NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
SYNTHESIS OF HIGHWAY PRACTICE 152

COMPACTION OF ASPHALT PAVEMENT

TRANSPORTATION RESEARCH BOARD
National Research Council

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CHARLES S. HUGHES
Virginia Transportation Research Council

Topic Panel

MAX ALEXANDER, *California Department of Transportation*
DAVID A. ANDERSON, *Pennsylvania State University*
JOHN J. CARROLL, *Federal Highway Administration*
CHARLES CHURILLA, *Federal Highway Administration*
JOHN A. D'ANGELO, *Federal Highway Administration*
WILLIAM G. GUNDERMAN, *Transportation Research Board*
JAMES A. SCHEROCMAN, *Consultant*

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TRANSPORTATION RESEARCH BOARD
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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

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The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the National Research Council and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Research Council and its Transportation Research Board.

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PREFACE

A vast storehouse of information exists on nearly every subject of concern to highway administrators and engineers. Much of this information has resulted from both research and the successful application of solutions to the problems faced by practitioners in their daily work. Because previously there has been no systematic means for compiling such useful information and making it available to the entire highway community, the American Association of State Highway and Transportation Officials has, through the mechanism of the National Cooperative Highway Research Program, authorized the Transportation Research Board to undertake a continuing project to search out and synthesize useful knowledge from all available sources and to prepare documented reports on current practices in the subject areas of concern.

This synthesis series reports on various practices, making specific recommendations where appropriate but without the detailed directions usually found in handbooks or design manuals. Nonetheless, these documents can serve similar purposes, for each is a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems. The extent to which these reports are useful will be tempered by the user's knowledge and experience in the particular problem area.

FOREWORD

By Staff
Transportation Research Board

This synthesis will be of interest to construction and materials engineers, paving contractors, equipment manufacturers, and others who are involved in assessing the performance of asphalt pavements. Information is presented on various issues related to compaction of asphalt pavements.

Administrators, engineers, and researchers are continually faced with highway problems on which much information exists, either in the form of reports or in terms of undocumented experience and practice. Unfortunately, this information often is scattered and unevaluated, and, as a consequence, in seeking solutions, full information on what has been learned about a problem frequently is not assembled. Costly research findings may go unused, valuable experience may be overlooked, and full consideration may not be given to available practices for solving or alleviating the problem. In an effort to correct this situation, a continuing NCHRP project, carried out by the Transportation Research Board as the research agency, has the objective of reporting on common highway problems and synthesizing available information. The synthesis reports from this endeavor constitute an NCHRP publication series in which various forms of relevant information are assembled into single, concise documents pertaining to specific highway problems or sets of closely related problems.

Compaction is one of the most important factors affecting the performance of asphalt pavements. This report of the Transportation Research Board describes the theory, methods, equipment, and specifications related to the compaction of asphalt pavements. A brief history of, the importance of, and factors affecting compaction are also discussed. Construction influences, density measurements, and trends are also considered.

To develop this synthesis in a comprehensive manner and to ensure inclusion of significant knowledge, the Board analyzed available information assembled from numerous sources, including a large number of state highway and transportation departments. A topic panel of experts in the subject area was established to guide the researcher in organizing and evaluating the collected data, and to review the final synthesis report.

This synthesis is an immediately useful document that records practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As the processes of advancement continue, new knowledge can be expected to be added to that now at hand.

CONTENTS

ACKNOWLEDGMENTS

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Special appreciation is expressed to Charles S. Hughes, Senior Research Scientist, Virginia Transportation Research Council, who was responsible for the collection of the data and the preparation of the report.

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William G. Gunderman, Engineer of Materials and Construction, Transportation Research Board, assisted the NCHRP Project 20-5 Staff and the Topic Panel.

Information on current practice was provided by many highway and transportation agencies. Their cooperation and assistance were most helpful.

COMPACTION OF ASPHALT PAVEMENT

SUMMARY

The performance of structurally adequate asphalt pavements is affected by two primary factors: a properly designed mix and compaction. Neither of these factors alone can assure satisfactory pavement life. Even the best-designed mix will be subject to reduced performance if not compacted sufficiently. Good compaction, however, can effectively improve the performance of a mix that is less than ideal. For this reason, compaction is considered to be the single most important factor affecting the performance of asphalt pavements. In this synthesis, variations in asphalt content and aggregate grading are discussed, along with the many other factors that affect compaction of the pavement.

may need new GYRATORY

Reducing air voids to an acceptable level during construction improves the strength, durability, resistance to deformation, resistance to moisture damage, and impermeability of the mix. The ability to reduce air voids to an acceptable level is influenced by the individual constituents of asphalt cement and aggregate, but even more by the selection of the optimum asphalt content chosen based on a uniform gradation of aggregate through a well-defined, rational mix design procedure. The inability to achieve the target air voids in the field is often caused by the lack of a rational mix design or materials that no longer meet the job mix formula for which the mix was designed. The compactive effort used to design the mix should be based on the level of traffic to which the mix will be subjected.

Tapered Joints

The move from method to end-result specifications is continuing at the present time. More than half of the state highway departments use an end-result specification for accepting density and of these most are using statistically based limits. Reducing air voids to an acceptable level in the vicinity of the longitudinal joint to prevent early deterioration is important and an area in asphalt construction that is often overlooked.

Vibratory rollers used in the breakdown roller position continue to be popular. However, with these rollers, coordination of frequency, amplitude, and speed is mandatory to achieve effective compaction and acceptable smoothness. There is some reemergence of the practice of using three-wheel rollers for breakdown rolling. Also regaining popularity is the use of pneumatic rollers for intermediate rolling to help ameliorate rutting, which is exacerbated by high-pressure truck tires.

The thermal environment of the asphalt layer plays an important role in the time available for obtaining the proper level of density. In cool weather the base temperature, laydown temperature, and lift thickness should be coordinated to determine that sufficient time is available to complete rolling before the layer reaches 175°F.

Nuclear gauges are often used by contractors as well as specifying agencies to

control density. Using these gauges for acceptance is often done after correcting the nuclear density by the use of a conversion factor based on other standard density measures. One popular method for establishing the conversion factor is through the use of cores and saturated surface dry density.

The nuclear gauge used as the method of measurement in conjunction with the control strip procedure is employed by many specifying agencies to develop the optimum rolling sequence on a project. This combination also lends itself to a specification for accepting density.

CHAPTER ONE

INTRODUCTION

The performance of structurally adequate asphalt pavements is affected by two primary factors: a properly designed mix and compaction. Neither of these factors alone can assure satisfactory pavement life. Even the best-designed mix will be subject to reduced performance if not compacted sufficiently. Good compaction, however, can effectively improve the performance of a mix that is less than ideal. For this reason, compaction is considered to be the single most important factor affecting the performance of asphalt pavements. In this synthesis, variations in aggregate grading and asphalt content, along with many other factors that affect compaction of the pavement, will be discussed.

Since the introduction of the first successful steamroller in the United States, built by Andrew Lindelof in 1875 (*1*), compaction has been considered an important aspect of the construction of asphalt pavements. The importance of compaction has been documented in hundreds of papers and articles on the subject. Recent tendencies to use stiffer asphalt binders, asphalt modifiers, variations in aggregates, and changes in construction procedures and equipment including recycling have only served to increase the importance of compaction. Greatly affecting the influence of compaction on performance are the increases in wheel loads and tire pressures, and the volume of traffic to which modern highways are being subjected.

Compaction is the process of reducing the air-void content of an asphalt concrete mixture. It involves the packing and orientation of the solid particles within a viscoelastic medium into a more dense and effective particle arrangement. Ideally this process takes place under construction conditions rather than under traffic.

The glossary may help the reader with many of the terms used. In reviewing the literature, the term density was often used instead of the more correct effect of compaction on air voids. In order to avoid paraphrasing, the word density has been retained in direct quotations.

OBJECTIVES

The primary objective of this synthesis is to provide information on the current state of practice of asphalt pavement compaction. Because the literature is replete with information on compaction of asphalt pavements, it could be questioned why more information is needed. The answer is that it was felt to be necessary for the literature to be available in a concise and organized form and there was seen to be a need for a list of references for more detailed explanation.

BRIEF HISTORY

Tunnicliff et al. (*2*) document the evolutions of rollers and their use in "A History of Plants, Equipment and Methods in Bituminous Paving" in *Proceedings,* Association of Asphalt Paving Technologists (AAPT) Vol. 43A. This 50th anniversary historical volume is very interesting reading for those interested in the early growth of the asphalt industry. The comments below are taken from this treatment of the history of compaction.

Although the information is sparse, apparently the first "compressed rock asphalt roadway" was laid in France in 1854. Evidently the sand-sized rock asphalt was reduced to individual impregnated particles, probably by heating, laid hot, and somehow "compressed." The success of compressed rock asphalt in France led to its introduction into the United States. Around 1870, interest in using asphalt in roads began to grow and in 1875 Lindelof introduced his tandem steamroller. Although not entirely satisfactory because of the wavy surface it produced, it was a popular method of compaction until about 1900 (Figure 1). At about this time, tandem rollers became known as "asphalt rollers," and three-wheel rollers became known as "macadam rollers."

Sheet asphalt, which is a rich sand asphalt mix, was very popular in the early 1900s, probably because of its smooth appearance and because it could be laid in thin layers. The rolling of this material was different from that of asphalt concrete. Rollers weighing from $2\frac{1}{2}$ to 8 tons were used for sheet asphalt, and 10-to-12-ton nominal weight rollers were used for asphalt concrete.

Gasoline engines became available around 1910, but the introduction of this equipment did not affect the compaction

FIGURE 1 Steamroller circa 1900 (*2*).

process. The capability of adding ballast to rollers began with a modification of the roller drum around 1938. This allowed heavier compactive efforts than previously possible. At about the same time, the three-axle tandem roller was introduced by Buffalo-Springfield, but this roller did not achieve the objective for which it was designed, i.e., a smoother pavement (Figure 2).

Roller equipment development beyond 1940 will be addressed in a later chapter of this synthesis. It is worthwhile noting that the operation of rollers has remained essentially unchanged since their early use.

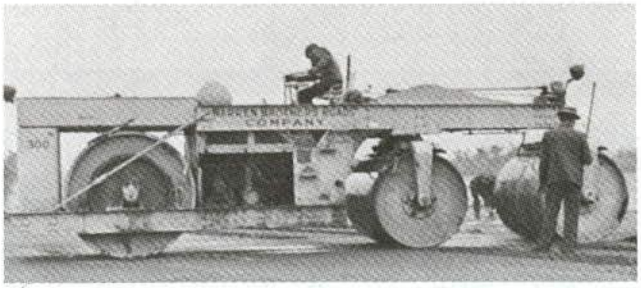

FIGURE 2 Three-axle tandem roller, Washington National Airport, 1939. Note that rolls are drums, an innovation of this decade (*2*).

CHAPTER TWO

IMPORTANCE OF COMPACTION

Compaction has always been recognized as an important factor in the construction of asphalt concrete pavements. Even when laydown was a manual operation at the turn of the century, operating rollers as close to laydown as possible, both physically and temporally, was considered a good construction practice. Over the years the importance of compaction is one fact that has been emphasized over and over.

Finn and Epps (*3*) have acknowledged that it is generally conceded that obtaining the proper compaction of asphalt concrete is one of the most critical factors associated with the performance of flexible pavements. Geller (*4*) agrees that "...compaction has always been emphasized as perhaps the single most important factor for achieving satisfactory pavement service life."

On the importance of compaction to construction, Marker (*5*) states in the *Proceedings* of the AAPT, "The compaction and densification of asphalt mixtures are the most important construction operations with regard to the ultimate performance of the completed pavement, regardless of the thickness of the course being placed." Noel (*6*) said at the 1977 AAPT meeting, "The single most important construction control that will provide for long-term serviceability is compaction."

Nijboer (*7*) does an excellent job of discussing the theoretical aspects of compaction as well as presenting a series of experiments that correlate well with theory. Nijboer's text *Plasticity as a Factor in the Design of Dense Bituminous Road Carpets* is recommended reading for the student of bituminous concrete although it transcends the subject of this synthesis.

Increasing density and reducing the percentage of air voids in asphalt concrete has a positive influence on the ability of the mix to perform as designed. Finn (*8*) shows in Table 1 that a high degree of compaction optimizes all desirable mix properties. What was true in 1967 is still true.

For the purpose of organizing this chapter, the author has redefined and reorganized Finn's mix properties as follows:

- Strength
- Durability/Aging
- Resistance to Deformation
- Resistance to Moisture Damage

TABLE 1

DESIRABLE CHARACTERISTICS TO OPTIMIZE MIXTURE PROPERTIES (*8*)

Mix Property	Asphalt Content	Aggregate Gradation	Degree of Compaction
Stability	Low	Dense	High
Durability	High	Dense	High
Flexibility	High	Open	-
Fatigue resistance	High	Dense[a]	High
Skid resistance	Low	Dense or open[b]	High[c]
Imperviousness	High	Dense	High
Fracture strength	High	Dense	High

[a]Assuming a heavy-duty, comparatively thick layer of asphaltic concrete.

[b]Both types of gradations have indicated good skid resistance characteristics. What appears to be more important is the texture of the aggregate particles.

[c]Although compaction is not normally indicated for this property, it is implied to insure that aggregate particles will not dislodge under the tractive forces applied to the surface.

- Impermeability
- Skid Resistance

It cannot be overemphasized that all of these properties are enhanced by reducing the percentage of air voids to an optimum value. This optimum value is very dependent on a proper mix design. The relationship among these elements and compaction will be discussed in the next chapter. The influence of the percentage of air voids on each property is discussed below.

STRENGTH

An increase in the strength of a pavement as a function of decreased air voids is well documented. Marshall stability, which is considered an empirical measure of strength, tends to increase as the void content decreases (*9*). McLeod (*10*) references Lefebvre (*11*) in Figure 3 and shows that as the density of laboratory-compacted samples increases, the Marshall stability increases. In this series of tests, the compactive effort by the Marshall compactor was increased from 2 to 60 blows on each face, resulting in an increase from 92 to 100 percent in the laboratory-compacted density. This increase in density corresponded to an increase in Marshall stability from approximately 100 lb to more than 1400 lb when a low-viscosity asphalt was used. A similar increase was shown when a high-viscosity asphalt was used. Similarly, Epps et al. (*12*) show a trend of decreased strength as measured by the Cohesiometer with an increase in air voids.

More rational measures of strength also show improvements with decreases in air voids. Livneh and Shklarsky (*13*) show general strength increases with decreases in air voids using the splitting tension test.

Tons and Krokosky (*14*) hypothesize that the presence of voids in asphalt concrete has two effects on tensile strength. First, a higher number of voids reduces the effective cross section of the stressed area and thus leads to a reduction of the potential strength; and second, the voids act as inducers of high stress concentrations, again effectively reducing tensile strength.

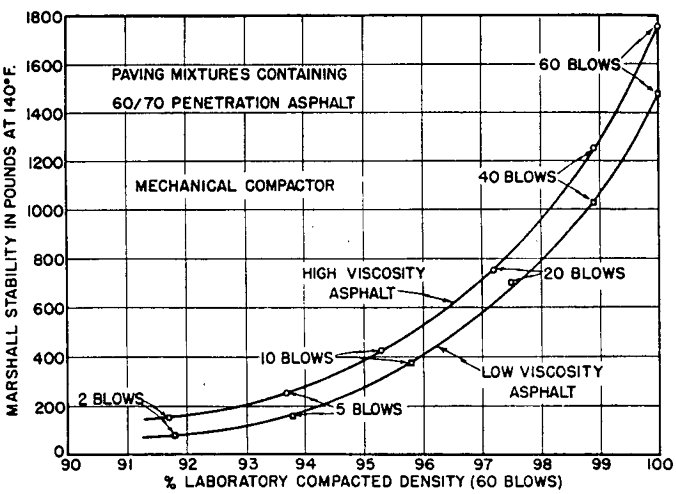

FIGURE 3 Marshall stability versus percent laboratory-compacted density (*10*).

Finn (*8*) indicates that "as the density of the mixture is increased, particularly the degree of packing of the aggregate, the fracture strength is also increased."

Stiffness has been shown to be dependent on air voids in reports by Deacon (*15*) and Epps and Monismith (*16*). Their experiments show that stiffness increases as air voids decrease, suggesting that a denser mixture results in greater load-supporting capabilities of the material.

