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by

Thomas W. Kennedy
Mansour Solaimanian
William E. Elmore

Research Report Number 468-3

Research Project 3-9-85/8-468

Field Evaluation to Obtain Density in Asphalt Mixtures

conducted for

Texas State Department of Highways and Public Transportation

in cooperation with the

U. S. Department of Transportation Federal Highway Administration

by the

CENTER FOR TRANSPORTATION RESEARCH

Bureau of Engineering Research
THE UNIVERSITY OF TEXAS AT AUSTIN

June 1991

NOT INTENDED FOR CONSTRUCTION,
PERMIT, OR BIDDING PURPOSES

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PREFACE

This is the third in a series of reports that examine the findings of a research project concerned with density of asphalt mixtures. This report provides information and guidelines for obtaining the necessary compaction to ensure producing the required pavement.

The work required to develop this report was provided by many people. Special appreciation is extended to Messrs. James N. Anagnos and Eugene Betts for their assistance in the testing program. Also, the assistance of personnel from the various districts is acknowledged. In addition, the authors would like to express their appreciation to Messrs. Billy R. Neeley and Paul Krugler of the Texas State Department of Highways and Public Transportation and to Mr. Peter A. Kopac of the Pavement Division, HNR-20, for their suggestions, encouragement, and assistance, and to other district personnel who provided data and information. Appreciation is also extended to the Center for Transportation Research staff who assisted in the preparation of the report. The support of the Federal Highway Administration, Department of Transportation, is acknowledged.

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June 1991

LIST OF REPORTS

Research Report 468-1, "Evaluation of the Troxler Model 4640 Thin Lift Nuclear Density Gauge," by Mansour Solaimanian, Richard J. Holmgreen, Jr., and Thomas W. Kennedy, is an evaluation of the Troxler Model 4640 Thin Lift Nuclear Density Gauge's ability to predict core densities. July 1990.

Research Report 468-2, "Evaluation of Methods of Determining the Theoretical Maximum Specific Gravity of Asphalt Concrete Paving Mixtures," by Mansour Solaimanian and Thomas W. Kennedy, summarizes a study comparing methods of estimating the theoretical maximum specific gravity of asphalt mixtures. April 1989.

Research Report 468-3, "Recommendations to Achieve Density for Asphalt-Aggregate Mixtures," by Thomas W. Kennedy, Mansour Solaimanian, and William E. Elmore, provides information and guidelines for obtaining the necessary compaction to ensure producing the required pavement. June 1991.

ABSTRACT

This report presents a compilation of the information developed on the importance of—and procedures for obtaining—the necessary density as measured by air voids in hot mix asphalt concrete paving mixtures.

SUMMARY

This report summarizes the information supporting the need for obtaining proper compaction and the factors that affect compactive efforts in paving operations. In addition, this report provides the information in the form of text and tables that will serve as a guide for the technician or inspector in ensuring a proper compactive effort.

IMPLEMENTATION STATEMENT

It is recommended that the information contained in this report be made a part of the Texas State Department of Highways and Public Transportation's operating procedures for obtaining the proper compaction of hot mix asphalt concrete pavements.

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CHAPTER 1. INTRODUCTION

Compaction is probably the single most important factor affecting the ultimate performance of asphalt concrete pavements. Adequate compaction of the mix to a low air void content increases the fatigue life, decreases permanent deformation (rutting), reduces oxidation or aging, decreases moisture damage, increases strength and stability, and decreases low-temperature cracking. An asphalt concrete mixture that has all the desirable mix design characteristics will perform poorly under traffic if that mix is not compacted to the proper density level. On the other hand, a marginal mix, one that does not have all of the properties of a highly desirable mix design, may perform well under traffic if that mix can be compacted to a low air void content during the construction process.

The purpose of this report is to summarize information related to the proper compaction of asphalt-aggregate mixtures and to provide guidelines for the use of field personnel. Chapter 2 is a discussion of compaction and density, the importance of density, and factors affecting compaction and compaction equipment and their operating characteristics. Chapter 3 contains guidelines for obtaining satisfactory compaction and summarizes the recommendations.

CHAPTER 2. DENSITY AND COMPACTION

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

Definitions

The terms density and compaction are often used interchangeably to describe the process of compressing an asphalt concrete mixture, thus increasing its unit weight. The two terms, however, are quite different.

Density

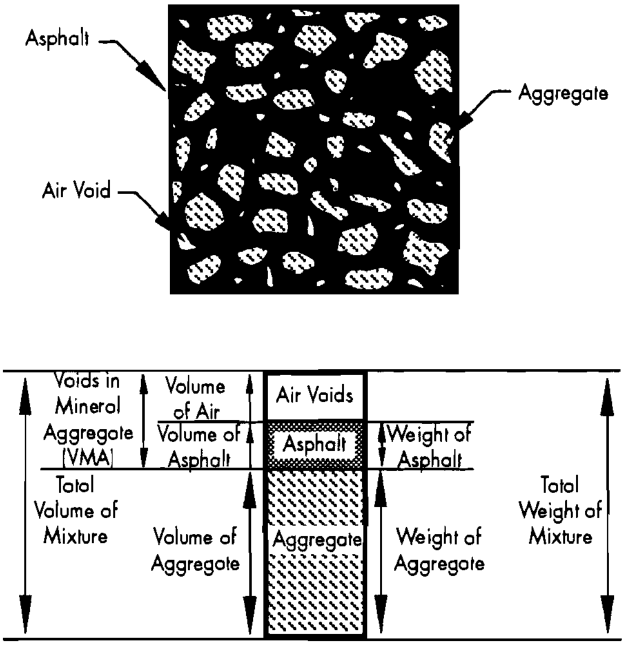
The density of a material is simply the weight of the material that occupies a certain volume. This density, or unit weight, is generally considered to be an indication of the degree of compaction of the mixture. Nevertheless, different paving materials made with different aggregates can have significantly different densities and amounts of air voids. An asphalt concrete mixture containing limestone aggregate might have a compacted density of 147 pounds per cubic foot, while an asphalt mixture manufactured with lightweight aggregate might have a compacted density of only 85 pounds per cubic foot of volume when compacted to the same air void content.

Compaction

Compaction is the process through which the asphalt concrete mix is compressed and reduced in volume. Compaction causes the unit weight or density of the mix to be increased by placing more materials in a given volume of space or by taking a given amount of material and compressing it into a smaller space or volume by forcing the asphalt-coated aggregates closer together, thus reducing the air void content in the mix. This increases aggregate interlock and interparticle friction.

Maximum Theoretical Density

Theoretically it is possible to compact an asphalt concrete mixture to a maximum value, called the maximum theoretical density, at which additional compaction would not increase density since there would be no air voids in the mix (a voidless condition) and all of the asphalt-coated particles would be in complete contact. The maximum theoretical density of a mix can be calculated from the percentages and the specific gravities of each component in the mix or by means of a laboratory test, the Rice



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

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

Figure 1 **Typical asphalt mixture containing asphalt, aggregate, and air voids (Ref 10)**

method, which is the recommended procedure (ASTM D-2041; Test Method Tex-227-F).

Air Void Content

Since it is impossible to compact a mix to the level of a voidless condition, all asphalt concrete mixes will contain some void spaces or air voids when the compaction process is completed by the rollers. The air void content of the mix is simply the volume of the space between the asphalt-coated particles divided by the total volume. Because the volume of those air voids is impossible to measure directly, a ratio of unit weight values is used. The air void content is expressed as the ratio of the difference between the maximum theoretical density and the actual density of the mix to the maximum theoretical density. Thus, if the compacted density of a cubic foot of limestone mix is 147 pounds and the maximum theoretical density of the same mix is 154 pounds, the air void content of the mix would be the difference in the two values (154 - 147 = 7) divided by the value of the maximum theoretical density (154), or 4.5 percent.

Importance of Density

This section, which deals with the importance of density, is quoted from Research Report 317-2F (Center for Transportation Research, 1986) by Kennedy et al.

Long-term satisfactory performance of asphalt pavements is highly dependent on the density, or more precisely, the void content of the asphalt mixtures. The three basic types of distress which, directly or indirectly, result in reduced pavement performance and increased pavement maintenance and rehabilitation are (1) thermal or shrinkage cracking, (2) fatigue cracking, and (3) permanent deformation or rutting.

Closely related to these types of distress are moisture damage and asphalt aging or hardening. Moisture damage, which includes both stripping (loss of adhesion) and softening (reduced cohesion), can weaken the pavement and cause increased fatigue cracking, rutting, and possibly flushing. Asphalt aging (hardening) tends to produce a brittle mixture which in turn can result in fatigue and thermal cracking of the pavement.'

While a number of factors involving the actual pavement structure, mixture characteristics, and construction variables can affect the magnitude of these distresses and the severity of moisture damage and oxidation, the air void content (density) is one of the most important. Generally, reduced air void content or increased density achieved by means of compaction will significantly reduce fatigue cracking, rutting and permanent deformation, moisture damage, and age hardening.

Fatigue Cracking

A number of laboratory studies (Refs 1, 2, and 3) that illustrate the effect of air void content on fatigue life (the number of load repetitions required to fail the material) have been conducted. The results indicate that mixtures containing high void contents have relatively short fatigue lives. As shown in Figures 2 through 4, a decrease in air void content from 10 to 3 percent increased fatigue life by approximately a factor of 10. It can also be seen in Figure 4 that at low strain levels, fatigue life decreased sharply with increased void contents. Decreased voids also increase the stiffness of the asphalt mixture (Figure 5), which in turn improves the load-carrying capacity of pavement sections by reducing the stresses transmitted to the underlying layers. In addition, stiffness is closely related to fatigue resistance. In general, for a repeated constant stress that simulates the conditions found in thick pavements, fatigue life will increase with increased stiffness, while for a repeated constant strain that simulates the conditions found in thin pavements, fatigue life will decrease with increased stiffness (Figure 6). The exception to this general rule is the effect of air void content. As shown in Figure 6, a decrease in void content produced both

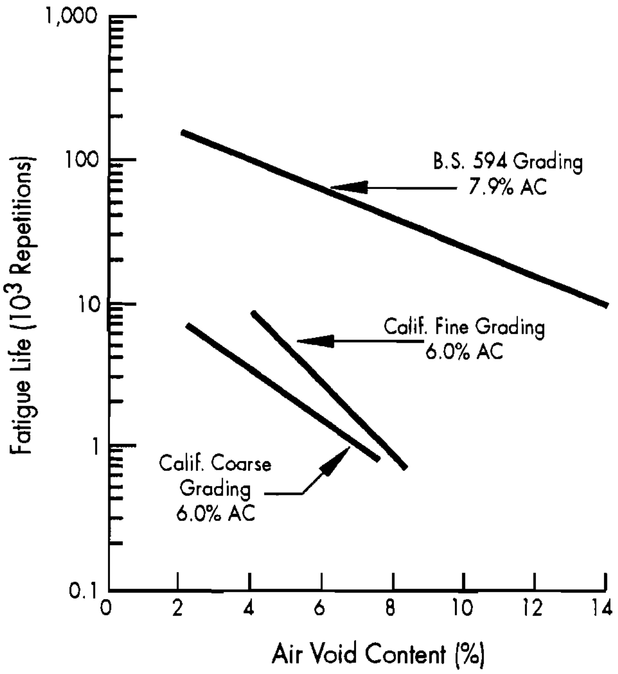


Figure 2 **Effects of void content on fatigue life (Ref 3)**

an increase in stiffness and an increase in fatigue life for both constant stress and constant strain.

