NCAT Report No. 89-2

A STUDY OF IN-PLACE RUTTING OF ASPHALT PAVEMENTS

by

E.R. Brown
Stephen A. Cross

Prepared for Presentation at the Annual Meeting of the Association of Asphalt Paving Technologists

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I. INTRODUCTION

In recent years, the amount and severity of rutting in asphalt pavements appears to have increased according to reports of engineers in many State Highway Departments. This apparent increase in rutting has been due to some extent to the increase in truck tire pressure, axle loads, and volume of traffic. Some studies have shown typical truck tire pressures to be approximately 120 psi (1). As a result of these higher loads and tire pressure, more attention must be given to selecting high quality materials, in designing the asphalt mixtures, and in quality control during construction.

Concern for rutting and high truck tire pressure led to a National Symposium on the subject in March 1987 (2). The general feeling at this symposium was that the higher truck tire pressure and increased truck weights definitely have led to increased rutting but the feeling was that more attention to selection of materials and construction could minimize the rutting problem as well as other problems that might affect the performance of asphalt pavements.

The objective of this study was to evaluate in-place pavements experiencing rutting and pavements experiencing no rutting to begin to classify asphalt mixtures that should perform satisfactorily and those that would likely rut under traffic.

The information reported herein is part of a larger study to evaluate rutting in the field and in the laboratory and to develop information that would insure improved performance. This report summarizes the work accomplished during the first 1-1/2 years of the study. The entire study is projected to continue for a total of five years.

Five pavements were selected for analysis and the results are reported in this portion of the study; four of the pavements had been identified as experiencing premature rutting and one pavement had been identified as having no rutting after more than 10 years of service. Rutting measurements were taken across the outside traffic lane and a trench was cut across the lane for each of the highways experiencing rutting. The trench was closely investigated to determine the extent of rutting in each layer of asphalt mixture. Cores were taken at approximately one foot intervals across the pavement lane, transported back to the laboratory, and analyzed to determine material and mixture properties. Laboratory tests included asphalt content, aggregate gradation, and analysis of in-place and recompacted mixture properties.

II. TEST PLAN

The overall test plan for the rutting study is shown in Figure 1. The plan of laboratory tests for the cores taken from the pavements is shown in Figure 2.

The field testing consisted of obtaining 4-inch and 6-inch diameter cores, rut depth measurements and viewing the pavement layers in a trench cut across the rutted pavements. The pavement cores were obtained using 4-inch and 6-inch diamond studded core barrels. Sixteen 4-inch diameter and six 6-inch diameter cores were obtained at each of the 5 sites. Ten of the 4-inch diameter cores were saved for future testing while six were tested and reported herein. In addition to the cores, a trench was cut across the outside traffic lane of the rutted pavements to determine the locations in the asphalt mix that rutting was occurring. A layout of the cores and trenches for each site is shown in Figure 3. A stringline was pulled across the top of each pavement layer inside the trench to aid in determining the location of the rutting. A typical trench with stringline pulled across the top the of second layer is shown in Figure 4.

Rut depth measurements were obtained using a 12' elevated straight edge to establish a horizontal reference line. The distance from the straight edge to the pavement surface was then recorded to the nearest 1/8 inch at l-foot intervals across the traffic lane. Rut depth measurements at each core location along with measurements of each core allowed determination of the relative elevation of each pavement layer.

The total rut depth and percent of the rut occurring in each pavement layer was determined from the plot of relative elevation of each pavement layer. The total rut was determined by measuring the vertical distance between a straight line connecting the high points on opposite sides of the rut and the low point near the middle of the rut. The rut depth in each pavement layer was determined in a similar manner.

Traffic information and construction dates were determined for each of the highways tested. The information is provided in Table 1. Sites 1, 2, and 5 consisted of an old asphalt pavement with an asphalt overlay. Site 3 consisted of an original concrete pavement which had been overlaid with an asphalt mixture. Site 4 consisted of an original pavement which had never been overlayed.

