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THE EFFECT OF SUBLAYER SUPPORT ON THE ATTAINMENT OF DENSITY IN AN ASPHALT CONCRETE OVERLAY

STATE OF THE ART

Final Report

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16. ABSTRACT

A considerable number of asphalt concrete overlays do not attain specified density requirements during construction. Although density is a function of many variables such as mix characteristics, climate, contractor equipment and operation, and acceptance test methods, a significant variable may be the ability of the existing pavement section to provide adequate support for the densification of the overlay. A literature review was performed as well as a survey of 25 selected states in order to determine the magnitude of the problem and to assimilate all available data on the subject. A conclusion is the density of properly designed and constructed asphalt concrete overlays is only marginally affected by the sublayer support. A suggested plan for future research is presented to further quantify the effect of sublayer support.

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THE IMPORTANCE OF COMPACTION

The volume of air voids in a layer of asphalt concrete, placed as a new pavement structure or as an overlay on an existing pavement surface, has a major effect on the ultimate durability of that layer with time and traffic. Once the asphalt concrete mix is laid by the paver, it is compacted by the rollers. The purpose of the compaction process is to increase the density or the unit weight of the mix, thereby reducing the air void content. Although most asphalt concrete mixtures are designed for an air void content in the laboratory of 3 to 5 percent, the acceptable level of density on the roadway, immediately after construction, is typically in the range of 7 to 9 percent air voids.

The degree of density in the compacted asphalt concrete mix affects the performance of the pavement layers. The volume of the air voids (inversely related to the level of density for a given mixture) governs many characteristics and properties of the mix. These include: (a) fatigue life, (b) permanent deformation, (c) distortion, (d) disintegration, (e) aging of the asphalt cement, and (f) moisture damage (1). In every case, an increase in the air void content of the mix increases the distress in the pavement structure.

Fatigue Life

The fatigue life of an asphalt concrete layer is inversely proportional to the air void content of the mixture. A number of studies have shown that as the air void content decreases -- as density increases -- the number of repetitions of load that the pavement can withstand before cracking increases significantly (2). Depending on mixture properties, loading variables, and environmental conditions, laboratory tests have found that a decrease in the volume of the air voids from 8 percent to 5 percent can more than double the fatigue life of the pavement layers (3). At high mix air void contents, over 10 percent, the number of load repetitions an asphalt concrete pavement structure can withstand may be only a small fraction of the number of repetitions at a low mix air void content, under 5 percent.

For relatively thick layers of asphalt concrete mix, the fatigue life of the material is governed by the stiffness of the mix in a controlled stress mode of loading. The mix stiffness can be increased in a number of ways -- by increasing the crushed content of the aggregate, by increasing the asphalt cement content (up to some optimum value), by using a higher viscosity asphalt cement, by using more mineral filler, and by using a dense aggregate grading. An increase in the density of the mix will usually increase the fatigue life more, at less cost, than any changes that can be made to the materials or mix design process.

Permanent Deformation

The amount of permanent deformation, or rutting, which occurs in an asphalt concrete pavement is also inversely proportional to the density of the mixture. Two types of wheel path rutting can occur. The first is a pure vertical consolidation or compression of the pavement layers under repeated traffic loading. The second is a lateral distortion or pushing of the pavement material sideways with a corresponding humping-up of the mix just outside of the wheelpaths.

The first type of permanent deformation is caused by a lack of adequate compaction -- too many air voids in the asphalt concrete mixture. If the rollers do not apply enough compaction effort to the mix to obtain the proper level of density, traffic will quickly compress the pavement material, causing rutting. If the mix design is proper and if the correct level of air voids has been achieved, very little, if any, additional densification of the material should occur under traffic.

The second type of permanent deformation, accompanied by lateral distortion, is usually caused by a mix design problem such as too much asphalt cement, too much moisture, too little crushed aggregate, too much fine aggregate, a temperature susceptible asphalt cement, or a non-uniform aggregate grading, among possible causes. This type of rutting failure, however, can be accelerated by a lack of proper density in an inadequate mix. Increased lateral distortion and rutting will occur more quickly if the density of the asphalt concrete mix is low. Even if the mix design is deficient in some way, a decrease in the air void content of the mix will in turn decrease the amount of rutting.

Distortion

Longitudinal distortion or shoving of the mix is also primarily a mix design problem. The severity of the shoving, however, is significantly affected by the amount of density in the mix. The shear strength of the asphalt concrete mixture is controlled in part by the air void content of the material. The greater the density of the mix, the greater the shear strength of the asphalt concrete and the more resistant the mix is to longitudinal distortion. The problem manifests itself at intersections when the braking action of vehicles occurs as well as in the areas of impact loading on the pavement surface. Reducing the air void content in the mix at time of construction decreases the shoving of the mix.

Disintegration

An asphalt concrete mixture will ravel under the action of traffic for one or two main reasons -- a lack of asphalt cement content and/or a lack of density. A mix without enough binder in it to hold the aggregate particles together will quickly disintegrate under the abrasive forces of the vehicle tires. Similarly, a mix with a high air void content will fail under traffic by ravelling. The fines are usually pulled out of the mix first. This leaves a mix with a much rougher surface texture caused by the coarse aggregate particles being left exposed. With additional traffic, the coarse particles are also lost. In some extreme cases, it is possible to wear completely through an inch of newly placed asphalt concrete in less than a week under high volume conditions.

A mix that has both a low asphalt content and a high void content is prone to ravelling or disintegration. An asphalt concrete surface course that has a relatively low void content but which also has been compacted to a low void content will serve well under traffic. The disintegration of the mix will be much reduced if the coarse and fine aggregate particles are pushed tightly together. The compaction of the mix decreases the amount of fines exposed to the vehicle tires and bonds the fines more tightly together with the available asphalt cement. Thus a reduction in the amount of disintegration is directly related to a greater amount of density in the mix.

Aging

With time, the asphalt cement in an asphalt concrete pavement layer will oxidize and become more brittle. This aging process causes the asphalt cement to decrease in penetration and increase in viscosity. If the asphalt cement becomes too hard and stiff, cracking can occur and the life of the pavement structure can be shortened considerably. The rate of oxidation of the asphalt cement is related to several material and mix characteristics, including the thickness of the binder film around each particle of aggregate.

The density of the asphalt cement mix directly affects the hardening rate. As the air void content in the mix increases, the rate of asphalt cement oxidation generally increases in proportion. The change in the amount of stiffening, however, is more important with a change in air void content from 4 to 5 percent than a change in air void content from 9 to 10 percent. For an asphalt concrete mix with given properties, the degree of aging or oxidation can be reduced by increasing the density of the mix.

Moisture Damage

The amount of moisture damage or stripping which occurs in an asphalt concrete mixture is primarily a function of the surface characteristics of the aggregate. The properties of the asphalt cement binder can affect the stripping tendency slightly. The amount of air voids in the mix can affect the degree of moisture damage significantly.

For stripping to occur, three factors must be present. First, the aggregates used in the mix need to be hydrophillic (water loving). Second, there must be a source of water available to the pavement layers. Third, there has to be enough air voids in the mixture to allow for the passage of water. By decreasing the permeability of the asphalt concrete mixture, the amount of potential moisture damage can be reduced significantly. Laboratory tests, using the modified Lottman indirect tension test procedure, have shown that the tensile strength ratio of a water conditioned mix increases greatly as the air void content of the mix is decreased (4). Indeed, a mix that suffers a significant degree of moisture damage at a 7 percent air void content may be affected little, if any, by water when the air void content in the mix specimen is less than 3 percent (5).

Summary

The amount of air voids in an asphalt concrete mixture is very important in building a pavement layer which will be durable under a variety of traffic and environmental conditions. A low value of density (high air void content) will be detrimental to the performance of the mix. A low air void content, on the other hand, contributes to an increase in the fatigue life of the pavement structure, decreases the amount of permanent deformation in the mix, reduces the distortion or shoving of the material, lessens the amount of ravelling or disintegration of the mix, reduces the relative degree or hardening and stiffening or aging of the asphalt cement binder, and greatly lessens the moisture damage which can occur in the mix containing a moisture sensitive aggregate.

An asphalt concrete mix must contain "enough" air voids to prevent bleeding or flushing of the asphalt cement. This air void content is usually taken to be in the range of 2 to 3 percent. In contrast, the mix should not contain "excess" air voids so as to be susceptible to fatigue damage, rutting, shoving, ravelling, cracking, or stripping. This air void content is typically believed to be above 5 to 6 percent. Good mix design practices usually requires laboratory air void contents of 3 to 5 percent, using either the Marshall or the Hveem method (6). At this density level, there is "enough" air voids to eliminate the bleeding potential but not an "excess" of air voids to reduce the performance of the asphalt concrete mixture.

FACTORS AFFECTING DENSITY

A wide variety of variables affect the ability of the compaction equipment to attain a given level of density on a newly placed layer of asphalt concrete (7,8,9). These factors can be divided into four major categories. The four classifications include: (a) the properties of the materials used in the asphalt concrete mix, (b) environmental factors, (c) conditions at the laydown site and (d) operation of the compaction equipment (10).

The goal of the paving contractor is to achieve a given level of density in the asphalt concrete layer being constructed. The amount of air voids desired in the mix is usually set in the contract when quality assurance specifications are used. In some cases, the degree of compaction is measured as a percentage of the laboratory determined density. In other cases, the air void content is determined directly as a percentage of the maximum theoretical density of the mix. In either case, the target value is preselected and it is up to the contractor and his ingenuity and inventiveness to obtain the required compaction level in the most efficient, effective, and economical way. This is in contrast to method type specifications where the type of compaction equipment used and the rolling process used is monitored instead of requiring a given level of density.

There are a number of variables which are under the control of the contractor during the mixing, hauling, placing and compacting process for an asphalt concrete mix. There are also a number of factors over which the contractor has little, if any, control during the construction procedure. Each of these variables can play a major or minor role in the actual density level achieved. Indeed, in many instances, there is considerable interaction between the factors. The interaction significantly increases the difficulty in assigning the reason for a low density value to any one given cause.

Material Properties

Aggregate. Several characteristics of the coarse and fine aggregate can affect the ability to obtain the proper level of density in an asphalt concrete mixture. One of these properties is the angularity of the aggregate or the number of crushed faces. As the crushed content of the aggregate increases, the compaction effort needed to achieve a specific level of density also increases. Similarly, if a manufactured sand is used in the mix instead of natural sand, the level of density obtained for a given compaction effort will usually be lower.

The surface texture of the individual aggregate particles is also important. Aggregate particles having a rough surface texture are harder to compact in an asphalt concrete mixture than when the mix is made using smooth, rounded aggregate. In addition, the compaction effort required is affected by the shape of the aggregate, with a cubical or block shaped aggregate needing a greater degree of manipulation before attaining a given density level.

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. This will be particularly true when the aggregate gradation has an excess of material in the mid-range of the sand grading, passing the No. 30 sieve and retained on the No. 50 sieve.

The filler content of the mixture (the amount of material passing the No. 200 sieve) also affects the achievable level of density. A low filler content usually makes for a workable mix and one which may be easy to compact. A high filler content produces a stiff asphalt concrete mixture, requiring an increase in compaction effort.

Asphalt Cement. The degree of density is also governed in part by the grade and amount of asphalt cement used to produce the mix. An asphalt cement which is higher in viscosity or lower in penetration will generally provide for a stiffer mix at a given mix temperature and therefore necessitate a greater compaction effort. A mix produced with an AC-30 viscosity graded asphalt cement will make a stiffer mix than a material manufactured with an AC-10 asphalt cement. The stiffness of the mix, however, is also affected by the temperature-viscosity relationship or temperature susceptibility of each particular asphalt cement.

