A STUDY OF RUTTING OF ALABAMA ASPHALT PAVEMENTS

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by

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ABSTRACT

Pavement rutting is the accumulation of permanent deformation in all or a portion of the layers in a pavement structure that results in a distorted pavement surface. The overall objective of this study was to develop recommendations for more rut resistant asphalt concrete mixtures which comprise the uppermost layers of flexible pavements. To accomplish project objectives a plan of study was conducted that included 1) an analysis of rutting data from the Alabama Highway Departments pavement condition data base, 2) a field evaluation and sampling program at thirteen test sites, 3) a laboratory testing program, and 4) analyses of data from the field and laboratory testing programs.

The analysis of the pavement condition data base indicated that rutting is increasing and that rutting susceptibility varies geographically because of the variable quality of locally available aggregate. Careful control of crushing of gravel and the development of a test to quantify and limit particle shape and texture of fine aggregate were identified as means for improving aggregate quality.

In most cases permanent deformation appeared to be combined to the top three or four inches of asphalt aggregate layers, thereby, implicating high tire pressures as the primary causative factor. A rate of rutting of 2×10^{-4} in/$\sqrt{\text{ESAL}}$ or 1.0×10^{-7}in/ESAL delineated good and poor performing pavements.

Mix and aggregate properties that appeared to be related to rutting include: layer thickness, voids, GSI, gyratory roller pressure, percent fractured faces, percent passing No. 200 sieve and creep strain. The correlation of these properties was not very strong, but in almost every case was caused by one or two points far outside the range of the bulk of the data. This illustrates the complexity of the rutting process and the necessity of considering a number of properties during material selection and mix design.

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INTRODUCTION

Pavement rutting is the accumulation of permanent deformation in all or a portion of the layers in a pavement structure that results in a distorted pavement surface. Longitudinal variability in the magnitude of rutting causes roughness. Water may become trapped in ruts resulting in reduced skid resistance, increased potential for hydroplaning and spray that reduces visibility. Progression of rutting can lead to cracking and eventually complete disintegration.

Flexible pavement rutting is not a new problem. As long as flexible pavements have been used, rutting has been recognized as a primary distress mechanism and a primary design consideration. For high flotation tires rutting may be confined to weaker materials such as subbases and subgrade soils. In the not to distant past, the consensus was that rutting was generally restricted to subgrades. In fact, the 1986 AASHTO Guide for Design of Pavement structures is based on performance models developed at the AASHO Road Test where tire inflation pressures were nominally 80 psi. Asphalt pavement design concepts are based on providing sufficient pavement structure (rutting resistant materials) to reduce stresses in the subgrade to the point where rutting will not develop, and on providing asphalt quality and thickness to resist fatigue cracking.

What is new regarding flexible pavement rutting is the awareness that permanent deformation in the high quality asphalt layers (surface, binder and base) has become a significant contributor to pavement rutting. No where is this more vividly demonstrated than in rutting of asphalt concrete overlays of Portland cement concrete pavements.

Repetitive applications of heavy trucks with increasingly high pressure tires drives rut formation in high quality asphalt layers. The stresses induced in near surface layers by the high pressure tires exceed the ability of the materials to resist densification below critical voids (4%) and subsequent plastic flow.

Recent studies (1-5) have shown that truck tire inflation pressures, and therefore contact pressures, have increased dramatically from 80 psi on which design procedures are commonly based. Average truck tire inflation pressures for radial tires are now around 100 psi. This means that a significant portion of truck tires have inflation pressures higher than 100 psi, often in the 130 to 140 psi range.

The study by Marshek, Chen, Connell and Hudson (6) notes several additional problems with high tire pressures. A commonly made assumption has been that contact pressure approximately equals inflation pressure. The study showed that increased tire pressure produced proportionally smaller gross contact areas. This suggests that the commonly made assumption of equal pressure becomes increasingly less valid. The study also showed that contact pressures were not uniform. This suggests some contact areas with pressures greater than a uniform pressure based on gross contact area.

Extraordinarily high tire pressures mean that asphalt concrete layers which are of the highest quality but nearest to the surface in a pavement structure are not immune to rutting. Although recent modifications such as asphalt content selection based on 75 blow Marshall compaction have increased rutting resistance, material quality provided by existing specification occasionally is insufficient to meet the demands of today's traffic.

Assuming that truck volume, loading and tire pressures are not likely to decrease; the obvious solution is to increase asphalt concrete resistance to permanent deformation. As with most simple and obvious solutions it must, however, be approached with caution. Beneficial changes in one property may lead to detrimental changes in another property. For example, decreasing asphalt content will result in increased rutting resistance, but decreased fatigue resistance. Increased asphalt cement viscosity will result in a stiffer mix, which may be more resistant to rutting, but a mix that is more likely to crack (traffic and environmental forces).

In Alabama the solution is complicated by available materials. Local natural sand and gravel are used extensively, particularly in the southern and western portion of the state. These materials generally have rounded particle shape which is detrimental to mix stability. Even when gravel is crushed, the larger particles that result are likely to have at least one uncrushed face since the maximum particle size of available natural gravel is around 1-1/2 inches.

The solution to the rutting problem in Alabama will likely not be obvious or simple but will require careful consideration and treatment of the entire problem. However, a solution, or even small improvemnts, are potentially enormously significant; considering the dominant role asphalt concrete will play in rehabilitating and upgrading the states over 10,000 miles of roadway. Of particular significance will be the requirements of the approximately 900 miles of interstate pavement which carries a disporportionately large volume of truck traffic.

OBJECTIVES

The overall objective of this study was to develop recommendations for more rut resistant asphalt concrete mixtures. To accomplish this overall objective the following five sub-objectives were:

To determine the nature and extent of rutting on Alabama Highways,

To conduct testing and evaluation of typical asphalt concrete mixtures,

To characterize mixtures that are susceptible to rutting and those that are not susceptible to rutting,

To review Alabama Highway Department (AHD) material selection and asphalt concrete mix design procedures, and

To formulate recommended modifications to current practices to enhance resistance of asphalt concrete mixes to permanent deformation.

SCOPE

The assessment of the nature and extent of rutting of asphalt pavements in Alabama was limited to an analysis of data from the 1984, 86, and 88 Alabama Highway Department pavement condition data bases. These data bases are part of the overall pavement management system being implemented by the Alabama Highway Department.

Testing and sampling was conducted at thirteen (13) test sites. Sites were selected to provide materials with a range of rutting resistance. Test pits were dug through and cores taken of all asphalt-bound layers. Laboratory testing of materials from the cores measured properties to characterize in-situ mix, recompacted mix, recovered aggregate and recovered asphalt cement.

Efforts to improve rutting performance of Alabama asphalt pavements were focused on consistant material selection and mix design for asphalt concrete. Consideration of structural pavement thickness design and construction aspects were beyond the scope of the study.

PLAN OF STUDY

To accomplish project objectives a three (3) phase study was executed. The three phases consisted of 1) an analysis of rutting data from the Alabama Highway Department's pavement condition data base, 2) field evaluation and sampling at thirteen test sites, and 3) a program of laboratory testing. Data from these studies was analyzed to develop a model for describing the rutting process and to formulate recommendations for improving the rutting resistance of asphalt concrete mixes.

Rutting Data from Pavement Condition Database

Condition and traffic data for the Alabama state and interstate system are collected from representative 200' long test sections in each lane mile of pavement. Data collection procedures are described in reference 7. Data collection was initiated by the Department in 1984 and has been repeated in 1986 and 1988. Data records for each lane mile contain identifying and descriptive information, quantitative pavement condition information (including rutting), pavement ratings developed from condition data, present serviceability indices (PSI) developed from roughness measurement, and estimated traffic data.

Eight rut depth measurements, four in the outer wheel path and four in the inner wheel path, are taken in 200' test sections for each lane mile of pavement. A four foot long straight edge is placed across the wheel path and the maximum rut depth measured. For this study these eight measurements were averaged and used to represent the rutting for each lane mile of pavement. Reference is made in the remainder of the text to ***average rut depth.*** Measurements were made in all lanes, but rut depths in outer lanes were always larger and were used exclusively in the analyses.

In the analyses, estimates of the traffic applied to the pavement were in terms of total numbers of 18 kip equivalent single axle loads (ESAL). Eighteen kip ESAL's were computed for two and four lane roadways using equations 1 and 2, respectively.

$$ESAL = (AADT)(CV)(0.5)(Age)(0.82) \quad ....(1)$$

$$ESAL = (AADT)(CV)(0.5)(Age)(0.82)(0.85) \quad ....(2)$$

where

AADT	=	Annual average daily traffic
CV	=	Percent commercial vehicles as decimel
0.5	=	Directional split
Age	=	$\left[(year + \frac{month\ rated}{12}) - (year + \frac{month\ built}{12})\right]365$
0.82	=	Average conversion factor from reference 8
0.85	=	Percent traffic in outer lane for 4-lane roadway

The annual average daily traffic and percent commercial vehicles used in the computation of ESAL's were the estimated values for the year in question. Traffic was assumed split evenly by direction (50/50). The pavement age, in days, was the difference between the date rated and the date the last surface layer was placed. For older pavements and pavements with significant traffic growth, this procedure will have over estimated total applied traffic. However, since most of the comparisons were relative this is not considered a serious problem that would warrant a more accurate estimation of traffic.

To determine the nature and extent of rutting three parameters were analyzed. These were average rut depth, mean (average rut depth/ESAL) and mean average rut depth/mean ESAL. The ratios of average rut depth to ESAL and mean average rut depth to mean ESAL provide indicators of the rate of rut formation with traffic. Comparisons of the three variables were made between Highway Department Divisions to detrmine if geographical differences exist, and between surface mix types. Data for these comparisons were grouped according to roadway type (state routes, interstate routes and combined) for the 1984, 86 and 88 data bases. The data was also combined for overall comparisons. Frequency analyses of average rut depth and (average rut depth)/(ESAL) were made to determine if the distribution of rutting is changing and if rutting severity is a function of roadway type (state or interstate routes).

Field Evaluation and Sampling

Thirteen test sites were selected for evaluation and testing. The approximate location of these sites is shown on Figure 1. Sites were selected to provide a relatively uniform statewide geographic distribution. Sites were also selected to provide examples in the Piedmont and Applachian Plateau geologic regions where crushed stone is available, and in the Coastal Plain geologic region where natural sands and gravels are the predominate aggregate used in hot mix asphalt. The sites were selected to provide a range of rutting performance. Five (5) sites were considered by Highway Department personnel to have provided good rutting performance and eight (8) to have provided poor rutting performance.

The development of rutting was investigated by cutting a trench and coring through all asphalt bound layers. All test sites were on four lane facilities and the trenches and cores were taken across outside lanes only. A typical sampling layout is shown in Figure 2. Two lines of 12 cores each, one of 4-inch cores and one of 4 and 6-inch cores, were cut.

Pavement surface profiles at the trench and at core lines were obtained by measuring the distance from a leveled 12 foot long straightedge as illustrated in Figure 3a. Once the trench was cut, similar measurements were made to layer interfaces, as illustrated in Figures 3b and 3c, to obtain a complete profile for all the asphalt-bound layers. Layer thicknesses were measured from cores (Figure 3d) and added to surface profile measurements as a second method for developing complete layer profiles. Cores were then used to provide material for the laboratory testing program described in the following section.

Laboratory Testing

There are a number of laboratory tests that have been used to predict rutting in asphalt pavements. These tests cannot be used individually in all cases to identify mixtures with a tendancy to rut under traffic, but all the tests combined have been shown to be a fairly good indicator of rutting. Tests that will be used in this study to correlate with rutting include: voids in place, voids in laboratory compacted samples, stability and flow of laboratory compacted samples, aggregate gradation, fractured face count of coarse aggregates, particle shape and texture of fine aggregate, gyratory shear index (GSI), gyratory roller pressure, creep, resilient modulus, and asphalt cement properties.

In Place Properties. Past studies have shown that in-place air voids are related to rutting (9,10,11). Most data indicates that once the air voids decrease to 3 percent or lower plastic flow is likely to occur. The in-place voids alone may not be a good predictor of rutting since some mixes with low voids do not rut and some mixes with higher voids do rut.

It has also been shown that in-place voids may decrease to a point and then increase again as rutting progresses. This increase of in-place voids during traffic makes it difficult to correlate rutting with in-place voids. For instance rutting may have been caused by low in-place voids but measurement of in-place voids may show higher voids if the voids increase when rutting begins. This process will be considered later during development of the model to describe rutting.

Approximately 24 cores were taken at each test, as illustrated in Figure 2. A number of the cores were combined and broken-up for tests such as Rice specific gravity, gradation, asphalt content, and recompacting. The bulk density of cores were then compared to the measured Rice specific gravity to determine in-place voids.

Properties of Laboratory Compacted Samples. Samples of asphalt mixture were combined, broken-up, heated and recompacted to evaluate properties of laboratory compacted samples. The properties of laboratory compacted samples is an indicator of original mix design properties. The Marshall stability will always be higher than the original mix design because the asphalt cement is now stiffer due to oxidation, however, the voids and flow appear to be approximately equal to those measured during mix design.

The use of voids of recompacted mix does have some advantage over use of in-place voids. For instance the in-place voids will vary across the traffic lane due to traffic and the in-place voids may actually begin to increase as rutting occurs. In-place voids are also a function of original density and traffic. Thus, in-place voids are dynamic (changing) and will vary depending or many factors making it difficult to predict performance. Recompacted voids on the other hand are more consistent and should be representative of the final in-place voids after significant traffic. Hence, recompacted voids may be a better indicator of rutting potential than the in-place voids. Samples were recompacted in two ways: hand hammer and gyratory.

Seventy-five blows per side with the hand hammer has been shown to provide a density approximately equal to that after traffic for high volme roads. Work with the gyratory testing machine (GTM) has shown that it provides a density approximately equal to that of the hand hammer when it is set at 120 psi (approximately equal to truck tire pressure), 1 degree angle, and gyrated for 300 revolutions.

Two additional properties of the asphalt mixture that are evaluated when using the GTM to recompact samples include gyratory shear index (GSI) and roller pressure (a measure of shear strength). Past studies have shown the GSI to be related to rutting. Mixes with a GSI equal to approximately one tend to be resistant to rutting while mixes with a GSI above about 1.3 tend to rut severely under traffic. Since the roller pressure is a rough measure of shear strength it potentially could relate to rutting.

Extracted Aggregate Properties. Mix from cores was separated into aggregate and asphalt cement components. Gradation, fractured face counts on coarse aggregate particles, and fine aggregate particle shape and texture tests were conducted on extracted aggregate.

The aggregate gradation of a mixture is important but there is disagreement about the gradation that should be used. Most people agree that the aggregate gradation should be approximately parallel to the maximum density curve, but should be offset to provide sufficient VMA. Some agencies specify that the gradation be above the maximum density curve while others specify that it be below the curve.

It is difficult to quantify and evaluate an aggregate gradation since 8-10 sieve sizes are normally used. In this study three sieve sizes will be used to evaluate gradation: 3/8 inch, No. 50, and No. 200. These three sieve sizes should be sufficient to accurately charaterize the aggregates gradation.

Studies have shown that the maximum aggregate size is important for rut resistant pavements. Larger maximum aggregate size mixtures are more resistant to rutting while finer mixtures tend to rut more. Mixtures with excessively high or low amounts of material passing the No. 200 sieve are more likely to rut. Mixtures with high natural sand content are also more likely to rut. The three selected sieve sizes should be sufficient to evaluate maximum aggregate size, percent passing No. 200, and amount of natural sand.

It has long been known that crushed aggregates produce mixes that are more resistant to rutting than mixes with natural aggregate that has more rounded particles. It is not clear however what the optimum fractured face count should be to insure good performance. AHD 1989 specifications have crushed particle requirements on minus 3/4" to plus No. 8 material when gravel is used in binder mixes and a requirement that 80% of the plus No. 4 particles used in wearing courses have two or more crushed faces. The problem with rounded aggregate can occur when gravels or natural sands are used since both of these may be the desired size without crushing.

The fractured face count was conducted on the plus No. 8 material. The percent of aggregate particles with zero, one, or two or more crushed faces were recorded. The material smaller than the No. 8 could not be tested since it was too small to evaluate the number of fractured faces.

Resilient modulus has become popular in recent years to characterize the stiffness properties of asphalt concrete. The test to measure resilient modulus is repeated load indirect tensile. Since resilient modulus is a tensile test it should be affected by changes in asphalt cement properties, but it is doubtful if it can be correlated to rutting since this is the result of shear strain in an asphalt mixture.

Tests were conducted on cores cut from the pavement. The test was performed by applying approximately 15% of the tensile strength for 0.1 seconds and allowing the asphalt mixture to recover for 0.9 seconds. Tests were conducted at 40, 77, and 104°F to establish temperature sensitivity.

It is generally believe that the creep test has potential to model rutting of asphalt mixes. The creep test is typically conducted at various temperatures. Compression loads can be applied statically or repetitively to unconfined or confined specimens. The most common mode is the static unconfined mode, because it is the easiest and simplest. However, this mode probably does the worst job of simulating what actually happens in the field.

Two major problem with the static unconfined test is that the temperature cannot be as high as 140°F (typical in-place temperatures) and the normal pressure must be much lower than 120 psi (typical truck tire pressures). High temperature or high pressures in unconfined tests will result in unrepresentative failure of the sample. For this study all tests were conducted in the static confined mode. Tests were conducted at a pressure of 120 psi and a temperature of 140°F. A confining pressure of 20 psi was used. When a particular asphalt layer was being investigated that was less than two inches thick, two or more cores were stacked to insure that a total thickness of at least two inches was obtained. When cores were stacked, cement mortar was applied between the cores to provide proper seating.

The shape and texture of fine aggregate particles is thought to be as important as the shape of coarse aggregate particles. A test for particle shape and texture of minus No. 8 material proposed by the National Aggregates Association (12) was conducted. Uncompacted voids of a graded samples (Method A) were measured.

In addition, 400 gm samples of ungraded minus No. 8 material were run through the apparatus and flow times recorded. These modified tests were performed because the uncompacted voids from Method A did not provide a wide range of values. It was felt that flow time might provide a wider range of values and better correlation with rutting susceptibility, but it did not.

Extracted Asphalt Cement Properties. The aggregate must support the load if rutting is prevented in asphalt concrete, however, the asphalt cement properties can also affect performance. If the asphalt mixture has a slightly high asphalt content, then the asphalt cement properties can greatly affect rate of rutting.

Asphalt cement was recovered from cores and tested for viscosity and penetration. Viscosity testing was conducted at 140° and 275°F, and penetration testing at 77 and 40°F.

PRESENTATION AND ANALYSIS OF RESULTS

Data and analyses of these data from the three phases of the study described in the preceding section are presented individually in this section. These analyses are then combined and a model proposed for describing rutting of asphalt-bound layers of flexible highway pavements.

Analysis of Rutting Data from Pavement Condition Database.

The rutting data in the 1984, 1986, and 1988 pavement condition data bases were analyzed to assess the nature and extent of the rutting problem in Alabama. As noted earlier, the data will be grouped and compared to isolate the effects of various parameters.

Combined Data. Table 1 contains a summary of all data from the 1984, 1986, and 1988 databases. The data is grouped according to roadway type (state routes, interstate routes and combined). Column 2 contains the frequency which is indicative of the number of lane miles of pavement. Column 3 contains the mean of average rut depths, Column 4 the ratio of the mean average rut depth to mean EASL, and colum 5 the mean of the average rut depth to ESAL ratio.

Values from Table 1 are plotted in Figure 4. From this figure the following observations can be made:

- Mean rut depths are larger on interstate routes than on state routes. This is likely due to the larger traffic volumes on interstate routes.
- The average rut depth has increased from 1984 to 1988.
- The average rut depth increase, from 1984 to 1988, is larger for interstate routes (0.01494 in.) than state routes (0.0036 in.).
- Because of the large frequency for state routes, the average rut depth for state route and combined data is similar.
- Because of the small frequency for interstate routes, the average rut depth relationship is more erratic, i.e., the level of the overaly program

can have an observable influence on mean rut depth.

- Values of the ratios of the means (b) are considerably different than values of means of the ratios (c). This is due to the large numeric differences between numerators (average rut depth) and denominators (ESAL) and the wide range of ESAL values. Values shown for both parameters are ratios multiplied by 10^7.
- Because of the large influence of extreme values of ESAL's, the ratio of the means is considered a better indicator of rate of rut development.
- Both ratios indicate that the rate of rut development is increasing.
- Both ratios indicate that the rate of rut development is much greater on state routes than interstate routes. This is likely due to higher quality pavements (including quality of asphalt bound materials) on the interstate system.
- The ratios of the means (b) show about the same increase in rate of rut development, from 1984 to 1988, for state routes (0.188) and for interstate routes (0.166).
- The mean of the ratios (c) show a much larger increase in rate of rut development, from 1984 to 1988, for state routes (1.859) than for interstate routes (-0.052).

To summarize, all but one of the parameters examined indicated that rutting is increasing. For rut depth this could be caused by an increase in pavement rutting susceptibility, an increase in traffic volume or an increase in loading severity (truck weight and/or tire pressure). For rate of rut development, possible causes would be restricted to rutting susceptibility and loading severity.

Highway Department Division. Comparisons by Highway Department Divisions were made for mean rut depth, the ratio of mean rut depth to ESAL's and the mean of the ratio of average rut depth to ESAL's. These comparisons were made to determine if geographical variations in rutting exists and to examine possible reasons for these variations. Speculation was that geology and, thus, the availability of variable quality aggregates might be a factor. As shown in Figure 1, Divisions 1, 3 and 4 are predominately in the Piedmont and Appalachian Plateau geologic provinces. Rock deposits in these areas are used for crushed stone and are the source of sand and gravel materials. Division 2 is divided between the Appalachian Plateau and the Coastal Plain region.

Divisions 5-9 lie below the Fall Line in the Coastal Plain region. Natural sands and gravels are available and are the predominate aggregate materials used in this region. The degree of weathering and, thus, particle size and shape of sand and gravel is influenced by the distance transported from the source material. Particles become more rounded and smaller as the transportated distances increases. Implications are that aggregate quality and, therefore, mix rutting susceptibility increases with movement southward as the distance from the rock source increases.

For natural sand (fine aggregate) and uncrushed gravel (coarse aggregate) in asphalt bound materials, the influence of particle size and shape is straight forward and well established. However, when gravel is crushed, the influence of gravel size is not as direct or as well documented. Coarse aggregate for surface and binder mixes is required to have some crushed particles. Therefore, natural gravel requires crushing. The problem created by using gravels is that the degree of particle fracturing will be directly related to original particle size. Smaller gravel particles will be less fractured and mixes containing these partially crushed particles will be more susceptible to rutting.

If indeed geology and, thus, geography is a factor, rutting susceptibility should be less in Divisions 1-4 than in Divisions 7-9. Divisions 5 and 6 should be intermediate. Figure 5 shows three histograms which illustrate the variability of rutting susceptibility between divisions. From the three histograms, it can be seen that the rut depth, ratio of mean rut depth to mean ESAL's and mean of the ratio of average rut depth to ESAL's are less for Divisions 1-4 than for Divisions 5-9. The averages of the three parameters for Divisions 1-4 are 0.07380 in, 1.286 inches x 10^{-7} and 8.510 inches x 10^{-7}. For divisions 5-9 the averages are 0.12759 inches, 2.750 inches x 10^{-7} and 13.656 inches x 10^{-7}.

The data shown in Figure 5 is from the 1984 database for combined state and interstate routes. Similar histograms were plotted for 1986 and 1988 databases for state, interstate and combined routes. A complete set of these histograms is contained in Appendix A. Averages from these histograms are shown in Table 2, and confirm the trends illustrated in Figure 6 for the 1984 combined data, i.e., that pavements in Divsions 5-9 are more susceptible to rutting than those in Divisions 1-4.

The most consistant indicator of this trend is the ratio of means which is an indicator of rate of rut development. Rut depth and the mean of the ratio of rut depth to ESAL's is more sensitive to pavement age. Between 1986 and 1988 the relationship between average rut depth and the mean of the ratio for combined and state route data reversed.

As can be seen in Table 2, the average 1988 rut depths on state and combined routes for Divisions 1-4 are about equal those in Divisions 5-9. The means of the ratios for 1988 become larger in Divisions 1-4. This reversal in trend is thought to be primarily due to a reversal in values for Divisions 4 and 5. Figure 6 is similar to Figure 5, but for 1988 data. Comparing Figures 5 and 6, it can be seen that the mean rut depths and ratios become larger for Division 4 in 1988; which is opposite what was observed in 1984 and 1986. The number of ESAL's applied to the pavement is an indicator of pavement age and, therefore, of the overlay program. In 1986 the average number of ESAL's on combined state and interstate routes in Division 4 was 306,000 and in 1988, 365,000. The trend in Division 5 was just the opposite, with applied ESAL's going from 450,000 in 1986 to 384,000 in 1988. This reversal in applied traffic (average pavement age) for Divisions 4 and 5 is thought to be primarily responsible for the reversal in trends.

Despite the exceptions noted above, the analyses of the data support the contention that rutting susceptibility is related to geographic location. In addition, geology and, thus, properties of available aggregate provide a logical explanation for the observed relationship between rutting susceptibility and geographic location. This phenomenon will be examined further in the analyses of the data from field test sites.

Mix Type. Data was grouped by existing surface mix type. Similar mix types were combined to obtain five mix type groups identified as 401 (surface treatment), 411, 416, 417 (latex) and 420 (open graded). Analyses were performed for the three parameters used previously, i.e., average rut depth, mean rut depth/mean ESAL and mean (average rut depth/ESAL). A complete set of histrgrams developed to study the influence of mix type on rutting susceptibility is contained in Appendix A.

Interstate routes are surfaced with primarily 416 mix with some open graded porous friction course (420) mix. A minimal amount of 417 mix shows up in 1988 but no 401 or 411 mix is used. Figure 7 shows 1988 interstate data, which is typical for 1984 and 1986. Average rut depths are about the same for pavments with 416 and 420 surface mixes. The relationship between the rate of rutting, as indicated by the ratio of means, for the mixes varies from year to year. However, the variation is small (minimum of 0.434×10^{-7} inches to maximum of 0.672×10^{-7} inches) indicating that the rate of rutting is similar for both mixes

The mean of the average rut depth to ESAL ratio varies considerably, but the value for 420 mix is always considerably smaller than 416 mix as shown in Figure 7. The large difference in age of surfaces with the two mixes is thought to cause this difference. No 420 mix has been placed recently, and badly rutted sections are overlaid. This results in a decline in the amount of 420 mix with only those pavements performing well increasing in age. Pavements are overlaid with 416 mix, thereby, decreasing or maintaining its age. Since the mean of the ratios is sensitive to extreme values of rut depth or ESAL's (indicative of age), the large differences in values is reasonable, but probably not a valid indicator of the mixes relative rutting susceptibility.

Analyses of all mixes is best accomplished by comparing data for state routes, considering that state routes are surfaced with all type mixes. Figure 8 shows how usage and rate of rutting for the various mixes is changing with time. Figure 89 shows that the usage of 401, 411 and 420 mix is decreasing, and that the usage of 416 and 417 mix is increasing. For 401, 411 and 416 mix, this reflects the upgrading of state routes to satisfy increased traffic demands. Use of 417 mix remains small, but its increased usage is, at least partially, motivated by the belief that latex improves rut resistance.

The rate of rutting is increasing for 401 and 416 mixes, but appears to be stabilizing for 411 mix. Traffic loading severity is an obvious reason for this increase, but as discussed for interstate routes, changes in usage patterns will influence relative age which may in turn affect the validity of rate of rutting indicators.

The limited use and age of 417 mix prevents drawing strong conclusions regarding its performance relative to 416 mix. However, several interesting trends are apparent from Figure 8. Its use is increasing rapidly, and its rate of rutting is approximately twice that of 416 mix. The relationship between the rate of rutting of the mixes may be a result of the limited use of 417 mix. As its use and age increases, its rate of rutting should become more comparable with 416 mix.

Figure 9 shows 1986 data grouped by mix for all three parameters. The histograms for mean rut depth and mean rut depth/mean ESAL are typical of 1984 and 1988. The data for the mean of the ratio of average rut depth to ESAL is more erratic, particularly for the 1988 data. Again, this is thought to be caused by extreme values and adversly affects the parameter as an indicator of rutting susceptibility. The ratio of means is a more valid indicator of rate of rutting.

Figure 9 shows that mean rut depths for 401, 411 and 416 mixes are about the same. This indicates consistency in the design of materials for the traffic loading intensities that these mixes are expected to withstand. Rate of rutting, as measured by the ratio of means, indicates that the rate of rutting for 411 and 416 mixes are about the same. Again this indicates consistency in material design for expected traffic. Rate of rutting for surface treatments (401) is higher. This is expected since rutting will develop in base, subbase, and possibly the subgrade in these pavements. Heavy truck loads and high tire pressures will be critical for pavements with surface treatments since they provide only minimal cover for base and subbase layers. Bases and subbases for these type pavements are usually comprised of unbound soil aggregate type materials which will not be particularly rutting resistant.

Rutting Frequency Distributions. Frequency distributions of average rut depth and rate of rutting, as measured by the ratio of average rut depth to 18 kip ESAL, were analyzed for trends with time and pavement type. A complete set of frequency distributions are contained in Appendix A.

Figures 10 and 11 show, respectively, 1988 state and interstate rut depth frequency distributions and 1988 state and interstate rate of rutting frequency distributions. The shapes illustrated are typical for 1984 and 1986 data. The rut depth distributions, Figure 10, show, as did Figure 4a, that rut depths are larger on interstate pavements. The rate of rutting distributions, Figure 11, show, as did Figure 4b, that the rate of rutting is smaller on interstate pavements. Figure 11 also shows a much wider range of rate of rutting on state route pavements. This is expected because of the greater diversity of materials, pavement structures and traffic on state routes.

Figures 12 and 13 show, respectively, rut depth and rate of rutting frequency distributions for 1984, 86, and 88 state route data. The trends illustrated for state routes were generally applicable for interstate routes. Figure 12 shows a change in shape for the rut depth distribution between 1984 and 1986. This appears to be an indication that the magnitude of rutting was significantly increasing, but comparison of the cumulative frequencies and percentages for 1984 and 86 reveal only minor changes. The shape of the 1988 distribution reverts back to the 1984 shape. Figure 13 shows consistent shapes and only minor changes in frequency for rate of rutting. Although significant changes with time in rut depth and rate of rutting are not visually apparent from the frequency distributions, mean values did increase with time as demonstrated in Figures 4a and c.

Analysis of Field Data.

Data from the thirteen (13) field sites was analyzed to determine where in the pavement structure permanent deformation was developing and the relationship between rut development and traffic. The locations of the 13 test sites are shown in Figure 1 and descriptions of the pavement structures given in Table 3.

Layer Profile Analysis. The profiles of the asphalt bound layers were analyzed to determine where rutting was developing. When trenches were opened, stringlines were stretched along layer interfaces, as illustrated in Figure 13, to defect depressions in the lower layer surface. These depressions would be indicative of permanent deformation in the layer itself or lower layers. As can be seen from the pavement structure descriptions in Table 3, nine of the 13 pavements were comprised of an original structure plus at least one overlay. This made the determination of the lower limit of rutting more difficult, but measurements in the trenches indicated that permanent deformation was primarily confined to near surface (approximately 4 inch depth) asphalt bound layers. In most pavements this limited permanent deformation to surface and binder layers. The interface between binder and black base layers were usually relatively depression free.

At only Site 9 was there evidence of rutting in base or subbase layers below asphalt bound layers. There was evidence of rutting in or below the sand-clay-shell base at this site. When this rutting occurred could not be determined. It may have developed in the original pavement when cover was only the "AKG" treatment and approximately one inch of asphalt concrete. Or, it may have developed later when the structure was thicker, but loads and tire pressures greater. At only Site 2 was there evidence that stripping may have contributed to rutting. At this site several cores in wheel paths disintegrated and could not be completely recovered. Stripping was confined to the original binder and base layer.

Profiles were also analyzed to determine the magnitude of rutting and where in the pavement structure permanent deformation was occurring. This analysis is illustrated in Figure 14. Profiles for all thirteen sites are contained in Appendix B. Total rutting was determined by averaging rut depths (R_i and R_o)

in inner and outer wheel paths at the trench and two core line locations. Rut depths are compiled in Table 4. Also shown in Table 4 are rut depths for the test sites compiled from the 1988 pavement condition database. Database rut depths are smaller primarily because of different measuring methods. A 4-foot straightedge was used for data base measurements and a 12-foot straightedge was used at test sites. Data base rut depths are the average of eight measurements per lane mile for design projects in which test sites were located. Design projects were several miles long.

The rut depths from Table 4 are plotted as a histogram in Figure 15. From this histogram the following can be noted:

- Rut depths at sites selected for good rutting performance are generally less than rut depths at sites selected for poor performance.
- Rut depths (12 foot straight edge) are generally less than 0.4 inches for sites with good performance and greater than 0.4 inchs for sites with poor performance.
- Rut depths (4 foot straight edge) are generally less than 0.2 inches for sites with good performance and greater than 0.3 inches for sites with poor performance.

While rut depth is an indicator of pavement performance, it is influenced by traffic (volume and load) which must be considered when assessing rutting susceptibility. The effects of traffic will be considered in the following section.

Permanent deformation in various layers was determined analyzing the shape of layer interfaces. As indicated by stringlining layer interfaces in trenches, the permanent deformation occurred primarily in upper layers. As illustrated in Figure 14, strait edges along binder/base interfaces indicated minimal rutting in lower layers (the exception being Site 9).

To get some idea of the permanent deformation in the various layers, layer thickness in wheel paths (T_{W1} and T_{W2}) were compared with layer thicknesses outside the wheel paths (T_{01}, T_{02} and T_{03}). The summation of the permanent deformation in all layers (T_0 - T_W) should approximate the total rutting (R).

This analysis was not successful for several reasons. Accuracy of measurements was likely one reason, but more importantly was inappropriatness of the method. Overlays create two problems. When rutted pavements are overlaid (without milling), layers in the wheel paths will be thicker, and not as well compacted. Secondly, permanent deformation in the existing pavement will not be related to rutting of the overlay. Finally, at those sites where plastic flow has occurred, upheaval outside the wheelpaths will distort the measurements. This process will be examined more closely in the section on the model for rutting, but material simply moves from the wheel path to adjacent areas giving a false impression of layer thickness. Some dilation may also occur in cases of severe rutting, causing further distortion.

To summarize, analysis of the layer profiles produced good measures of total rutting and good qualitative indications that permanent deformation was limited to near surface layers (surface and binder). However, the anlaysis to quantify permanent deformation in individual layers was not successful. Total rutting will be combined with traffic and analyzed in the following section.

Rutting vs Traffic Analysis. To study the relationship between traffic and rutting at test sites, traffic was converted to total18 kip ESAL's applied to the pavement since construction or since overlay. Equation 2 was used to convert AADT and percent commercial vehicles to 18 kip ESAL's. Traffic data from the 1986 data base with no growth factors was used for this purpose. Since pavements were constructed from 1974 to 1985 and also rated in 1988 and

1989, computed 18 kip ESAL's are approximations.

Traffic data for the thirteen test sites is compiled in Table 5. All test sites were on outer lanes of four lane facilities and the 18 kip ESAL's are estimates for these lanes. Traffic volumes ranged from 0.3 x 10^6 ESAL's at Site 12 to 6.6 x 10^6 ESAL's at Site 1. This represents a 22 fold difference and must be considered when evaluating the influence of traffic on rutting. The model that will be subsequently proposed to describe the rutting process with traffic is highly nonlinear and the rate of rutting development will be dependent on location of traffic vs rutting along the curve.

The ratio of rut depth to 18 kip ESAL's provides a measure of rate of rutting. Using rut depths from measurements at the test sites and from the 1988 pavement condition database, ratios were computed and compiled in Table 4. These ratios are plotted as a histogram in Figure 16. Except for Site 13, the histogram provides a clear distinction between the good and poor performing pavements. The histogram also suggests a 1.0 x 10^{-7} inch/ESAL rate of rutting criteria for delineating rutting and nonrutting pavement. Rate of rutting will be used with laboratory data in the following section to develop correlations with aggregate, asphalt and mix properties.

General Model for Rutting in Asphalt Bound Layers

Observation of pavement cross sections at test sites and examination of in-place mix properties indicates rutting in asphalt pavements develops in two phases. This process is graphically depicted in Figure 17. In the first phase repeated load applications causes densification from as constructed void content (8% or less). In properly designed mixes, densification stabilizes at about 4% and in good performing pavements, rut depth development ceases or decreases to very low rates as illustrated in Figure 17a.

Most mixes are designed to have approximately 4% voids, but are normally compacted during construction to 7-8% voids. After construction, the pavement surface should be flat and free of ruts. Traffic will continue to compact a well designed mix to the 4% design voids. Voids may stabilize at higher voids, but if much higher durability problems may develop. The additional compaction will result in small ruts. For example, an 0.08 inch rut will develop in a 2-inch thick layer with a 4% reduction in voids.

At about 4% voids, the ability to resist permanent deformation in properly designed mixes is optimum. It is critical that the aggregate skeletal structure have the ability to resist further densification. This is best accomplished with well graded aggregate with angular rough textured particles.

Asphalt content is also critical as the mix reaches about 4% voids. Excess asphalt will decrease intergranular contacts weakening the aggregate skeletal structure and leading to further densification. Excess asphalt can weaken otherwise very stable aggregate structures. This emphasizes that aggregate properties and optimum asphalt content are equally important aspects of the mix design and construction process.

For pavements that experience severe rutting, densification continues and second phase conditions develop. When voids reach 2-3%, the mix becomes very unstable and plastic flow will develop with continued traffic, as illustrated in Figure 17b. Rut depth increases rapidly and upheaval outside wheel paths will begin. Carried to extremes, pushing and shoving may develop causing a dramatic increase in roughness. Dilation may occur as the material shears and flows plastically from wheelpaths causing an apparent increase in voids. Large voids, Figure 18, were visible in cores adjacent to wheel paths at Sites 5 and 6 where advanced second phase conditions had developed.

At sites selected for good rutting performance (1, 4, 7, 11 and 13), only first phase densification had occurred and void content was stable as illustrated in Figure 17a. Voids in the surface layer within wheel paths at these sites were 5.0, 4.7, 4.1, 9.4 and 3.2%, respectively.

At the remainder of the sites, selected for poor performance, rutting was at several stages of development, as illustrated in Figure 17b. Site 12 had received only a small amount of traffic and was considered at the beginning of first phase densification (voids were 6.8%). Sites 2, 3 and 10 were still experiencing first phase densification, with voids of 3.0, 2.1 and 3.7%, respectively, but appeared about to go into second phase plastic flow. Site 5 and 6 were well into second phase plastic flow with voids of 2.3 and 2.1%, respectively. It is of interest to note here that the last overly at Sites 5 and 6, as well as Site 2, was thin (125-130 lb/sy) asphalt concrete over a surface treatment. Asphalt cement from the surface treatment, particularly for heavy applications, may migrate upward, softening the asphalt concrete and contributing to rutting.

Site 8, where traffic volume was low, appeared to be into the initial stages of second phase plastic flow development. The void content of the surface layer in the wheel paths was 1%, but very high asphalt content (7.8%) is thought to have contributed to this low value. Void content at Site 9 was 3.8%, but no conclusions could be drawn regarding the stage of rutting development because of evidence that lower layers might also be contributing.

A properly designed and constructed asphalt-aggregate mixture will have 7-8% voids after construction. It will slowly compact to approximately 4% voids and stabilize. An improperly designed mix, one that will result in rutting, will usually initially have voids above 4-5%, but will compact under traffic to 2-3% voids.

Since the proposed model for describint rut development with traffic is nonlinear, ratios of rut depth to several functions of ESAL's were examined. The ratio of rut depth to √18 kip ESAL's seemed to provide the best measure of rate of rutting. Using rut depths from measurements at the test sites ratios were computed and compiled in Table 4. These ratios are plotted as a histogram in Figure 19. The histogram provides a clear distinction between the good and poor performing pavements. The histogram also suggests a 0 .2 x 10^{-3} inch/√ESAL rate of rutting criteria for delineating rutting and nonrutting pavement.

Analysis of Laboratory Data.

After completion of all laboratory testing a detailed statistical analysis using SAS program was performed to determine those properties that are related to rutting. In-place mix properties, Table 6 included asphalt content, voids, resilient modulus and creep strain. Properties of recompacted mix, Table 7, included voids, stability and flow of samples compacted with a manual Marshall hammer and with a gyratory testing machine. During compaction in the gyratory, roller pressure was measured and gyratory shear index (GSI) was computed. Properties of recovered asphalt, Table 8, included penetration and viscosity. Properties of recovered aggregate, Table 9, included gradation, fractured face counts on coarse aggregate particles, and uncompacted voids and flow time for fine aggregate fractions.

To be useful a model must include rut depth and traffic. Three relationships were conisdered: (Rut Depth)/ESAL, (Rut Depth)/√ESAL, and (Rut Depth)/ln ESAL. It was determined that (Rut Depth)/√ESAL was the parameter that correlated best with laboratory properties. Correlation coefficients from the linear regression between (Rut Depth)/√ESAL and various parameters are tabulated in Table 10. A correlation coefficient close to 1 indicates a good correlation and a correlation coefficient close to a 0 indicates a poor correlation.

Since most of the rutting that was observed occurred in the top four inches and generally in the top layer, the analysis was made considering only the properties of the top layer. The correlation coefficient between

(Rut Depth)/$\sqrt{ESAL}$ and thickness was high enough (-0.59) to indicate that the thickness of the top layer was an important factor for evaluating rutting potential. The relationship between top layer thickness and (Rut Depth)/$\sqrt{ESAL}$ is shown in Figure 20.

A discussion of the results for various properties that affect rutting is presented below. The results are based on samples throughout the State of Alabama and may not be appropriate in other states or even in Alabama when materials, thicknesses, environment, traffic, and other factors are different than those analyzed in this study.

In-Place Voids. It has been known that rutting is a function of in-place voids. Brown and Cross (9), Ford (10), and Huber and Herman (11) showed that once in-place voids drop below approximately 3 percent rutting is likely to occur. Table 10 shows that the correlation coefficient for in-place voids and (Rut Depth)/$\sqrt{ESAL}$ is -0.66.

The voids in wheel paths are usually lower due to compaction, hence, it appears that these lower in-place voids should be compared to rutting. Some projects, however, show that the lower voids are in between the wheel paths. One explanation for the cause of this is that the voids in the wheel path may decrease to some minimum amount at which rutting occurs. Once rutting begins to occur it is likely in some cases that the density in the wheel path actually decreases due to plastic flow resulting in an increase in voids. The analysis in this study was made by first computing the average core density and the standard deviation. The critical in-place voids were then calculated at the 80th percentile. In other words 80 percent of the voids would be higher than the selected value and 20 percent would be lower. This is an acceptable minimum void level for comparing to rutting.

Six pavements had in-place 80 percentile voids below 3 percent in the top layer. These pavements were at sites 2, 3, 5, 6, 8, and 9. These six sites along with site 10 had the highest (Rud Depth)/√ESAL values and hence rut at a faster rate. Site 10 had very low in-place voids (1.6 percent) in the second layer which likely explains why it had a high rate of rutting.

Although the in-place voids are closely related to rutting there is no way to use this information in the initial mix design and construction control of asphalt mixtures. The in-place voids can only be measured after the mixture has been placed which makes this property useless for mix design and quality control. Laboratory compactive effort has been calibrated in the past to provide a density equal to the in-place density after traffic. If this correlation is correct then the in-place density can be predicted with laboratory compacted samples.