Many researchers have shown that fatigue properties are greatly improved with decreased air voids. Pell and Taylor (*17*) conclude that voids have a detrimental effect on fatigue life, showing that an increase in void content is associated with a decrease in fatigue life. Pell (*18*), in a discussion of an AAPT paper by Lister and Powell, shows the calculated stiffness of base layers at three different binder contents and three different void contents using the Shell nomograph. In reference to Figure 4, he states, "It is seen that the effect of voids is far more significant than that of binder content and emphasizes the importance of compaction for good fatigue performance in this type of construction." Epps and Monismith (*16*) state, "Both fatigue life and mixture stiffness are reduced by an increase in air void content." Finn et al. (*19*), referring to the above-mentioned works by Pell, Epps, and Monismith, say that ". . .fatigue properties can be reduced by 30 to 40 percent for each one percent increase in air void content." A more recent study in Oregon (*20*) concludes, "It was found that the mix level of compaction is the dominant factor for all mix dynamic properties. Increasing the mix density increases the mix stiffness and fatigue life." This study indicates a 1 percent reduction in air voids can produce a 10 percent increase in dynamic properties.

DURABILITY/AGING

Finn (*8*) defines durability of a paving mixture as its resistance to weathering, including aging, and to the abrasive action of traffic. As in the association between strength and air voids, many studies have been conducted to investigate the relationship between air voids and aging, primarily measured by the hardening of the asphalt cement. Figure 5 is from McLeod's (*10*) earlier-mentioned Highway Research Board paper. It shows a relationship between retained penetration and air voids in the pavement for four-year-old pavements. He states:

> A number of investigations undertaken during the past 30 years have shown that when the asphalt binder hardens to about 20 to 30 penetrations, pavement deterioration can be expected. . . .Consequently, compacting a well-designed paving mixture to low air voids retards the rate of hardening of the asphalt binder, and results in longer pavement life, lower pavement maintenance, and better all-around pavement performance.

Another study relating aging of the asphalt binder with the percentage of air voids is by Vallerga et al. (*21*) in a Federal Highway Administration (FHWA)-sponsored study entitled "Changes in Fundamental Properties of Asphalts During Service in Pavements." One objective of this study was "to measure changes in fundamental physical and chemical properties of asphalt cements after 11 to 13 years service in pavements." Figures 6 and 7 illustrate that recovered penetration and viscosity, both obtained at 77°F, are strongly affected by air voids (*21*). As the penetration drops below a value of about 30, the matrix tends to become brittle and the mix more susceptible to

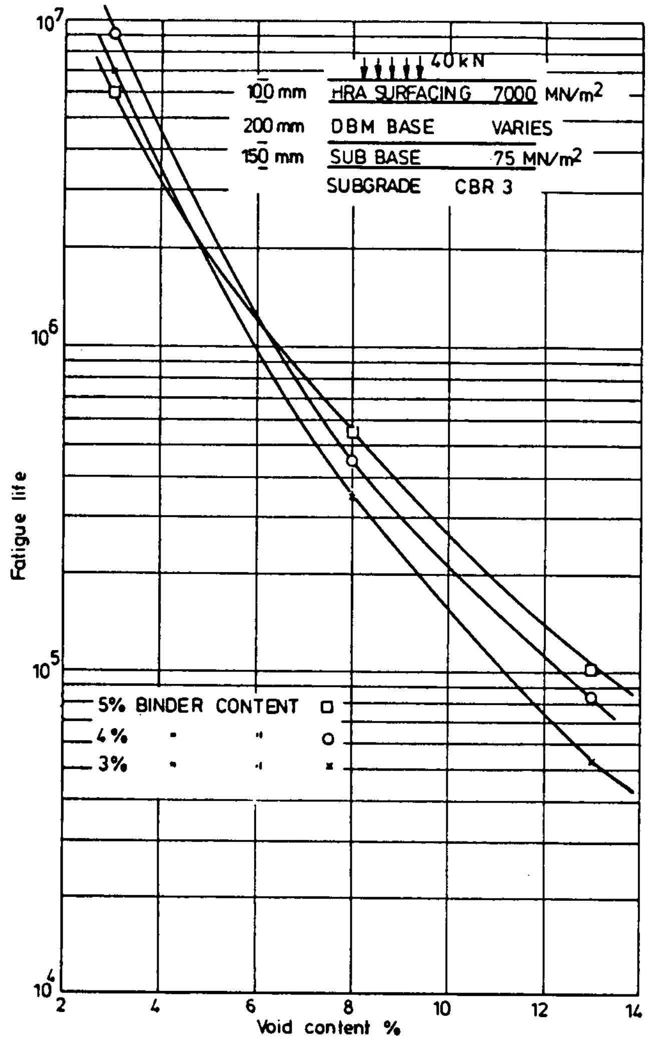

FIGURE 4 Fatigue of dense macadam base (*18*).

cracking. The value of 30 is reached with air voids that exceed an average value of about 3 percent. One conclusion from this report was, "The most important factor in hardening of the asphalt binder in a pavement is voids content of the pavement."

Santucci et al. (*22*) investigated premature failures on a number of roads in Oregon. One of the conclusions from the report was, "High air void contents in dense-graded asphalt pavements or overlays accelerate the hardening of the asphalt binder and hence, influence the long-term durability of the pavement."

Kandhal and Koehler (*23*) also investigated premature pavement distress in Pennsylvania and found a strong correlation between raveling and the percentage of air voids, as shown in Figure 8. They concluded, "Lack of adequate compaction was the primary cause of the premature distress." This research led to the development of a statistical specification with payment factor percentages based on three important mixture variables: density, bitumen content, and material passing the 75 μm (No. 200) sieve. They state, "The final combined payment factor percentage is computed from a formula that gives 50 percent weight to the compaction and 25 percent weights each to bitumen content and minus no. 200 material content, since compaction is considered more crucial in preventing the premature distress."

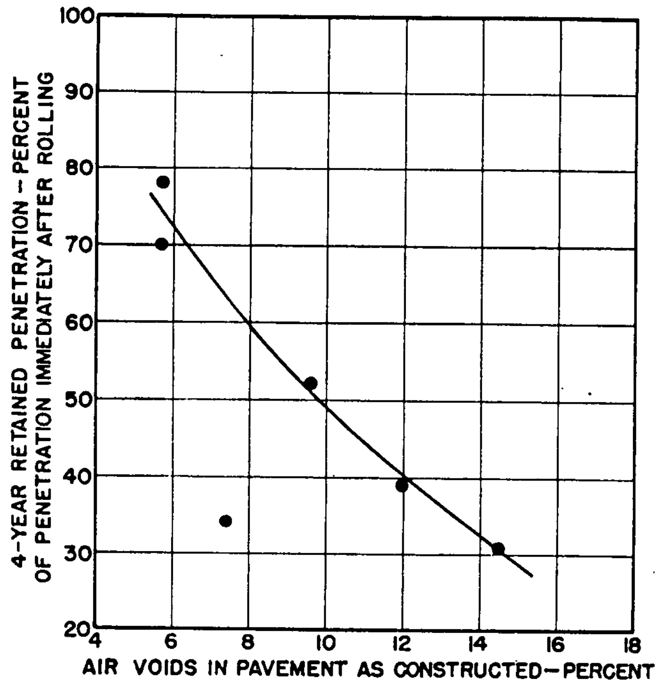

FIGURE 5 Effect of initial air voids on change in penetration of asphalt (*10*).

RESISTANCE TO DEFORMATION

Finn (*8*) defines stability as the resistance to deformation. Because of potential confusion with Marshall and Hveem stability, the author has chosen to use the term resistance to deformation as the desirable mix property.

Rutting and shoving are the two most common manifestations of a lack of resistance to deformation. In the 1980s, the FHWA

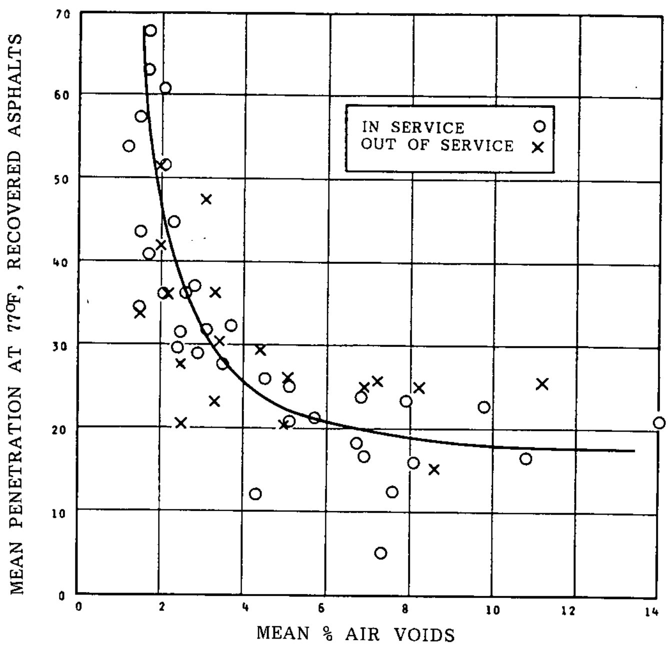

FIGURE 6 Relation of retained penetration to air voids of field-aged asphalts (*21*).

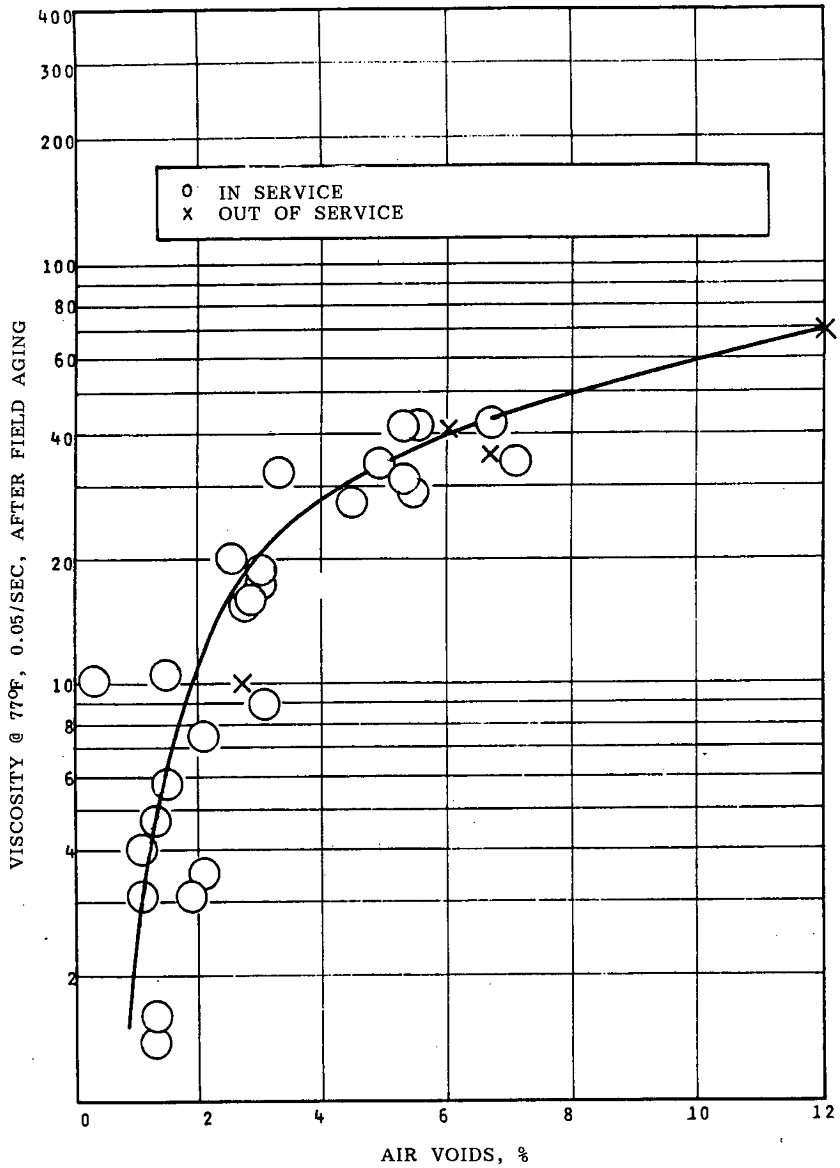

FIGURE 7 Relation of viscosity at 77°F to air voids of field-aged asphalts (*21*).

(*24*) stated that rutting is one of the two most common distresses existing on heavily traveled roads. Shoving has become a fairly common occurrence at heavily trafficked intersections. Rutting is not a recent malady, as discussed by Lingle (*25*), who quotes from Research Series Number 1 of the Asphalt Institute, dated October 15, 1935:

> Resistance to displacement under traffic and durability are the two primary requisites of a satisfactorily compressed asphalt paving mixture. No matter how carefully and scientifically the mixture is designed, it will be lacking in both of these properties if it is not thoroughly compressed. For any properly designed mixture, resistance to displacement has been found to be almost a direct function of its degrees of compression.

It should be emphasized that more than 50 years ago it was recognized that a well-designed asphalt mix will not perform well if not properly compacted or, in Lingle's terminology, properly compressed.

Rutting has two primary origins, consolidation and distortion (*26*). Consolidation develops from the continued compaction of channelized traffic. With the heavier truck loads and higher tire pressures, the continuation of the compaction process after construction has become more severe than ever before. Thus, to prevent rutting, it is very important to reduce the voids during construction to as close as practicable to the air-void content that will be attained under traffic. The alternative is to achieve compaction under traffic, and this will lead to rutting.

The validity of this discussion is dependent on the use of a rational mix design to determine the proper asphalt content. If too high an asphalt content is used, the air-void content can be reduced to such a low level that the second origin of rutting, distortion, takes place. With some mixes, this can occur during construction. Distortion can be caused by factors other than simply high asphalt content. Scherocman (*26*), discussing distortion, says, "The second type of pavement rutting is usually caused by a mix design problem." He mentions several possibilities for the mix design problem.

The desired resistance to rutting tends to make achieving the

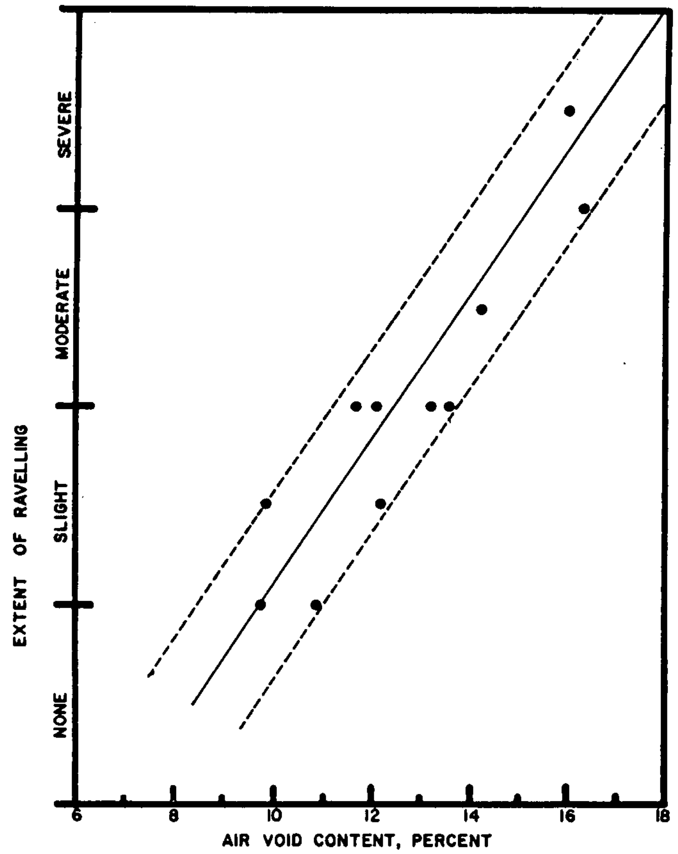

FIGURE 8 Air-void content versus raveling (*23*).

desired density more difficult in that the more resistant a mix is to rutting, the harder it is to compact during construction. But the harder a mix is to compact, the more important that an efficient compaction process is used so that the air voids are reduced to as close to the optimum value as practicable.

RESISTANCE TO MOISTURE DAMAGE

The subject of moisture damage in asphalt concrete has been recognized for many years (*27–29*). The FHWA has noted that this is the second most common distress observed in modern roads. Because of recent increases in this failure mode, it has been discussed with increasing frequency (*24, 30, 31*). In discussing the subject of moisture damage and methods to minimize the damage caused by this failure mechanism, the need for adequate compaction to reduce the permeable voids frequently arises (*24, 26, 32, 33*). Brown (*33*) wrote a summary for FHWA of individual state investigations of causes of moisture damage. The following statements relating moisture damage, often termed stripping, to the percentage of air voids are pertinent to this discussion:

> Georgia—The percentage of air voids in an asphalt pavement is very important in relation to stripping. Laboratory testing for moisture susceptibility should be done at the expected voids level after construction. Void levels should be low enough in all dense-graded mixes to prevent the intrusion of water.
>
> Louisiana—The faster deterioration of the binder course may be caused by a design air-void content that is too high.
>
> New York—Air voids and pavement age were found to be significant factors in relation to stripping.
>
> North Carolina—The percentage of air voids should be held in the lower range of the present specifications. Every effort should be made during the construction phase of projects to obtain specified levels of density.

