# Density of Asphalt Concrete—How Much Is Needed?

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Density is one of the most important parameters in construction of asphalt mixtures. A mixture that is properly designed and compacted will contain the optimum amount of air voids. Because density of an asphalt mixture varies throughout its life, the voids must be low enough initially to prevent permeability of air and water and high enough after a few years of traffic to prevent rutting caused by plastic flow. There are three primary methods of specifying density: (a) percent of control strip, (b) percent of laboratory density, and (c) percent of theoretical maximum density. If used correctly, all three methods can result in satisfactory compaction. The initial in-place air voids must be below approximately 8 percent and are determined by comparing bulk density and theoretical maximum density (TMD). The final in-place air voids, which must be above approximately 3 percent, are estimated by comparing the bulk density of laboratory-compacted samples and the TMD. The two methods that have been used to measure bulk density of asphalt mixture are physical measurements of cores and use of the nuclear gauge. The nuclear gauge is fast and nondestructive but is not as accurate as the core method.

The amount of voids in the asphalt mixture is probably the factor that most affects performance throughout the life of an asphalt pavement. Voids are primarily controlled by asphalt content, compactive effort during construction, and additional compaction under traffic. The density requirements and the methods of measuring density vary considerably from state to state. Some states construct a control test strip, measure the density on the strip, and use that density as the target density for the project. Other states compact samples in the laboratory during mix design and construction and use that density as the target density. Finally, other states measure the theoretical maximum density (TMD) (ASTM D2041) and use some percentage of that density as the target density. All of these techniques have been used successfully to build well-performing pavements, but they have also been misused, resulting in poor performance. Which method should be used? How much density should be specified and obtained during construction to ensure good performance?

A problem with density is the method of measurement. The two primary methods that have been used include measurement of bulk density of cores taken from the in-place pavement, and use of a nuclear gauge to measure the in-place density. The nuclear gauge method is not considered as accurate as measuring the density of cores. Many states use the nuclear gauge for developing rolling patterns but specify that cores be taken and measured for acceptance or rejection of the in-place mix. However, several states use the nuclear gauge for acceptance testing of the asphalt mixture.

The existing methods of specifying density of asphalt mixtures are compared in the following paragraphs. The relationship of each method to construction and performance is discussed, along with the various methods of measuring density during construction.

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## DESIRED ASPHALT DENSITY

The voids in an asphalt mixture are directly related to density; thus, density must be closely controlled to ensure that the voids stay within an acceptable range. Previous work has shown that the initial in-place voids should be no more than approximately 8 percent and should not fall below approximately 3 percent during the life of the pavement. High voids lead to permeability of water and air, resulting in water damage, oxidation, raveling, and cracking. Low voids lead to rutting and shoving of the asphalt mixture.

In a study for the state of Arkansas, Ford (*1*) showed that asphalt mixtures should be designed and constructed so that the in-place air voids stay above 2.5 percent. He demonstrated that, as long as the voids are above that amount, the expected rut depth will be no greater than 10/32 in. (see Figure 1). Ford's work was based on tests conducted on asphalt samples that were obtained from in-place pavements. The rut depth reported was from actual measurements on these pavements.

Brown and Cross (*2*), in a study of rutting of asphalt pavements, showed that significant rutting was likely to occur once the in-place voids reached approximately 3 percent (see Figure 2). When a suitable aggregate was used and the voids stayed above 3 percent, rutting was normally not a problem. Some of the projects evaluated showed significant rutting when the in-place voids were well above 3 percent. It was speculated that rutting began after the voids had decreased to an unacceptable level. Once rutting began, the integrity of the mix was lost and the voids increased. For these mixes, it was generally found that recompacting the mixtures in the laboratory with standard compactive effort produced low voids, which helped explain why the rutting occurred.

In a study of asphalt mixtures in Canada, Huber and Heiman (*3*) considered a number of causes of rutting. It was determined that one of the primary causes was low voids (below 3 percent) in the asphalt mixtures.

