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# DENSITY OF ASPHALT CONCRETE - HOW MUCH IS NEEDED?

by

**E. Ray Brown**

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ABSTRACT

Density is one of the most important parameters in construction of asphalt mixtures. A mixture that is properly designed and compacted will contain enough air voids to prevent rutting due to plastic flow but low enough air voids to prevent permeability of air and water. Since 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 plastic flow.

There are three primary methods of specifying density: percent of control strip, percent of laboratory density, and percent of theoretical maximum density. All three methods can be used to obtain satisfactory compaction if used correctly. The initial in-place air voids must be below approximately eight percent and the final in-place air voids must be above approximately three percent. The initial in-place air voids are determined by comparing bulk density to theoretical maximum density (TMD) and the final in-place air voids are estimated by comparing bulk density of laboratory compacted sampler to the TMD.

The two methods that have been used to measure bulk density of asphalt mixture are physical measurements of cores and nuclear gage. The nuclear gage is fast and non-destructive but is not as accurate as the core method.

# DENSITY OF HOT MIX ASPHALT - HOW MUCH IS NEEDED?

## INTRODUCTION

### Background

The amount of voids in an asphalt mixture is probably the single most important factor that affects performance throughout the life of an asphalt pavement. The 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 during construction and use that density as the target density. Finally, other states measure the theoretical maximum density (ASTM D 2041) and use some percentage of that density as the target density. All of these techniques have been used successfully to build good performing pavements; but all have also been misused, thus resulting in poor performance. Which method should be used? How much density should be specified and obtained during construction to insure good performance? These are questions that need to be answered.

A second problem with density that has been observed is the method of measurement. The two primary methods that have been used to measure density include measurement of bulk density of cores taken from the in-place pavement and use of a nuclear gage to measure the in-place density. Most engineers agree that measuring density with a nuclear gage is not as accurate as measuring the density of cores, Many states use the nuclear gage 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 gage for acceptance testing of the asphalt mixture.

## Objective and Scope

The objectives of this report are to compare the existing methods of specifying density of asphalt mixtures and to discuss how each relates to construction and performance. Methods of measuring density during construction will also be discussed.

Information for this study was obtained from on-going research, from conversations with a number of state bituminous engineers, and from a review of recent literature on compaction.

## DESIRED DENSITY

The voids in an asphalt mixture are directly related to density; thus, density must be closely controlled to insure that the voids stay within an acceptable range. There has been much work that has shown that the initial in-place voids should be no more than approximately 8 percent and the in-place voids should never 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.

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

Brown and Cross, 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 (Figure 2) (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 while the in-place voids were well above 3 percent. It was speculated that one explanation for this was that the voids decreased to an unacceptable level at which time rutting began. 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 to explain why the rutting occurred.

Huber, in a study of asphalt mixtures in Canada, looked at a number of causes of rutting (3). It was determined from this study that one of the primary causes of rutting was low voids (below 3 percent) in the asphalt mixtures.

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

Brown and Brownfield, in a study of segregated mixes, showed that the asphalt mixes in that study were impermeable to water as long as the air void content was below approximately 8 percent (Figure 4) (5). The permeability increased rapidly as the void content increased above 8 percent.

Santucci and others (6) showed that the retained penetration of asphalt cement is affected by the air voids in the asphalt pavement (Figure 5). The loss in asphalt penetration is greatly increased for air voids significantly greater than eight percent. Asphalt mixes must be constructed with low air voids (below 8 percent) to prevent rapid oxidation leading to cracking and raveling of the asphalt mixture.