Tests were conducted in the laboratory to characterize the material and mixture properties. Tests conducted included asphalt mntent (ASTM D2172), aggregate gradation, Rice Specific gravity (ASTM D2041), unit weight, resilient modulus (ASTM D4123), Indirect tensile strength (ASTM D4123), Marshall stability and flow (ASTM D1559). Some of the mix was tested as received while some mix was reheated, broken-up, and recompacted to evaluate the mixture using standard compactive effort. Three compactive efforts were used to recompact most mixtures: 75 blow manual hammer; Gyratory Testing Machine (GTM) set at 120 psi, 30 revolutions, and 1 degree angle; and GTM set at 120 psi, 300 revolutions, and 1 degree angle. The height of the samples compacted with 300 revolutions with the GTM was measured over a range of revolutions to help evaluate voids as a function of revolutions. The recompacted samples were tested for unit weight, stability and flow. The voids of the recompacted samples were compared to the in-place voids and to the desired voids to evaluate original mix design.

The Gyratory Shear Index (GSI) was determined for all samples compacted in the GTM. A GSI of 1.0 is normal for a mixture that is stable during compaction. A higher GSI has been shown to indicate more unstable mixtures. A plot demonstrating determination of GSI is shown in Figure 5. Compaction of asphalt in the GTM simulates densification and eventual plastic flow that is observed in the field. An asphalt mix is stable until voids are closed during compaction to the point that plastic flow begins to occur. An increase in GSI above 1 measured during compaction in the GTM simulates plastic flow in the field.

In. FIELD MEASUREMENTS

The relative surface elevation was measured across the traffic lane at one foot intervals using an elevated straight edge that had been leveled. The results of measurements to determine thickness of each layer in each core were combined with the surface measurements to plot the relative elevation of the top of each pavement layer. Measurements were also made at each trench to locate the limits of rutting (Figure 4). AU significant rutting "in the pavements investigated had occurred within 3-4 inches of the pavement surface.

It is clear from Figures 5,6, and 7 that a significant amount of rutting had occurred in the surface of the pavement at site 1. This particular pavement had experienced rutting in the past and had been milled, patched, and overlaid at various times to alleviate the rutting problem. The large amount of maintenance work explains why the various layers vary in thickness and grade. After observing the trench for site 1 and closely reviewing Figure 6 it is apparent that most of the rutting had occurred in the surface layers (the surface layers consisted of three thin layers of asphalt mix).

Figures 8 and 9 show that a small rut had occurred adjacent to the shoulder for the pavement at site 2. Very little rutting was observed adjacent to the centerline. The shoulder paint stripe had moved in some locations which is often a result of stripping. The rutting at this site appeared to be partially related to stripping which explains why the rut is adjacent to the shoulder (source of water). Observations while cutting the trench and during the laboratory testing operation showed a significant amount of uncoated aggregate which was concluded to be stripping.

Measurements taken at site 3 showed very little rutting (Figures 10 and 11) however there were locations where the material had shoved outward adjacent to the shoulder. These were localized areas and did not result in significant rutting. Site 3 consisted of an old PCC pavement which had been overlaid with asphalt concrete. The asphalt mix contained primarily uncrushed aggregate and had clearly stripped. During the trenching operation many aggregate particles were observed that had been completely stripped of asphalt. It is anticipated that the high amount of stripping and the localized shoving that has begun will very rapidly lead to a significant rutting problem.

Site 4 was selected as a pavement that had performed over ten years with no major performance problems (Figure 12). The plot in Figure 13 shows that this asphalt mix has a small rut but this did not appear to be a typical rut. The surface was perfectly straight except for a slight dip at 8 feet from the centerline. This depression was well within the allowable tolerance of construction variation and obviously had no effect on the traffic using the roadway.

Site 5 had experienced some rutting primarily adjacent to the centerline. Figures 14 and 15 show that most of the rutting here had occurred in the friction and surface course. Cores were obtained during rain and it was clear that the rut adjacent to the centerline held water.

l-v. RESULTS OF THE LABORATORY TESTS

Some of the asphalt concrete cores were tested in the laboratory to determine the asphalt content and aggregate gradation. The asphalt content and aggregate gradation results are shown in Table 2. The asphalt content was measured without correcting for ash and therefore the numbers reported are somewhat high. They are reported here for information but the measured asphalt contents were not used for calculating other mixture properties. The three top courses for site 1 were combined because of their varying thin thicknesses. The combined asphalt content for these three layers appears to be high which may be the result of high asphalt content in one or more of the three mixes or it may be the result of excessive tack coats between the layers. The aggregate gradations used for the 5 sites were approximately equal for a particular mix type. Site 3 was an exception. The mixes used for site 3 did not contain crushed aggregate and as a result had very little material passing Nos. 50, 100, and 200 sieves.