Permanent Deformation

Similarly, it was shown by Hicks et al (Ref 4) that an increasing air void content resulted in a significant loss of pavement life in terms of rutting or permanent deformation. A decrease in void content increased the number of loads required to produce failure by a factor of 10 (Figure 7).

Asphalt Aging

Pauls and Halstead (Ref 5) employed a hardness index which ranged from 0 (for no hardening) to 100 (which corresponded to a penetration value of approximately 10). The hardness index increased significantly with an increase in void content (Figure 8), indicating a significant increase in aging or hardening of the asphalt. In addition, the Oregon study (Ref 4) reported significant increases in hardening (reduced penetration) for increased void contents (Figure 9).

Moisture Damage

High void contents consistently have been shown to be related to high levels of moisture damage such as stripping. In many cases, highly moisture-susceptible mixtures have performed satisfactorily when compacted to relatively high density. For example, an analysis (Refs 7 and 8) of a pavement failure in Texas found that one section of the roadway failed by rutting while another section performed extremely well with no signs of rutting. The evaluation of these sections indicated that the primary cause of the rutting was stripping with associated high moisture contents. Both sections contained essentially the same aggregates and asphalts; however, a high density was achieved in the section that performed satisfactorily, which apparently prevented moisture penetration and thus moisture damage. Test samples taken from the roadway also indicated lower moisture contents for the satisfactory pavement sections.

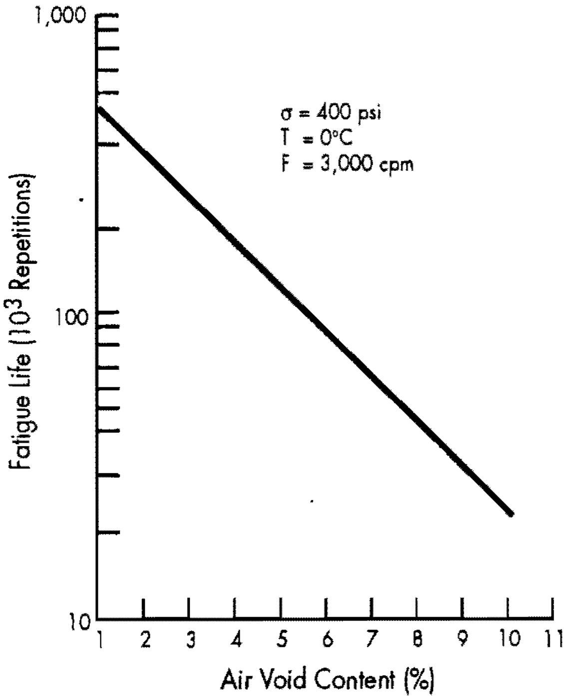


Figure 3 **Effects of void content on fatigue life (Ref 1)**

Factors Affecting Compaction

Four primary factors affect the ability of the compaction equipment to densify an asphalt concrete mixture. These four are: the (1) properties of the materials in the asphalt concrete mixture, (2) environmental variables, (3) pavement characteristics, and (4) the type of compaction equipment.

Properties of the Materials

A variety of material properties and/or characteristics can affect the compactability of the mixture.

Aggregates. The particle shape of the coarse aggregate, the number of fractured faces, and the surface texture can affect the ability to obtain a specified density. Aggregates with a cubical or block shape require a greater degree of manipulation before achieving a given density level. As the crushed content of the coarse aggregate fraction of the mixture increases, a greater compactive effort is required to obtain a specific level of density, since angular particles offer more resistance to manipulation than rounded aggregate particles. Similarly, a mixture with more manufactured sand generally requires greater compactive effort than a mixture with more natural sand, because manufactured sand generally is more angular than natural sand. Aggregates with a rough surface texture also tend to be more difficult to compact than aggregates with a smooth surface texture.

A uniformly graded aggregate, from coarse to fine, will be easier to compact than will a mixture with either a single-sized aggregate gradation or a mix containing a skip-graded or gap-graded aggregate. A mix containing a large proportion of coarse aggregate typically requires a greater compactive effort to obtain the desired density. An oversanded or finely graded mix, on the other hand, tends to be extremely workable. Nevertheless, it may be difficult to achieve density for such a mix because of the inherent tender nature of such an oversanded mix. Mixes that contain an excess of mid-size fine aggregate (between the No. 30 and No. 50 sieves or between the No. 40 and No. 80 sieves), as shown in Figure 10, are difficult to compact because of their lack of internal cohesion, which causes them to displace laterally rather than compress vertically.

The filler content also significantly affects density. Increase in filler content (material passing the No. 200 sieve) increases the viscosity and stiffness of the mix and, therefore, increases resistance to compaction. If the amount of filler is too high, the mixture becomes too stiff and gummy and is difficult to compact. Compacting the mixture is generally difficult if the amount of filler exceeds 6 or 7 percent. However, the filler added to the mix fills voids, and this tends to reduce the air void content. Mineral filler in the mixture tends to improve resistance against rutting because of apparent increases in viscosity and cohesion. However, the larger the amount of filler, the greater the amount of asphalt cement required, since there is a larger surface area to be coated by asphalt.

The effect of various filler types on properties of asphalt cement and asphalt concrete has been

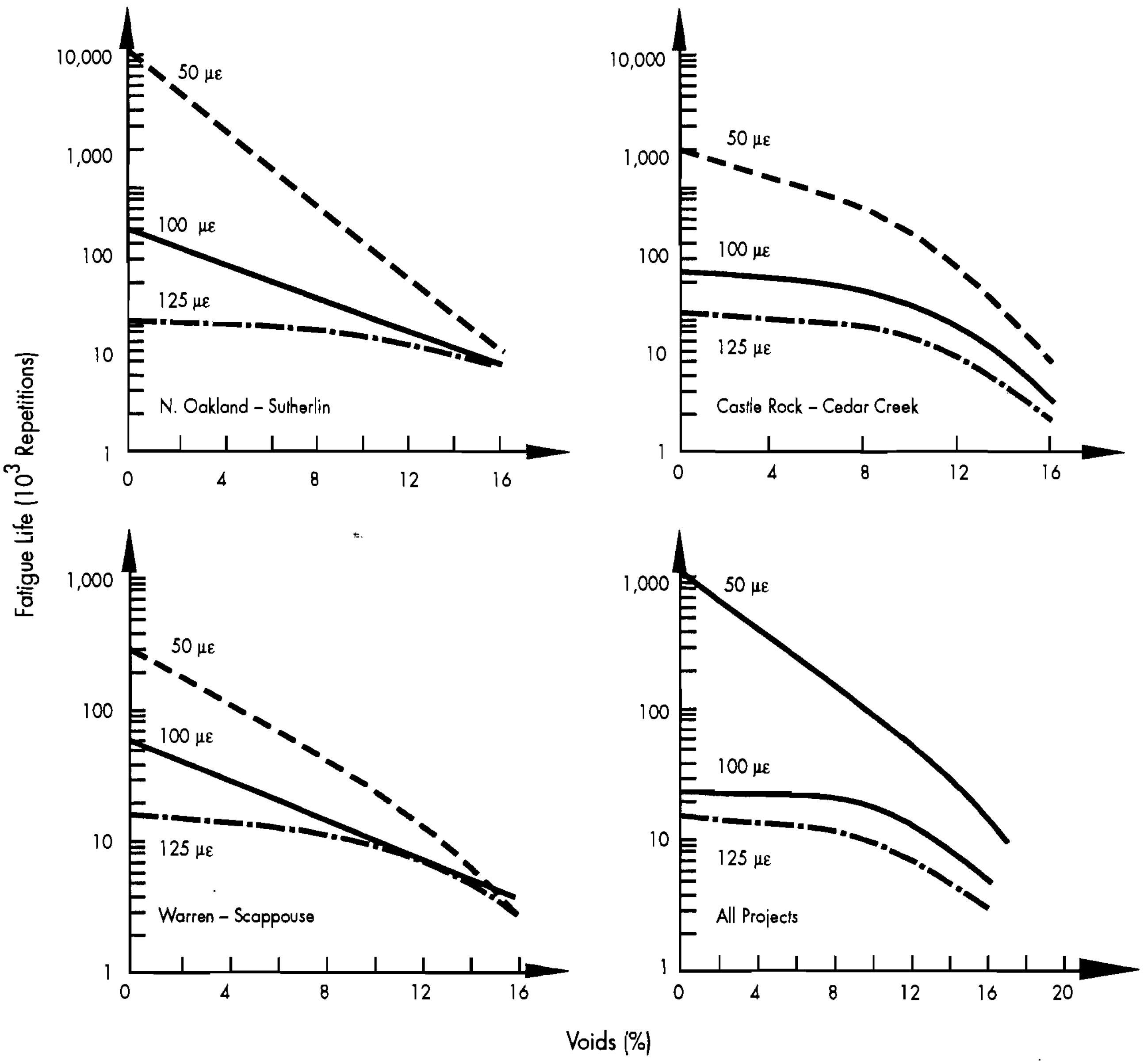


Figure 4 Effects of air void content on fatigue life at three different strain levels (Ref 4)

investigated in a number of studies. Some investigations of this kind indicate that the void-filling ability of the fillers and the air void content are not affected by the type of the mineral filler added to the mixture (Refs 16 and 17).

Sometimes during production, the filler material is constructed over and above the amount of fine material in stockpiles used to develop the laboratory mix design. This can increase density by filling voids. However, the excessive amount of filler may result in an under-asphalted mix which is harsh and hard to work with.

Highly absorptive aggregate may also increase the compaction resistance of the mix by reducing the thickness of the asphalt cement film around the aggregate particles and decreasing the lubricating effect of the binder material.

Asphalt Cement. The grade and amount of asphalt cement used in the mix affects the ability to densify the mix. An asphalt cement that is more viscous generally will produce a stiffer mix at a given mix temperature and therefore require a greater compactive effort. Thus a mix produced with an AC-30 viscosity graded asphalt will typically be stiffer, at any particular temperature, than will a similar mix that contains an AC-10 asphalt cement. The stiffer the mix, the more compactive effort is required to reach a given density level. This stiffness trend, however, may be significantly affected by the temperature-viscosity relationship of the particular asphalt binder (Figure 11).

Thus the compactability of a mix is affected by the temperature susceptibility of the asphalt cement. For a highly temperature-susceptible asphalt binder material, less time will be available for compaction because the mix will change stiffness more quickly with a change in temperature than will a mix containing a less temperature-susceptible asphalt (Figures 11a and b).