Figure 21 graphically shows the effect of in-place voids on rut depth. This figure shows a general trend of increasing rut depth with decreasing in-place voids. In place voids near four percent and higher typically result in a (Rut Depth)/√ESAL of approximately .0002 or less. This means that the expected rut depth for these mixes after 1 million ESALs would be no more than 0.2 inches and after 4 million ESALs, it would be no more than 0.4 inches.

Resilient Modulus (M_R). The correlation coefficient between M_R and (Rut Depth/√ESAL was determined to be -0.65 (Table 10). This is a relatively high correlation and shows that an increase in M_R should result in a decrease in rut depth. The data in Figure 22 does show a definite trend. Since the M_R was conducted on field samples, it is likely that the mixes with higher voids aged more rapidly than other mixes and thus, resulted in higher M_R values. Since M_R changes with age of the asphalt mix, it would be impossible from this study to determine minimum M_R values to specify for new construction.

Creep. No correlation analysis was performed for the creep strain data because six of 13 samples failed during testing (Table 6). The remaining seven samples had measurable creep strains ranging from 0.015 to 0.039. Five of the six samples that failed during testing had (Rut Depth)/√ESAL greater than 0.0002, but only four of the samples with measurable creep strain had (Rut Depth)/√ESAL greater than 0.0002. Creep strain in general identifies mixes that are susceptible to rutting, and samples that deform excessively when loaded with 120 psi compression at 140°F are particularly unstable and susceptible.

Recompacted Voids (Hand Hammer). Some of the mix taken from the in-place pavement was heated, broken up and recompacted using 75 blows with the Marshall hand hammer. This process should provide an estimate of the original laboratory compacted mix properties. Table 10 shows that the correlation coefficient between recompacted voids and (Rut Depth)/√ESAL is -0.47. This is not as high as the correlation for in-place voids but is still a reasonable correlation.

Figure 24 shows that there is considerable scatter, but there is a general trend for lower rut depth with higher voids. For example two of the four pavements with (Rut Depth)/√ESAL less than 0.0002 had voids above four percent. Only one of the remaining nine samples with (Rut Depth)/√ESAL greater than 0.0002 had voids above four percent.

While recompacted voids do not relate as well with rutting as in-place voids, it does relate well enough to be effective in minimizing rutting. If laboratory voids are four percent or higher, rutting should not be a major problem provided all other properties are acceptable.

Recompacted Voids (Gyratory Testing Machine). Samples recompacted in the gyratory provide similar results as those recompacted with hand hammer. The correlation coefficient for samples compacted in the GTM is -0.57 which is slightly better than that for hand hammer. Figure 25 shows that there is again considerable scatter in the data, but it does indicate that voids do affect rutting. Seven of the nine pavements with (Rut Depth)/√ESAL greater than 0.0002 had recompacted voids less than four percent. Three of the four pavements with (Rut Depth)/√ESAL less than 0.0002 had recompacted voids greater than four percent

Marshall Stability (Recompacted with Hand Hammer). The correlation between (Rut Depth)/√ESAL and Marshall stability of samples recompacted with a hand hammer is very high (correlation coefficient = -0.74). This indicates that an increase in stability will result in a decrease in rutting. This correlation is somewhat surprising since most pavement engineers believe that Marshall stability is not related to rutting.

The actual Marshall stability values measured are generally very high since the asphalt has oxidized and stiffened. Even if Marshall stability is closely related to rutting it would be difficult to establish stability requirements from the data in this report since the stability values reported are much higher than that which would be expected for new mix.

The relationship between rutting and stability for hand hammer compaction is shown in Figure 26. There is a definite trend showing a reduction in rutting for an increase in stability.

There are at least two explanations for the strong correlation between stability and rutting even if a good correlation does not exist. It is known that mixes with high voids will oxidize faster than mixes with low voids. Hence, it is likely that mixes with high voids (more rut resistant) oxidized more and artifically increased the Marshall stability. Hence, it is reasonable to expect mixes with high voids to have high stability and mixes with low voids have low stability. A statistical evaluation of the data shows that the correlation coefficient between Marshall stability (hand compaction) and in-place voids is

0.70 and Marshall stability (gyratory compaction) and in-place voids is 0.67. These high correlations between voids and stability likely explains part of the reason that rutting and stability appear to be closely correlated.

Another explanation for the good correlation is the way sites were selected for this project. Those sites with more rutting had generally been in-place a shorter time than those sites with little rutting. Everything else being equal, this would result in the least rutted pavements having higher stbility that the more rutted pavements simply because of pavement age. The older pavements being more oxidized would have higher stabilities.

Considering the above discussion it is still likely that there exist some correlation between stability and rutting.

Marshall Stability (Recompacted with Gyratory). The correlation coefficient between the stability (gyratory compacted) and (Rut Depth)/$\sqrt{}$ESAL is -0.66. Again this is a high degree of correlation. The explanation provided for stability (hand hammer compaction) also applies to the stability measured here. A plot of the data is shown in Figure 27. Again there is a definite trend that indicates an increase in stability results in a decrease in rutting.

Marshall Flow (Hand Compacted). Flow is considered a reasonably good indicator of rutting. The correlation coefficient between Marshall flow (hand compacted) and rutting for this study was measured to be 0.50 (Table 10). A flow of 16 is specified by most agencies as the maximum allowable flow. Figure 28 shows that four of the five mixes with a flow above 16 had (Rut Depth/$\sqrt{}$ESAL greater than 0.0002. Five of the mixes with flow 16 or less had (Rut Depth)/$\sqrt{}$ESAL greater than 0.0002. Only two of the seven mixes with flow 16 or less had (Rut Depth)/$\sqrt{}$ESAL greater than 0.0003. Again, there is a trend which indicates that mixes with a flow above 16 are more likely to rut.

Marshall Flow (Gyratory Compacted). The correlation coefficient between Rut Depth/√ESAL and Marshall Flow (Gyratory Compacted) is 0.41 (Table 10). These results are plotted on Figure 29. Four of the five mixes with a flow greater than 16 have a (Rut Depth)/√ESAL greater than 0.0002. Only four of eight mixes with flow less than sixteen have (Rut Depth)/√ESAL greater than 0.0002.

Gyratory Shear Index (GSI). The GSI has been shown to be a good indicator of rutting (9). As shown in Table 10 the correlation coefficient between GSI and Rut Depth/√ESAL was 0.64. Figure 30 shows that there is significant scatter about the best fit line. The data that plots well above the best fit line generally has low fractured face count and the data below the line generally has a high fractured face count. Much data is grouped next to GSI = 1.0 since this is the lowest value that a mix can have.

Previous studies have shown that mixes with a GSI greater than 1.3 are expected to exhibit severe rutting (9). The data shows that 4 of the 5 mixes with GSI above 1.3 had experienced a Rut Depth/√ESAL greater than .0002.

Gyratory Roller Pressure. The correlation coefficient between roller pressure and (Rut Depth)/√ESAL is -0.61 (Table 10). The roller pressure is that force required to produce a 1 degree gyration angle in the asphalt mix. A mix that is more resistant to deformation should require a higher pressure to deform it during the compaction progress. Figure 31 shows that there is considerable scatter about the best fit line but there is a definite trend. Lower roller pressure is typical for those mixtures that have high rutting. Seven of the eight mixes with a roller pressure of 14 psi or less had Rut Depth/√ESAL greater than 0.0002. Three of the five mixes with a roller pressure greater than 14 psi had Rut Depth/√ESAL less than 0.0002.

Aggregate Gradation. The aggregate gradation definitely affects the rutting resistance of an asphalt mixture but this is a difficult property to analyze. Studies have shown that the maximum aggregate size is important as well as percent passing No. 200 sieve are important (13,14). However, the overall evaluation of individual gradations is difficult. For this project the percent passing 3/8 inch sieve, percent passing No. 50, and percent passing No. 200 sieve were analyzed to determine their affect on rutting. As shown in Table 10 the correlation coefficient between Rut Depth/$\sqrt{}$ESAL and percent passing the 3/8 inch sieve is -0.47. This indicates that an increase in percent passing the 3/8 inch sieve will decrease rutting. This is opposite from the expected trend. A plot of the data in Figure 32 shows that there is considerable scatter in the data with only limited range. The high correlation coefficient is basically the result of one data point that has a very low percent passing the 3/8 inch sieve and very high rutting. Based on the findings by others and the data scatter it is concluded that clear trend between Rut Depth/$\sqrt{}$ESAL and percent passing the 3/8 inch sieve is not shown in this study.

The second sieve size that was investigated was the perent passing the No. 50 sieve. The correlation coefficient of 0.17 (Table 10) and the data scatter shown in Figure 33 indicate very little trend between Rut Depth/$\sqrt{}$ESAL and percent passing No. 50 sieve.

The correlation coefficient of 0.37 and the data scatter in Figure 34 indicate a poor correlation between (Rut Depth)/$\sqrt{}$ESAL. Figure 28 does show, however, that the two most severely rutted pavements had more than seven percent passing the No. 200 sieve.

Fractured Faces. The fractured face count of an aggregate should affect its ability to resist rutting. Some percentage of fractured aggregate is almost always specified for high volume roads but there is very little field data to support or contradict this type specification. The correlation coefficient between fractured face count and (Rut Depth)/ √ESAL for the study was -0.13 (Table 10). This is a very low correlation that shows a slight trend toward less rutting for higher fractured face count.

The correlation appears to be much better than this after reviewing Figure 35. The two mixes with highest (Rut Depth)/√ESAL (Site 5 = 77.1×10^{-5} and Site 8 = 79.2×10^{-5}) also had high fractured face counts (Site 5 = 81.0% and Site 8 = 98.1%). These mixes had low in-place voids (Site 5 = 2.3% and Site 8 = 0.6%). Site 5 was the most severely rutted site studied (Rut Depth = 1.09 inches) with rutting well into plastic flow. Plastic flow had not started at Site 8, but the mix was characterized by verh high asphalt content (7.8%) and very low in-place voids (0.6%). If the data for Site 8 is eliminated, for unrealistically high asphalt content, the correlation coefficient becomes -0.41 indicating a much stronger trend.

The data in Figure 35 shows that all six mixes with fractured face percentages of 80 or less had a (Rut Depth/ √ESAL greater than .0002. The data also shows that four out of seven mixes with a fractured face count greater than 80 had (Rut Depth/ √ESAL less than .0002, including the two mixes discussed above.

Fine Aggregate Shape & Texture. Uncompacted voids from the NAA flow test (12) and time from the modified test measure particle angularity and texture. Higher voids and flow times indicate rougher textured and more angular particles. The correlation coefficients in Table 10 shows that flow time from the modified NAA test has very little correlation (0.05). Uncompacted voids from the NAA test have better (0.15), but still very poor correlation.

Figure 36 shows the weak trend for uncompacted voids, but the trend indicates that an increase in voids will result in an increase in rutting. This is opposite of the expected trend. It appears from Figure 36 that the data from

Sites 5 and 8, which have the two highest rates of rutting, do not follow the pattern of the data at other sites. If the data point for Site 8 (45.9, 79.2×10^{-5}) is omitted, for unrealistically high asphalt content, the correlation coefficient becomes -0.25 indicating a stronger trend. More importantly the sign of the correlation coefficient is reversed and indicates, as expected, that rate of rutting decreases as uncompacted voids increases.

Figure 37 illustrates the very weak correlation for flow time. Again, if the data point for Site 8 (23.9, 79.2×10^{-5}) is omitted, the correlation coefficient becomes - 0.37. This not only represents a dramatic increase in magnitude, but the change in sign means that the trend is in the expected direction, i.e., rate of rutting decreases as flow time increases. The performance of the mix at Site 8 demonstrates the multiplicity of factors that can influence rutting performance, and the importance of both aggregate properties and asphalt content during material selection and mix design.

Asphalt Penetration. The data in Table 10 shows that the correlation coefficient between (Rut Depth/√ESAL and penetration is 0.46. The data plotted in Figure 38 shows an obvious trend indicating an increase in penetration would result in an increase in rutting. Since most asphalt pavements in Alabama begin with similar penetration, it is not clear what this trend indicates. As before, it may be that larger voids result in more oxidation of the asphalt and better resistance to rutting. At any rate it is reasonable to expect more rutting when using an asphalt with higher penetration.

Viscosity. The correlation coefficient between (Rut Depth)/√ESAL and viscosity is -0.50 as shown in Table 10. The trend is shown graphically in Figure 39. This indicates that an increase in viscosity would result in a decrease in Rutting. The discussion under asphalt penetration will also be true for viscosity.

Predictive MOdel. In developing a combined predictive model, those properties that were independent of each other that appeared to correlate best with rutting and those easily measured were selected. After evaluation of several combinations it was determined that the best combination included the following three properties: voids in laboratory compacted samples, percent of fractured faces, and percent of material passing the No. 200 sieve. This model which has an R^2 of 0.35 is shown in Figure 40. The equation can be used to estimate (Rut Depth/$\sqrt{ESAL}$) from the three aggregate and mix properties. Mixes resulting in estimates greater than 0.0002 should be examined carefully for redesign.

Geographic and Aggregate Property Relationships.

In the section on the analysis of rutting data from the AHD pavement condition database, it was concluded that pavement rutting susceptibility was related to geographical area and that variable geology and, thus, variable quality aggregate was the most probable cause. Specifically it was concluded that pavements in Divisions 5-9 which are located in the Coastal Plain, where natural sands and gravels are used, are more susceptible to rutting than pavements in Divisions 1-4 which are located predominately in the Appalachian Plateau and Piedmont geologic regions, where crushed stone is available.

Particle shape and texture are assumed to be indicators of aggregate quality and several parameters will be compared for the extracted aggregates from Sites 1-4 and 5-6. Average values for the parameters are contained in Table 11.

For the fine aggregate fraction (minus No. 8, voids from the NAA test and flow time from the modified NAA test were compared. Average NAA voids and flow times are larger for the sites in Divisions 1-4 indicating more angular particles with rougher surface texture. This was the expected response since both angularity and surface texture are indirectly related to weathering or distance transported.

Crushed face counts are a measure of particle angularity and were made on coarse (plus No. 8) aggregate particles. These counts can also be used to indicate angularity of coarser fractions, i.e., plus No. 4 particles. The plus No. 4 fraction is considered because AHD specifications for surface mix aggregate have the requirement that 80% of these particles have two (2) or more crushed faces. Percentages of particles having two or more crushed faces for the plus No. 8 and plus No. 4 fractions are shown in Table 11. The numbers are somewhat different but both sizes indicate the same differences between the aggregate from sites in Divisions 1-4 and the aggregate from sites in Divisions 5-9.

For surface mixes the percentages of particles with two or more crushed faces is only slightly larger in Divisions 1-4 than in Divisions 5-6. This is probably due to the widespread use of crushed gravel coarse aggregate statewide with only slightly more granite and slag used in Divisions 1-4.

For binder mixes the percentages in Divisions 1-4 are 100% and approximately twice those in Divisions 5-6. This si due to the sidespread use of crushed limestone in Divisions 1-4. For combined mixes the percentages for both size fractions are larger in Divisions 1-4 than in Divisions 5-6, indicating more angular course aggregate particles in Divisions 1-4.

CONCLUSIONS AND RECOMMENDATIONS

Analyses of the Department's pavement condition database indicate that rutting in Alabama is increasing, and that this increase is attributible to either increased loading intensity or increased asphalt concrete rutting susceptibility. The analyses also indicate that rutting varies geographically and that this variation can be explained by quality of locally available aggregate. Those areas with crushed stone and angular natural sands are less susceptible to rutting.

Analyses of data from field test sites indicate that permanent deformation causing rutting is generally confined to the top 3 to 4 inches (surface and binder courses). There was little evidence that lower base/subbase courses or subgrade were significant contributors to rutting. At only one site was there evidence that stripping may have contributed to rutting. There was some evidence that surface treatment layers used in conjunction with thin overlays may have contributed to rutting susceptibility. A rate of rutting of 2×10^{-4} in/$\sqrt{\text{ESAL}}$ or 1.0×10^{-7} in/ESAL delineated good and poor performing pavements.

The properties measured in this study that appear to be useful in minimizing rutting include: layer thickness, voids, GSI, Gyratory roller pressure, percent of fractured faces, percent passing No. 200 sieve, Marshall flow, and creep strain. The R^2 for most of these properties were low, however, there appeared to be a definite trend shown in the figures. The low R^2 in almost every case was caused by one or two of the data points being far outside the range of the other data. This shows that rutting is a very complicated process and is affected by a large number of factors and hence, to use only a small number of properties to accurately predict rutting is impossible.

The best model selected for predicting rutting had an R^2 equal to 0.35 and included the voids in laboratory compacted samples, percent coarse aggregate with two or more faces, and percent of materials pasisng the No. 200 sieve.

The crushing of gravel should be more carefully controlled to insure that the 80% requirement for particles with two fully fractured faces is met. This may require limitations on minimum particle size for crushing. On heavily traveled roadways (state primary and interstate routes) crushed particle requirements for binder mixes should be the same as surface mixes. The use of a test, such as the National Aggregate Association's uncompacted voids method, to quantify and limit particle shape and texture of fine aggregate should recieve additional study but this study showed no correlation.

The use of surface treatment interlayers, particularly in conjunction with thin overlays, should receive further study. This study should focus 1) on identifying conditions where surface treatment interlayers should and should not be used, and 2) on construction control procedures that will prevent excess asphalt cement that could soften the overlay and increase rutting susceptibility.

Procedures should be adopted for better control of asphalt content during construction. Target job mix formula asphalt content should not be changed without sufficient test results to justify changes.

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TABLES

TABLE 1. SUMMARY RUT DEPTH DATA, OUTER LANES

Year	Frequency	MRD(in.)	MRD/MESAL (in. x 10^{-7})	M(RD/ESAL)(in. x 10^{-7})
			State & Interstate	
1984	22,683	0.10258	1.919	10.918
1986	22,004	0.10259	2.076	11.983
1988	21,444	0.10694	2.123	12.564
			State	
1984	21,503	0.10049	2.551	11.424
1986	20,801	0.10070	2.720	12.601
1988	20,260	0.10409	2.739	13.283
			Interstate	
1984	1180	0.14067	0.448	1.540
1986	1203	0.13526	0.504	1.068
1988	1184	0.15561	0.614	1.488

Frequency - Number of test site. Eight rut depth measurements at each test site, four in inner and four in outer wheel paths.

MRD - Mean **average rut depth**.

MRD/MESAL - Ratio of mean **average rut depth** to mean 18 kip equivalent single axle loads.

M(RD/ESAL) - Mean of the ratio of **average rut depth** to 18 kip equivalent single axle loads.

TABLE 2. SUMMARY OF RUTTING SUSCEPTIBILITY BY AHD DIVISION

Routes	Divisions	Database Year 1984	1986	1988
		Average Rut Depth (inches)		
State & Interstate	1 - 4	0.07380	0.08491	0.10572
	5 - 9	0.12759	0.11615	0.10756
State	1 - 4	0.07368	0.08568	0.10513
	5 - 9	0.12464	0.11197	0.10104
Interstate	1 - 4	0.10006	0.09128	0.11099
	5 - 9	0.18646	0.18685	0.17707
		Mean Rut Depth/Mean ESAL (inch x 10^{-7})		
State & Interstate	1 - 4	1.286	1.560	2.145
	5 - 9	2.750	2.751	2.480
State	1 - 4	1.690	2.018	2.595
	5 - 9	3.628	3.424	3.000
Interstate	1 - 4	2.396	2.639	3.908
	5 - 9	6.616	7.708	8.470
		Mean (Average Rut Depth/ESAL) (inch x 10^{-7})		
State & Interstate	1 - 4	8.510	11.073	15.095
	5 - 9	13.656	12.730	10.465
State	1 - 4	8.822	11.636	15.095
	5 - 9	14.536	13.452	10.872
Interstate	1 - 4	0.660	0.373	1.354
	5 - 9	1.585	1.383	1.500

TABLE 3. TEST SITE PAVEMENT DESCRIPTION.

Site	Route	Direction	Mile Post	Pavement Structure
1	I-59	S	27.3-32.4	100#/SY 328 Mix placed 05/75 300#/SY 327 Mix placed 05/75 832#/SY 227 Mix placed 05/75 Soil-Aggregate Base
2	I-59	N	42.5-52.5	130#/SY 416 Mix placed 10/83 "G" Treatment placed 10/83 100#/SY 328 Mix placed 1975 300#/SY 327 Mix placed 1975 594#/SY 227 Mix placed 1975 Soil-Aggregate Base
3.	I-10	E	0-6.0	125#/SY 416 Mix placed 01/84 300#/SY 414 Mix placed 01/84 "L" Treatment placed 01/84 10 in. Plain PCC placed 1965
4.	I-10	E	6.0-12.0	60#/SY 420 Mix placed 09/81 90#/SY 416 Mix placed 09/81 300#/SY 414 Mix placed 09/81 "L" Treatment placed 09/81 10 in. Plain PCC placed 1965
5.	I-65	N	93-8-106.0	125#/SY 416 Mix placed 09/83 "H" Treatment placed 09/83 100#/SY Surface placed 1969 100#/SY Leveling placed 1969 100#/SY Leveling placed 1969 100#/SY Surface placed 1962 250#/SY Binder placed 1962 Cement Treated Base
6.	I-85	S	5.8-10.6	125#/SY 416 mix placed 06/82 "G" Treatment placed 06/82 100#/SY 328 Mix placed 1967 300#/SY 327 Mix placed 1967 620#/SY 227 Mix placed 1967 Select Soil Subbase
7.	I-85	N	64.9-72.0	90#/SY 416 Mix placed 10/79 "G" Treatment placed 10/79 100#/SY Surface placed 1965 150#/SY Surface placed 1960 250#/SY Binder placed 1960 Crushed Stone Base

TABLE 3 continued. TEST SITE PAVEMENT DESCRIPTION.

Site	Route	Direction	Mile Post	Pavement Structure
8.	US280	W	68.5-71.8	125#/SY 416 Mix placed 05/85 300#/SY 414 Mix placed 05/85 432#/SY 327 Mix placed 05/85 Crushed Stone Base
9.	US231	S	32.3-40.6	170#/SY 416 Mix placed 02/83 100#/SY 416 Mix placed 1980 "G" Treatment placed 1980 130#/SY Surface placed 1972 120#/SY Surface placed 1960 "AKG" Treatment placed 1960 Sand-Clay-Shell Base
10.	US78	E	61.9-66.5	150#/SY 416 Mix placed 12/83 100#/SY 416 Mix placed 1977 4 layers (7") Asphalt Concrete
11.	US78	E	77.8-82.7	100#/SY 328 Mix placed 12/74 300#/SY 327 Mix placed 12/74 100#/SY 411 Mix placed 1966 "F" Treatment placed 1966 2 layers (5") Asphalt Concrete Cushed Stone Base
12.	SR157	S	494.9-500.0	100#/SY 416 Mix placed 11/85 325#/SY 414 Mix placed 11/85 "G" Treatment placed 11/85 Crushed Stone Base
13.	US72	E	128.5-133.2	100#/SY Surface placed 11/76 300#/SY Binder placed 11/76 490#/SY Black Base placed 11/76 Crushed Aggregate Base

TABLE 4. TEST SITE RUTTING ANALYSIS DATA.

Site	18kip ESAL	Rut Depth Test• Site (in)	Rut Depth 1988+ DB (in)	RD/ESAL Test Site (in)	RD/ESAL 1988 DB (in)	RD/√ESAL Test Site (in)
1*	$6.6x10^6$	0.48	0.38	$0.73x10^{-7}$	$0.58x10^{-7}$	$18.7x10^{-5}$
2	$2.6x10^6$	0.45	0.30	$1.73x10^{-7}$	$1.15x10^{-7}$	$27.9x10^{-5}$
3	$2.9x10^6$	0.47	0.41	$1.62x10^{-7}$	$1.41x10^{-7}$	$27.6x10^{-5}$
4*	$4.3x10^6$	0.30	0.20	$0.70x10^{-7}$	$0.47x10^{-7}$	$14.5x10^{-5}$
5	$2.0x10^6$	1.09	0.35	$5.45x10^{-7}$	$1.75x10^{-7}$	$77.1x10^{-5}$
6	$3.7x10^6$	0.84	0.43	$2.27x10^{-7}$	$1.16x10^{-7}$	$43.7x10^{-5}$
7*	$3.6x10^6$	0.22	0.13	$0.61x10^{-7}$	$0.36x10^{-7}$	$11.6x10^{-5}$
8	$0.5x10^6$	0.56	0.20	$11.20x10^{-7}$	$4.00x10^{-7}$	$79.2x10^{-5}$
9	$1.6x10^6$	0.66	0.39	$4.12x10^{-7}$	$2.44x10^{-7}$	$52.2x10^{-5}$
10	$2.0x10^6$	0.53	0.28	$2.65x10^{-7}$	$1.40x10^{-7}$	$37.5x10^{-5}$
11*	$5.9x10^6$	0.35	0.18	$0.59x10^{-7}$	$0.30x10^{-7}$	$14.4x10^{-5}$
12	$0.3x10^6$	0.14	0.02	$4.67x10^{-7}$	$0.67x10^{-7}$	$25.6x10^{-5}$
13*	$1.5x10^6$	0.26	0.16	$1.73x10^{-7}$	$1.07x10^{-7}$	$21.2x10^{-5}$

*Sites selected for good rutting performance.

•Rut depth measured with 12 foot straight edge across lane.

+Rut depth measured with 4 foot straight edge across wheel path. Average of 8 measurements per mile for entire design section in which test site located.

TABLE 5. TRAFFIC DATA FOR TEST SITES.

Site	Route	Direction	AADT	% Comm Vehicles	Date Built	Date Sampled	18Kip ESAL
1	I59	S	9152	42	5/75	11/88	6.6×10^6
2	I59	N	9672	41	10/83	11/88	2.6×10^6
3	I10	E	21084	21	1/84	3/89	2.9×10^6
4.	I10	E	21619	21	9/81	3/89	4.3×10^6
5.	I65	N	10721	26	8/83	3/89	2.0×10^6
6.	I85	S	19751	20	6/82	10/89	3.7×10^6
7.	I85	N	12810	22	10/79	10/89	3.6×10^6
8.	US280	W	6592	14	5/85	10/89	0.5×10^6
9.	US231	S	12151	16	2/83	10/89	1.6×10^6
10.	US78	E	20444	13	12/83	11/89	2.0×10^6
11.	US78	E	19198	16	12/74	12/89	5.9×10^6
12.	SR157	S	2310	25	11/85	12/89	0.3×10^6
13.	US72	E	5961	15	11/76	12/89	1.5×10^6

Notes:
1. 1986 traffic data used with no growth factors applied.
2. Age is difference between date sampled and date placed.
3. Traffic distribution for 4 lanes is 85% outer lane and 15% inner lane (Ref. 8).
4. Truck distribution factor of 0.82 used to convert traffic to 18 kip ESAL's (Ref. 8)

TABLE 6. PROPERTIES OF IN-PLACE ASPHALT MIXTURES

Site	Layer	Thickness (in)	Asphalt Content (%)	Average Voids (%)	80th Percentile Voids (%)	Resilient Modulus at 104° (ksi)	Confined Creep Strain (140°F)
1	1	0.91	6.2	5.3	4.5	158	0.016
	2	2.73	3.9	4.4	3.6	145	0.009
2	1	1.18	6.6	4.2	2.8	---	**
	2	0.91	5.7	7.0	5.7	---	0.028
	3	1.91	5.4	5.9	5.1	200	0.011
3	1	1.14	6.0	2.7	2.0	---	0.031
	2	2.73	4.8	4.4	3.4	99	0.016
4	2*	0.82	5.7	4.7	3.7	---	0.019
	3	2.73	4.5	3.8	2.8	119	0.010
5	1	1.14	5.9	2.3	1.2	67	**
	2	1.82	5.6	4.7	2.7	137	0.015
	3	1.04	5.0	4.0	2.9	155	0.022
6	1	1.14	6.3	2.1	1.1	57	**
	2	0.91	5.5	6.6	5.8	---	**
	3	1.95	4.2	4.3	3.5	61	0.011
7	1	0.82	5.5	4.7	3.4	---	**
	2	0.91	4.7	9.7	8.4	174	**
	3	1.36	4.2	5.1	3.9	113	**
8	1	1.14	7.8	0.6	0.0	59	**
	2	2.73	4.4	7.6	6.2	144	0.018
9	1	1.54	5.8	4.6	2.9	70	**
	2	2.09	5.9	6.3	5.0	---	**
10	1	1.36	5.4	5.4	4.0	203	0.039
	2	0.91	5.6	2.4	1.6	148	0.026
11	1	0.91	8.2	9.4	8.1	126	0.033
	2	2.73	4.4	7.9	6.8	129	0.014
12	1	0.91	5.4	7.4	6.6	124	0.019
	2	2.95	3.6	11.4	9.8	313	0.021
13	1	0.91	6.4	4.3	3.0	---	0.015
	2	2.73	4.3	4.8	3.9	210	0.017

*Layer 1 was friction course.
**Sample failed during test.
Resilient modulus tests could not be performed on samples from some layers.

TABLE 7. PROPERTIES OF RECOMPACTED ASPHALT MIXTURES

Site	Layer	75 Blow Voids (%)	75 Blow Stability (lbs)	75 Blow Flow (0.01 in)	GTM Voids (%)	GTM Stability (lbs)	GTM Flow (0.01 in)	GSI	Roller Pressure (psi)
1	1	5.7	7400	15	5.5	5300	12	1.00	18
	2	4.5	6000	13	4.6	5100	12	1.00	20
2	1	1.0	3100	21	1.1	2900	19	1.37	17
	2	3.6	6000	16	5.6	4400	15	1.00	11
	3	5.5	5000	13	5.3	3700	13	0.95	16
3	1	2.2	3300	16	2.4	2600	12	1.03	14
	2	4.0	4400	12	3.8	3300	12	0.97	16
4	2*	—	—	—	4.4	2500	—	1.00	15
	3	3.2	4000	13	2.9	3100	11	1.00	15
5	1	1.5	2000	20	1.6	1800	18	1.39	11
	2	3.6	5000	13	3.7	4200	13	1.01	12
	3	4.2	4800	11	3.7	4000	11	1.00	12
6	1	0.0	2100	21	0.0	1900	21	1.60	6
	2	—	—	—	5.9	4100	13	1.00	16
	3	4.8	4600	10	5.2	3000	10	1.00	16
7	1	1.4	6400	20	2.4	5000	20	1.30	13
	2	7.2	8000	16	8.9	5200	16	1.00	17
	3	1.6	5800	18	2.1	4600	15	1.10	12
8	1	1.0	2700	28	1.4	2300	24	1.80	9
	2	2.4	5000	17	2.8	4600	17	1.20	15
9	1	3.3	3300	11	2.7	2700	10	1.00	14
	2	4.1	2600	10	3.5	2000	10	1.00	16
10	1	3.0	5600	13	3.5	4100	13	1.00	14
	2	1.2	2600	25	0.8	2100	25	1.70	6
11	1	6.8	5500	14	8.1	4000	16	1.00	15
	2	3.8	5500	16	3.3	4200	14	1.04	14
12	1	4.2	6300	12	5.1	4300	12	1.00	16
	2	6.5	5700	12	6.5	4700	16	1.00	18
13	1	2.6	7100	16	4.5	4600	16	1.01	14
	2	3.1	3900	19	2.5	3300	19	1.11	12

*Layer 1 was friction course.

TABLE 8. PROPERTIES OF ASPHALT RECOVERED FROM ASPHALT MIXTURES

Site	Layer	Penetration (77°F,100g,5S)	Penetration (40°F,200g,60S)	Penetration (40°F,100g,5S)	Viscosity 140°F(P)	Viscosity 275°F(Cst)
1	1	21	11	3	50,112	1524
	2	33	15	4	11,391	910
2	1	23	13	4	140,327	2074
	2	21	14	5	31,349	856
	3	30	16	6	35,411	1568
3	1	74	47	14	2,734	493
	2	53	33	9	4,543	570
4	*2	48	36	13	6,187	670
	3	40	26	10	11,554	830
5	1	40	25	9	7,746	777
	2	15	10	5	399,381	2676
	3	19	11	4	53,440	2229
6	1	50	30	10	5,916	651
	2	14	9	3	177,240	2509
	3	28	15	5	21,210	861
7	1	13	7	3	96,973	2140
	2	20	14	4	69,671	3200
	3	27	15	5	21,092	861
8	1	63	39	13	3,892	542
	2	56	32	10	3,835	560
9	1	30	19	7	38,506	1161
	2	26	19	10	50,282	1305
10	1	18	10	2	65,940	1550
	2	55	23	8	3,318	539
11	1	16	13	5	153,205	1909
	2	28	18	6	27,023	1201
12	1	21	18	6	57,638	1369
	2	31	23	8	27,368	1021
13	1	19	5	5	218,330	2204
	2	48	30	10	7,424	639

*Layer 1 was a friction course

TABLE 9. PROPERTIES OF AGGREGATE RECOVERED FROM ASPHALT MIXTURES.

Site	Layer	NAA** Voids (%)	Flow** Time (Sec)	Fractures Faces on Plus No. 8 Material (%)			Percent Passing Sieve Size (%)		
				0	1	2 or more	3/8 in.	No. 50	No. 200
1	1	44.3	20.6	1.6	0	98.4	94	26	7.6
	2	40.5	18.8	27.1	1.4	71.5	70	17	4.9
2	1	41.8	20.5	3.1	3.5	93.4	84	23	6.1
	2	41.6	19.2	0.4	0.9	98.7	95	18	5.2
	3	40.8	18.7	32.5	3.0	64.5	72	17	3.5
3	1	42.4	20.5	11.6	8.4	80.0	91	21	5.3
	2	42.3	19.9	38.1	8.1	53.7	67	20	5.2
4	2*	42.0	19.6	2.3	1.5	96.2	90	28	6.2
	3	43.2	19.1	39.8	6.8	53.4	68	25	6.7
5	1	41.9	20.1	8.4	10.6	81.0	71	21	7.2
	2	41.6	19.2	19.6	0.0	80.4	92	26	7.8
	3	41.6	19.5	8.6	0.8	90.6	85	21	5.3
6	1	42.6	21.3	31.0	11.1	57.9	90	18	8.1
	2	42.5	20.9	17.1	0.2	82.7	94	12	4.2
	3	43.1	21.1	68.9	9.5	21.5	68	10	2.6
7	1	43.7	22.6	0.0	0.0	100.0	86	18	7.0
	2	43.4	21.4	2.1	0.0	97.9	95	15	4.7
	3	44.6	21.1	4.0	0.4	95.5	77	18	7.8
8	1	45.9	23.9	1.9	0.0	98.1	92	24	9.1
	2	45.0	21.1	0.0	0.0	100.0	77	22	7.9
9	1	44.4	20.7	30.8	11.4	57.8	91	26	5.7
	2	43.3	19.8	74.8	10.6	14.6	93	33	6.6
10	1	41.6	19.5	47.3	7.0	45.6	92	24	8.1
	2	42.6	20.7	36.4	0.0	63.6	93	22	10.7
11	1	45.2	24.3	10.0	0.0	90.0	97	17	8.1
	2	46.1	23.1	0.0	0.0	100.0	81	16	9.6
12	1	40.8	19.7	32.6	6.9	60.5	90	19	5.8
	2	45.2	26.7	0.0	0.0	100.0	74	14	7.7
13	1	43.6	21.8	41.8	2.1	56.1	94	19	6.0
	2	45.0	24.3	0.0	0.0	79.7	63	12	6.7

*Layer 1 was a friction course.
**Minus No. 8 material.

TABLE 10. CORRELATION COEFFICIENTS BETWEEN RUT DEPTH/√ESAL AND VARIOUS AGGREGATE, ASPHALT AND MIX PROPERTIES.

Property	Correlation Coefficient
Thickness, inches	0.59
Voids (In-Place), %	-0.66
Resilient Modulus, psi	-0.65
Recompacted Voids (Hand), %	-0.47
Recompacted Voids (Gyratory), %	-0.57
Marshall Stability, lbs	-0.74
Gyratory Stability, lbs	-0.66
Marshall Flow, .01 inches	0.66
Gyratory Flow, .01 inches	0.41
GSI	0.64
Gyratory Roller Pressure, psi	-0.61
Passing 3/8 inch, %	-0.47
Passing No. 50, %	0.17
Passing No. 200, %	0.37
Fractured Faces, %	-0.13
NAA Voids, %	0.15
Flow Time, sec	0.05
Asphalt Penetration (77°F)	0.46
Asphalt Viscosity (140°F)	-0.50

TABLE 11. AVERAGE AGGREGATE PROPERTIES FOR DIVISIONS 1-4 AND DIVISIONS 5-9.

Aggregate Property	Divisions 1-4 Sites 7,8 & 10-13	Divisions 5-9 Sites 1-6 & 9
Fine Aggregate (-#8)		
NAA Voids	44.1%	42.3%
Flow Time	22.3 sec.	20.0 sec.
Coarse Aggregate (+#8)		
Two or More Crushed Faces		
Surface Mixes	78.6%	77.7%
Binder Mixes	100.0%	52.9%
Combined Mixes	85.2%	70.4%
Coarse Aggregate (+#4)		
Two or More Crushed Faces		
Surface Mixes	87.4%	82.7%
Binder Mixes	100.0%	52.7%
Combined Mixes	91.3%	73.9%

FIGURES

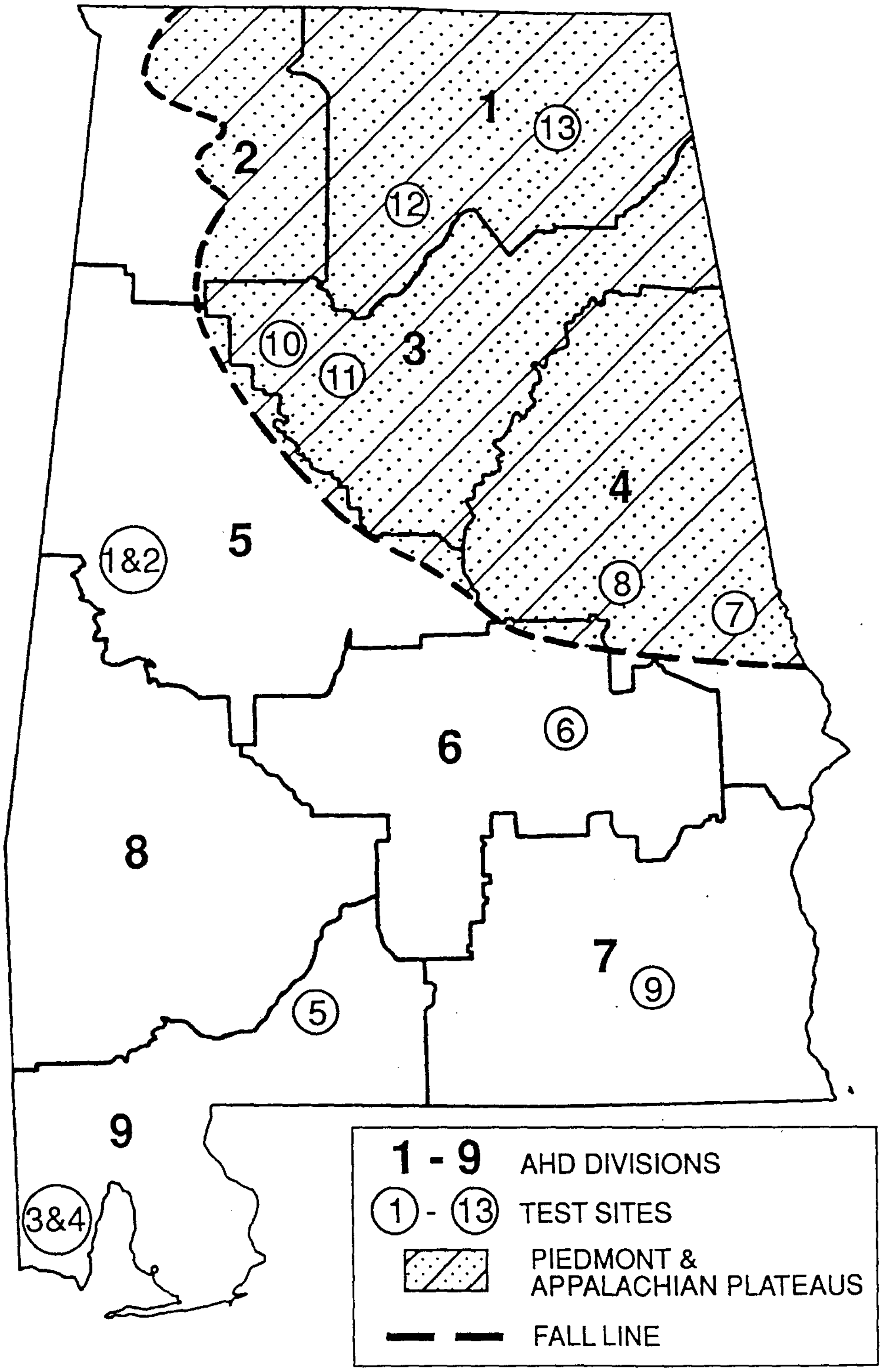


FIGURE 1. LOCATION OF FIELD TEST SITES.