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

## DENSITY SPECIFIED AS PERCENT 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 or 75 blows with the Marshall hammer. In recent years most states have required 75 blows for high volume roads. Typically specifications will require at least 95 percent of laboratory density in some cases to as much as at least 98 percent in others. Some specifications do not allow mixes to be compacted to a density greater than 100 percent of laboratory density. When mixes which are 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. First of all 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 reference density. If the air voids are not satisfactory in the laboratory compacted samples during construction, then 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 since the laboratory properties will be somewhat different from test results on plant produced materials. Sometimes aggregates break down during mix production, creating an increase in dust, 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 should be calibrated to produce a density equal to that obtained in the field after traffic. The procedures specified in ASTM D 1559 and AASHTO T245 for the Marshall test require that the manual hammer be used or the method used should be calibrated with the manual hammer. Density data from eight construction projects is shown in Table 1. The data for these eight projects shows that the in-place density (80th percentile) after traffic is 2.2 pounds per cubic foot higher than that obntained in the mix design. There are likely two reasons for this higher density after traffic. First of all the mix likely changed some during production to increase the laboratory density. Secondly it is likely that the laboratory compaction effort was insufficient and thus should be increased to be more representative of traffic. It also noted that the density of the mexes recompacted with the manual hammer compare closely to the in-place density. This data emphasis the need to compact samples in the laboratory during construction to verify voids in the mixture and it verifies 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, then a small rut (5 percent of layer thickness, 0.10″ for 2″ layer) will result after additional channelized compaction under traffic increases the density from 95 percent 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 due to rutting is likely. If the laboratory compactive effort is satisfactory, then past experience has shown that it is not practical for the contractor to compact the mix to a density greater than 100 percent. Hence, any project which 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 1) laboratory samples are compacted during construction to establish reference density, 2) correct laboratory compaction techniques are used, and 3) minimum compaction requirement is set to insure that in-place air voids after compaction do not exceed approximately 8 percent.

## DENSITY SPECIFIED AS PERCENT OF THEORETICAL MAXIMUM DENSITY

A second method that is often used to specify compaction requires that the contractor compact the asphalt mixture to some minimum percentage of the theoretical maximum density (TMD). This is a direct method of specifying maximum in-place air voids and an indirect method for controlling compaction. This method involves taking a sample of the asphalt mixture during construction and conducting tests to measure TMD (ASTM D2041). The bulk density of the asphalt mixture is measured after compaction and compared to the TMD. This comparison provides a direct measurement of in-place voids. For instance, a mixture compacted to 93 percent of 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.

Based on statements that have been made by several state bituminous engineers, it is evident that some states do not compact samples of asphalt mixture in the laboratory during construction. The feeling of many engineers is that laboratory compaction of samples is not necessary since 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. Samples must be taken during construction and compacted in the laboratory to adequately control the construction process. The voids in the laboratory compacted samples must be measured and evaluated to determine the final expected in-place voids. It does not do any good to compact an asphalt mixture to 7-8 percent air voids initially if the voids ar going to be reduced to 1-2 percent after one summer of traffic. The only way to estimate the final in-place voids (which is 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, then the mix (usually asphalt content) must be modified to produce acceptable voids.

This type density specification has been misused in many cases. 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. This 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 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 tests must be conducted during construction to insure that the voids are maintained within an acceptable range. The TMD must be measured on the actual material being placed to insure an accurate determination of TMD. Additional asphalt content must never be added for the sole purpose of reducing the in-place voids. If the in-place voids are too high, assuming the mixture has been properly designed, then more compactive effort must be exerted to decrease in-place voids. 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.

## DENSITY SPECIFIED AS PERCENT OF CONTROL STRIP

A third method "that has been used to specify density is to compare the bulk density of the in-place asphalt mixture to the bulk density of a control strip that had been constructed earlier. The control strip is constructed using standard compaction techniques. Most specifications require that the control strip be compacted to some minimum percentage of the standard laboratory density or to some minimum percentage of TMD. If the specifications do not require some minimum density for the control strip, then the inspector must closely evaluate the contractor's compaction equipment and rolling procedures to ensure 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. This method does allow the compactability of a mixture to be evaluated, but it is very difficult for an inspector to know when a contractor has applied a reasonable compactive effort to the control strip. Too many items affect density and a change in any of these items may alter the results obtained from a control strip. Some of the items that affect density include gradation (especially -200 content), asphalt content, moisture content, mix temperature, air temperature, layer thickness, roller weight, roller pattern, roller speed, etc. Hence, it is easy to see that it is basically impossible to know when a reasonable effort has been applied to the control strip by the contractor.