The asphalt content of the mixture influences its compatibility. A material containing either too much or too little asphalt cement is difficult to compact. A rich mix is tender and will shove under the compaction equipment. A lean mix is stiff. An "optimum" asphalt content is needed for each particular mixture in order to achieve the desired level of air voids with minimum compaction effort.

Mix Properties. Temperature affects the workability of an asphalt concrete mixture. A mix which is higher in temperature, up to a certain point, is easier to compact than the same asphalt concrete mix placed at a lower temperature. The viscosity of the asphalt cement is, of course, decreased as the mix temperature increases. If the initial mix temperature is too high for a particular mix, however, the material will be tender and difficult to compact until the mix temperature decreases and the viscosity of the asphalt cement increases enough so that the mix can support the weight of the compaction equipment.

A mixture which is at the proper fluids content will be easy to compact. Fluids content is the sum of the asphalt cement content and the moisture content of the mixture. If the asphalt batch or drum mix plant is operated properly, the amount of water in the asphalt concrete mixture at the time of discharge from the plant should be less than 0.5 percent, by weight of the mix. Thus a dry mix which is at the "optimum" asphalt content will be readily compacted. 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. Any mixture which has a high fluids content will shove instead of densify.

Contractor Control. Under a quality assurance specification, a paving contractor can select his own sources of coarse and fine aggregates. The type of aggregate selected, of course, is dependent on the locally available materials, both in terms of quality, quantity, and cost. A contractor can obtain any combination of aggregate which meets the required mix design specifications but often the deciding factor in choosing the mix components is the desire to minimize the cost of the constituent materials. Thus, the aggregate selected by the contractor often meets only the minimum requirements instead of being optimized in terms of mix quality.

There is a tendency to reduce the amount of asphalt cement used in a mix in order to decrease the cost of the product. This tendency exists both on the part of the state and the contractor. It is aggravated by the state's desire to reduce the amount of rutting which occurs in mixes under traffic. The asphalt content is thus often set on the low side of the mix range. The temperature susceptibility of the asphalt cement is not controlled at all, either by the state or the contractor, as long as the material supplied from the refinery meets specs. The contractor can control the temperature at which the asphalt concrete is manufactured (within limits) and placed, and he can regulate the amount of moisture left in the mix upon plant discharge. The trend, based on economics, is to reduce fuel usage and to leave some moisture in the mix in order to "aid compaction".

Environmental Variables

Environmental Factors. Two temperature related factors affect the ability of the compaction equipment to achieve the desired density level. The first is the ambient air temperature. The higher the air temperature, all other factors being equal, the easier it will be to compact a given layer thickness with a selected combination of rollers. Lower air temperatures contribute to more rapid cooling of the mix thus decreasing the time available to achieve the required air void content before the mix reaches a temperature of 175^{O}F. At mix temperatures below this threshold value, additional density is essentially impossible to obtain regardless of the compaction effort expended.

The temperature of the layer on which the new asphalt concrete layer is placed also contributes to the level of density which is attainable. If the existing surface is cool, heat will be rapidly removed from the asphalt concrete mixture, reducing the time available for compaction. The base temperature has a greater affect on thin lifts of asphalt concrete than it does on thicker courses.

A strong wind can cause the surface temperature on the new asphalt concrete mat to decrease quickly. This reduces the time for the mix to cool from laydown temperature to the compaction cutoff temperature. More compaction effort is thus needed on a windy day compared to a calm day. The amount of cloud cover is an environmental variable which is of some importance. An asphalt concrete mix will stay warmer for a longer period of time on a bright, sunny day. On a cloudy day, the mix will cool somewhat faster, necessitating an increase in compaction effort from the rollers.

If the surface of the sublayer is wet from dew or rainfall, the water acts as a heat sink. The heat in the mix is needed to evaporate the water on the existing surface. This rapidly reduces the temperature of the mix, making the compaction process more difficult. Thus it is important that the asphalt concrete mix be laid on a dry surface.

Contractor Control. The paving contractor can not control the weather. He can choose, however, the days on which he places the asphalt concrete mix. He can select the starting time at which paving begins each morning. He can determine how long the crew continues to lay mix once rain commences and how soon the paving starts again once the precipitation ends. Thus, with attention to the environmental variables, a contractor can exercise a significant degree of control over some of the factors which affect the ability to attain density.

Some projects are let to contract late in the year when weather conditions are less desirable than earlier in the paving season. Some jobs also have political implications and need to be completed by a certain date, regardless of environmental conditions. In these cases, the contractor may find it necessary to place the mix in marginal weather. The ability to obtain the required density level in the mat is directly affected, however.

Laydown Site Conditions

Mat Thickness. The most important factor which affects the ability to attain density at the laydown site is the thickness of the layer being placed. The thicker the lift, the slower the mixture will cool from the laydown temperature. Thin courses lose heat fast, thereby decreasing significantly the time available for densification. The retained heat in the thicker layers makes it easier to obtain the desired air void content. In poor weather conditions, increasing the thickness of the mat being placed is the best way to extend the time available to achieve density.

At course thicknesses greater than three inches, the amount of heat held in the asphalt concrete mixture is enough to keep the asphalt cement fluid for a longer period of time. On cool days, this is a definite advantage. On hot summer days, however, thick lifts can take a long time to cool enough to support the weight of the rollers without undue displacements. Under these conditions, the mix discharge temperature should be reduced at the plant in order to lower the laydown temperature.

Aggregate Size. The lift thickness in relation to the maximum size aggregate in the asphalt concrete mixture is a second paving site variable related to the ability to attain the desired level of density. If the course depth is at least twice the maximum aggregate size, adequate density can be obtained with normal compaction effort. When the lift thickness is less than two times the thickness of the larger of the aggregate pieces, a rough surface texture results when the aggregate pieces are dragged beneath the paver screed. The high voids content in the mix from the dragged aggregate negates any effort to obtain the proper density level in the material.

Thickness Uniformity. The uniformity of the lift thickness is another factor to be considered. It is easier to compact an asphalt concrete layer of constant thickness compared to a course which varies in depth. Asphalt concrete leveling courses, which, by their vary nature and purpose, are nonuniform in thickness, are very difficult to compact, especially with a rigid steel wheel roller. The compaction rolls of a tandem, three wheel, or vibratory roller tend to bridge over the low spots in the sublayer surface. Thus adequate density is usually not obtained throughout the mix and particularly not in the rutted wheelpaths. A pneumatic tire roller can be employed, however, to achieve density in the low points on the existing pavement surface as well as on the high spots.

Sublayer Support. A fourth factor which affects the degree of density obtained is the amount of support provided by the existing surface under the new asphalt concrete mat. If the sublayer is soft and yielding, the compaction effort applied to the mix will be diminished somewhat because of a lack of a firm foundation to compact against. The effect of subgrade support, however, depends on a number of factors including the degree of softness of the base and the thickness of the new layer.

Contractor Control. The laydown contractor usually can not control the lift thickness used on the project -- that is preset on the plans. There is no doubt, however, that an increase in the mat thickness can significantly lengthen the time available for compaction. Thus, all other factors being equal, a contractor can not be expected to achieve an adequate level of density if a thin lift of asphalt concrete is required to be placed in marginal environmental conditions. Where the contractor is allowed to change the depth of the course being constructed, a thicker lift usually can be equated with a greater degree of densification in the asphalt concrete mix.

As a rule of thumb, the mat thickness should be at least twice the depth of the maximum size aggregate piece. When this can not be accomplished, such as when a variable thickness leveling course is being placed, it will be very difficult to attain the desired density level. In lieu of placing a leveling course to fill in the low spots, the contractor should have the option of using a cold planing machine to remove the high points in the existing pavement surface. This latter procedure will allow the placement of a more uniform thickness of the first resurfacing layer and thus allow attainment of a more consistently uniform density level.

When an existing pavement structure is overlaid, all needed repair work should be completed before the resurfacing begins. Failed areas should be cut out and replaced. Cracks should be cleaned out and sealed. Ruts should be filled in or the surface milled. The existing sublayer should be brought into as uniform a condition as feasible. The amount or the type of rehabilitation work is not normally left up to the contractor -- it is specified in the plans. A contractor trying to place a uniform asphalt concrete layer on a base of varying stiffness may not be able to obtain the required degree of density in the asphalt concrete overlay.

Compaction Equipment

Screed Density. The initial density of an asphalt concrete layer is obtained under the screed of the paver as the mix is placed by that machine. If the paver is operated at a slow forward speed and if the impact energy of the screed is high, the compaction effort applied to the mix can be increased. This, in turn, reduces the amount of density which must be acquired during the compaction process. Depending on the mixture characteristics, paver speed and force, and environmental variables, the initial density of the asphalt concrete mixture can range from 75 percent to 85 percent of the final density. Increasing the compaction effort of the screed on the laydown machine decreases the compaction effort needed from the rollers.

Type of Rollers. The type of equipment used to compact an asphalt concrete mixture has a significant effect on the degree of density which can be obtained in a given number of passes of a particular roller. Three major roller types are currently being used in the compaction process. These are: (a) static steel wheel rollers, (b) pneumatic tire rollers, and (c) vibratory rollers, either single or double drum.

For static steel wheel rollers, the gross weight of the roller and the contact area of the roller with the asphalt concrete mixture are both important in determining the compaction effort of the machine. Effective weight, in terms of pounds per square inch of contact area, is a key variable in the compaction effort for this type of equipment.

Similarly, for pneumatic tire rollers, the area of each tire footprint as well as the gross weight of the compactor are the important factors in judging the effectiveness of this roller. On harsh mixes, the tire pressure of the pneumatic tires can be increased in order to gain compaction effort. For tender mixes, the air pressure in the pneumatic tires can be reduced (to 50 to 60 psi) in order to spread the weight of the roller over a larger contact area and thus not displace the mixture being compacted.

For vibratory rollers, the applied force to each compaction roll is the primary variable. Included are the effects of both the amplitude and frequency of vibration. In general, as the amplitude of the applied force increases, the density obtained using the roller also increases. Further, as the frequency of the vibratory impact increases, density also increases for a given roller speed because the spacing between impacts decreases with a higher frequency setting.

Roller Speed. The faster a roller moves over a stretch of asphalt concrete mix, the less effective a given compaction pass will be in increasing the density of the mat. A slower machine speed increases the "dwell time" for a static roller over each point in the pavement layer, which in turn increases density and reduces the air void content of the mix. For vibratory rollers, the slower compaction speed decreases the distance between impacts, for a given vibratory frequency. It is usually recommended that all compaction equipment be operated at speeds of less than 2.5 miles per hour.

Roller Pattern and Zone. The more passes a given roller makes over each point on the asphalt concrete mix surface, the greater the density that will be gained in the pavement. The mix, however, is cooling while the compaction operation is in progress. Because the compaction effort usually ceases to be effective when the mat temperature declines below 175 degrees F., and because it is easier to compact the asphalt concrete mix when it is hotter, more density is gained with the earlier compaction passes than with the later roller passes. Thus simply making more passes of the roller over the mix surface does not necessarily assure that the final pavement density will be brought to a satisfactory level.

A properly designed asphalt concrete mixture should be able to support the weight of the breakdown compaction roller as soon as the mix passes out from beneath the paver screed. The first roller compaction effort should therefore be applied directly behind the laydown machine. If the rolling zone can be kept right back of the paver, the compaction process can be started while the asphalt cement is less viscous -- while the mix is still hot. If the mix is tender and can not support the weight of the breakdown roller without displacement immediately after placement, the mix design needs to be modified. The rolling zone for all rollers should be quite close to the paver, obtaining density while the material is still fluid enough to be densified.