The degree of hardening that occurs in the asphalt cement during the manufacture of the mix also affects the compactability of that material. Different asphalts harden more than other asphalts during the mixing process (Figures 11c and d). The degree of hardening is also a function of the type of asphalt mix plant, with more hardening normally occurring during mixing in a batch plant than in a drum mix plant. Further, hardening is a function of the mixing temperature at the plant, with higher manufacturing temperatures typically producing stiffer mixes. Also, an increase in wet mixing time for batch plants will produce stiffer mixes.

Generally, as the amount of asphalt cement increases, resistance to compaction energy decreases.

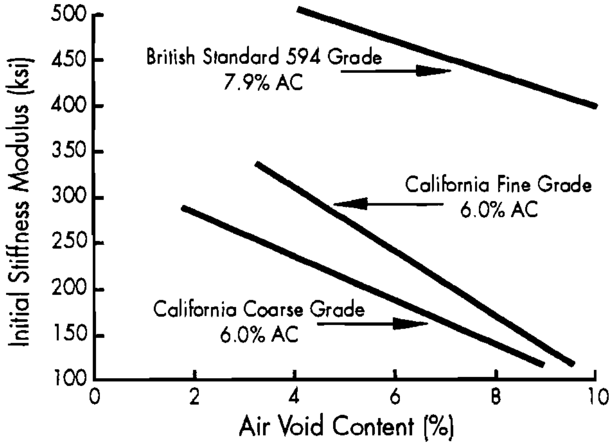


Figure 5 **Effects of air void content on initial stiffness modulus (Ref 3)**

		Effect of Change in Factor		
			On Fatigue Life	
Factor	**Change In Factor**	**On Stiffness**	**In Controlled Stress Mode**	**In Controlled Strain Mode**
Asphalt Penetration	Decrease	Increase	Increase	Increase
Asphalt Content	Increase	Increase[1]	Increase[1]	Increase[2]
Aggregate Type	Increase Roughness and Angularity	Increase	Increase	Increase
Aggregate Gradation	Open to Dense Gradation	Increase	Increase	Increase[3]
Air Void Content	Decrease	Increase	Increase	Increase[3]
Temperature	Decrease	Increase[4]	Increase	Increase

[1] Reaches optimum at level above that required by stability considerations

[2] No significant amount of data; conflicting conditions of increase in stiffness and reduction of strain in asphalt make this speculative

[3] No significant amount of data

[4] Approaches upper limit at temperature below freezing

Figure 6 **Factors affecting the stiffness and fatigue behavior of asphalt concrete mixtures**

This phenomenon occurs mainly because asphalt cement acts as a lubricating factor for aggregates during compaction. As the amount of asphalt cement increases, the aggregates will more easily roll over each other and align themselves to create a more dense mixture, making the compactive effort more effective. A significant increase in the density level may be achieved by just a 0.2 to 0.3 percent increase in asphalt content. Increased asphalt cement also fills some of the voids that were occupied by air, leading to reduced air void content.

Higher asphalt content also increases the mix durability because of the thicker coating on aggregates and because of less aging and hardening. However, too much asphalt cement causes excessive lubrication, significantly reduces stability, and creates a tender mix that easily shoves away under the rollers and becomes difficult to compact. Increasing asphalt cement (to a degree such that resistance is excessively reduced) has adverse effects on compaction. Even if the mix can be compacted, its long-term performance will not be satisfactory, and it may undergo excessive bleeding, flushing, distortion, displacement, and rutting. Therefore, asphalt content should not be arbitrarily increased in the field to achieve density. Other design and construction factors should be examined to determine why density is not being achieved.

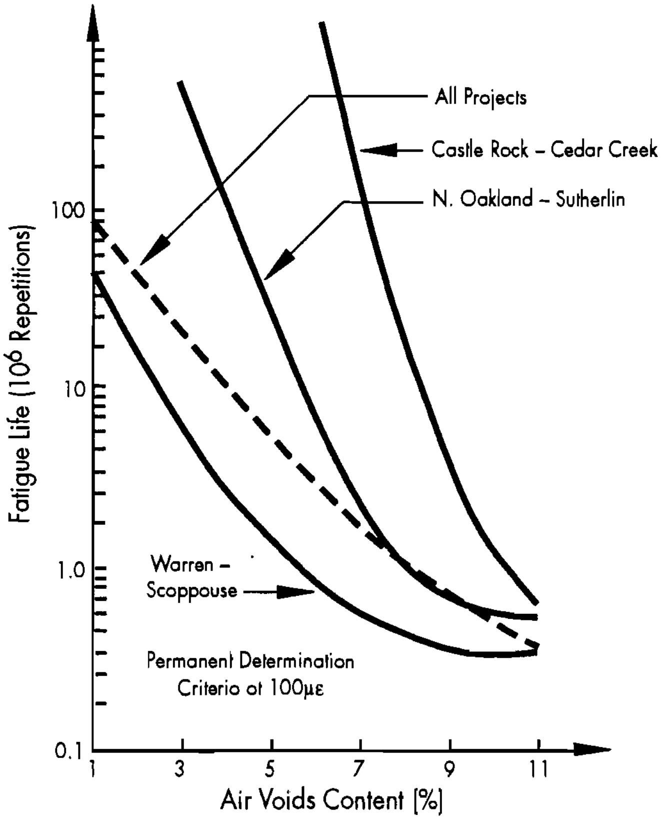


Figure 7 **Effects of air void content on fatigue life (data from Ref 4)**

One way to increase air voids in the mix is to reduce the asphalt content. However, insufficient asphalt content can lead to a too-thin coating on aggregates, premature hardening, brittleness, and loss of durability. Too low an asphalt content also causes a significant reduction in lubricating effect. In this case, the mix will be harsh and difficult to compact.

Mix Properties. A mix that is placed at a higher temperature will be easier to compact than will a mix that is placed at a lower temperature. If the initial mix temperature is too high, however, the mix will be tender and difficult to compact until the mix temperature decreases and the viscosity of the asphalt cement increases. If the mix temperature is low, an increased amount of compactive effort will be required, and with the temperature too low, the required density or air voids cannot be achieved.

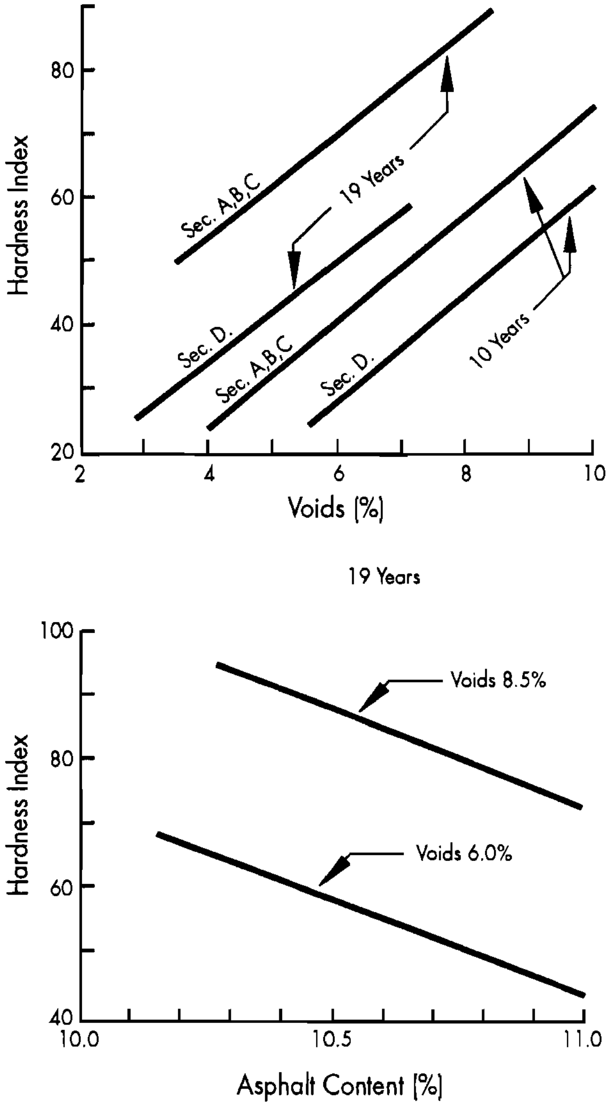


Figure 8 **Effects of air void content on hardness index (Ref 6)**

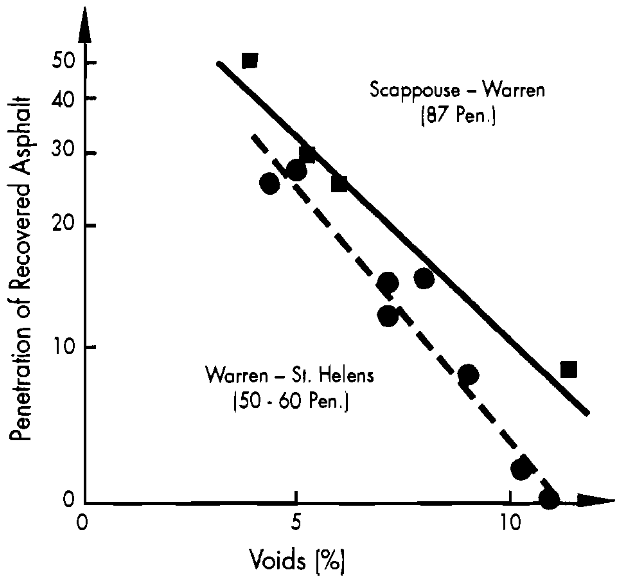


Figure 9 **Effects of air void content on penetration of recovered asphalt (Ref 4)**

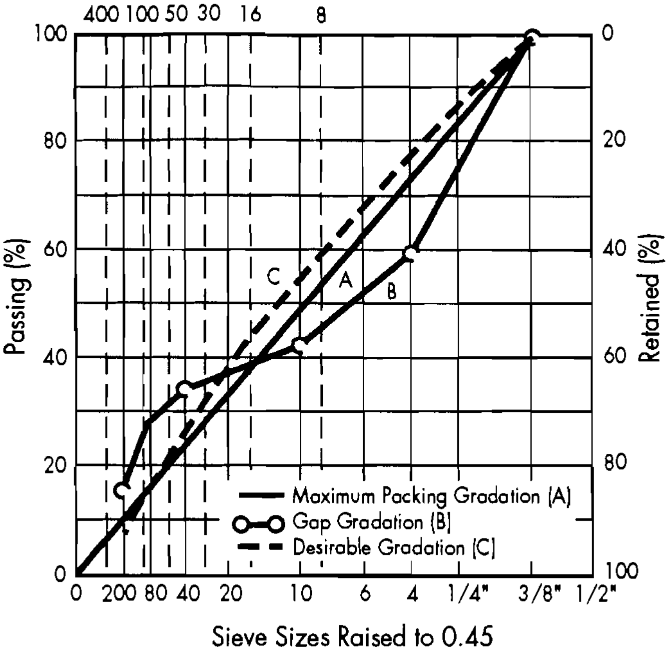


Figure 10 **Typical aggregate gradations (Ref 9)**

The asphalt content of the mix influences its compactability. A mix containing either too little or too much asphalt cement is difficult to compact. A lean mix will be stiff. A rich mix will be tender and will shove under the rollers (Ref 14).