Tests were conducted on cores as received to determine in-place properties. Tests included Rice Specific Gravity, Stability, Flow, Resilient Modulus, and Indirect Tensile Strength. The results of these tests are shown in Table 3 and Table 4. The amount of voids in total mix (vTM) is likely the most important physical property of asphalt mixtures that relates to rutting. The VTM varies

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The air voids vary across the paving lane and therefore the data is difficult to cm-relate to performance. The 20th percentile was selected as the void level to be correlated with performance. The 20th percentile (Table 4) has 80 percent of the in-place voids above the selected value and 20 percent of the in-place voids below the value. This appears to be a reasonable percentile to use to predict rutting. Five mixes from the five sites investigated had the 20th percentile voids below three percent, two of these mixes were from site 1 and three were from site 5. Sites 1 and 5 were the two sites that definitely showed rutting due to plastic flow.

Samples of the asphalt mix were reheated, broken-up, and recompacted. Data determined from the recompacted samples included GSI, VMA, Air Voids, Stability, and Flow. The results of these tests are provided on Table 5. This data shows that the GSI for the higher number of revolutions is high for the top layers at sites 1, 2, and 5. This high GSI is an indication of rutting potential and these three pavements had experienced the most rutting. Very low air voids and very high flow values were observed at sites 1 and 5.

V. ANALYSIS OF TEST RESULTS

One of the criteria for selection of asphalt pavements to be evaluated in this study was that rutting was the result of an asphalt mix problem and not a result of subgrade or base problems. Hence, pavements were selected for investigation in which it appeared that rutting had occurred in the various layers of asphalt. Since the properties of the asphalt mixture in the different layers varied considerably in some cases, it is a difficult problem to relate the asphalt mixture properties to rutting. An attempt was made to determine the amount of rutting that had occurred in each of the layers. This was accomplished by determining the rut depth at the top of each layer. The rut depth as a result of a particular layer then is the difference between the rut depth at the top of the layer and the rut depth at the bottom of the layer. The rut depth for each layer determined using this approach is shown in Table 6. To be meaningful, the rut depth in each layer is also reported as percent of layer thickness. There is some scatter in the data due to overlaying rutted pavements, milling prior to overlays, and construction variation. Notice that the deepest ruts occurred at sites 1, 2, and 5. Another important observation is that the largest percent of rutting has emu-red in the top 2 layers for all 5 sites. Many of the ruts that are necessarily attributed to traffic are actually a result of construction methods such as milling, patching, and overlays. This explains why one of the ruts measured in one layer shown in Table 6 is negative.

Several correlations were developed to relate rutting as a percent of layer thickness to properties such as voids in total mix, flow, GSI, tensile strength, and resilient modulus. To have meaning the correlation had to be developed for the mix in each layer since the mix properties generally change from layer to layer. For this part of the analysis only the latest asphalt mix constructed was used. If an overlay of an existing asphalt pavement consisted of two layers then both layers were used in the analysis.

Straight line regressions were used to develop correlations between rutting and mixture properties. With the limited amount of data reported herein a more detailed approach to fitting the data could not be justified. Trends only are identified at this point. When sufficient data becomes available more effort will be spent in developing the best correlation between rutting and mix properties.

The amount of traffic is definitely a factor in rutting of asphalt mixtures. Traffic was not evaluated as a factor in causing rutting at this time due to the limited data and due to approximately equal volumes of traffic for the mixes evaluated at the five sites (Table 1).

One of the primary causes of rutting is well-documented in the literature to be low air voids (3,4). A look at the relationship between rutting and minimum in-place air voids shows that the relationship between the two parameters has an R^2 0.06 (Figure 15). The data does show a trend of more rutting at lower air voids but the correlation coefficient is too low to be useful. It is possible the relationship between rutting and air voids is affected by an increase in air voids once the pavement begins to rut and shove. There is a good possibility that the void level decreases under compaction to some point at which rutting begins to occur and at which time the void level begins to increase due to shoving of the mixture.