Contractor Control. Under a quality assurance type specification, a contractor has complete control of the whole laydown and compaction operation. Rollers can be applied to the mix in a wide variety of combinations. Static steel wheel rollers, pneumatic tire rollers, single drum vibratory rollers and double drum vibratory rollers can all be used as the initial piece of compaction equipment. The type of intermediate roller or rollers can also vary among the various types of machines available. Similarly the number of passes made over each point on the pavement surface by each roller can be changed within a wide range. The travel speed for each compactor can be set between 0.5 and 5.0 miles per hour, but should be less than 2.5 miles per hour. Finally the location of the rollers in regard to the paver (the rolling zone) is under the control of the contractor.

The use of vibratory rollers adds two more variables to the process. Both the amplitude and the frequency of the applied force can be varied. In general, a high amplitude setting should be used with thick lifts (over 4 inches) and a low amplitude setting with thin lifts (over 1 inch and under 2 1/2 inches). On many projects, the frequency setting of the vibratory roller should typically be at the maximum available on the roller. This high frequency value will allow for the most impacts per foot of distance, thereby increasing the compaction effort of a given roller. Usually a vibratory roller will be run at a frequency of 2,400 vibrations per minute or more.

If one combination of roller type and pattern is not sufficient to attain the required level of density, the contractor always has the option of trying another combination of equipment and operating procedures. What works one day under certain environmental conditions and mix characteristics is not guaranteed to work under a different set of variables. Too often a contractor does not take the time to understand all the variables under his control before he commences the compaction process.

Summary

Table 1 summarizes the variables which affect the compaction process for asphalt concrete mixtures. The table is divided into three parts, one column for those factors that are controlled solely by the state highway department or other owner agency. The second column includes those variables which may be under state jurisdiction and which may be partly under the control of the paving contractor. The last column is for items which are completely governed by the contractor. On some projects, under a given set of specifications, the actual degree of control over any particular variable might be somewhat different than that shown in the table.

In any case, the number of variables which play a hand in the level of density obtained in an asphalt concrete pavement layer is large. None of these variables operates independently. Each particular factor is interrelated with at least one or two other variables. This fact makes it difficult, usually, to determine the exact reason for a low density value on a paving project.

THE EFFECT OF SUBLAYER SUPPORT

The Problem

One of the factors described above which affects the ability of a contractor to attain the required level of density is the amount of support offered by the layer on which the new asphalt concrete course is being placed. There is a concern that an adequate degree of densification will not, or can not, be achieved if the sublayer is soft and/or yielding under the laydown and the compaction equipment. That this concern is valid is not the question. The problem is to determine to what degree this factor plays a part in the effort to meet a density specification. What is the magnitude of the problem?

Full Depth Asphalt Concrete. When an asphalt concrete base course is constructed as part of a full depth asphalt pavement structure, the first layer is placed directly on the subgrade soil. If that subgrade material is a sandy soil which has a high CBR, R, or resilient modulus value, the initial pavement course can typically be placed and rolled without difficulty. If the subgrade soil is a wet clay or silty clay material, however, the CBR, R, or resilient modulus value will be very low. The soil will have a tendency to pump under the movement of the haul trucks. The subgrade material, being soft and yielding, does not support either the paver or the compaction equipment very well.

When this problem occurs, good engineering practice calls for the stabilization of the soft soil, either by chemical (hydrated lime) or mechanical (aggregate interlock) means. If the asphalt concrete must be placed on an unstable subgrade soil, the haul trucks are usually only partially loaded. This reduces the force on the weak soil. A track paver, rather than a rubber tire paver, is used in order to increase the floatation of that load on the subgrade material. Finally the rolling is delayed until the mix cools enough to support the weight of the compaction equipment. By delaying the rolling, the mix becomes stiff enough (it cools) to withstand the compaction effort of the rollers. In many cases, only a small, lightweight roller is used to compact the mix. Evidence of the soft subgrade problem can usually be readily seen by the roller marks left in the pavement surface.

When the rolling is delayed and when the compaction effort is reduced, the required level of density can not be attained in the initial base course layer. When this occurs, the first course of asphalt concrete really becomes a working platform for the placement of subsequent layers rather than a structural layer itself. This means, in turn, that the full depth asphalt concrete pavement will be underdesigned because of the reduction in the load carrying ability of the bottom layer of mix.

Asphalt Concrete on Granular Base. Many pavements are built where one or more layers of asphalt concrete mix are placed on top of an untreated granular subbase or base course. If the granular material is composed of crushed aggregate and is well compacted, the first layer of asphalt concrete mix can be readily laid and rolled. When an uncrushed, untreated, unstable granular material is used, the base or subbase layer has a tendency to rut under the haul trucks. In addition, there is usually some lateral distortion of the material. This phenomenon creates a widely variable thickness for the overlaying asphalt concrete mixture. This variable thickness of mix -- thick in the haul truck wheelpaths and thin just outside of the wheelpaths -- makes the attainment of adequate density much more difficult.

Faced with such a situation, the paving contractor will usually compensate for the weak base by reducing his compaction effort. Breakdown rolling will be delayed until the asphalt concrete cools significantly. Lighter rollers will be employed. Less roller passes will be used. The contractor will typically attempt to "bridge over" the soft areas and hope that the pavement lasts long enough for him to get paid before distress becomes evident. Density tests, if run, will be ignored because "everyone knows that the contractor should not be expected to get density over a weak base course like that".

Asphalt Concrete Overlays. Asphalt concrete is used to resurface both existing asphalt concrete and Portland cement concrete structures. Before an asphalt concrete overlay is placed, it is good engineering practice to repair any failed areas in the existing pavement structure. This means that the potholes in the roadway should be patched and that the punchouts in the continuously reinforced concrete pavement should be removed and replaced. It also means that the cracks in the asphalt concrete pavement should be blown out and sealed with a crack filler. In essence, for an asphalt concrete overlay to perform adequately for a number of years, proper preparation of the existing pavement is of paramount importance.

If an alligator cracked area is overlaid with an asphalt concrete mix, the thickness of the mix placed will vary somewhat, particularly if the failed area is low. The screed on the asphalt paver will place mix in the low spot to the same surface elevation as the surrounding mix. Asphalt concrete compacts roughly 20 to 25 percent under the rollers. Thus about 1 1/4 inches of asphalt concrete must be placed by the paver to attain a 1 inch thick compacted layer. If a steel wheel roller is used, either static or vibratory, the mix will be compressed, but the elevation of the finished surface will be all the same elevation, over the good area as well as the low failed spots. This means that there will be a lack of density in the original low areas. When a pneumatic tire roller is used, the proper density can be obtained in the low areas, but a slight depression will remain in the new surface over the original failed area due to the differential compaction phenomena. Thus, when resurfacing an uneven existing surface with asphalt concrete, there is a definite trade off to be made between layer density and layer smoothness.

Portland cement concrete pavement slabs curl and warp due to temperature and moisture differentials between the top and the bottom of the slab. These same slabs can also rock under applied traffic loads when the subbase material has been pumped out through the transverse and longitudinal joints. Good engineering practice before overlay would be to stabilize the existing pavement by undersealing with asphalt cement, grouting with a cement-flyash blend, or cracking and seating the slabs. In most cases the present pavement is simply resurfaced with asphalt concrete mix. If the slabs are curled upward when the overlay is placed, a thinner layer of mix will be placed in the area adjacent to each transverse joint. If the slabs are curled downward, more mix will be placed in the joint area. This variable thickness of mix typically does not create a compaction problem since the change in layer depth is relatively small, but does contribute to a possible rougher ride in the new overlay at the old joint location as the concrete slabs continue to curl and warp.

<u>The Problem</u>. There are many paving situations where it is intuitively felt that the support, or lack of support, of the sublayer has contributed to the inability of the paving contractor to attain the required density level in the asphalt concrete mix. The question is how to quantify the problem.

Literature Review

The bibliography lists the multitude of technical papers on asphalt concrete mixture compaction that were reviewed to determine the significance of sublayer support on the ability to obtain density in an overlying asphalt concrete course. The information contained in the literature is very meager. The discussion of sublayer support is usually part of a much longer explanation of some of the factors that affect compaction effort. Definitive data is totally lacking. Some authors indicate that the effect of sublayer support must be considered, but none suggest how to measure it or take it into account.

Transportation Research Board. In 1972, the Highway Research Board, now the Transportation Research Board, published Special Report 131, entitled State of the Art: Compaction of Asphalt Pavement (11). Chapter Three is titled "Environmental Conditions". The first section is labeled "Foundation Solidarity". The whole concept of sublayer support is covered in one paragraph as follows: "Foundation condition has a direct relation to compaction of the overlaid asphalt pavement. Foundation density is important; however, stability is equally important. It is possible to have foundation density and yet lack stability. For example, it would be practically impossible to straighten a bent nail using a rubber block as an anvil, whereas, with an anvil made of steel, the process would be simple. By analogy, placing thin overlays on an unstable foundation is futile; however, the use thick layers, such as four inches, can reduce compaction problems on unstable foundations."

The same Transportation Research Board committee published a Transportation Research Circular in April 1982 entitled State of the Art: Vibratory Compaction of Asphalt Pavements (12). The report discusses a number of variables which affect the ability of vibratory rollers to achieve density in an asphalt concrete mixture, such as vibratory frequency and amplitude, roller speed, mix temperature, and rolling pattern. The publication is silent, however, about the effect of sublayer support.

Asphalt Institute. Vaughn Marker, then Chief Engineer for The Asphalt Institute, wrote a paper in November 1979 entitled Factors Affecting Compaction (7). Part of the treatise is a section on compaction forces. The report states: "In order for densification of an asphalt mixture to occur, it is absolutely necessary for the mix being densified to be confined." The discussion continues: "It is essential that the subgrade be firm, otherwise the confinement at the bottom of the mix will not be sufficient. It is not possible to satisfactorily compact an asphalt mixture against a yielding subgrade. If the subgrade is soft or yielding for any reason, it must be improved or strengthened.

"The methods to do this are: (a) to remove and replace the material in the yielding area; (b) to stabilize the subgrade in the yielding area with additional sound, untreated material; (c) to stabilize the subgrade in the yielding area with some type of additive; (d) to bridge the yielding area with a layer of asphalt concrete placed in a single lift of sufficient thickness". There is no concrete information provided, however, on what constitutes a yielding sublayer or how to determine what degree of firmness is required.

New York State DOT. One of the most definitive reports on sublayer support was published by the State of New York Department of Public Works (now Department of Transportation) in 1965, both as an AAPT paper and as a departmental report (13,14). In 1962, the highway department constructed 47 test sections on a total of 12 different paving projects. The jobs: "...were all built under similar conditions and construction techniques, and contained similar materials". The purpose of the research effort was "...to determine the influence of such variables as mix composition, pavement thickness, mix temperature, and number of roller passes on pavement density".

Cores were cut from the test sections at various locations and the layer density determined. The density was found to vary greatly in the transverse and insignificantly in the longitudinal directions. Several factors may have contributed to the differences in density. One of the factors "...that may have had an effect on wheel path density is the supporting strength of the underlying pavement. The compaction effort of the rolling may have been dissipated by either plastic or elastic deformation of underlying layers."

A regression analysis was run to calculate the relationship between density and the factors which influenced that density. The "...percent air voids was correlated with the following variables: (a) aggregate gradation, (b) asphalt content by volume (c) top course pavement thickness, (d) asphalt viscosity at the start of rolling, (e) number of breakdown roller passes (f) number of intermediate roller passes, (g) number of final roller passes, (h) deflection of underlying pavement, and (i) underlying pavement surface temperature prior to mix laydown."

Pavement rebound deflection measurements were conducted on 9 of the 12 test projects in September 1984. A Benkleman beam was employed to determine the deflection of the resurfaced pavement (approximately two years after construction). Evidently deflection measurements were not made on the original pavement surface before overlay, and thus only relative differences in the amount of deflection between test sections could be determined and not the change in the degree of deflection between the surface of the sublayer and the surface of the new overlay for any particular project.