The total fluids content of the mix also affects the compactive effort needed. Fluids content is the sum of the asphalt cement content and the moisture content of the mix. When the amount of moisture in the mix exceeds approximately 0.5 percent by weight of mix, the extra fluids content may increase the tenderness of the mix. A "dry" mix that is at optimum asphalt content may be readily compacted, while a "wet" mix, containing an excess of moisture, may have a tendency to displace under the compaction equipment, and thus may be difficult to compact.

Environmental Variables

Six major factors control the rate of cooling of an asphalt concrete layer and thus the viscosity of the asphalt cement. These factors are layer thickness, air temperature, base temperature, initial mix laydown temperature, wind velocity, and solar radiant flux.

Layer Thickness. Layer thickness is probably the single most important variable in the rate of cooling of asphalt concrete mixtures, especially for thinner courses. As the thickness of the layer being compacted increases, the time available for compaction increases. The time is not directly proportional, but rather geometrically proportional, to layer thickness—it takes considerably longer than a factor of 2 for a 4-inch-thick layer to cool to a minimum compaction temperature of 175°F than for a 2-inch-thick layer to cool to the same minimum temperature. For early spring and late fall paving, layers of mix less than 2 inches in compacted thickness are very susceptible to premature failure of the pavement owing to the inability of the compaction equipment to adequately densify the mix before it cools below the minimum compaction temperature. It should be noted that it is virtually impossible to obtain the desired density on thin lifts of mix in cool weather because of the rapid loss in temperature of the mix.

Air Temperature. A portion of the heat in the asphalt concrete layer is lost to the air. All other factors being equal, an increase in the ambient air temperature decreases the rate of cooling of the mix. This increase in air temperature allows more time for the compaction equipment to achieve the desired density level in the mix.

Base Temperature. Heat in the mix is also lost to the layer on which the new material is placed. There usually is more rapid cooling of the mix downward to the base than upward into the ambient air. Thus, base temperature is actually more important than air temperature in determining the time available for compaction.

It is often assumed that air and base temperature are the same. This is usually not true, particularly in cool weather. In early spring, the base temperature or surface temperature of an existing pavement layer will be lower than the ambient air temperature early

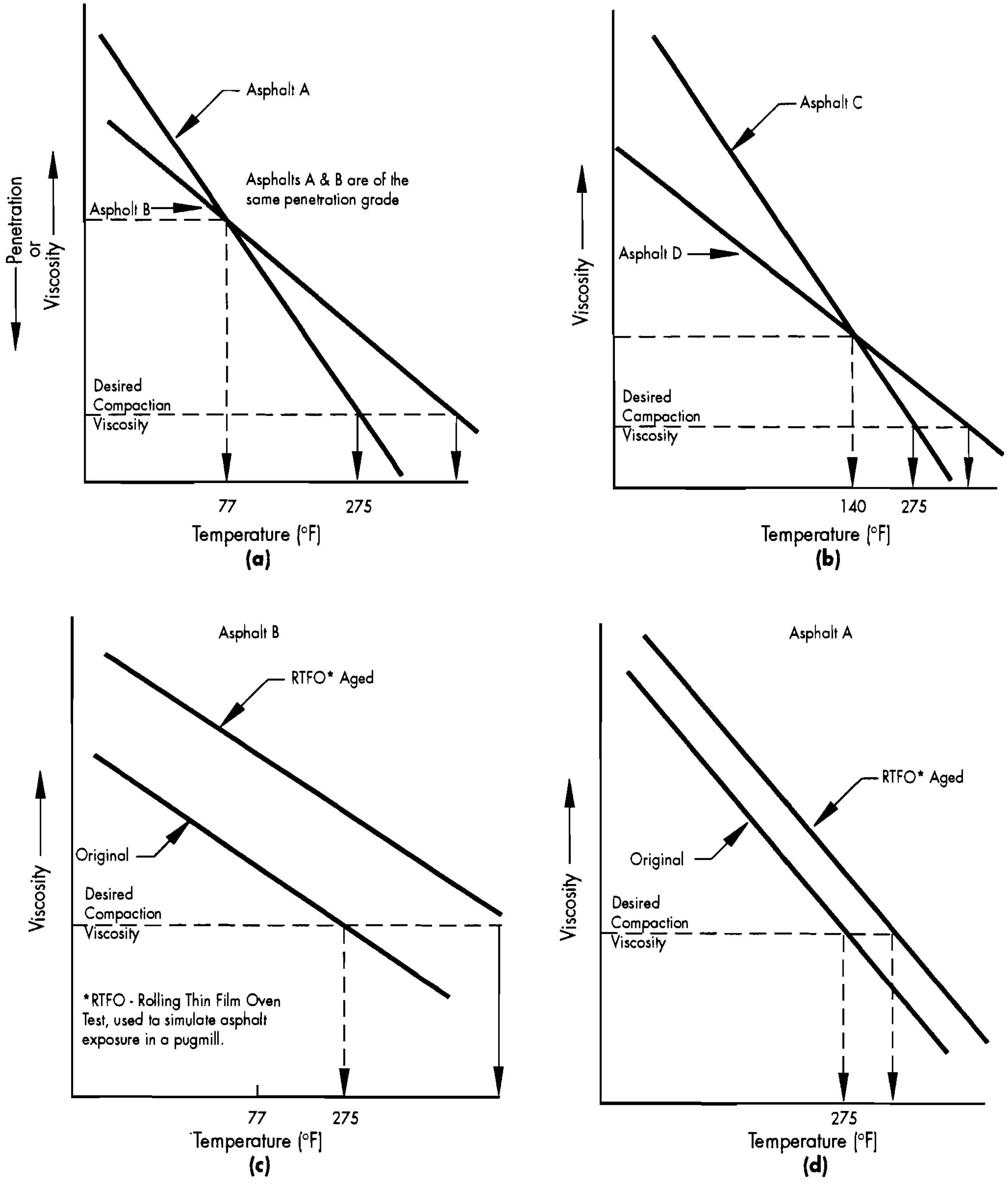


Figure 11 Temperature-viscosity relationship for asphalts (Ref 10)

in the morning. The air temperature may be "40°F and rising," but the base might be 5°F or 10°F below the air temperature. This low base temperature will cause the newly placed course to cool quickly, reducing significantly the time available to achieve adequate density. Base temperatures are often higher in the late fall than in the early spring for the same overnight air temperature. Thus less heat is lost to the base and more time is generally available to compact a given thickness of material in the fall compared with the spring.

A moist base layer significantly increases the cooling rate of the new overlying asphalt concrete layer. Heat is lost from the mix to the moisture, turning water into steam and increasing the rate of heat transfer. Paving on a wet or damp surface is extremely detrimental to the ability to gain proper density in the mix. The presence of the moisture causes the mix to cool too rapidly for the compaction equipment to obtain the proper air void content in the mix before it reaches 175°F.

Mix Laydown Temperature. Asphalt mixes are usually produced in asphalt plants at temperatures between 270°F and 325°F. Depending on environmental conditions and the length of haul, the mixture can lose between 5°F and 25°F from the plant to the paver. It is not the plant mixing temperature which is important in determining the time available for compaction, but the temperature at which the mix comes out from under the paver screed. As the initial mix laydown temperature is increased, the time available for compaction also increases. Within limits, the mixing temperature should be determined by the laydown temperature and the compaction requirements.

Wind Velocity. A thin layer of mix will cool more quickly in a strong wind than in little or no wind. Wind has a greater effect at the surface of the mix than within the mix and can cause the surface to cool so rapidly that a crust will form. This crust must be broken down by the rollers before the actual compaction process can begin. The velocity of the wind must be considered more for thin layers of mix placed in cool weather than for greater thicknesses of mix laid in warmer temperatures.

Solar Flux. The amount of radiant energy available from the sun (solar flux) is a function of many variables including the position of the sun, the elevation of the paving project, the amount of dust in the air, and the degree of cloud cover. A mix will cool more slowly on a sunny day than on a cloudy one. The amount of solar flux is more important with respect to its effect on base temperature than its effect on mix temperature. The base temperature will be higher on a sunny day, for a particular ambient air temperature, than it will be on a day with heavy cloud cover. This higher base temperature will reduce the rate of cooling of the mix and increase the time available for compaction.

Pavement Characteristics

A number of factors at the laydown site directly affect the ability of the compaction equipment to gain the required level of pavement density. The most important of these is the thickness of the layer being placed. As discussed previously, the thicker the lift, the more slowly the mix will cool down and the more time will be available for compaction. The retained heat of the thicker courses makes it easier to obtain the desired air void content.

The relationship between lift thickness and maximum aggregate size in the mix is another variable which affects the amount of density that can be obtained. If the course depth is at least twice the maximum aggregate size, adequate density can be achieved with normal compactive effort. When the lift thickness is less than two times the dimensions of the largest aggregate pieces, a rough surface texture results when the large aggregate pieces are dragged by the paver screed. The voids created in the mix from the dragged aggregate have a tendency to negate any efforts to obtain the proper level of density in the mix.

The uniformity of the lift thickness is another factor to be considered. It is much easier to compact an asphalt concrete layer that has a constant thickness than it is to compact a course that varies in depth. Asphalt concrete leveling courses which, by their very nature and purpose, are nonuniform in thickness, are very difficult to compact, especially when placed over an existing rutted roadway.

Static steel wheel rollers tend to bridge over the rut. Vibratory steel wheel rollers also tend to be supported by the high points in the surface, but the vibratory action has some beneficial effect on compacting the mix in the rut. Thus adequate density is usually not obtained throughout the mix, particularly in the rutted areas where it is needed the most. Use of a pneumatic tire roller will be helpful in achieving density in the low spots (ruts) as well as in the high spots on the pavement surface.

The initial density of the layer, as obtained by the screed on the paver, influences the amount of compactive effort that needs to be applied by the rollers. The slower the speed of the paver and the more compactive effort applied by the vibratory screed, the less rolling is needed behind the paver to gain the required degree of density.

Compaction Equipment

The equipment used to compact the asphalt mixture obviously has a significant effect on the density that can be obtained in a given number of passes. Three types of self-propelled compaction equipment are currently being used. They are static steel wheel rollers, pneumatic tire rollers, and vibratory steel wheel rollers.

Static Steel Wheel Rollers. Static steel wheel rollers normally range in weight from 3 to 14 tons and have compression drums that vary in diameter from approximately 40 inches to over 60 inches. The gross weight of the roller can usually be altered by adding ballast to the roller, but this adjustment cannot be made while the roller is operating and is not normally changed during the term of a paving project. For this type of roller, the gross weight of the machine and the contact area of the drums with the mix are both important in determining the compactive effort applied by the roller.