Zube (*4*) showed that asphalt mixtures become permeable to water at approximately 8 percent air voids (see Figure 3). As long as the voids were below 8 percent in the 10 projects studied, permeability was not a problem. However, the permeability increased quickly as the void level increased above 8 percent.

In a study of segregated mixes, Brown et al. (*5*) showed that the asphalt mixes were impermeable to water as long as the air void content was below approximately 8 percent (see

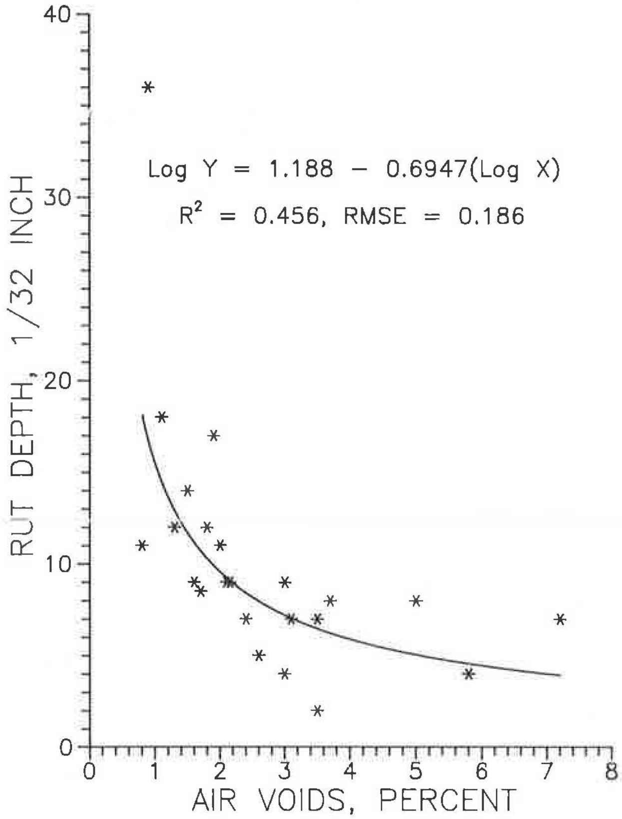


**FIGURE 1 Relationship between air voids and rut depth in Arkansas (*1*).**

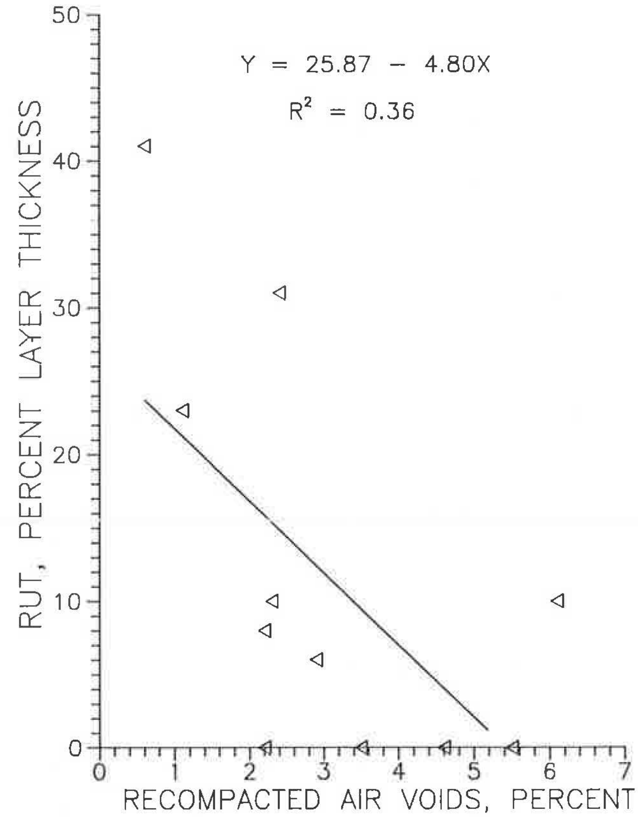


**FIGURE 2 Relationship between air voids and rut depth in rutting study by National Center for Asphalt Technology (*2*).**

Figure 4). The permeability increased rapidly as the void content increased above 8 percent.