Brown summarizes the individual state conclusions with the conclusion that

> air-void content in asphaltic concrete mixes is a very important factor relating to potential stripping problems. Void levels should be low enough (in dense-graded mixes) to prevent the intrusion of water. Specification limits should be set as low as possible (without creating other problems such as flushing, rutting, etc.) and emphasis should be placed on enforcement of the specified requirements.

IMPERMEABILITY

Permeability, the ability for water and air to pass through an asphalt mix, has an appreciable influence on durability and the susceptibility to moisture damage (*8, 34*). Impermeability, the converse of permeability, is also important. The Asphalt Institute states, "Impermeability is the resistance of a pavement to the passage of water and air through it. Impermeability is achieved by making the pavement dense enough to prevent connecting voids in the mass. This can be done by proper compaction of well-designed mixes" (*35*). Impermeability does not mean the construction of pavements with zero air voids, which is quite undesirable.

Several papers have been written associating both air and water permeability to air voids (*36–38*). Zube (*38*), using water permeability as an indicator of air voids, states that "field tests indicate that adequate compaction, together with some form of pneumatic rolling, are very important factors in reducing pavement permeability."

There are mixes, namely open graded friction courses, that are designed to be permeable. Durability is provided by thick films of asphalt, and compaction of these mixes consists of orienting the aggregate particles by a relatively low compactive effort.

SKID RESISTANCE

Of all the desirable properties, the property of skid resistance is probably the least affected by compaction. Finn (*8*) states that the prevention of raveling is one of the benefits of compaction on skid resistance. Generally speaking, high compactive efforts that result in the reduction of air voids, which may produce a mix with little aggregate texture, tend to decrease skid resistance. This is an area in which gradation selection and mix design are more important than compaction.

SUMMARY OF IMPORTANCE OF COMPACTION

Two works (*39, 40*) summarize the information presented in this chapter by specifically addressing the beneficial effects of compaction on mix performance. Bell et al. (*39*) quantify the magnitude of changes of mix stiffness, resistance to fatigue cracking, and deformation with changing air-void levels. This report states, "The results of the test program indicated that percent compaction (or void content) was the most significant factor affecting mix performance. An increase in void content is associated with a decrease in modulus, fatigue life, and resistance to permanent deformation." Lister and Powell (*40*) reported on a field investigation of asphalt base courses. They conclude that improving the compaction of dense asphalt concrete is beneficial to pavement performance as measured by dynamic modulus, resistance to fatigue, and decrease in deflection.

CHAPTER THREE

FACTORS AFFECTING COMPACTION

There are numerous factors that affect compaction, as shown in Figure 9 (*12*). This diagram is a flow chart that provides an excellent indication of the interrelationship of the many factors affecting compaction. This chapter will concentrate on the effect of material properties listed at the top of the diagram, specifically the influence of aggregate, asphalt cement, and mix properties on density, as well as the importance of mix design to achieving proper air voids. Other factors from the figure, such as construction conditions and equipment, will be addressed in subsequent chapters.

MATERIAL PROPERTIES

Aggregate Properties

Several properties of both the coarse and fine aggregates are important in achieving the desired density. Particle shape or angularity, absorption, and surface texture are important properties of the individual aggregates. The gradation of the combination of aggregates as influenced by the maximum aggregate size, the concentration of coarse aggregate, the amount of sand-size material, and the amount and type of filler all play important roles in influencing density. An excellent illustration of the gradation curve is provided using the .45 power chart developed by Goode and Lufsey (*41*) (Figure 10). The straight line plotted on this chart represents the maximum density gradation for a mix with ½ in. top-size aggregate. By plotting the actual gradation on this chart, the deviation from the maximum density can be visualized (Figure 11). The manner in which the maximum density line is drawn can provide an estimate of the effective maximum-size aggregate. It is recommended to draw the maximum density line from the origin through the gradation point immediately below the sieve that has 100 percent passing. The intersection of the maximum density line with the 100 percent passing line estimates the effective maximum-size aggregate. In Figure 11, this is between ⅜ and ½ in. An exception occurs when the point of intersection occurs to the right of the sieve that has 100 percent passing. Logically, in this case the effective maximum-size aggregate is that at 100 percent passing.

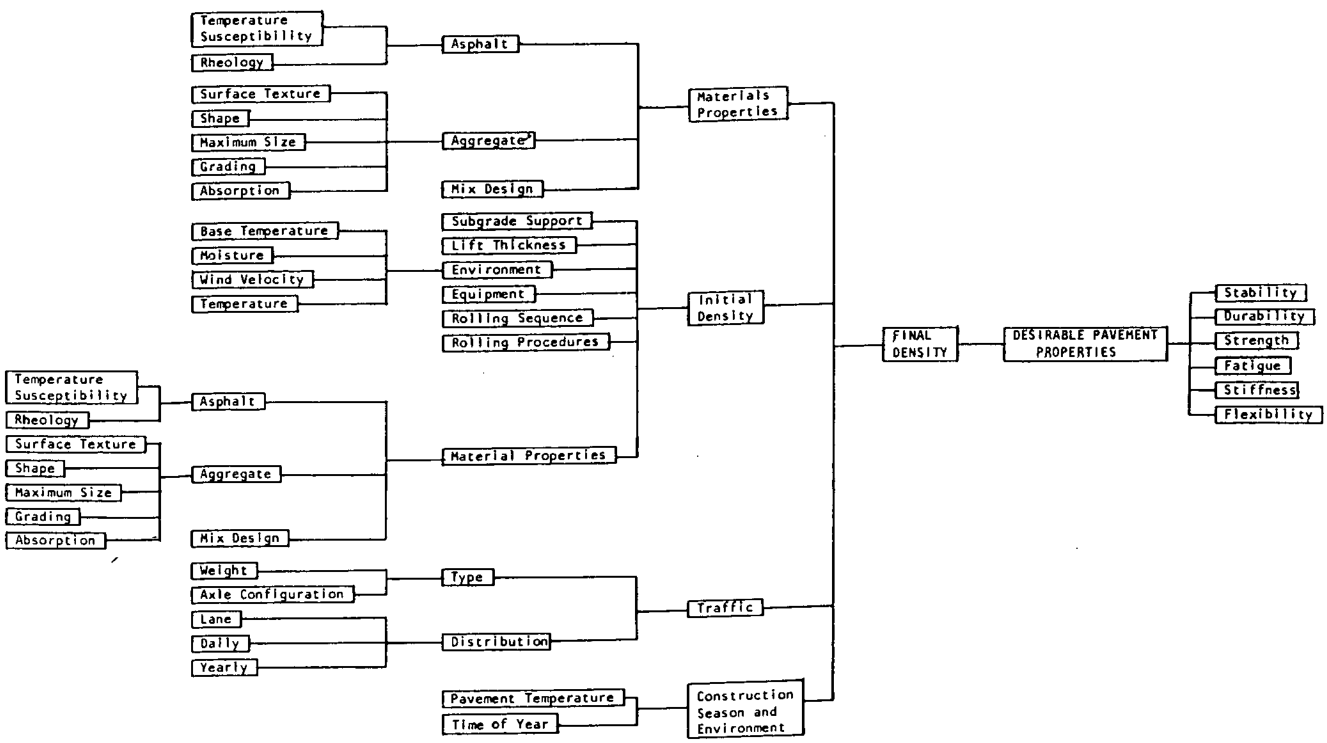

FIGURE 9 Factors influencing compaction of asphalt concrete pavements (*12*).

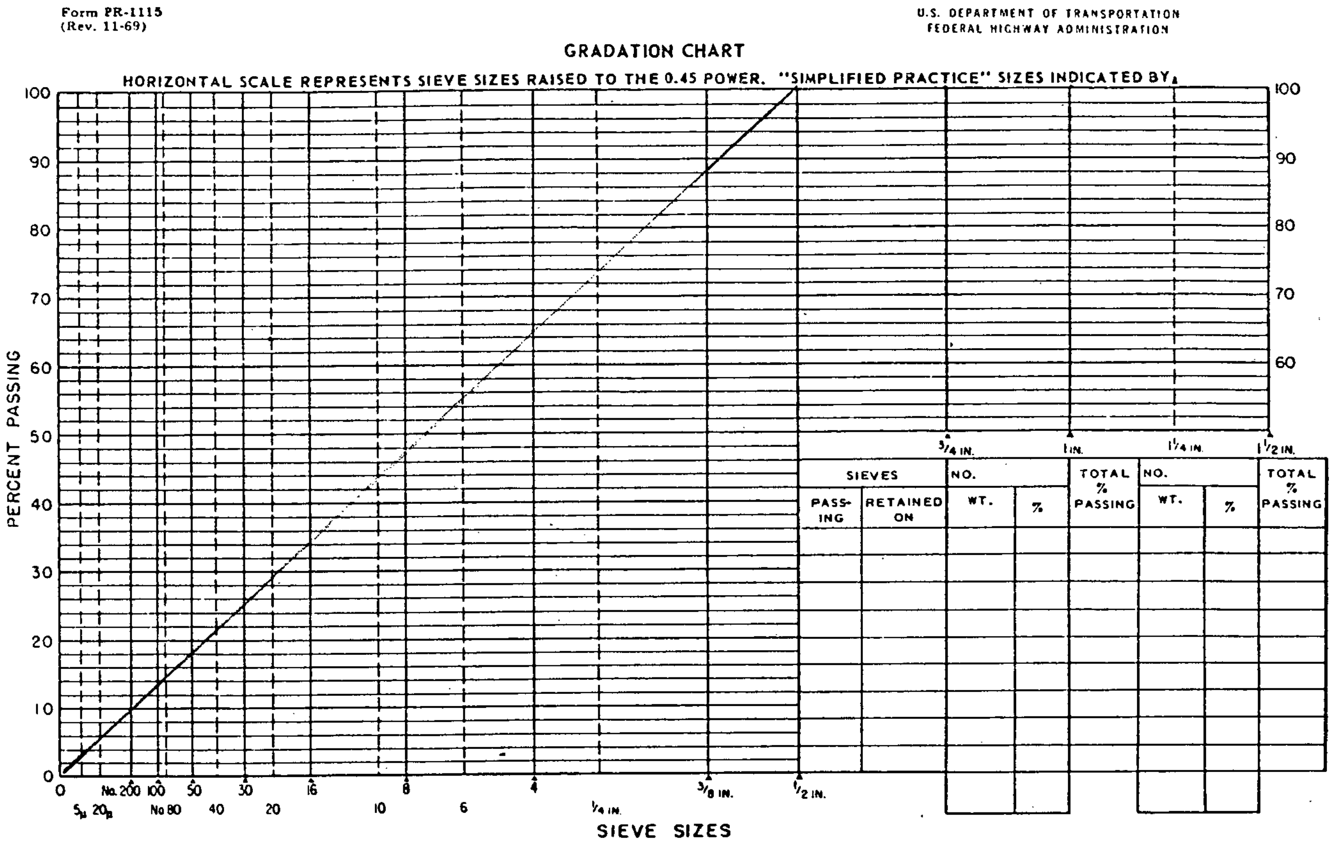

FIGURE 10 Gradation chart using .45 power (*41*).

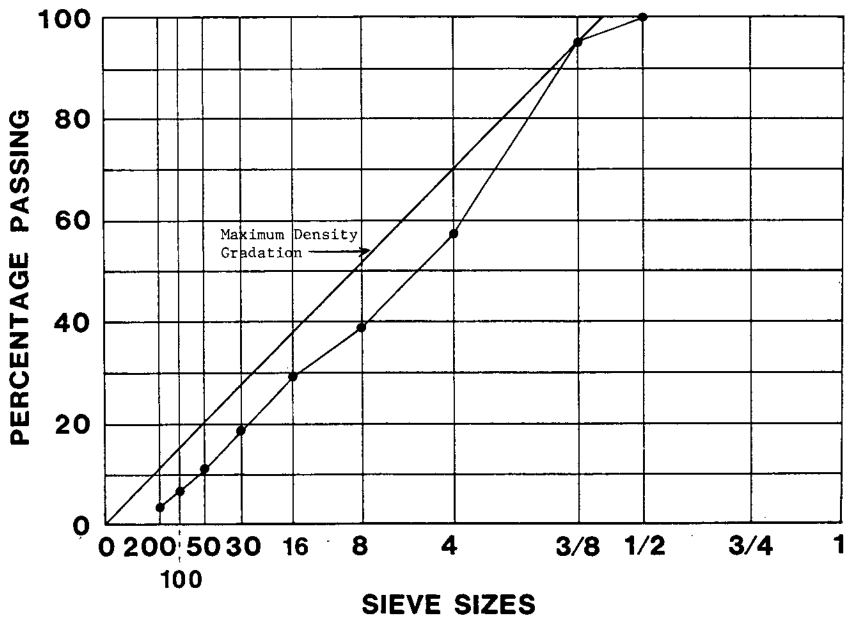

FIGURE 11 Gradation and maximum density line plotted on .45 power graph.

Graphs to this scale are also useful in indicating the potential for a tender mix (i.e., one that is unstable under the roller), which can occur when a "hump" exists in the gradation in the vicinity of the 600 μm (No. 30) and 300 μm (No. 50) sieves (Figure 12).

Finn (*8*) discusses the importance of aggregate frictional resistance on the resistance to deformation, which, of course, is related to compaction. He says that frictional resistance is a major contributor to resistance to deformation. For high temperatures and slowly applied loads that are usually considered, the contribution of interparticle friction to stability is predominant. For these circumstances, the aggregate characteristics, particularly particle surface texture, exert a major influence. Improper compaction or high asphalt contents tend to reduce this friction, and permit plastic deformations to develop more readily.

Fromm (*42*) found crushed granite with rough crystalline faces more difficult to compact than the smooth face of a crushed carbonate aggregate. Santucci and Schmidt (*43*) relate aggregate gradation and angularity, filler content, moisture, and compactive effort to the setting rate or toughness of a compacted mix. They define slow setting mixes as those that easily become overstressed during rolling and are characterized by low stability, low fines content, high sand fraction, and small maximum-size aggregate. They add, "Aggregate shape and surface texture contribute to the toughness of a mix. The most critical are those produced from rounded, uncrushed material having a smooth surface texture." One conclusion of this report is that "adequate compaction is not easily reached in critical mixes. These mixes are often overstressed, resulting in excessive shoving of the mix under the roller." Scherocman (*44*) also states the importance of surface texture and particle shape in influencing compaction. He further comments on the gradation with the statement:

> All other factors being equal, 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 mixture containing a skip or gap graded aggregate. A harsh mix, or one incorporating a large proportion of coarse aggregate, requires a significant increase in compaction effort to obtain the required air void content. An oversanded or finely graded asphalt concrete mixture, on the other hand, can be extremely workable. It is still difficult to get the proper density level, however, because an oversanded mix will tend to shove under the compaction equipment and be hard to compact.

Hudson and Davis (*45*) list several conditions under which voids are reduced in a continuous gradation as:

- The arrangement of the particles or type of compaction;
- The relationship between sizes of aggregate particles, or the ratio between the percents passing adjacent sieves in the standard logarithmic series;
- The maximum aggregate size;
- The shape of the aggregate.

Filler and the ratio of filler to asphalt content, often called the filler-asphalt ratio, both have an influence on the density of a mix. The reader is referred to Tunnicliff (*46*) for a very thorough review of the effect of filler on mix design. Kallas and Krieger (*47*) have shown that the type of filler influences density. Figure 13 shows the effect on air voids using the same number of compaction gyrations with the gyratory shear compactor by filler type. Nijboer (*7*) discusses the influence of filler and what he terms filler-bitumen (filler-asphalt) ratio (F/B) in great detail. He points out that the type and the gradation or fineness have a significant effect on void content.

With more stringent controls on asphalt plant emissions, the use of baghouses to control fines emission has increased dramatically in the 1970s and 1980s. The increase in the use of baghouses has had a pronounced effect on the amount and size of fillers retained in the mix (*48, 49*). Maupin (*49*) states that dust, or "fines," influences the compaction of the mixture during construction. He conducted a laboratory study of mixes in which he varied the amount of baghouse fines in each mix using four different mixes, each with a different type of dust. Figure 14,

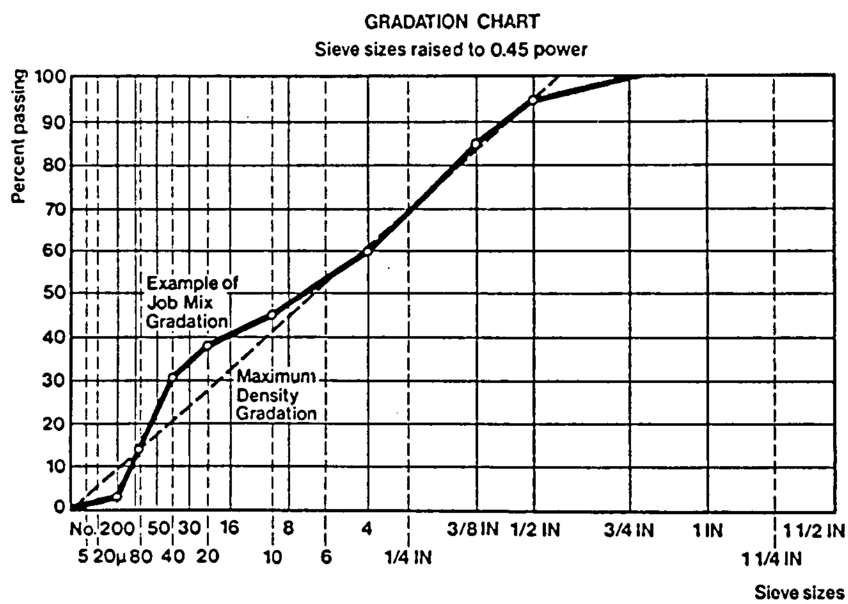

FIGURE 12 Hump in gradation curve indicates potential for a tender mix (*24*).