Effective weight or contact pressure, in terms of pounds per square inch of contact area, is the key variable for this type of equipment and is dependent on the depth of the penetration of the drums into the mix. As shown in Figure 12, the greater the depth of penetration, the greater the contact area and thus the less the contact pressure. This means that during the first pass of the roller, when the indentation of the drums into the mix is the greatest, the roller exerts less compactive effort than during subsequent passes when the mix is denser. Thus, as the mix becomes denser, the compaction drums penetrate the mix to a lesser degree and the compactive effort obtained by the roller is increased.

Drawbar pull is defined as the horizontal force required to move the roller forward. The most efficient roller is the machine with the smallest drawbar pull. Rollers with large-diameter drums have lower drawbar pull since they do not tend to penetrate as far into the mix as does a roller with smaller-diameter drums.

Once the size and weight of a static steel wheel roller is selected, the only variables under the control of the roller operator are the speed of the roller and the position of the roller on the mat in relation to the paver.

Pneumatic Tire Rollers. For pneumatic tire rollers, the compactive effort applied to the mix is a function of the total weight of the machine, the tire pressure, the tire design (tire size and ply rating), and the depth of penetration of the tires into the mix. The area of each tire footprint and the gross weight of the roller are the primary factors in judging the effectiveness of a rubber tire roller. The greater the contact pressure between the tire and the mix, the greater the compactive effort applied by the roller. As multiple passes are made with the pneumatic tire roller, the roller tends to "walk out" of the mix and the area of penetration of the tires into the mix becomes less. This increases the effective compactive effort of the rubber tires as the mix becomes more dense.

Tire pressures can normally be varied between 50 and 110 psi for most types of tires on these machines. If the mix is tender, a lower tire pressure will displace the mix less than will a higher pressure in the tires. For a stiff mix, a higher tire pressure can be used because the mix will be stable enough to support the weight of the roller without the mix shoving laterally under the tires. Tire pressure is normally kept constant for a particular project, but the level selected should be dependent on the properties of the mix being compacted and the position of the roller on the mat. The tire pressure should not necessarily be the same if the pneumatic tire roller is used in the breakdown position, compared with the intermediate position, in the roller train.

Some pneumatic tire rollers have the capability of changing tire pressure during the compaction process—the "air on the run" or centralized tire-inflation control system. In theory, this feature allows the roller operator to change tire pressures as the mix becomes more dense—using a low tire pressure for the initial passes of the roller and a higher tire pressure as the mix stiffness is increased (as the density of the mix becomes greater). In practice, however, this process is seldom used because the operator cannot develop a consistent rolling pattern and is not able to properly continue to adjust the tire pressure as the mix and environmental variables change throughout the day.

The tires on the pneumatic roller will often pick up the mix. This is particularly true when an oversanded surface course mix is being compacted. Many times attempts are made to eliminate this pickup problem by spraying water or a release agent on the tires during the rolling process. This does not always solve the problem. A better solution is to allow the tires on the roller to reach the same

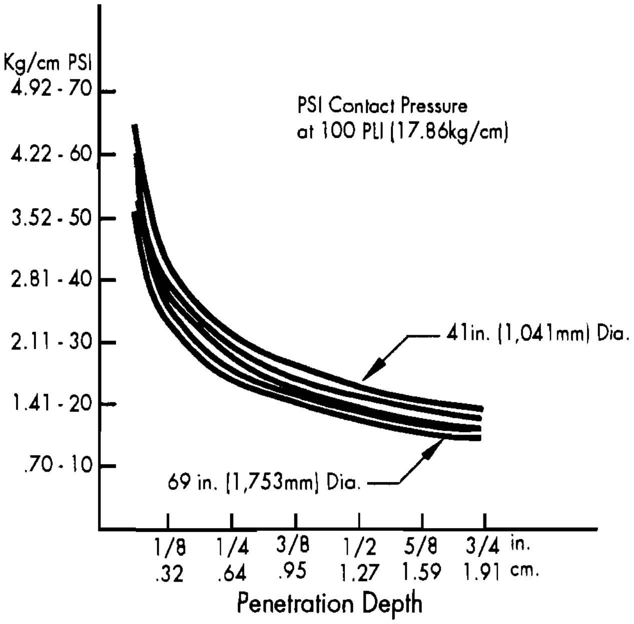


Figure 12 **Relationship between contact pressure and both drum diameter and penetration (Ref 11)**

temperature as the mix being compacted without adding water or release agent to the tires. When the pneumatic tires and the mix are at the same temperature, the amount of pick-up will be minimized or eliminated.

If this type of roller is to be used as the breakdown roller in the roller train at the start of paving in the morning, the roller should be operated for ten minutes or so, before the paver begins to lay mix, in order to start heating up the tires. Once paving commences, the rubber tire roller should be operated in the intermediate position, behind a static steel wheel roller or a vibratory roller, for another ten minutes while the temperature of the tires increases to the same level as that of the mix. During the heating process, some pick-up of the mix may occur with the tires. Once the tires have reached the same temperature as the mix, however, the pneumatic tire roller can be moved into the breakdown position and should be able to operate successfully without pick-up of the mix. If the paving process is interrupted for any significant length of time, this heating start-up procedure will have to be repeated.

Once the size of the pneumatic tire roller and the tire pressure are selected, the only variables which can be easily controlled by the operator are the rolling speed and the location of the roller with respect to the paver.

Vibratory Steel Wheel Rollers. Vibratory rollers come in a variety of configurations (Figure 13). Single-drum vibratory rollers are manufactured with both a rigid frame and an articulated frame. Double-drum vibratory rollers are produced in rigid frame, single articulated frame, and double articulated frame models. These rollers can be operated in any one of three modes—static (with the vibrators off), with one drum vibrating and one drum static, and with both drums vibrating.

These rollers thus have two types of compactive force that is applied to the asphalt concrete mix—static weight and dynamic (impact) force. The compactive effort derived from the static weight of

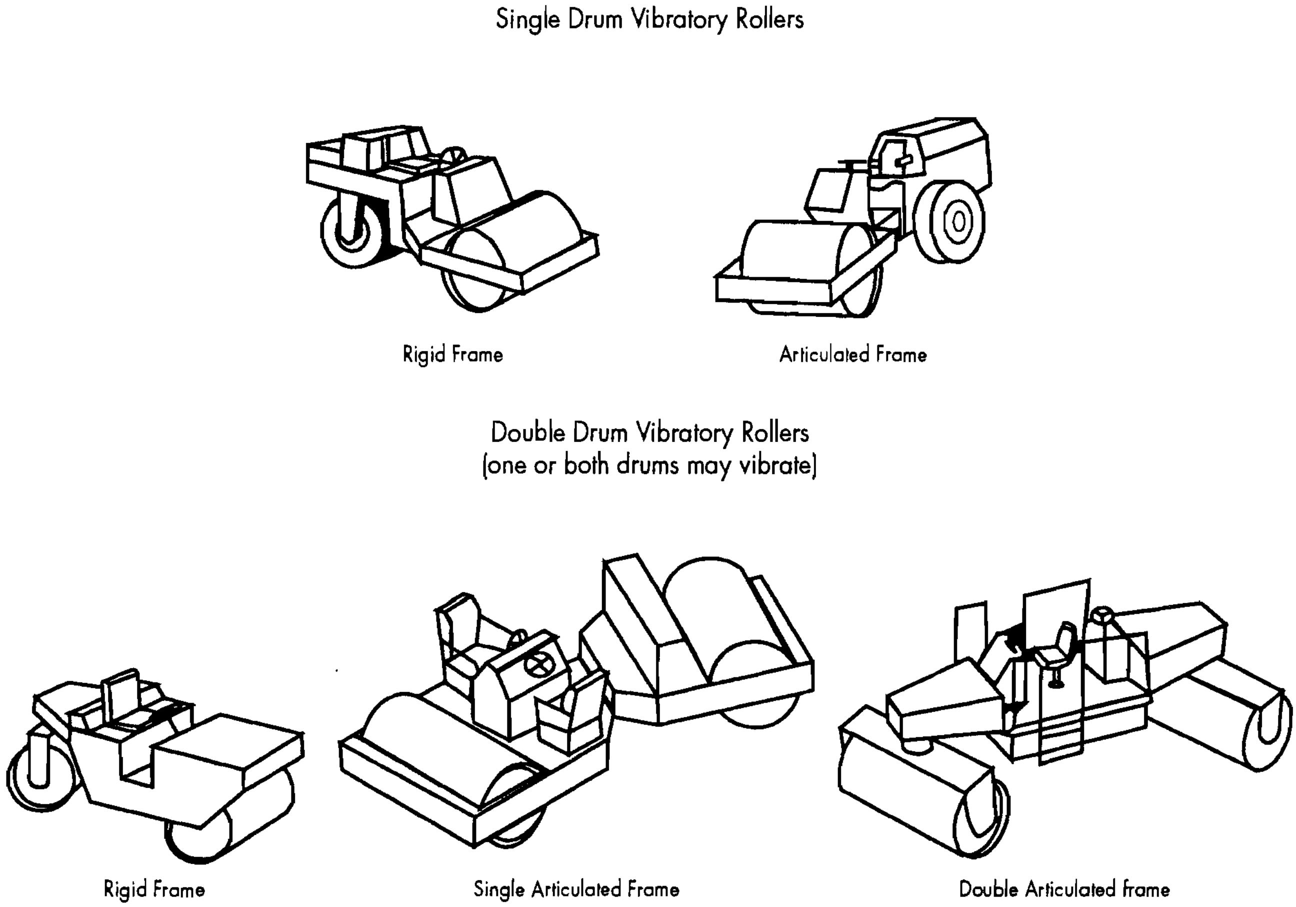


Figure 13 Representative vibratory roller types commonly encountered in asphalt mixture compaction (Ref 12)

the roller is due to the weight of the roller drums and frame. The "dry" weight of the roller can be increased through the use of ballast, usually water. The compactive effort derived from the impact force is produced by a rotating eccentric located inside the drum (or drums). As the eccentric rotates about the shaft inside the drum, a dynamic force is produced. This force is proportional to the mass of the eccentric, the square of the rotational velocity of the eccentrics, and the length of the eccentric radius, as shown in Figure 14. Increasing the radius of rotation increases the dynamic force applied by the drum to the pavement surface.

The total applied force is the sum of the static weight and the impact force. This total applied force is converted to unit force, which is the force per linear inch of drum at a given frequency. The unit force is determined by both the amplitude and the frequency of the vibration. The amplitude is one-half of the peak-to-peak distance that the drum moves vertically during a complete cycle of vibration, with the drum in a freely suspended condition. The amplitude is a function of the weight of the drum, the location of the eccentrics, and the resistance (density) of the material being compacted.

Normal values of amplitude range from 0.25 to 1.00 mm. Some of the older rollers can operate at only one fixed amplitude. Other rollers have only "high" and "low" amplitude positions. The more modern vibratory rollers are equipped with infinitely variable amplitude settings which can be easily changed by the operator. An increase in the applied amplitude of vibration increases the compactive effort applied to the asphalt concrete mixture.