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

The control strip method of specifying density can be used to obtain satisfactory results. However, the specifications should be written so that the initial in-place voids in the asphalt mixture do not exceed approximately 8 percent, and the final in-place voids do not fall 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 insure that the initial. in-place voids and the final in-place voids are acceptable then this procedure can be used satisfactorily to specify compaction requirements.

## MEASUREMENT OF DENSITY - CORE METHOD

The core method of measuring density is the referee procedure for density measurement and is the standard to which other methods (nuclear) are compared. This method does require a significant amount of time since 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 using the core method are obtained the day following 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 has been placed on the existing surface prior to overlaying to reduce bond between layers. When this is done, the core can be easily separated 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 bond between two layers. Since there is a lack of bond in this location, there is some concern that 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 very reliable and is not widely used today.

The method most often used to obtain core samples is to randomly locate samples and to cut the core full depth and saw or otherwise separate the layers being tested from the remaining material. This should be the most accurate method of evaluating the overall density of the pavement and 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 time to dry before obtaining the dry weight. The core should be allowed to air dry prior to measuring density. 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** showed that the variability of density test results was less when measured with cores than when measured with a nuclear device (8). They looked at three nuclear gages on two construction projects and found that there was a statistically significant difference in the average density when measured with cores and nuclear gages.

## MEASUREMENT OF DENSITY - NUCLEAR GAGES

Nuclear gages have been used for a number of years to measure the bulk density of asphalt mixtures. This technique has several advantages in that the method is rapid and non-destructive.

Most density measurements on asphalt mix have been done in the backscatter mode. In this method, the gage 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 inches of material, but the layer being evaluated may only be 2 inches thick. Part of the error is removed by calibrating the nuclear gage to provide the same density as that provided by cores. Errors still exist due to variations in layer thickness and variations in density in the underlying layers.

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

The best use of nuclear gages is in development of rolling patterns and quickly determining approximate density. Because of the possibility of error with nuclear gages, they should never be used alone for acceptance testing. Some cores should routinely be taken to verify the accuracy of the nuclear gage and to insure that an acceptable density is obtained.

Many projects have been constructed in which the nuclear gage was the only method used to measure density. Even if the gage is calibrated daily, problems can develop that result in inaccurate readings. This is not a good practice to follow.

SUMMARY

The amount of voids is the single most important property of an asphalt mixture. The voids vary throughout the life of the pavement, hence, the initial voids and final voids (after traffic) must be controlled. The final voids are controlled by compacting samples (using manual hammer or equivalent) 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 initial in-place voids are determined by comparing the bulk density to the TMD. The initial in-place voids should not exceed approximately 8 percent. 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 the specification is written to insure that maximum voids do not exceed 8 percent and minimum voids do not fall below 3 percent, then density can be specified as percent of laboratory, percent of control strip, or percent of TMI). 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 since voids are directly related to density. The nuclear gage is quick and non-destructive 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.

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Table 1. Comparison of Job Mix Formula (JMF) 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 |