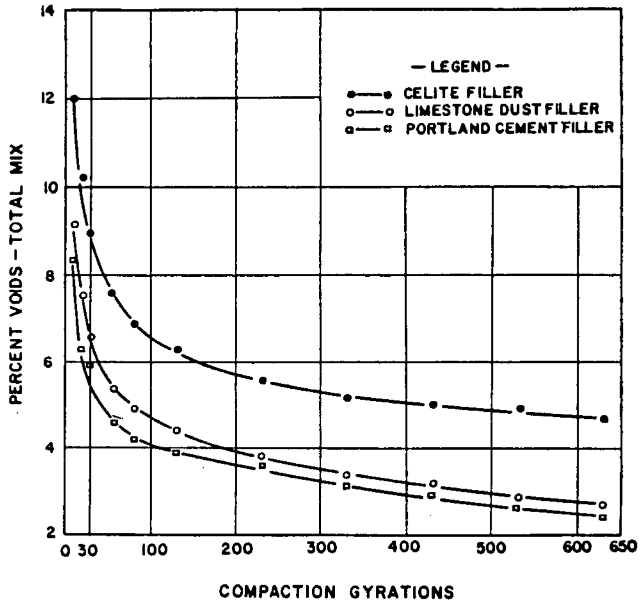

FIGURE 13 Effect of fillers on the compaction of 4% 85-100 penetration grade asphalt mixtures (*47*).

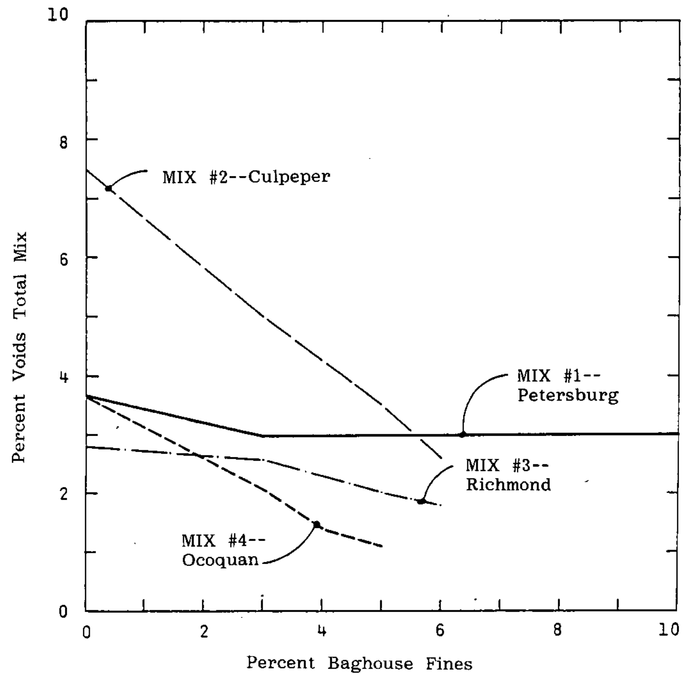

FIGURE 14 Voids total mix versus percentage of baghouse fines (*49*).

from his report, shows how air voids are influenced not only by the percent of baghouse fines but also by the sources of the fines. Mixes number 2 and number 4 in this figure had significantly finer baghouse fines than did mixes number 1 and number 3, as Figure 15 shows. The difference in fineness is particularly important below the 0.01 mm (10 μm) size because, for this size, the fines are contained in the asphalt film and act as an asphalt extender. For mixes number 2 and number 4, the fines extended the asphalt sufficiently to significantly reduce the air voids.

Asphalt Cement Properties

The viscosity of the asphalt has an influence on the stiffness of the mixture (*12, 43*) and is related to the compactability of the mix. The Asphalt Institute "Factors Affecting Compaction" (*35*) discusses the importance of viscosity:

> Asphalt viscosity affects compaction greatly. High viscosity tends to hold back movement of aggregate particles when the mix is rolled. If the viscosity is too low, the particles move easily during compaction, but not enough cohesion develops to hold the par-

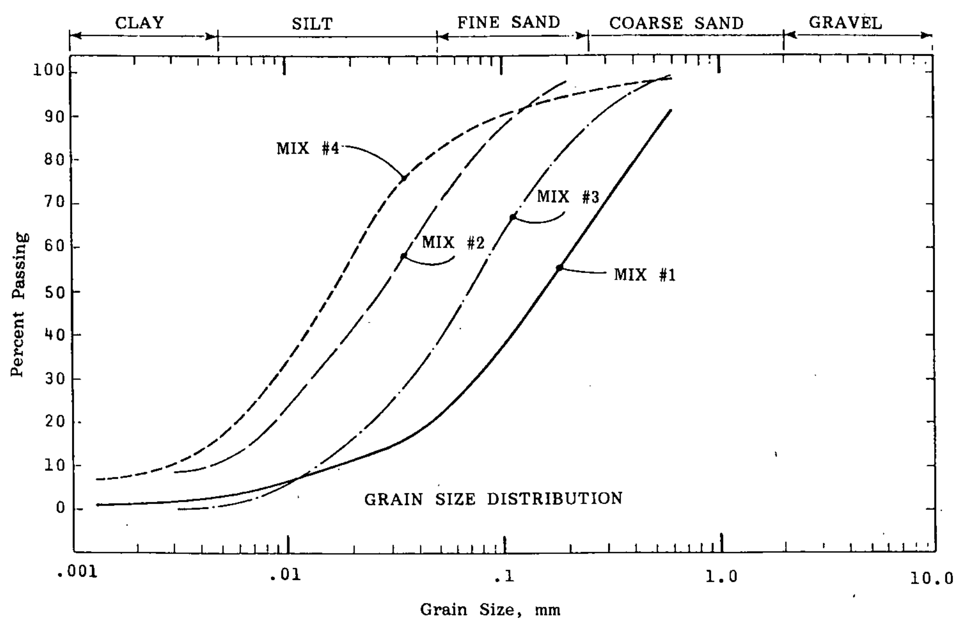

FIGURE 15 Gradations of baghouse fines (*49*).

ticles in position once compaction is completed. While hot, asphalt acts as a lubricant, overcoming the interparticle friction of the aggregate. Once the mix has cooled, asphalt acts as a binder holding the aggregate particles together.

The viscosity of asphalt is measured at 275°F to provide an indication of the asphalt stiffness at a typical compaction temperature. Also, the slope of the viscosity-temperature curve provides an indication of how much temperature change is necessary to increase or decrease the viscosity a desired amount. Generally speaking, the higher the viscosity at 275°F, the more resistant the mix is to reducing the air voids at a given temperature. Therefore, for a high-viscosity asphalt, higher mix temperatures resulting in higher compaction temperatures are necessary to reduce the viscosity to a level that will facilitate compaction.

Santucci and Schmidt (*43*) show in Figure 16 the influence of asphalt viscosity at the time of rolling on the final pavement density. This figure provides an indication that the final density of a mix increases as the viscosity of the binder, at the time of breakdown rolling, drops.

McLeod (*10*) shows in Figure 17 the influence of asphalt viscosity on the ease of compacting paving mixtures. The figure indicates that at a given compaction temperature a low-viscosity asphalt will attain a higher density and that by increasing the compaction temperature the high-viscosity asphalt can attain a density as high as that of the low-viscosity asphalt. Thus, it is important to know the viscosity of the asphalt at the compaction temperature, and if necessary, change the compaction temperature so that the viscosity will not be too high.

For tender mixes the other extreme may exist and it may be necessary to reduce the compaction temperature so that the asphalt viscosity will increase. Such an increase would mean that the compaction equipment could be supported without excessive movement of the mix.

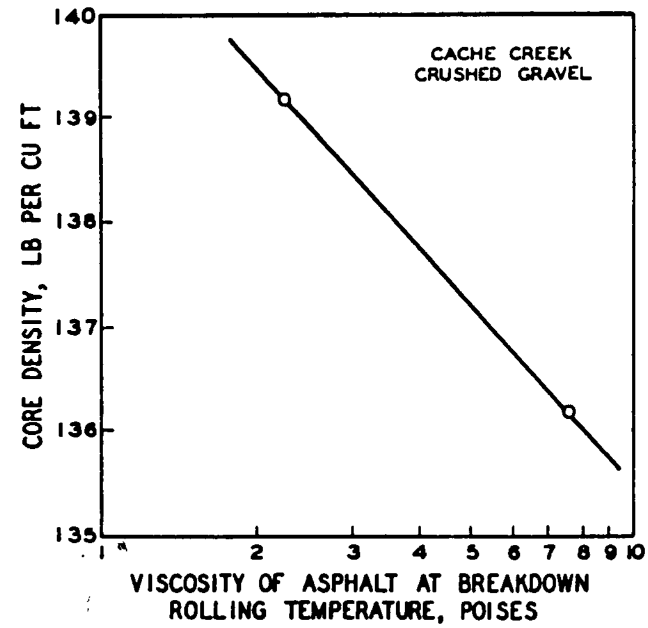

FIGURE 16 Asphalt viscosity versus density (*43*).

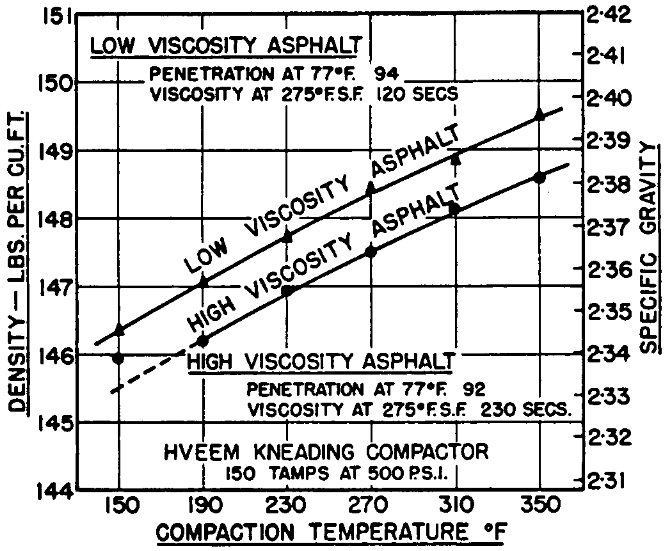

FIGURE 17 Influence of asphalt viscosity on ease of compaction of paving mixtures (*10*).

Mix Properties

Because the properties of the individual mix ingredients, i.e., aggregate and asphalt, play such an important role in relation to compaction, it is logical that the combination of ingredients, likewise, influences compaction. In fact, it can be argued that properties of the mix influence compaction even more than the properties of the individual ingredients.

The determination of the optimum asphalt content through a thorough mix design procedure is extremely important. A mix having too little asphalt is difficult to compact, because the low asphalt content results in poor lubrication and makes a dry, harsh mix. On the other hand, too much asphalt lubricates the mix excessively, making it unstable and plastic under the roller (*35*). It is possible by increasing the efficiency of the compaction process to reduce voids to an acceptable level in a mix with a lower than desirable asphalt content, but if the asphalt content is higher than optimum, little or nothing at the time of compaction can prevent ultimate deformation of the mix.

Another important combination of materials is the filler-asphalt ratio (F/A) discussed previously. With the increased use of baghouses, which capture small grain material heretofore airborne or wasted in a wet-wash pollution-control system, the fineness as well as the quantity of filler has become important. Kandhal (*50*) concludes, "Some baghouse fines have a tremendous stiffening effect on the F/A systems which offered resistance to compaction of asphaltic concrete." In some instances researchers have reported that baghouse fines can act as an asphalt extender either replacing the asphalt cement or, more likely, producing a mix that behaves as if it has too much asphalt (*48, 51, 52*). Therefore, depending on the properties of the baghouse fines, a mix may be stiffened or softened by the addition of baghouse fines.

A third mix factor that has a strong influence on compaction is the temperature at the time of compaction. The influence of asphalt viscosity has previously been discussed. However, the mixture viscosity is influenced not only by asphalt viscosity but also by factors such as the F/A, which can increase or decrease stiffness. A mix that has a higher temperature, generally, is easier to compact than the same asphalt mix placed at a lower temperature. A mix that tends to be tender will generally have to be rolled at a cooler temperature than a stiffer mix.

Another mix property that affects compaction is what Scherocman terms fluid content (*44*). This is the sum of the asphalt content and the moisture content of the mix. He states, "A wet mix, one containing an excess of moisture, will have a tendency to displace under the compaction equipment and thus be difficult to compact."

Compaction vs. Asphalt Content

As stated previously, the key ingredients to asphalt pavements performing well for their design life are both properly designed and compacted mixes. Claiming that compaction is more important than asphalt content is no reason to overlook the importance of determining the proper asphalt content through a rational mix design procedure or the importance of controlling the asphalt content during construction. If the asphalt content is on the low side of the optimum, it may be possible to compensate for this through the compaction procedure by reducing the air voids to an acceptable level. This very likely will require a more efficient compactive effort than if the asphalt content were at the proper level. On the other hand, even a well-designed mix with the proper control on the asphalt content will very likely not perform well if it is not compacted to an adequate void content level.

RELATIONSHIP BETWEEN LABORATORY AND FIELD DENSITY

Laboratory Density

The most widely used method of mix design for hot-mix asphalt concrete is the Marshall method (*53*), with the accompanying method of compaction being the Marshall hammer. Different compactive efforts are achieved by varying the number of blows to each side of the specimen. Compactive efforts of 35, 50, and 75 blows are recommended by the Asphalt Institute (Table 2) for compacting specimens for mixes to be used on light, medium, and heavily trafficked roads (*54*) respectively. This assumes that the compactive effort provided by 35 blows is related to the air voids achieved after several years of light traffic loading, 50 blows compaction is related to the air voids under medium traffic, etc.

Another widely used design procedure is the Hveem method. This procedure uses the California Kneading Compactor for fabricating specimens (*55*). The California Kneading Compactor applies 20 tamping blows at 250 psi foot pressure, followed by 150 tamping blows at 500 psi foot pressure. A 1000 psi static leveling load is used to finish compacting the specimen.

A third method of mix design, which is gaining notoriety, uses the U.S. Army Corps of Engineers Gyratory Testing Machine (*56*). The compactive effort with this device can be varied by changing ram pressure, number of revolutions of gyration, and angle of gyration. A similar device, the Texas gyratory compactor, has a fixed angle of gyration of approximately 6° for a 4-in. specimen (ASTM D 40131).

There have been several studies undertaken to correlate these various compaction devices (*12, 57–59*) either by air voids or mixture properties.

Field Density

In relating field density to laboratory density, the most important aspect of the field density is the time at which it is determined. Epps et al. (*12*) provide an excellent discussion of the factors that affect initial compaction (i.e., compaction during construction); long-term compaction (i.e., compaction caused by traffic); and the relationship between initial and long-term compaction (Figure 9). Initial compaction is extremely important. Pavements that have high air voids after construction allow water and air to infiltrate and reduce the durability of the mat. Consolidation resulting in rutting may also be an adverse consequence.

Generally, compaction caused by traffic over two to four years causes a decrease in air voids from that attained during construction from 2 to 8 percent when air voids were initially relatively high (Figure 18) (*12*). Hughes (*60*) found a decrease in average air voids from a range of 7.2 to 8.5 percent at the time of construction to average values of 5.4 to 6.5 percent after two years under traffic. This decrease in air voids of about 2 percent shows up as rutting (between 0.05 in. and 0.20 in.) caused almost entirely by consolidation (Figure 19). Under similar conditions the rutting caused by the consolidation associated with an 8 percent decrease in voids would be between 0.2 in. and 0.8 in. Thus, if the initial air voids after construction are higher, the layer is thicker, or the traffic is heavier, there will be more rutting after several years of traffic. That is why the percentage of air voids obtained during construction should be as close as possible to the percentage of air voids found in the pavement after several years of service.