The effectiveness of an increase in the amplitude value, however, is dependent on the thickness of the layer being densified. For layers less than 1-1/4 inches in compacted thickness, the vibratory roller should be operated in the static mode without vibration. This is due to the fact that the roller, on such thin layers, will bounce because of the stiffness of the underlying pavement courses and possibly decompact instead of compact the mix. As a rule of thumb, for layers 1-1/4 inches through 2 inches in compacted thickness, a "low" amplitude setting should be used on the vibratory roller. For lift thicknesses from 2-1/4 inches through 4 inches, the best compactive effort will normally be found when the amplitude is set in the "medium" position. For thick lifts of mix, over 4 inches in compacted thickness, the "high" amplitude setting should be used on the roller.

The frequency of vibration is the number of complete cycles that the eccentrics rotate per minute. The faster the rotation of the eccentrics, the greater the frequency of vibration. Some of the older vibratory rollers have a very limited selection of frequencies. For most newer vibratory rollers, the range of frequencies is between 1,600 and 3,000 vibrations per minute.

The spacing of the impacts of the applied force is a function of the frequency of the vibration and the travel speed of the roller. A decrease in the frequency of vibration and an increase in the roller

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 x r, in - lb
Centrifugal Force = $W \times r \times 4 \times \pi^2 \times n^2$, lb

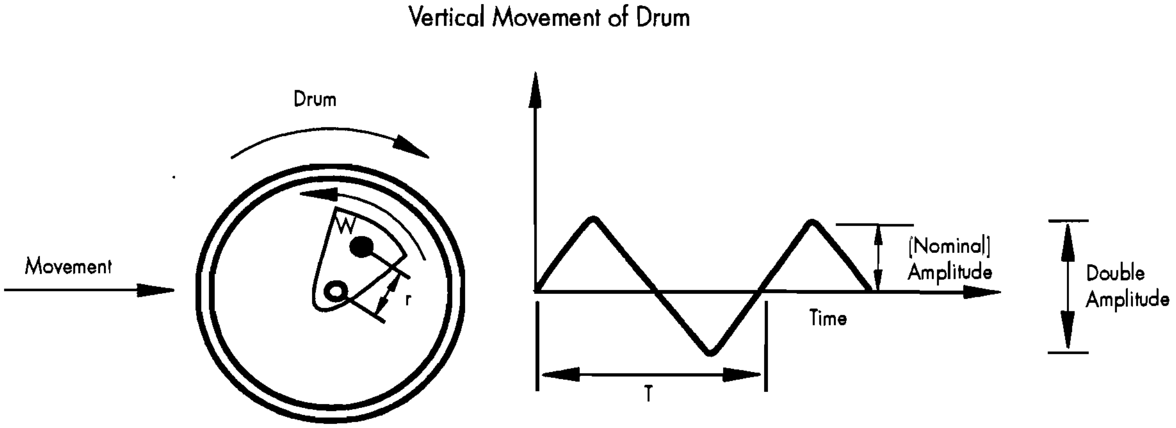


Figure 14 Mechanics of the rotating eccentric (Ref 10)

speed both serve to increase the distance between impacts on the surface of the mix (Figures 15 and 16). Conversely, an increase in the vibratory frequency and a decrease in the roller speed both cause the number of impacts per foot of distance to increase, thereby increasing the compactive effort applied by the roller. A small impact spacing—a greater number of impacts per foot—is thus preferred.

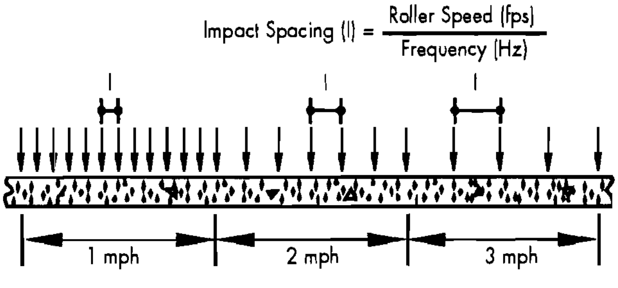


Figure 15 **Effect of roller speed on impact spacing (Ref 10)**

The ideal impact spacing is in the range of 8 to 10 impacts per foot. This spacing can be determined by dividing the roller speed by the frequency of vibration:

$$\text{Impact spacing} = \frac{\text{Roller speed (fps)}}{\text{frequency (Hz)}}$$

In general, the vibratory roller should be operated at the highest frequency possible for the conditions, rather than at a low frequency. This increases the number of impacts per foot and the compactive effort. Thus, depending on the compactor, the frequency of vibration will normally be 2,400 to 3,000 vibrations per minute.

The roller operator is in control of more variables when using a vibratory roller. In addition to roller speed and location on the layer being compacted, both the amplitude and the frequency of the vibratory impact can be varied. This allows the operator to determine, to a greater degree, the compactive effort applied to the mix, and it makes the vibratory roller more versatile than either the static steel wheel or the pneumatic tire rollers.

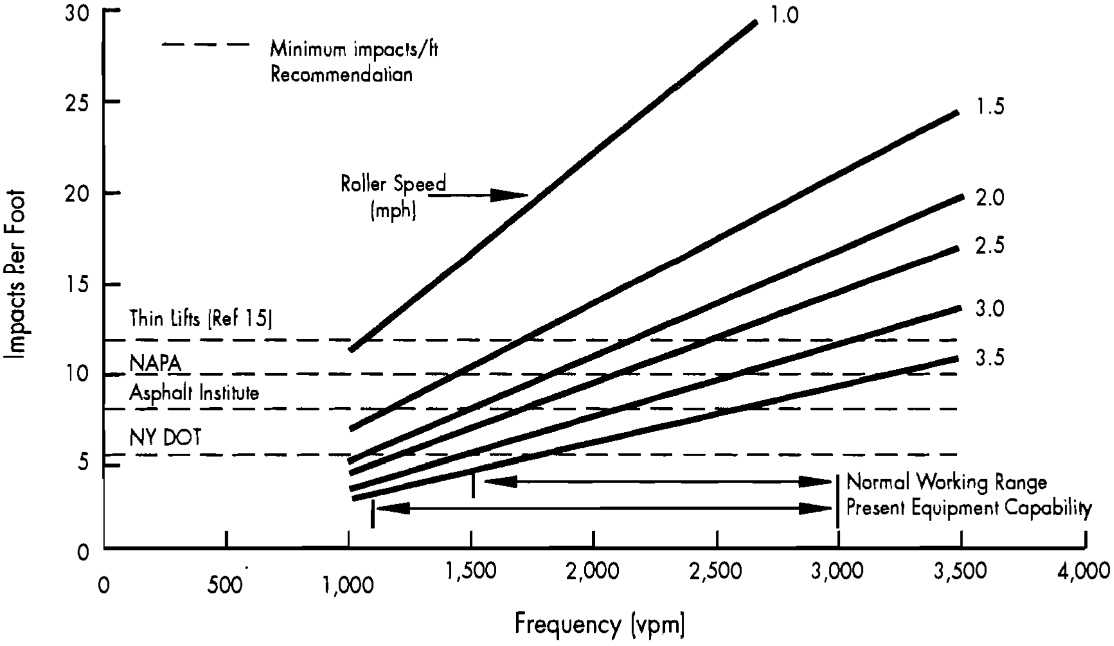


Figure 16 **Relationship between impact spacing, roller speed, and frequency (Ref 10)**

CHAPTER 3. OPERATIONAL GUIDELINES FOR COMPACTION

The successful compaction of the final product is the result of pavement structure design, proper material selection, mixture design, plant operation, and placement operations. The guidelines set forth in this chapter are intended for the actual placement operations.

Time Available for Compaction

The time available for compaction is defined as the time, in minutes, it takes for a mix to cool from laydown temperature to a minimum compaction temperature, normally 175°F. Below this temperature, internal friction and cohesion of the mix increase to the point that little density gain is achieved with the application of additional compactive effort. In fact, additional rolling, except to remove roller marks, normally results in fracture of the aggregate in the mix as well as in a decrease in density. Laydown temperature is the mix temperature when the mix passes out from under the paver screed.

The six variables previously discussed have the greatest effect on the rate of cooling of a layer of asphalt concrete. Those variables are: layer thickness, air temperature, base temperature, initial mix temperature, wind velocity, and solar flux.

Cooling Curves

Dickson and Corlew published a series of "cooling curves" for asphalt concrete mixtures (Ref 13). These graphs, shown in Figures 17a and 17b (page 16), illustrate the amount of time available for compaction under different combinations of variables. For these two figures, it is assumed that the material being compacted is a dense-graded asphalt concrete mix. Ambient air temperature is assumed to be equal to the surface temperature of the base. A constant wind velocity of 10 knots (about 11.1 miles per hour) and a constant degree of solar radiation (solar flux of 50 BTU per square foot per hour) are also used to generate the graphs. The curves then provide the time, in minutes, for the mix to cool from the laydown temperature to the minimum compaction temperature of 175°F for different compacted layer thicknesses.

To use the graphs, it is necessary to determine the value of three different variables—initial mix laydown temperature, base surface temperature (which is assumed to be equal to the ambient air temperature), and compacted layer thickness. Figure 17a is to be used for mix laydown temperatures of both 250°F and 300°F. Figure 17b is to be used when the mix laydown temperature is 225°F or 275°F. The range of base temperatures for each set of curves is from 10°F to 60°F. The range of mix layer thicknesses is from 1/2 inch to 6 inches.

Effect of Layer Thickness. As the thickness of the layer being placed increases, the time available for compaction also increases. For example, based on Figure 17a, for a mix laydown temperature of 250°F and a base of 40°F, a 1-inch-thick mat will cool from the 250°F temperature to the 175°F compaction cutoff point in less than 4 minutes. For a 2-inch-thick layer, under the same mix and base temperature conditions, it will take about 10 minutes for the material to cool to 175°F. Doubling the lift thickness from 1 to 2 inches increases the time available for compaction from 4 to 10 minutes. If the layer depth is 4 inches, the time to cool changes to about 29 minutes, a significant increase in available compaction time under similar temperature conditions.

Using the same figure, the relative effect of pavement lift thickness is the same for a mix laydown temperature of 300°F and a base temperature of 40°F. As the course depth is decreased from 4 inches to 2 inches to 1 inch, the time available for the mix to cool from 300°F to 175°F decreases from over 40 minutes, to 16 minutes, to only 6 minutes, respectively. From these data, it is apparent that the time available to compact a thin layer of asphalt concrete is extremely limited.