Santucci et al. (*6*) showed that the retained penetration of asphalt cement is affected by the air voids in the pavement (see Figure 5). The loss in asphalt penetration was greatly increased for air voids significantly greater than 8 percent. They concluded that asphalt mixes must be constructed with low air voids (below 8 percent) to prevent rapid oxidation that leads to cracking and raveling of the asphalt mixture.

From these studies, it is apparent that asphalt mixes must be constructed with an initial air void content below approximately 8 percent and that the final air void content after traffic should remain above approximately 3 percent. The initial air void content is determined by comparing the in-place bulk density and the TMD for the mix being evaluated. The final in-place air voids are estimated on the basis of the mix design and field quality control testing. The voids obtained during the mix design and laboratory compaction of samples during construction are used to estimate the in-place voids after traffic. A Marshall hammer was selected to provide voids in laboratory-compacted samples equal to the measured voids after traffic (*7*).

## SPECIFICATION OF ASPHALT DENSITY

### Percentage of Laboratory Density

One method that has been used to specify density is to require that the in-place material be compacted to some percentage of the laboratory density. The standard laboratory density is specified as 50 to 75 blows with a Marshall hammer. In recent years most states have required 75 blows for high-volume roads. Some specifications require at least 95 percent of laboratory density, whereas others require at least 98 percent. Some specifications do not allow mixes to be compacted to a density greater than 100 percent of laboratory density. When mixes designed to have 4 percent voids are compacted to a density greater than 100 percent, premature rutting is likely to occur.

Several items are important for this method of specification to work effectively. Samples of the mix produced during construction have to be compacted in the laboratory to establish a reference density and to determine the air voids in the mix at that density. If the air voids are not satisfactory in the laboratory-compacted samples during construction, the mix must be adjusted so that acceptable air voids are obtained. Most often, the adjustment simply involves a modification in the asphalt content. The density produced during the mix design should not be used as the reference density because the laboratory properties will be somewhat different than test results on plant-produced materials. Aggregates sometimes break down during mix production, creating an increase in dust and thus altering the properties of the compacted asphalt mixture.

The density produced with a manual hammer has been shown to correlate with density in the field after traffic (*7*). Hence, any other type of compaction (mechanical or otherwise) must be calibrated to produce a density equal to that obtained with the hand hammer or, better yet, a density equal

