 for impact spacing.

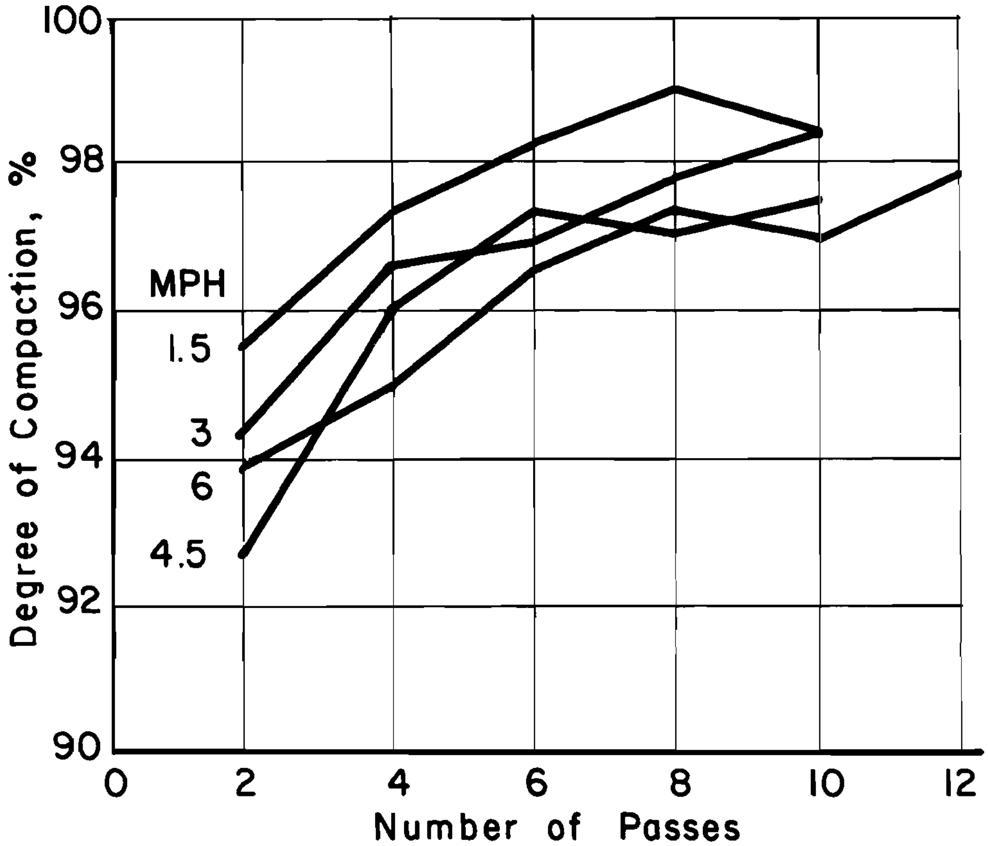


Fig 9. Effect of roller speed on degree of compaction for increasing roller passes (Ref 13).