Effect of Base/Air Temperature. As the temperature of the ambient air and existing pavement surface increases, the time for the mix to cool from the laydown temperature to 175°F also increases. Figure 17b shows that, for a mix of 275°F and a lift thickness of 3 inches, it takes only 22 minutes for the mix to cool when the base and air temperatures are both

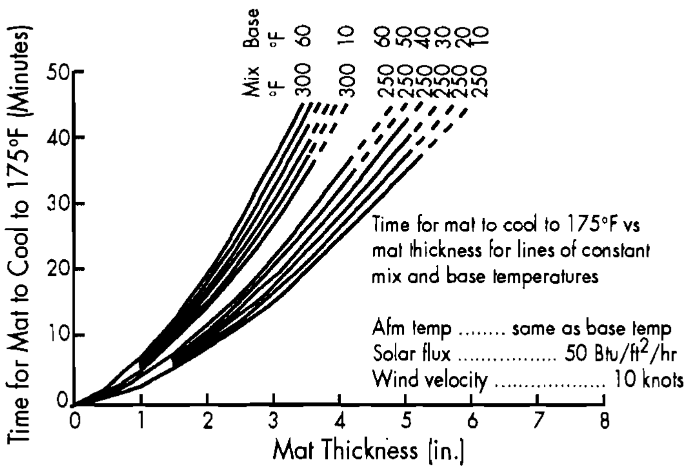


Figure 17a **Time for mat to cool to 175°F versus mat thickness for lines of constant mix and base temperature (Ref 13)**

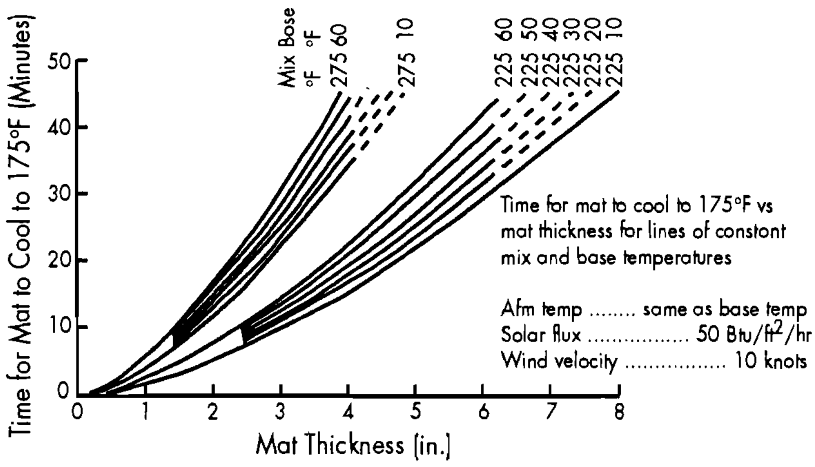


Figure 17b **Time for mat to cool to 175°F versus mat thickness for lines of constant mix and base temperature (Ref 13)**

20°F. The time available is extended to 27 minutes for a base/air temperature of 40°F and to 30 minutes for a 60°F base/air temperature.

For a 2-inch lift thickness, using the same mix laydown temperature of 275°F (Figure 17b), the time to cool to 175°F increases from 11 minutes to 13 minutes, and to 15 minutes for a base/air temperature of 20°F, 40°F, and 60°F, respectively. The temperatures of the ambient air and base surface are important, but not nearly so crucial as mat lift thickness in determining the time available for compaction.

Effect of Laydown Temperature. As the temperature of the asphalt concrete being placed is increased, the time available for compaction is increased, as shown in Figure 17a, for laydown temperatures of both 250°F and 300°F. For a lift thickness of 2 inches and a base/air temperature of 40°F, the time to cool to 175°F increases from 9 minutes to 16 minutes as the placement temperature increases from 250°F to 300°F. For a 3-inch course thickness and a 60°F base/air temperature, a change in laydown temperature from 300°F to 250°F reduces the time available for compaction from 38 minutes to 22 minutes.

The effect of mat laydown temperature is more significant for thin mats and lower base temperatures. As the time to cool to 175°F becomes shorter, an increase in the mix laydown temperature normally increased the available compaction time significantly.

Obtaining Density. Compaction of the mix requires common sense. As lift thickness decreases, air and base surface temperatures are both reduced, laydown temperature is less, amount of solar flux is decreased, or wind velocity is increased, and the time available to properly obtain the required level of density before the mix cools to 175°F also decreases. A significant change in any one of the above factors can make the difference between constructing a durable pavement structure or building an early pavement failure.

Perhaps the best solution to a potential compaction problem is to increase the thickness of the material being placed. One-inch-thick layers cool so quickly, even in good environmental conditions, that proper density is almost impossible to obtain. Of particular importance is the fact that these thin mats must achieve an adequate density to perform adequately. Thus, it is recommended that thin mats not be placed because of the difficulty in achieving density and because they offer little in the way of structural improvements. The minimum course thickness that should be specified under the best of circumstances should be 1-1/2 inches. For early-spring or late-fall paving projects, at least 2 inches of compacted asphalt concrete mix should be placed in a single lift.

The easiest solution to a potential time availability problem is to increase the discharge temperature of the asphalt concrete mix at the plant. This will permit an increase in the laydown temperature of the mix behind the paver screed, thereby allowing more time for the mix to cool to 175°F, all other factors being constant. Increasing the mix temperature may not be enough, however, to provide adequate time for compaction under adverse environmental conditions and for thin layers of material.

Another means to achieve proper density levels is to use the compaction equipment more effectively. The rollers can be placed side by side instead of end to end. Two rollers running in echelon can cover a given area much more quickly than two rollers operating in the conventional fashion, i.e., end-to-end compaction train. The level of density obtained will be increased because more compactive effort will be applied before the asphalt concrete mat cools to 175°F. In essence, the suggested method provides for two breakdown rollers instead of one breakdown roller and one intermediate roller.

Compaction Variables

The primary compaction variables for all types of rollers that can be controlled during the rolling process are: roller speed, number of roller passes, rolling zone, and roller pattern. In addition, for vibratory rollers, the vibration frequency, vibration amplitude, and direction of travel are also under the control of the operator. Each of these factors has an effect on the level of density achieved under the compactive effort applied to the mix.

Roller Speed

The faster a roller passes over a particular point in the new asphalt surface, the less time the weight of the roller "dwells" on that point. This in turn means that less compactive effort is applied to the mixture. As roller speed increases, the density achieved with each roller pass decreases.

Typically 2.5-3.0 miles per hour (220 feet per minute) is the maximum speed that a roller should travel. Rollers can move faster or slower than this value but compaction varies directly with roller speed. Roller speed will also be governed by the lateral displacement or tenderness of the asphalt concrete mix. If the mixture moves excessively under the rollers, the speed of the compaction equipment should be reduced. In addition, for vibratory compactors, roller speed also affects the impact spacing, as shown in Figures 15 and 16. As previously discussed, this spacing controls the dynamic compaction energy applied to the mix and also the resulting surface smoothness.

Unfortunately, roller speed is usually established by the speed of the paver—if the paver pulls away from the rollers, the roller speed is increased in order to catch up. This causes the density developed in the asphalt mixture to decrease for the same number of roller passes. If the paver continually pulls ahead of the rollers, several courses of action can be taken. First, paver speed can be reduced to match both plant production and roller production. Too often, the paver is operated on a "hurry and wait" basis between truckloads. If plant production capacity necessitates higher paver speeds, additional rollers will be required to achieve adequate density. Wider rollers can be employed; for example, a 7-foot-wide vibratory roller can be used in place of a 4-1/2-foot-wide tandem roller. The type of roller used can also be changed—a double-drum vibratory roller employed in lieu of a single-drum vibratory roller.

Varying the speed of the compaction equipment merely causes variations in density. "Slow and steady" is the key to proper compaction.

Number of Roller Passes

To gain the target air void content in an asphalt mixture, it is necessary to roll over each point in the pavement mat a certain number of times. The actual number of passes depends on many variables. The type of compaction equipment is one very important consideration. Three-wheel steel rollers, tandem steel wheel rollers, pneumatic tire rollers, and single- or double-drum vibratory rollers have different compaction capabilities.

The capabilities of each type of roller, however, vary with mat thickness, mix temperature, mix design (asphalt content and aggregate characteristics), and environmental conditions. In addition, the number of passes required depends on the position of the rollers in the roller train. It may be possible, for example, to obtain an increase in density when a large pneumatic tire roller is switched to the breakdown roller position from the intermediate roller position.

To determine the minimum number of roller passes needed to achieve proper density levels, a test strip should be constructed at the start of any major paving project. A number of different combinations of rollers and roller patterns should be tried to determine the "optimum" combination of compactive efforts to achieve the required density level as efficiently as possible. Rarely will the first-tried combination of rollers, roller passes, and rolling zones provide the most economical rolling sequence.

Roller passes must be distributed uniformly over the width and length of the mat. All too often, the center of the paver lane (the area between wheelpaths of a single lane pavement) receives adequate roller coverage while the edges of the mat receive considerably less compactive effort. As discussed further under the section on roller patterns, the uniformity of roller passes is just as important as the number of passes.

Rolling Zone

Compaction must be achieved while the viscosity of the asphalt cement in the mix is low enough to allow for reorientation of the aggregate particles under the action of the rollers. In other words, the mat must still be hot enough to achieve the proper level of air voids (175°F minimum).

To reach the required density level, initial compaction should occur directly behind the laydown machine. If the stability of the asphalt concrete mixture is high enough, breakdown rolling can be achieved very close to the paver, while the mat temperature is still high. More density is obtained with one pass when the mix temperature is 250°F than with a similar pass when the mat is at 220°F. Thus, the rolling zone—the distance the breakdown roller operates behind the paver—should be as short as possible.

Many times a tender mix is placed. Because of the lack of stability in the mix, the initial rolling is often delayed to avoid excessive shoving of the mix by the rollers. This is a poor and incorrect solution to the problem. A mix that cannot be compacted directly behind the paver needs to be redesigned. The rolling zone should not be arbitrarily lengthened. When a tender mix is encountered, the mix design, not the compaction process, should be changed.

Roller Patterns

Rollers are "busy" most of the time on a paving project. The question is whether they operate correctly and effectively. Generally, compaction is applied, but not necessarily in the right place. Numerous compaction studies have shown that the middle of the width of the paver pass typically receives more compactive effort than the edges of the pavement. This is unfortunate because traffic uses the wheelpath areas and travels near the edge of the pavement more often than in the center of the lane.

If an adequate number of roller passes are provided on each edge of the lane being compacted, the density level in the center of the lane will always be more than enough to meet specifications. Thus, roller patterns should be structured to assure proper compaction of the outside portion of each paver pass—the center will take care of itself.

For each roller employed on a project, the mat width can be divided by the width of the compaction drums to determine the number of passes needed to cover each transverse point in the surface. A tandem roller, 4-1/2 feet wide, would need to make at least three passes over a 12-foot-wide mat. A 5-1/2-foot-wide vibratory roller would also have to travel three times up or back to get full width coverage. A 7-foot-wide pneumatic tire roller would need only two passes over a 12-foot-wide lane to gain complete coverage of the pavement surface. A 6-1/2-foot-wide three-wheel roller would also need two passes to get full width coverage.