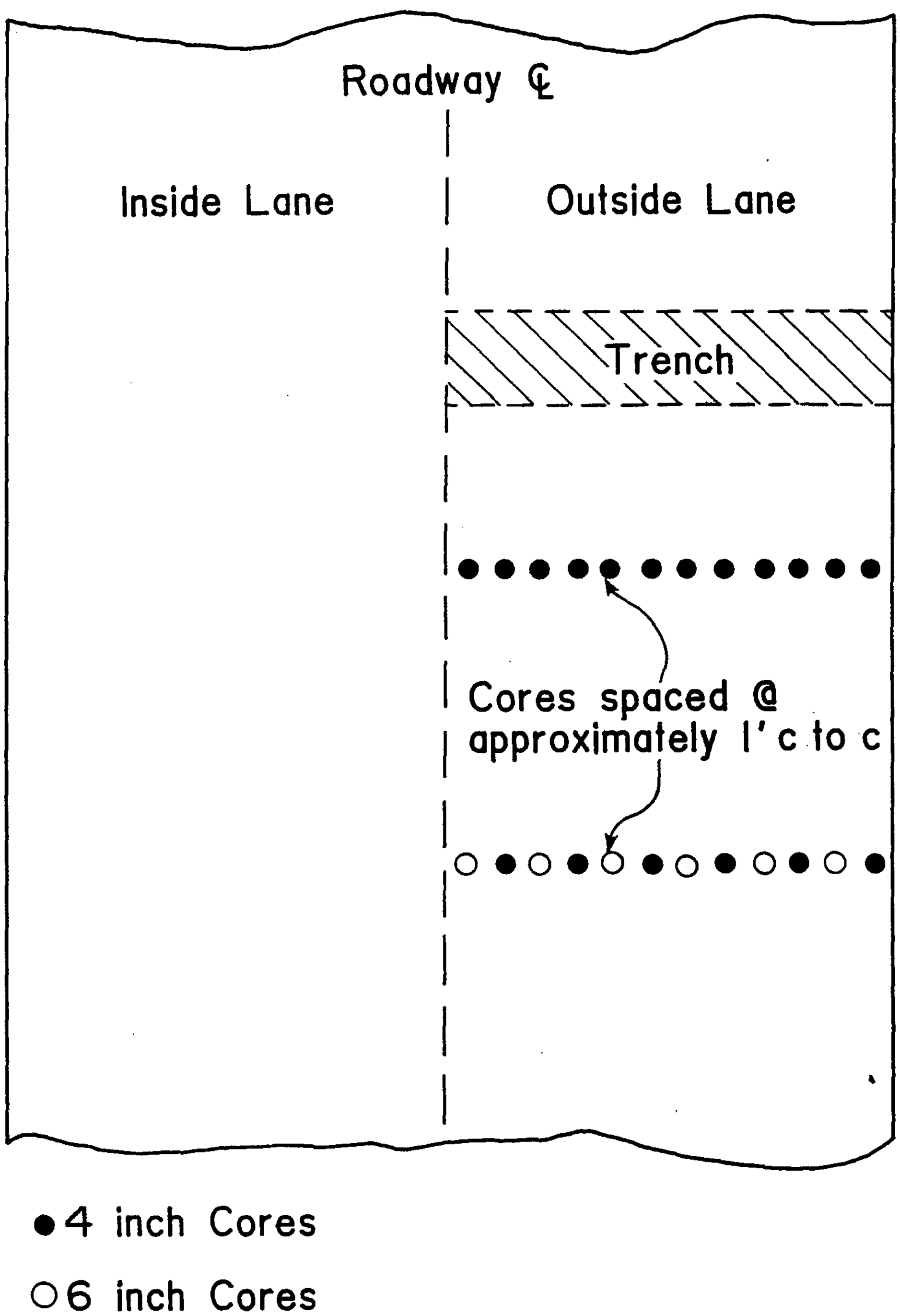
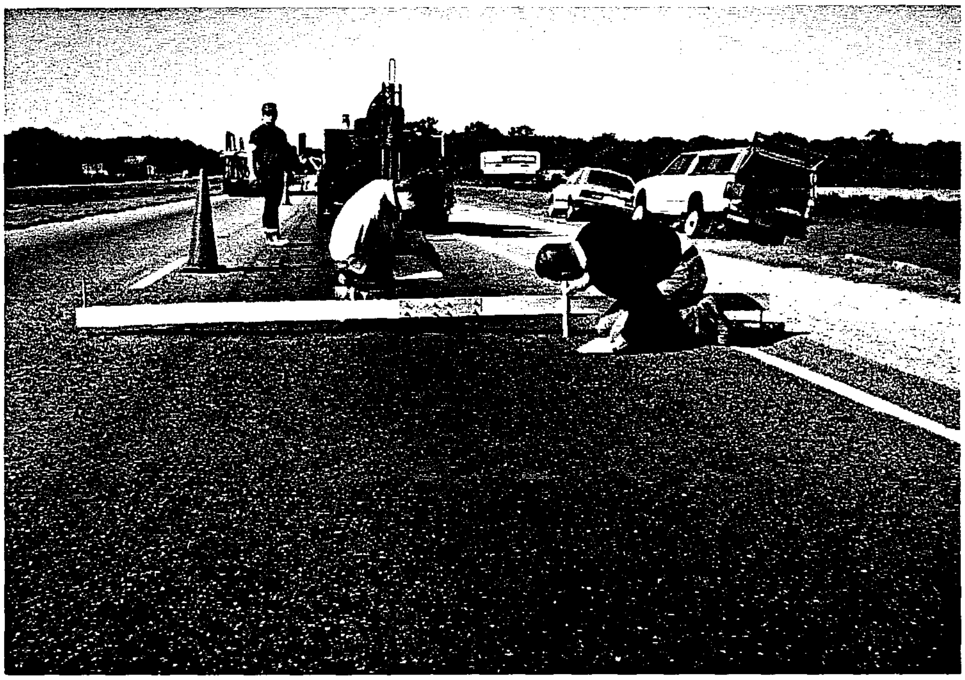
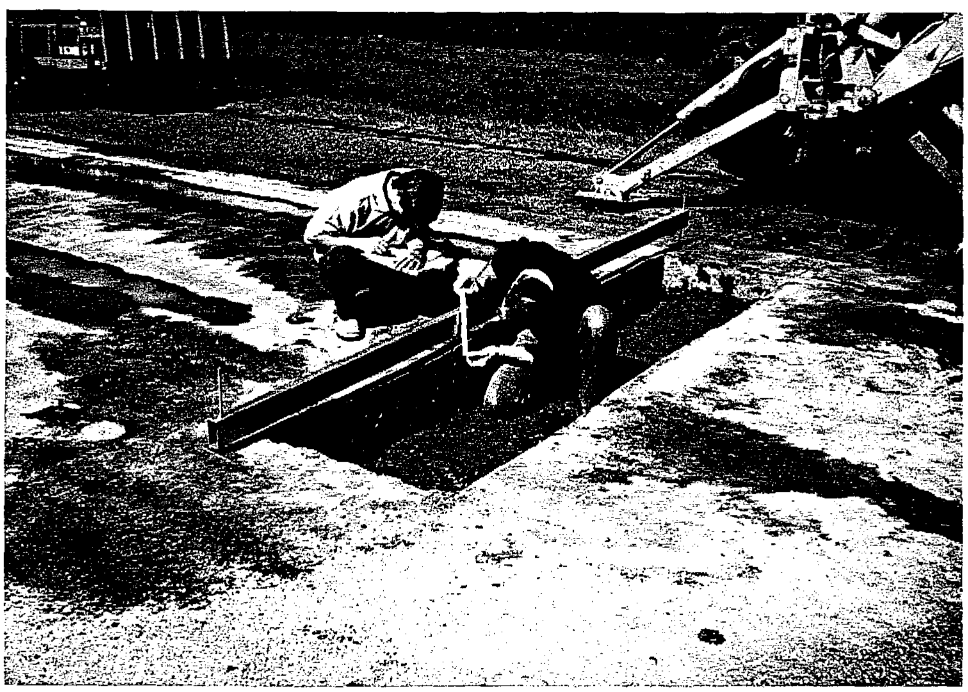


FIGURE 2. TYPICAL SITE SAMPLING AND EVALUATION LAYOUT.



a. Measurement of Pavement Surface Profile



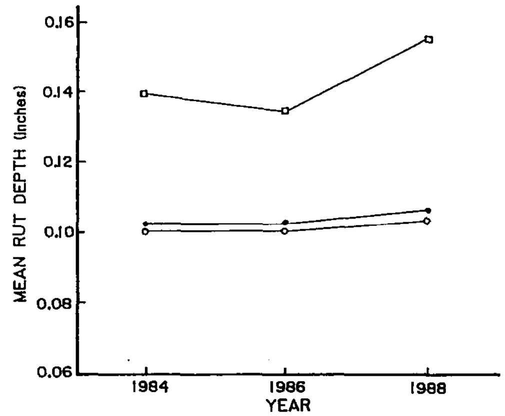
b. Measurement to Layer Interface.

FIGURE 3. LAYER PROFILE DEVELOPMENT.

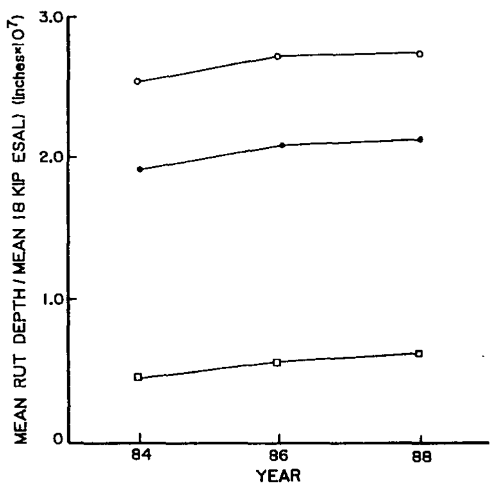
c. Measurement to Layer Interface.

d. Layer Thicknesses From Cores.

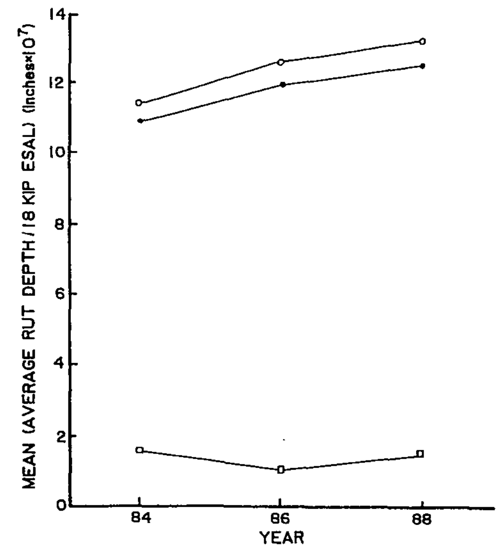
FIGURE 3. LAYER PROFILE DEVELOPMENT.
(continued)



a. Mean Rut Depth



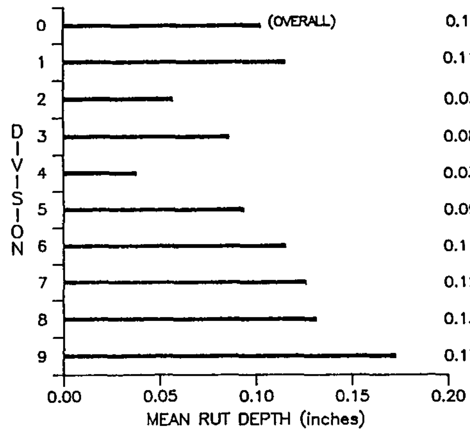
b. Mean Rut Depth / Mean ESAL



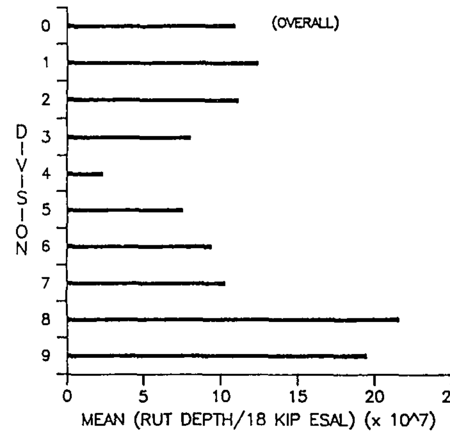
c. Mean (Rut Depth / ESAL)

○ State
□ Interstate
● Combined

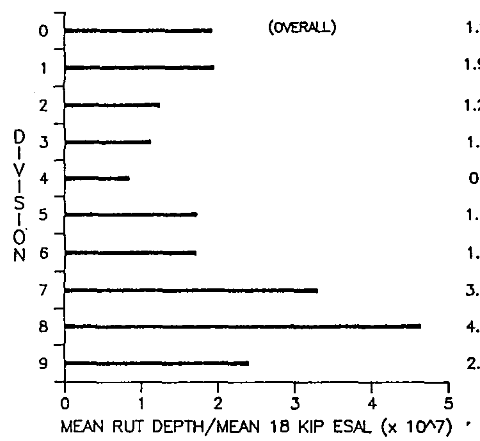
FIGURE 4. COMBINED DATA FROM PAVEMENT CONDITION DATABASES.



VALUE	FREQUENCY	PERCENT
0.10258	22,683	100
0.11511	2411	10.6
0.05670	1964	8.7
0.08570	2746	12.1
0.03769	2727	12.0
0.09344	2861	12.6
0.11522	2443	10.8
0.12574	3184	14.0
0.13106	2394	10.6
0.17250	1953	8.6



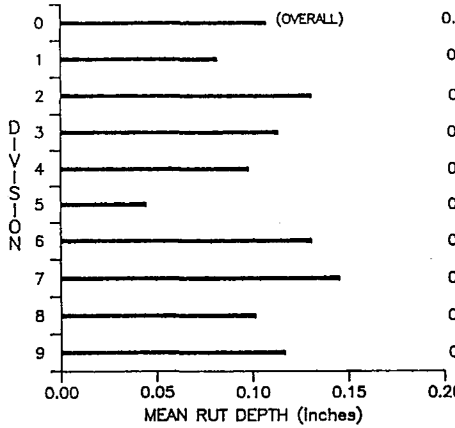
VALUE (x 10^7)	FREQUENCY	PERCENT
10.918	22414	100
12.424	2400	10.7
11.190	1956	8.7
8.085	2646	11.8
2.342	2705	12.1
7.560	2825	12.6
9.434	2437	10.9
10.272	3148	14.4
21.552	2374	10.6
19.462	1923	8.6



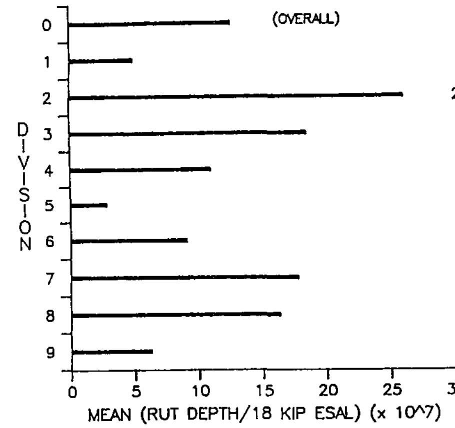
VALUE (x 10^7)	FREQUENCY	PERCENT
1.919	22414	100
1.941	2400	10.7
1.239	1956	8.7
1.122	2646	11.8
0.843	2705	12.1
1.723	2825	12.6
1.709	2437	10.9
3.291	3148	14.0
4.632	2374	10.6
2.395	1923	8.6

1984 DATA
STATE AND INTERSTATE
OUTER LANES

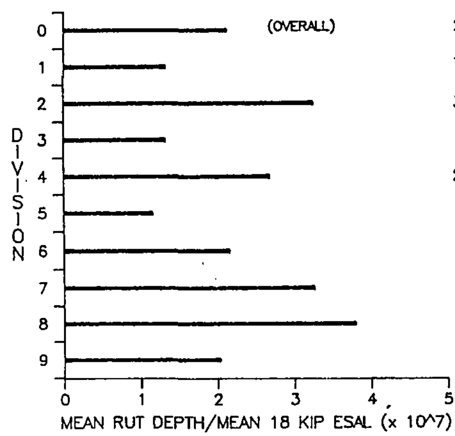
FIGURE 5. RUTTING AND RATE OF RUTTING WITH AHD DIVISION, 1984 STATE AND INTERSTATE DATA.



VALUE	FREQUENCY	PERCENT
0.10694	21,444	100
0.08146	2355	11.0
0.13043	1861	8.7
0.11314	2680	12.5
0.09787	2613	12.2
0.04431	2433	11.3
0.13050	2258	10.5
0.14509	3073	14.3
0.10126	2285	10.7
0.11663	1886	8.8



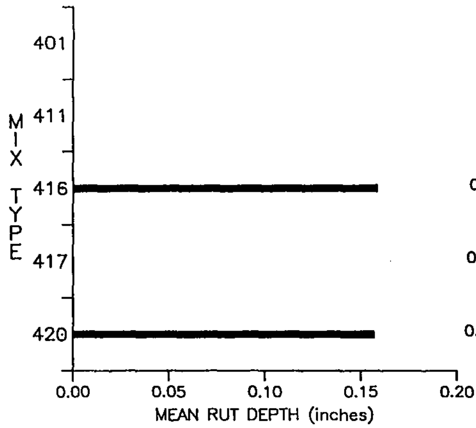
VALUE (x 10^7)	FREQUENCY	PERCENT
12.564	21444	100
4.901	2355	11.0
26.030	1861	8.7
18.467	2680	12.5
10.981	2613	12.2
2.825	2433	11.3
9.072	2258	10.5
17.790	3073	14.3
16.362	2285	10.7
6.279	1886	8.8



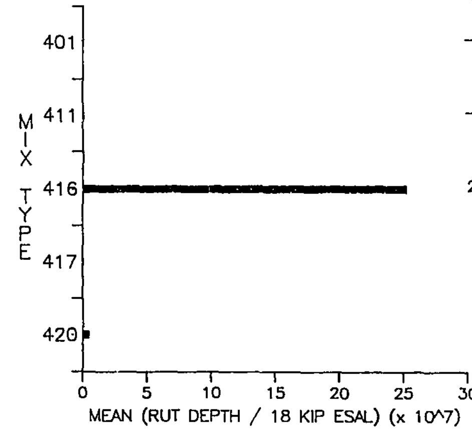
VALUE (x 10^7)	FREQUENCY	PERCENT
2.123	21444	100
1.323	2355	11.0
3.251	1861	8.7
1.323	2680	12.5
2.682	2613	12.2
1.155	2433	11.3
2.157	2258	10.5
3.259	3073	14.3
3.794	2285	10.7
2.033	1886	8.8

1988 DATA
STATE AND INTERSTATE
OUTER LANES

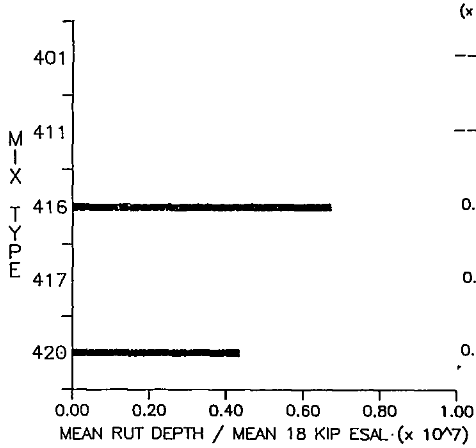
FIGURE 6. RUTTING AND RATE OF RUTTING WITH AHD DIVISION, 1988 STATE AND INTERSTATE DATA.



VALUE	FREQUENCY	PERCENT
---	---	---
---	---	---
0.15840	987	83
0.00000	22	1.9
0.15689	185	15.6



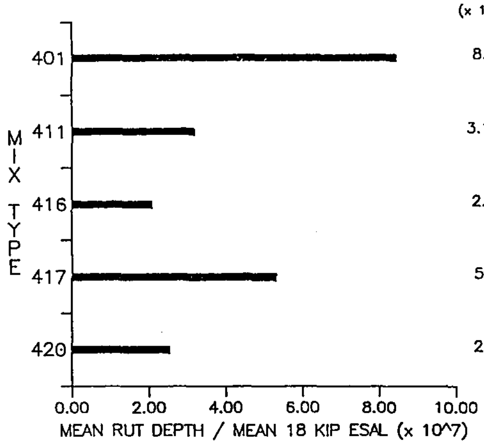
VALUE (x 10^7)	FREQUENCY	PERCENT
----	----	----
----	----	----
25.196	987	83.0
0.000	22	1.9
0.436	185	15.6



VALUE (x 10^7)	FREQUENCY	PERCENT
----	----	----
----	----	----
0.672	987	83.0
0.000	22	1.9
0.434	185	15.6

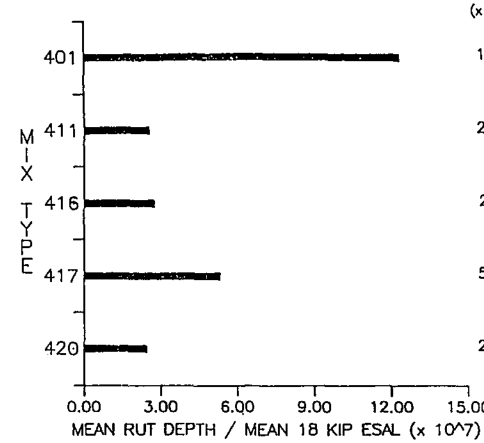
1988 DATA
INTERSTATE
OUTER LANES

FIGURE 7. RUTTING AND RATE OF RUTTING WITH MIX TYPE, 1988 INTERSTATE DATA.



VALUE (x 10^7)	FREQUENCY	PERCENT
8.422	1210	6.0
3.168	10941	54.4
2.068	6014	29.9
5.304	10	0.05
2.529	487	2.4

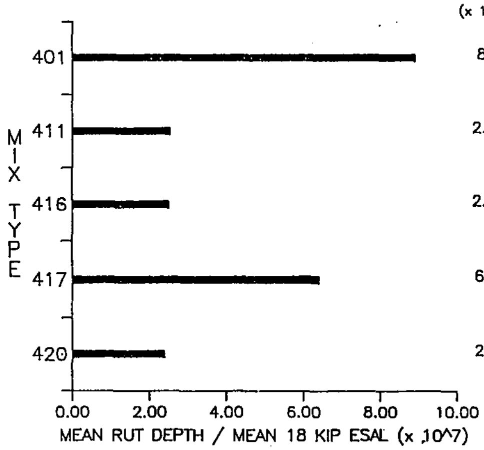
1984 DATA



VALUE (x 10^7)	FREQUENCY	PERCENT
12.288	876	4.3
2.503	6605	32.4
2.716	11664	57.3
5.295	747	3.7
2.439	271	1.3

1988 DATA

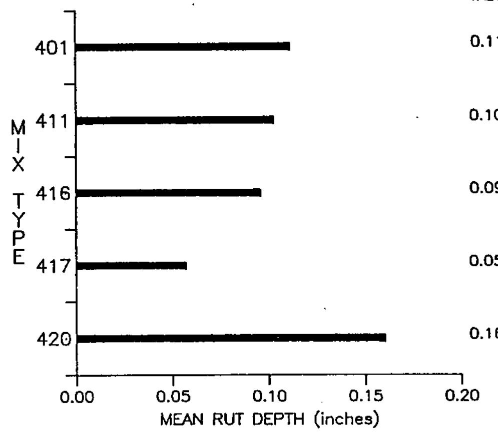
STATE
OUTER LANES



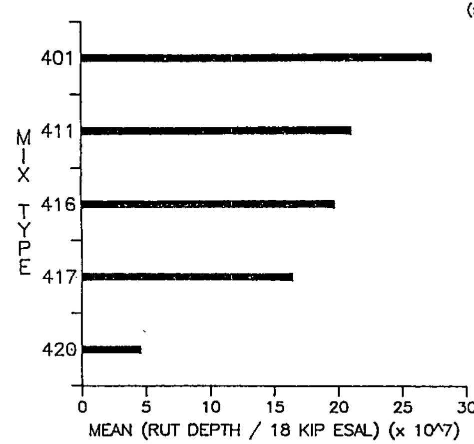
VALUE (x 10^7)	FREQUENCY	PERCENT
8.908	1112	5.3
2.542	7921	37.7
2.501	8824	42.0
6.401	163	0.8
2.385	336	1.6

1986 DATA

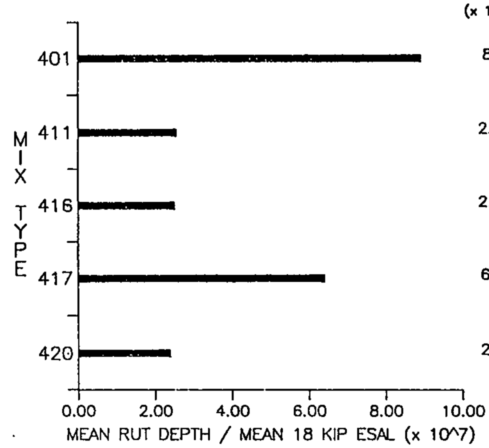
FIGURE 8. RATE OF RUTTING WITH MIX TYPE 1984, 1986, 1988 STATE ROUTE DATA.



VALUE	FREQUENCY	PERCENT
0.11132	1178	5.6
0.10276	9514	45.3
0.09569	9603	45.8
0.05688	179	0.9
0.16030	410	2.0

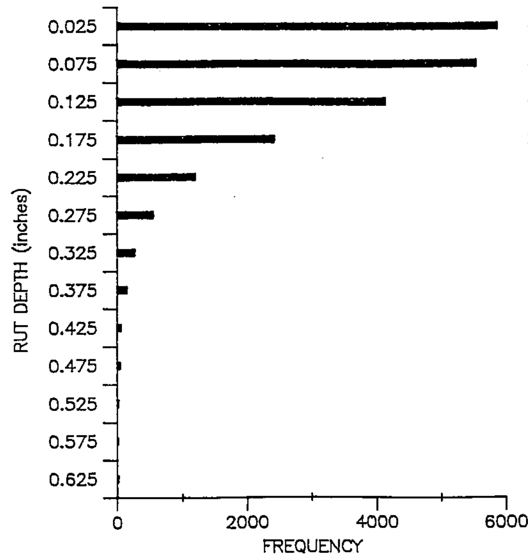


VALUE (x 10^7)	FREQUENCY	PERCENT
27.318	1112	5.3
21.025	7868	37.5
19.719	8717	41.5
16.453	163	0.8
4.546	322	1.5



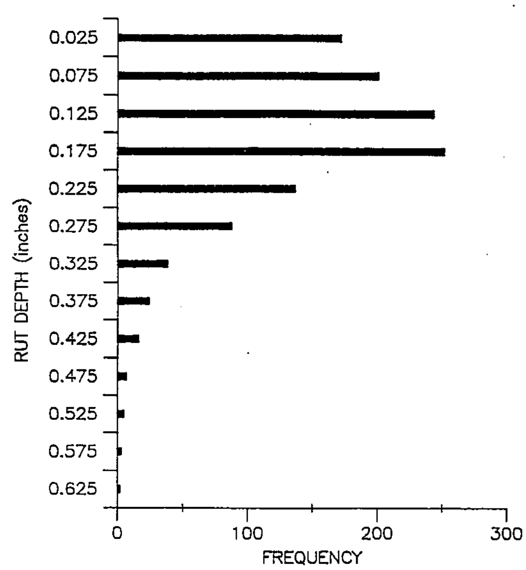
VALUE (x 10^7)	FREQUENCY	PERCENT
8.908	1112	5.3
2.542	7921	37.7
2.501	8824	42.0
6.401	163	0.8
2.385	336	1.6

FIGURE 9. RUTTING AND RATE OF RUTTING WITH MIX TYPE, 1986 STATE ROUTE DATA.



FREQ	CUM. FREQ	PERCENT	CUM. PERCENT
5852	5852	28.88	28.88
5532	11384	27.31	56.19
4123	15507	20.35	76.54
2414	17921	11.92	88.46
1203	19124	5.94	94.39
553	19677	2.73	97.12
269	19946	1.33	98.45
152	20098	0.75	99.20
62	20160	0.31	99.51
47	20207	0.23	99.74
20	20227	0.10	99.84
16	20243	0.08	99.92
17	20260	0.08	100.00

1988 DATA
STATE ROUTES
OUTER LANES

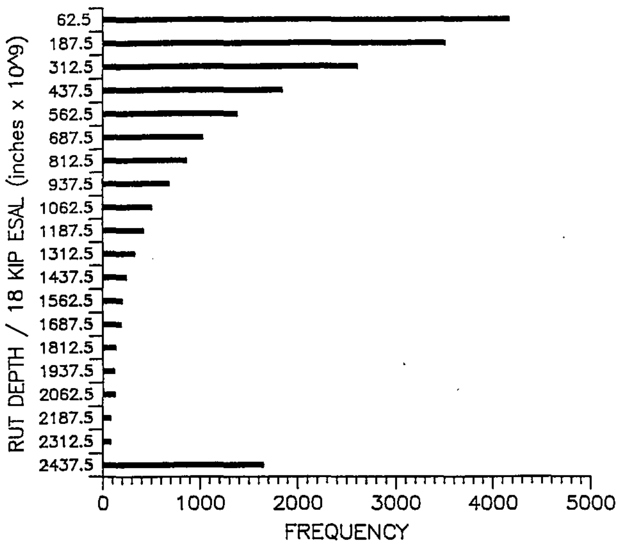


FREQ	CUM. FREQ	PERCENT	CUM. PERCENT
172	172	14.47	14.47
201	373	16.90	31.37
244	617	20.52	51.89
252	869	21.19	73.09
137	1006	11.52	84.61
88	1094	7.40	92.01
38	1132	3.20	95.21
24	1156	2.02	97.22
16	1172	1.35	98.57
7	1179	0.59	99.16
5	1184	0.42	99.58
3	1187	0.25	99.83
2	1189	0.17	100.00

1988 DATA
INTERSTATE ROUTES
OUTER LANES

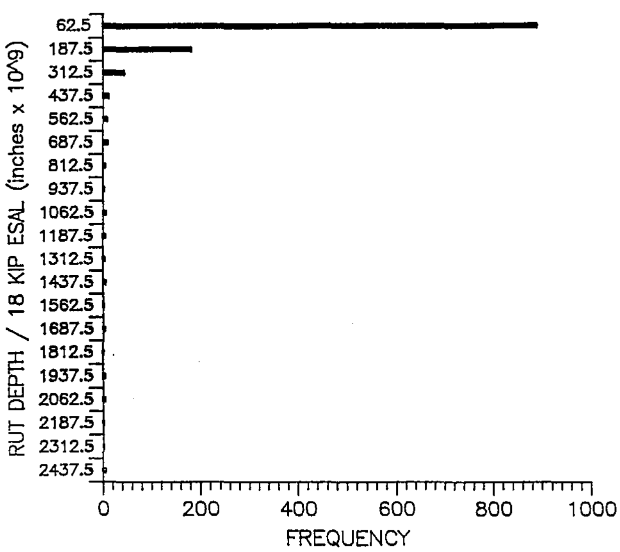
FIGURE 10. 1988 RUTTING FREQUENCY DISTRIBUTIONS.

FREQ	CUM. FREQ.	PERCENT	CUM. PERCENT
4166	4166	20.71	20.71
3503	7669	17.42	38.13
2605	10274	12.95	51.08
1841	12115	9.15	60.24
1377	13492	6.85	67.08
1026	14518	5.10	72.19
860	15378	4.28	76.46
684	16062	3.40	79.86
503	16565	2.50	82.36
419	16984	2.08	84.45
325	17309	1.62	86.06
239	17548	1.19	87.25
200	17748	0.99	88.25
189	17937	0.94	89.19
132	18069	0.66	89.84
113	18182	0.56	90.40
123	18305	0.61	91.02
82	18387	0.41	91.42
78	18465	0.39	91.81
1647	20112	8.19	100.00



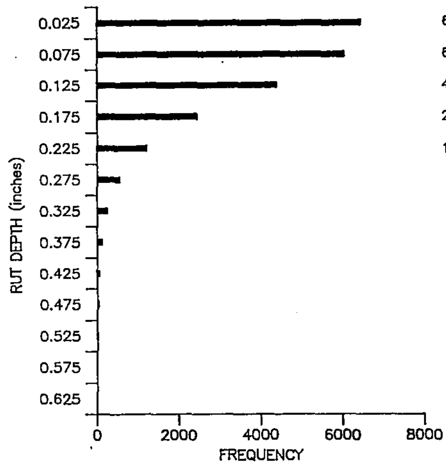
1988 DATA
STATE ROUTES
OUTER LANES

FREQ	CUM. FREQ.	PERCENT	CUM. PERCENT
890	890	74.85	74.85
182	1072	15.31	90.16
44	1116	3.70	93.86
11	1127	0.93	94.79
8	1135	0.67	95.46
10	1145	0.84	96.30
4	1149	0.34	96.64
2	1151	0.17	96.80
5	1156	0.42	97.22
5	1161	0.42	97.65
3	1164	0.25	97.90
5	1169	0.42	98.32
1	1170	0.08	98.40
3	1173	0.25	98.65
1	1174	0.08	98.74
4	1178	0.34	99.07
4	1182	0.34	99.41
1	1183	0.08	99.50
1	1184	0.08	99.58
5	1189	0.42	100.00



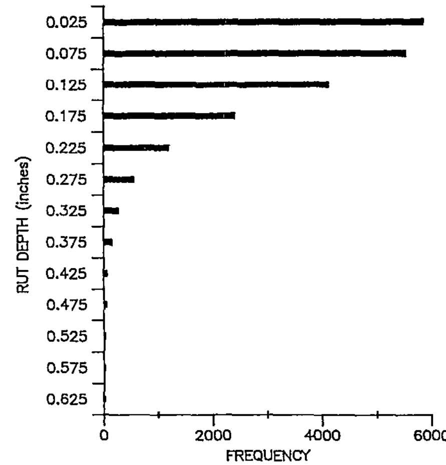
1988 DATA
INTERSTATE ROUTES
OUTER LANES

FIGURE 11. 1988 RATE OF RUTTING FREQUENCY DISTRIBUTIONS.



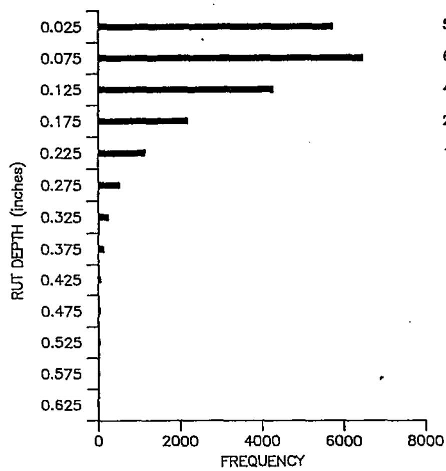
RUT DEPTH	FREQ	CUM. FREQ	PERCENT	CUM. PERCENT
0.025	6442	6442	29.96	29.96
0.075	6038	12480	28.08	58.04
0.125	4289	16769	19.95	77.98
0.175	2450	19219	11.39	89.38
0.225	1212	20431	5.64	95.01
0.275	553	20984	2.57	97.59
0.325	255	21239	1.19	98.77
0.375	130	21369	0.60	99.38
0.425	61	21430	0.28	99.66
0.475	36	21466	0.17	99.83
0.525	20	21486	0.09	99.92
0.575	8	21494	0.04	99.96
0.625	9	21503	0.04	100.00

1984 DATA



RUT DEPTH	FREQ	CUM. FREQ	PERCENT	CUM. PERCENT
0.025	5852	5852	28.88	28.88
0.075	5532	11384	27.31	56.19
0.125	4123	15507	20.35	76.54
0.175	2414	17921	11.92	88.46
0.225	1203	19124	5.94	94.39
0.275	553	19677	2.73	97.12
0.325	269	19946	1.33	98.45
0.375	152	20098	0.75	99.20
0.425	62	20160	0.31	99.51
0.475	47	20207	0.23	99.74
0.525	20	20227	0.10	99.84
0.575	16	20243	0.08	99.92
0.625	17	20260	0.08	100.00

1988 DATA

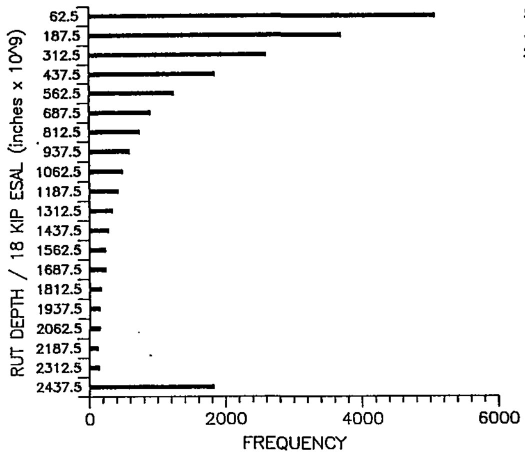


RUT DEPTH	FREQ	CUM. FREQ	PERCENT	CUM. PERCENT
0.025	5715	5715	27.47	27.47
0.075	6454	12169	31.03	58.50
0.125	4272	16441	20.54	79.04
0.175	2199	18640	10.57	89.61
0.225	1142	19782	5.49	95.10
0.275	518	20300	2.49	97.59
0.325	241	20541	1.16	98.75
0.375	130	20671	0.62	99.38
0.425	59	20730	0.28	99.66
0.475	32	20762	0.15	99.81
0.525	24	20786	0.12	99.93
0.575	10	20796	0.05	99.98
0.625	5	20801	0.02	100.00

1986 DATA

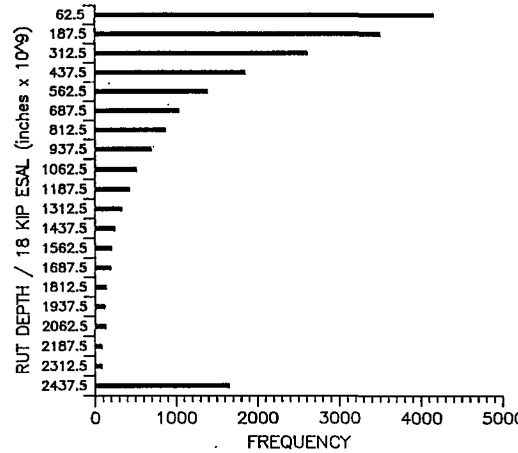
STATE ROUTES
OUTER LANES

FIGURE 12. RUT DEPTH FREQUENCY DISTRIBUTIONS.



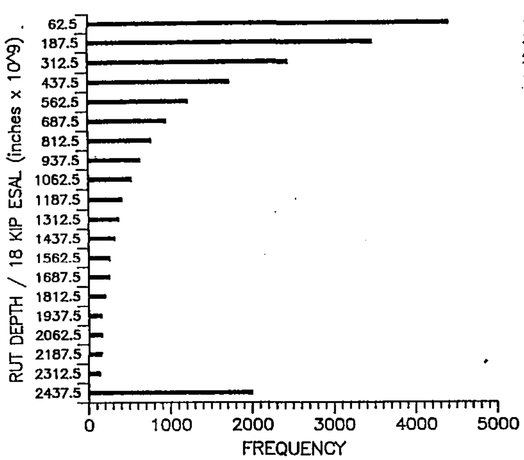
RUT DEPTH	FREQ	CUM. FREQ.	PERCENT	CUM. PERCENT
62.5	5078	5078	23.88	23.88
187.5	3699	8777	17.39	41.27
312.5	2598	11375	12.22	53.49
437.5	1847	13222	8.69	62.17
562.5	1245	14467	5.85	68.03
687.5	900	15367	4.23	72.26
812.5	740	16107	3.48	75.74
937.5	591	16698	2.78	78.52
1062.5	490	17188	2.30	80.82
1187.5	426	17614	2.00	82.83
1312.5	339	17953	1.59	84.42
1437.5	279	18232	1.31	85.73
1562.5	231	18463	1.09	86.82
1687.5	237	18700	1.11	87.93
1812.5	167	18867	0.79	88.72
1937.5	147	19014	0.69	89.41
2062.5	152	19166	0.71	90.13
2187.5	129	19295	0.61	90.73
2312.5	145	19440	0.68	91.41
2437.5	1826	21266	8.59	100.00

1984 DATA



RUT DEPTH	FREQ	CUM. FREQ.	PERCENT	CUM. PERCENT
62.5	4166	4166	20.71	20.71
187.5	3503	7669	17.42	38.13
312.5	2605	10274	12.95	51.08
437.5	1841	12115	9.15	60.24
562.5	1377	13492	6.85	67.08
687.5	1026	14518	5.10	72.19
812.5	860	15378	4.28	76.46
937.5	684	16062	3.40	79.86
1062.5	503	16565	2.50	82.36
1187.5	419	16984	2.08	84.45
1312.5	325	17309	1.62	86.06
1437.5	239	17548	1.19	87.25
1562.5	200	17748	0.99	88.25
1687.5	189	17937	0.94	89.19
1812.5	132	18069	0.66	89.84
1937.5	113	18182	0.56	90.40
2062.5	123	18305	0.61	91.02
2187.5	82	18387	0.41	91.42
2312.5	78	18465	0.39	91.81
2437.5	1647	20112	8.19	100.00

1988 DATA



RUT DEPTH	FREQ	CUM. FREQ.	PERCENT	CUM. PERCENT
62.5	4409	4409	21.40	21.40
187.5	3481	7890	16.89	38.29
312.5	2444	10334	11.86	50.15
437.5	1730	12064	8.40	58.54
562.5	1221	13285	5.93	64.47
687.5	958	14243	4.65	69.12
812.5	770	15013	3.74	72.85
937.5	634	15647	3.08	75.93
1062.5	529	16176	2.57	78.50
1187.5	413	16589	2.00	80.50
1312.5	370	16959	1.80	82.30
1437.5	322	17281	1.56	83.86
1562.5	259	17540	1.26	85.12
1687.5	260	17800	1.26	86.38
1812.5	204	18004	0.99	87.37
1937.5	154	18158	0.75	88.12
2062.5	161	18319	0.78	88.90
2187.5	153	18472	0.74	89.64
2312.5	137	18609	0.66	90.30
2437.5	1998	20607	9.70	100.00

1986 DATA

STATE ROUTES
OUTER LANES

FIGURE 13. RATE OF RUTTING FREQUENCY DISTRIBUTIONS.

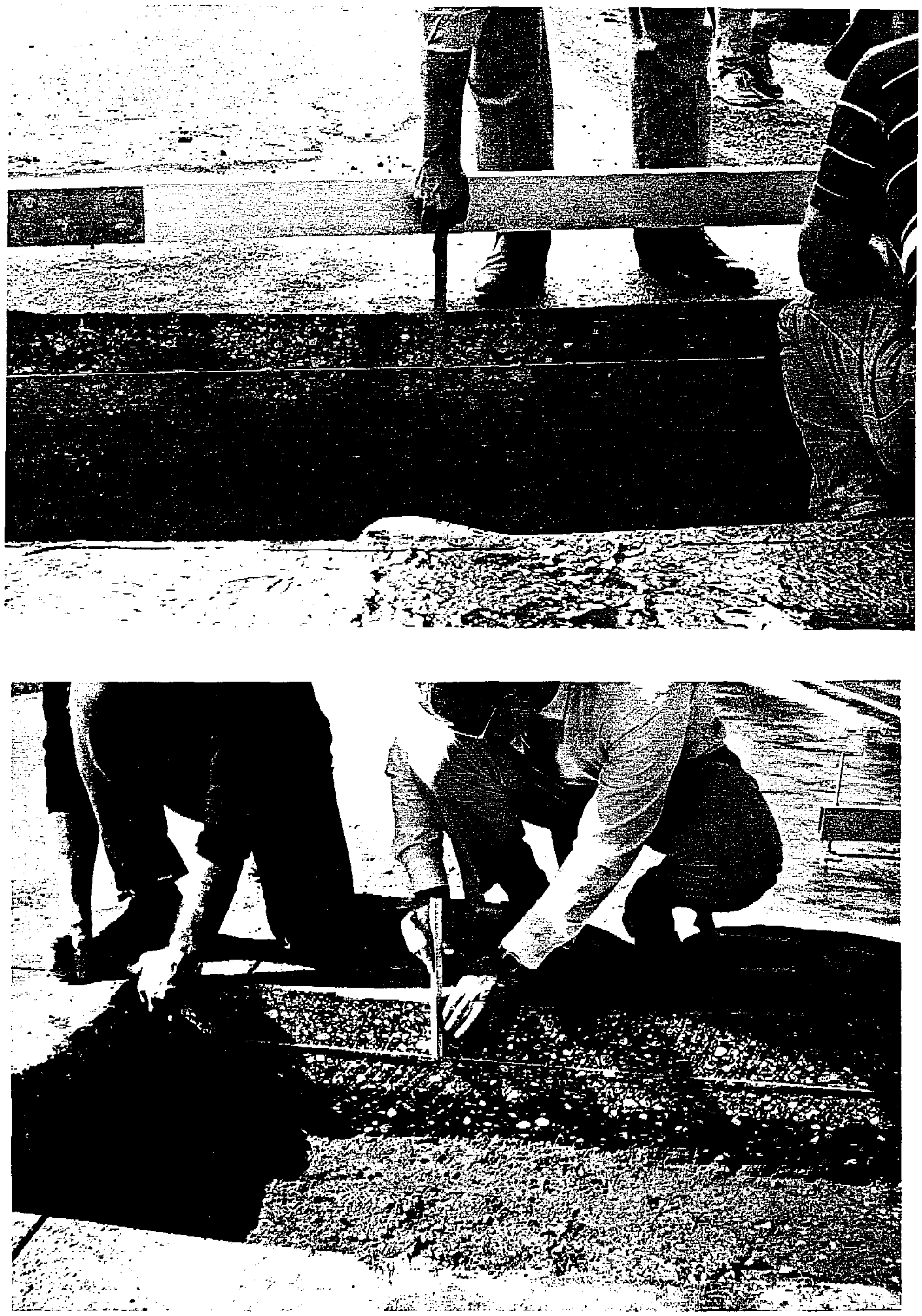


FIGURE 13. STRINGLINING LAYER INTERFACES TO DETECT PERMANENT DEFORMATION.