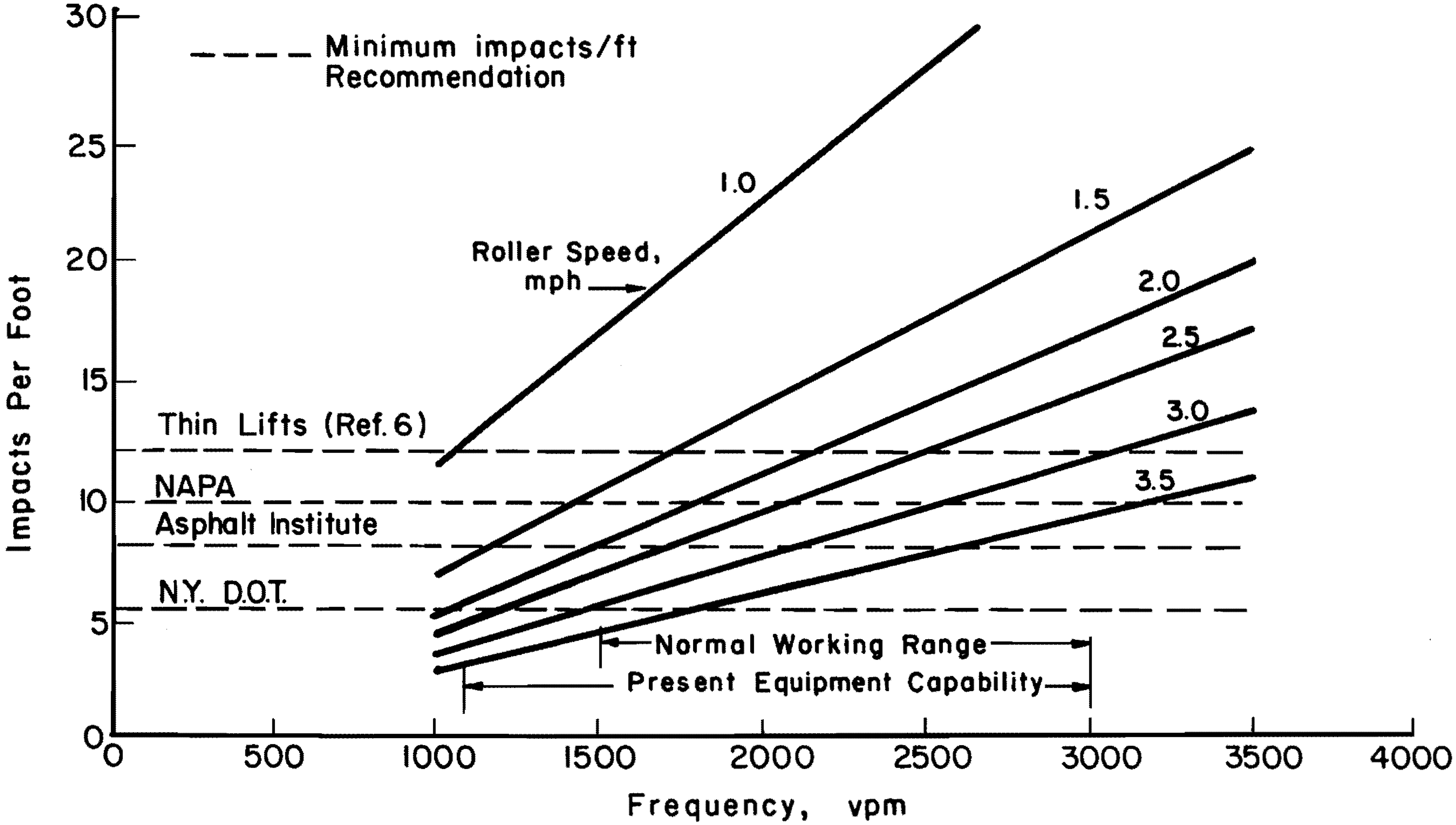


Fig 10. Relationship between impact spacing, roller speed, and frequency.

CHAPTER 4. GUIDELINES FOR OPERATION

It is the responsibility of the contractor to provide the required number and type of rollers that when operated properly will produce a compacted mixture that has the previously discussed desirable engineering properties. Nevertheless, the inspector or engineer should be familiar with the operating characteristics of the proposed rollers or obtain a copy of the operator's manual. In most cases the rolling pattern proposed by the contractor should fall within the guidelines suggested in the manufacturer's operating procedure and summarized in this report.

The following sections of this report contain recommendations related to the operation of the rollers and rolling patterns.

DIRECTION OF TRAVEL

When using a single drum rigid frame roller, the drum should normally be operated with the drive drum near the laydown machine with the tiller drum trailing. This ensures maximum compaction due to the additional weight and frictional action of the drum. In addition, it provides a more stable mat to reduce tears or displacements caused by the tiller drum during the steering action. A single drum articulated frame roller should also be operated with the drive drum near the laydown machine. Again this ensures maximum compaction due to the additional weight and frictional action of the drum and minimizes tire penetration of the mat (Ref 14).

Double drum rigid frame rollers should be operated with the vibrated drum near the laydown machine and the tiller drum trailing. Double drum articulated frame rollers operate the same in either direction so that direction of travel is not a consideration.

SELECTION OF FREQUENCY, IMPACT SPACING, AND ROLLER SPEED

Frequency, impact spacing, and roller speed are interrelated as shown in Fig 10, and there is no universally accepted criterion for the selection of operating values of the three parameters. General recommendations are summarized below.

Frequency

Generally the frequency should be as high as possible regardless of mat thickness, mixture characteristics, or underlying base resistance. It has also been suggested (Ref 15) that thin lifts be compacted at high frequencies and that thick lifts be conducted at lower frequencies. Final decision should be based on an evaluation of the resulting densities obtained on a test strip.

Impact Spacing

Impact spacing should be from 1.5 to 1.2 inches (8 to 10 impacts per lineal foot) (Refs 11 and 16). In some cases, an impact spacing of 1 inch has been recommended for thin lifts and a spacing equal to mat thickness for thick lifts (Ref 15).

Roller Speed

Based on the above recommendations, the maximum roller speed should be 3.5 mph. At lower frequencies the maximum speed would be less as shown in Fig 10. Final roller speed should be selected as a result of the densities obtained from a test strip on the actual project. Generally the best roller speed should be slow enough to achieve density, high enough to meet production requirements subject to the maximum speed for impact spacing (Fig 10). If production requirements cannot be satisfied, additional rollers will be required.

SELECTION OF AMPLITUDE

No theoretical procedure exists that allows the amplitude to be set without evaluating the resulting density. Manufacturers' recommendations are based on mat thickness; however, characteristics of the mixture also must be considered. There are two basic methods of changing amplitude, mechanical and fluid. The mechanical means will provide a precise nominal amplitude for a given setting. The fluid means also provides a precise nominal amplitude providing the system does not lose fluid. Most modern vibratory compactors do not have absolute value of amplitude; rather, manufacturers communicate operating instructions in terms of high, medium, and low. General guidelines are contained in Fig

LOWER AMPLITUDES | HIGHER AMPLITUDES

Parameter Level	PARAMETER	Parameter Level
Thin* < 2"	MAT THICKNESS	Thick 2"
Rigid	BASE SUPPORT	Flexible
Low	AC VISCOSITY	High
Rounded	AGGREGATE	Angular
Smooth	AGGREGATE SURFACE TEXTURE	Rough
Poorly Graded	AGGREGATE GRADATION	Dense
High	TEMPERATURE MIXTURE BASE AIR	Low

*For very thin lifts, especially on rigid base supports, vibration is not recommended.

Fig 11. Guidelines for selecting the amplitude of vibration.