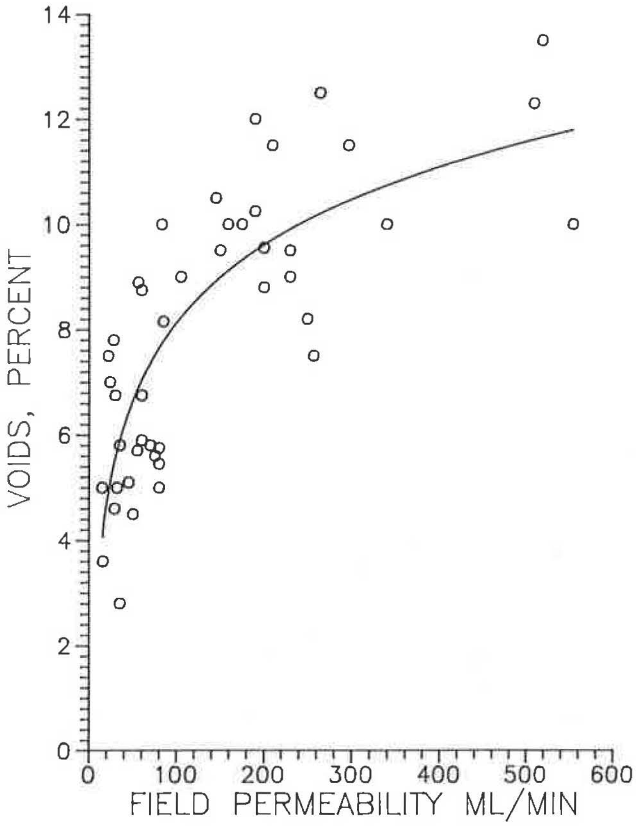


**FIGURE 3 Relationship between air voids and permeability in California study (*4*).**

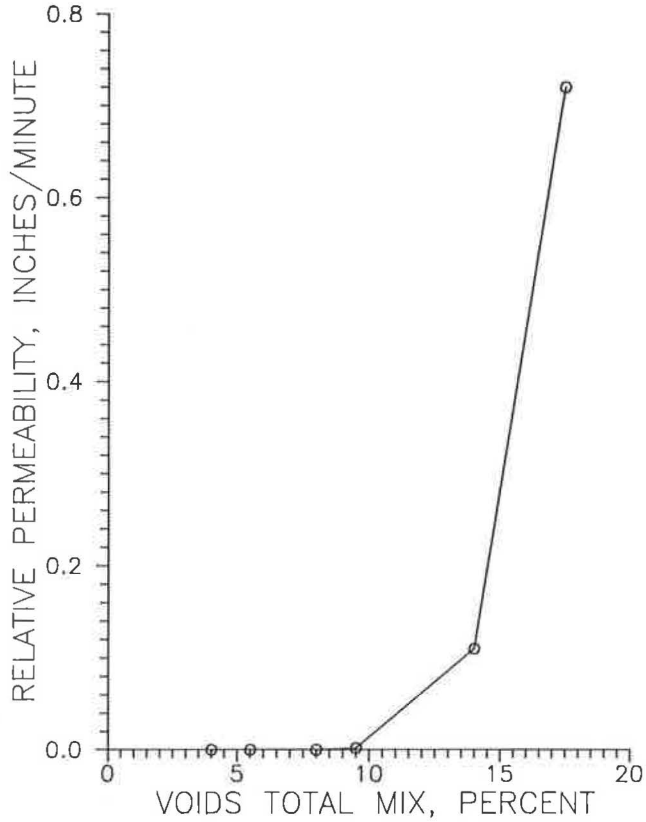


**FIGURE 4 Relationship between air voids and permeability in Georgia study (*5*).**

to that obtained in the field after traffic. The procedures specified in ASTM D1559 and AASHTO T245 for the Marshall test require that the manual hammer be used or that the method used be calibrated with the manual hammer. Density data from eight construction projects are presented in Table 1. These data show that the in-place density (80th percentile) after traffic is 2.2 lb/ft$^3$ higher than that obtained in the mix design. There are two likely reasons for this higher density after traffic. First, the mix probably changed somewhat during production to increase the laboratory density. Second, the laboratory compaction effort was probably insufficient and thus should be increased to be more representative of traffic. As shown in the table, the density of the mixes recompacted with the manual hammer compares closely to the in-place density. This finding emphasizes both the need to compact samples in the laboratory during construction to verify voids in the mixture and the need to use correct laboratory compactive effort.

Suppose a mix is designed to provide 4 percent voids and is specified to be compacted to at least 95 percent of laboratory density. This specification will result in up to 9 percent voids immediately after compaction and should result in approximately 4 percent voids after several years of traffic. The initial voids (9 percent) may be a little high with this specification; however, the final voids (4 percent) should be acceptable. The high initial voids may result in increased oxidation, causing more cracking and raveling if not subjected to significant traffic to provide further compaction. If this mix is subjected to a high volume of traffic, a small rut (5 percent of layer thickness, or ⅒ in. for a 2-in. layer) will result after additional channelized compaction under traffic increases the density from 95 to 100 percent of laboratory density.

If a mix is designed to have 4 percent air voids and is compacted to a density greater than 100 percent, immediate failure caused by rutting is likely. If the laboratory compactive effort is satisfactory, it is not practical for the mix to be compacted to a density greater than 100 percent. Hence, any project that continually approaches or exceeds 100 percent of laboratory density is likely the result of low laboratory density, not excessive compaction in the field.