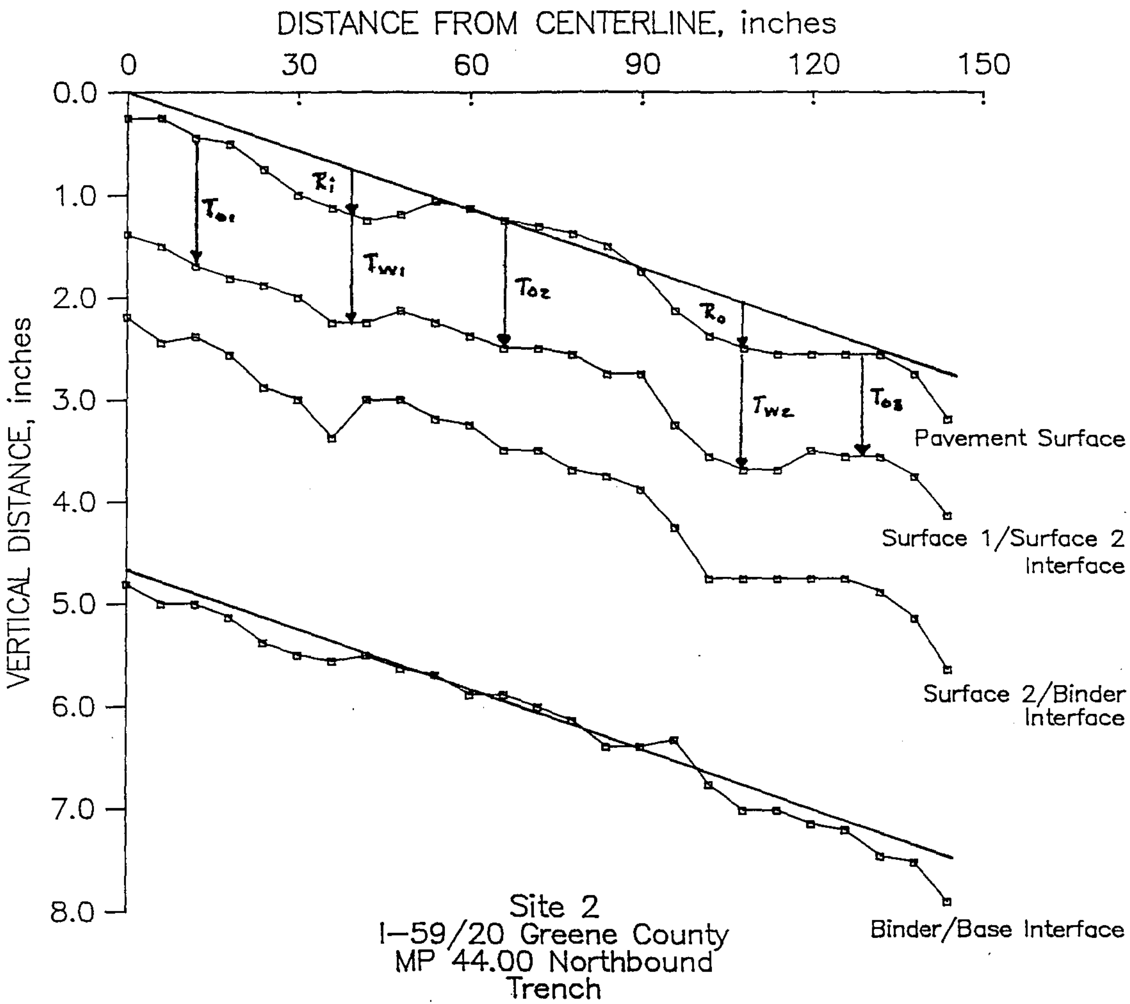


FIGURE 14. MEASUREMENT OF RUTTING AND LAYER COMPRESSION.

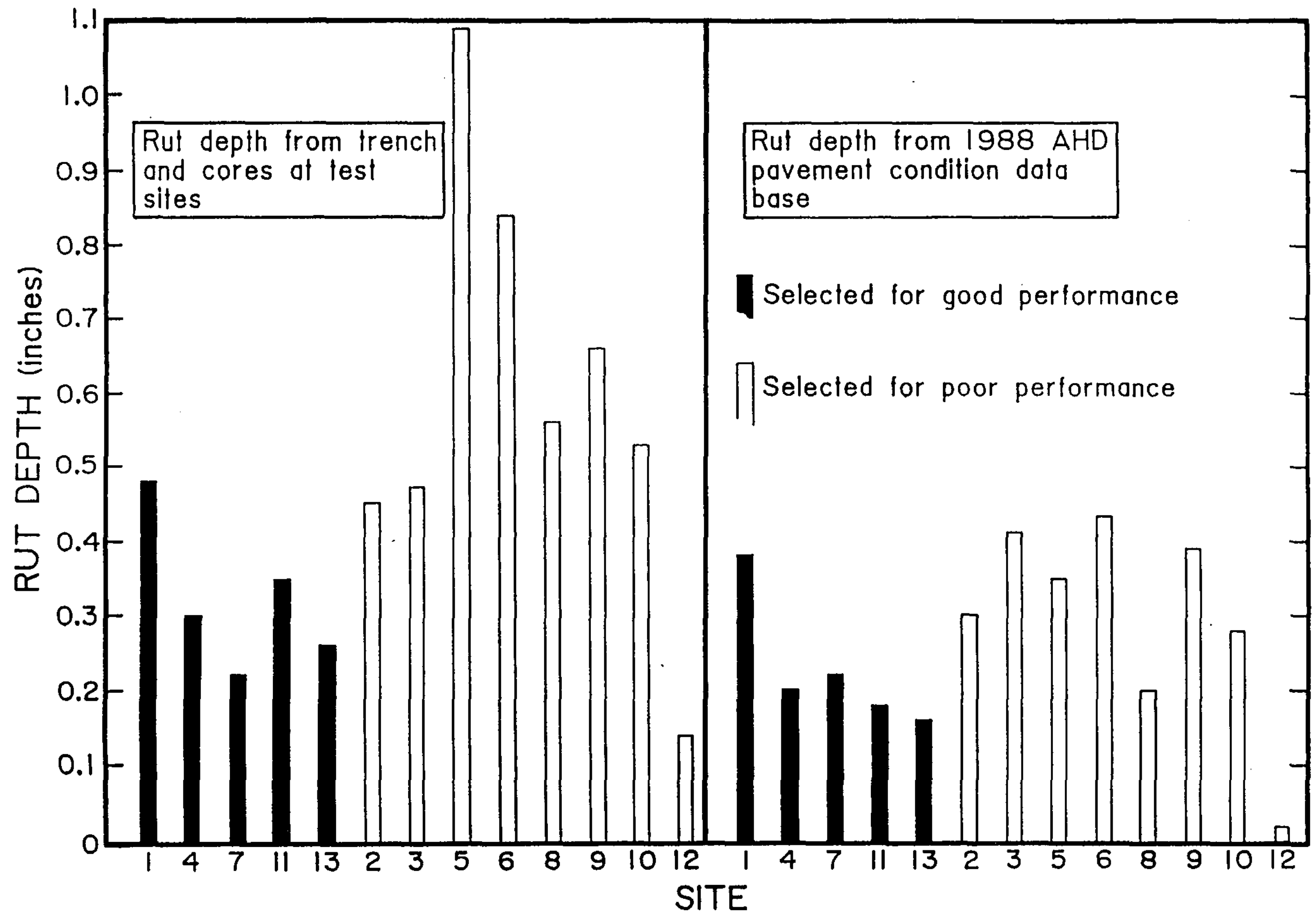


FIGURE 15. RUT DEPTHS AT TEST SITES.

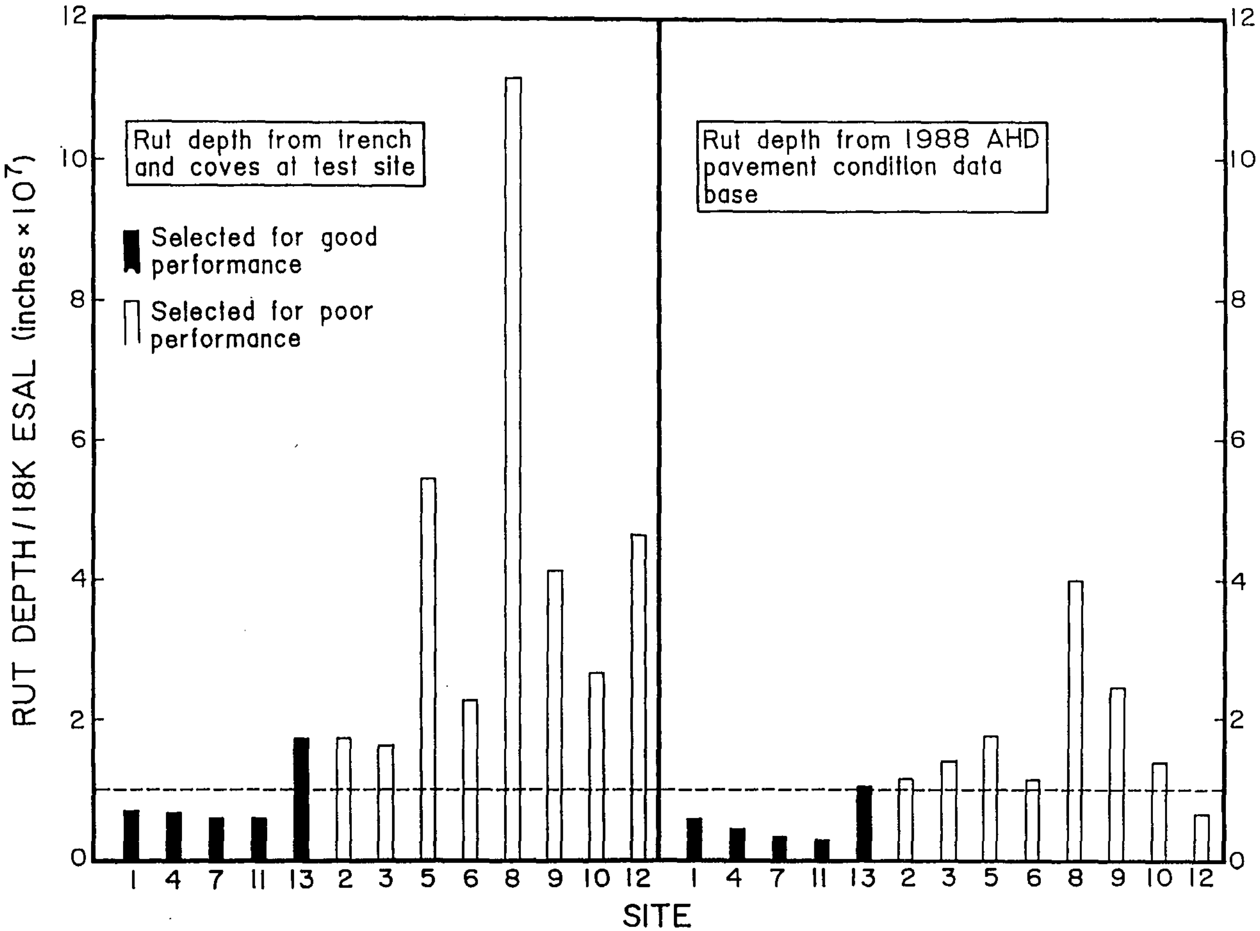
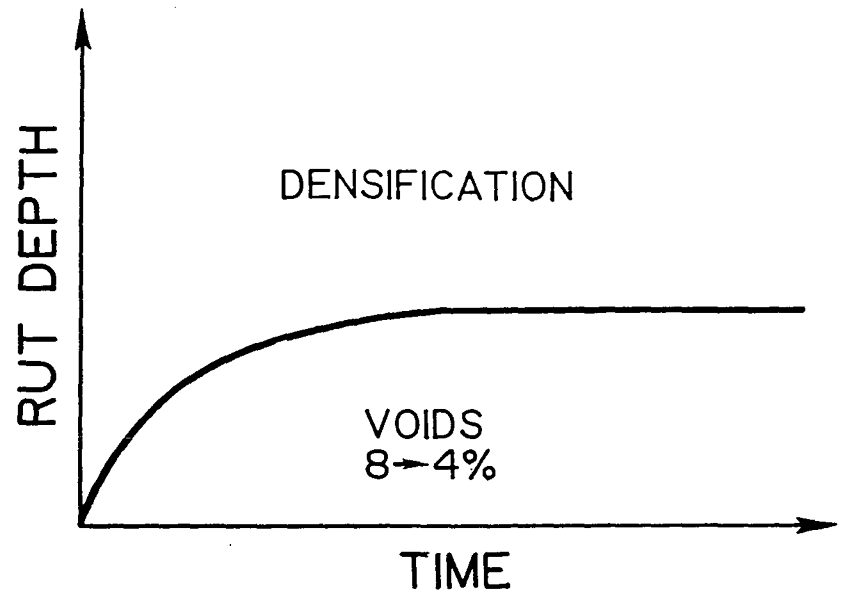
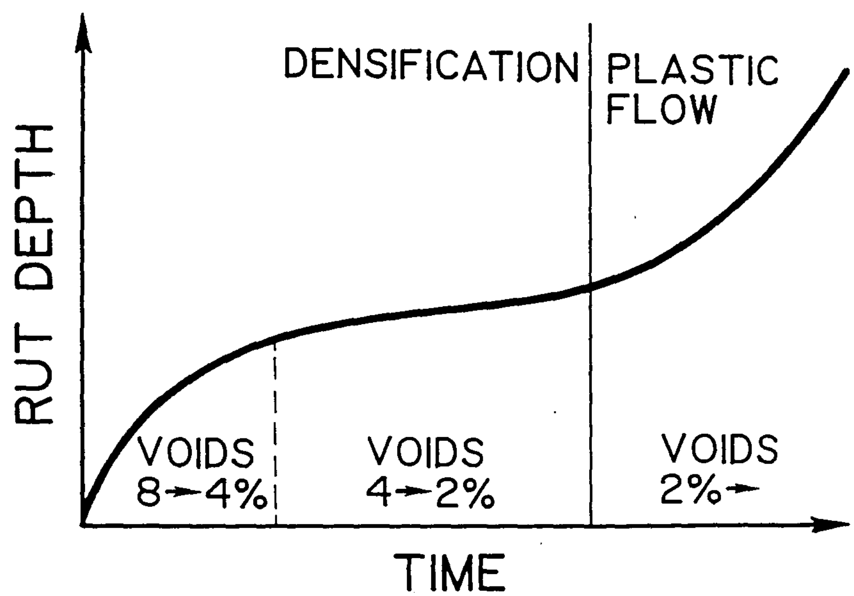


FIGURE 16. RATE OF RUTTING AT TEST SITES.



a. Pavement Performing As Designed.



b. Pavement Rutting Excessively.

FIGURE 17. MODEL FOR RUT DEVELOPMENT.

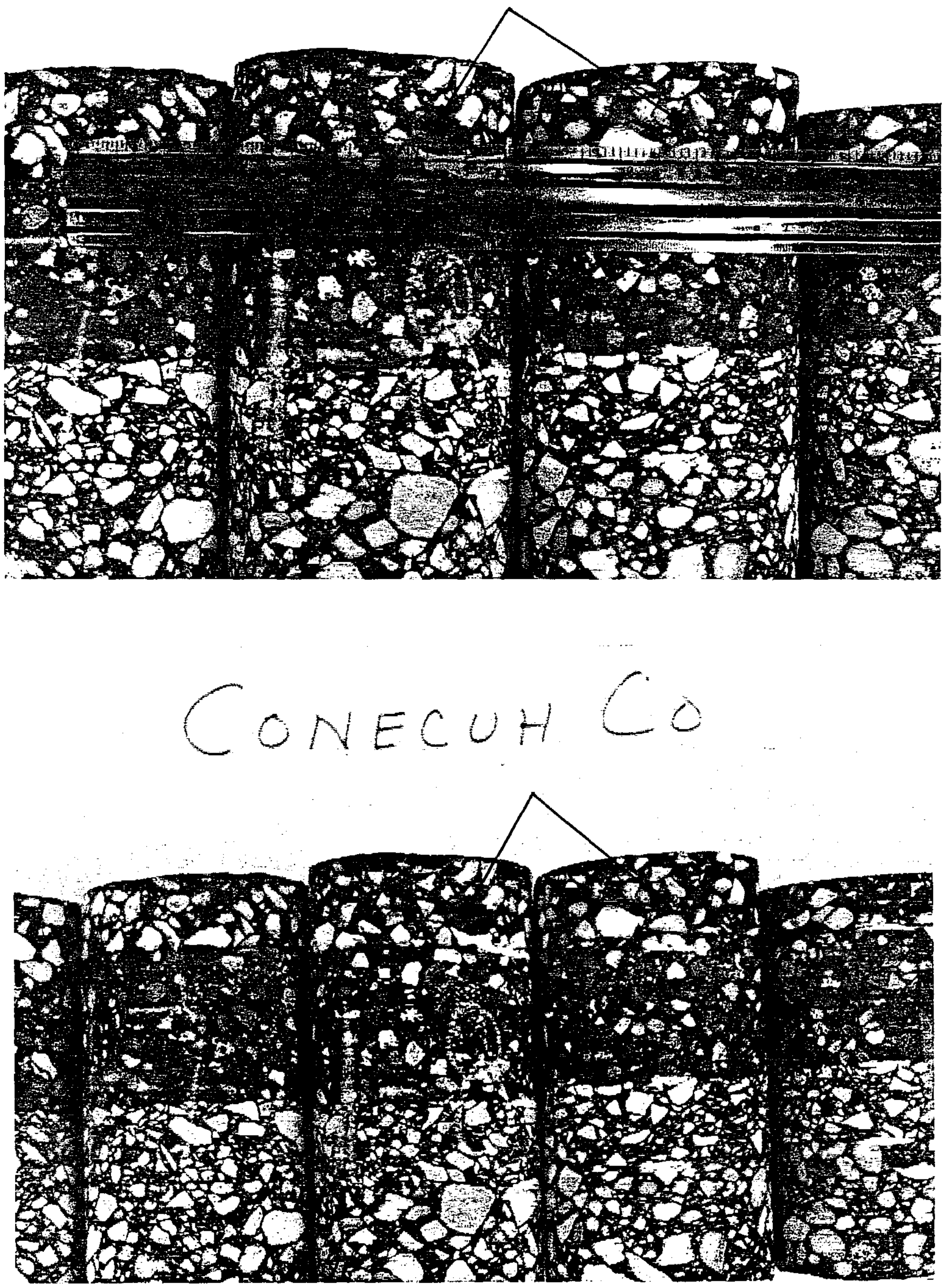


FIGURE 18. VOIDS IN CORES DUE TO DILATION DURING PLASTIC FLOW.

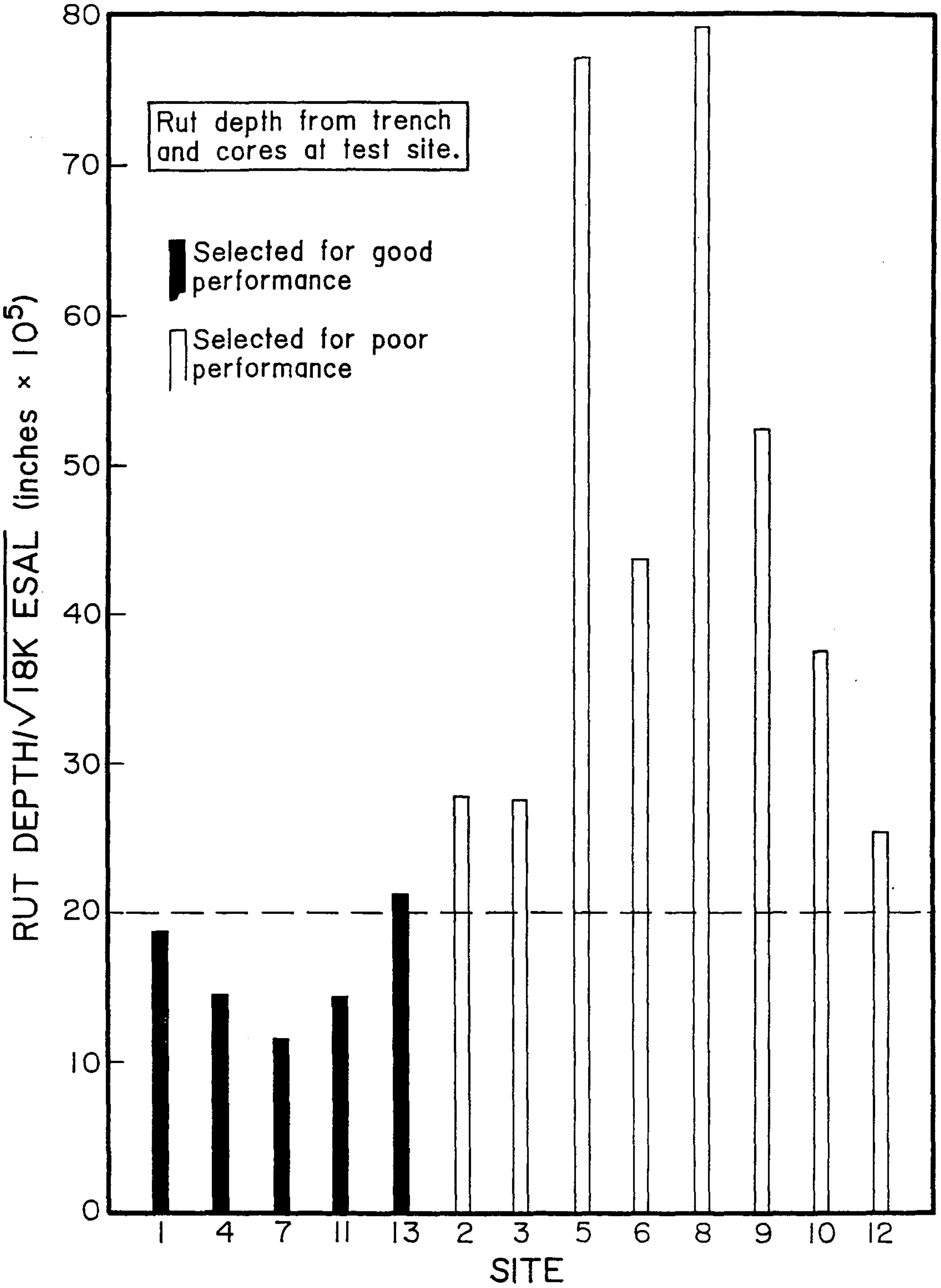


FIGURE 19. (RUT DEPTH)/√ESAL AT TEST SITES.

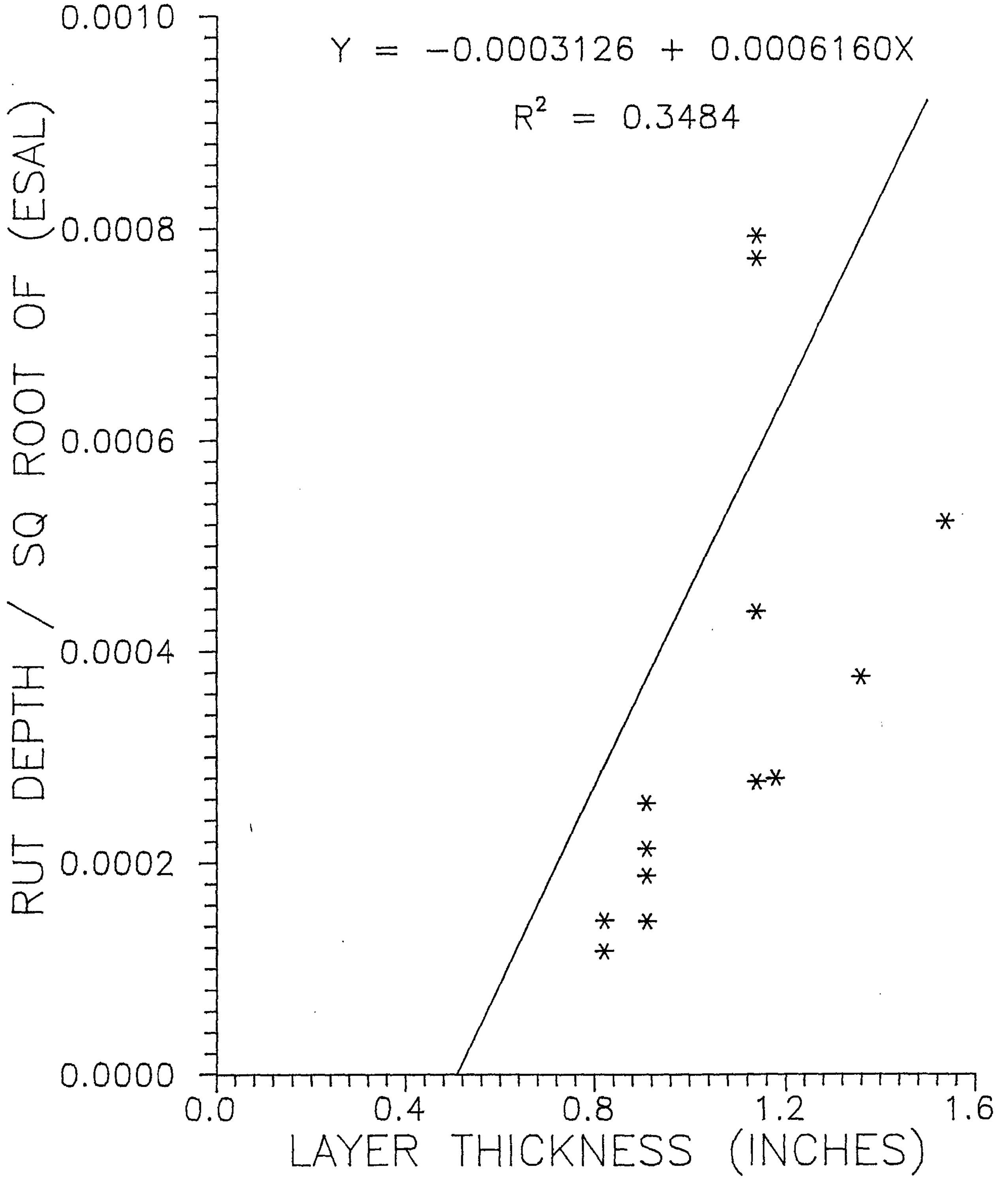


FIGURE 20. LAYER THICKNESS CORRELATION.

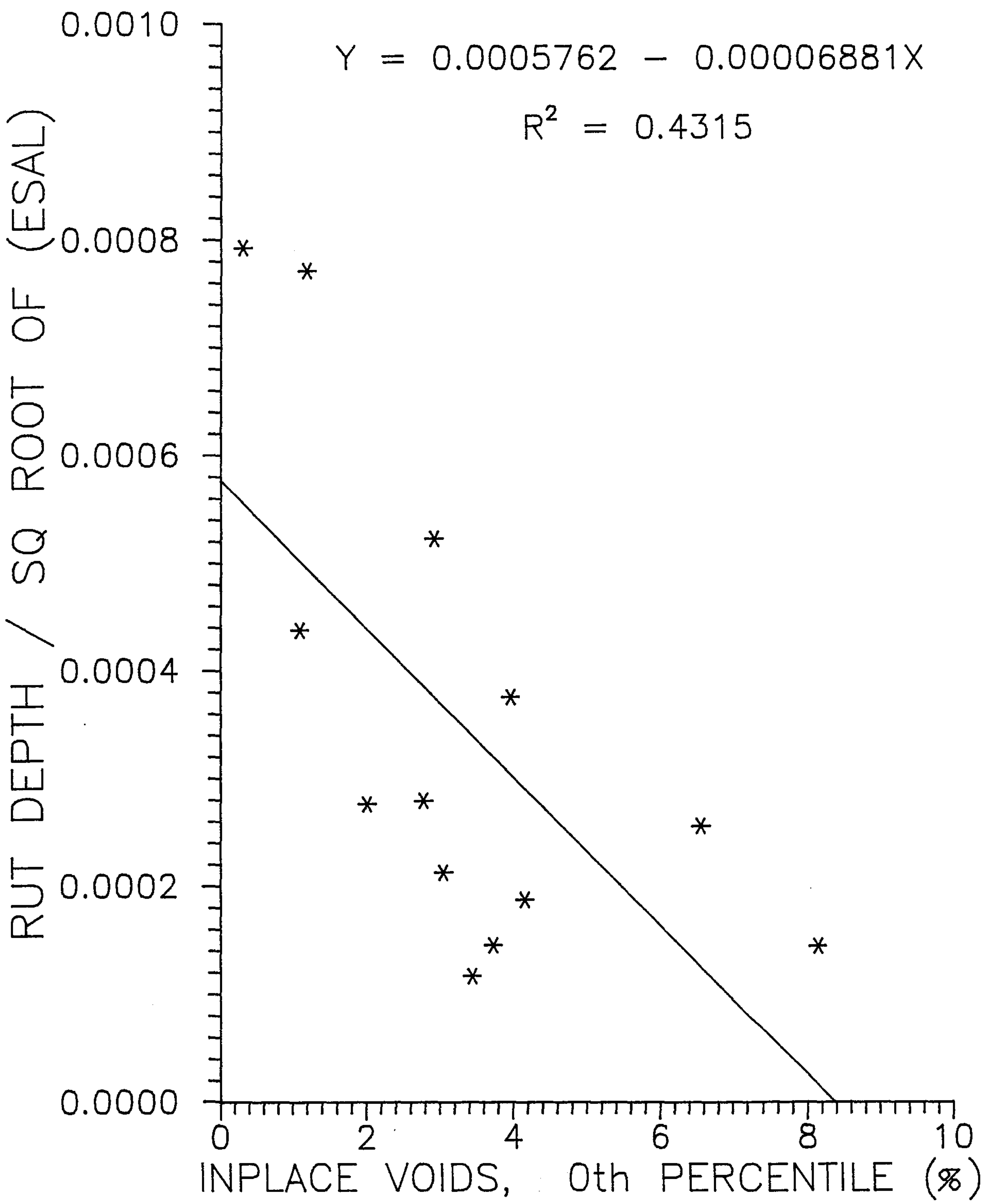


FIGURE 21. IN-PLACE VOIDS CORRELATION.

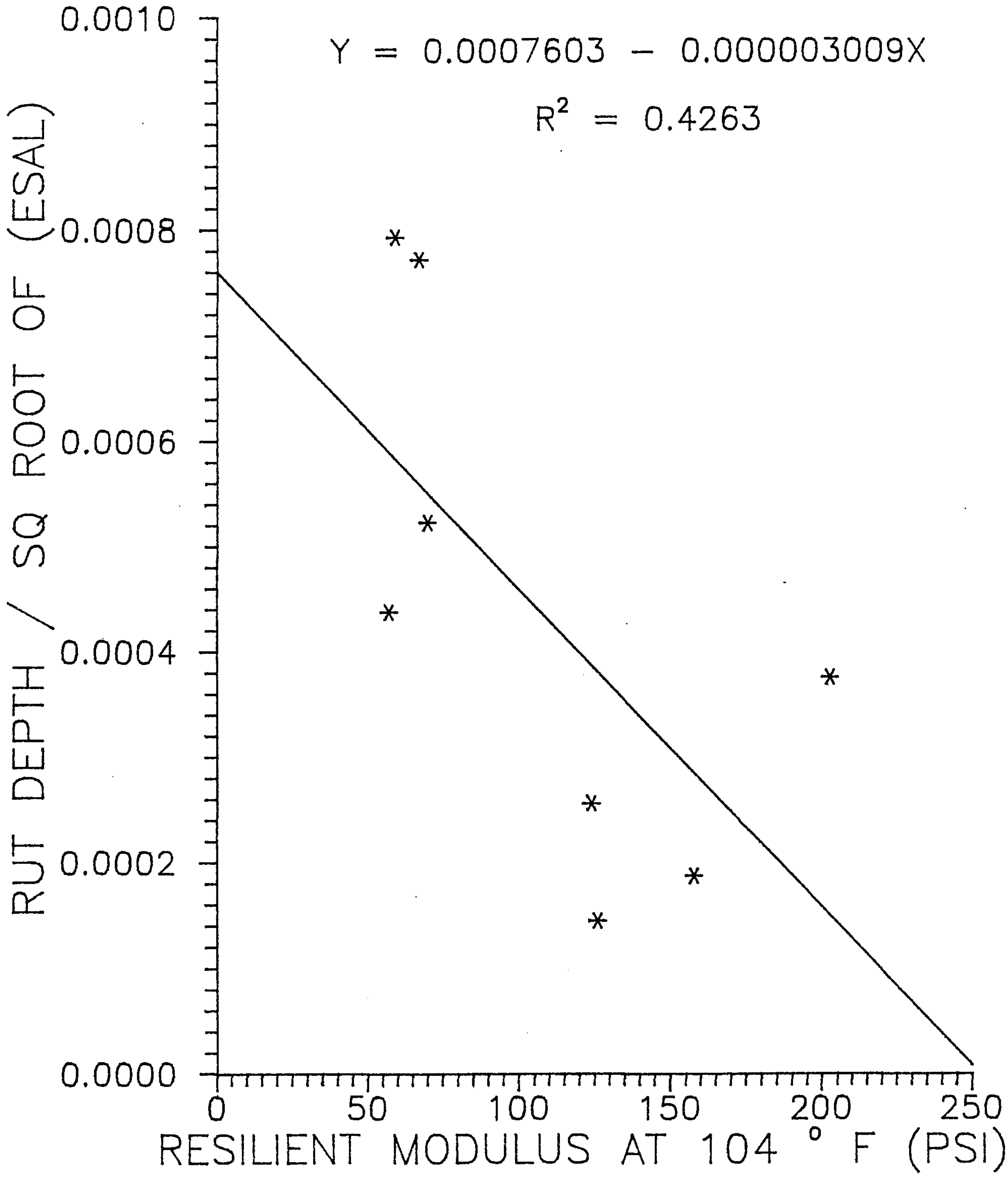


FIGURE 22. IN-PLACE MIX RESILIENT MODULUS CORRELATION.

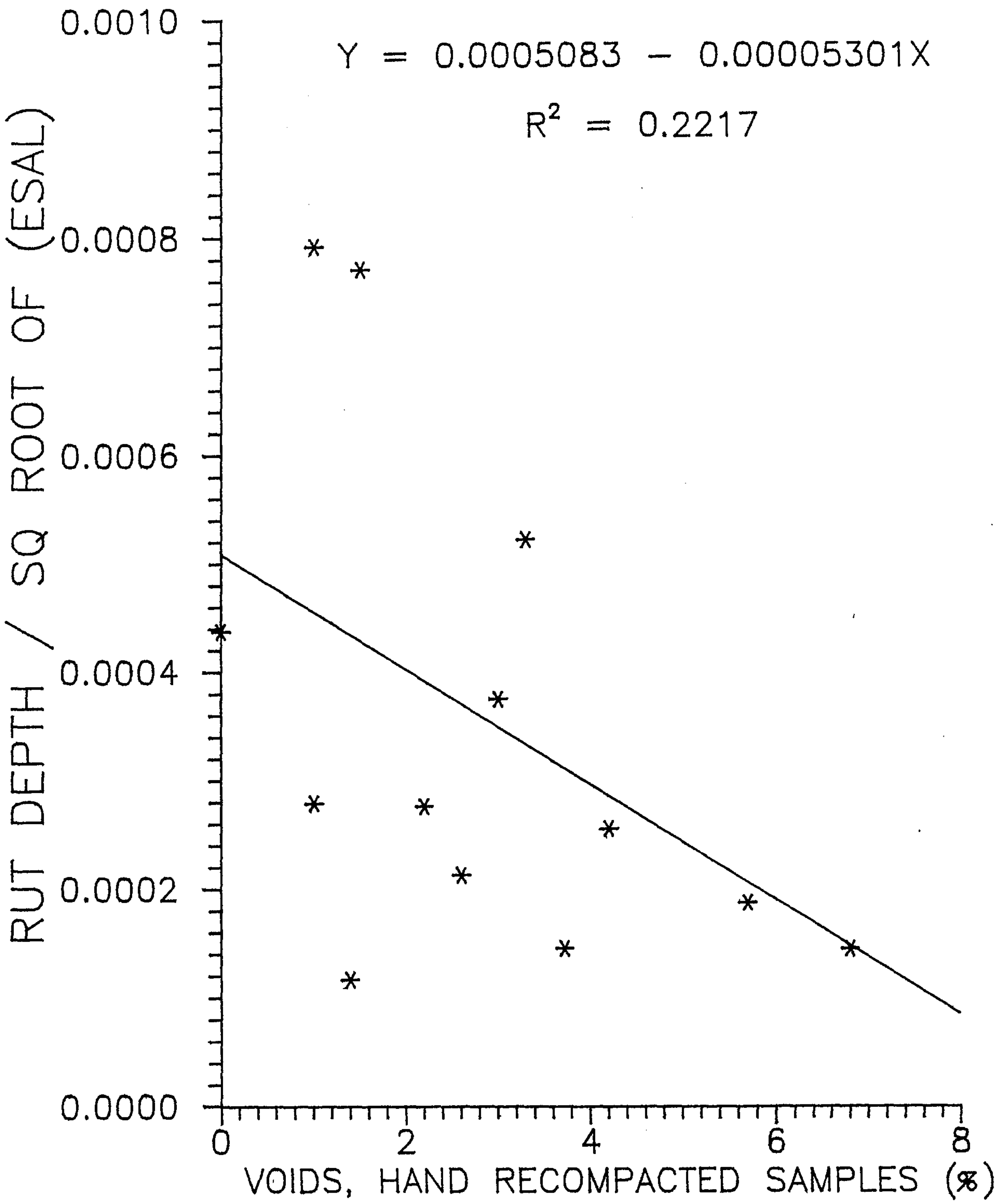


FIGURE 23. MANUALLY RECOMPACTED VOIDS CORRELATION.

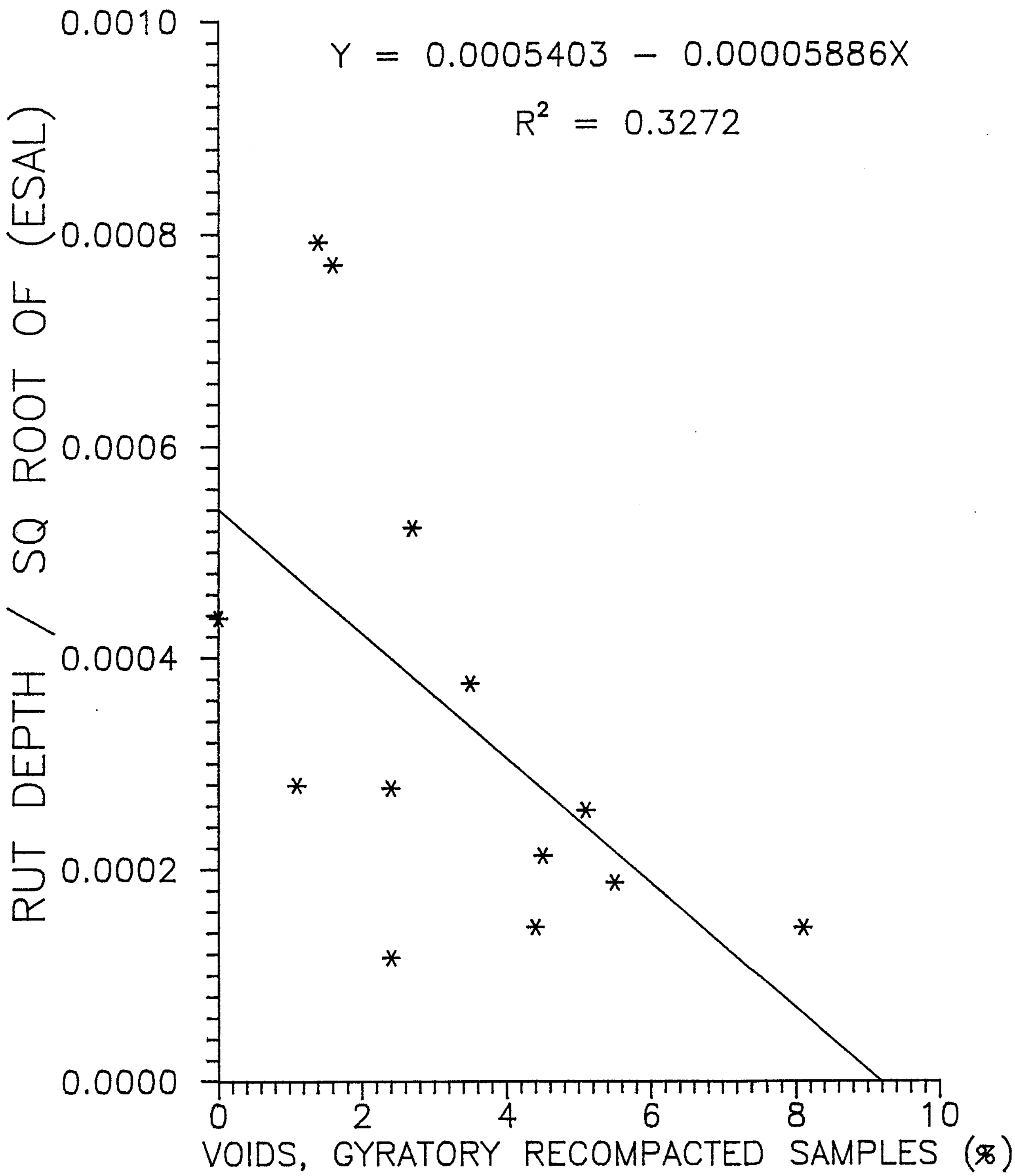


FIGURE 24. GYRATORY RECOMPACTED VOIDS CORRELATION.