MODE OF OPERATION (VIBRATION VS. NO VIBRATION)

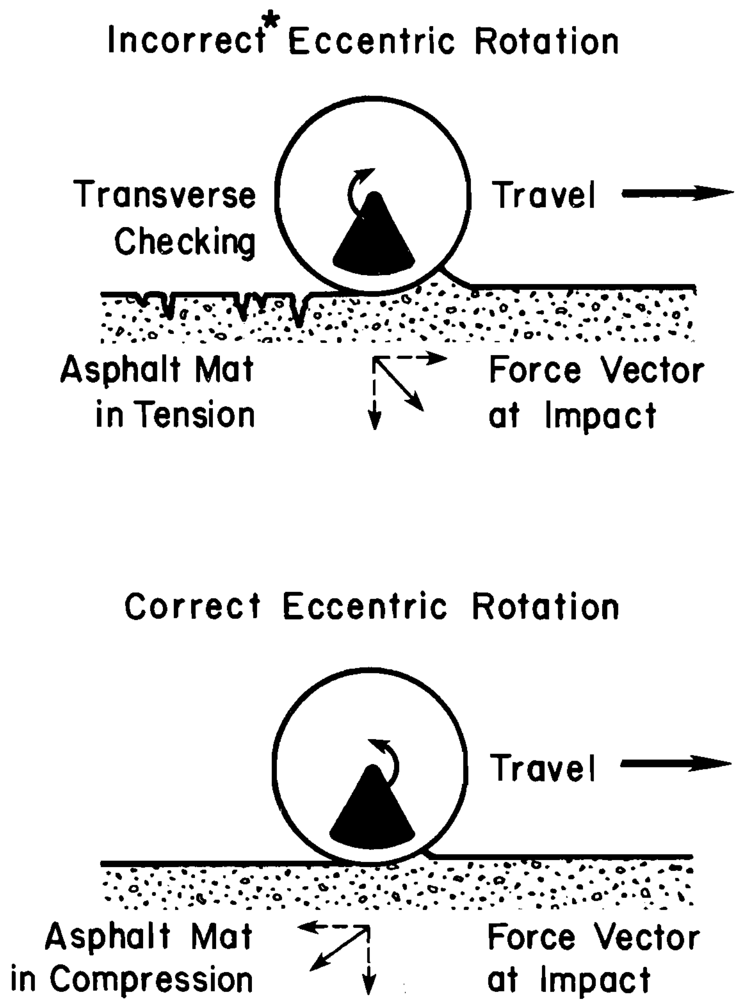
A vibratory roller can be operated in any of three modes: (1) static mode (vibrator off), (2) dynamic mode (vibrator on), or (3) a combination mode, with one drum vibrating and the other static. The mode selection is primarily a function of mixture behavior immediately following laydown.

For harsh mixtures, breakdown rolling is accomplished with all drums vibrating. Subsequent compaction passes are also made in the vibratory mode.

For mixtures with normal stability, breakdown should be accomplished in the vibratory mode. If, however, a combination mode, i.e., one drum static and one drum vibrating, is required for the first pass, subsequent compaction passes should be in the vibratory mode. For the combination mode the trailing drum is usually operated statically to provide a smoother finish (Ref 11).

For tender mixtures, breakdown is usually accomplished in the static mode. Subsequent passes are usually made in the combination mode if mixture displacement is not too significant. When in the combination mode for tender mixtures the trailing drum is usually vibrated.

1. Vibratory rollers generally should not be used on thin mats especially with a rigid base support such as a thin overlay over portland cement concrete. This does not necessarily imply that vibratory rollers cannot be used on thin mats if the results obtained on a test strip indicate satisfactory compaction.
2. The roller should not be vibrating when it is not moving or when it is changing directions. Most modern vibratory rollers automatically stop vibrating when the roller speed drops below some value. Older rollers, however, may require that the operator manually control vibration.
3. The eccentric should be rotating in the opposite direction to the movement of the roller (Fig 12). Incorrect eccentric rotation may result in transverse checking of the mat (Ref 17). Most manufacturers market rollers which automatically reverse the rotation of the eccentric when the roller changes direction. At least one manufacturer indicates that no surface irregularities have ever been directly attributed to improper eccentric rotation and that checking is primarily a mixture problem which would occur



*See page 29 for discussion.

Fig 12. Normal rotation of eccentric in relation to direction of travel (Ref 17).

even with a static roller. Thus if checking does occur, the mixture design as well as the direction of the eccentric rotation should be considered. If the direction of rotation is determined to be the problem and if the direction does not change automatically, it must be done manually or vibration must be stopped while the roller is operating in that direction.

DETERMINATION OF ROLLING PATTERN

The actual rolling pattern and procedures should be based on the results obtained on a test strip on the actual construction project using the proposed rollers. Final decisions regarding frequency, impact spacing, and amplitude should be based on the results obtained from the test strip.

In addition to fine tuning the operational characteristics, the number of coverages required to produce the target density is determined from the test strip. Adjacent passes should overlap about 6 inches. During test strip rolling, the roller should operate as close to the laydown machine as possible. The rolling pattern established in the test strip should produce a final product that meets density and finish requirements in an efficient and economical manner. The following discussion is an aggregation of procedures that have produced favorable results (Refs 18-22).

Determination of Roller Type and Number

The first step in developing a rolling pattern involves selecting the number and type of roller to be used. This decision is based on an evaluation of production requirements in terms of width of roller and availability of equipment. Production requirements are usually expressed in tons per hour which is used to determine if the effective paving width is adequate.

Selecting a Test Site

The second step is to select a project site that is representative of overall project conditions. If project conditions are highly variable with respect to conditions of support and confinement, a test strip should be rolled for each condition. A representative 200- to 300-foot straight strip should be chosen. The density of the compacted material should be determined after varying the following factors:

(1) operation mode (vibration on or off),

(2) speed,

(3) amplitude and frequency,

(4) number of passes, and

(5) length of rolling zone.