This method of specifying compaction will result in good performance of properly designed mixes if (a) laboratory samples are compacted during construction to establish reference density, (b) correct laboratory compaction techniques are used, and (c) a minimum compaction requirement is set to ensure that in-place air voids after compaction do not exceed approximately 8 percent.

### Percentage of Theoretical Maximum Density

A second method often used to specify compaction requires that the asphalt mixture be compacted to some minimum percentage of the TMD. This procedure is a direct method of specifying maximum in-place air voids and an indirect method of controlling compaction. It involves taking a sample of the asphalt mixture during construction and conducting tests to measure the TMD (ASTM D2041). The bulk density of the asphalt mixture is measured after compaction and compared to the TMD, providing a direct measurement of in-place voids.

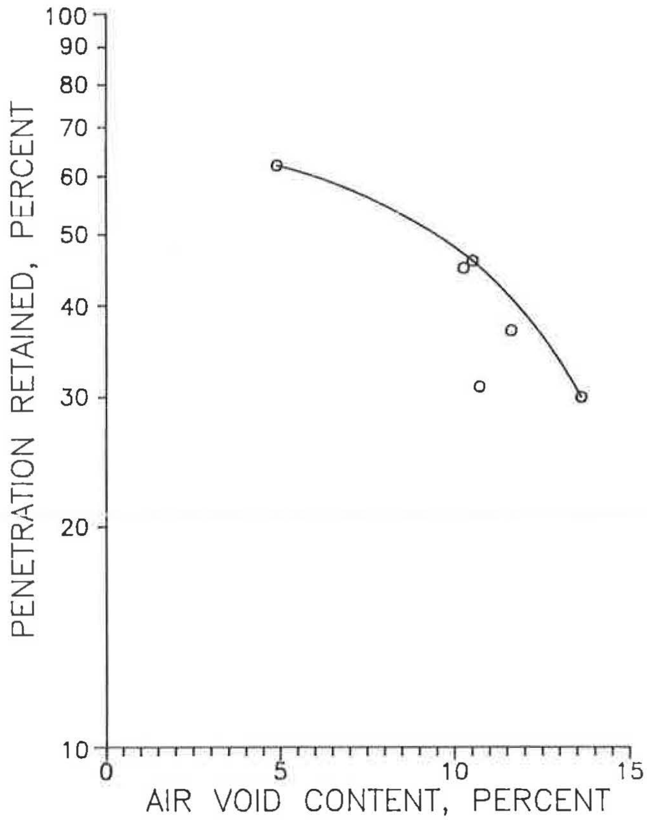


**FIGURE 5 Relationship between retained penetration and air voids (6).**

For instance, a mixture compacted to 93 percent of the TMD will have 7 percent air voids.

This type of compaction specification requires that the TMD, which is the reference density, be measured routinely during construction. The TMD measured during mix design should not be used as a reference for the mix being produced at an asphalt plant. As stated before, the materials change when heated and mixed at an asphalt plant, hence the TMD must be measured on these plant-produced materials.

Some states do not compact samples of asphalt mixture in the laboratory during construction. Many bituminous engineers do not believe that laboratory compaction of samples is necessary because the relative density is now the TMD and the time normally spent on compacting and testing laboratory samples can be used to conduct other tests. To control the construction process adequately, samples must be taken during construction and compacted in the laboratory. The voids in the laboratory-compacted samples must be measured and evaluated to determine the final expected in-place voids. It is not worthwhile to compact an asphalt mixture to 7 or 8 percent air voids initially if the voids are going to be reduced to 1 or 2 percent after one summer of traffic. The only way to estimate the final in-place voids (one of the most critical properties of an asphalt mixture) is to compact samples in the laboratory using the specified technique (manual or equivalent) and to measure the voids. If the voids are not acceptable, the mix (usually asphalt content) must be modified to produce acceptable voids.