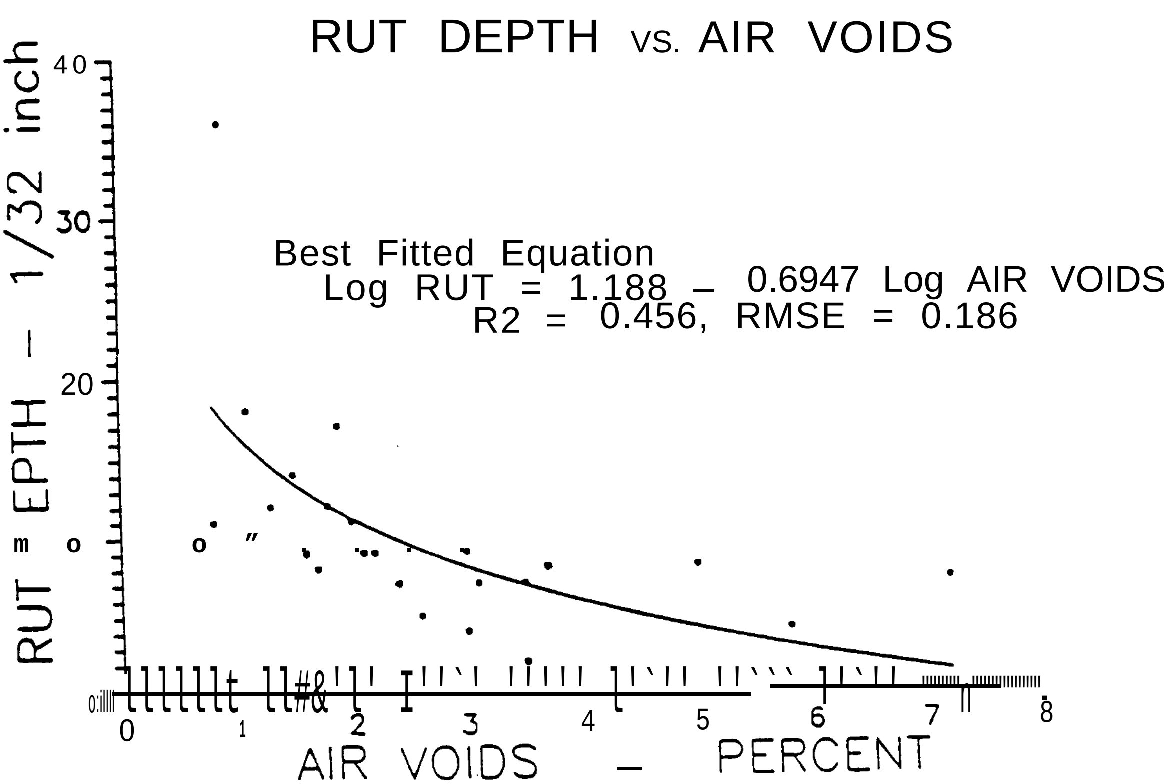


Figure 1. Relationship between air voids and rut depth in Arkansas (after Ford).