Laboratory vs. Field Density

It is important that the density of laboratory-compacted specimens approximate that obtained in the field in terms of (a) the structure of the mix and (b) the quantity, size, and distribution of the air voids. Many studies have been undertaken to correlate results obtained by laboratory compaction to those obtained in the field. Early studies by both Endersby (*61*) and Hveem and Davis (*62*) state that the kneading action of a device such as the California Kneading Compactor is necessary to produce laboratory specimens representative of actual field samples.

Brown (*63*), of the Texas State Department of Highways and Public Transportation, in a 1951 AAPT paper discussion states that the Texas gyratory compactor, "and most likely the other kneading type procedures, closely reproduce the density imparted by rolling during construction and subsequent traffic action and that ultimate density is reached in the test specimen. The method also closely reproduces results obtained in typical construction in regard to degradation and orientation of aggregate particles."

Because the Marshall hammer compacts by impact, not many engineers believe it simulates field compaction. Its advantages are practical features such as convenience, portability, etc.

More recent testing on the NCHRP Asphalt Aggregate Mixture Analysis System (AAMAS) (*59*) indicates that strength properties produced by the Texas gyratory shear compactor most nearly match those obtained from field cores. The purpose of the substudy in the AAMAS project was to try to find the most practical laboratory-compaction procedure that most

TABLE 2

THE ASPHALT INSTITUTE MARSHALL DESIGN CRITERIA

	Light Traffic Surface & Base		Medium Traffic Surface & Base		Heavy Traffic Surface & Base	
Marshall Method Mix Criteria[1]	**Min.**	**Max.**	**Min.**	**Max.**	**Min.**	**Max.**
Compaction, number of blows each end of specimen	**35**		**50**		**75**	
Stability, Newtons	**3336**		**5338**		**8006**	
(lb.)	**(750)**	**—**	**(1200)**	**—**	**(1800)**	**—**
Flow, 0.25mm (0.01 in.)	**8**	**18**	**8**	**16**	**8**	**14**
Percent Air Voids	**3**	**5**	**3**	**5**	**3**	**5**

NOTES:

[1]All criteria, not stability value alone, must be considered in designing an asphalt paving mix.
Hot-mix asphalt bases that do not meet these criteria when tested at 60°C (140°F) are satisfactory if they meet the criteria when tested at 38°C (100°F) and are placed 100 mm (4 in.) or more below the surface. This recommendation applies only to regions having a range of climatic conditions similar to those prevailing throughout most of the United States. A different lower test temperature may be considered in regions having more extreme climatic conditions.

[2]Traffic Classifications:

Light: Traffic conditions resulting a Design EAL $<10^4$.

Medium: Traffic conditions resulting a Design EAL between 10^4 and 10^6.

Heavy: Traffic conditions resulting in a Design EAL $>10^6$.

[3]Laboratory compactive efforts should closely approach the maximum density obtained in the pavement under traffic.

[4]The flow value refers to the point where the load begins to decrease.

[5]The portion of the asphalt cement lost by absorption into the aggregate particles must be allowed for when calculating percent air voids.

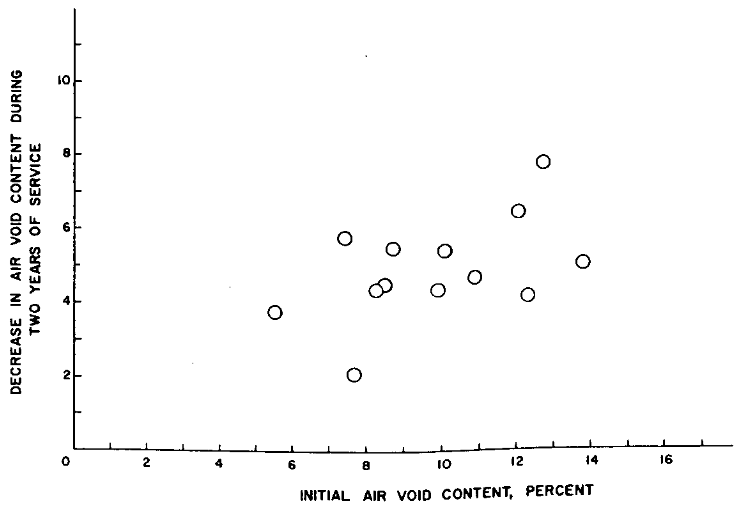

FIGURE 18 Density change as a function of initial compaction (*12*).

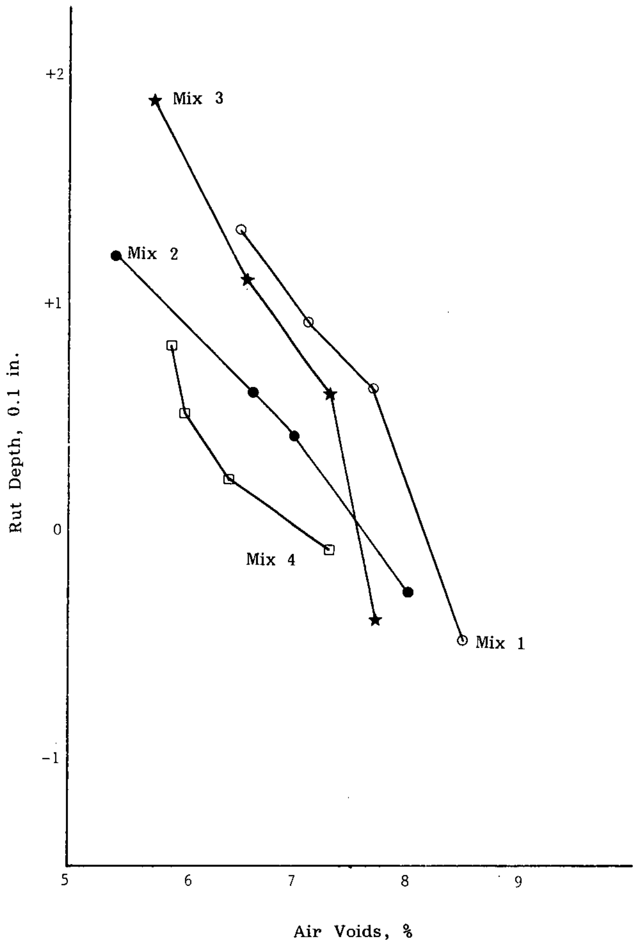

FIGURE 19 Rutting as influenced by consolidation (*60*).

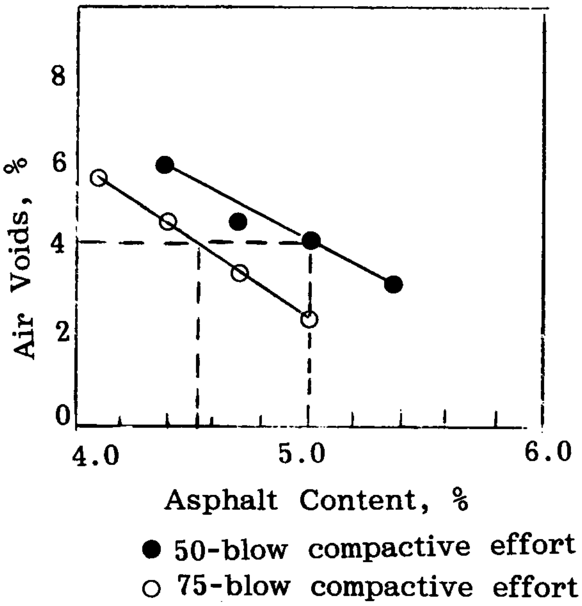

FIGURE 20 Relationship between compactive effort and air voids.

nearly simulates field compaction. Other compaction procedures used in this study were the Marshall hammer, a kneading compactor, a rolling wheel compactor, and the University of Arizona vibratory/gyratory compactor.

Irrespective of the laboratory-compaction procedure used, there is a relationship that exists between the laboratory density, asphalt content, and the ability to achieve density in the field. For example, if a mix is designed by the Marshall method using a 50-blow compactive effort, the optimum asphalt content might be 5.0 percent and the air voids 4.0 percent. If the compactive effort is increased to 75 blows and the optimum asphalt content is still chosen at 4.0 percent air voids, the optimum asphalt content will decrease, from 0.2 to 0.6 percent asphalt (Figure 20). The amount of the decrease is dependent on the sensitivity of the gradation to changes in asphalt content. It follows that the field compaction will have to be more efficient to achieve the same air-void level when the 75-blow laboratory compaction is used for mix design as when the 50-blow laboratory compaction is used.

Gradation can have a similar effect on the relationship between laboratory density and field density. Sand mixes, or those with fine, top-size aggregate, usually require a higher optimum asphalt content than coarse mixes. The finer mixes will also have higher air-void levels although the air voids are likely to be smaller than those in coarse mixes. As stated earlier in this chapter, it may be difficult to compact a fine-graded mix to a low air-void content.

CHAPTER FOUR

SPECIFICATIONS

The subject of specifications is sufficiently broad that three NCHRP syntheses have been devoted to the subject (*64–66*). Another NCHRP report, entitled *Development of Guidelines for Practical and Realistic Construction Specifications* (*67*), presents a thorough discussion of the rationale for specifications and is suggested if the reader would like additional information on this subject.

A brief description of various specification types might be helpful to understanding the various compaction specifications that exist. There are two basic types of specifications: method and end result. Although end-result specifications take many forms, the specification limits are usually intuitively derived or statistically based. Because specifications are produced through an evolutionary process, combinations of the different types are not unusual.

SPECIFICATION TYPES

Method

The method specification, which is the oldest type in use, puts maximum control in the hands of the buyer. The seller is required to follow step-by-step procedures using specified equipment and a required number of passes of the roller. A disadvantage of method specifications is that they do not allow a contractor to use the most economical or "innovative" procedures to produce the product sought. Another disadvantage is that the compaction process requires continuous, full-time monitoring to assure that the specified rolling is completed within the time and temperature limitations.

End Result

Specifications that require a stated level or end result of some particular property in a product have been used in lieu of or in combination with method specifications for years. The responsibility for the control of the process is assigned to the contractor. The limits for these specifications are usually derived intuitively from what the specification writer feels is achievable or are based on statistically derived population estimates.

Intuitively Based Limits

One of the most widespread and publicized uses of specification limits in intuitively based end-result specifications was in the AASHO Road Test. The limits used for field compaction were required to be a minimum of 96 percent of the laboratory-compaction results and were intuitively derived from the expert opinion of a panel of advisers to the road test. During the road test it was found that this minimum limit was so restrictive that 12 percent of the tests on the binder course and 19 percent of the tests on the surface course did not meet the specification limit (*68*).

Statistically Based Limits

To overcome the problem of end-result specifications being too tight and often lacking definition, the FHWA promoted studies in the 1960s to determine what process average and variability should reasonably be expected in a specification. These studies led to the use of terms such as "statistical end-result specifications," "statistically based specifications," and, more recently, "quality assurance programs."

Associated with specifications are such items as lot size, type, and number of tests per lot, average and variability of a lot, and price adjustment systems. Stating the responsibility for separate quality control and acceptance procedures is also a primary requisite for this type of specification.

PRESENT PRACTICE

A survey undertaken by Oregon (*69*) in 1979 points out the diversity of specifications, acceptance procedures, and "pay adjustment factors" at that time. At approximately the same time, an NCHRP synthesis on quality assurance (*65*) was published. This report contained information of specification types in use at that time. It reported that 32 of the 43 states responding to a survey used a combination of method and end-result specifications; 10 used method specifications; and 1, West Virginia, used only statistically oriented end-result specifications. Hughes reported in an ASTM paper (*70*) in 1978 that 25 state agencies had either a fully operational or an experimental statistical quality assurance specification for density. Since that report, Ohio and Minnesota have implemented a statistically based specification for compaction and the states of California (*71*), Nevada, and Texas have either tried one or are studying its use.

In 1983 the TRB Committee on Instrumentation Principles and Applications did a survey on the use of nuclear density gauges for measuring asphalt concrete compaction (*72*). One of the questions asked respondents to describe the compaction control specifications as end result, method, or a mixture of the two. Six states used a method specification on full-depth pavements and 16 used method specifications on thin overlays (1 to 2 in. thick).

In order to get a more up-to-date analysis of the types of specifications being used at present, a brief survey of the practice of 13 states was made for this synthesis. These states were chosen to obtain geographical diversity (Figure 21). (The two questionnaires, one for specifying agencies and one for contractors, appear in Appendix A.)

The results of a recent questionnaire concerning the effect of compaction on asphalt performance were reported to the 1989 TRB Annual Meeting by researchers from the state of Washington (*73*). This paper provides the most up-to-date information on specifications and practices used by the 48 state highway agencies that responded.

Method Specifications

There are several states that still use method specifications for compaction. Some also use an end-result specification as a supplemental specification. A fairly typical method specification requires a minimum of three passes with a 10-to-12-ton steel wheel roller, either three wheel or tandem, three passes with a pneumatic roller with a minimum wheel load of 2000 lb per wheel, and an 8-to-10-ton steel wheel roller to iron out roller marks for finishing. Modifications to this rolling requirement may consist of the use of a vibratory roller for breakdown using two to three passes in the vibratory mode and the same roller applying two passes without vibrations to provide intermediate rolling. The 8-to-10-ton steel wheel roller is usually required for finish rolling. If paving production is high, the vibratory roller may not be able to keep up adequately as a breakdown and intermediate roller.

In the survey of practice for this synthesis, one of the questions asked concerning roller weights was how often the roller weights are verified. The general response was that the roller is approved by its manufactured rating and is not actually weighed. In a method specification this would appear to be a potentially serious oversight. The roller should be weighed before it is approved to meet specifications.

Those agencies that use method specifications often think that this type of specification takes less inspection manpower than an end-result specification. The fallacy in this thinking is that for the specification to be satisfactorily enforced, continuous inspection is necessary to count passes and monitor time and temperature.

End-Result Specifications

Intuitively Based Limits

It is somewhat difficult to ascertain exactly how specification limits were derived and whether they are intuitively or statistically based. Given the fact that some states use a combination of a method specification and a minimum density requirement and others use only a minimum of some percent of laboratory compaction, it could be speculated that specification limits determined through engineering judgment are still being used. Specifications that allow acceptance based on single sample results are not likely to have statistically based limits because of the high probability of accepting an out-of-specification product.

A typical intuitively based end-result specification may require the field density to be a minimum of 95 percent of a standard density, often based on a 50-blow Marshall compactive effort. Field verification is often accomplished by coring with acceptance based on each core result. With the speed and convenience afforded by nuclear density gauges, these are often used in lieu of a coring requirement. Another popular measure of relative density uses the nuclear gauge and requires a minimum density percentage, usually 98 percent, of the average density obtained on a control strip.

The other basis for a specification is an absolute measure of a voidless mix or a percentage of the theoretical maximum density (TMD). A typical density specification might require a minimum of 92 percent of the TMD. However, the TMD can be determined experimentally by AASHTO T209 (the Rice method) or by calculating the TMD from the specific gravities of the components. Because the Rice method is determined on the mix produced, it is preferred for its accuracy (*24*).

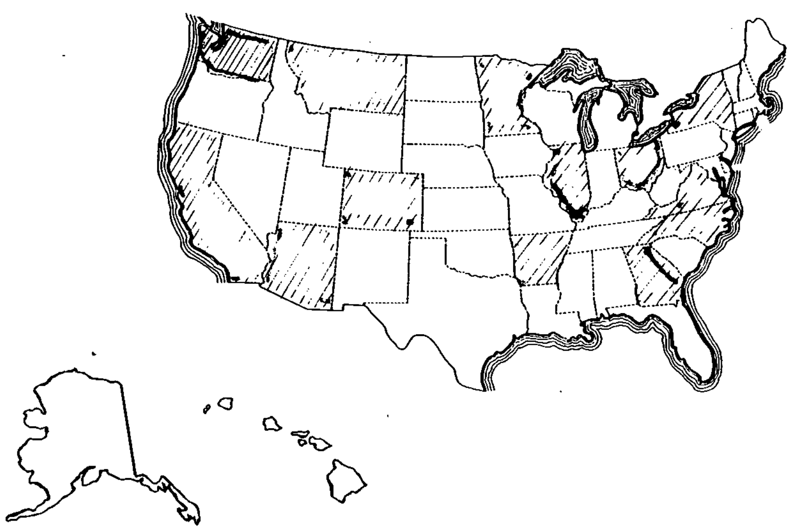

FIGURE 21 States contacted in survey.

Statistically Based Limits

These specification limits attempt to define the acceptable population of air-void percentages by establishing a target value and an acceptable level of variability, not just a minimum.

Most statistically based specifications stipulate some level of contractor responsibility for quality control of the product. This is often related to the use of nuclear gauges for monitoring density. This responsibility is definitive and separate from acceptance testing, which is normally the responsibility of the specifying agency.

Typical lot sizes are based on either tonnage (e.g., 2000 to 2500 tons), area (e.g., 1000 to 7000 sq yd) or time (e.g., a day's production). The number of tests per lot varies, depending on the lot size and the method of tests. As few as two cores per lot and as many as 20 nuclear tests per lot are not uncommon.