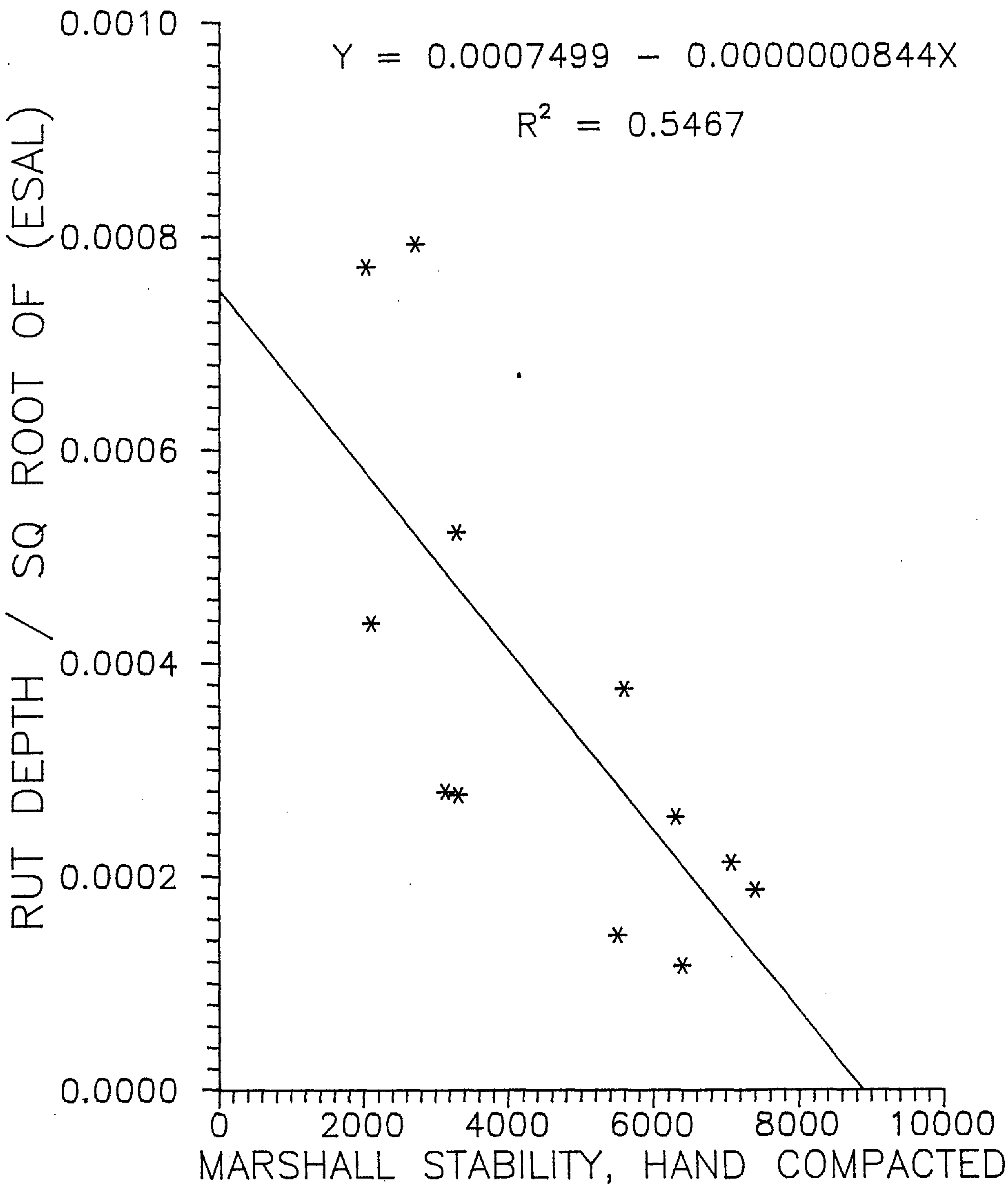


FIGURE 25. MANUALLY COMPACTED MARSHALL STABILITY CORRELATION.

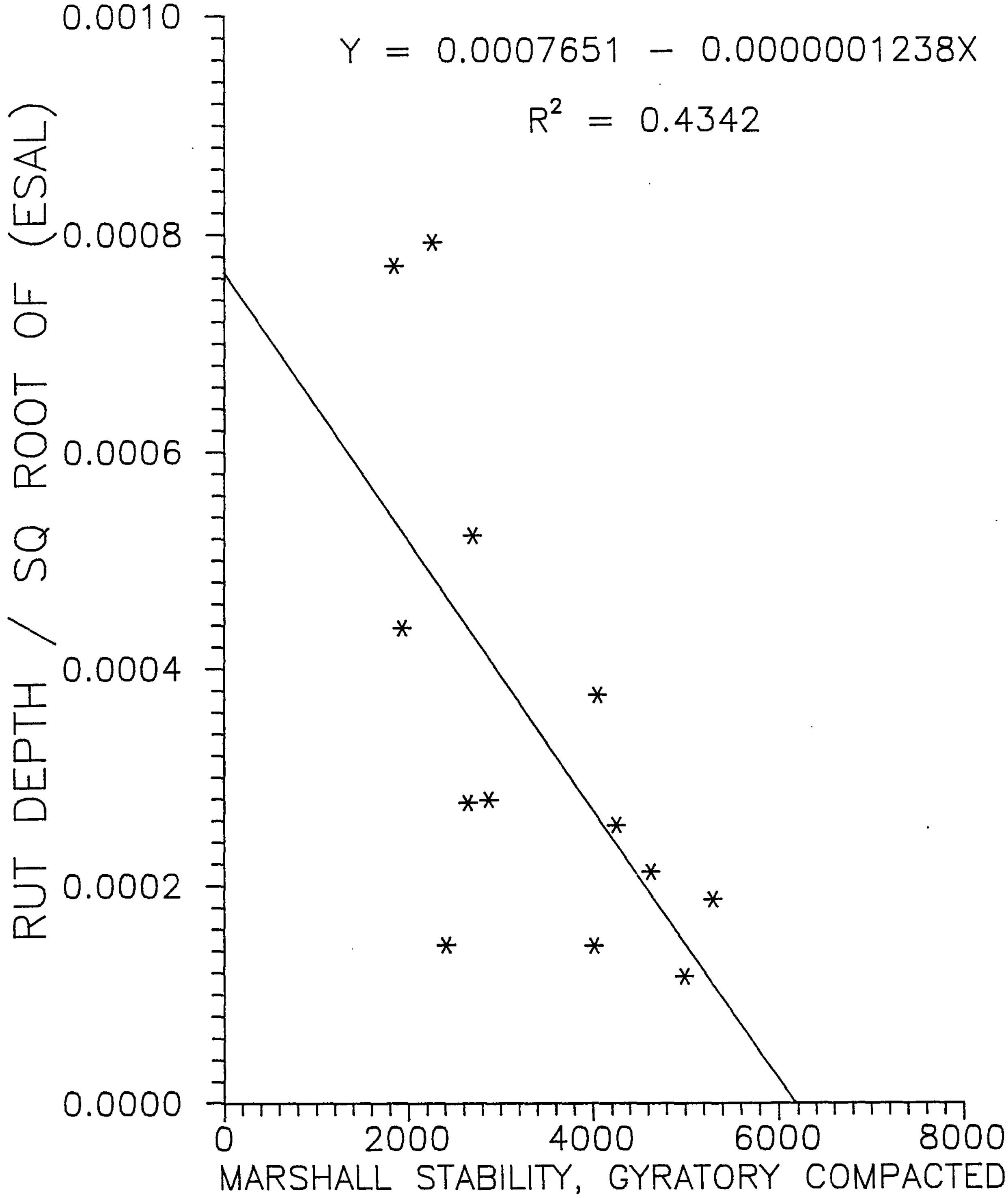


FIGURE 26. GYRATORY COMPACTED MARSHALL STABILITY CORRELATION.

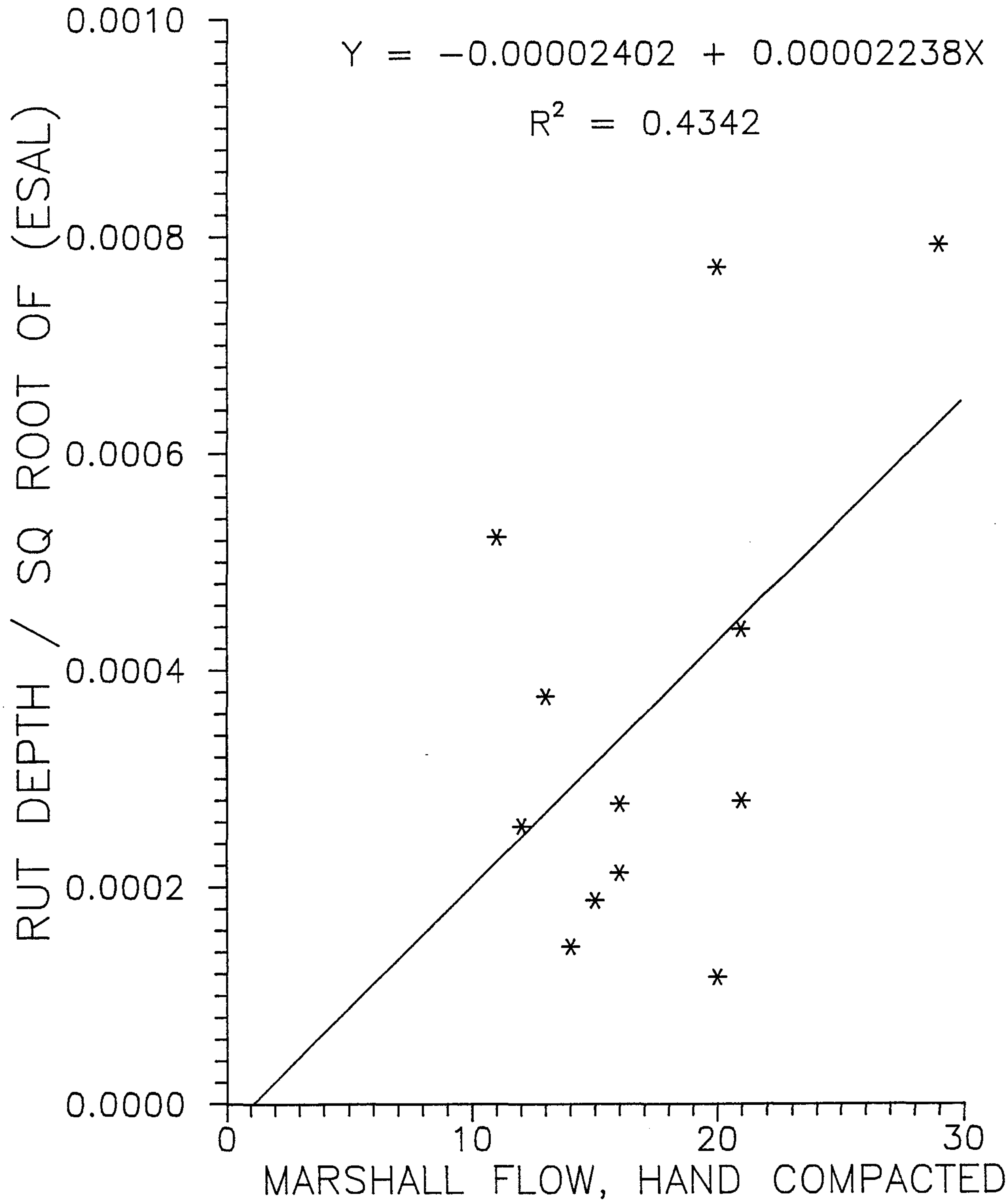


FIGURE 27. MANUALLY COMPACTED MARSHALL FLOW CORRELATION.

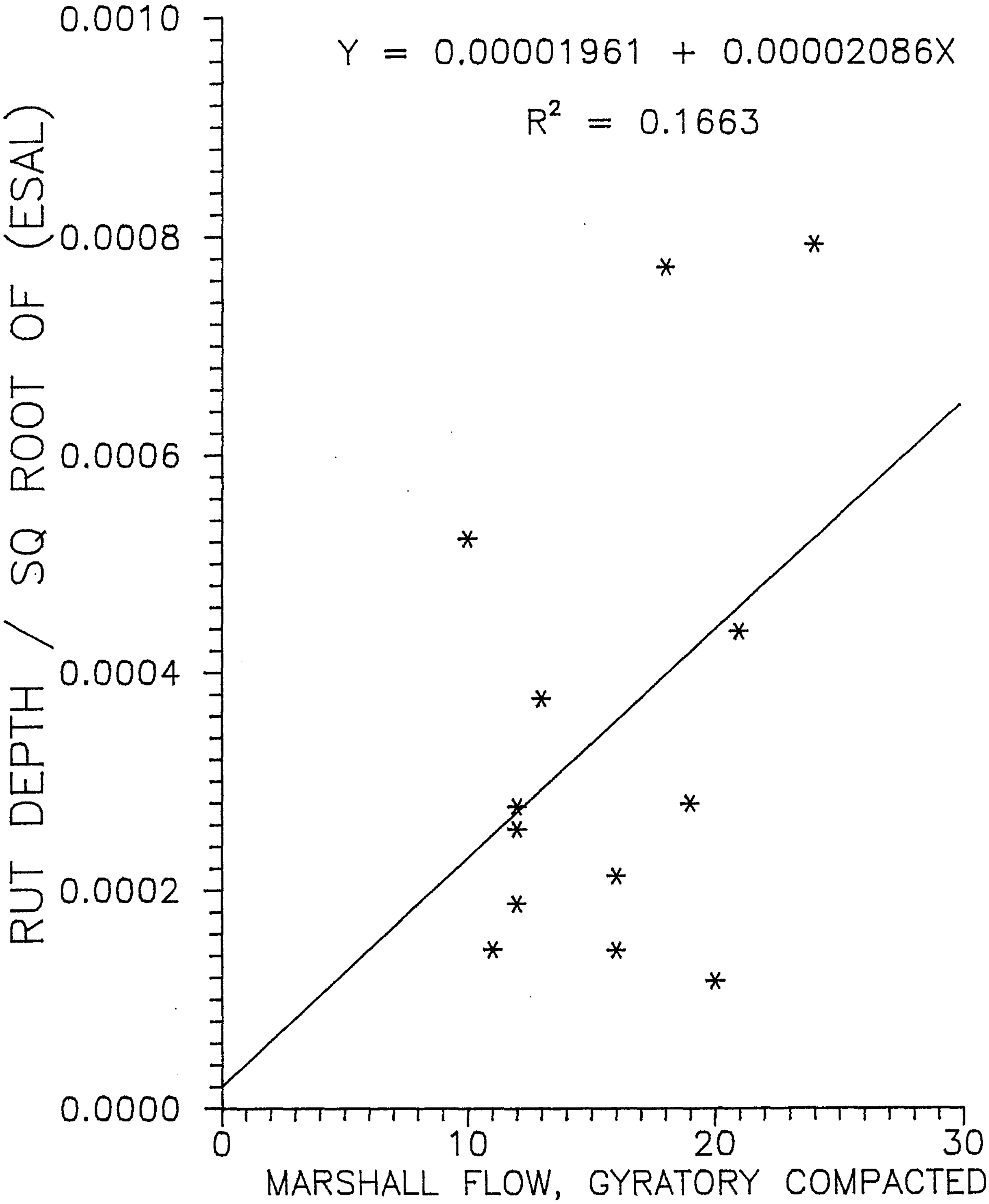


FIGURE 28. GYRATORY COMPACTED MARSHALL FLOW CORRELATION.

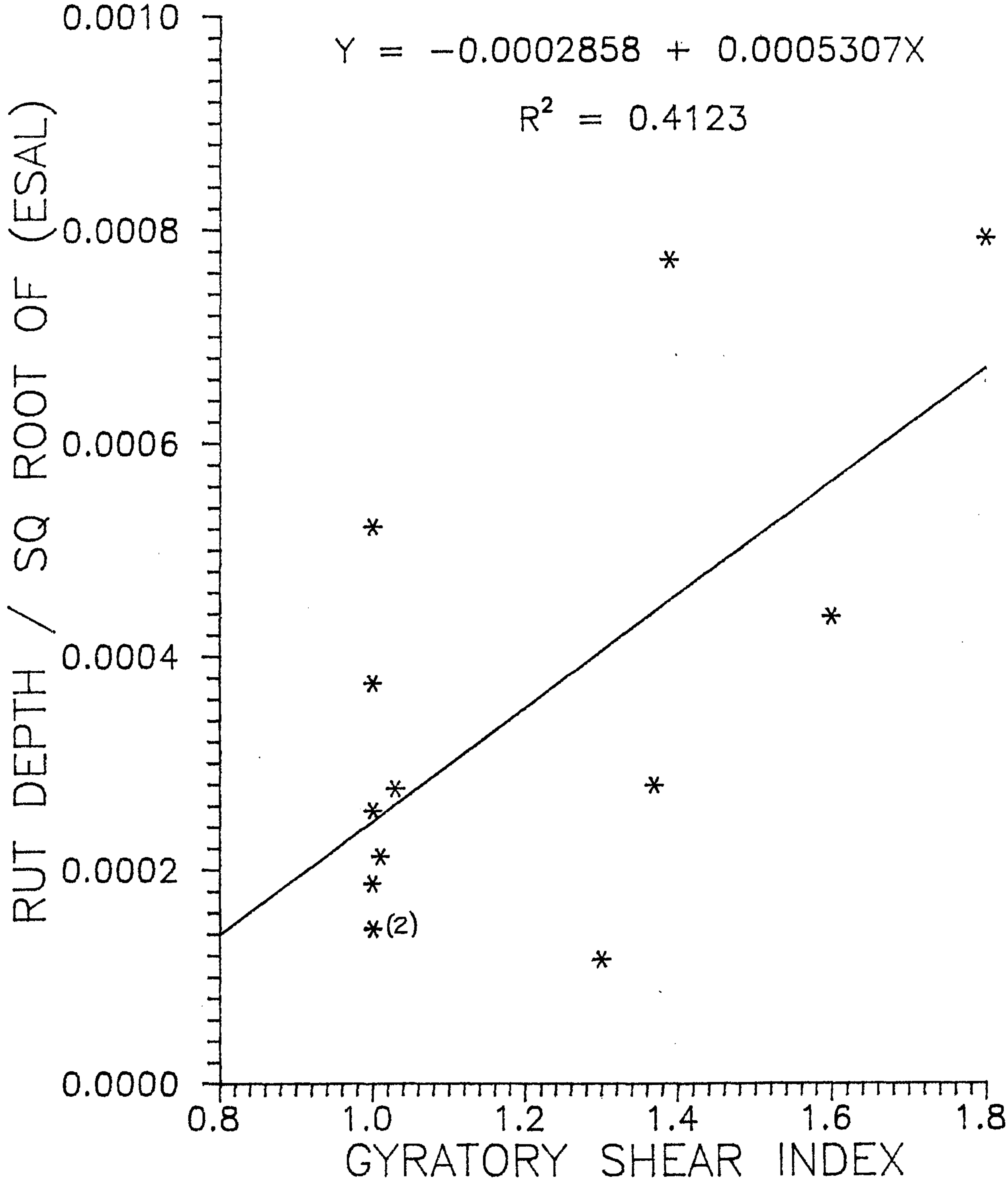


FIGURE 29. GYRATORY SHEAR INDEX CORRELATION.

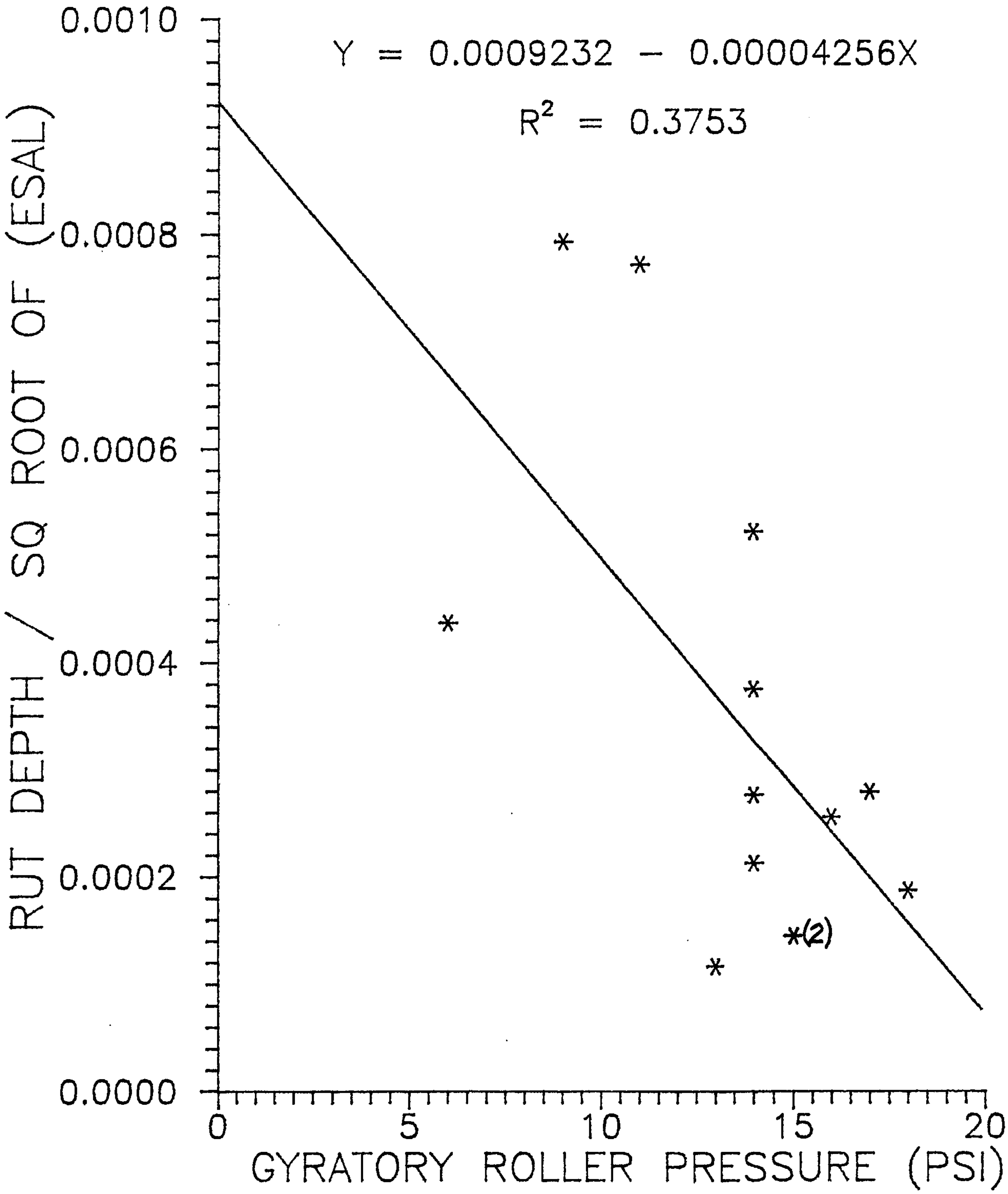


FIGURE 30. GYRATORY ROLLER PRESSURE CORRELATION.

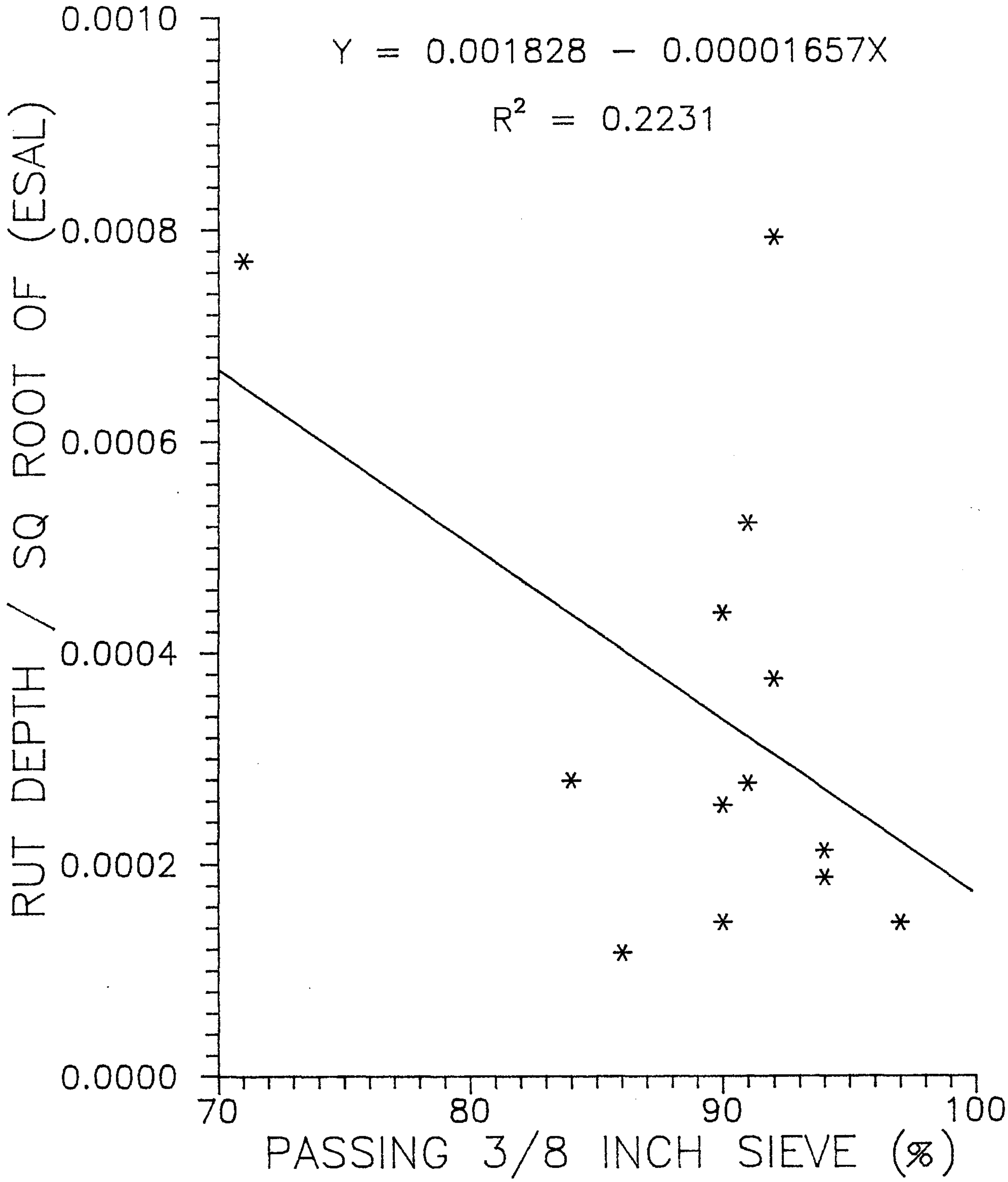


FIGURE 31. PERCENT PASSING 3/8 INCH SIEVE CORRELATION.

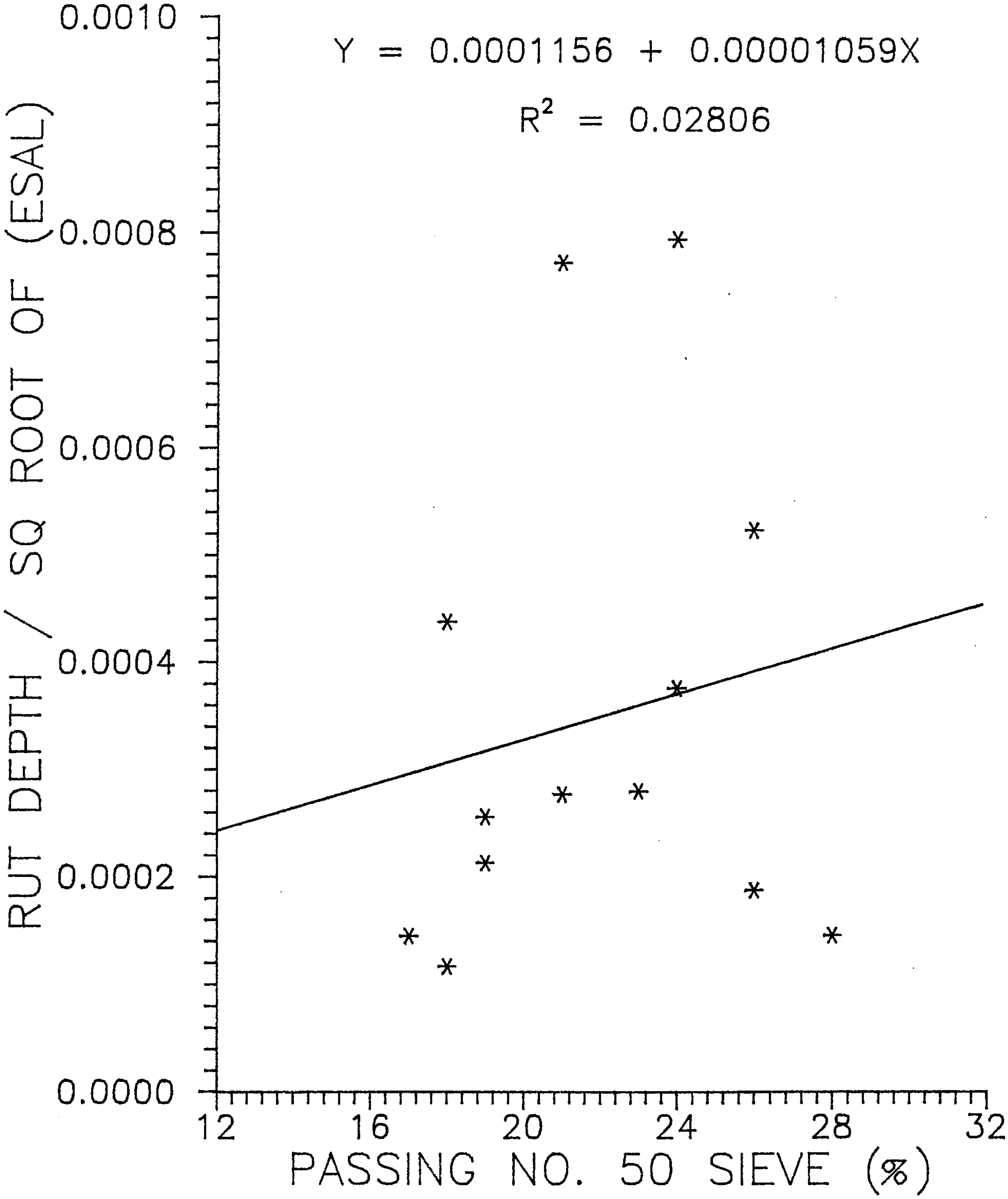


FIGURE 32. PERCENT PASSING NO. 50 SIEVE CORRELATION.

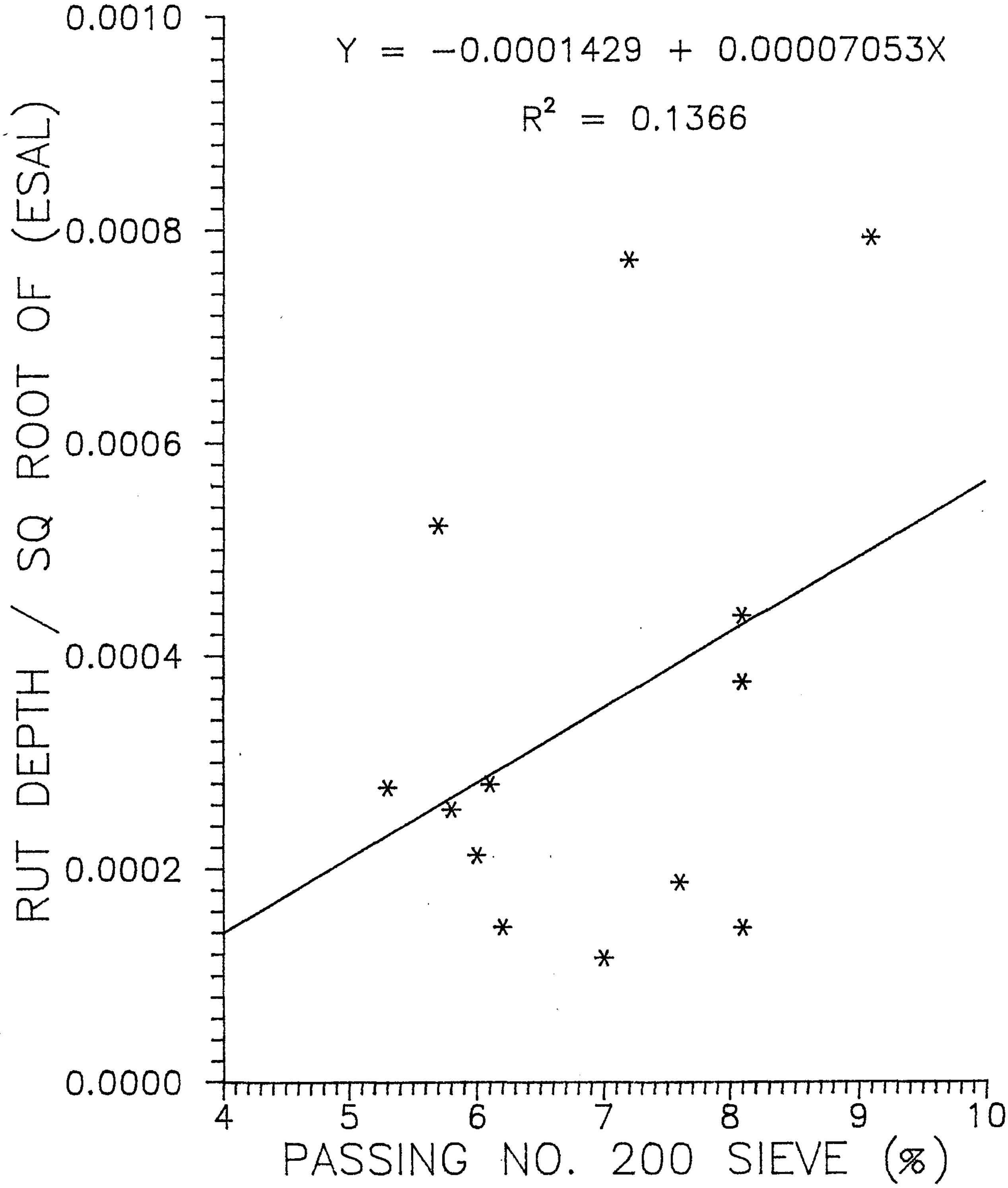


FIGURE 33. PERCENT PASSING NO. 200 SIEVE CORRELATION.

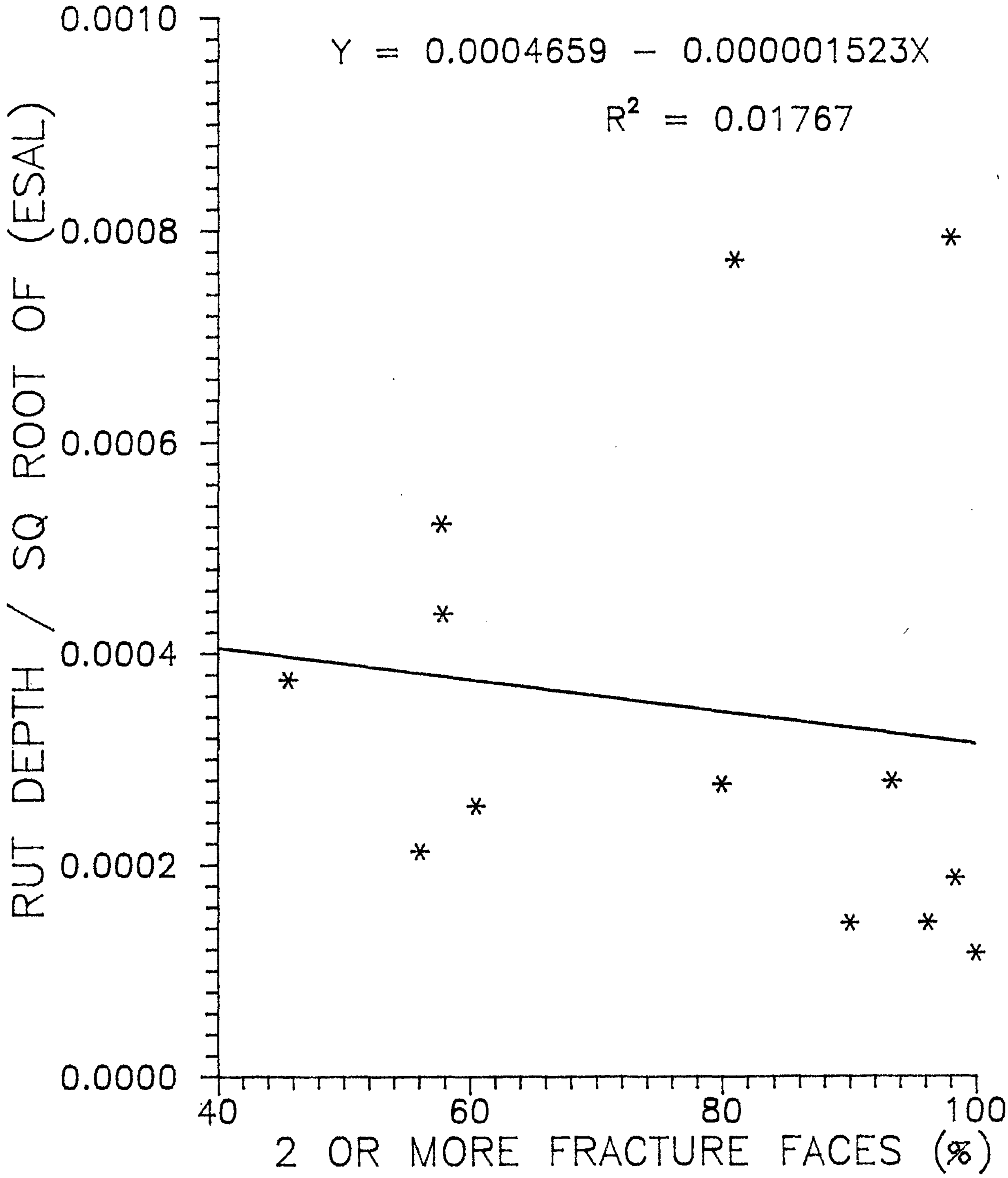


FIGURE 34. COARSE AGGREGATE FRACTURED FACE COUNT CORRELATION.

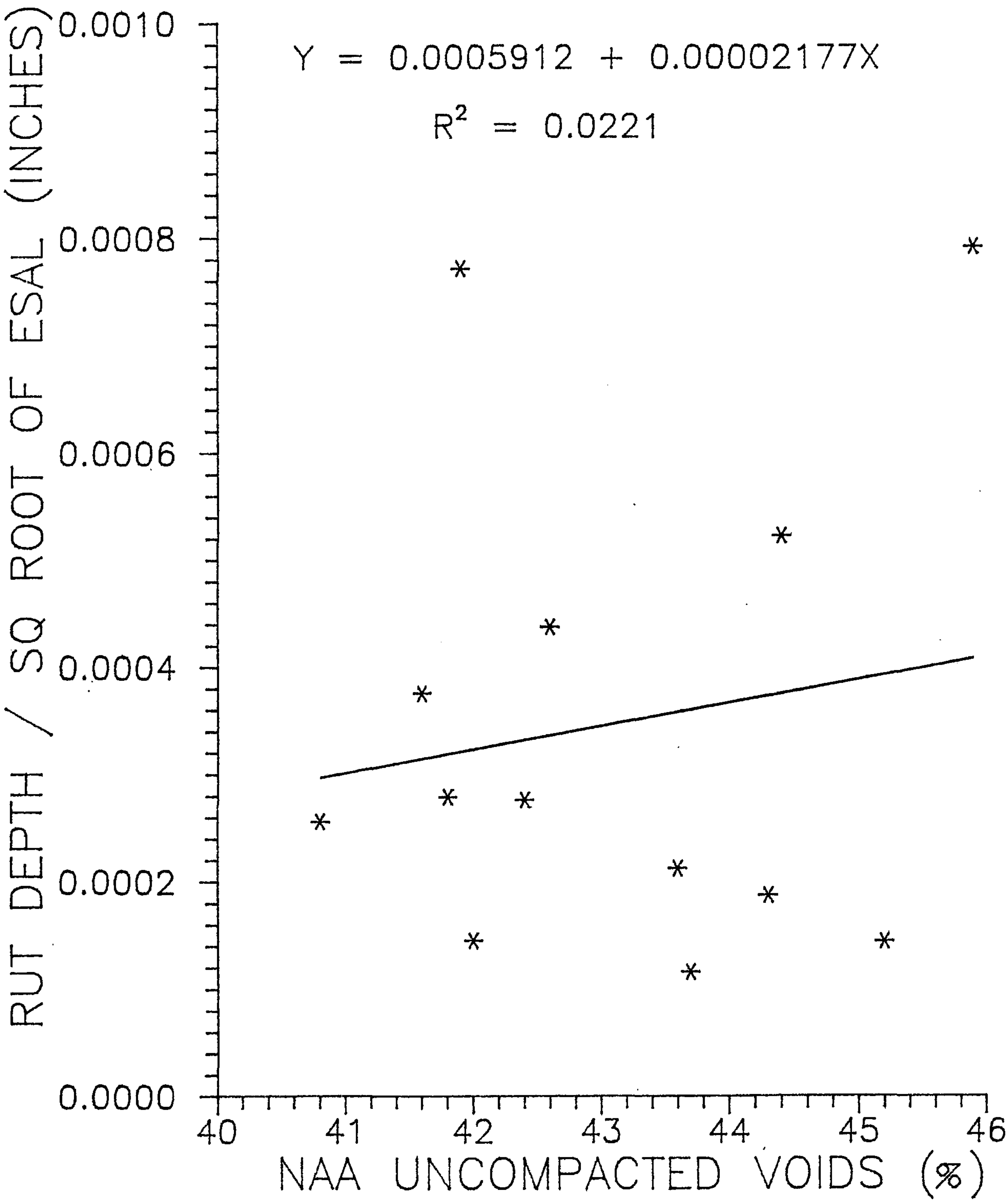


FIGURE 35. FINE AGGREGATE UNCOMPACTED VOIDS CORRELATION.

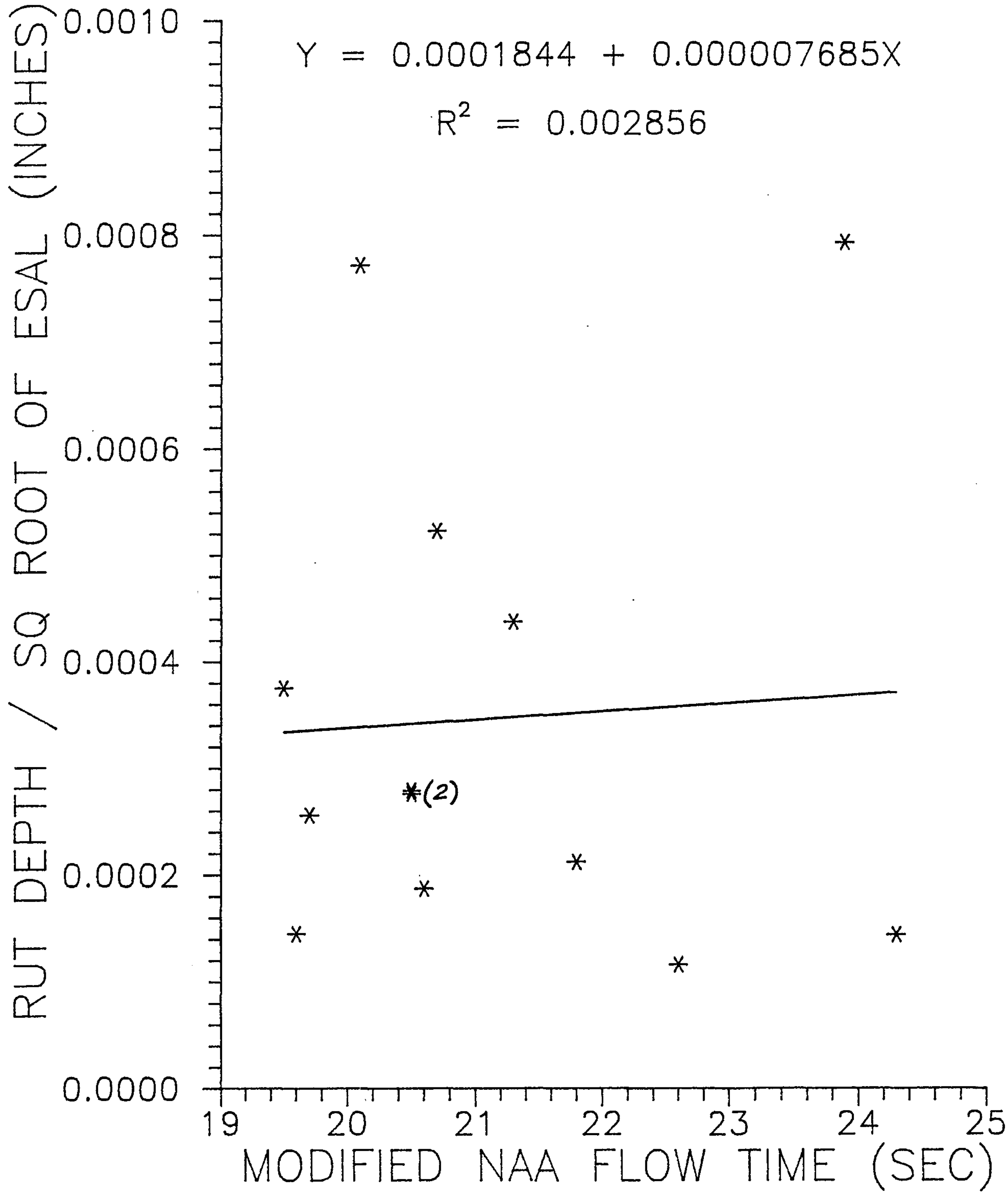


FIGURE 36. FINE AGGREGATE FLOW TIME CORRELATION.