The most common method for monitoring changes in density with roller passes is with nuclear density gauges. These devices emit radiation that is transmitted into the mat. The amount of radiation that is reflected back to the device is measured for a specified length of time. This count data can be related to the relative density of the mat. Some gauges have a counting interval as short as 15 seconds which allows monitoring of density after each roller pass.

Constructing the Test Strip

The third step involves actually constructing the pavement on the test strip. Following each pass the nuclear gauge should be placed at least 2 feet from the edge and preferably in the center of the mat and a 15-second count taken. A relationship between density and number of passes like the one shown in Fig 9 can then be generated. When the density approaches the target or specification value, 60-second counts should be taken. Once the target value is achieved, rolling should cease since additional rolling could reduce density through decompaction forces.

Thick Lifts. For mats thicker than 2 inches the breakdown and subsequent compaction passes should be in the vibratory mode. After density has been achieved, any additional passes to remove objectionable roller marks should be in the static mode.

Thin Lifts. For mats thinner than 2 inches, the first pass is normally made in the vibratory or combination mode with subsequent passes in the static mode. If an excessive number of passes in the static mode is required, the number of vibratory mode passes should be increased.

Rolling Pattern Troubleshooting

If the proposed test pattern does not achieve the required density, adjustments to the pattern should be attempted. An initial adjustment might be to reduce the speed of the roller. Density readings taken after each pass will show the effect of each adjustment. Roller speed reduction may adversely affect production requirements. Therefore roller speed can be gradually increased (not exceeding 3.5 mph) using the same pattern until density requirements are not achieved. A pattern should be selected that has the highest acceptable roller speed and still meets density requirements.

If production requirements cannot be met because of low roller speed, the number of rollers should be increased. In addition, if the mat is cooling quickly, i.e., in cool weather with thin lifts, the number of rollers should probably be increased to ensure that the mixture is compacted at a temperature high enough to achieve the desired engineering properties. Figure 13 summarizes the steps normally included in establishing a rolling pattern. The procedures used by the Texas SDHPT for establishing rolling patterns may be found in TEX-207-F, Part III (Ref 3).

LONGITUDINAL JOINTS AND EDGES

Usually a 6-inch overlap (Fig 14) is necessary on the first pass when the joint is next to a previously compacted surface with the drum primarily on the new mat. Sometimes joints are compacted with the roller almost entirely on the previously compacted surface with a 6-inch overlap onto the new surface. Another technique (Fig 14), known as pinching (Ref 12), involves the drum entirely on the new mat within approximately 6 inches of the joint. A subsequent pass is then required to compact the remaining 6-inch strip. When the first pass is partially on a cold mat, the vibrator must be turned off.

Edges that are to have an adjacent mat placed should be rolled with a 6-inch overhang. When rolled in this manner (Fig 15) less than 1/4-inch side push will usually occur. Confined joints should be rolled with no overlap or gap (Fig 15).

Edges of thick mats ($t > 2$ inches) that are to remain unconfined should be rolled with the drum edge approximately 6 inches to the inside of the mat (Fig 16). When rolling the previously uncompacted 6-inch section the vibrator should be turned off. Edges of thin mats ($t < 2$ inches) should be rolled with a 6-inch overhang (Fig 16). It should be noted that material adjacent to unconfined joints generally will have lower density than confined joints.