In the final regression equation, the effects of sublayer support on air void content was related to the square root of the "...inches of rebound deflection of the underlying pavement caused by a 22,400 pound single axle load moving at creep speed (multiplied by 1,000)". It was determined that "...greater deflections of the underlying pavement increased the percent air voids."

A sensitivity analysis was conducted to determine how much each variable could change the air voids in the compacted mix. The range of deflection measured on the two year old overlays was from 0.006 to 0.036 inches. Within this degree of change in deflection, it was calculated that the percent change in air voids would be 3.7 percent. This was the second greatest amount of change in density for any factor, being exceeded only by the effect of a change in the volume of the asphalt cement used in the mix, in the range of 13 to 17 percent, which caused a change in air void content of 4.4 percent.

The authors of the research report state: "The influence of the rebound deflection of the underlying pavement on the top course density ... is not only significant, but also substantially consistent. The influence of this variable on pavement density was not anticipated when this study was undertaken. Consequently, it was not until an investigation was made of the possible influence of subgrade support that it was concluded that pavement rebound deflection was a factor that possibly should be included with the other variables. For this reason there was a two year interval mentioned previously between pavement construction and pavement rebound deflection measurements".

It is not known, from the information provided in the published report, what the condition of the original pavement structure was on each project prior to overlay. It is also not known what traffic volume was carried on each test section between the resurfacing in 1962 and the deflection measurements made in 1964. The highways were subjected to different environmental conditions. Because of the lack of initial deflection data on the original pavement surface, before overlay, the conclusions reached using the Benkleman Beam deflection data taken on top of the resurfaced pavement two years later must be treated with some concern. There is no data provided on how the amount of sublayer support on any one test section affected the ability to achieve density on that particular test section.

Dynapac. The Dynapac Manufacturing Co, through Mike Geller, Vice President of Marketing, participated in a series of workshops on asphalt pavement compaction in the late 1970's and early 1980's. (9,15,16) In the presentations at these seminars, Geller discussed means to achieve density in the field. He stated "...any material subject to pressure will take the easiest way out to avoid the pressure. This is why we use a laboratory mold to confine the sample as we compact it. But what is the equivalent to the mold in the field? It is the underlying base, the material surrounding the area under compaction and the contact area surface of the steel wheel or pneumatic tire. Roller compaction effort is diluted by an improper degree of confinement such as soft bottom or an unsupported edge. The remedies available to the roller are rather limited for an unconfined edge and they are zero for a soft bottom" (15).

In another paper, Geller states that several factors including the selection and condition of the equipment and the number of rollers, the rolling pattern, and the skill of the operator are all under the control of the contractor during the compaction process. Several factors, however, are not under contractor control. These encompass the behavior of the mix, base conditions, and allowable rolling time (17). He continues that "Confinement problems are threefold in nature: (a) the unconfined edge, (b) soft base, and (c) insufficient confinement of the surrounding mix due to a low viscous resistance of the mix."

Geller comments further on the problem of soft base. "When this condition is present, the mix can be very stable and it can be rolled and rerolled; yet density falls in and out of specification without apparent rhyme and reason. If the base deflects during the rolling process, it is very difficult to achieve passing density. The greater the applied compaction effort, the more the base may deflect. It is a Catch-22 situation.

"It is sometimes possible to detect this condition in the field by using a nuclear gauge and measuring the density of the base prior to laydown to determine the dispersion of readings about a central value. If it is possible to take a reading in an area known to have sufficient stiffness for compaction, this reading then becomes the relative standard to measure other readings taken at random. If a soft base condition can be predicted, it should be brought to the attention of the resident engineer for a resolution of the problem."

Finally, Geller presented a paper at an ASTM Technical Symposium in 1982 entitled "Compaction Equipment for Asphalt Mixtures" (18). A small portion of that report dealt with rolling patterns for compaction equipment. It was pointed out that laboratory and field conditions for densification are difficult and that the stiffness of the underlying layer affects the ability to obtain density. As in the other paper, however, no definitive data is provided as to how great the influence of sublayer support really is on the density levels. Thus, it is stated once again that sublayer stiffness is important but the degree of effect is not quantified.

Dynapac published a series of booklets on tips for roller operators (19,20,21). One entitled Procedures for Rolling a Test Strip with a Dynapac Vibratory Roller, contains a section on compaction problems (19). The booklet states "When the mix lacks stability and/or a poor subgrade exists, it may be necessary to roll the first pass in low amplitude and the balance with the vibration off. Or, in worst cases, roll all passes without vibration. In all problem mix situations, it will be necessary to experiment to find the right combination to meet density, finish and production requirements."

University Research. In 1969, the Texas Transportation Institute published a report entitled Compaction of Asphalt Concrete Pavements (22). Less than a half page out of a 152 page treatise is devoted to the subject of subgrade support. Fifteen field test sections were built in 1965-66-67 in various parts of Texas. Benkleman Beam rebound deflection measurements were made on each pavement section "initially, and in selected cases at regular intervals during the study." Deflection measurements were taken "at the same locations during both summer and winter months to determine if seasonal variations in the pavement flexibility are a factor influencing the surface compaction". For this research project, the asphalt concrete mixtures being compacted were both new and overlay type construction over both rigid and flexible pavement bases. The conclusions reached by the authors stated: "Data collected in this project relating pavement density ... with subgrade support ... do not indicate a trend."

Swanson, Nemec, and Tons looked at "...the hardness of the supporting medium" as a variable which affected the densification of asphalt concrete during compaction (23). A laboratory study undertaken in the mid 1960's used three different sublayer support stiffnesses on which to compact two inch thick, 12 inch by 12 inch square asphalt concrete slabs. The base materials employed were foam rubber (k = 100 pci), urethane elastomer (k = 300 pci) and hard rubber (k = 2000 pci). It was determined from this research that the effect of base course stiffness or smoothness on density-stability of a 2 inch layer under compaction conditions described in this report was found to be small from a practical point of view, although the harder bases gave slightly higher densities and stabilities.

Chu, in a 1979 report by the University of South Carolina, discussed the use of a roller control strip to improve the level of density on asphalt concrete overlays (24). He stated that "...application of the control strip techniques were found to be successful in increasing the percent of compaction in some cases but not effective in others, especially on secondary road sites. The general belief by many engineers is that difficulties in achieving high degrees of compaction in the case of light traffic highways, such as some of the secondary roads, is primarily due to the inadequate support from the base and subgrade under the rollers." As part of this research study, Chu conducted a limited number of Benkelman Beam deflection measurements on some experimental pavement roadway sections. The "...test results show, however, that there are too many variations in pavement deflection within an individual experimental section so that no correlation can be made between pavement compaction and deflection."

A study entitled Compaction of Hot Mix Asphalt Concrete, by Finn and Epps, was done at the Texas Transportation Institute in 1980 (25). A very short section on subgrade support quotes Vaughn Marker of The Asphalt Institute that: "It is necessary for the rolling effort to be supported by a firm base" (26). The paper continues: "Most engineers agree with this statement; however, there are no criteria to apply. A visual evaluation based on experience is required. If the equipment is causing excessive deflection, it may be necessary to use lighter loads at higher temperature". Thus, once again, no definitive information is provided on the actual influence of the amount of sublayer stiffness on the ability to obtain density.

Kennedy, et al, in a report called Compaction of Asphalt Mixtures and the Use of Vibratory Rollers, make only one brief mention of the effect of sublayer support on pavement density (27). Reference is made to a presentation by Hensley (28) that "...thicker lifts tend to protect the subgrade ... allowing adequate compaction on yielding subgrades".

Government Agency Research. In the mid 1970's, Fuehlke of the Wisconsin Department of Transportation published a report entitled Compaction of Bituminous Pavement (29). Without any supporting data, he stated: *"It has been shown that the* stiffness or the supporting strength of the bases or underlying pavement courses can greatly effect the compactability of the mixtures. The greater the deflection that occurs when rolling the surface course, the more difficult will it be to achieve required compaction." That takes care of the total discussion of the subject in this paper.

According to research work conducted by Hughes, it is possible for a contractor to obtain the required level of density in an asphalt concrete mixture on both primary and secondary roadways (30). The study was concerned with the adequacy of the density being attained on asphalt concrete overlays of existing pavements. A review was made of the density levels obtained on Virginia highways from 1976 through 1982. The results showed "...that overlays on the secondary roads with typically weaker bases can be adequately compacted as those on primary and Interstate pavements". This conclusion was reached even though it was stated that: "Contractors have complained that it (a new density specification) has been applied on roads with weak bases and the level of compaction cannot be obtained". Thus it appears, at least in Virginia, that the effect of sublayer support on low volume roadways is not a factor in obtaining adequate density levels.

A presentation made at an asphalt compaction conference in New York in 1979 by Afferton of the New Jersey Department of

Transportation was concerned with why compaction is necessary (31). It was stated that "Ideally, a firm foundation is needed to achieve good compaction. Experience has shown that it is virtually impossible to uniformly densify a thin bituminous mixture on an unstable subgrade. However, with thick lifts, greater than four inches, foundation instability has proven to be a less significant deterrent to mixture compaction." No supporting information is provided for either statement, however. Whatever experience is available is evidently not quantified.

The US Army Corps of Engineers Waterways Experiment Station conducted a study to evaluate vibratory rollers (32). Several asphalt concrete overlays were constructed "...over sections of a rigid pavement and a flexible pavement with both a strong and weak foundation." Some 30 test sections were constructed with the overlay consisting of 1 1/2 inches of asphalt concrete or tar-rubber mix. From the data presented in the report, adequate levels of density could be achieved in either mix over any of the sublayer conditions. Different vibratory rollers obtained the required density levels at various amplitudes, frequencies, speeds, and number of passes, but the variability of the sublayer stiffness did not prove to be a problem.

A study was undertaken in England to determine if an asphalt concrete mixture could be placed and compacted directly on weak subgrade soils (33). Two different mixtures, a rolled asphalt and a dense coated macadam, were placed on three different strength bases at the Transport and Road Research Laboratory test pit. The three foundations included a clay with a CBR of 2 to 3, another clay with a CBR of 12 to 15, and a rigid concrete slab. The two asphalt concrete mixtures were placed approximately six inches thick over each different stiffnesses of base. Multiple passes were made over each mix and subgrade soil combination using a 10 ton tandem roller. It was found "that after 6 passes of the roller, the average levels of compaction achieved on the three foundations were not very much different. Additional rolling resulted in improved compaction except with the dense bitumen macadam on the weak foundation where the density of the material did not increase ... and cracks developed". Beams cut from the test sections were tested for dynamic stiffness. The results indicated "a high level of stiffness even in the materials laid on the weakest foundation".

Other Reports. At the 1982 annual meeting of the Texas Hot Mix Asphalt Pavement Association, Kemp presented a talk entitled "In-Place Density -- Contractor's View" (34). One of the points discussed was the problem of compacting a mix "...if the density or stability of the old surface is low. You have nothing to compact against." No data or research results were brought forth to quantify the problem however.

Summary. The review of literature leads to several conclusions. First, a significant number of technical papers have been written over the last twenty years on the subject of asphalt pavement compaction. Many of these reports discuss some of the factors which directly affect the ability to attain a desired level of density in the pavement layer. Only a few of the research works, however, identify the stiffness or support of the sublayer as an important factor to be considered in obtaining density.

Second, all but two of the reports lack any data to substantiate the claims that sublayer support affects density. Many authors state that this variable can cause a density problem, but they do not provide any information to back up their statements. Only the research work done by the New York State Department of Transportation in 1964 (13,14) and the more recent 1986 paper by the English Transport and Road Research Laboratory (33) contain any significant amount of hard data.

The final conclusion from the literature review, therefore, is that while some people seem to feel that the stiffness of the sublayer is important and affects the level of density that can be attained in a newly placed overlying asphalt concrete course, no one seems concerned enough about the problem to do much research into it, on to try to quantify the problem.