This type of density specification is often misused. On many projects, so much emphasis has been placed on the initial in-place voids after compaction that the asphalt content has been arbitrarily increased to reduce the initial in-place voids to an acceptable range. This increase in asphalt content is often done when paving in cold weather or at other times when compaction is difficult. The increase in asphalt content will lower the air voids in laboratory-compacted mixes to an undesirable level and will likely result in rutting when subjected to a significant amount of traffic. If voids are high during construction, more compactive effort, improved roller patterns, or a modified mix design should be used to increase density. An increase in asphalt reduces the TMD and typically increases the actual density, which can significantly decrease the voids in the mix after being exposed to traffic.

This method of specifying density does encourage higher asphalt content and higher filler content; however, it can be correctly used if properly monitored. Laboratory compaction

TABLE 1 COMPARISON OF JOB MIX FORMULA DENSITY, IN-PLACE DENSITY, AND RECOMPACTED DENSITY

| Project | JMF Density (pcf) | In-Place Density (80 percentile) (pcf) | Recompacted Density (75-blow Hand Hammer) (pcf) |
|---|---|---|---|
| 1 | 143.1 | 149.9 | 151.1 |
| 2 | 143.7 | 145.6 | 147.4 |
| 3 | 145.5 | 143.9 | 143.3 |
| 4 | 144.4 | 147.1 | 147.3 |
| 5 | 145.8 | 147.7 | 148.9 |
| 6 | 146.6 | 146.0 | 148.7 |
| 7 | 146.6 | 148.9 | 151.0 |
| 8 | 147.3 | 151.4 | 151.0 |
| Average | 145.4 | 147.6 | 148.3 |

tests must be conducted during construction to ensure that the voids are maintained within an acceptable range. The TMD must be measured on the actual material being placed to ensure an accurate measurement. Additional asphalt must never be added for the sole purpose of reducing in-place voids. If the in-place voids are too high and the mixture has been properly designed, more compactive effort must be exerted to decrease them. In particular, more asphalt should not be added to decrease voids when paving in cold weather. Again, more compactive effort must be applied to the asphalt mix.

### Percentage of Control Strip Density

A third method used to specify density is to compare the bulk density of the in-place asphalt mixture to that of a previously constructed control strip. The control strip is constructed using standard compaction techniques. Most specifications require that it be compacted to some minimum percentage of the standard laboratory density or the TMD. If the specifications do not require a minimum density, the inspector must closely evaluate the contractor's compaction equipment and rolling procedures to ensure that reasonable compactive effort is being applied to the asphalt mix. Any significant changes in the mix during construction should require that a new test strip be constructed and evaluated.

This method of density control is probably the least desirable of the three methods discussed. Although it does allow the compactibility of a mixture to be evaluated, it is difficult for an inspector to know when a contractor has applied a reasonable compactive effort to the control strip. Many items affect density, and a change in any of them may alter the results obtained from a control strip. Some of the items that affect density include gradation (especially for content of particles passing No. 200 sieve), asphalt content, moisture content, mix temperature, air temperature, layer thickness, roller weight, roller pattern, and roller speed.

As stated earlier, a minimum density is normally required for the control strip. This requirement ensures that the contractor does apply some minimal effort during compaction. The specification requires a minimum density in the control strip and then a minimum percentage of the control strip density in the remaining work. This specification could be made simpler by requiring the compacted mix to meet some percentage of the laboratory density or TMD. For example, assume a specification requires that a control strip have a density of at least 94 percent of the TMD and that all asphalt mix placed after the control strip have a density at least 98 percent of that of the control strip. This specification could be simplified by requiring that the mixture be compacted in place to a minimum density of 92 percent of the TMD. These two examples of specifying density result in similar compaction requirements.

The control strip method of specifying density can achieve satisfactory results. However, the specifications should require that the initial in-place voids in the asphalt mixture do not exceed approximately 8 percent and that the final in-place voids do not decrease below approximately 3 percent. This requires that samples be compacted in the laboratory during construction to estimate the final in-place voids and that the initial in-place air voids be measured during the construction process. As long as sufficient testing is performed to ensure that the initial and final in-place voids are acceptable, then this procedure can be used satisfactorily to specify compaction requirements.