In a longitudinal direction, the rollers should not stop at the same transverse end point with each pass of the roller. The reversal points should be staggered to prevent shoving of the mix. A slight change in direction, or curl, is needed at each reversal spot to further reduce the tendency of the mix to shove under the compactor and to eliminate the possibility of a bump at the point where the roller reversal occurs. The roller should not sit and wait while parked on the hot mat. A long delay, owing to lack of haul trucks at the paver or to filling the compactor with water, allows the roller to indent the new mat.

It is generally impossible to later roll out these marks once the mat has cooled.

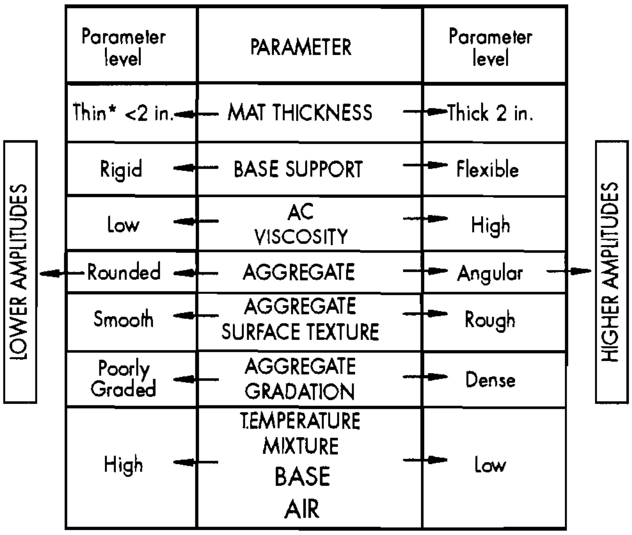
Vibration Frequency

Vibratory rollers have two major variables that must be controlled during the compaction process. The first is the frequency of the vibration. Most vibratory rollers have a range of frequencies available to the operator. With very few exceptions, the maximum frequency setting available should be used. This procedure allows for more compaction to be exerted by a given roller. Rarely should vibratory rollers be operated at frequency settings under 2,000 vpm.

Speed, in combination with frequency, plays a significant part in the effectiveness of a vibratory roller. As shown in Figure 15, an increase in roller speed from one to three miles per hour significantly decreases the number of impacts per foot. The more impacts per foot—the slower the roller speed at a given vibration frequency—the greater the density increase achieved per pass.

Vibration Amplitude

Regardless of project conditions, many vibratory rollers that have the capability to change amplitude settings are operated at a constant amplitude setting. Use of the proper amplitude setting is important in obtaining the required density level as quickly and efficiently as possible (Figure 18). Basically, the chosen amplitude depends on the asphalt mix characteristics and on the mat thickness. Greater compactive effort, or a greater amplitude setting, is needed when (1) the asphalt cement used in the mix is of higher viscosity or lower penetration, (2) an angular or crushed aggregate is used in the mix, (3) a coarse aggregate gradation is used rather than a fine grading, (4) a larger top size coarse aggregate is used in the mix, and (5) a stiffer mix is placed (one containing a higher mineral filler content).



Parameter level	PARAMETER	Parameter level
Thin* <2 in.	MAT THICKNESS	Thick 2 in.
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.

Figure 18 **Guidelines for selecting the amplitude of vibration (Ref 10)**

The amplitude setting is primarily a function of layer thickness and material behavior, however. In general, thick lifts require a greater amplitude than thin lifts. A high amplitude setting on a thin lift (more than 1-1/4 inches and less than 2 inches) will typically cause the vibratory roller drum to bounce, making it difficult to obtain the desired air void content level. Vibration can be used on lifts with thicknesses over 1-1/4 inches, providing the roller operator limits the number of vibratory passes and maintains a consistent roller pattern. Vibratory compaction should not be used on very thin lifts (less than 1-1/4 inches).

Direction of Travel and Mode of Operation

When using a single-drum rigid frame roller, the vibratory drum should normally be operated toward the paver with the tiller wheels trailing. This assures that the maximum compactive effort of the vibratory drum is placed on the mat before the lesser compactive effort of the steering wheels. In addition, it provides a denser layer to better resist displacement of the mix caused by the continual movement of the tiller wheels during the steering action. A single-drum articulated frame roller should also be operated with the drive drum toward the laydown machine. Again, this assures that the maximum compactive effort is applied to the mix as quickly as possible.

When only one drum is operated in vibration, double-drum rigid frame rollers should normally be operated with the vibrated drum toward the laydown machine and with the tiller drum trailing. Double-drum articulated frame rollers operate in the same fashion in either direction—thus the direction of travel is not a consideration for this type of roller.

For harsh or stiff mixtures, breakdown rolling is normally accomplished with both drums vibrating. Subsequent compaction passes are also made in the full vibratory mode. For mixtures with normal stability, breakdown rolling with a vibratory roller should be accomplished in the full vibratory mode or in a combination mode. The full vibratory mode is more efficient in terms of compactive effort, however, than is the combination mode. 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 instead of the front drum is usually vibrated.

Determination of the Rolling Pattern

Choice of Compaction Equipment

The actual rolling pattern to be used to compact the mix on a paving project should be determined at the start of the project through the construction of a roller test strip. This strip should be located at a convenient point where the pavement layer placed will remain as part of the final pavement structure. The mix and the thickness of the layer compacted should be the same as that to be used for the rest of that particular layer. The length of the test strip should be at least 300 feet. The condition of the underlying layers should be representative of that on the rest of the project.

Due consideration should be given to the selection of rollers that are to be employed to densify the pavement layer. The combination of rollers used on a previous project might not be the most cost-efficient or effective for the variables involved in the present job. Although vibratory rollers are usually used for breakdown rolling and pneumatic tire rollers for intermediate rolling, a greater degree of density with a fewer number of total roller passes is often obtained when the pneumatic tire roller is used in the breakdown position with the vibratory roller following in the intermediate position. Determination of the "optimum" combination of rollers and roller patterns might require the construction of two or more test sections.

Desired density levels are easier to obtain when the asphalt concrete mix is hot. Instead of using the rollers in the traditional roller "train" concept, consideration should be given to using two breakdown rollers instead of a breakdown roller followed by an intermediate roller. Two 7-foot-wide rollers, operating adjacent to each other, provide more efficient compaction of a 12-foot-wide pavement lane than do the same two rollers operating end to end in normal fashion. This will be particularly true in unfavorable environmental conditions.

Rolling Pattern

The first calculation that is needed concerns the amount of mix to be produced by the plant, the width of the pavement lane, and the depth of the mix. Once the typical speed of the paver is known, the maximum speed of the rollers should be selected. Except under unusual circumstances, that maximum speed should be no more than 2.5 miles per hour.

The next calculation that must be made concerns a comparison of the width of the layer being placed and the width of the rollers to be used, in order to determine the number of transverse passes of each roller needed to cover the whole width of the pavement. With the paver speed, the roller speed, and the number of transverse passes needed to obtain full width coverage of the roadway surface, the number of passes that each roller can place over each point in the pavement and still keep up with the paver can be determined. Typically each roller should be able to make two or three passes over the whole lane width before it moves on to another section of pavement to repeat the rolling pattern.

For most asphalt concrete mixes, approximately four to six breakdown and intermediate roller passes over each location on the pavement surface are necessary to obtain adequate density levels (not counting the passes of the finish roller used to take out roller marks). Thus, depending on the speed of the paver, it will normally take two rollers (plus the finish roller) to apply the necessary compactive effort to the mix. In warm weather and thick layer of mix, fewer rollers may be needed. In cool weather and for thin lifts, additional compaction equipment may be required in order to obtain the specified density.

The most common method for monitoring changes in density with roller passes is the use of a nuclear density gauge. Density is estimated by transmitting gamma rays into the mix and measuring the amount of radiation reflected back to the device in a given amount of time. The count data that is obtained can be related to the relative density of the layer. Nuclear gauge readings should be taken after each pass of each roller and the rate of increase in density after each pass determined. When no appreciable increase in density is obtained with the application of additional roller passes, the maximum relative density for that mix has been obtained.

The maximum density determined with the nuclear gauge is only relative, however; it is the most that can be obtained at that time, under those environmental conditions, and with the combination of rollers used. The maximum relative density may not be adequate to meet project specifications. Cores must be cut from the test section after the rolling process is complete to determine the unit weight of the compacted mix, and that weight must be compared with the maximum theoretical unit weight of the mix in order to calculate the actual air void content of the layer.

If the proposed test section rolling pattern does not achieve the required density, as measured by the cores, changes to the pattern should be effected. An initial adjustment might be to reduce the speed of the rollers. A pneumatic tire roller instead of a vibratory roller might be used in the breakdown position. The frequency of vibration and the applied amplitude from a vibratory roller might be increased. The air pressure in the tires of a pneumatic tire roller might be increased. The first two rollers might be run in echelon instead of end to end as in a normal roller train. If none of these changes can increase the density of the mix enough and still permit the rollers to keep up with the production requirements of the paver, additional rollers should be used to obtain the proper density levels.

Roller Operating Techniques

In order to properly densify an asphalt concrete layer, the rollers should be used efficiently to compact the mix while it is still above the minimum compaction temperature. The factors that should be observed when monitoring the compaction process are:

1. The time available for compaction is primarily related to the thickness of the layer being placed. An increase in lift thickness can substantially increase the time available for the roller to densify the mix.
2. An increase in the laydown temperature of the mix behind the paver can significantly increase the amount of time available for compaction.
3. A decrease in the speed of the rollers will increase the compactive effort applied to the mix.
4. The breakdown roller and intermediate roller should be operated as close to the paver as possible in order to obtain density before the mix cools to a minimum temperature of 175°F.
5. If the mix cannot support the weight of the compaction equipment, the mix should be redesigned.
6. The roller pattern should be monitored to assure that the compaction equipment is applying the same amount of compactive effort at all points transversely across the lane being paved.
7. The speed of the compaction equipment should not exceed 3.5 miles per hour and should ideally be less than 2.5 miles per hour.
8. A vibratory roller should be operated at the maximum possible vibratory frequency in order to increase the number of impacts per foot. At least 8 to 10 impacts per foot are needed to obtain adequate density and layer smoothness.
9. The amplitude setting on the vibratory roller should be determined by the characteristics of the mix and by the thickness of the layer being compacted. In general, vibratory rollers should be operated in the static mode when the compacted lift thickness is less than 1-1/4 inches. For layers from 1-1/4 inches to 2 inches in thickness, a low amplitude setting should be used. For layers more than 2 inches thick, the amplitude should be increased in proportion to the increase in compacted thickness of the layer.
10. The optimum combination of rollers and roller patterns for a past project may not be the same optimum combination for a current project or even for a different type or layer of mix on the same project. Test sections should be constructed to determine the most efficient and most effective combination of compaction equipment and roller patterns to use for each combination of job variables.
11. Two rollers run side by side (in echelon) will typically produce a greater level of density in the mix, with the same number of roller passes, than will the same two rollers operated end to end (in the roller train concept).
12. If the rollers cannot keep up with the speed of the paver, more rollers should be used.

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