Survey of the States

Part of this State-of-the-Art report included a survey of current compaction practices by some selected state highway departments. For this effort, a brief questionnaire form was developed, as shown in Table 2. Telephone calls were made to engineers in the materials or construction departments in each agency and the questions asked. The results of the survey are given below.

A total of 25 different states were contacted. The states selected were chosen primarily for their geographic location and type of compaction specification (method specification or quality assurance specification). In alphabetical order, the states questioned were: Alabama, Alaska, Colorado, Connecticut, Florida, Georgia, Indiana, Iowa, Kentucky, Louisiana, Mississippi, New Mexico, New York, North Carolina, Ohio, Oregon, Pennsylvania, South Carolina, Texas, Utah, Virginia, Washington, West Virginia, Wisconsin, and Wyoming.

Alabama. This state indicated that the question of sublayer stiffness in regard to pavement density had not been a problem in the past. The primary difficulty with density revolved around thin lift surface course construction, particularly when layers of 100 psy or less of mix were placed. The problem was solved by increasing the minimum course thickness to 125 psy.

Alaska. If the required density level is not obtained on a pavement layer in this state, the contractor is required to make changes in his compaction techniques. This includes increasing the mix temperature, adding rollers, changing the type of compaction equipment, and changing the roller pattern. In a few cases, the asphalt cement content of the mix was increased. After several adjustments are made by the contractor, and if the desired level of density is still not attainable, the DOT assumes control of the compaction operation under a method type of specification. Alaska has not had any major problem due to lack of sublayer support because thick, free-draining gravel bases are used under all asphalt concrete courses.

Colorado. Colorado has had problems in obtaining the required density values on some projects when an asphalt concrete base course layer has been placed directly on a soft clay subgrade soil (full depth construction). "Engineering judgement" is used to adjust the target density values for the first layer of mix. Each problem is handled on a job-by-job basis, usually at the district level. The problem of sublayer support also occurred on one project where a sand mix was placed as a leveling course on top of a Portland cement concrete pavement which had extensive cracking in the slabs due to an alkali-aggregate reaction. The contractor could not get density in the first dense graded asphalt concrete layer laid over the sand mix material.

The state owns a Dynaflect machine. This equipment is sometimes used to measure the deflection of the existing pavement structure on an interstate highway before resurfacing.

Deflection measurements are also occasionally taken on the new overlay and the change in strength of the structure calculated. This information, however, is used for research purposes only. Colorado has not made any changes in the required density level on any job based on the initial deflection values.

Connecticut. This state has not experienced any major problems in attaining density on their asphalt concrete layers. Where the contractor has not been able to achieve the necessary density early in the project, he has adjusted his compaction process in some manner to make the specification level.

Florida. Because asphalt concrete pavement layers are built on limerock base courses, Florida has not had any problems with sublayer support. The limerock material is self-cementing and sets up when compacted at optimum moisture content. The base course thus is quite stiff, like a cement treated base course. The specification compaction requirements in this state are relatively low, and few difficulties are encountered by the contractor in achieving the required density level.

Georgia. Although this state has a QC/QA specification for density, the DOT really controls the compaction process. A control strip is constructed by the contractor for each mix used on a project. If the necessary level of density is not attained, as compared to the maximum theoretical density for the mixture, the contractor and the state engineers decide how to change the compaction operation. If the density level is still not reached, the district materials engineer has the authority to waive the density specification. In 1985, 6 percent of the jobs built in Georgia operated under a so-called "Practical Density" specification.

The change in the specification requirements is usually due to thin lift construction, weather conditions, or mix design problems -- asphalt content, aggregate gradations, or changes in the aggregate characteristics. The problem of sublayer support is a very minor one. Most of the lack of density problems are due to poor construction practices.

Indiana. This state operates under a method type specification and the highway department controls the compaction process. Density is not measured -- a standard roller pattern is used for each project. Any problems that might occur with sublayer support are either ignored or handled on the project. Since the contractor is not responsible for the level of density required, and since the actual compaction level obtained is not determined, Indiana essentially never has a density problem.

Iowa. In 1985, Iowa collected over $200,000 in price adjustments from its contractors because of the level of density on paving projects. In general, the problems were related to poor mix design or poor construction practices rather than to a deficiency in sublayer support. As a standing rule, density requirements are not "relaxed" on interstate or primary highway paving projects. Adjustment to the penalties applied are made, however, on paving work done on some secondary roadway projects. The primary reason for the penalty relaxation is the thin lift construction specified in the plans. When a weak sublayer condition is suspected, the contractor usually adds more rollers to the compaction train or adds more asphalt cement to the mix. In this state the contractor is in complete charge of the compaction operation. When failing density results are obtained, the contractor can usually quickly alter some phase of his paving and compaction process to bring the density levels up to 100 percent pay levels.

Kentucky. This state highway department has a provision written into its standard specifications to allow a project engineer to accept lower levels of density than specified. The specifications state that when the attained density is less than required, the engineer may accept the course based on the character of the underlying material. This determination is made on a project by project basis by the engineer in charge of the job. The density waiver provision applies only to the first asphalt concrete course placed. The contractor is expected to obtain the required density levels on all layers above the initial courses.

Kentucky has experienced difficulties in attaining density in the past. This was primarily true on low asphalt content mixes. As the price of asphalt cement increased, the amount of binder specified in the mix decreased. By returning to more optimum asphalt cement contents, the compaction problem has been reduced. Contractors also have difficulty occasionally in getting density on thin lifts and variable thickness leveling courses. When a problem with density occurs, paving is suspended until an acceptable solution is found. No penalties are applied. A combined contractor - state effort is made to correct the problem.

Louisiana. In the past few years, as Louisiana changed their compaction requirements to increase the density level needed on an asphalt concrete mixture, some problems have occurred when the first layer of mix was placed on a granular base course. The contractor, operating under QA/QC specifications, had the responsibility to attain density regardless of the project conditions. On several projects, however, the underlying granular base materials yielded under the rollers. In these cases, the highway department took charge of the compaction operation. The density specifications were waived for the initial asphalt concrete layer due to a lack of sublayer support. This was done on a project by project basis, usually at the district level.

This state has operated under quality assurance specifications for many years. Density attainment problems have been few. The contractor has his choice of corrective actions to take if the required density levels are not reached. He can add rollers, change the mix design, etc. The state believes that the contractor can achieve density, even on a soft sublayer, if he is really required to. Most contractors, however, will attempt to get the specification waived instead of initially trying to improve their compaction operation.

Mississippi. This state also believes that its contractors can attain the level of density requirement in the specifications. No problems have been encountered with lack of sublayer support. No major problems have occurred with density. If the contractor can not obtain the necessary density levels when constructing a roller test strip, he must change his operation in some manner to reach the required density plateau.

New Mexico. This state has a QA/QC specification for density. Few problems have been encountered with the attainment of density. If the contractor does encounter problems, the problems are investigated and if the cause is beyond his control the density specification is modified. Problems have been encountered with soft sublayers and the specification has been modified generally only after review by the central office.

New York. Density levels are not measured in New York. Method specifications for compaction are used with the state setting the compaction equipment and rolling procedure requirements. Problems with the lack of density attainment due to poor sublayer support do not theoretically exist.

North Carolina. A combination of method and end result specifications are used in North Carolina. The contractor is required to have at least two steel wheel rollers on the job and is also required to attain a minimum percentage of laboratory density. The contractor is allowed a period of time to adjust his operation to achieve the needed density level. After that period, the operation is suspended while the state and the contractor attempt to find a mutually acceptable solution to the difficulty. Because of the cooperation attitude, few density penalties are applied.

On paving projects where a yielding sublayer has been encountered, adjustments will be made by the state highway department to the required density levels. This is accomplished at the project level by the state's engineer, based on his engineering judgement. The problem primarily exists on new construction jobs and on the first lift of asphalt concrete placed on the subgrade soil or granular base materials.

Ohio. On Interstate and primary highway paving projects, Ohio requires that the contractor meet a minimum percent of maximum theoretical density. In general, under QC/QA specs, there have been minimal problems meeting the density specifications. On secondary roadways, density levels are controlled by method specifications. Because of this procedure, problems with attaining density when a soft underlying layer is encountered on low volume roads are not recorded or reported.

Oregon. The Oregon Highway Department routinely conducts a deflection survey of its pavement structures which are scheduled for resurfacing. The deflection values are used to determine the thickness of the overlay needed on each project. These deflection readings are available to the project engineer and act as a guide to areas where density attainment might be a problem. This rarely occurs, however, because the density specifications call for a minimum of 91 percent of the maximum theoretical density. Before penalties are assessed, the contractor need only to attain 98 percent of the base density value (this means up to 10.8 percent air voids in the mix). The contractors have little trouble attaining the density level, even on soft yielding sublayer conditions. Indeed, there are very few price adjustments taken for density.

Pennsylvania. Similar to Ohio, Pennsylvania uses QC/QA specifications for density on projects on major highways and uses method specifications for overlay work on secondary roadways. They have not had any major problems with the contractors attaining density on the higher traffic volume pavement resurfacing projects. On the method spec jobs, where there is a perceived problem due to a yielding sublayers, the state will make an adjustment in the desired density level. The potential density problem, however, must be identified by the contractor before paving commences. No "hindsight" adjustments to the density levels are allowed. The state project engineer is empowered to make the necessary changes in the compaction requirements based on his knowledge of the job and engineering judgement.

South Carolina. This state uses a control strip procedure to set the density requirements on a project. According to the information received, South Carolina has not experienced any problems attaining density. They have also not had any difficulty with lack of sublayer support.

Texas. Texas has not had any major problems related to sublayer support. Most of the general density attainment difficulties are related "...to the contractor's lack of willingness to try to obtain the necessary density level". It was the distinct feeling that a contractor can reach the density needed if he conducts his compaction operation properly. On one project where the shoulder adjacent to the mainline pavement was in poor condition and was being overlaid, the state agreed with the contractor to reduce the required compaction level. Because the districts in Texas are so autonomous, it is difficult to generalize in regard as to how density specifications are enforced or waived. Paving problems are solved at the district level on a job by job basis. If problems occur, they are handled locally. Few density penalties are ever assessed.

Utah. To eliminate past problems with attaining density, Utah has increased it minimum course thickness for any layer to 2 1/2 inches. This significant mat depth allows more heat retention and more time for the contractor to achieve compaction before the mix cools. Density requirements are not difficult -- the average of four cores must be at least 93 percent of the Rice density and no single value can be less than 89 percent of the maximum theoretical density. If density problems do occur, the state project engineer has the authority to increase the asphalt cement content in the mix. This change typically "solves" the density problem. No lack of compaction difficulties have been blamed on lack of sublayer support.

Virginia. The project managers for the state highway department can waive the density specifications on a project where it is believed that a yielding sublayer condition is influencing the contractors ability to obtain the required compaction levels. This occurs occasionally when an asphalt concrete overlay is constructed on top of a surface treated pavement structure. In general, however, poor sublayer support is not a major problem. Density attainment problems occur on about 2 percent of the Virginia projects. These are not one specific type of difficulty, but are more related to the contractor's operation and to a lack of quality control.

Washington. The contractor can choose to operate under a QC/QA spec or a method spec in this state. Under the quality assurance specification, the contractor builds a density control strip at the start of the job. If a soft spot is found in the grade at some point in the paving process, and if the contractor can prove that the yielding sublayer affects his ability to achieve density, using the same equipment and roller patterns as on the test strip, any density penalty would be adjusted or waived. This action, however, can only by accomplished at the headquarters construction office, not at the district or the project level.