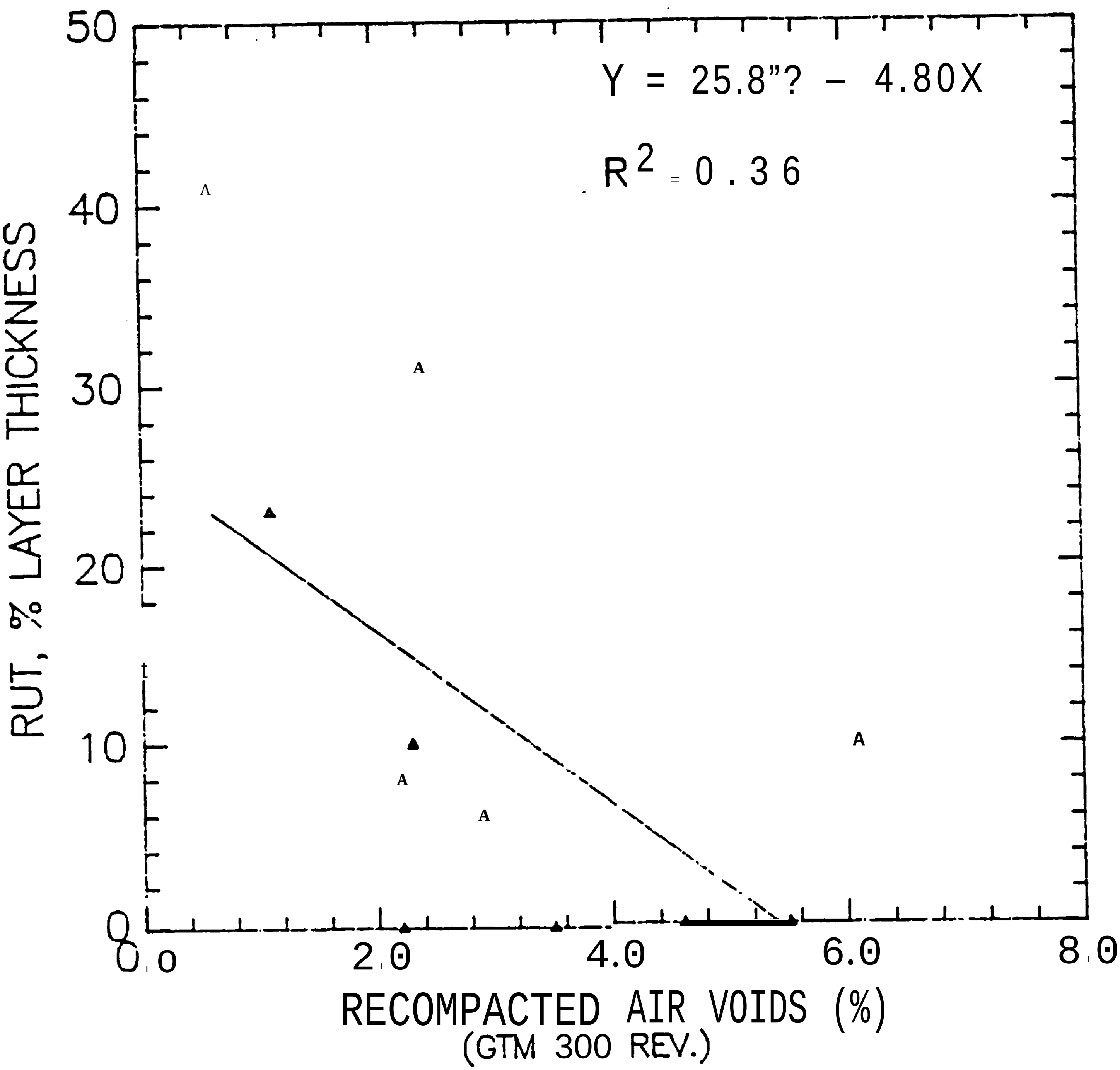


Figure 2. Relationship between air voids and rut depth in NCAT Rutting Study (after Brown and Cross).