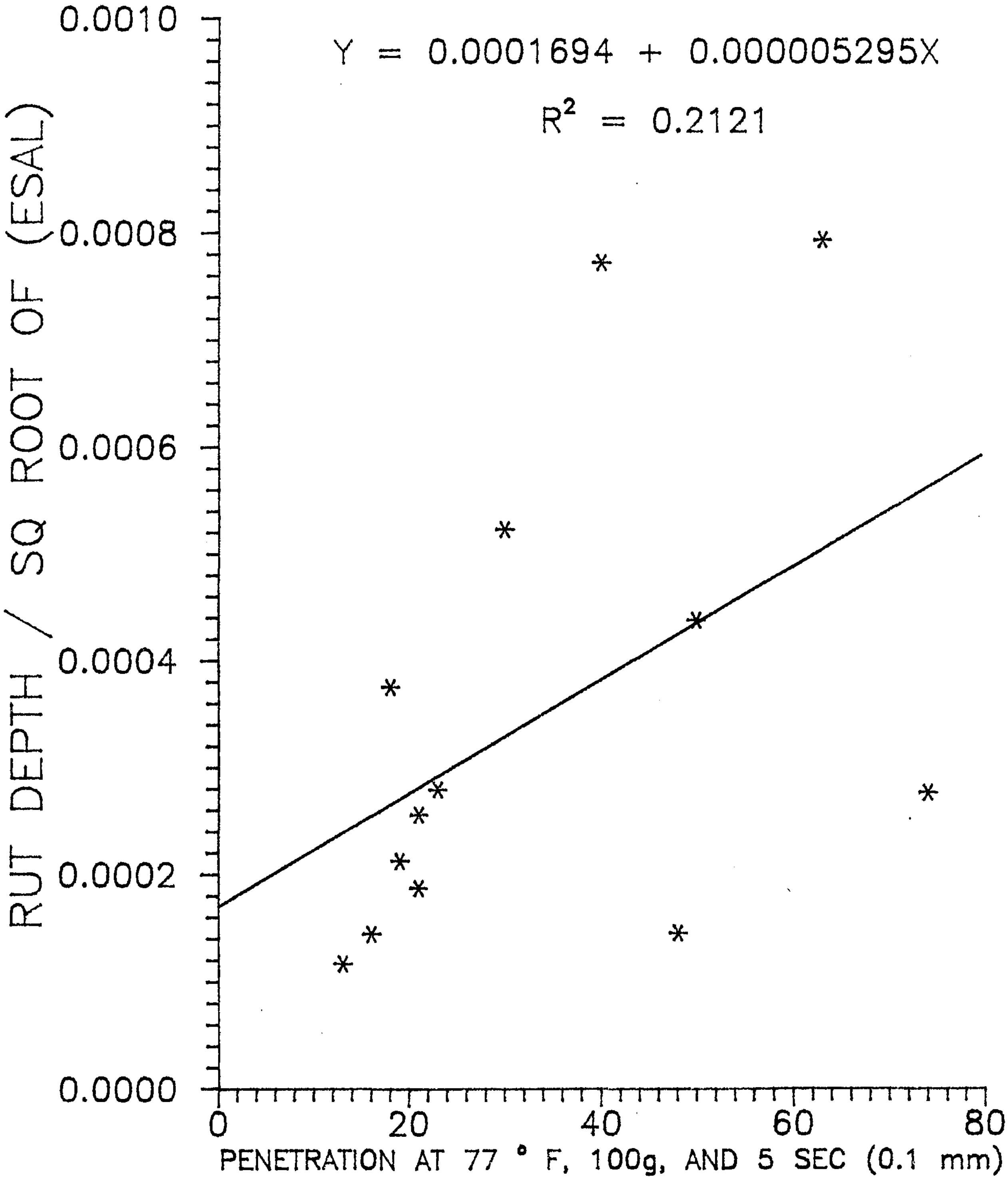


FIGURE 37. ASPHALT CEMENT PENETRATION CORRELATION.

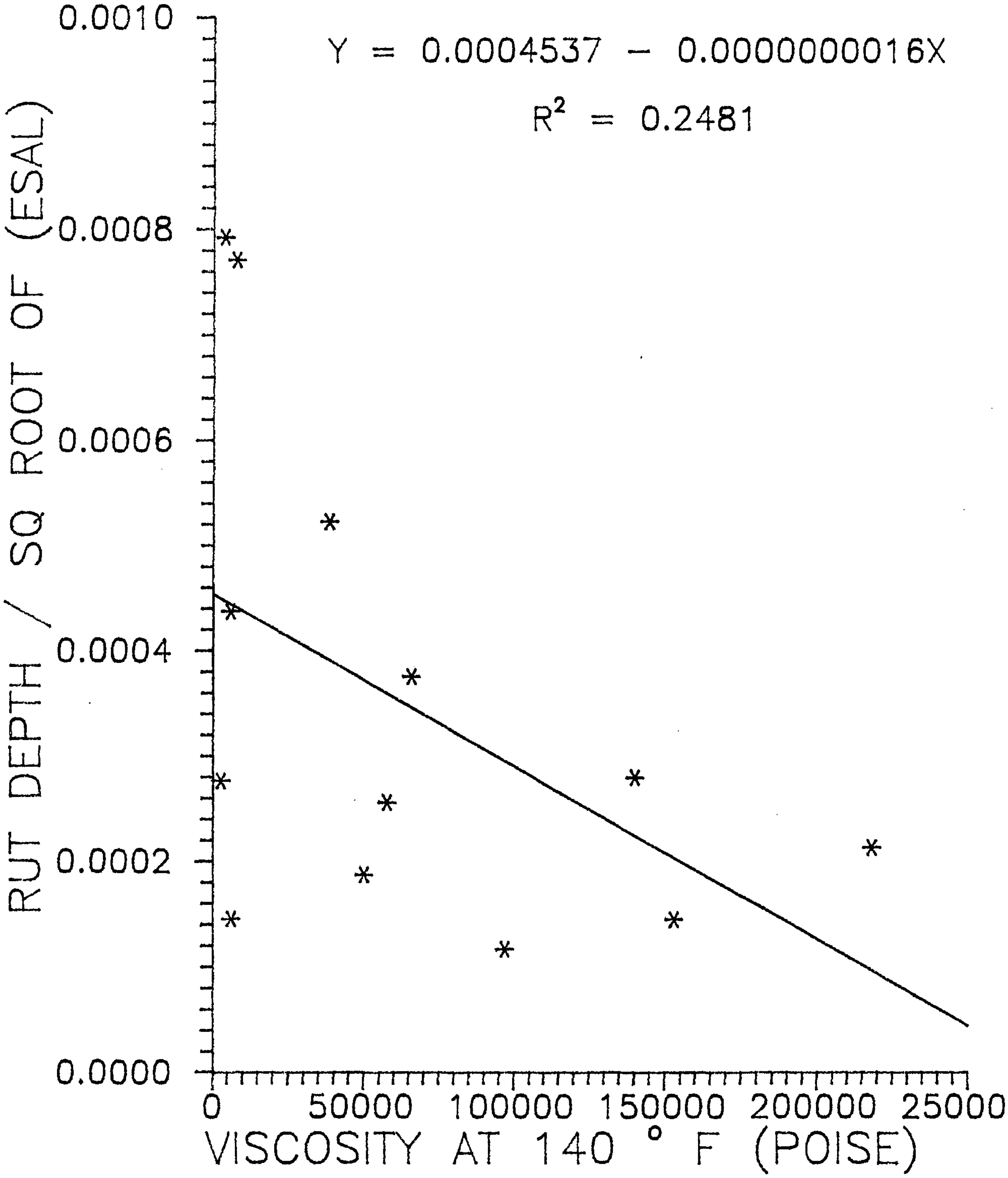


FIGURE 38. ASPHALT CEMENT VISCOSITY CORRELATION.

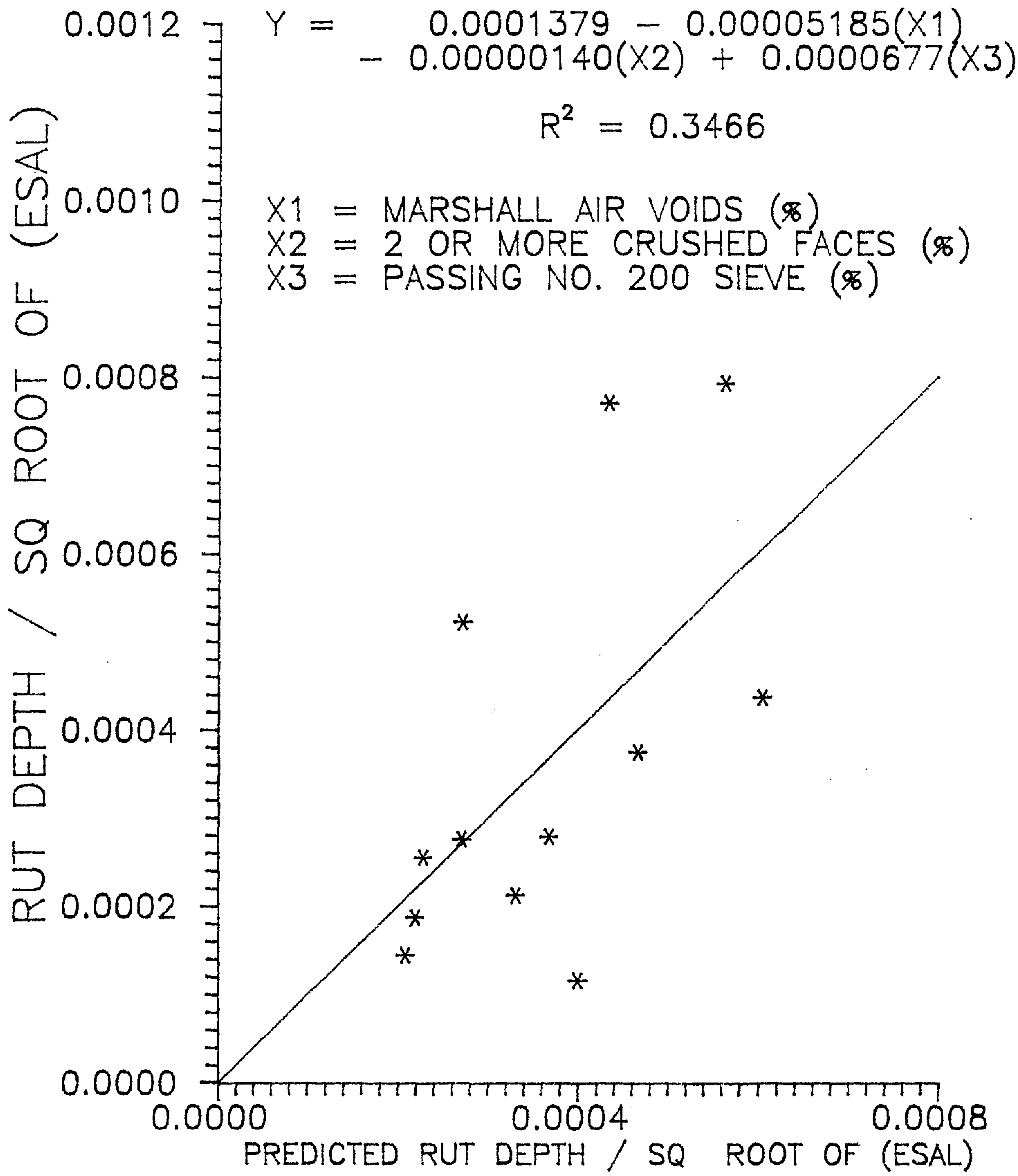
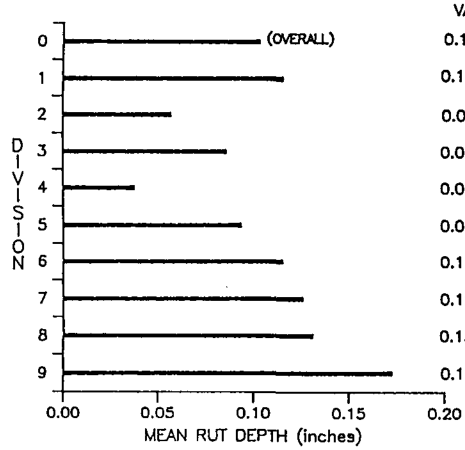


FIGURE 39. PREDICTIVE MODEL FOR RUTTING POTENTIAL.

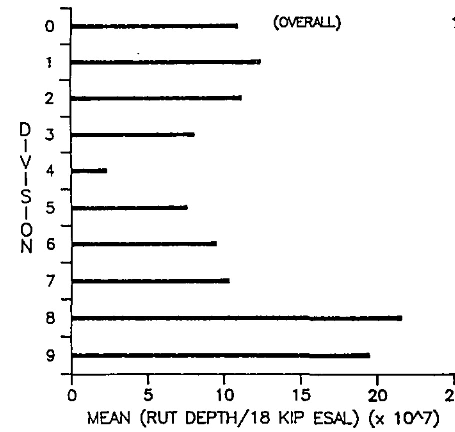
APPENDIX A

RUTTING DATA FROM PAVEMENT CONDITION DATABASES

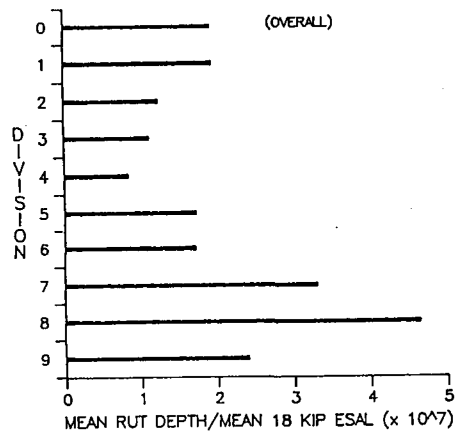
DATA SORTED BY AHD DIVISION



VALUE	FREQUENCY	PERCENT
0.10258	22,683	100
0.11511	2411	10.6
0.05670	1964	8.7
0.08570	2746	12.1
0.03769	2727	12.0
0.09344	2861	12.6
0.11522	2443	10.8
0.12574	3184	14.0
0.13106	2394	10.6
0.17250	1953	8.6



VALUE (x 10^7)	FREQUENCY	PERCENT
10.918	22414	100
12.424	2400	10.7
11.190	1956	8.7
8.085	2646	11.8
2.342	2705	12.1
7.560	2825	12.6
9.434	2437	10.9
10.272	3148	14.4
21.552	2374	10.6
19.462	1923	8.6



VALUE (x 10^7)	FREQUENCY	PERCENT
1.919	22414	100
1.941	2400	10.7
1.239	1956	8.7
1.122	2646	11.8
0.843	2705	12.1
1.723	2825	12.6
1.709	2437	10.9
3.291	3148	14.0
4.632	2374	10.6
2.395	1923	8.6

1984 DATA
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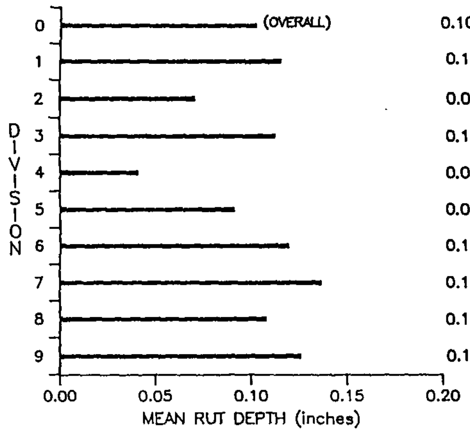
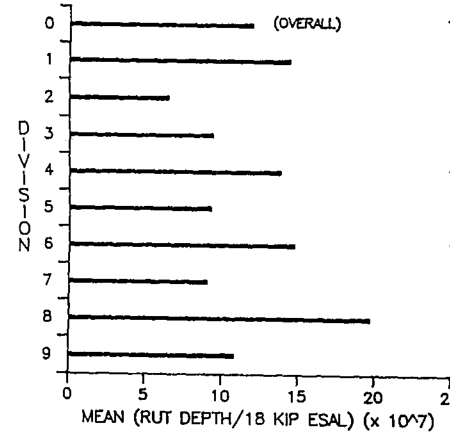
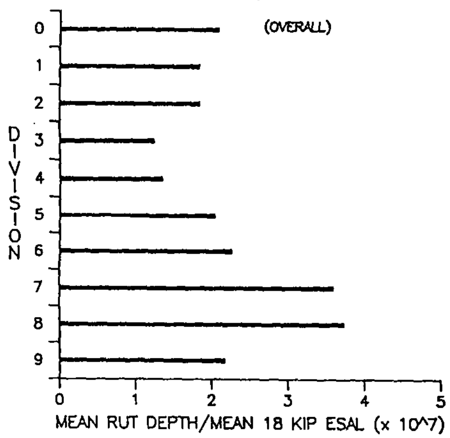


VALUE	FREQUENCY	PERCENT
0.10259	22,004	100
0.11541	2427	11.0
0.07082	1917	8.7
0.11245	2648	12.0
0.04095	2710	12.3
0.09110	2659	12.1
0.11948	2415	11.0
0.13654	3113	14.1
0.10781	2271	10.3
0.12585	1844	8.4

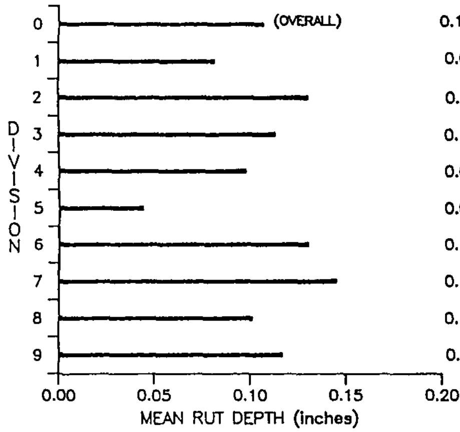


VALUE (x 10^7)	FREQUENCY	PERCENT
11.983	21774	100
14.449	2416	11.1
6.525	1911	8.8
9.436	2578	11.8
13.882	2688	12.3
9.316	2624	12.1
14.790	2409	11.1
9.031	3081	14.1
19.694	2253	10.3
10.820	1814	8.3

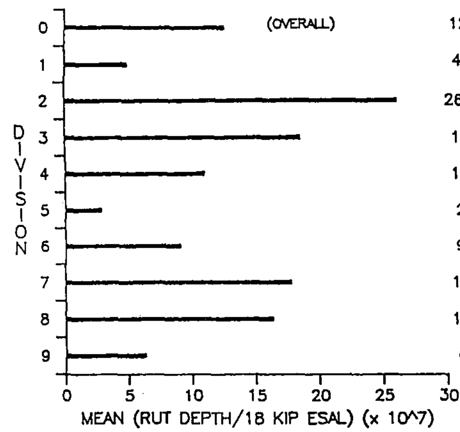


VALUE (x 10^7)	FREQUENCY	PERCENT
2.076	21774	100
1.829	2416	11.1
1.835	1911	8.8
1.238	2578	11.8
1.340	2688	12.3
2.026	2624	12.1
2.250	2409	11.1
3.581	3081	14.1
3.723	2253	10.3
2.175	1814	8.3

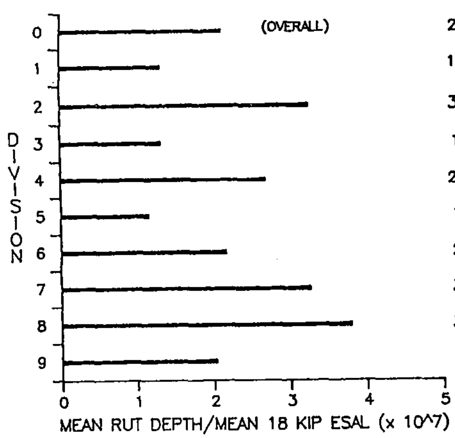
1986 DATA
STATE AND INTERSTATE
OUTER LANES



DIVISION	VALUE	FREQUENCY	PERCENT
0 (OVERALL)	0.10694	21,444	100
1	0.08146	2355	11.0
2	0.13043	1861	8.7
3	0.11314	2680	12.5
4	0.09787	2613	12.2
5	0.04431	2433	11.3
6	0.13050	2258	10.5
7	0.14509	3073	14.3
8	0.10126	2285	10.7
9	0.11663	1886	8.8

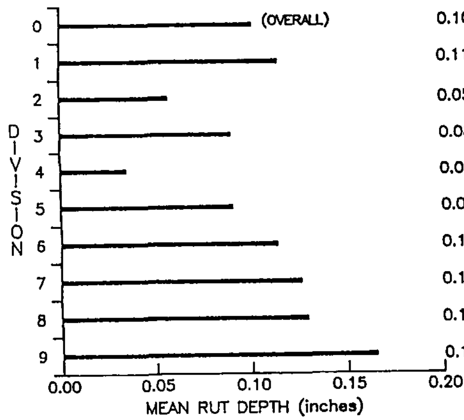


DIVISION	VALUE (x 10^7)	FREQUENCY	PERCENT
0 (OVERALL)	12.564	21444	100
1	4.901	2355	11.0
2	26.030	1861	8.7
3	18.467	2680	12.5
4	10.981	2613	12.2
5	2.825	2433	11.3
6	9.072	2258	10.5
7	17.790	3073	14.3
8	16.362	2285	10.7
9	6.279	1886	8.8

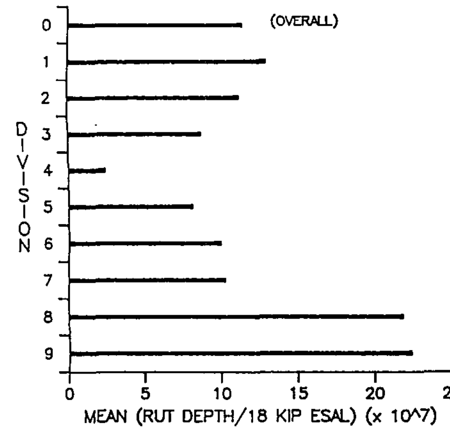


DIVISION	VALUE (x 10^7)	FREQUENCY	PERCENT
0 (OVERALL)	2.123	21444	100
1	1.323	2355	11.0
2	3.251	1861	8.7
3	1.323	2680	12.5
4	2.682	2613	12.2
5	1.155	2433	11.3
6	2.157	2258	10.5
7	3.259	3073	14.3
8	3.794	2285	10.7
9	2.033	1886	8.8

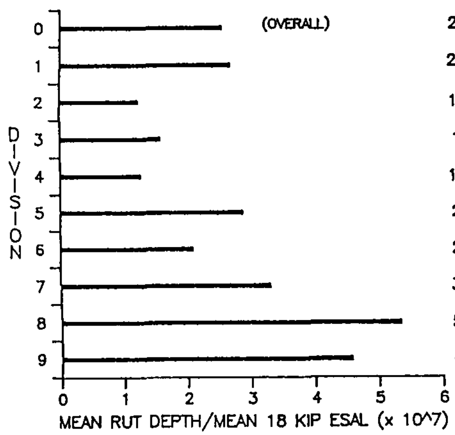
1988 DATA
STATE AND INTERSTATE
OUTER LANES



DIVISION	VALUE	FREQUENCY	PERCENT
0 (OVERALL)	0.10049	21503	100
1	0.11379	2306	10.7
2	0.05670	1964	9.1
3	0.08970	2519	11.7
4	0.03451	2619	12.2
5	0.09020	2626	12.2
6	0.11327	2293	10.7
7	0.12575	3184	14.8
8	0.12910	2358	11.0
9	0.16486	1634	7.6

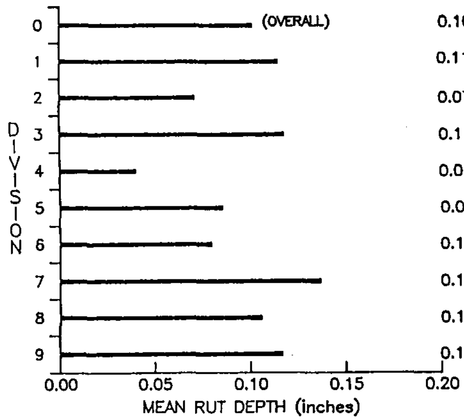


DIVISION	VALUE (x 10^7)	FREQUENCY	PERCENT
0 (OVERALL)	11.424	21266	100
1	12.951	2297	10.8
2	11.190	1956	9.2
3	8.727	2429	11.4
4	2.422	2597	12.2
5	8.160	2590	12.2
6	9.996	2287	10.8
7	10.272	3148	14.8
8	21.869	2338	11.0
9	22.385	1624	7.6

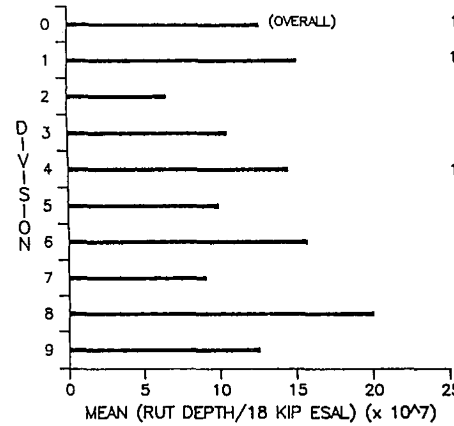


DIVISION	VALUE (x 10^7)	FREQUENCY	PERCENT
0 (OVERALL)	2.551	21266	100
1	2.682	2297	10.8
2	1.239	1956	9.2
3	1.573	2429	11.4
4	1.265	2597	12.2
5	2.868	2590	12.2
6	2.083	2287	10.8
7	3.291	3148	14.8
8	5.332	2338	11.0
9	4.567	1624	7.6

1984 DATA
STATE
OUTER LANES

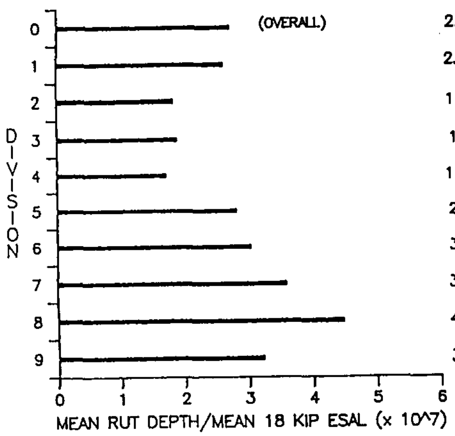


Division	VALUE	FREQUENCY	PERCENT
0 (OVERALL)	0.10070	20801	100
1	0.11415	2324	11.1
2	0.07082	1917	9.2
3	0.11765	2362	11.4
4	0.04012	2600	12.5
5	0.08545	2453	11.8
6	0.11595	2266	10.9
7	0.13654	3113	15.0
8	0.10545	2232	10.7
9	0.11646	1534	7.4

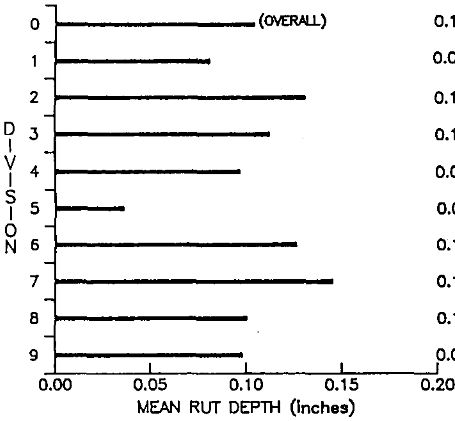


Division	VALUE (x 10^7)	FREQUENCY	PERCENT
0 (OVERALL)	12.601	20607	100
1	15.062	2315	11.2
2	6.525	1911	9.3
3	10.498	2306	11.2
4	14.461	2578	12.5
5	9.953	2418	11.7
6	15.705	2260	11.0
7	9.031	3081	15.0
8	20.022	2214	10.7
9	12.551	1524	7.4

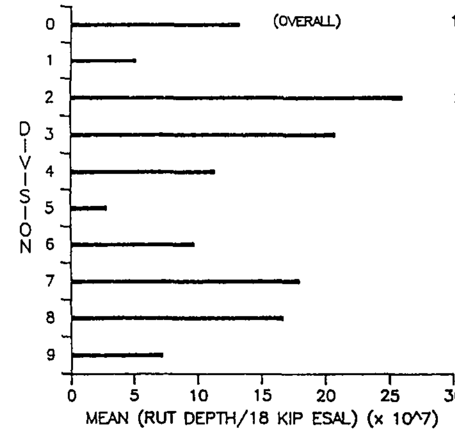
1986 DATA
STATE
OUTER LANES



Division	VALUE (x 10^7)	FREQUENCY	PERCENT
0 (OVERALL)	2.720	20607	100
1	2.629	2315	11.2
2	1.835	1911	9.3
3	1.888	2306	11.2
4	1.718	2578	12.5
5	2.815	2418	11.7
6	3.028	2260	11.0
7	3.581	3081	15.0
8	4.475	2214	10.7
9	3.220	1524	7.4

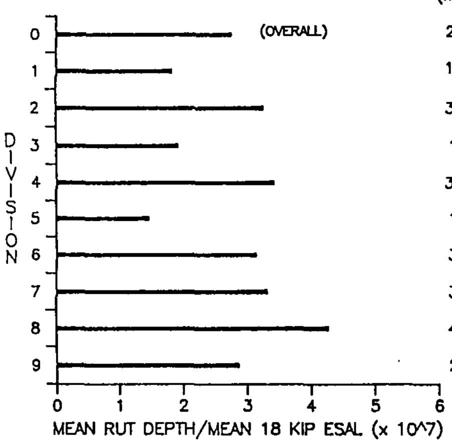


VALUE	FREQUENCY	PERCENT
0.10409	20260	100
0.08088	2254	11.1
0.13043	1861	9.2
0.11225	2409	11.9
0.09697	2502	12.3
0.03597	2235	11.0
0.12609	2113	10.4
0.14509	3073	15.2
0.10001	2242	11.1
0.09802	1571	7.8

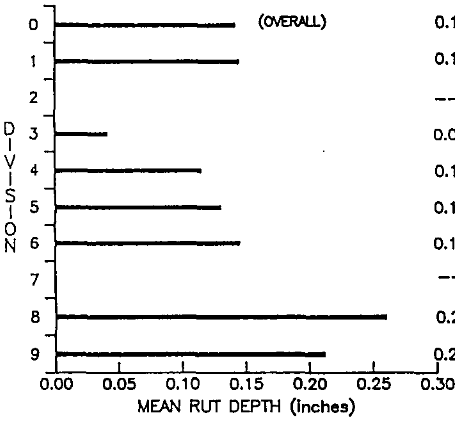


VALUE (x 10^7)	FREQUENCY	PERCENT
13.283	20112	100
5.118	2244	11.2
26.030	1861	9.3
20.816	2361	11.7
11.354	2481	12.3
28 570	2210	11.0
9.678	2104	10.5
17.934	3044	15.1
16.677	2238	11.1
7.215	1569	7.8

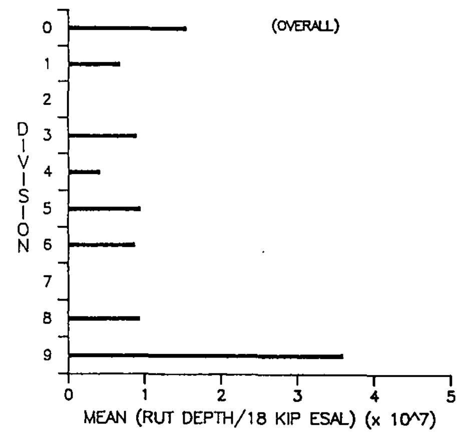
1988 DATA
STATE
OUTER LANES



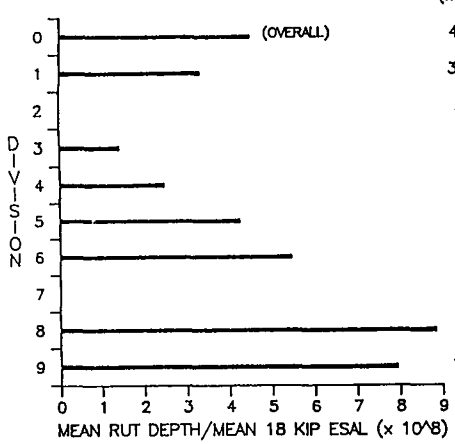
VALUE (x 10^7)	FREQUENCY	PERCENT
2.739	20260	100
1.811	2254	11.1
3.251	1861	9.2
1.913	2409	11.9
3.405	2502	12.3
1.453	2235	11.0
3.128	2113	10.4
3.299	3073	15.2
4.259	2242	11.1
2.863	1571	7.8



DIVISION	VALUE	FREQUENCY	PERCENT
0 (OVERALL)	0.14067	1180	100
1	0.14410	105	8.9
2	-----	---	---
3	0.04131	227	19.2
4	0.11477	108	9.2
5	0.12970	235	19.9
6	0.14508	150	12.7
7	-----	---	---
8	0.25944	36	3.1
9	0.21164	319	27.0

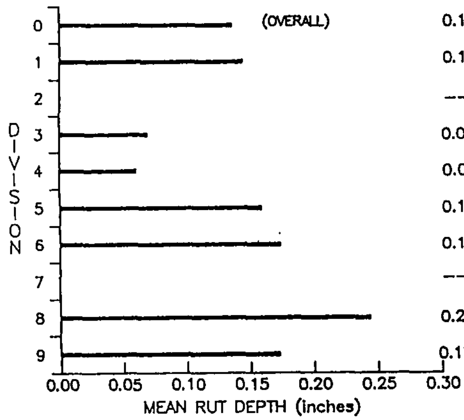


DIVISION	VALUE (x 10^7)	FREQUENCY	PERCENT
0 (OVERALL)	1.54	1148	100
1	0.671	103	9.0
2	---	---	---
3	0.894	217	18.9
4	0.414	108	9.4
5	0.951	235	20.4
6	0.870	150	13.1
7	---	---	---
8	0.932	36	3.1
9	3.588	299	26.0

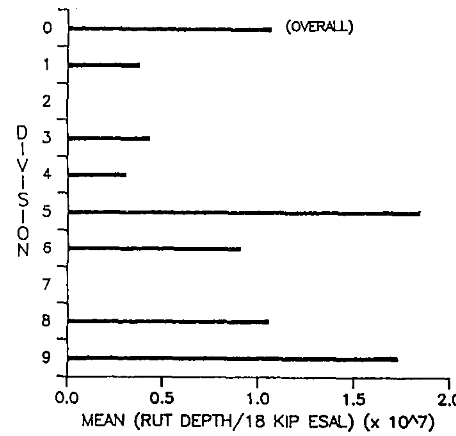


DIVISION	VALUE (x 10^8)	FREQUENCY	PERCENT
0 (OVERALL)	4.477	1148	100
1	3.307	103	9.09
2	---	---	---
3	1.411	217	18.9
4	2.471	108	9.4
5	4.247	235	20.5
6	5.450	150	13.1
7	---	---	---
8	8.841	36	3.1
9	7.925	299	26.0

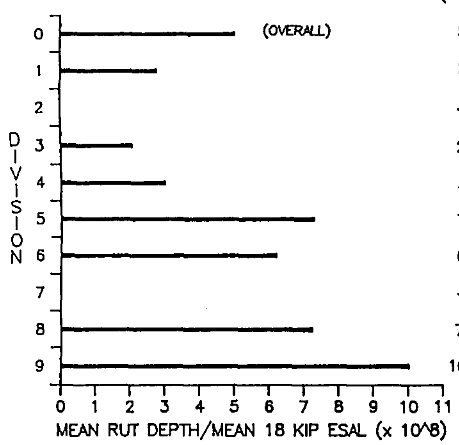
1984 DATA
INTERSTATE
OUTER LANES



DIVISION	VALUE	FREQUENCY	PERCENT
0	0.13526	1203	100
1	0.14377	103	8.6
2	-----	---	---
3	0.06952	286	23.8
4	0.06056	110	9.1
5	0.15843	206	17.1
6	0.17318	149	12.4
7	-----	---	---
8	0.24343	39	3.2
9	0.17236	310	25.8

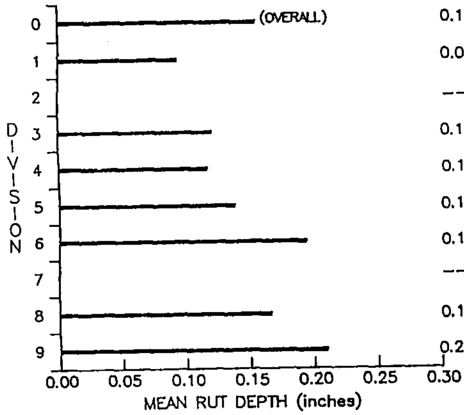


DIVISION	VALUE (x 10^7)	FREQUENCY	PERCENT
0	1.068	1167	100
1	0.378	101	8.7
2	---	---	---
3	0.433	272	23.3
4	0.309	110	9.4
5	1.844	206	17.7
6	0.907	149	12.8
7	---	---	---
8	1.056	39	3.3
9	1.726	290	24.9

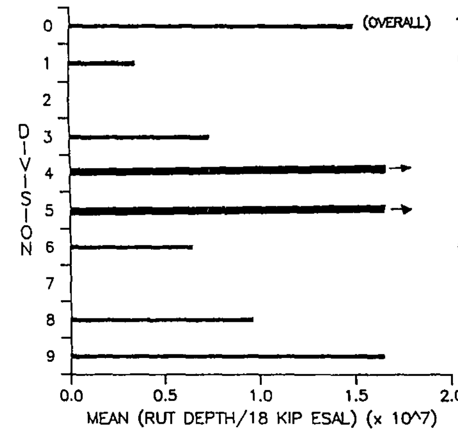


DIVISION	VALUE (x 10^8)	FREQUENCY	PERCENT
0	5.037	1167	100
1	2.798	101	8.7
2	---	---	---
3	2.089	272	23.3
4	3.031	110	9.4
5	7.314	206	17.7
6	6.232	149	12.8
7	---	---	---
8	7.257	39	3.3
9	10.027	290	24.9

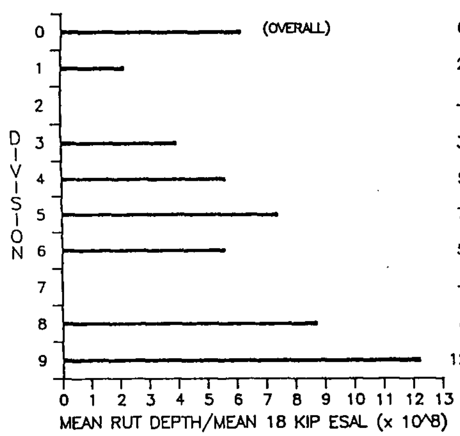
1986 DATA
INTERSTATE
OUTER LANES



DIVISION	VALUE	FREQUENCY	PERCENT
0 (OVERALL)	0.15561	1189	100
1	0.09427	101	8.5
2	-----	---	---
3	0.12112	271	22.8
4	0.11757	112	9.4
5	0.13849	198	16.7
6	0.19417	147	12.4
7	-----	---	---
8	0.16616	43	3.6
9	0.20947	317	26.7



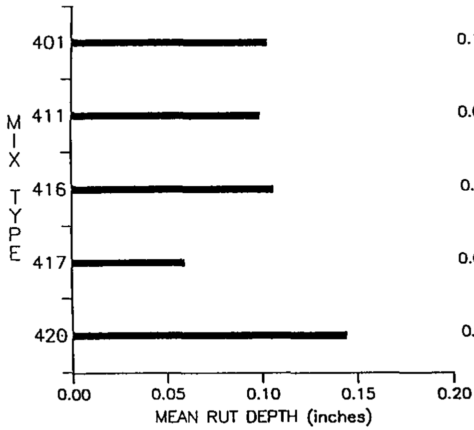
DIVISION	VALUE (x 10^7)	FREQUENCY	PERCENT
0 (OVERALL)	1.488	1189	100
1	0.349	101	8.5
2	---	---	---
3	0.738	271	22.8
4	2.976	112	9.4
5	2.738	198	16.7
6	0.649	147	12.4
7	---	---	---
8	0.963	43	3.6
9	1.648	317	26.7



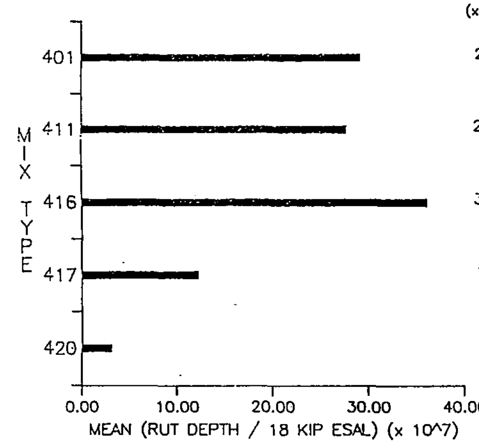
DIVISION	VALUE (x 10^8)	FREQUENCY	PERCENT
0 (OVERALL)	6.139	1189	100
1	2.164	101	8.5
2	---	---	---
3	3.953	271	22.8
4	5.607	112	9.4
5	7.382	198	16.7
6	5.581	147	12.4
7	---	---	---
8	8.707	43	3.6
9	12.208	317	26.7