For low density determinations, not related to sublayer support, the contractor is in charge of altering his compaction operation to achieve the desired density. He can change the type of equipment used, the roller pattern employed, or the number of rollers operated. If none of these changes bring the density values up to the required levels, the state will add more asphalt cement to the mix and/or adjust the aggregate gradation. On method spec jobs, density levels are controlled by the state and compaction levels are not monitored.

West Virginia. The state requires the construction of a compaction test strip at the start of each project. A nuclear gauge is used to determine when the maximum relative density is obtained. No cores are cut, however, and no correlation to actual air void content is determined. Nuclear density tests are run throughout the rest of the job, but no penalties are applied if the required density level is not attained. The contractor is merely requested to alter his rolling operation to try to gain more density. When a situation arises where a weak foundation layer is present, the contractor is allowed to revert to a roller pass type specification over the yielding sublayer. In any case, density is not measured. Essentially the density requirements (which don't really exist) are waived, as necessary by project personnel.

Wisconsin. On late season paving projects, problems with density and sublayer stiffness have occurred when the base course materials are wet. When this occurs, the state's engineer has the option of relaxing the density requirement or waiving the specifications are instituted. In regard to density requirements generally, a problem occasionally exists when harsh mixes are produced. The contractor is expected to increase hiscompaction effort in order to achieve the required density level. Density problems overall are minimal.

Wyoming. This state has one of the most stringent density requirements -- an average of 95% of maximum theoretical density with no individual tests less than 92 percent (although the specification is rarely enforced). A control strip is constructed and the density obtained is measured. If the contractor does not achieve the required density level, a second strip is compacted at state expense. If this section also fails density the contractor builds a third strip at his expense. If the highway department feels that the contractor has made a sincere effort to make density but still can not, the state will alter the mix design -- increasing the asphalt cement content or changing the aggregate gradation. The density specifications are waived, by the central materials laboratory, on some projects where thin lifts are shown on the plans. On low volume roadways with poor base support, a method compaction spec is substituted for the normal density requirement.

Summary. From the results of the telephone survey, it is evident that the problem of sublayer stiffness occurs occasionally in most states. The problem, however, is not quantified. None of the state highway departments consciously take sublayer support into account when setting up the compaction specification for a particular new construction or resurfacing project. Most choose to require the same degree of density in all asphalt concrete layers on all types of jobs. The exceptions are the states that use quality assurance specifications on their high traffic volume roadway projects and who also allow the use of method type specifications for overlay work on secondary highways.

When a density problem occurs on a project, the state requires the contractor to change his compaction operation in some manner -- by increasing the number of rollers, by changing roller types, and by altering roller patterns -- in order to increase the compaction effort applied to the mix. If none of these changes increase the level of density being obtained, the state will typically alter the mix design. This is normally done by first increasing the asphalt cement content in the material. If this fails to increase the density obtained, a change in aggregate gradation is tried next. In most cases, a cooperative attitude exists between the state and the contractor in trying to solve the lack of density difficulty. Full price adjustments for failure to meet density requirements are evidently applied only when the contractor does not try to solve the problem on his own or has a belligerent position towards the state personnel.

In regard to sublayer support, the problem is generally handled on a project by project basis, typically at the local (project or district) level. If the state personnel know that the pavement layers underlying the new overlay are weak and yielding, the density specifications are often waived. The same is true when an asphalt concrete layer is placed on a soft subgrade soil. There does not appear to be any definite written rules, however, as to when the specifications are set aside and when they are enforced. The "best faith" effort on the contractor seems to play a major role in helping the state to decide to waive or relax the density requirements. If the contractor can convince the project engineer that he can not attain density because of the weak foundation, the specifications are usually set aside.

A strong note of caution must be stated, however. In most states the compaction requirements for asphalt concrete mixtures are not very difficult to achieve. One reason why more compaction problems are not evident is that the specification requirements are very low to begin with. The states with the higher density requirements normally have more density problems than do the states with lower specification limits. This is true for the question of sublayer support also. Thus the reason a state does not have difficulty in obtaining the required asphalt concrete density levels on a weak foundation may be due entirely to the level of density specified rather than to a real lack of the problem. A state whose density specifications require attainment of 94% of laboratory density (approximately 9.8 percent air voids) will have less density problems than a state which requires compaction to a level of 93 percent of the maximum theoretical density (7 percent air voids). Thus it is difficult, if not impossible, to truly compare the degree of density problems related to sublayer support from one state to another.

MEASUREMENT OF DENSITY

Density Standards

Three different standards are in current use by various state highway departments as a reference to determine the acceptability of the level of compaction of an asphalt concrete mixture. The first standard is the theoretical maximum specific gravity (density) of the mix. The second is the laboratory compacted density of the material and the third is the density obtained during the compaction of a field test strip.

Maximum Theoretical Density. The standard which provides an indication of the air void content in a compacted asphalt concrete mix directly is the theoretical maximum specific gravity. This value can be determined in two ways. First, the maximum specific gravity can be calculated from the specific gravity can be calculated from the specific gravity values of the various components of the mix (6). For this determination, the effective gravities of each of the aggregate fractions must be known. The specific gravity of the asphalt cement must also be measured. In addition, the amount (weight) of each mix component must be known. The accuracy of the values calculated for the theoretical maximum specific gravity, however, depends directly on the accuracy of the specific gravity measurements for each of the components. A small error in the calculation or measurement of the individual values can make a significant change in the maximum specific gravity determined for the mix.

The theoretical maximum specific gravity of the mix can be measured directly using a sample of the actual asphalt concrete mixture. The method used is known as the Rice procedure and is found in ASTM specification D 2041 (35). A vacuum is used to extract all the air from the mix and then the specific gravity of the voidless mix is determined. To improve the accuracy of the measurements, at least three replicate samples should be run at each selected asphalt content. It is important, further, that the specific gravity values be reported to at least three decimal places to provide for a more precise determination of the voidless mix density value.

Laboratory Density. The second means of density comparison is with a laboratory compacted sample of asphalt concrete mix. In this procedure, the mix to be used on the paving project is placed in a mold and compacted. Several different types of compaction equipment can be employed: (a) the Marshall hammer, (b) kneading compactor, (c) gyratory compactor, (d) double punch method, or (e) vibratory force. Each of these devices is capable of exerting different compaction efforts on the mix. Thus it is easily possible to obtain significantly different density values on samples of the same mixture when different compaction equipment and compactive efforts have been used to prepare the specimens. In addition, the air void content in the specimens will vary somewhat even when "constant" compaction conditions are employed.

The air void contents of the laboratory compacted samples can not be determined directly. The bulk specific gravity of the specimens must be measured and the air void contents calculated. Typically most state highway departments desire the laboratory compacted samples to have an air void contents in the range of 3 to 5 percent, by weight of mix. The level of density required in the field for the compacted asphalt concrete mix is usually set as a percentage of the laboratory compacted density, generally in the range of 92 to 97 percent of the lab density.

A considerable variation can exist in the air void content of the mixture compacted to a percent of lab density. If the required field density level is 95 percent of lab density and the lab specimen contains 3 percent air voids (97 percent of the voidless mix density), the field sample will contain about 7.8 percent air voids. If the lab specimen has 5 percent air voids, however, the field mix, compacted to a 95 percent relative density value, will contain about 9.7 percent air voids. Thus, depending on the actual amount of air voids in the laboratory prepared sample, the level of density (air void content) can vary significantly. This is true even though a constant percentage of laboratory density is required in the field compaction specification. Using laboratory density as a standard does not directly provide information on the actual air void content of the compacted mix.

Field Test Strip Density. The third density standard, the field control section, is also a relative one. It is the maximum density which can be obtained in an asphalt concrete mix on the roadway under a given set of conditions. For a particular asphalt concrete mixture, the maximum density that can be attained is a function of many variables, such as mix temperature, lift thickness, air and base temperature, other environmental conditions, time of initial rolling, type of compaction equipment, compaction effort applied, and rolling pattern. What might be the maximum attainable field density under one combination of variables might be considerably different level of density under another set of conditions.

Given the opportunity, a contractor can determine to a significant degree the level of density obtained in the control strip. By using less compaction effort and delaying rolling, the "target density" of the field test section can be reduced. This in turn makes it easier for the contractor to reach some set percentage of the control strip density when compacting the rest of the mixture on the project.

The maximum attainable density of a field control strip, under a given combination of compaction conditions, must result in a mix which contained 3 percent or 8 percent actual air voids. If the compaction specifications for a project require that the minimum acceptable density level was 96 percent of the control strip, this might mean that the compacted pavement could contain from 6.8 to 11.7 percent air voids, depending on the amount of actual air voids in the control strip (3 and 8 percent in this example). Thus, the field control strip method suffers from the fact that the true air void level in the mix is not really controlled.

Percent Refusal Density. The Department of Transport in England has conducted some research on a new method to determine the target density value, called the percent refusal density test (36). In this procedure, the bulk density of a paraffin coated core sample taken from the compacted asphalt concrete mix from the roadway is calculated. The wax coating is then removed and the sample is heated. A vibratory hammer is next employed to compact the specimen as completely as possible -- to refusal. The bulk density of the modified sample is then determined, without the paraffin coating. The percent refusal density is then defined as the ratio of the bulk density of the sample as compacted by the rollers to its refusal density.

This means of measuring density has not been used to date in the United States. It does provide a means of setting a target density value as well as a way to measure the density of the mix as obtained by the compaction equipment. The primary drawback to the method is that the amount of air voids in the refusal specimen is not known. It is doubtful that the specimen can really be compacted down to a zero air void content. Thus the density value obtained is a relative value and not directly related to an actual air void content.

Summary. Of the three most commonly used methods to set a standard for density measurement, it is recommended that the maximum theoretical specific gravity procedure, using ASTM specification D2041 be employed. This procedure allows the air void content of the asphalt concrete mixture to be determined directly, without the need for intermediate calculation steps. The air void content of the asphalt concrete mix is necessary to determine the durability of the mix. The Rice standard allows a direct comparison of the compacted mix density to density of a voidless mix, the exact comparison required.

The standard density of the mix without air voids is subject to minimal manipulation by the testing agency and none by the contractor. With this procedure, the actual mix to be employed on the project can be used to establish the target value for compaction comparison purposes. The target value is constant. It is not subjected to alteration by changes in mix temperature, compaction equipment, compactive effort, or environmental conditions as are the laboratory density and field test strip density methods. The target value for this method changes only if there is a change in the asphalt concrete mixture itself. Thus, for more accurate setting of the target value for pavement compaction, the maximum theoretical density procedure is suggested.

Density Measurement

Two primary methods are available to measure the density of a compacted asphalt concrete pavement. One method is destructive. It requires that cores or small slabs be cut out of the course surface. The second method is non-destructive. A nuclear gauge is used to determine a count rate value for each reading. This value is readily converted into a density reading.

Cores. The "old fashioned" method to determine the density of a section of an asphalt concrete mat is to cut a core from the mix. The unit weight of the cores can be determined using either ASTM standard D1188 using paraffin coated specimens or ASTM standard D2726 using saturated surface-dry specimens (35). The air void content of the cores can be calculated using ASTM D3203 (35).

The debate continues as to the size of the cores to be cut. The vast majority of the states that use cores cut ones that are 4 inches in diameter. Several states, however, feel that this small a diameter core causes inaccuracies in the density measurement, particularly if the pavement surface has a relatively rough texture and the cores are not paraffin coated. At least two states, therefore, cut 6 inch diameter cores and one state uses small slabs or plugs which are sawed from the pavement course.

There is no doubt that density of a pavement core is subject to some variation. Two cores cut from adjacent points in the same longitudinal line in the pavement surface will vary somewhat in density. Some of the difference is due to sampling and testing and some is due to actual differences in the density of the material. This variation, however, can be easily compensated for by using multiple samples and statistical specifications when calculating the density of core samples.