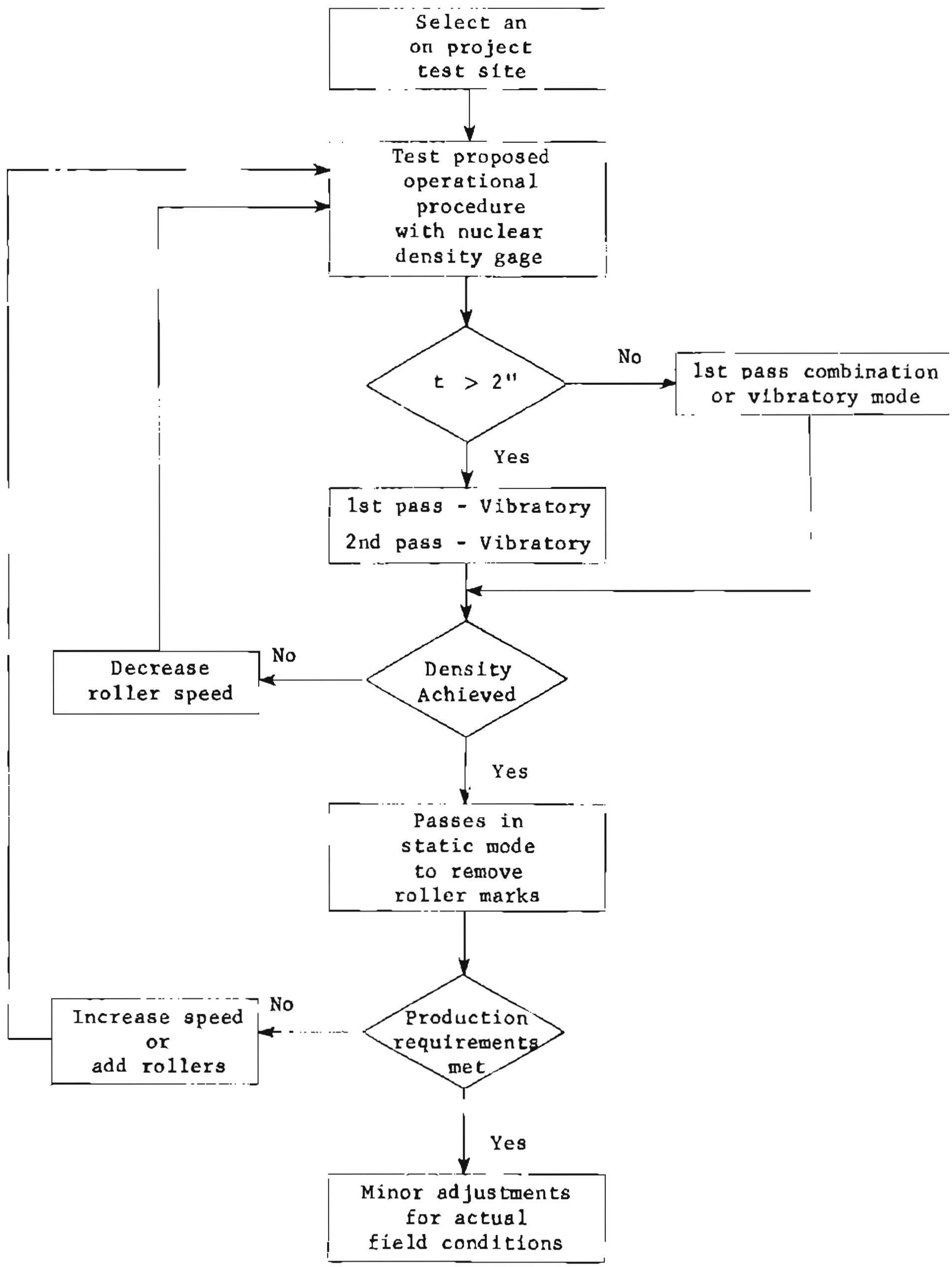
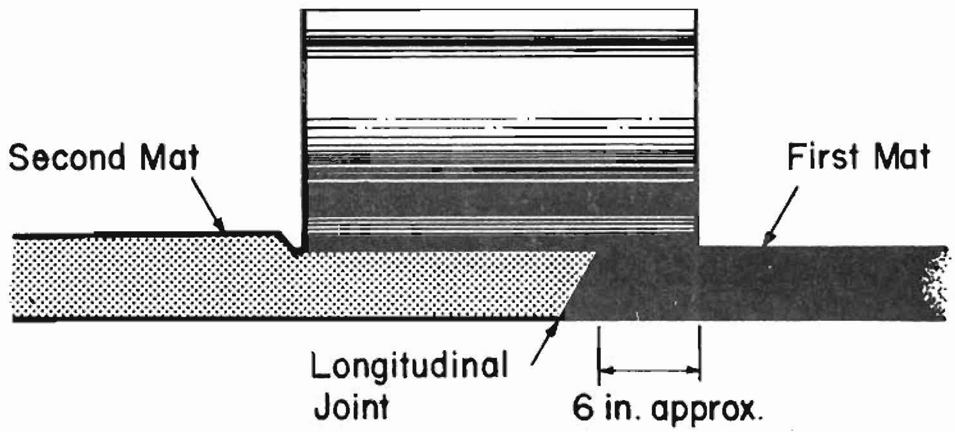
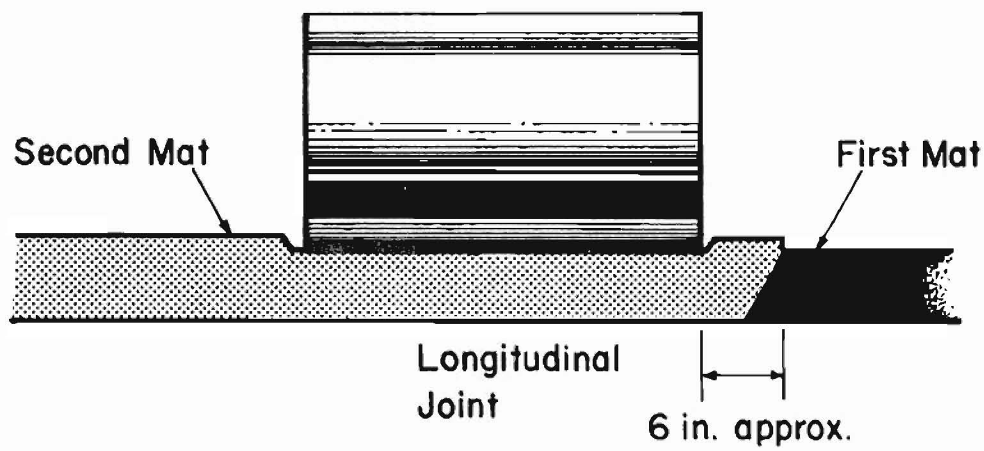


Fig 13. Steps for determination of a rolling pattern.



Normal Procedure



Pinching Procedure

Fig 14. Rolling procedure for longitudinal joints.