1988 DATA
INTERSTATE
OUTER LANES

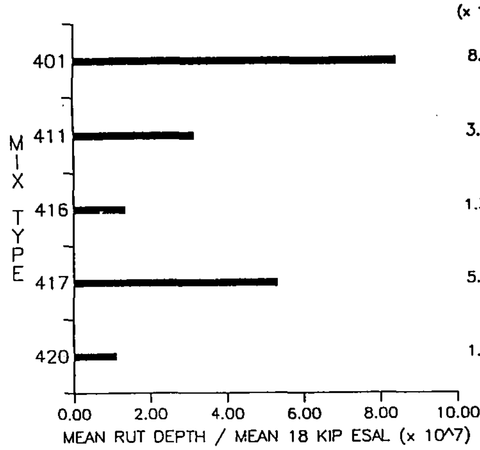
DATA SORTED BY MIX TYPE



VALUE	FREQUENCY	PERCENT
0.10233	1284	6.0
0.09868	11376	53.4
0.10549	7411	34.8
0.05932	22	0.1
0.14392	822	3.9

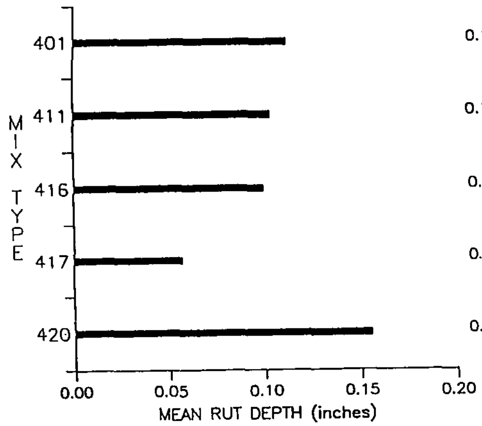


VALUE (x 10^7)	FREQUENCY	PERCENT
29.208	1208	5.7
27.705	10866	51.0
36.118	6821	32.0
12.296	10	0.05
3.137	804	3.8

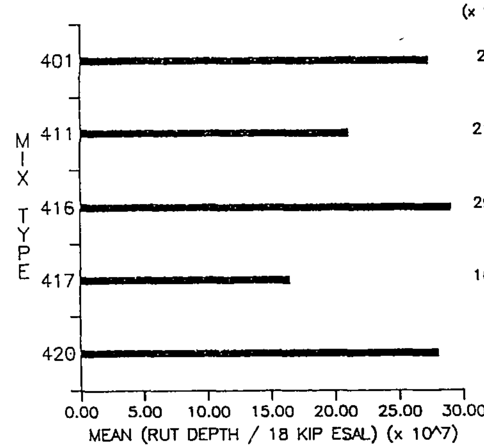


VALUE (x 10^7)	FREQUENCY	PERCENT
8.422	1210	5.7
3.168	10941	51.3
1.354	6883	32.3
5.304	10	0.05
1.109	818	3.8

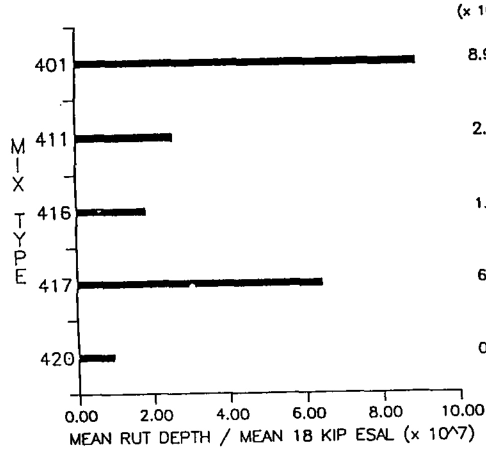
1984 DATA
STATE AND INTERSTATE
OUTER LANES



VALUE	FREQUENCY	PERCENT
0.11132	1178	5.3
0.10276	9514	42.8
0.09902	10566	47.6
0.05688	179	0.8
0.15543	668	3.0

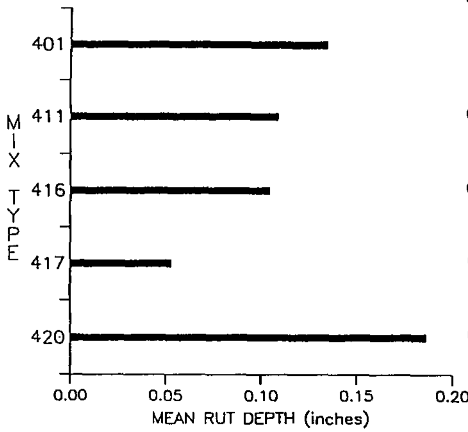


VALUE (x 10^7)	FREQUENCY	PERCENT
27.318	1112	5.0
21.025	7868	35.4
29.054	9680	43.6
16.453	163	0.7
2.803	580	2.6

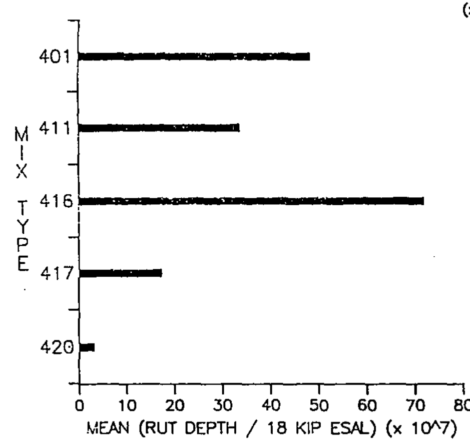


VALUE (x 10^7)	FREQUENCY	PERCENT
8.908	1112	5.0
2.542	7921	35.7
1.813	9787	44.1
6.401	163	0.7
0.941	594	2.7

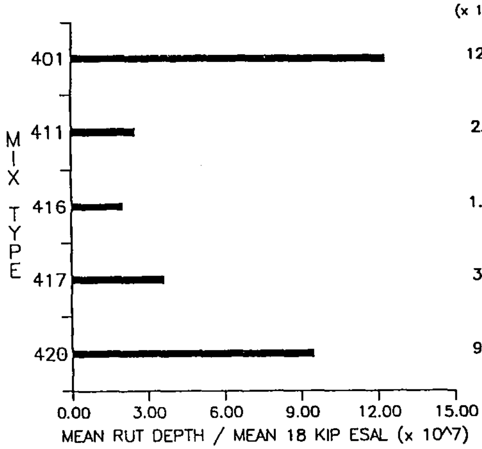
1986 DATA
STATE AND INTERSTATE
OUTER LANES



VALUE	FREQUENCY	PERCENT
0.13422	876	4.1
0.10879	6628	30.7
0.10436	12687	58.9
0.05307	769	3.6
0.18605	456	2.1

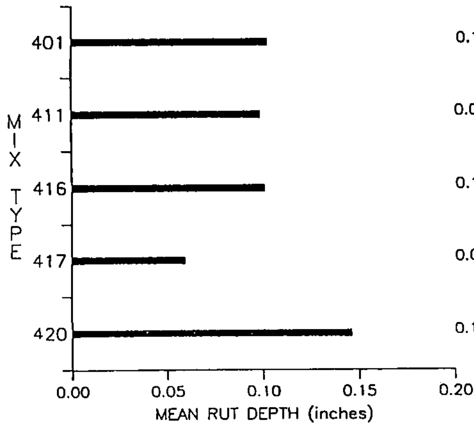


VALUE (x 10^7)	FREQUENCY	PERCENT
48.462	876	4.1
33.739	6556	30.4
71.959	12552	58.2
17.292	769	3.6
3.086	456	2.1

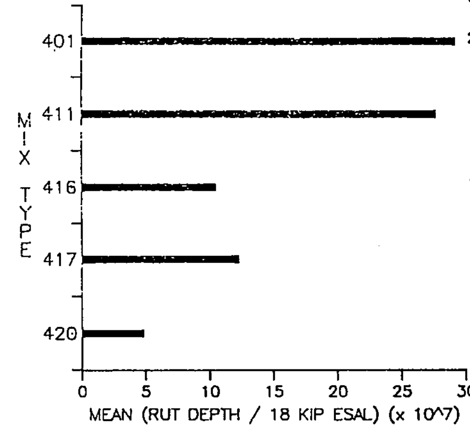


VALUE (x 10^7)	FREQUENCY	PERCENT
12.288	876	4.1
2.503	6605	30.6
1.997	12651	58.7
3.622	769	3.5
9.455	456	2.1

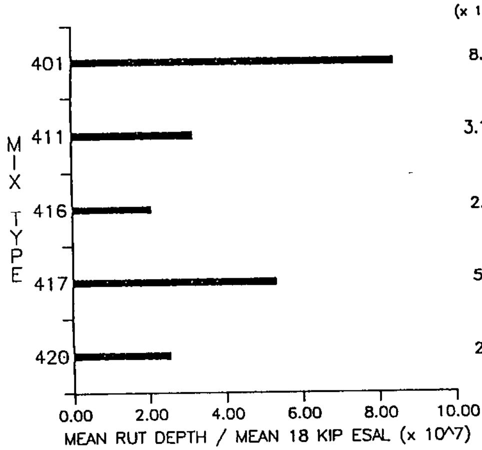
1988 DATA
STATE AND INTERSTATE
OUTER LANES



VALUE	FREQUENCY	PERCENT
0.10233	1284	6.4
0.09868	11376	56.6
0.10090	6542	32.5
0.05932	22	0.1
0.14604	491	2.4

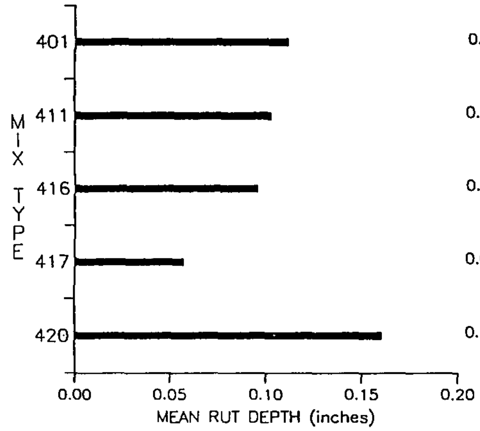


VALUE (x 10^7)	FREQUENCY	PERCENT
29.208	1208	6.0
27.705	10866	54.0
10.519	5952	29.6
12.296	10	0.05
4.813	473	2.4

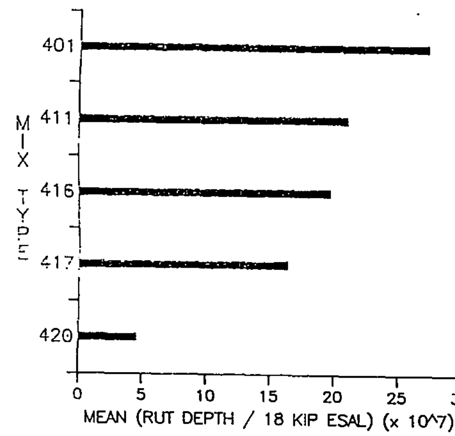


VALUE (x 10^7)	FREQUENCY	PERCENT
8.422	1210	6.0
3.168	10941	54.4
2.068	6014	29.9
5.304	10	0.05
2.529	487	2.4

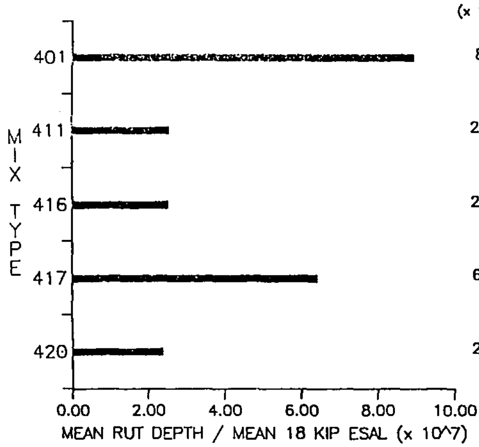
1984 DATA
STATE
OUTER LANES



VALUE	FREQUENCY	PERCENT
0.11132	1178	5.6
0.10276	9514	45.3
0.09569	9603	45.8
0.05688	179	0.9
0.16030	410	2.0

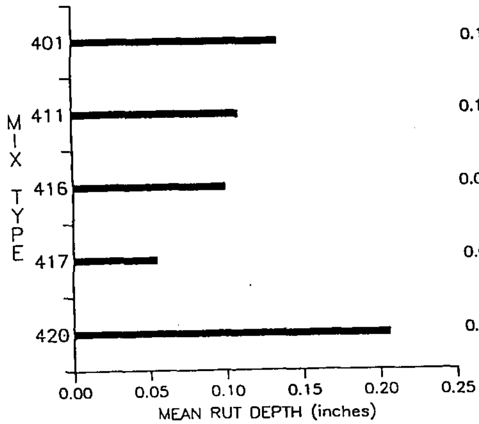


VALUE (x 10^7)	FREQUENCY	PERCENT
27.318	1112	5.3
21.025	7868	37.5
19.719	8717	41.5
16.453	163	0.8
4.546	322	1.5

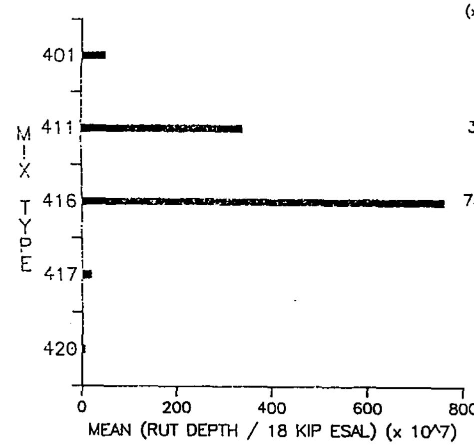


VALUE (x 10^7)	FREQUENCY	PERCENT
8.908	1112	5.3
2.542	7921	37.7
2.501	8824	42.0
6.401	163	0.8
2.385	336	1.6

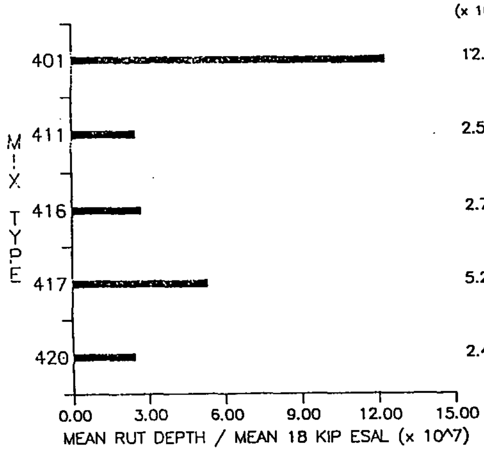
1986 DATA
STATE
OUTER LANES



VALUE	FREQUENCY	PERCENT
0.13422	876	4.3
0.10879	6628	32.6
0.09981	11700	54.5
0.05463	747	3.7
0.20596	271	1.3

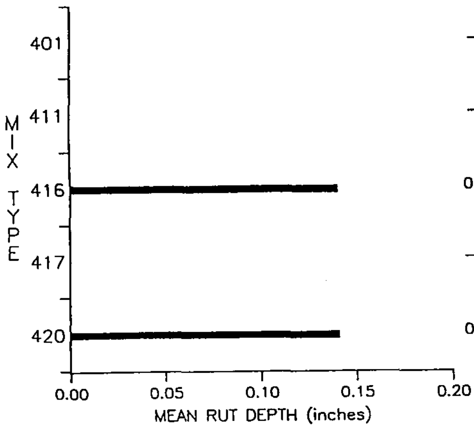


VALUE (x 10^7)	FREQUENCY	PERCENT
48.462	876	4.3
337.393	6556	32.2
759.497	11565	56.8
17.802	747	3.7
4.896	271	1.3

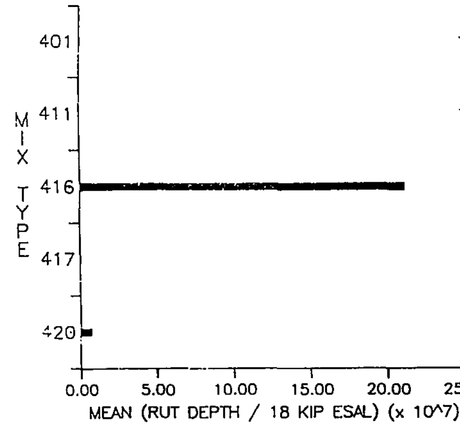


VALUE (x 10^7)	FREQUENCY	PERCENT
12.288	876	4.3
2.503	6605	32.4
2.716	11664	57.3
5.295	747	3.7
2.439	271	1.3

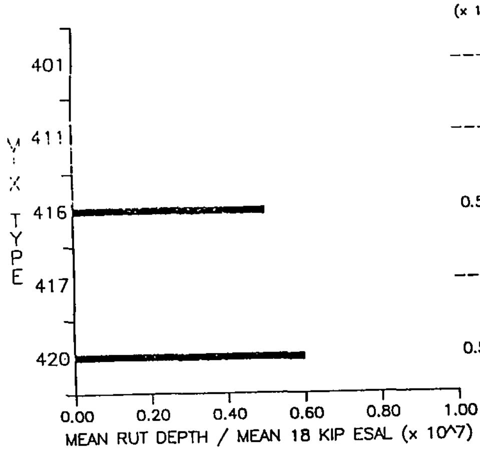
1988 DATA
STATE
OUTER LANES



VALUE	FREQUENCY	PERCENT
---	---	---
---	---	---
0.14003	869	73.6
---	---	---
0.14076	331	28.1

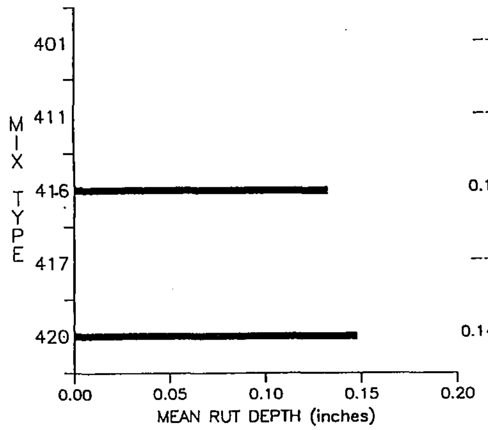


VALUE (x 10^7)	FREQUENCY	PERCENT
----	----	----
----	----	----
21.145	869	73.6
----	----	----
0.742	331	28.1

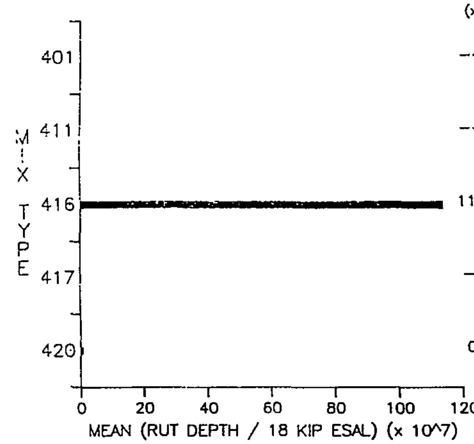


VALUE (x 10^7)	FREQUENCY	PERCENT
----	----	----
----	----	----
0.501	869	73.6
----	----	----
0.597	331	28.1

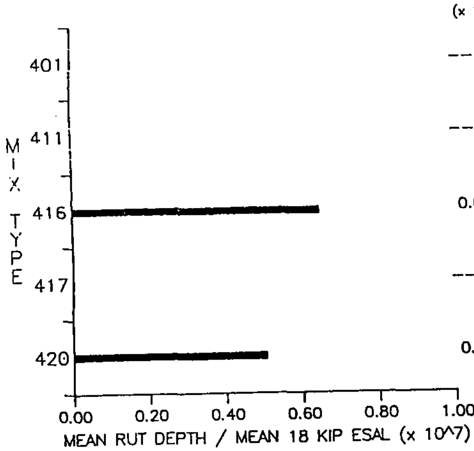
1984 DATA
INTERSTATE
OUTER LANES



VALUE	FREQUENCY	PERCENT
---	---	---
---	---	---
0.13224	963	80.0
---	---	---
0.14768	258	21.4

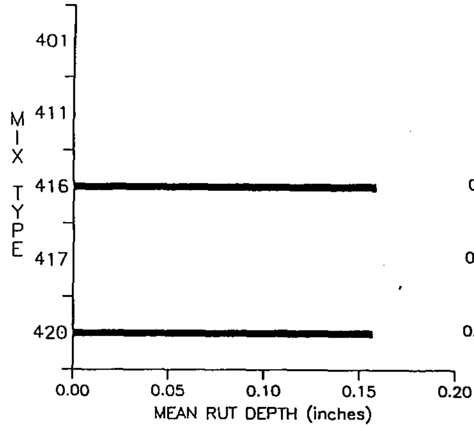


VALUE (x 10^7)	FREQUENCY	PERCENT
----	----	----
----	----	----
113.560	963	80.0
----	----	----
0.627	258	21.4

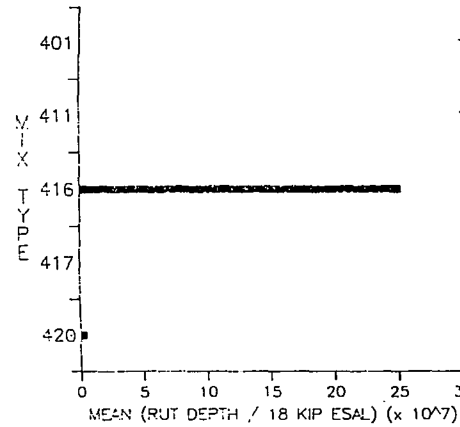


VALUE (x 10^7)	FREQUENCY	PERCENT
----	----	----
----	----	----
0.647	963	80.0
----	----	----
0.505	258	21.4

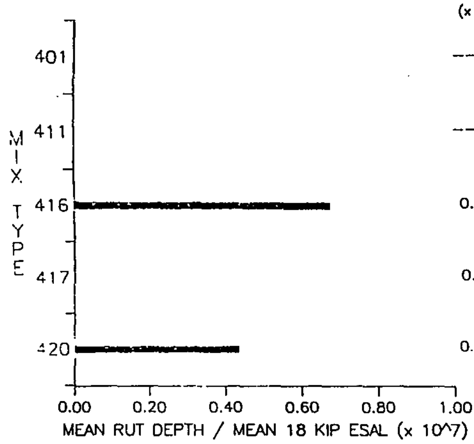
1986 DATA
INTERSTATE
OUTER LANES



VALUE	FREQUENCY	PERCENT
---	---	---
---	---	---
0.15840	987	83
0.00000	22	1.9
0.15689	185	15.6



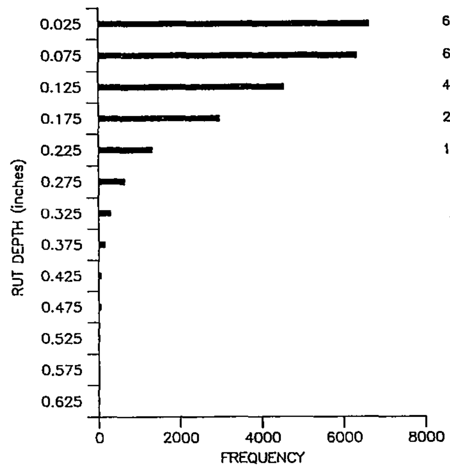
VALUE (x 10^7)	FREQUENCY	PERCENT
----	----	----
----	----	----
25.196	987	83.0
0.000	22	1.9
0.436	185	15.6



VALUE (x 10^7)	FREQUENCY	PERCENT
----	----	----
----	----	----
0.672	987	83.0
0.000	22	1.9
0.434	185	15.6

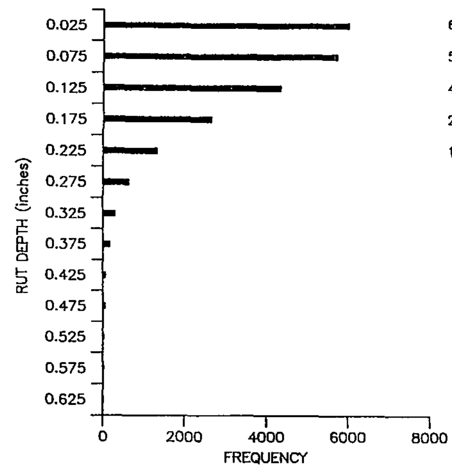
1988 DATA
INTERSTATE
OUTER LANES

FREQUENCY DISTRIBUTIONS



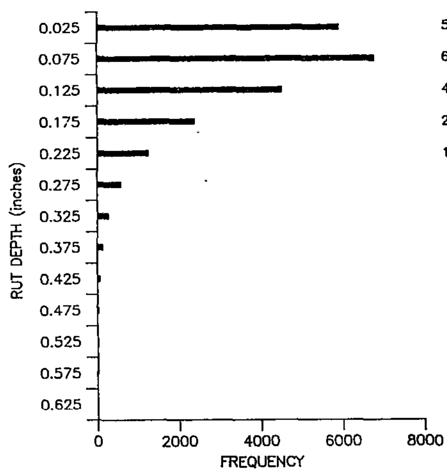
RUT DEPTH	FREQ	CUM. FREQ	PERCENT	CUM. PERCENT
0.025	6626	6626	29.21	29.21
0.075	6319	12945	27.86	57.07
0.125	4541	17486	20.02	77.09
0.175	2654	20140	11.70	88.79
0.225	1317	21457	5.81	94.60
0.275	634	22091	2.80	97.39
0.325	293	22384	1.29	98.68
0.375	146	22530	0.64	99.33
0.425	68	22598	0.30	99.63
0.475	46	22644	0.20	99.83
0.525	21	22665	0.09	99.92
0.575	8	22673	0.04	99.96
0.625	10	22683	0.04	100.00

1984 DATA



RUT DEPTH	FREQ	CUM. FREQ	PERCENT	CUM. PERCENT
0.025	6024	6024	28.09	28.09
0.075	5733	11757	26.73	54.81
0.125	4367	16124	20.36	75.17
0.175	2666	18790	12.43	87.60
0.225	1340	20130	6.25	93.85
0.275	641	20771	2.99	96.84
0.325	307	21078	1.43	98.27
0.375	176	21254	0.82	99.09
0.425	78	21332	0.36	99.45
0.475	54	21386	0.25	99.71
0.525	25	21411	0.12	99.82
0.575	19	21430	0.09	99.91
0.625	19	21449	0.09	100.00

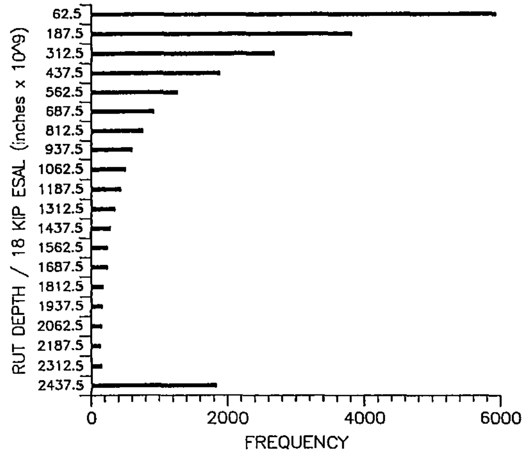
1988 DATA



RUT DEPTH	FREQ	CUM. FREQ	PERCENT	CUM. PERCENT
0.025	5910	5910	26.86	26.86
0.075	6778	12688	30.80	57.66
0.125	4513	17201	20.51	78.17
0.175	2386	19587	10.84	89.02
0.225	1257	20844	5.71	94.73
0.275	590	21434	2.68	97.41
0.325	273	21707	1.24	98.65
0.375	145	21852	0.66	99.31
0.425	68	21920	0.31	99.62
0.475	41	21961	0.19	99.80
0.525	26	21987	0.12	99.92
0.575	11	21998	0.05	99.97
0.625	6	22004	0.03	100.00

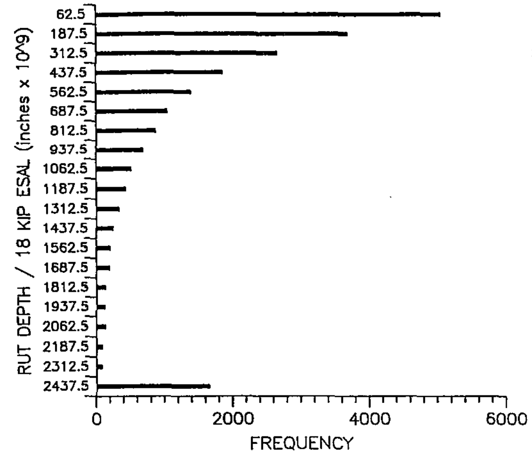
1986 DATA

STATE AND INTERSTATE
OUTER LANES



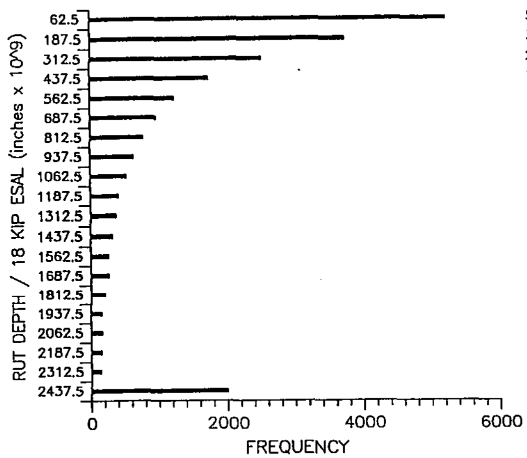
RUT DEPTH	FREQ	CUM. FREQ.	PERCENT	CUM. PERCENT
62.5	5925	5925	26.43	26.43
187.5	3808	9733	16.99	43.42
312.5	2676	12409	11.94	55.36
437.5	1882	14291	8.40	63.76
562.5	1265	15556	5.64	69.40
687.5	912	16468	4.07	73.47
812.5	752	17220	3.36	76.83
937.5	600	17820	2.68	79.50
1062.5	498	18318	2.22	81.73
1187.5	427	18745	1.91	83.63
1312.5	340	19085	1.52	85.15
1437.5	279	19364	1.24	86.39
1562.5	235	19599	1.05	87.44
1687.5	237	19836	1.06	88.50
1812.5	168	20004	0.75	89.25
1937.5	154	20158	0.69	89.93
2062.5	152	20310	0.68	90.61
2187.5	129	20439	0.58	91.19
2312.5	147	20586	0.66	91.84
2437.5	1828	22414	8.16	100.00

1984 DATA



RUT DEPTH	FREQ	CUM. FREQ.	PERCENT	CUM. PERCENT
62.5	5056	5056	23.74	23.74
187.5	3685	8741	17.30	41.04
312.5	2649	11390	12.44	53.47
437.5	1852	13242	8.69	62.17
562.5	1385	14627	6.50	68.67
687.5	1036	15663	4.86	73.53
812.5	864	16527	4.06	77.59
937.5	686	17213	3.22	80.81
1062.5	508	17721	2.38	83.19
1187.5	424	18145	1.99	85.18
1312.5	328	18473	1.54	86.72
1437.5	244	18717	1.15	87.87
1562.5	201	18918	0.94	88.81
1687.5	192	19110	0.90	89.71
1812.5	133	19243	0.62	90.34
1937.5	117	19360	0.55	90.89
2062.5	127	19487	0.60	91.48
2187.5	83	19570	0.39	91.87
2312.5	79	19649	0.37	92.24
2437.5	1652	21301	7.76	100.00

1988 DATA

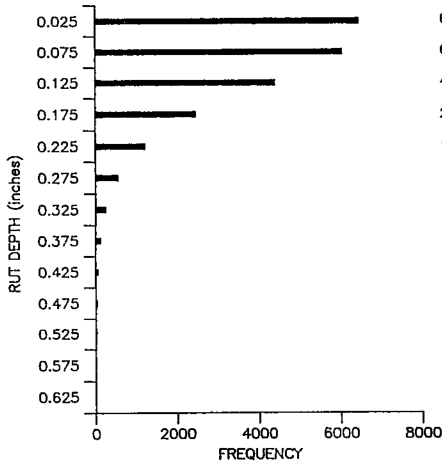


RUT DEPTH	FREQ	CUM. FREQ.	PERCENT	CUM. PERCENT
62.5	5216	5216	23.96	23.96
187.5	3731	8947	17.14	41.09
312.5	2515	11462	11.55	52.64
437.5	1742	13204	8.00	60.64
562.5	1235	14439	5.67	66.31
687.5	967	15406	4.44	70.75
812.5	772	16178	3.55	74.30
937.5	636	16814	2.92	77.22
1062.5	529	17343	2.43	79.65
1187.5	413	17756	1.90	81.55
1312.5	370	18126	1.70	83.25
1437.5	322	18448	1.48	84.72
1562.5	259	18707	1.19	85.91
1687.5	260	18967	1.19	87.11
1812.5	204	19171	0.94	88.05
1937.5	154	19325	0.71	88.75
2062.5	161	19486	0.74	89.49
2187.5	153	19639	0.70	90.19
2312.5	137	19776	0.63	90.82
2437.5	1998	21774	9.18	100.00

1986 DATA

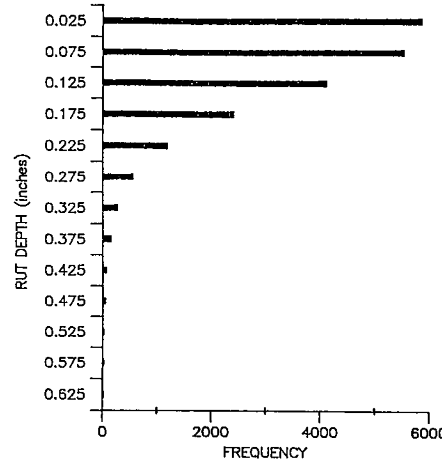
STATE AND INTERSTATE OUTER LANES

STATE ROUTES OUTER LANES



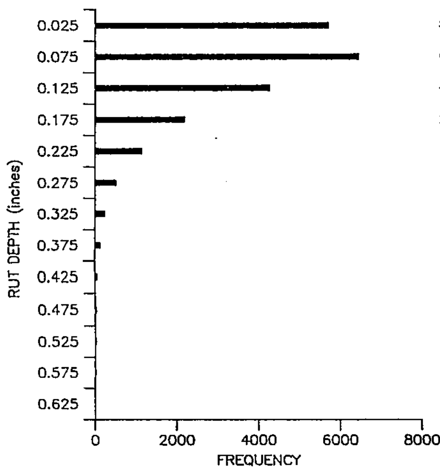
FREQ	CUM. FREQ	PERCENT	CUM. PERCENT
6442	6442	29.96	29.96
6038	12480	28.08	58.04
4289	16769	19.95	77.98
2450	19219	11.39	89.38
1212	20431	5.64	95.01
553	20984	2.57	97.59
255	21239	1.19	98.77
130	21369	0.60	99.38
61	21430	0.28	99.66
36	21466	0.17	99.83
20	21486	0.09	99.92
8	21494	0.04	99.96
9	21503	0.04	100.00

1984 DATA



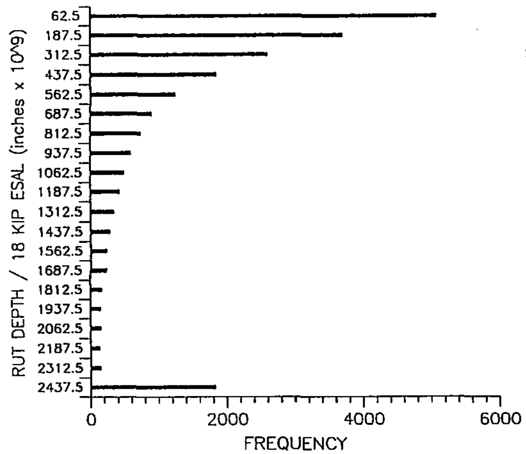
FREQ	CUM. FREQ	PERCENT	CUM. PERCENT
5852	5852	28.88	28.88
5532	11384	27.31	56.19
4123	15507	20.35	76.54
2414	17921	11.92	88.46
1203	19124	5.94	94.39
553	19677	2.73	97.12
269	19946	1.33	98.45
152	20098	0.75	99.20
62	20160	0.31	99.51
47	20207	0.23	99.74
20	20227	0.10	99.84
16	20243	0.08	99.92
17	20260	0.08	100.00

1988 DATA



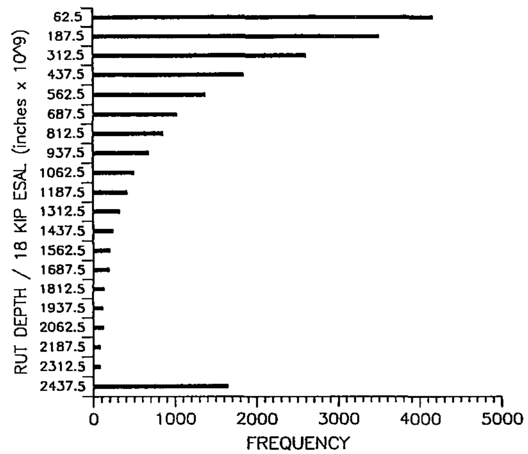
FREQ	CUM. FREQ	PERCENT	CUM. PERCENT
5715	5715	27.47	27.47
6454	12169	31.03	58.50
4272	16441	20.54	79.04
2199	18640	10.57	89.61
1142	19782	5.49	95.10
518	20300	2.49	97.59
241	20541	1.16	98.75
130	20671	0.62	99.38
59	20730	0.28	99.66
32	20762	0.15	99.81
24	20786	0.12	99.93
10	20796	0.05	99.98
5	20801	0.02	100.00

1986 DATA



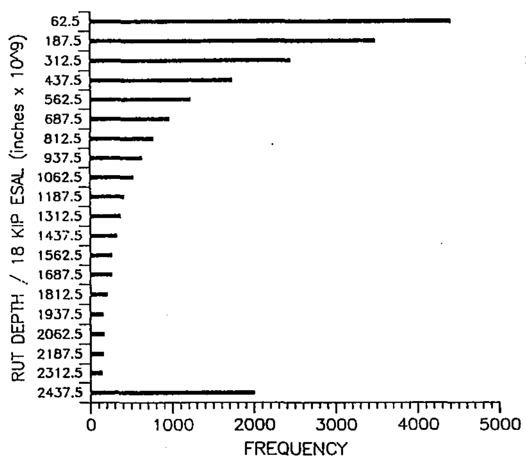
FREQ	CUM. FREQ.	PERCENT	CUM. PERCENT
5078	5078	23.88	23.88
3699	8777	17.39	41.27
2598	11375	12.22	53.49
1847	13222	8.69	62.17
1245	14467	5.85	68.03
900	15367	4.23	72.26
740	16107	3.48	75.74
591	16698	2.78	78.52
490	17188	2.30	80.82
426	17614	2.00	82.83
339	17953	1.59	84.42
279	18232	1.31	85.73
231	18463	1.09	86.82
237	18700	1.11	87.93
167	18867	0.79	88.72
147	19014	0.69	89.41
152	19166	0.71	90.13
129	19295	0.61	90.73
145	19440	0.68	91.41
1826	21266	8.59	100.00

1984 DATA



FREQ	CUM. FREQ.	PERCENT	CUM. PERCENT
4166	4166	20.71	20.71
3503	7669	17.42	38.13
2605	10274	12.95	51.08
1841	12115	9.15	60.24
1377	13492	6.85	67.08
1026	14518	5.10	72.19
860	15378	4.28	76.46
684	16062	3.40	79.86
503	16565	2.50	82.36
419	16984	2.08	84.45
325	17309	1.62	86.06
239	17548	1.19	87.25
200	17748	0.99	88.25
189	17937	0.94	89.19
132	18069	0.66	89.84
113	18182	0.56	90.40
123	18305	0.61	91.02
82	18387	0.41	91.42
78	18465	0.39	91.81
1647	20112	8.19	100.00

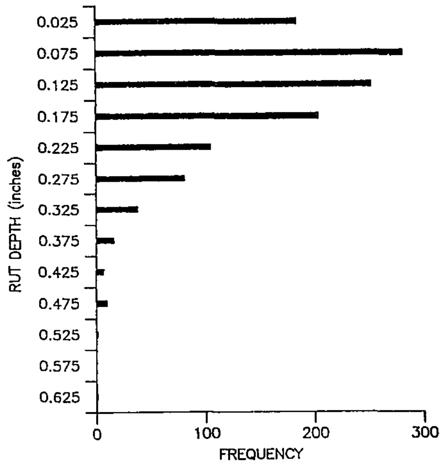
1988 DATA



FREQ	CUM. FREQ.	PERCENT	CUM. PERCENT
4409	4409	21.40	21.40
3481	7890	16.89	38.29
2444	10334	11.86	50.15
1730	12064	8.40	58.54
1221	13285	5.93	64.47
958	14243	4.65	69.12
770	15013	3.74	72.85
634	15647	3.08	75.93
529	16176	2.57	78.50
413	16589	2.00	80.50
370	16959	1.80	82.30
322	17281	1.56	83.86
259	17540	1.26	85.12
260	17800	1.26	86.38
204	18004	0.99	87.37
154	18158	0.75	88.12
161	18319	0.78	88.90
153	18472	0.74	89.64
137	18609	0.66	90.30
1998	20607	9.70	100.00

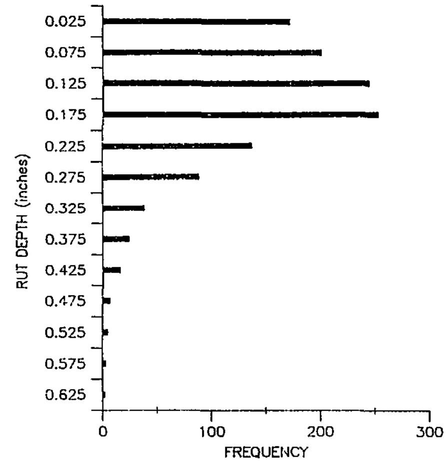
1986 DATA

STATE ROUTES
OUTER LANES



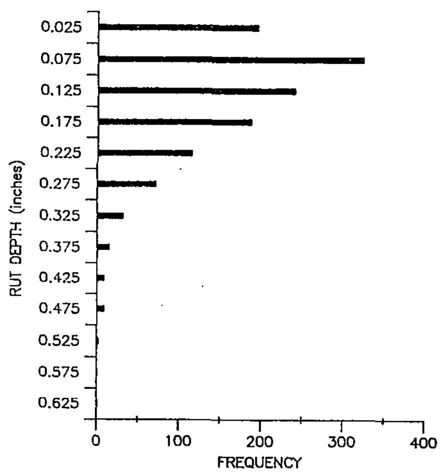
FREQ	CUM. FREQ	PERCENT	CUM. PERCENT
184	184	15.59	15.59
281	465	23.81	39.41
252	717	21.36	60.76
204	921	17.29	78.05
105	1026	8.90	86.95
81	1107	6.86	93.81
38	1145	3.22	97.03
16	1161	1.36	98.39
7	1168	0.59	98.98
10	1178	0.85	99.83
1	1179	0.08	99.92
0	1179	0.00	99.92
1	1180	0.08	100.00

1984 DATA



FREQ	CUM. FREQ	PERCENT	CUM. PERCENT
172	172	14.47	14.47
201	373	16.90	31.37
244	617	20.52	51.89
252	869	21.19	73.09
137	1006	11.52	84.61
88	1094	7.40	92.01
38	1132	3.20	95.21
24	1156	2.02	97.22
16	1172	1.35	98.57
7	1179	0.59	99.16
5	1184	0.42	99.58
3	1187	0.25	99.83
2	1189	0.17	100.00

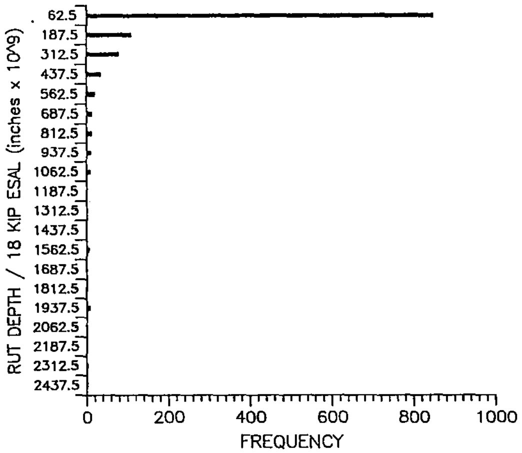
1988 DATA



FREQ	CUM. FREQ	PERCENT	CUM. PERCENT
195	195	16.21	16.21
324	519	26.93	43.14
241	760	20.03	63.18
187	947	15.54	78.72
115	1062	9.56	88.28
72	1134	5.99	94.26
32	1166	2.66	96.92
15	1181	1.25	98.17
9	1190	0.75	98.92
9	1199	0.75	99.67
2	1201	0.17	99.83
1	1202	0.08	99.92
1	1203	0.08	100.00