Nuclear Density. Nuclear density gauges are non-destructive testing devices. They measure density quickly and easily and make the test results available rapidly. The major problem with this type of equipment is that there is a lack of correlation between the density values determined with the nuclear gauges and the pavement density measured by the pavement cores.

In an FHWA publication dated June 1967, it was pointed out that "...if the nuclear gauge is to be used to determine absolute densities comparable to those obtained by conventional methods, a separate calibration must be established for each different mix". (37) In the intervening twenty years not much has changed. Burati and Elzoghbi presented two extensive reports at the Transportation Research Board Meeting in 1986 which discussed the correlation of nuclear density results with core densities, both for the mainline pavement and for longitudinal joints (38,39). It was determined that there were significant differences in the results obtained from different nuclear devices, both in the mean density values and with the amount of variation about the mean.

Another Burati study showed that the nuclear gauges gave significantly lower density values for the asphalt concrete mixes tested compared to the core densities. In addition, the relationship between the core and nuclear values varied from project to project. The report stated that "...the findings of this research do not support the use of nuclear gauges for acceptance decisions. The use of nuclear gauges in lieu of coring, but with the same acceptance limits that were developed based on core results, is not appropriate" (40).

From the results of the telephone survey of the 25 state highway departments, it was found that a number of states use nuclear gauges for the acceptance of asphalt concrete pavement density. Some of these states use the devices to determine the relative density of the pavement layers compared to a density control strip. Since density is not measured directly in either case, the lack of correlation is not of concern. The fact that the density "passes", however, should not be taken to mean the pavement layer has a low air void content. The nuclear gauges merely provide an indication that the pavement material is relatively as dense as the control strip material.

Some states attempt to correlate the nuclear gauge readings with cores. A field control strip is constructed. Cores are cut from the test section. Nuclear readings are taken from adjacent locations. A correlation is developed from the data gathered between the nuclear values and the core densities. This correlation is then used throughout the rest of the job to estimate the density of the pavement course. On a statistical basis, however, the correlation value calculated is usually not valid because not enough core samples or nuclear readings have been taken for proper development of the correlation coefficient.

Summary. The literature on the use of nuclear density gauges suggested strongly that these devices can and should be used to measure density only on a relative basis. The equipment should not be employed to attempt to determine the absolute density of the asphalt concrete material. The relationship between the nuclear density reading and the core density value depends on the type of gauge being used, the mix being tested, and the number of samples in the correlation.

Density and Sublayer Support

In terms of the relationship between sublayer support and pavement density, the most stringent density specification is the one which would combine the use of maximum theoretical density as the standard and the use of cores to measure density (depending, of course, on the actual level of density required by the specification). The standard is not affected by the field conditions in any manner, only by the characteristics of the mix itself. The density of the cores are subject to the resiliency of the sublayer material and the compaction effort applied to the mix. Further, the core density can be related directly to air void content of the mix.

The density specification which should theoretically be the "most forgiving" in terms of a lack of sublayer stiffness or support is one which combines the use of a field control strip and nuclear gauges to measure density. If the strength of the sublayer is uniformly poor throughout a project, this condition will be a factor during the construction of the density test strip. The weak, yielding sublayer will reduce the contractor's chances, to some degree, to obtain a very high level of density in the control strip. What will be obtained, and measured with the nuclear gauges, is the maximum density which can be attained with that given set of conditions, equipment, and compaction procedures. If the condition of the sublayer remains approximately the same as under the control section, the relative density values measured should also be approximately the same. Thus the sublayer support factor would cancel itself out and the specification requiring a certain percent of the control strip nuclear density reading would be readily met.

The problem of sublayer support and its effect on the ability to obtain density thus depends on several factors. It is affected by the type of standard used to establish the target density. It is determined by the method used to measure the density attained -- nuclear gauge or cores. It is also dependent on the degree or level of density required -- the greater the percentage of the density of a voidless mix specified, the more the lack of a stiff sublayer will become a problem and contribute to failing density values for the contractor.

CONCLUSIONS

There are four primary categories of variables which affect the ability of a contractor to attain the required level of density on an asphalt concrete paving project. The first is related to the characteristics of the mix being placed, including the properties of the aggregate, the asphalt cement, and the combination of materials in the mix. The second is concerned with environmental conditions during laydown, including air temperature, base temperature, wind velocity, and cloud cover. The third category consists of conditions at the laydown site, including the thickness of the mat, the maximum aggregate size, the uniformity of the layer thickness, and the degree of sublayer support. The fourth group, the compaction equipment and procedures, includes both the type of rollers employed on the project and the operation of that equipment.

The level of support, or the stiffness, of the layer on which a new asphalt concrete course is being placed is thus only one of many variables which affect the degree of density obtained on a given job. The significance of this factor in contributing to a lack of compaction, or high void content, in an asphalt concrete mixture appears relatively minor compared to the importance of some or the other variables. There is no doubt that on some projects, the weak condition of the underlying layer directly affects the density attained in the new asphalt concrete layer. In each case, the degree of sublayer support becomes an important factor only when good engineering practice is ignored.

If a subgrade soil is compacted at the proper moisture content and level of density, it will be stiff enough to support the weight of the laydown and compaction equipment as well as provide a strong foundation for the asphalt concrete mixture to be compacted against. If the subgrade soil is a wet clay or silty clay, or if it is a cohesionless sand, it is good practice to stabilize the soil in some manner in order to provide a high level and more uniform degree of support for the new asphalt concrete layer. The same is true when a granular subbase or base course layer is incorporated into the pavement structure under the asphalt concrete layers. If the untreated aggregate materials are properly placed and compacted, and if they contain the required degree of internal stability, there generally is no problem in attaining the desired level of density in the asphalt concrete placed on the granular subbase or base course.

When an existing asphalt concrete or Portland cement concrete pavement is being overlaid, it is common practice to do the necessary crack sealing and patching work to increase the stability and strength of the pavement structure in the failed areas. The objective of the repair, rehabilitation, and replacement effort is to provide a uniform degree of sublayer support for the new overlay. If the corrective work is properly carried out, and if the other compaction conditions are favorable, adequate density can be obtained on the overlaying asphalt concrete layer.

In general, the degree of sublayer support is not a significant factor in the attainment of density in an asphalt concrete mixture. This is shown by the review of literature which reveals an almost total lack of discussion of the subject of sublayer support. Only a dozen of the more than one hundred technical reports and articles which were reviewed for this study even mentioned this variable. When the subject is mentioned, it is done in very brief fashion -- usually no more than a sentence or two, or perhaps a paragraph or two in some papers, out of a very long report on the density of asphalt concrete mixtures. Further, no definitive data is presented in the literature. Several authors allude to the need for a solid foundation in order for the compaction equipment to properly densify the new asphalt concrete layer. None of the writers, however, provide any "hard numbers" or suggest any means to measure the degree of sublayer support necessary for adequate compaction. No specification recommendations for the required level of sublayer support are found in any of the technical papers reviewed.

When there is a problem identified with asphalt concrete mixtures or pavement structures, such as fatigue cracking, moisture damage, or permanent deformation, for example, a reviewer can find a multitude of reports describing causes and solutions for each particular problem. In terms of compaction, many articles have been written on the importance of obtaining an adequate level of density. None of these studies has focused on the effect of sublayer support on the attainment of density. Thus it can be concluded, by inference, that sublayer support must not be a major problem, or even a minor one, or much more definitive information would be available in the technical literature.

From the data gathered from the survey of the state highway departments, it can be concluded that most of the engineers contacted believe that a contractor can attain the specified level of density, even on a weak foundation, if the proper effort is made. Many individuals commented that the average contractor usually tries to obtain a reduction in the density requirement, or a waiver of the specification, whenever there is a problem in attaining density on a paving job. This is true regardless of the reason for the difficulty. When the lack of sublayer support is cited as the cause of the problem, the contractor will attempt to show that the sublayer is yielding under his equipment and that he is thus unable to achieve the density required.

If the state engineers do not agree to the waiver request, however, the contractor is typically able to achieve the compaction level needed. When faced with a penalty for lack of density, the consensus seems to be that the paving contractor can obtain density, even on a weak foundation. It is noted, however, that some state highway departments require a lower level of density on paving projects on secondary roadways, which usually have weaker existing pavement structures, than on jobs built on interstate or primary highways.

If density problems do occur because of a lack of adequate sublayer support, the solution to the difficulty can typically be found in a change in the compaction operation. This might include using different rollers or using the normal compaction equipment in a different order or roller pattern. It might also include changing the rolling process -- roller speed, rolling zone, number of roller passes, vibratory impact (amplitude and frequency), and pneumatic tire pressure. Too often, however, only the "standard rolling pattern" is used on a project, regardless of the level of support available from the sublayer course. If density is not attained, it is generally because little, if any, attempt was made to adjust the compactive effort to account for the difference in the degree of sublayer support available.

For each asphalt concrete mixture, each layer thickness, each combination of environmental conditions, each set of paving site variables, there is a wide variety of compaction effort that can be employed in order to achieve an adequate level of density, even on a weak foundation. The challenge to the contractor is to determine the "optimum" combination of equipment variables and compaction operation variables in order to obtain the specified degree of density. The compaction effort which is satisfactory on one project may be inadequate on the next job. The number of roller passes needed yesterday may not be enough tomorrow. Too often, both the contractor and the state personnel expect one preselected combination of compaction equipment and compaction process to be applicable to all jobs under all conditions. It is more reasonable to assume that the compaction effort applied to the mix will need to be changed as field conditions vary.

It is concluded, therefore, 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 modification of his compaction equipment and his rolling techniques, it is believed that the paving contractor can achieve adequate density even on a relatively weak sublayer course.

FUTURE RESEARCH

The conclusion which can be reached from the literature review and from the conversations with the various state highway engineers is that there is a problem with attaining an adequate level of density when the stiffness of the sublayer is low, but that the problem is relatively minor. The prevalence of the problem depends on whether the state controls density by method type specifications or quality assurance type specifications. There are not reportable difficulties when method specs are used. The magnitude of the problem under quality assurance specs is dependent on the degree of difficulty in normally attaining an adequate level of density -- how tough the spec is and how rigidly it is enforced.

The literature has some references to the effect of sublayer support on the ability to attain density in an asphalt concrete layer. Only two of these references, however, contain hard data on the true extent of the problem. Everyone seems to believe that a firm foundation is needed to compact against, but no one has felt strongly enough to quantify the situation. Even the data in the New York State DOT reports (13,14) is suspect because deflection measurements were not taken before the overlays were placed and thus no comparison can be made. Further, this highway department never followed up its original research work on the importance of sublayer support even though it later published a number of technical papers on the subject of compaction of asphalt concrete.

Problems related to sublayer support do exist in paving projects. Most of those difficulties seem to hava assignable causes, however. In the majority of the cases, the solution to the problem is provided at the project or district level. The solution usually involves working with the contractor to try to increase the density level over the soft base. If an adequate degree of compaction is not attained, a decision is typically made to either relax or waive the density specification. The exact response depends on the magnitude of the problem and the relationship between the contractor and the state highway department.

The number of factors which can affect the ability of a contractor to attain density on a project is great. Most of those variables have a distinct and direct effect on the density level achieved. From the information gathered for this report, it would appear that the effect of sublayer support on the attainment of density in an asphalt concrete overlay is very, very small, and related only to certain expected cases where there is prior knowledge that a problem may exist with the stiffness of the sublayer material.

Data Review

The Arizona Department of Transportation, as part of its pavement management program, collects data on pavement deflections on a periodic basis. That deflection data is taken on pavement surfaces of various ages, including new overlays and aged wearing courses. The deflection measurements are gathered on pavement structures which carry a great variety of traffic, including urban and rural interstate highways, four and two lane primary roadways, and two lane rural pavements. These pavement sections are made up of a number different materials and course thicknesses, providing pavement structures with a wide variety of stiffnesses and load carrying ability.