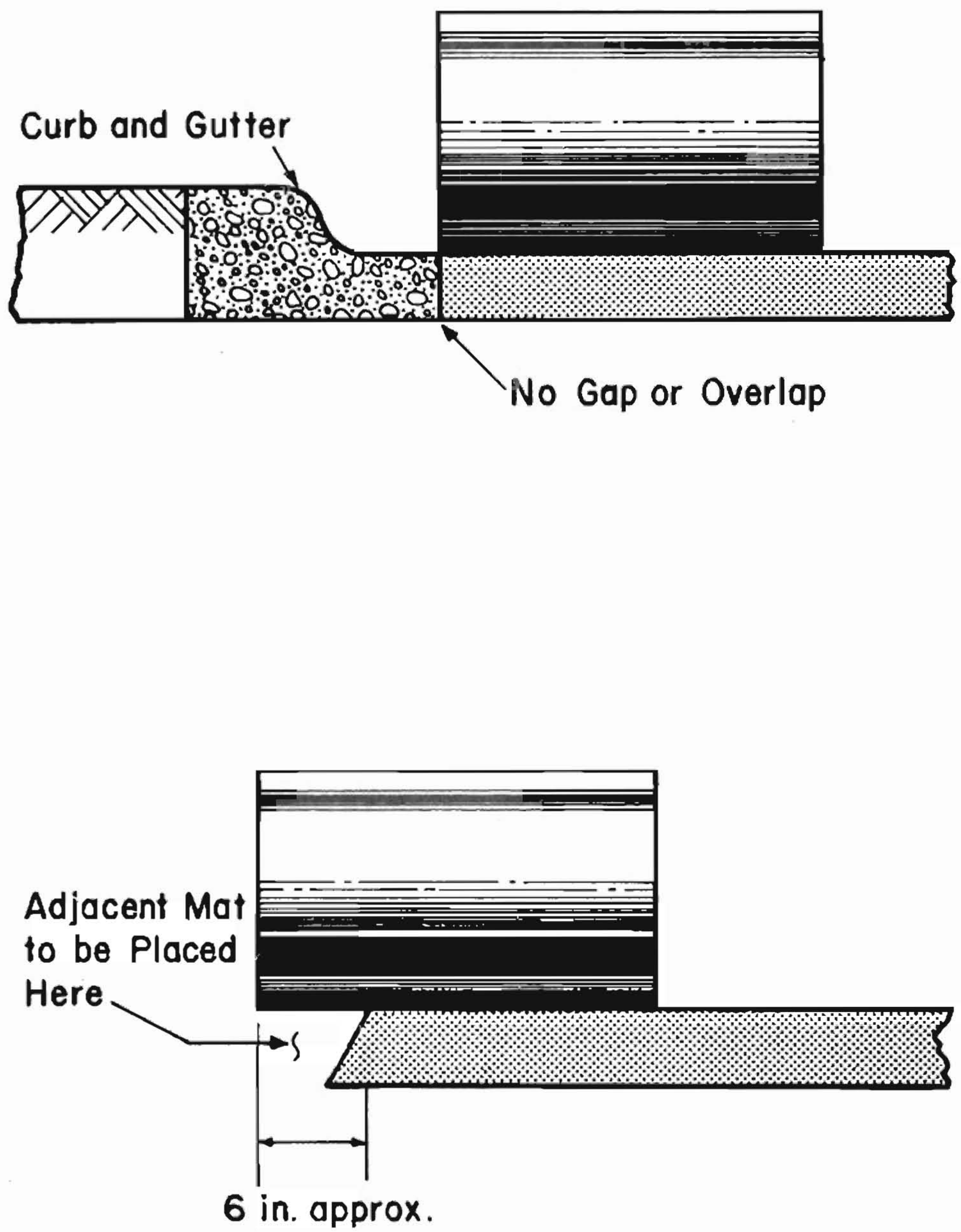
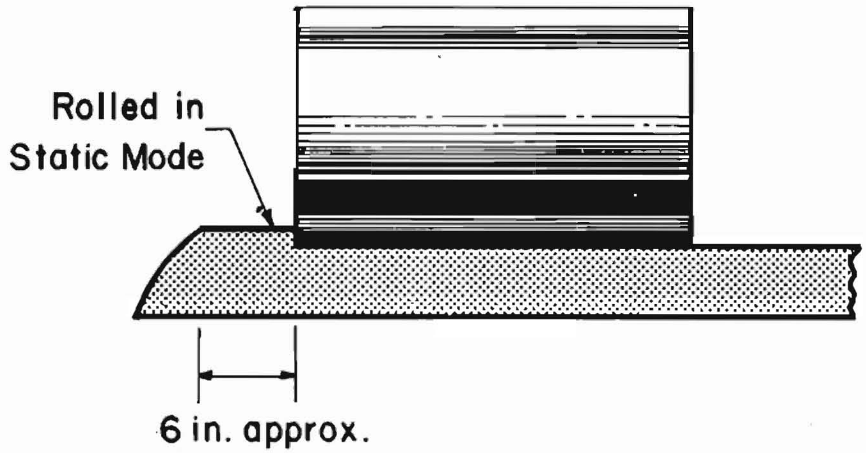


Fig 15. Rolling procedure for curb and gutter section and for longitudinal joint to be confined later.



Thick Lift Procedure

Thin Lift Procedure

Fig 16. Rolling procedure for longitudinal edges to remain unconfined.

SUPERELEVATION

When operating on curved sections that have high superelevation, vibratory rollers tend to slip toward the inside of the curve. This tendency may be minimized by increasing rolling speed and/or compacting in the static mode. In either case, additional passes are required to achieve density. In addition, rolling on curved sections (Ref 23) begins on the inside with the roller progressing to the outside of the curve (Fig 17).

DIRECTION CHANGES

Accepted practice calls for the vibrator to be off when reversing directions. This action prevents the formation of a depressed area under the vibrating roller. Almost all modern vibratory rollers are equipped with devices which automatically stop vibration just before the roller stops.

Although modern rollers are highly maneuverable, sharp turns, especially on fresh, hot mats, should be avoided. Figure 18 illustrates proper reversing and rolling zone change procedures. Tearing and distortion may result when sharp turns are made.