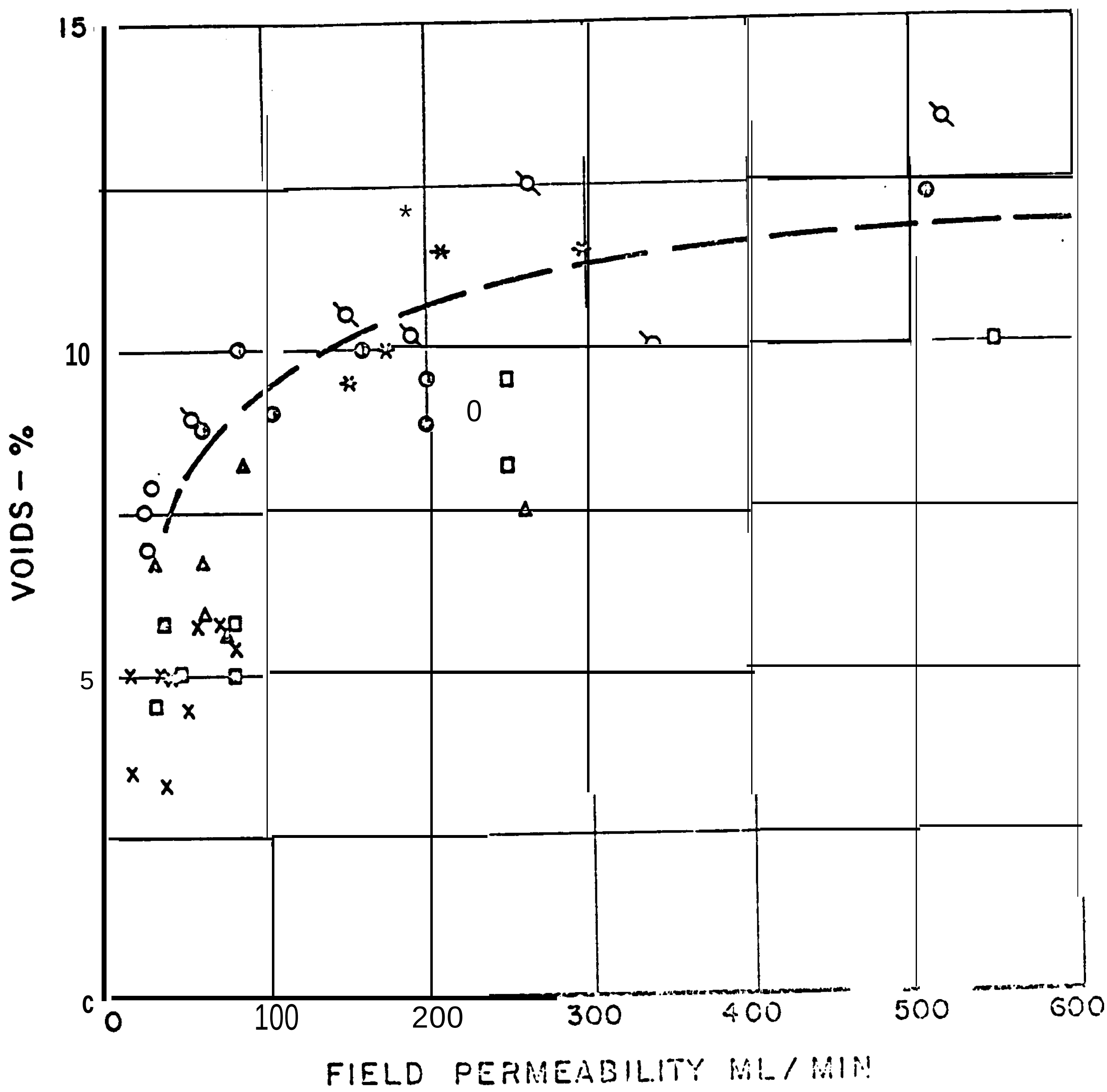


Figure 3. Relationships between air voids and permeability (after Zube) in California study.