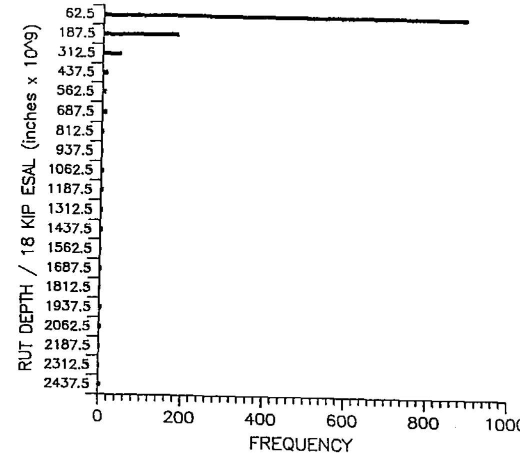
1986 DATA

INTERSTATE ROUTES
OUTER LANES



FREQ	CUM. FREQ.	PERCENT	CUM. PERCENT
847	847	73.78	73.78
109	956	9.49	83.28
78	1034	6.79	90.07
35	1069	3.05	93.12
20	1089	1.74	94.86
12	1101	1.05	95.91
12	1113	1.05	96.95
9	1122	0.78	97.74
8	1130	0.70	98.43
1	1131	0.09	98.52
1	1132	0.09	98.61
0	1132	0.00	98.61
4	1136	0.35	98.95
0	1136	0.00	98.95
1	1137	0.09	99.04
7	1144	0.61	99.65
0	1144	0.00	99.65
0	1144	0.00	99.65
2	1146	0.17	99.83
2	1148	0.17	100.00

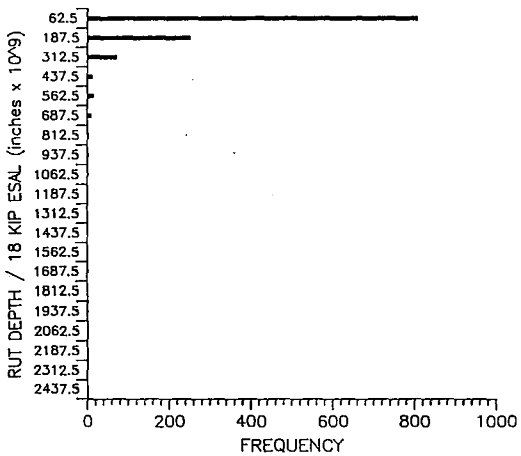
1984 DATA



FREQ	CUM. FREQ.	PERCENT	CUM. PERCENT
890	890	74.85	74.85
182	1072	15.31	90.16
44	1116	3.70	93.86
11	1127	0.93	94.79
8	1135	0.67	95.46
10	1145	0.84	96.30
4	1149	0.34	96.64
2	1151	0.17	96.80
5	1156	0.42	97.22
5	1161	0.42	97.65
3	1164	0.25	97.90
5	1169	0.42	98.32
1	1170	0.08	98.40
3	1173	0.25	98.65
1	1174	0.08	98.74
4	1178	0.34	99.07
4	1182	0.34	99.41
1	1183	0.08	99.50
1	1184	0.08	99.58
5	1189	0.42	100.00

1988 DATA

INTERSTATE ROUTES OUTER LANES

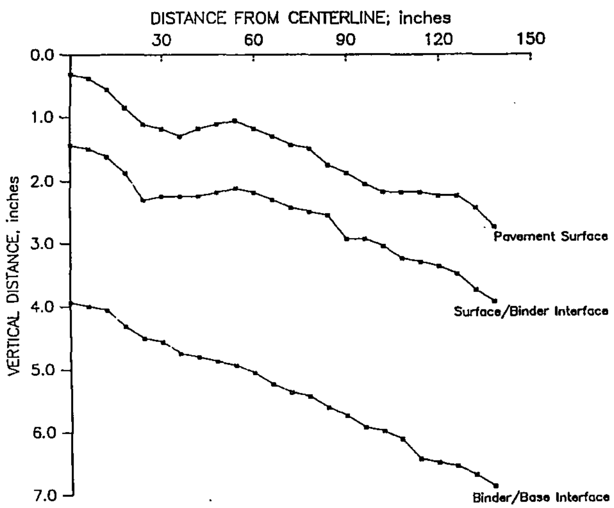


FREQ	CUM. FREQ.	PERCENT	CUM. PERCENT
807	807	69.15	69.15
250	1057	21.42	90.57
71	1128	6.08	96.66
12	1140	1.03	97.69
14	1154	1.20	98.89
9	1163	0.77	99.66
2	1165	0.17	99.83
2	1167	0.17	100.00
0	1167	0.00	100.00
0	1167	0.00	100.00
0	1167	0.00	100.00
0	1167	0.00	100.00
0	1167	0.00	100.00
0	1167	0.00	100.00
0	1167	0.00	100.00
0	1167	0.00	100.00
0	1167	0.00	100.00
0	1167	0.00	100.00
0	1167	0.00	100.00
0	1167	0.00	100.00

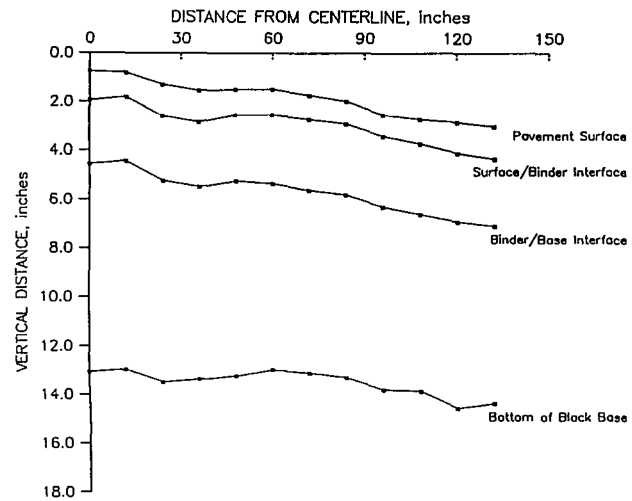
1986 DATA

APPENDIX B

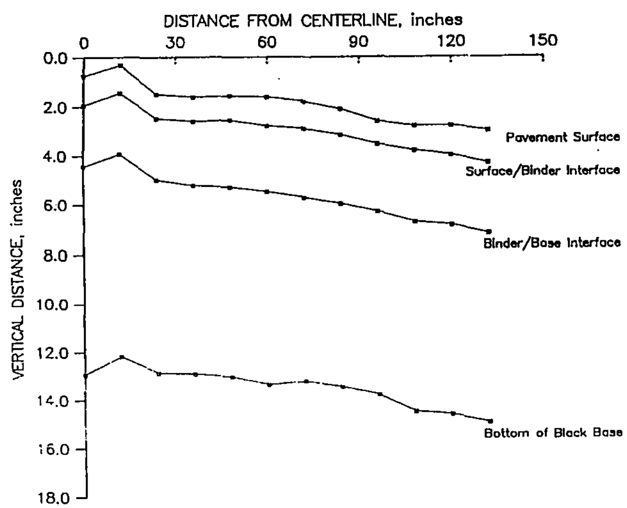
LAYER PROFILES FROM FIELD TEST SITES



Trench

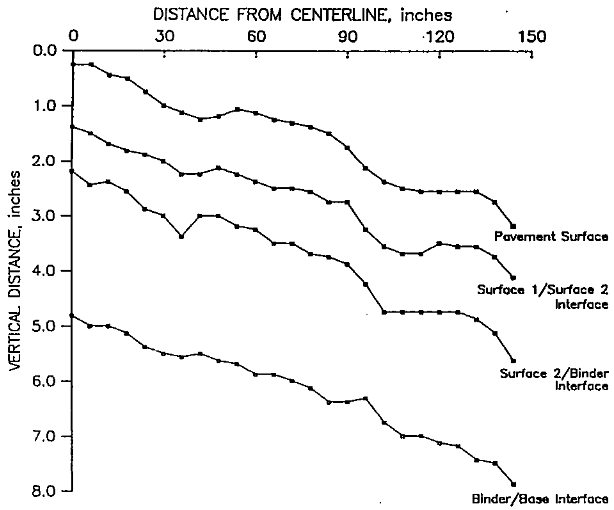


4 and 6 Inch Cores

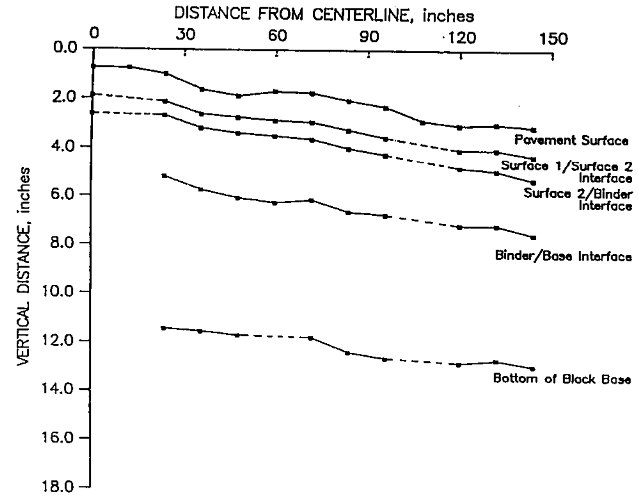


4 inch Cores

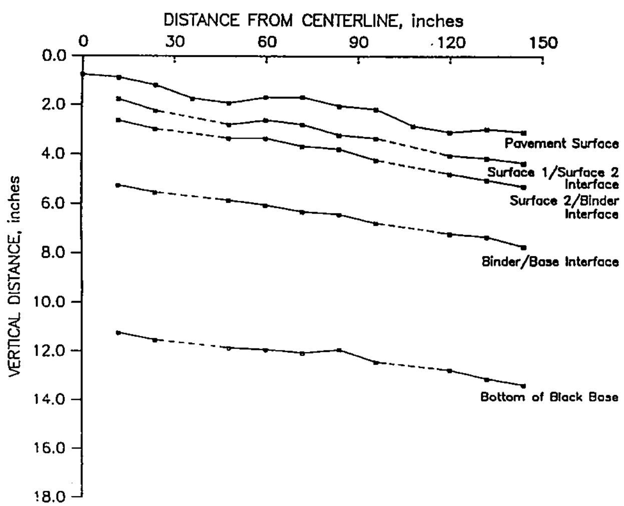
Site 1
I–59/20 Greene County
MP 30.25 Southbound



Trench

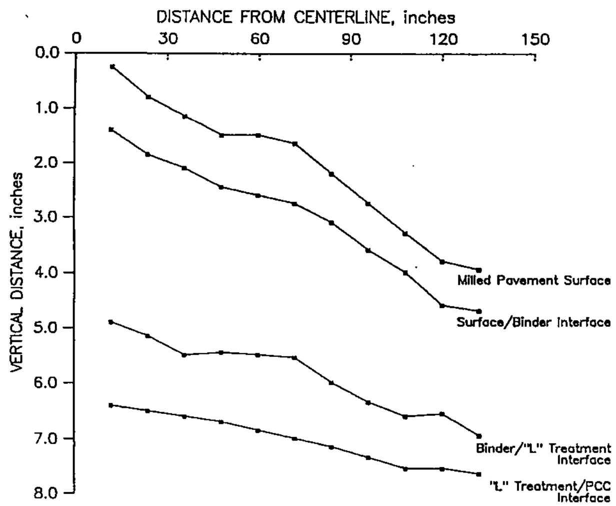


4 and 6 Inch Cores

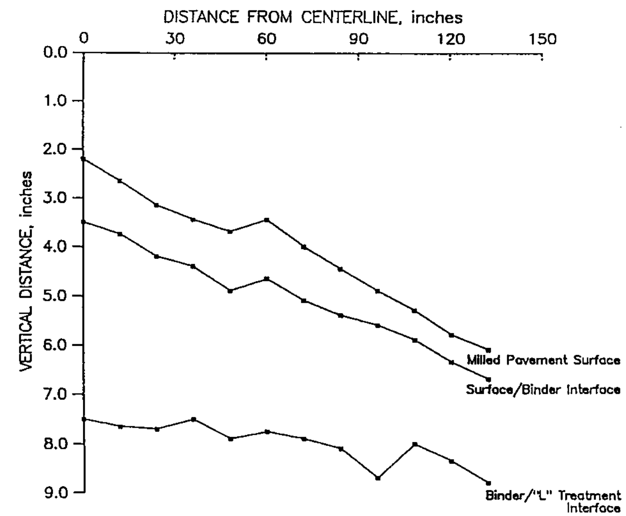


4 inch Cores

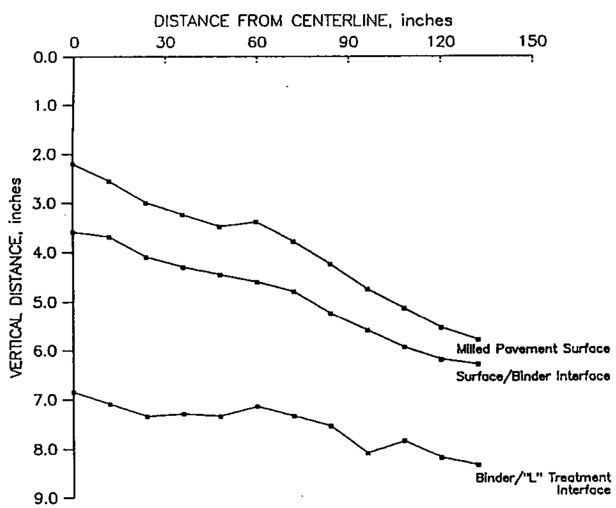
Site 2
I-59/20 Greene County
MP 44.00 Northbound



Trench

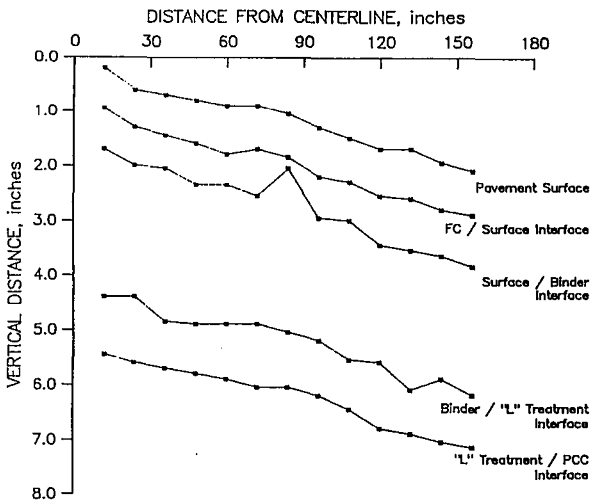


4 and 6 Inch Cores

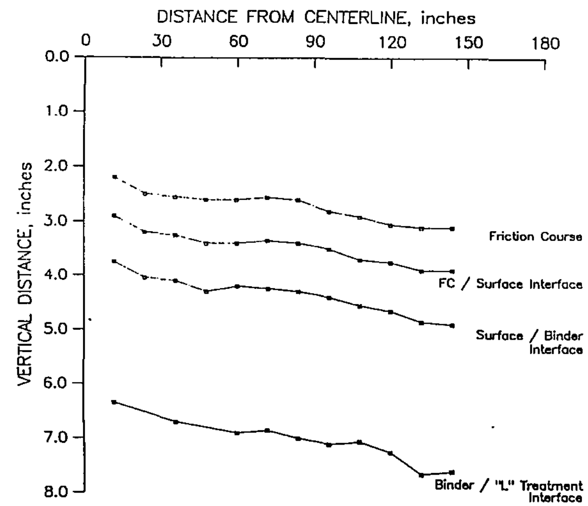


4 inch Cores

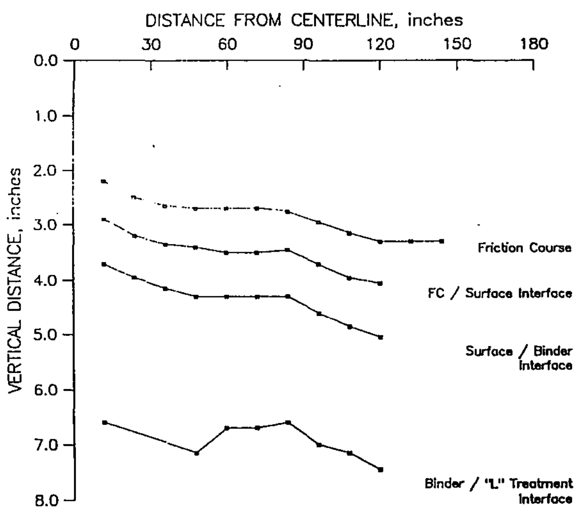
Site 3
I-10 EB Mobile County
MP 1.3



Trench

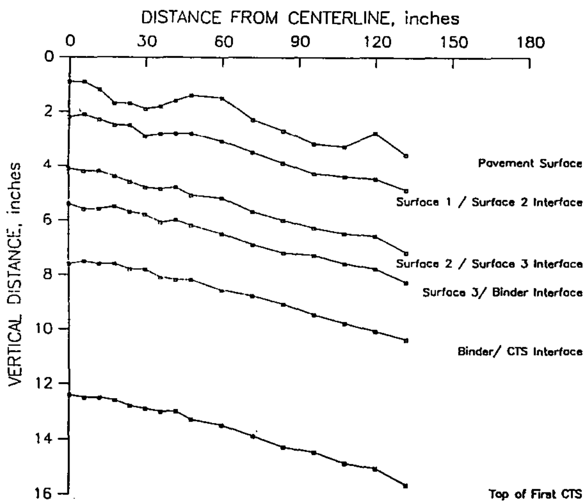


4 and 6 Inch Cores

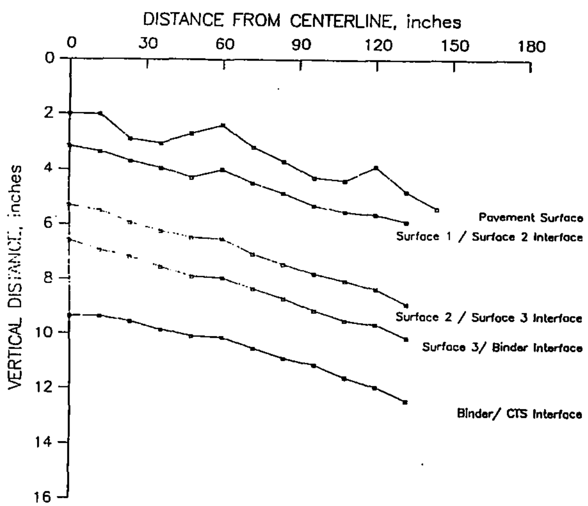


4 Inch Cores

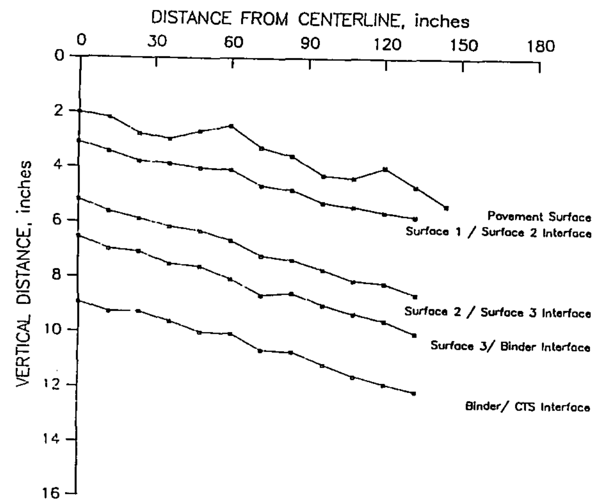
Site 4
I–10 Mobile County
M.P. 9.0 EB



Trench

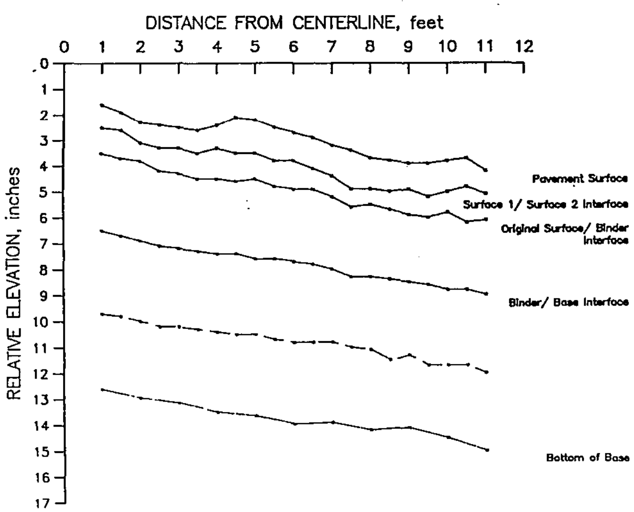


4 Inch Cores

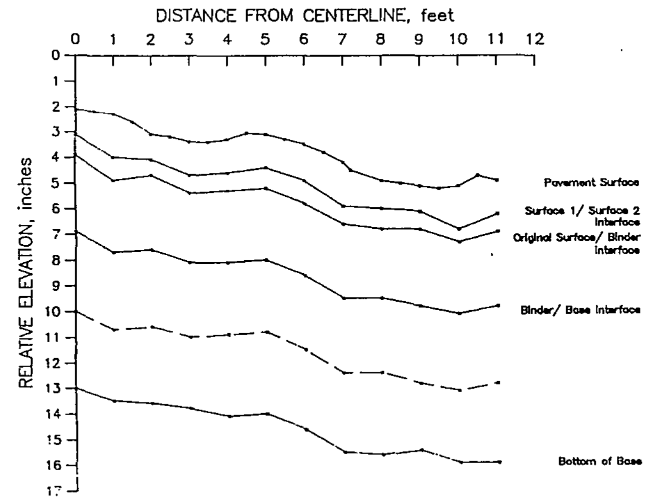


4 and 6 Inch Cores

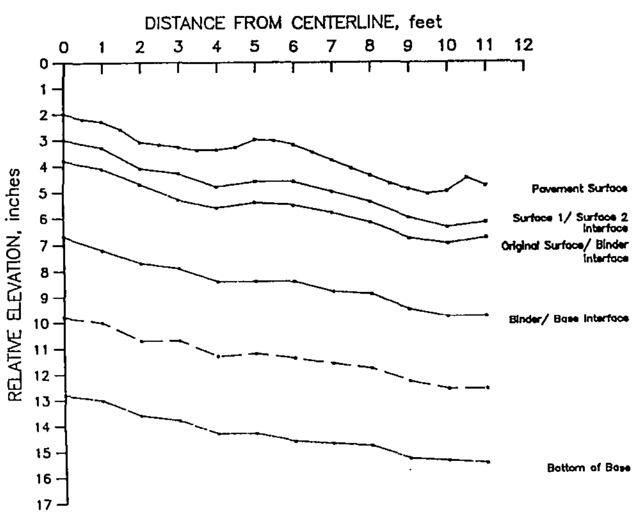
Site 5
I–65 Conecuh County
M.P. 93.1 NB



Trench

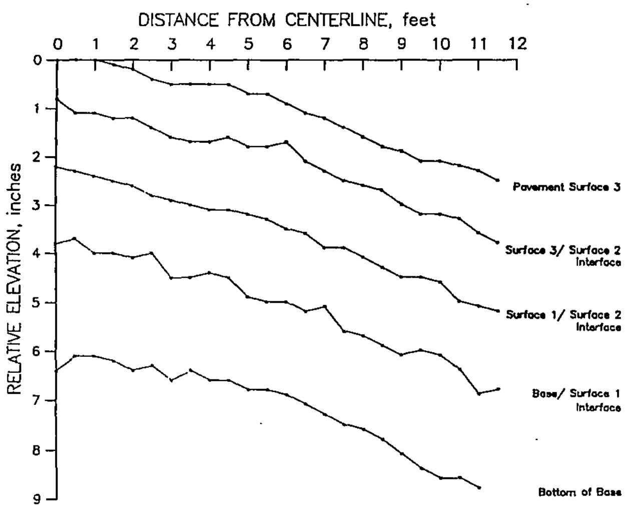


4 and 6 Inch Cores

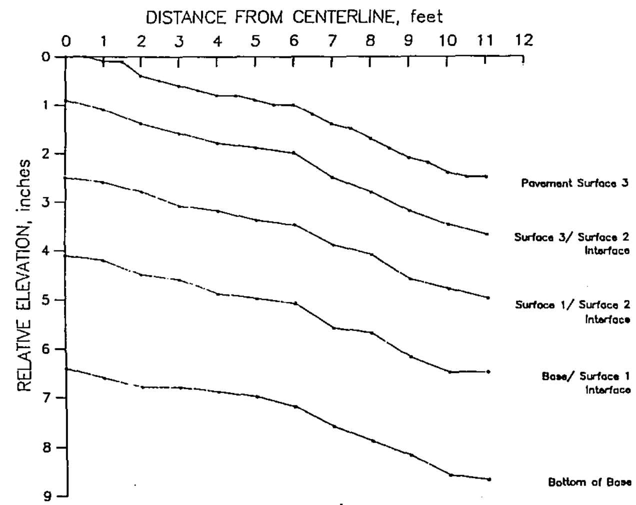


4 Inch Cores

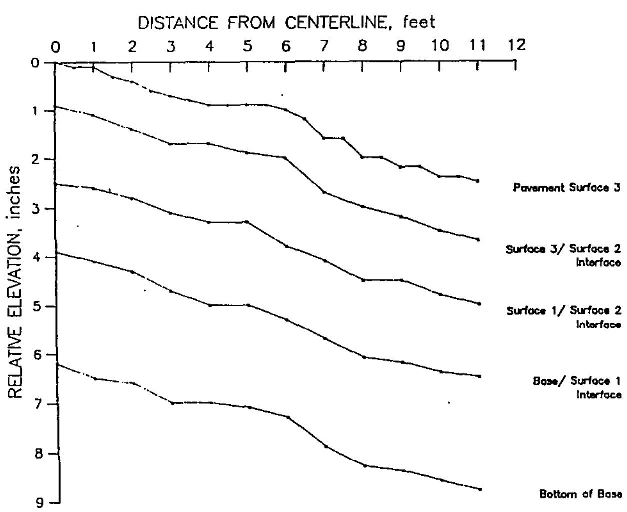
Site 6
I-85 Montgomery County
M.P. 10.0 SB



Trench

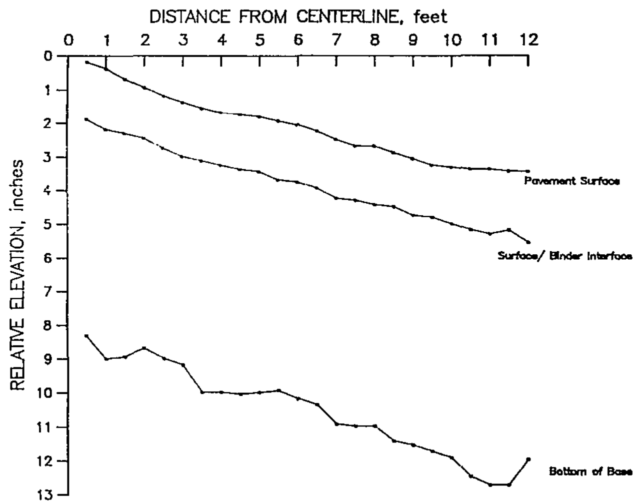


4 and 6 Inch Cores

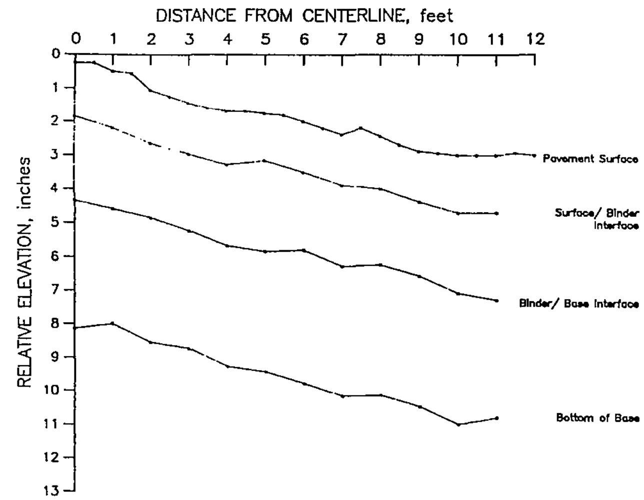


4 Inch Cores

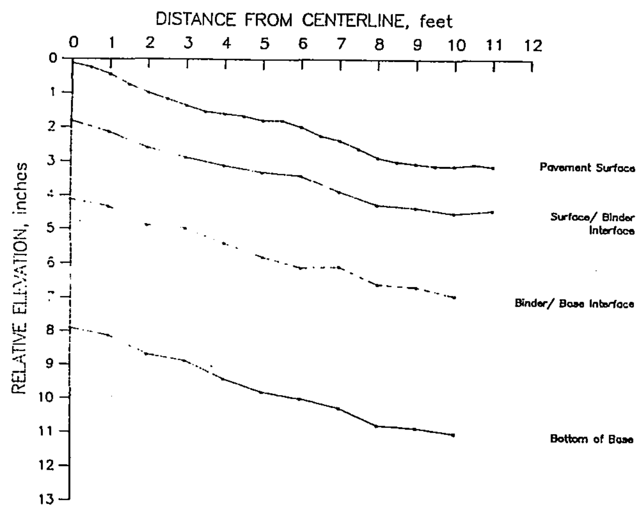
Site 7
I-85 Chambers County
M.P. 70.0 NB



Trench

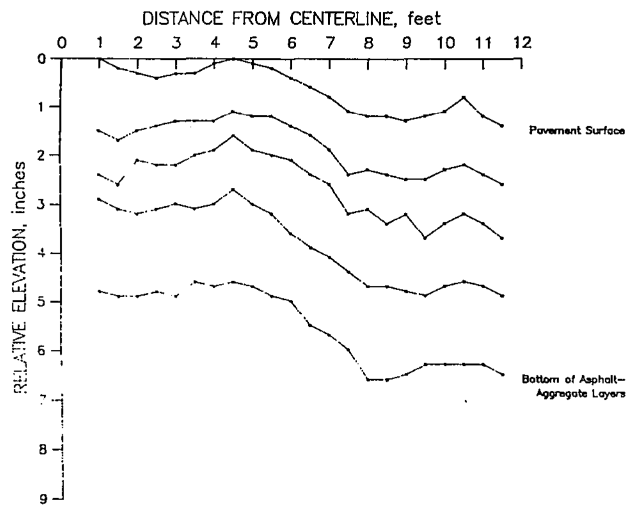


4 and 6 Inch Cores

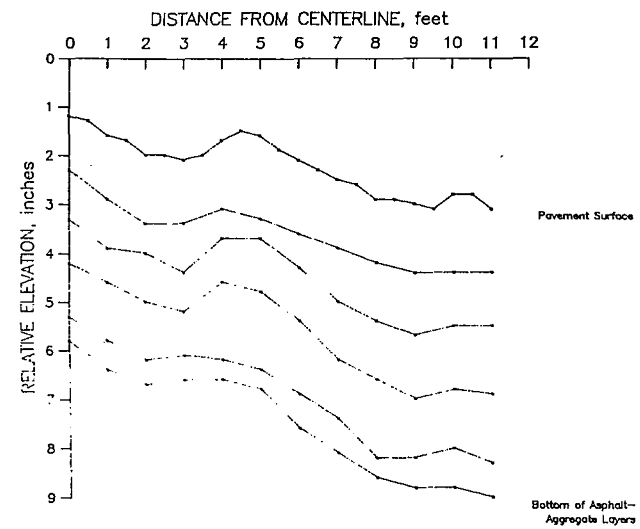


4 Inch Cores

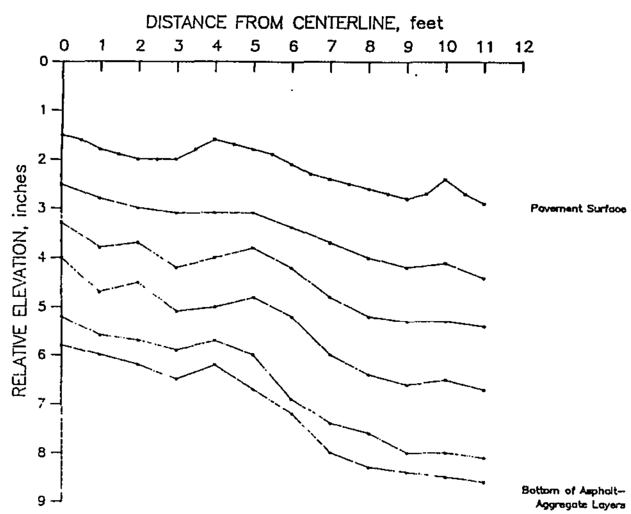
Site 8
U.S. 280 (S.R. 38) WB
Tallapoosa County M.P. 69.4



Trench

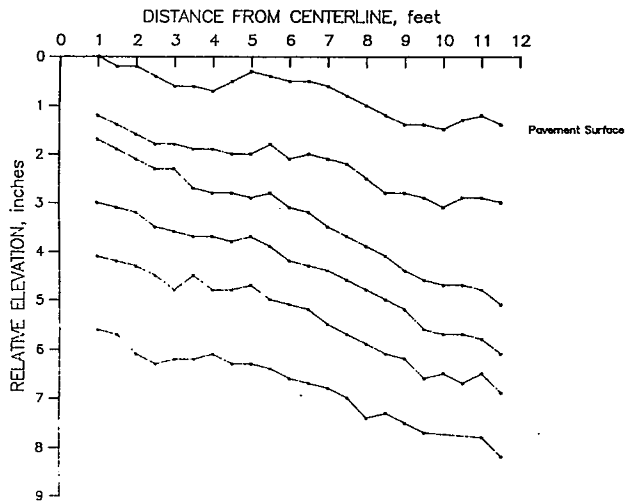


4 and 6 Inch Cores

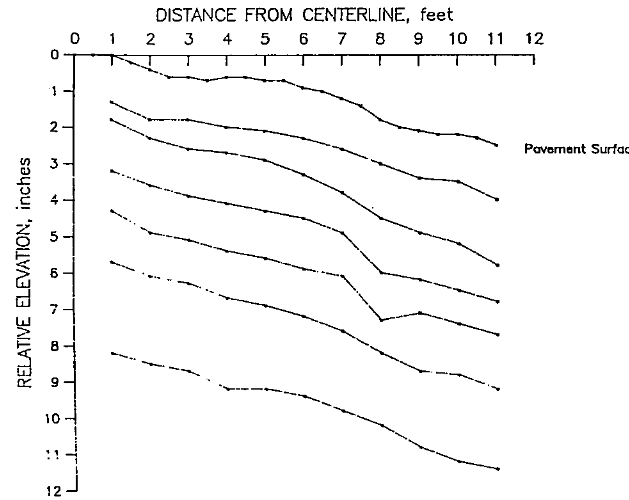


4 Inch Cores

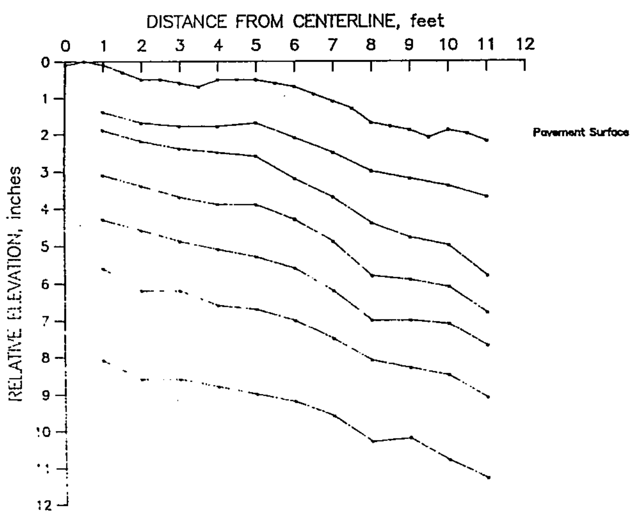
Site 9
U.S. 231 Dale County
M.P. 32.3 SB



Trench

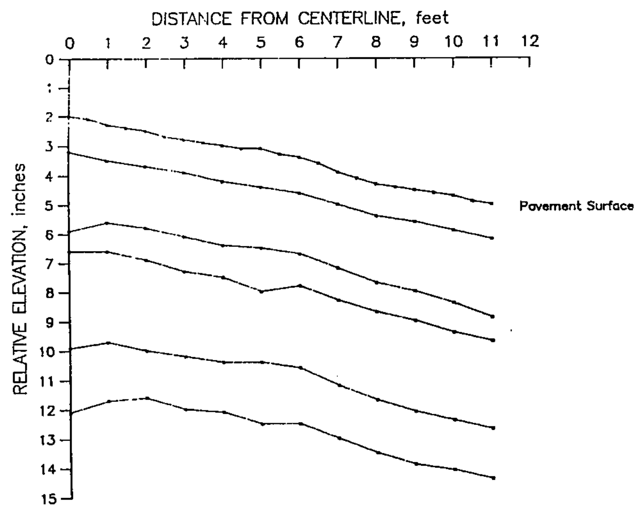


4 and 6 Inch Cores

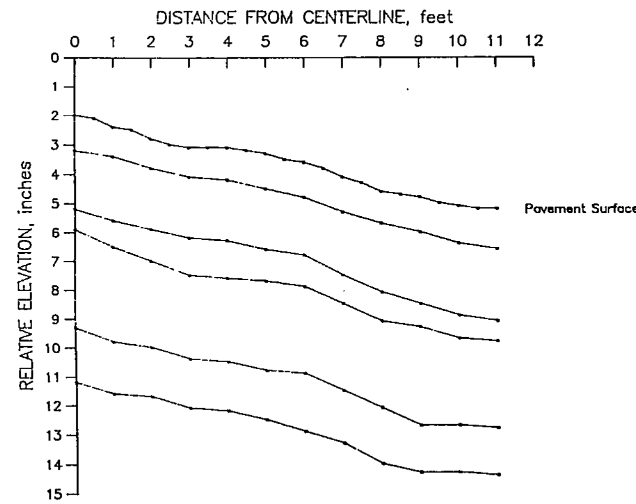


4 Inch Cores

Site 10
U.S. 78 Walker County
M.P. 65.8 EB

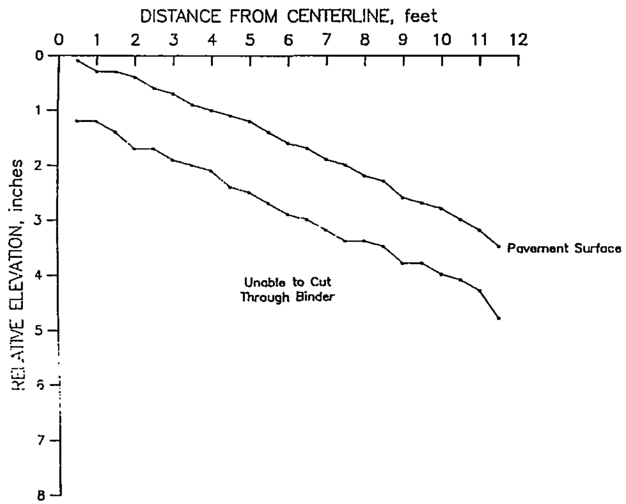


4 Inch Cores

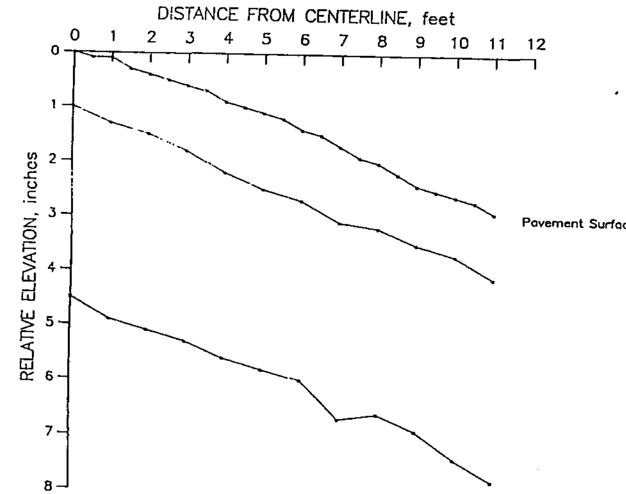


4 and 6 Inch Cores

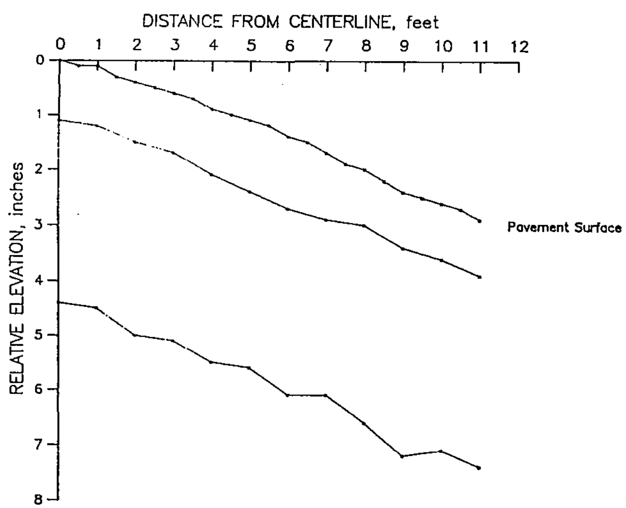
Site 11
U.S. 78 EB
Walker / Jefferson County Line



Trench

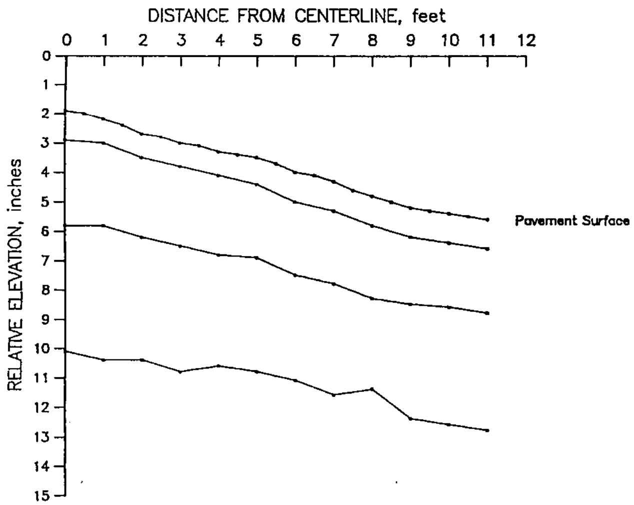


4 and 6 Inch Cores

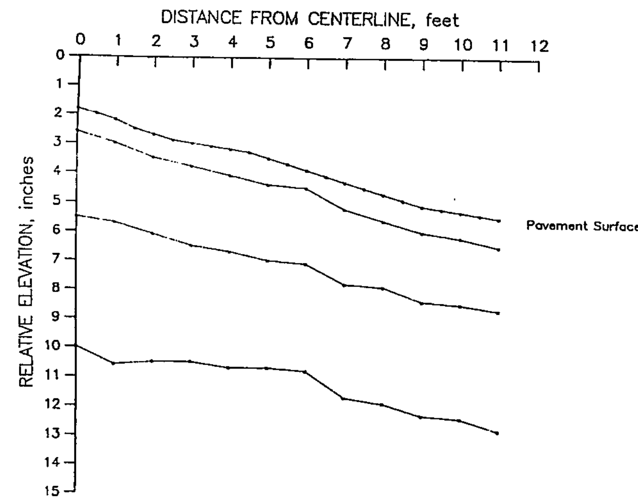


4 Inch Cores

Site 12
S.R. 157 Cullman County
M.P. 495.4 SB



4 Inch Cores



4 and 6 Inch Cores

Site 13
U.S. 72 Jackson County
M.P. 129.2 EB