Most statistically based specifications have a minimum value that the average of a lot must meet and may be based on percent TMD; 92 percent is fairly typical. An additional parameter of the population that is specified is some measure of variability, typically standard deviation or range. Typical standard deviations have been reported by Kennedy et al. in a Texas study to be from 1.0 to 3.9 percent of the TMD with an average standard deviation of about 2.0 percent (*74*). Hughes found a slightly lower standard deviation of about 1.3 percent in Virginia (*75*).

The previously mentioned 1978 survey (*70*) found that 16 states that were not using statistically based specifications at that time for density were considering their use. It appears that 10 years after that questionnaire no more than five or six additional states have adopted statistically based specifications.

The 1980 Oregon report (*69*) indicates that of the 43 states that evaluate compaction, 27 had some type of price adjustment system. The report points out that there is a wide disparity between the agencies, with 10 different approaches being used for determining the pay factor. An example of this disparity is shown in Table 3. In addition, the agencies using the same approach have widely varying values for the pay factor applied to a common level of compaction. The Washington State report (*73*) concludes that a 10 percent loss in pavement life results for each 1 percent increase in air voids. This information could be useful in determining realistic pay schedules.

Although only a few contractors were contacted, those in states that use end-result specifications all prefer end-result specifications to method specifications. Their reasoning is that the former allow them to use their equipment and manpower more efficiently than the latter.

An additional benefit that accrues from the use of statistically based specifications is the ability to generate operation characteristics (OC) curves that describe the power of the specification to detect defective work.

Control Strips

One particular type of end-result specification that has become popular for controlling density is the control strip procedure. This procedure was first introduced in the 1960s (*76*) and combines the speed of testing afforded by the nuclear density gauge with statistical concepts. TRB Circular 32 (*72*) indicates that 18 state agencies use the control strip to establish the standard or target density to be used in the field.

Procedure

The author recommends the following approach for the control strip procedure. First, the contractor starts the project by placing a 500 ft strip that is designated as the control strip on the field site. Next, randomly selected nuclear density gauge readings are taken from three stratified locations on the strip after each pass of the roller. The density is plotted against the number of passes to develop a density growth curve, typically called the roller pattern. A typical roller pattern is shown in Figure 22. The maximum attainable density is defined as the density at which no significant increase in density (i.e., < 1.0 pcf per pass) is found with additional roller passes. Because nuclear density gauges provide relative densities that are dependent on aggregate type, surface texture, and depth of bituminous mix, as well as compaction equipment, the actual density should be determined at the conclusion of establishing the roller pattern. ASTM D 2950-82, "Density of Bituminous Concrete in Place by Nuclear Method," is recommended as a guide to

TABLE 3

COMPACTION PAY FACTORS FOR PERCENT OF TARGET DENSITY

Connecticut		Hawaii		Louisiana		Mississippi	
% Target	% Pay	% Target	% Pay	% Target	% Pay	% Target	% Pay
95-100	100	95-100	100	94-100	100	94.9-100	100
90-94.9	90	94-95	99	93-93.9	95	94.2-94.8	90
87-89.9	85	93-94	96	91-92.9	80	93.5-94.1	70
<87	70	92-93	93	<91	50	92.8-93.4	50
		91-92	85			<92.8	0
		90-91	69				
		<90	10				

North Dakota		South Dakota		Utah	
% Target	% Pay	% Target	% Pay	% Target	% Pay
97-100	100	95-100	95-100	96-100	100
96-97	97	94	90-95	92-95.9	90
95-96	93	93	80-90	<92	50
94-95	85	92	70-80		
<94	75	<91	40		

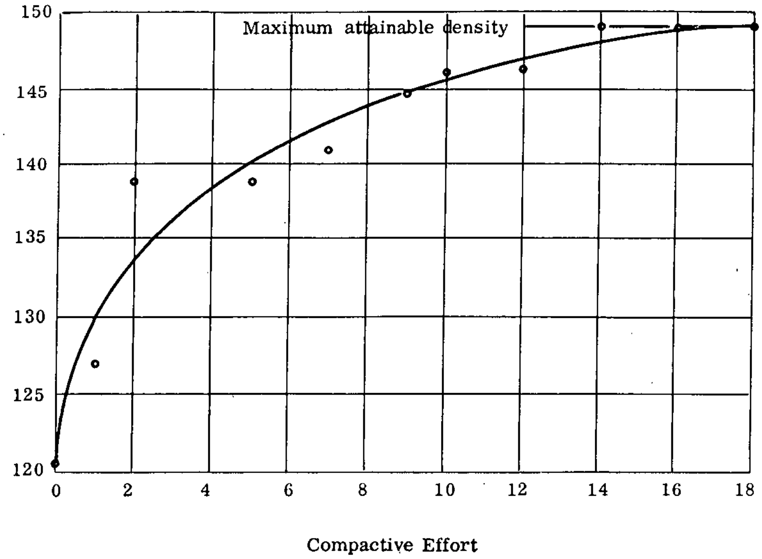

FIGURE 22 Density as a function of compactive effort (*76*).

converting nuclear density to actual density. This procedure recommends that seven cores and seven nuclear densities be averaged to determine the conversion factor.

Because the density obtained by the roller pattern will become the target density for the remainder of the project it is important that the level of density be adequate and that the level be determined with acceptable precision. Thus, the actual density as determined by averaging the cores should be at least 93 percent TMD. If this level of density cannot be reached, either another control strip should be constructed using an increased compactive effort or the mix should be analyzed for possible deficiencies. If the 93 percent TMD level of density is reached, 10 nuclear readings should be taken on the control strip, averaged, and with the use of the conversion factor, the target density established.

Acceptance of the remainder of the project should be in lots of 2000 ft called test sections. Each test section would require the average of five nuclear gauge tests to be at least 98 percent of the target density. Because some measure of variability is needed, limiting the standard deviation of the five tests to 2 percent is an effective way of accomplishing this.

California Practice

The California Department of Transportation (Caltrans) does not think that it is necessary to use cores to convert nuclear densities to actual densities and prefers to use standard calibration blocks for correcting nuclear density values. The Caltrans end-result procedure was introduced on an experimental basis in 1985 (*71*). An evaluation of the experimental specification reported (*77*) that 95 percent relative compaction, based on specimens compacted with a kneading compactor (California Test 375), is achievable with a reasonable effort on the part of the paving contractor.

The point to be made here is that there are a variety of procedures available for determining both in-place and maximum densities. It is important that the maximum density be determined and that the density test in the field be related to the percentage of the maximum density so that the level of air voids can be determined during construction.

JOINTS AND EDGES

Two areas in a pavement tend to receive less compaction than the rest of the cross section (*40*). These are the longitudinal joint and the unsupported edge. Foster et al. (*78*), in a study of longitudinal joints, reported that a density gradient was found at the longitudinal joint when the first lane paved was allowed to cool before paving the second lane. Values of density between the area immediately adjacent to the joint on the first lane paved were 5 to 7 lb/ft^3 (pcf) lower than the same area of the second lane paved because of the unsupported edge on the initial pass. The lower density at the longitudinal joint led the Federal Aviation Agency (FAA) to institute a price adjustment provision for joint density on a project-by-project basis. Dissatisfaction with this specification led to a study by Burati and Elzoghbi (*79*), who concluded that indeed "joint density values. . .are significantly lower than the mat density values." They also concluded that if percent compaction is to be based on laboratory Marshall density following the FAA procedure, a population mean and standard deviation of 93.5 and 2.1 percent, respectively, could be used to determine acceptance limits. This would allow the average air-void content at the joints to be as high as 8.4 percent. They recommend, however, that procedures using percent compaction be based on the in-place air voids as determined from the specific gravities of cores and that the TMD be based on Rice determinations. This approach as the basic concept for density acceptance is a good one.

In a questionnaire sponsored by TRB Committee A2F02 on Flexible Pavement Construction and Rehabilitation it was found that no state agency has a separate density specification for joints (*80*). The area of the longitudinal joint is sufficiently critical that attention should be given to proper density. A recent report sponsored by the National Asphalt Pavement Association

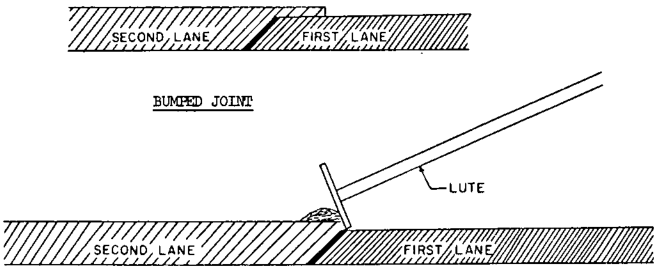

FIGURE 23 Overlapping and "setting up" a cold longitudinal joint (*78*).

entitled "Improving Performance of Longitudinal Construction Joints in Hot Mix Asphalt Pavements" (*81*) emphasizes the importance of adequately compacted joints and is recommended for additional information on this subject.

New Jersey has recently completed a study (*82*) that has led to the requirement of a wedged longitudinal joint to improve durability. Several other states indicate (*80*) that they are considering specific construction practices to improve the performance of the pavement at the longitudinal joint.

The paving practice in many states is to pave one lane at a time. When this occurs, the first lane paved is cold and the unsupported edges have a high percentage of air voids by the time the adjacent lane is paved. Reducing the air voids on the edge of the first lane paved is very difficult. Removal of the low-density edge is possible but seldom done, as is reheating the cold edge (*80*). Paying particular attention to the construction process in the vicinity of the joint can improve joint durability. When safety allows, the following practices are recommended if a cold longitudinal joint is constructed:

- Keep the paver close to the previously constructed lane. An overlap of no more than 1 to 2 in. wide should be consistently maintained.
- Push the overlapped material to a vertical position just adjacent to the joint with a lute. Do not push the overlapped material across the lane being placed (Figure 23).
- Use the first pass of the breakdown roller to "crowd" the overlapped material to a position even with the previously constructed lane while the material is still hot.
- Apply an extra pass or two to the 12-to-18-in. area adjacent to the joint.
- Use the proper rolling procedure applicable to static or vibratory rollers.

When traffic is traveling adjacent to the paving, it is unsafe to use the above approach. In that case, using a wedge joint, as required by New Jersey, or maintaining the overlap of 1 in. without the use of a lute are possible ways of improving joint durability.

CHAPTER FIVE

EQUIPMENT

PAVERS

The initial density of the asphalt concrete mat is provided by the paver screed. This initial density influences the amount of additional density that can be obtained during rolling. Mechanized spreading of hot asphalt mix dates back only to the 1930s (*83*). The early paving machines used a tamping-bar type of screed for compaction. Modern pavers use vibratory screeds, which tend to place a higher-density, smoother mat when the paver is operated such that the compacting forces at the screed are maintained at a reasonably constant level. Some of the factors that affect the forces on the screed are (a) speed of the paver, (b) uniformity of material fed to the auger and, hence, the screed, and (c) thickness of mat being laid.

The air-void content in the mat immediately behind the paver depends on mix type, laydown thickness, mix temperature, etc., but a general range of 15 to 25 percent is typical. Increasing the compactive effort of the screed on the paver will, in general, decrease the amount of compactive effort needed from the rollers.

ROLLERS

As mentioned in Chapter One, steel wheel rollers date back to about 1875, with gasoline-powered rollers being introduced in the mid 1920s. There are three basic types of rollers in use at present: (a) static steel wheel rollers, (b) pneumatic or rubber tire rollers, and (c) vibratory rollers.

Static Steel Wheel

The tandem steel wheel roller has been popular throughout the entire 20th century; modifications, such as adding a third axle to improve smoothness, have been tried but have not been successful.

Two very good references on compaction with steel wheel rollers are HRB Bulletins 246 (*1*) and 251 (*84*). What Parker (*1*) calls two-axle "tricycle" type rollers, now commonly called three-wheel rollers, have retained their popularity, and after several years of manufacturer dormancy they are being manufactured again. The three-wheel rollers are popular because with the large diameter and relatively narrow width of the rear wheels they exert a high compactive effort, tend to overcome the "bridging" that may occur with tandem rollers, and are highly regarded as being effective in "pinching" the longitudinal joint. Some asphalt technologists have been concerned about the compactive effort applied by the rear wheels being appreciably higher than that applied by the leading drum and the possible nonuniform transverse compaction this can cause unless the rear wheels are lapped uniformly across the pavement. With the width of each of the rear wheels on the order of 20 in. and the total width of the roller being approximately 78 in., it will take five passes to obtain full coverage of a 12 ft lane with a reasonable wheel overlap. Parker makes a good argument for the benefit of large-diameter rolls (wheels), which at the time of the article (1960) favored three-wheel rollers. (Some currently manufactured three-wheel rollers have the same 60-in.-diameter rolls on all three wheels.) As he further states and several states in their specifications agree, the compressive force applied by a steel wheel roller should be in the range of 250 to 350 lb/lin in. of roll.

Tandem steel rollers are popular because of their versatility in being used directly behind the paver in the breakdown position and as a finish roller.

Pneumatic

Tractor-drawn pneumatic tire rollers were used as early as the late 1930s (*2*). It was not until the early 1950s that the self-propelled pneumatic tire roller was routinely used to compact hot-mix asphalt. Toward the late 1950s, variable air pressure rollers called "air-on-the-run" were developed. This development enabled the operator to vary the tire inflation pressure, and thus the tire contact area, to suit the stability of the mix as rolling progressed. This proved to be more useful theoretically than practically (*85*). The basic seven- or nine-wheel pneumatic rollers have retained their popularity over the years.

A very informative discussion of pneumatic tire rollers by Geller (*86*) states, "Pneumatic tire rolling has had strong advocates but there have been a number of reports that did not carry the same strength in their conclusions." He goes on to say, "It appears that pneumatic rollers and static steel wheel rollers do exert the same range of pressures. Therefore, the differences in the respective performances have to do with shape of the contact area, the size of the contact area for a given pressure, and the difference in the macro surface texture developed by steel versus rubber."

A very real concern, particularly when the pneumatic roller is used in the breakdown position, is to prevent asphalt from adhering to the tires. Geller states, "This tendency is minimal when the tire temperature approaches the temperature of the mat, but it is sometimes difficult to maintain the tires at proper temperature during job circumstances. As a solution, diesel fuel is an effective release agent, but is objectionable because of the inherent risk to the fresh pavement if it is not used carefully."

As for advantages and unsubstantiated claims, these comments taken from Geller are pertinent:

- Pneumatic tire rollers do have the advantage of being able to eliminate hairline cracks and checks, which are probably more unsightly than physically detrimental. When these cracks exist, pneumatic tire rollers are ideally used as a finishing roller working just behind the breakdown roller. When used in this manner they usually operate on a temperature zone that does not involve pickup of material.
- For harsh mixtures, the pneumatic tire roller has not demonstrated any particular advantage over static steel wheel rollers. Claims for decreasing the permeability of mixes by using pneumatic tire rollers are not well supported by evidence of permeability tests conducted on pavement sections compacted with static steel and pneumatic tire rollers.
- There is a visual difference in the surface texture of the mat when rolled by a pneumatic tire roller compared with a steel wheel roller. But this difference gradually disappears with time as traffic compacts the surface.
- Pneumatic tires have a greater tendency to deform an unsupported edge than steel wheel rollers do.
- Claims for the benefits derived from the kneading effect of a pneumatic tire roller are also not especially well substantiated in test report literature. Unless there is a substantial penetration of the tire into the mix, the kneading or manipulative effect of a pneumatic tire roller is limited to the upper layer of the lift.

Two reports from California indicate that pneumatic compaction is important in reducing permeability and air voids. The positive results reported by Zube (*38*) have already been discussed. Schmidt et al. (*87*) found that intermediate pneumatic compaction at high pavement temperatures resulted in a denser mat than was obtained with steel wheel rolling alone. It was concluded that high density, low permeability, low air voids, and highly durable pavements can be obtained with the use of a pneumatic roller for intermediate compaction of a mix at high temperatures (> 195°F).

Serafin and Kole (*88*) found that a tighter-looking surface texture results from pneumatic tire rolling.

It seems logical that the results of compaction by pneumatic tire rollers should be influenced by the contact pressure. Figure 24 shows that the contact pressure is determined by wheel loads and tire inflation pressure, which in turn is affected by ply rating and tire size.

In 1959 Louisiana (*89*) conducted a study that used pneumatic rollers with contact pressures from 55 to 85 psi. One of the conclusions from this report was, "In order to obtain maximum compaction of asphalt-concrete pavement capable of withstanding high volumes of traffic, it is necessary to: (a) select an adequate combination of contact pressure—number of passes of the pneumatic roller which is representative of the contact pressures encountered in service, and (b) obtain through adequate laboratory design an optimum asphalt content." With present-day truck tire pressures as high as 120 to 135 psi, it would take a heavy pneumatic roller to produce representative contact pressures.