TIME AVAILABLE FOR COMPACTION

The time available to achieve compaction is primarily dependent on environmental conditions and mat thickness. Thus most highway agencies specify environmental limitations for placement of asphalt concrete based on air temperature and, in a few cases, base temperatures. These limitations which specify an air temperature below which paving must cease are generally based on experience and are intended to ensure favorable conditions for adequate compaction.

Dempsey (Ref 24) developed procedures using data from Frenzel, et al., (Ref 25) which specify a time period available for compaction based on date, percent sunshine, time of day, mixture temperature, wind velocity, air temperature, surface temperature, mat thickness, and a cessation temperature of 175°F.

Using this procedure, Smith and Epps (Ref 26) generated curves for typical Texas conditions. The reader may obtain additional information and guidelines from both Refs 24 and 26. Generally, however, compaction should occur at 275°F with a minimum cessation temperature of 175°F.

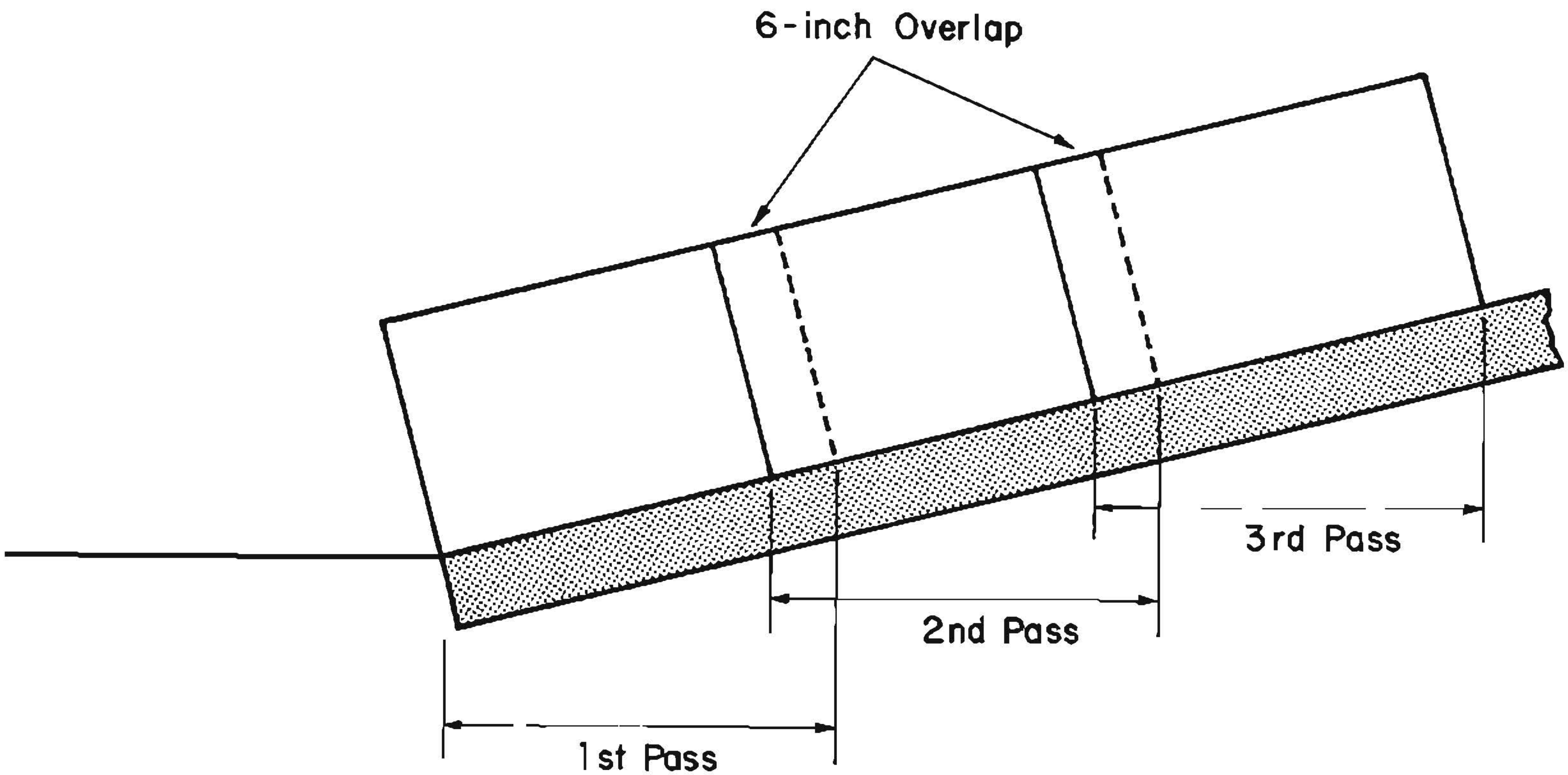
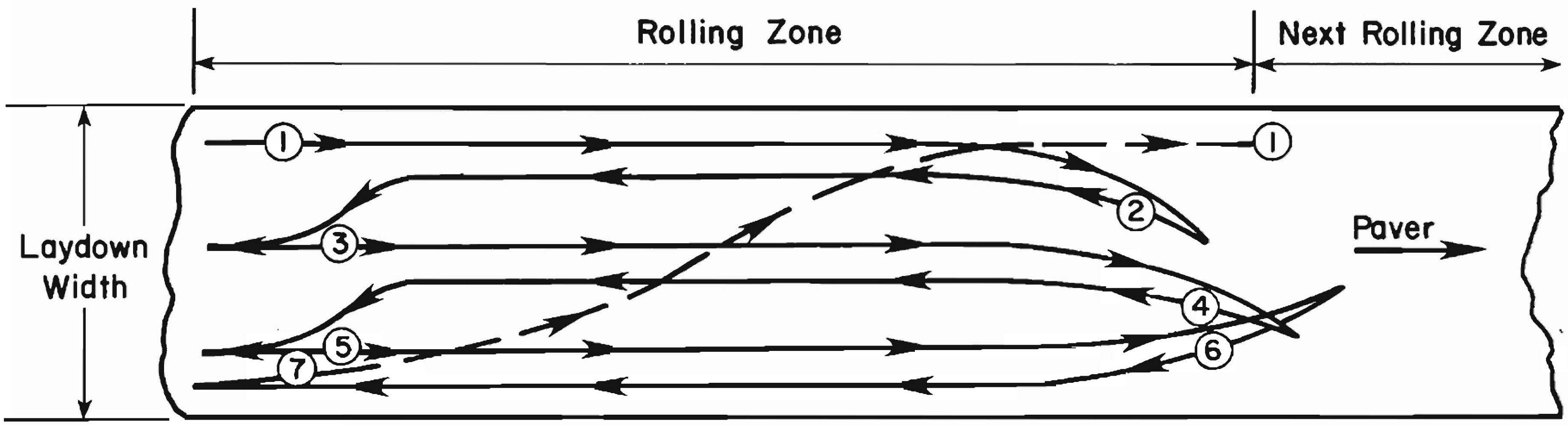