## MEASUREMENT OF ASPHALT DENSITY

### Core Method

The core method is the referee procedure for density measurement and is the standard to which other methods are compared. It requires a significant amount of time because the pavement has to cool before cores can be taken and the cores must be air-dried to obtain dry weight. In most cases, the density results are obtained the day after construction.

After cutting the core from the pavement, the material outside the layer in which density is being measured must be removed. In some cases, paper or other material is placed on the existing surface before overlaying to reduce the bond between layers. The core can then be separated easily so that the density of the asphalt layer being placed can be measured. The location must be carefully marked so that the core can be taken over the paper. There are some problems in using paper to break the bond between two layers. Because there is a lack of bond in this location, this method may result in lower density over the paper. This approach also identifies the location at which cores will be taken and, hence, may result in some additional rolling in these locations by the contractor. This method of taking cores is not reliable and is not widely used today.

The method most often used to obtain core samples is to randomly locate samples, cut the core full depth, and saw or otherwise separate the layers being tested from the remaining material. This method is usually the most accurate way to evaluate the overall density of the pavement and is the least disruptive to the paving operation.

A problem that sometimes occurs in measuring the bulk density of a core is failure to allow the core sufficient time to dry before obtaining the dry weight. The core should be allowed to air-dry before the density is measured. Drying in an oven at an elevated temperature may result in distortion of the core and, hence, result in an error in density measurement. Measuring density of a core that is not completely dry will result in an erroneously high density value.

Burati and Elzoghbi (*8*) showed that the variability of density test results was less when measured with cores than when measured with a nuclear device (described in the following section). They examined three nuclear gauges on two construction projects and found that there was a statistically significant difference in the average density when measured with cores and nuclear gauges.

### Nuclear Gauges

Nuclear gauges have been used for a number of years to measure the bulk density of asphalt mixtures. This technique has the advantage of being rapid and nondestructive.

Most density measurements on asphalt mix have been done in the backscatter mode. In this method, the gauge is set on top of the pavement and a reading is taken that represents the average density for the top several inches of material. For instance, the average density may be representative of the top 6 in. of material, but the layer being evaluated may only be 2 in. thick. Part of the error is removed by calibrating the nuclear gauge to provide the same density as that provided by cores. However, errors still exist because of variations in thickness and density in the underlying layers.

In recent years, a nuclear gauge has been developed to measure the density of thin lifts. This gauge should provide greater accuracy in density measurements when compared to the previous gauge, but sufficient tests to show overall accuracy have not been developed.

The best use of nuclear gauges is in development of rolling patterns and quick determination of approximate density. Because of the possibility of error, nuclear gauges should never be used alone for acceptance testing. Some cores should be taken routinely to verify the accuracy of the gauge and to ensure that an acceptable density is obtained.

Many projects have been constructed in which the nuclear gauge was the only method used to measure density. This practice is not recommended because, even if the gauge is calibrated daily, problems can develop that result in inaccurate readings.

## CONCLUSION AND SUMMARY

The amount of voids is the most important property of an asphalt mixture. Because voids vary throughout the life of the pavement, the initial and final voids must be controlled. Initial in-place voids are determined by comparing the bulk density to the TMD. They should not exceed approximately 8 percent. Final voids are controlled by compacting samples (using a manual hammer or similar method) in the laboratory during the construction process. The voids in these samples will be representative of the final in-place voids if correct compactive effort is used. The final in-place voids should not be below approximately 3 percent. Typically, the mix design is performed to provide 4 percent voids in the mix.

As long as a specification is written to ensure that maximum voids do not exceed 8 percent and minimum voids do not fall below 3 percent, then density can be specified as a percentage of laboratory density, control strip density, or TMD. All three methods of specifying density will provide acceptable results if properly used, but the TMD method has been grossly misused.

The method of measuring density must be controlled because voids are directly related to density. The nuclear gauge is quick and nondestructive but is not as accurate as cores. Some cores should always be taken during the construction process to verify that acceptable initial in-place density is obtained.

## ACKNOWLEDGMENT

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