With the importing of vibratory rollers from Europe in the late 1960s and their domestic manufacture in the early 1970s, attention was diverted to the higher densities arrived at by using vibrating rollers and away from the use of pneumatic rollers. However, with the recurrence of rutting in the 1980s, attention is again being given to the use of pneumatic rollers to simulate the compaction stresses imparted by the heavy truck loads.

Thus the reemergence of the pneumatic roller is being observed at the present time. Of the 13 states contacted, contractors in California, Colorado, Georgia, North Carolina, and Ohio typically use pneumatic rollers, some even if they are not required by the state DOT. Other states, such as Virginia, are investigating the potential of improved compaction on joints and reduced transverse variability with the use of pneumatic rollers with ground contact pressures (GCP) of 80 psi or above (Figure 24). Montana has a provision in its specifications that

	50	55	60	65	70	75	80	85	90	95	100	105	110	115	120	125	130	INFLATION PRESSURE
WHEEL LOAD	6 PLY RATING ——>								7:50×15						——> 14 PLY			TIRE SIZE
2500 lb	57				67				73				80				90	Contact psi
1134 kg	4				4.7				5.1				5.6				6.3	pressure kg/cm²
3000 lb	60				70				77				85				94	Contact psi
1361 kg	4.2				4.9				5.4				6.0				6.6	pressure kg/cm²
3500 lb	62				73				81				88				98	Contact psi
1588 kg	4.4				5.1				5.7				6.2				6.9	pressure kg/cm²
4000 lb					76				84				91				101	Contact psi
1814 kg					5.4				5.9				6.4				7.1	pressure kg/cm²
	16 PLY RATING								9:00×20									TIRE SIZE
4000 lb	57					68			75			81			88			Contact psi
1814 kg	4.0					4.8			5.3			5.7			6.2			pressure kg/cm²
5000 lb	61					72			78			85			93			Contact psi
2268 kg	4.3					5.1			5.5			6.0			6.6			pressure kg/cm²
6000 lb	65					75			82			89			96			Contact psi
2722 kg	4.6					5.3			5.8			6.3			6.8			pressure kg/cm²
	18 PLY RATING								11:00×20									TIRE SIZE
5000 lb							74		79			86			93			Contact psi
2268 kg							5.2		5.6			6.1			6.6			pressure kg/cm²
6000 lb							77		82			88			95			Contact psi
2722 kg							5.4		5.8			6.2			6.7			pressure kg/cm²
	26 PLY RATING								1300:×24									TIRE SIZE
6600 lb	74						85					96			108		118	Contact psi
2994 kg	5.2						6.0					6.8			7.6		8.3	pressure kg/cm²
10000 lb	80						91					101			114		124	Contact psi
4536 kg	5.6						6.4					7.1			8.0		8.7	pressure kg/cm²

FIGURE 24 Typical contact pressures, pneumatic tire rollers (*86*).

allows it to require a pneumatic roller on mixes that it identifies as "difficult to achieve adequate density." The FHWA Technical Advisory T5040.27 (*24*) states, "The use of pneumatic rollers in the compaction process is strongly encouraged. When used in the intermediate rolling it will knead and seal the mat surface and aid in preventing the intrusion of surface water into the pavement layers. It will also contribute to the compaction of the mat."

Vibratory

Vibratory rollers were introduced in the United States in the 1960s. This type of equipment became probably the most widely investigated in the history of asphalt compaction. Virginia (*90*), Kentucky (*91*), California (*92*), Louisiana (*93*), and New York (*94*) are examples of some states issuing reports on vibratory compaction between 1970 and 1977. A symposium (*95*) held at the 1977 AAPT annual meeting produced many excellent papers on vibratory rolling, both from users and manufacturers.

Dillard (*96*) reports on the use of a German-manufactured self-propelled vibratory roller (ABG) on test sections in Virginia in 1960. This report does not include critical information such as vibrating frequency, amplitude, or speed, about which very little was known at that time. In fact, *Highway Research Board Special Report 131: State of the Art: Compaction of Asphalt Pavements,* dated 1972 (*97*), states, "Vibratory rollers are becoming popular as a tool for compaction. However, at this time insufficient knowledge is available to draw intelligent conclusions." In April 1982, the TRB committee on Flexible Pavement Construction updated *HRB Special Report 131* to include information on vibratory compaction (*98*). This publication references more than 14 papers on the subject of vibratory compaction. Several comments in this publication are pertinent to the discussion of the early dissatisfaction with vibratory rollers, and it also includes definitions and discussion of factors, such as the amplitude and frequency of the vibration and travel speed, that must be controlled for vibratory compaction to be successful. Some of these comments are paraphrased below:

- Early attempts at using vibratory rollers to compact asphalt pavements were often unsatisfactory in terms of pavement density, surface smoothness, or both.
- The early vibratory rollers were designed to compact soil and granular bases, so it is not surprising that they were used improperly with asphalt.
- Perhaps the most important lesson that has been learned is that to use a vibratory roller effectively, the roller has to fit the circumstances of each job. . . .All vibratory rollers do not fit all jobs.
- The important features of vibratory rollers that influence compaction are frequency and amplitude of the vibration, which must be present in the proper relationship to each other and to travel speed if the roller is to be used effectively.
- Well-trained personnel are needed to use vibratory compaction properly. Because vibratory rollers are more sophisticated than static rollers, additional training beyond that necessary for static rollers is needed.

Geller (*99*) describes some of the concerns peculiar to using vibratory rollers as follows:

> The operators need more discipline than do operators of static rollers in carrying out the roller pattern. The selection of the wrong force level, rolling too fast, and making too many vibratory passes, especially on thin lifts, all have the potential to cause problems such as roughness. Current vibratory roller designs have numerous features to assist the operator in maintaining roller pattern discipline, and this trend is increasing and the features are improving.

There is no question that vibratory rollers have made a large impact on the compaction train in present-day asphalt paving. Although some states such as California and New York (*100*) qualify vibratory rollers, no states are believed to disallow them. However, this does not mean that there are no opponents of vibratory rollers. At least two of the contractors interviewed for this synthesis do not use vibratory rollers in their compaction train. They prefer either a three-wheel or a tandem steel wheel. There are also some state engineers who prefer static rollers. The typical criticism often centers around two points. The first is the compaction of thin lifts, e.g., less than $1^1/_2$ in. With the greater compactive effort provided by large vibratory rollers, it is possible to overcompact these thin lifts very quickly (*101*). The other criticism is the typical lack of training of the operator. As mentioned earlier by Geller, more operator discipline is necessary for vibratory rollers.

The question of whether overcompaction was considered a problem was asked in the interview to the state agencies. Ten out of 13 did not consider it a problem. Three said that it can be a problem with vibratory rollers.

As a guideline, when compacting thin lifts, the highest frequency (at least 2000 vibrations per minute) and the lowest amplitude available should be used. Also, the speed should be controlled so that the number of impacts is about one per in. Depending on frequency, this may be about 3 mph. Kennedy et al. (*101*) show the influence of various pavement and mix parameters on the amplitude to be used (Figure 25).

LOWER 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

HIGHER AMPLITUDES

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

FIGURE 25 Guidelines for selecting the amplitude of vibration (*101*).

CHAPTER SIX

CONSTRUCTION INFLUENCES

As stated in Chapter Three, there are factors other than material properties and equipment that affect the reduction of air voids. The list of factors given by Epps et al. in Figure 9 uses the categories of environment, lift thickness, and subgrade support.

ENVIRONMENT

Dickson and Corlew (*102*) studied the thermal environment that controls the transfer of heat from the hot-mix asphalt concrete to its surroundings. It consists of (a) atmospheric temperature, (b) wind velocity, (c) solar radiant flux, (d) initial temperature of the mix, (e) initial base temperature distribution, and (f) thickness of lift. They show in this study that the heat loss to the base exceeds that to the atmosphere; thus, the temperature distribution of the entire mat with time is of importance when considering compaction. Base temperature, laydown temperature, air temperature, and mat thickness are the four most important factors affecting cooling rate. Using appropriate values for solar flux and wind velocity, they developed a family of cooling rate curves for various paving conditions.

It is generally agreed that with a normally behaving mix, the ability to reduce air voids during construction becomes appreciably more difficult at about 175°F. (This temperature is used as a rule of thumb and is dependent on the viscosity of the mix.) It is generally agreed that below this temperature very little, if any, additional compaction can be obtained after the initial reduction in air voids. As stated, the base temperature is more important than the atmospheric temperature, and in a subsequent study, Dickson and Corlew (*103*) show that the moisture in the base is more important than the temperature of the base, because the former, acting as a large heat sink, requires higher laydown temperatures to provide sufficient time to cool to a specified temperature.

The cessation limit approach determines the length of time available for rolling before the mat temperature reaches a predetermined cessation temperature. This use of this limit was a great improvement over specifications that prevent paving when air temperatures are below a certain level or those that do not allow paving after a certain date. The cessation limit approach allows the time for rolling to be determined when the base temperature, laydown temperature, and lift thickness are known.

If the base temperature or thickness is such that shorter periods of time are available for rolling before the mat temperature reaches 175°F, more breakdown rollers can be used. Another alternative to compensate for cold base temperatures is to increase the lift thickness to meet the temperature-time limitations.

In addition to the laydown temperature being too low to allow the proper air voids to be reached, it is possible for the laydown temperature to be too high. This is usually only a serious problem when rolling tender or, according to Schmidt, "critical" mixes. One of the ways to classify a mix as being tender is that it is unstable under the breakdown roller. When a mix of this type is encountered, the only alternative at the compaction stage is to allow the mix to cool so that it will develop sufficient stiffness to support the roller. The chances of reducing the air voids to an acceptable limit in mixes of this nature are greatly reduced.

On normal mixes, high laydown temperatures, i.e., those above 300°F, may not be detrimental to compaction, but very likely harden the asphalt and decrease the life of the mix from a durability standpoint.

There is one additional aspect to pavement temperature that should be discussed. That is the temperature at which the pavement is opened to traffic. Much of the maintenance overlay paving is done with traffic ready to use the road as soon as the traffic controls are removed. Thus, there is a tendency to open the road to traffic as soon as possible. When the traffic is allowed on the freshly placed mat, if the surface temperature is above 160°F, the traffic will act like many pneumatic rollers, continuing the compaction process and creating early rutting. The pavement should be allowed to cool naturally, or with the aid of water (*104*), to about 150°F before traffic is allowed on it. A hand-held infrared thermometer is a handy tool for making temperature measurements of the surface.

LIFT THICKNESS

Lift thickness is important from three standpoints: (a) the absolute thickness of the lift being compacted, (b) the thickness in relation to the largest size of aggregate in the mix, and (c) the uniformity of the thickness.

The absolute lift thickness has a strong influence on the time available for obtaining the proper air voids. The thicker the lift, the slower the mixture will cool, the more time is available for compacting before the temperature has decreased to the cessation limit. Thin lifts lose heat very quickly, significantly decreasing the time available for compaction. From Dickson and Corlew (*102*), for a 1 in. lift thickness having a laydown temperature of 300°F and lying on a base with a temperature of 60°F, less than 7 min is available to obtain the density (Figure 26). Figure 27, from Tegeler and Dempsey (*105*), shows that a 6 in. lift placed at 300°F on a base temperature of 40°F and air temperature of 32°F will take two hr to cool to 175°F. A 3 in. lift under the same conditions will take approximately 35 min

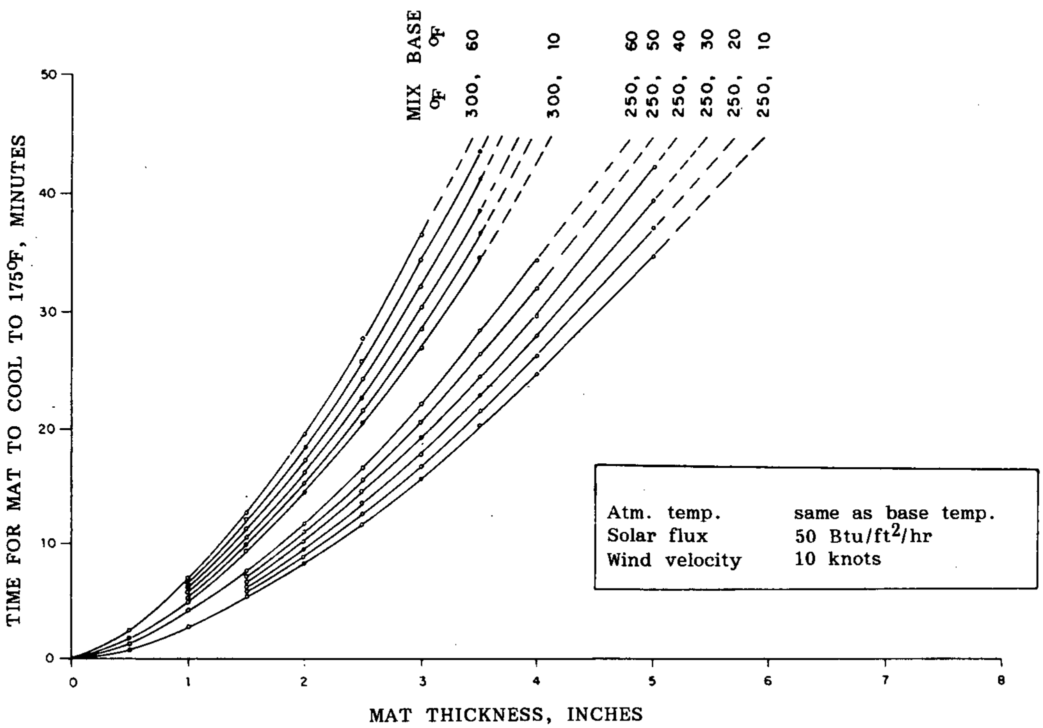

FIGURE 26 Time for mat to cool to 175°F versus mat thickness for lines of constant mix and base temperatures (*102*).

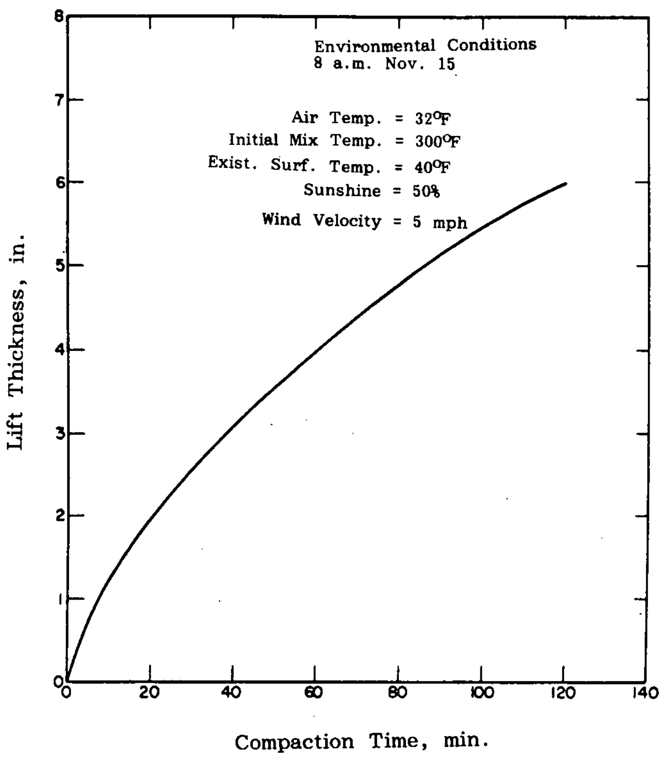

FIGURE 27 Effect of lift thickness on compaction time (*105*).

to cool to 175°F. This curve agrees well with the Dickson and Corlew work.

The relationship between maximum aggregate size and lift thickness is important when trying to obtain the desired density. Epps et al. (*12*) and Scherocman (*44*) suggest for density and smoothness, the maximum aggregate size should not exceed one-half the course thickness.

The uniformity of the thickness of the mat is related to the uniformity of density that can be obtained in the mat. As an example, if a thin overlay (i.e., less than 2 in.) is placed over a pavement with ¾ in. ruts, the depth differential of the mat being placed will affect the density. One of two possibilities will occur. Most likely the roller will bridge the rutted areas producing a smooth cross section but an appreciable variation in transverse density. The other possibility is to obtain a more uniform density transversely but produce a cross section that reflects at least some of the original ruts. Thus, in order to achieve a more uniform density, ruts greater than ½ in. should be removed before overlaying.

SUBGRADE SUPPORT

In specifications with price adjustment factors, the question of the importance of subgrade or base support often arises when attempts to obtain the specified density fail. It is logical to assume that the stiffness of the material being compacted against is important. The analogy often used is that an asphalt mix cannot be compacted if that mix is placed on a mattress.