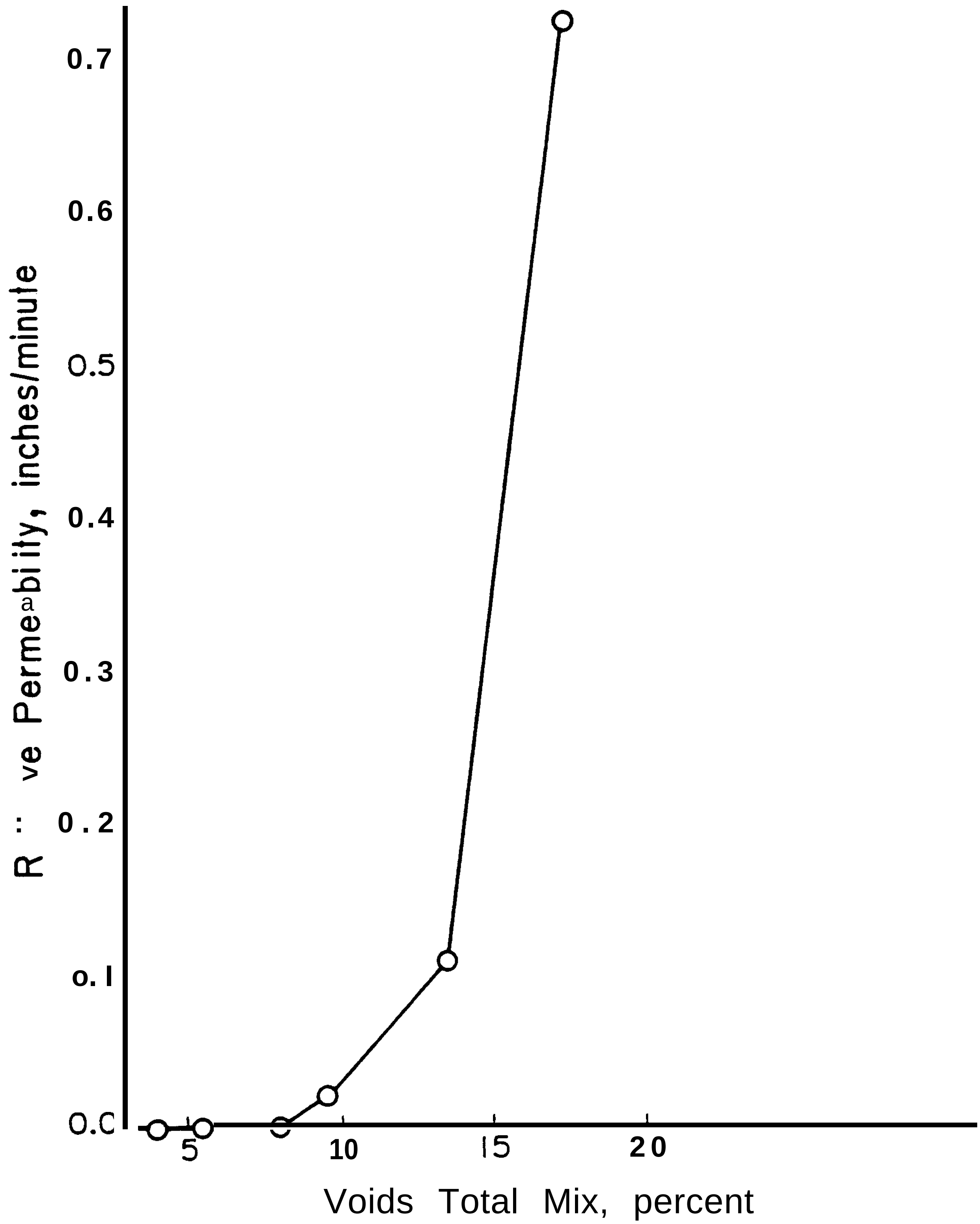


Figure 4. Relationship between air voids and permeability in Georgia Study (after Brown, Collins, and Brownfield).

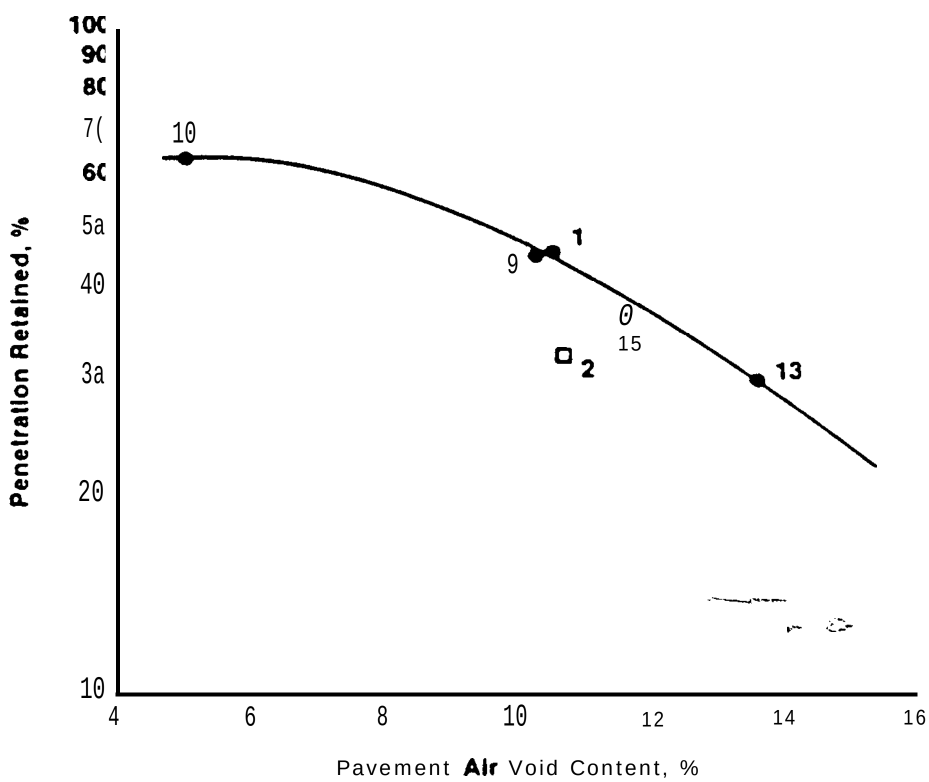


Figure 5. Relationship between retained penetration and air voids (after Santucci and others).