Fig 17. Rolling procedure for a superelevated section (Ref 23).



Numbers in Circles Indicate Movements

Fig 18. Rolling procedure for reversals and rolling zone changes.

Cessation temperature is the minimum temperature below which the asphalt viscosity is too high to facilitate adequate compaction.

The National Asphalt Pavement Association (Ref. 16) also developed a set of recommendations of minimum laydown temperature involving base temperature, mat thickness, and allowable rolling time. An example, shown in Table 3, illustrates the short rolling time available before a minimum laydown temperature of 175°F occurs. The values shown are not recommended for direct use and definitely are not applicable for Texas conditions.

TABLE 3. RECOMMENDED MINIMUM LAYDOWN TEMPERATURES AND AVAILABLE ROLLING TIMES FOR VARIOUS MAT THICKNESSES AND BASE TEMPERATURES (REF 16)

Recommended Minimum Laydown Temperature

Base Temp.	1/2"	3/4"	1"	1-1/2"	2"	3" and Greater
20-32	---	---	---	---	---	285
+32-40	---	---	---	305	295	280
+40-50	---	---	310	300	285	275
+50-60	---	310	300	295	280	270
+60-70	310	300	290	285	275	265
+70-80	300	290	285	280	270	265
+80-90	290	280	275	270	265	260
+90	280	275	270	265	260	255
Rolling time, min.	4	6	8	12	15	15

Increase by 15° when placement is on base or subbase containing frozen moisture.

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

Based on the findings from this study, the following conclusions and recommendations are made.

CONCLUSIONS

(1) Design technology has advanced to the point that vibratory rollers can be effectively used to compact asphalt mixtures.

(2) Experience in other states as well as in Texas has shown that if used properly, vibratory rollers can compact an asphalt mixture in a manner to obtain properties that ensure a durable and serviceable surface.

(3) Most of the difficulties with the use of vibratory rollers to compact asphalt mixtures occurred because of:

   (a) improper use of rollers (using rollers not designed for compacting asphalt mixtures, e.g., low frequency combined with high amplitude),

   (b) improperly trained operators, and

   (c) combinations of the above.

RECOMMENDATIONS

(1) Density of a mixture should be achieved primarily by compaction rather than by filling the void with additional asphalt.

(2) Based on laboratory and field evaluations, it is recommended that the air voids in the final mixture be between 3 and 5 percent.

(3) The Rice Method (ASTM D 2041) should be used to determine maximum theoretical density.

(4) The Texas State Department of Highways and Public Transportation should allow the use of vibratory rollers but only under the conditions outlined in the subsequent recommendations.

(5) The responsibility of choosing a roller and a rolling pattern should be the responsibility of the contractor. Inspectors should be sufficiently familiar with operational characteristics of rollers and rolling patterns to allow them to evaluate conformity to specifications.

(6) The operator's manual for the roller, containing the operational characteristics, should be available for the project engineers and inspectors.

(7) The contractor's proposed rolling pattern should be verified by rolling an on-project test strip using a nuclear density gauge to monitor the densification process. A set of cores or sections of pavement should be taken to correlate with the final nuclear density readings. Then, during construction, if conditions of support, confinement, or mixture properties change from those in the test strip, a new test strip should be compacted to establish a new rolling pattern.

(8) The operational procedures outlined in Chapter 4 may be used as general guidelines but in no case should supersede manufacturer recommended procedures unless warranted by project experience.

(9) If compaction difficulties arise, construction should immediately cease until the cause is determined and corrected. Mixture problems should be corrected by design changes (e.g., tenderness of a mixture should be corrected by changing the mixture design, not by allowing the mixture to cool before compacting) rather than by changes in operational procedures.

(10) If difficulties arise in obtaining the minimum in-place density specified, the rolling pattern (including selection of compaction equipment) should be modified to improve density. Only after these efforts have been exhausted should the mix design be changed to accommodate ease of compaction.

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