Arizona was recently faced with determining the importance of the sublayer support on the ability to achieve density. Scherocman (*44*) did a literature survey and subsequently wrote a state-of-the-art report on this subject. The report concludes that "...the level of sublayer support on a given project plays only a minor role in the ability of a contractor to attain density in the newly placed asphalt concrete layer. With proper modifications of his compaction equipment and his rolling technique, it is believed that the paving contractor can achieve adequate density even on a relatively weak sublayer course." The report indicates that obviously the magnitude of the problem is closely related to how difficult the density specification is to meet and how strictly it is enforced. If the specification is difficult to meet and is strictly enforced, the contractor is more likely to seek relief using the lack of subgrade support as a possible cause for not achieving density.

A study reported by Graham et al. (*106*) from New York used Benkelman beam rebound deflections under a 22,400 lb, single-axle load as one factor in a regression equation to predict air voids. This analysis indicated that of seven factors, only the volume of asphalt content was more important than rebound deflection in its influence on the percentage of air voids. They found the higher the Benkelman beam deflections were, the higher were the percentage of air voids. Initial deflections at the time of construction were not obtained, but the analysis was based on deflections obtained two years after construction. The absence of initial deflection information cast some doubt on the relationship between deflection and air voids.

A laboratory study of compaction by Swanson et al. (*107*) measured the unit weights of a 2-in.-thick layer of asphalt concrete on three different base supports. The base support was termed K, the modulus of support reaction in pounds per cubic inch. Values for K of 100, 300, and 2000 simulated by 1-in.-thick pads of foam rubber, urethane elastomer, and hard rubber, respectively, were used. Figure 28 shows the results of the unit weights on K values of 100 and 2000 and led to the conclusion that "the effect of the stiffness of base support on the compaction process of a 2 inch bituminous concrete mat was found to be small, although the harder bases gave slightly higher densities and stabilities."

In the study of Epps et al. (*12*), no trend between pavement density and subgrade support was found.

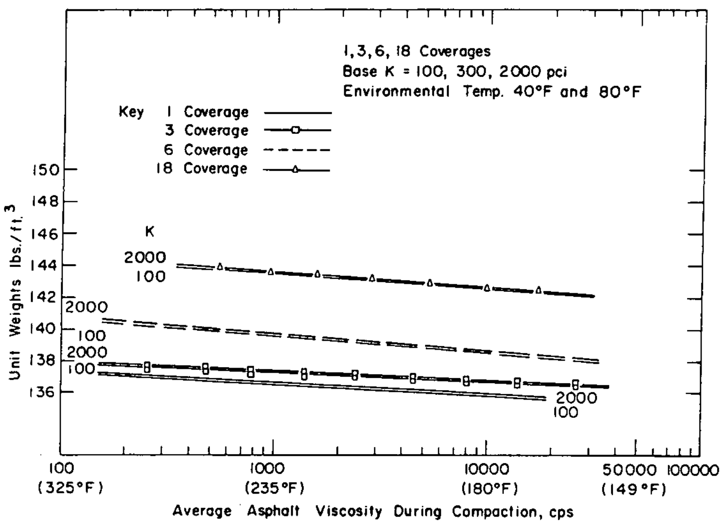

FIGURE 28 Unit weights versus average asphalt viscosity, rubber roller (*107*).

CHAPTER SEVEN

DENSITY MEASUREMENTS

There are two general classes of field density measurements, destructive and nondestructive.

DESTRUCTIVE MEASUREMENTS

Sampling

There are three primary methods of removing samples from the compacted pavement for the measurement of density: cores, sawed samples, and split ring.

Coring is probably the most popular method of removing samples from the road for density testing. Truck- or trailer-mounted core drills are readily available in most highway departments. Although core barrels are available in many diameters, the 4 in. core is probably the most popular because after testing it for density, various standard strength tests can be made on the sample. The one disadvantage to coring is that water usually is used in the process, which may delay testing if the core sample must be dried before performing the test.

To overcome this disadvantage and to allow quick field determinations of density, sawed samples that are cut with the aid of a cooling material such as dry ice can be used to produce a usable sample (*108*). Virginia follows a procedure in which dry ice or CO_2 is used to cool the pavement immediately after rolling. A power saw equipped with a Carborundum blade is then used to cut a sample that can be used for a density measurement.

Split rings are inserted in the pavement behind the paver. They are placed before rolling to make the sample easy to remove without coring. Problems associated with inserting the ring in the pavement, the height of the ring in relation to the thickness of the lift being sampled, and the confining effects of the ring have virtually eliminated its use.

Density Tests

Once the sample has been removed from the pavement, the most common method of determining the bulk specific gravity is the saturated surface-dry (SSD) procedure, ASTM D 2726. This is a quick test and can be conducted in the field if the sample has not been taken with the aid of water (*108*). Once the bulk specific gravity has been determined, either the relative percent compaction or the percentage of air voids can be determined. For mixes with relatively high air-void contents, the bulk specific gravity can be determined using paraffin-coated specimens, ASTM D 1188. This method is more time consuming than the SSD procedure and for this reason is not used often for the acceptance or control of density.

NONDESTRUCTIVE MEASUREMENTS

Nuclear

As discussed in Chapter Four, the use of nuclear gauges grew rapidly during the 1970s. The short test time for nuclear testing allowed sampling frequencies to be increased and made the control strip procedure for controlling density practical. It also provided contractors with density information while the asphalt concrete was still hot enough to compact further when necessary. In the TRB survey of 1983 (*72*), 28 states used nuclear tests and 9 used cores exclusively for measuring density. Eight others used a combination of nuclear tests and cores.

The use of nuclear gauges has expanded to two additional areas recently. The first is the thin lift gauge. Many of the states that responded to the 1983 survey that used nuclear gauges with an end-result specification for full-depth compaction used a method spec or cores for thin lift (< 1.5 in.) compaction control. With recently available thin lift gauges that read only to about 2 in. depths, the use of nuclear gauges on thin lifts will increase. A recent federally funded research project is comparing thin lift gauges with the older types of gauges and also is evaluating the other new gauge technology, which is termed "roller-mounted gauges." These gauges allow the roller operator to determine when the desired compaction level has been attained. Both of these areas of gauge development will be of interest in the measurement of density.

Even with properly calibrated nuclear gauges, field conditions such as aggregate type and surface texture may not correspond to the calibration conditions, and thus nuclear results are considered by many to be relative measures of density (*109*). Because these measurements are relative, a statistically valid correlation with core results, which can be related to air voids, is often undertaken when starting a project. Some states, such as California, recognize that nuclear density is usually lower than core density and use a lower relative compaction requirement.

Permeability

The quantitative measurement of air voids is certainly important. However, many engineers are equally concerned about the distribution of air voids and particularly whether they are interconnected. Permeability tests using both water and air have been studied in past years as a measure of the degree of interconnected voids.

Zube (*38*) proposed a simple and rapid test for measuring the tendency of surface water to enter the pavement. Measuring the quantity of water applied inside a ring formed with grease, a

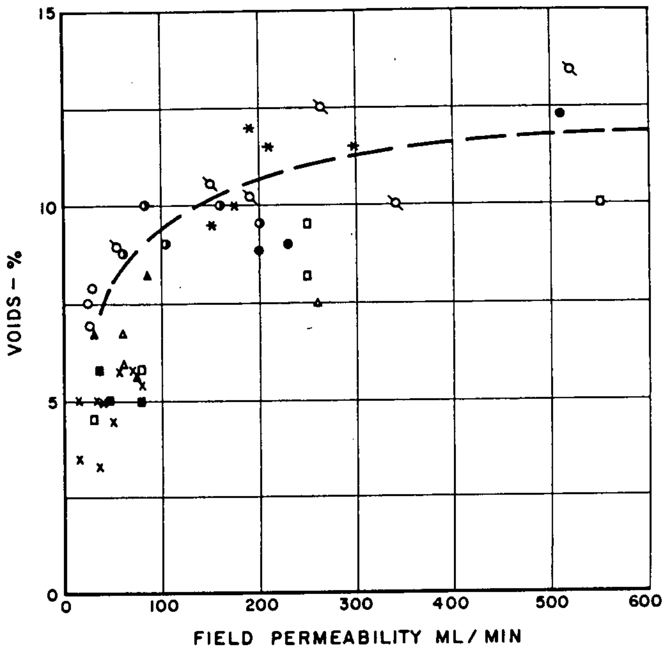

FIGURE 29 Permeability—voids relation for 10 different projects (*38*).

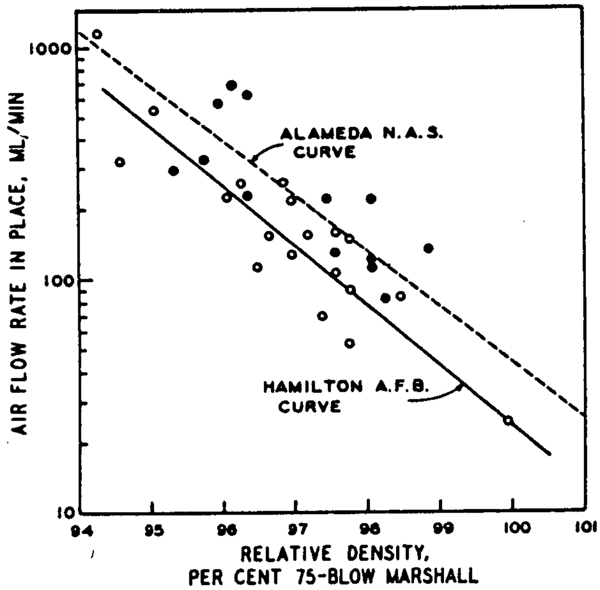

FIGURE 30 Air flow rates used to predict relative density of cores (*110*).

correlation was developed between field permeability and the percentage of air voids (Figure 29).

Air permeability measurements were popular in the 1960s (*87, 110, 111*). However, the conclusions of these reports were not always consistent. Kari and Santucci (*110*) developed a correlation between air permeability (flow rate) and relative density (Figure 30). An ASTM paper by Hein and Schmidt (*111*) indicated that void contents are not necessarily proportional to permeability.

Generally speaking, permeability tests have been considered more applicable for research purposes than for field control.

CHAPTER EIGHT

TRENDS

There are two broad areas in which trends in compaction are apparent. One is in specifications and the other is in equipment.

SPECIFICATIONS

Specifying agencies are moving in the direction of end-result specifications for compaction. The evolution appears to be toward the more defensible statistically based specifications. One area in particular in which end-result specifications appear to be growing is in the compaction of thin lifts, particularly overlays. Several states have relied on method specifications for density of thin lifts because a test method that is readily able to be implemented has been either unavailable or highly questionable. Great care is required to remove a core of less than 1½ in. thickness from a freshly laid pavement without disturbing it. Nuclear gauges in the past have been sufficiently influenced by the density of the underlying layer so as to raise questions about the accuracy of the measurement of the density of the top lift. The development of the thin lift nuclear gauge is an attempt to answer these questions, and it is one reason states are rethinking the issue of statistically based end-result density specifications for thin lifts. Because the specifications and the accompanying pay factors vary a great deal from state to state, it would seem logical to try to reach a consensus on a national basis.

In the author's opinion, some correlation is needed between the density obtained by nuclear testing and either the TMD or standard laboratory density of the material.

EQUIPMENT

The use of vibratory rollers has continued to increase since their introduction in the 1970s. No indications are evident that their use will decrease. Their versatility of compacting in both vibrating and static modes makes them suitable for vibrating thick lifts and, if necessary, for applying static compaction on thin lifts.

Because of the increase in rutting failures brought on by heavy traffic loads and high tire pressure, the use of pneumatic rollers in the intermediate and even finish position (*112*) to help mitigate this failure mode has been increasing. The concept of obtaining as close to the ultimate density as possible before opening the road to traffic appears to be gaining momentum, at least partially because of rutting problems.

CHAPTER NINE

CONCLUSIONS AND RECOMMENDATIONS

Geller (*112*) states, "Compaction is the most economical alternative for achieving an increase in the life expectancy of new and rehabilitated pavement." The information presented in this synthesis totally supports this statement.

From the information presented herein, the following conclusions and recommendations are offered.

CONCLUSIONS

- Compaction is the single most important factor that affects pavement performance in terms of durability, fatigue life, resistance to deformation, strength, and moisture damage.
- The relationship between the use of the proper asphalt content and the level of compaction attained is extremely important, particularly on high-traffic roads.
- Material properties play an important role in the ability to achieve the proper level of compaction. Of these, aggregate gradation and particle shape and asphalt content are the most important. Their interaction and relationship to density can only be determined with a rational mix design procedure.
- It is important that the compactive effort used in the laboratory to determine the optimum asphalt content be related to the traffic loadings that exist in the road.
- A realistic, defensible compaction specification is necessary to define the level of density required. In this regard, statistically based end-result specifications appear to be the most useful type.
- When vibratory rollers are used, it is important to control and coordinate amplitude, frequency, and travel speed.
- Pneumatic rollers are being viewed as valuable tools in minimizing rutting under traffic.
- The length of time available for compaction is primarily determined by base temperature, moisture in the base, laydown temperature, and lift thickness.
- Nuclear density testing, correlated with cores, is a convenient method of controlling density.
- The viscosity-temperature relationship is an important factor in determining the compaction temperature that should be used.

RECOMMENDATIONS

- Because compaction is so important to performance, the use of a realistic specification is necessary.
- Realistic target values for density using a statistically based end-result specification are an average of 93 percent TMD and a standard deviation of 1.5 percent TMD.
- Nuclear density gauges should be correlated to cores at the beginning of the job. After this correlation, nuclear tests can be used to measure density. (See Chapter Seven.)
- When pneumatic tire rollers are used, the Ground Contact Pressure (GCP) should be determined. If it is desired to approach the tire pressures of tandem trucks, a minimum GCP of 80 psi should be required. (See Chapter Five.)
- Control strips are a good way of establishing the proper rolling pattern for the equipment being used. The maximum attainable density should be established and related to either TMD or a standard laboratory density.
- Special attention should be given to constructing and compacting longitudinal joints so that early joint deterioration does not occur.
- When traffic will be turned on the pavement soon after compaction, the surface temperature of the mix should be reduced to 150°F before the lane is opened. An infrared thermometer is convenient for making this measurement.

GLOSSARY

Air voids The total volume of air between the coated aggregate particles in a compacted paving mixture expressed as a percent of the bulk volume of the compacted mixture. Also called voids total mix.

Compactive effort The energy or work used in the compaction process.

Consolidation The additional compaction that takes place under traffic. The resultant reduction of air voids is not accompanied by lateral displacement.

Density The weight per unit volume of material, often in pounds per cubic foot. [It is common practice in the engineering profession to concurrently use pounds to represent both a unit of mass and of force. This usage implicitly combines two systems of units, that is, the absolute system and the gravitational system. The recording of density in pounds (force) per cubic foot should not be regarded as nonconforming, although the use is scientifically questionable. Pounds (force) per cubic foot is also referred to as unit weight.]

Percent of laboratory compaction A relative measure of density, in which the density of the field-compacted material is expressed as a percent of density of samples compacted by a standard laboratory-compactive effort.

Specific gravity The ratio of the weight per unit volume at a stated temperature to the weight of the same volume of water.

Theoretical maximum density (TMD) Theoretical maximum specific gravity multiplied by 62.4.

Theoretical maximum specific gravity The theoretical compression of aggregate and asphalt to an air-void content of 0 percent, i.e., a voidless mass.

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APPENDIX A

QUESTIONNAIRES

Questionnaire for State Agencies

State__________
Person_________

1. How important do you consider compaction to be in relation to pavement performance? (On a scale from 1 - very important, 5 - not important)

2. Do you have a compaction specification for asphalt concrete?

   Yes____________ No____________

3. Is it a method or end-result spec.? A combination of the two?

   a) If method, how many passes______ roller types______

      ______ ______

      ______ ______

      How often do you verify roller weights?

   b) If end result, is it based on:

      Maximum Theoretical Density ___________ Minimum Percent ____________

      Rice (AASHTO T209) ___________

      Calculated ___________

      Laboratory (Marshall) ____________ Minimum Percent ____________

      (Other) ____________ Minimum Percent ____________

      Nuclear Control Strip ____________ Minimum Percent ____________

   c) Is nuclear correlated to cores?
      If no, how do you verify nuclear results?

4. Do you consider over compaction to be a problem?

5. What are the greatest problems you are trying to overcome with the compaction spec.?

6. Is your agency conducting any research in this area at present?

QUESTIONNAIRE FOR CONTRACTORS

State ___________

Company__________

Person___________

1. Do you modify your roller pattern or equipment used under any of the following conditions?

   Mix Type
   Weather
   State directive

2. How important do you consider compaction to be in relation to pavement performance (scale: 1 - very important, 5 - not important)?

3. How much, if any, training to you give your roller operators?

4. What rollers do you typically use in your compaction train for

   Breakdown ___________
   Intermediate_________
   Finish rolling_______

5. With the reemergence of three-wheel and pneumatic rollers, do you use these in your normal compaction train? Why?

6. Do you prefer method or end-result specs for compaction? Why?

7. Do you use nuclear density gauges for quality control? Other purposes?

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