It is therefore proposed that a review be made of the deflection data already on hand. This review should attempt to accomplish a number of points. First, the range of deflection values which typically exist on Arizona highways should be determined. Second, the deflection values which indicate a weak pavement structure should be calculated. These values will obviously depend on the materials in the existing roadway and the level of traffic being carried. Third, the search should be focused on pavements with weak foundations (high deflection values) which have been resurfaced within a short period of time after the deflection readings were collected.

A further review should be made of the construction records for the placement of the overlays on those projects where the deflection data indicated a lack of sublayer support may exist. The construction records should be inspected to see if there is any information as to whether or not a density problem existed on the resurfacing work. If the records do not indicate any deficiency in the density levels obtained, but if the deflection data shows a lack of sublayer stiffness, the resident engineer for the project should be contacted to determine if density problems really did exist but just didn't get into the daily reports. If the project records do indicate compaction problems, contact should be made to the appropriate engineering personnel to ascertain the cause or causes of the lack of compaction. Emphasis would obviously be placed on learning whether or not the sublayer support condition was a factor in the ability to obtain the required density level.

For projects where deflection measurements were taken both before and after an overlay was constructed, the deflection values can also be used to calculate whether the resurfacing layer was beneficial in reducing the total deflection of the overlaid pavement structures. If the overlay reduced the pavement deflections as expected, in proportion to the thickness of the courses placed, the condition of the existing pavement (sublayer) can be assumed to have been adequate. If, however, the new resurfacing did not materially change the deflection measurements, then the density records for the overlay paving should be checked to see if any difficulties occurred in obtaining density on the overlay. The lack of decrease in the deflection measurements after construction of the overlay may indicate a weak asphalt concrete layer, with the lack of strength being due in part to a lack of density.

Depending on the form of the construction records, the data review might take place in the reverse order. The search could be initiated for paving project where attainment of density was a problem. This could include jobs where a penalty was assessed due to low compaction or when the project reports show that the density specification was waived for some reason. This information could then be used to look up the deflection values, if any, available for the same project before the roadway was resurfaced.

The objective of this review of the deflection data and the construction records is to determine if any correlation exists between projects when the deflection values were high, indicating a lack or sublayer support for the new overlay, and difficulties in attaining density in the asphalt concrete overlay. This investigation and correlation, if it could be accomplished, would establish the extent of the density problem due to sublayer support in Arizona.

Project Monitoring

The Arizona DOT has a number of resurfacing contracts scheduled for paving in 1987. The list of these jobs should be reviewed to determine if any of the projects might be located on a site where the existing pavement structure may be weak. A check should be made of the pavement management records to see if the deflection test results for the same job indicate a lack of sublayer support for the new overlay. It is expected that several jobs will be found where there is an indication that there may be areas of excessive deflection on part or all of the project.

The information from the list of projects and the deflection data should be compiled so that two candidate projects can be selected for monitoring during the paving process. One of the projects ideally will have a fairly uniform, but weak, condition of sublayer support, over the length of the job. The second project selected should have a variable condition of sublayer support, including areas where the existing pavement surface is stiff and stable and places where the present surface might be more yielding and weak. The purpose of the choice of these two projects for monitoring is to see if there is a correlation between deflection of the present pavement surface and the ability of the contractor to attain the required density level in the new asphalt concrete overlay.

Once the two candidate projects have been selected, deflection measurements should be conducted on each job to delineate the sections of differing degrees of sublayer support. Strip maps should be prepared pinpointing areas where excessive deflections have been measured. In both cases, the deflection testing should be accomplished well before the paving commences on the project. The results of the deflection tests should not be made available to either the state project personnel or the contractor's people. The deflection analysis work should be done "for research purposes" as far as the project staffs are concerned.

The contractor on each job should be allowed to proceed in a normal fashion with his laydown and compaction operation. He should not be asked to alter his regular paving routine in any way. In particular, no extra effort should be made to increase the compaction effort applied to the mix in any location by the rollers. Normal compaction compliance procedures should be carried out by the state engineer. There should not be any indication to either the state inspector or the paving crew that the job is special or to be treated differently than any other project. Care must be taken to assure that the compaction operations are routine.

When the paving has been completed, a set of deflection measurements should be run on the same locations as for the preconstruction survey. A comparison should be made of the deflection values to see if the new overlay has uniformly increased the strength of the pavement structure throughout the length of the job. Since one of the two candidate projects should have been more uniform in sublayer support to begin with, it will be meaningful to review the change in deflection values that occur at various locations on both jobs. The change in deflection measurements should be analyzed to develop a correlation, if possible, between the initial deflection values and the degree of deflection after the overlay. It would be desirable to see how the uniform thickness (or supposedly, stiffness) resurfacing layer alters the strength of the pavement structure.

A significant number of cores should be cut from both projects after all the paving is finished in areas where differences in sublayer support were indicated by the initial deflection readings. The density of each core should be determined and the comparable air void content calculated based on the maximum theoretical density for the mix. Enough cores should be taken from each area to assure a statistically valid sample. The core data and deflection data, both before and after overlay, should be plotted and analyzed to determine if any correlation exists between the values.

For the project with relatively uniform, but weak, existing pavement structure, emphasis should be placed on investigating what change in density has occurred in the length of the job. Even though the sublayer condition might be weak, the core data may show areas where adequate compaction levels were achieved and other areas where the required density level is lacking. This information may then show that it is possible to obtain density even on an overlay on a weak foundation. Indeed, the variation in density values obtained along a project built on a uniformly poor sublayer would indicate that other factors, beside sublayer support, are important to the contractor's ability to achieve density.

For the project with the varying sublayer conditions, emphasis should be placed on reviewing why some areas with supposedly the same initial deflection values have different air void contents in the asphalt concrete overlay. Indeed, it should be determined whether other variables beside sublayer support would cause the contractor to obtain different density levels on areas where the deflection values would suggest a different answer. It should be ascertained whether or not a greater degree of compaction was achieved on an area of weak support than at a location when the sublayer was stiffer.

The final phase of the monitoring study should be to review the construction records for the two selected projects to see whether all the density tests, taken by the state personnel during the routine testing program for compaction acceptance, passed. A correlation should be attempted between the data on the compaction reports and the core and deflection data gathered by the research personnel. It would be desirable to determine if the normal testing procedures detected any differences in compaction levels which are comparable to what was measured by the extensive coring study. Care must be taken during this phase of the monitoring project not to embarrass the state personnel assigned to each project by make public any differences in the test results.

It must be emphasized that the two projects <u>must</u> be constructed in a normal manner by both the contractor and the state engineers. No attempt should be made to influence or control the compaction procedure in any manner. It would be best if the research personnel were not even present on the jobs during the construction operation. The initial deflection values should be obtained before the paving starts. The final deflection values and cores should not be taken until the paving is completed (but before a significant amount of traffic is applied to the new overlay). The project construction records should only be gathered and reviewed when the jobs have been finished. No indication should be provided to cause the contractor any concern that his compaction operation will be inspected later.

The purpose of the monitoring study is to see how the amount of sublayer support affects the contractors ability to attain the required density levels. When a contractor knows that his rolling operation will be subjected to special scrutiny, he will typically made an attempt to increase the compaction effort applied to the mix. While this is beneficial to the ultimate durability of the pavement, it will defeat the purpose of this investigation.

Test Section Construction

The implementation of this third phase of the future research work will depend on the results of the data review and project monitoring phases. If the first two studies illustrate that there is a strong relationship between density and the level of sublayer support, a research project should be set up to formally investigate the extent of the problem.

A paving project should be selected which has at least three distinctly different levels of deflection measurements on the existing pavement structure. The information for the choice of job should be first obtained from the pavement management data. This should be confirmed, however, by conducting detailed deflection measurements on the selected project to assure that several different levels of sublayer support are really present. The paving site ultimately selected can be one where a resurfacing contract has already been awarded but paving not yet started, or one when an overlay contract will be let in the near future. The final choice will depend on the logistics and problems of writing an extra work contract for the job already underway verses the need to write special provisions for the job to be bid.

The areas of different sublayer support on the project should be carefully delineated on the roadway. For each of the three sublayer sections, at least two different overlay mix thicknesses should be placed for the initial course. It is recommended that one thickness be in the range of 1 to 1-1/2 inches and the second thickness be between 2 and 2-1/2 inches. These suggested depths of the mat, however, can be altered to fit project needs and conditions. In any case, at least two thicknesses of the asphalt concrete mat should be incorporated into the job.

For each layer of sublayer support and each mat thickness, a minimum of two levels of compaction effort should be employed on the asphalt concrete mix. One level of effort should be the normal rolling procedure. The same compaction equipment, rolling zone and pattern, and compaction effort should be accomplished as for regular paving work. The second level of applied force should be as much rolling as can be accomplished without "overrolling" or breaking up the pavement layer. This basically would be the "maximum" compactive effort attainable. The exact rollers used, the sequence of rolling, and rolling pattern would be picked based on what equipment the contractor had available at the laydown site.

The proposed research project outlined above should be a full factorial experiment. This means that there would be a minimum of 12 test sections constructed (3 levels of sublayer support, 2 levels of asphalt concrete mix thickness, and 2 levels of compactive effort). Several replicate sections should also be built to make the results statistically valid.

For each test section, cores should be cut from the compacted pavement layers and the air void content of each sample determined. Nuclear density test readings should also be conducted. A correlation should be attempted between the nuclear density values and those measured by the cores. The core data, however, would be used to establish the relationship between the degree of sublayer support and the density level attained by the compaction operation.

TABLE 1

FACTORS AFFECTING COMPACTION

Factor	State Control	Joint Control	Contractor Control
A. Material Properties			
1. Aggregate			
a. Angularity		X	
b. Surface Texture		X	
c. Shape		X	
d. Gradation		X	
e. Sand Type		X	
f. Filler Type		X	
2. Asphalt Cement			
a. Grade	X		
b. Temperature Susceptibility	X		
c. Quantity		X	
3. Mix Properties			
a. Temperature			X
b. Moisture Control			X
B. Environmental Variables			
1. Air Temperature			X
2. Base Temperature			X
3. Wind Speed			X
4. Cloud Cover			X
C. Laydown Site Conditions			
1. Mat Thickness	X		
2. Maximum Aggregate Size	X		
3. Thickness Uniformity	X		
4. Sublayer Support	X		
D. Compaction Equipment			
1. Screed Density			X
2. Type of Rollers			X
a. Static Steel Wheel			X
b. Pneumatic Tire			X
c. Single Drum Vibratory			X
d. Double Drum Vibratory			X
3. Vibratory Roller			X
a. Amplitude			X
b. Frequency			X
4. Roller Speed			X
5. Roller Pattern			X
6. Roller Zone			X

TABLE 2

STATE COMPACTION QUESTIONNAIRE

1. What are your state's current requirements for the degree of compaction of asphalt concrete mixtures? Method specs or Quality Assurance (QA) specs?
    a. For surface course
    b. For leveling course
    c. For binder course
    d. For base course

    Please send a copy of the present density specification.

2. How is the level of density obtained measured?
    a. Not measured - method spec
    b. Nuclear gage - compared to what standard -- maximum theoretical density, test strip, cores
    c. Cores - compared to what standard -- lab density, max theoretical density
    d. How is the correlation between the measured density level and an actual air void content in the mix obtained?

3. For both new construction and overlays, how do the density specifications take into account the condition (stiffness) of the underlying subgrade, aggregate base, or existing asphalt concrete layer?
    a. How do you measure the stiffness of the underlying layer?
    b. How do you change the density requirements to take into account differences in sublayer support value?

4. Have you had any major problems obtaining density in asphalt concrete layers?
    a. On new construction - subgrade or granular base
    b. On resurfacing -
        (1) AC over granular base
        (2) AC over existing AC
        (3) AC over PCC

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