The relationship between layer rutting and recompacted air voids which has an $R^2 = 0.10$ is shown in Figure 17. This information clearly shows for the pavements tested that very little rutting occurs when the recompacted air voids are 3.0 percent or higher for compactive efforts of 75 blow Marshall and Gyratory with 120 psi, 1 degree and 300 revolutions. The voids data in Figure 17 was determined with the GTM. Three of the four mixes with more than 3 percent air voids have no rutting while the other mix has only 10 percent rutting. Significant rutting occurs in those layers having less than 3.0 percent recompacted air voids. In this case 3 of the 8 pavement layers have more than 20 percent rutting which is significant.

Another parameter that appears to relate well with layer rutting is the GSI which has an $R^2 = 050$ (Figure 18). When the GSI exceeds 1.1 the data shows that significant rutting can be expected. Only one of the five pavement layers that had GSI values less than 1.1 had experienced significant rutting.

Plots of resilient modulus and indirect tensile strength versus layer rutting are shown in Figure 19 and 20 ($R^2 = 0.01$ and 0.10, respectively). It is obvious from these plots that there is no good relationship between layer rutting and these two parameters. There is no reason to expect a good relationship to exist between these parameters and rutting since rutting is due to compressive stresses and both of these tests measure tensile properties of the mixes.

It appears from the test results that low voids (in recompacted samples and/or field samples) are the cause of most rutting in the five pavements evaluated. For a given asphalt mix, the low voids are the result of high asphalt content. Several factors may cause the asphalt content to be excessive in an asphalt mixture. One cause that has been observed in many cases is insufficient compaction during mix design and mixture testing resulting in a higher required asphalt content to obtain the specified void level. In this case, compaction during construction and under traffic results in a density higher than laboratory density and therefore lower voids than measured during mix design. Compaction during mix design and field quality control has to produce a density in the laboratory equal to that obtained in the field after a few years of traffic.

Part of the problem with low voids in the field is explained by the data in Table 7. The density obtained during mix design and field quality control should be equal to that density which is obtained in the field under traffic. The job mix data was available for some of the mixes evaluated. Those mixes are provided in Table 7. Five of the nine mixes have in-place densities higher than the mix design. Four of the mixes are more than 1 pound per cubic foot higher than the job mix density, This is an indication that the lab density is lower than required for satisfactory mix design and quality control. The 75 blow manual Marshall hammer used for recompaction is equal to or slightly higher than the in-place density.

Another cause of low voids is lack of control of the asphalt mixture during construction. Many states arbitrarily increase the asphalt content to meet specification requirements for in-place voids. This adjustment in asphalt content will result in low voids under traffic. This adjustment of asphalt content is often made when paving in cold weather. When satisfactory density is not being obtained during construction, additional compactive effort should be provided instead of increasing the asphalt content. The asphalt content is very critical to satisfactory performance of a mixture and hence should only be modified by those familiar with the mix design process.

Some mixtures are simply designed to have low voids to insure minimum cracking during cold weather and to insure other desirable properties. The data from the pavements investigated show that rutting occurs below approximately 3 percent voids, therefore, the mix design should be selected so that the void content in-place never decreases to 3 percent. The void content should be designed between 4 and 5 percent (using the proper laboratory compactive effort) for very high traffic volume roads. Low temperature cracking can be minimized by compacting this mixture to approximately 6-7 percent air voids during construction.

The Marshall flow in the recompacted samples appears to be an indicator of rutting potential with an R^2=0.25 (Figure 21). A flow above 16 for the pavements tested resulted m rutting equal to approximately 10-40 percent of layer thickness. A flow below 16 resulted in only 1 of the mixes having more rutting than 10 percent of layer thickness.

The rutting at site 3 was likely the result of stripping of the asphalt from the aggregate. The amount of rutting was small but the roughness caused by the rutting had resulted in loss of ride quality. This stripping and rutting would have been prevented or minimized if a high quality crushed aggregate had been used (5).

CONCLUSIONS

The results of this study show that mixes can be produced to support todays traffic. The pavements evaluated which had rutted under traffic in most cases appeared to have rutted due to low air voids (in recompacted samples and/or in the field). Only two of the pavements investigated had rutting sufficiently high to require rehabilitation.

One of the best indicators of rutting is low air voids in the laboratory compacted asphalt mixture. Satisfactory laboratory compaction effort (providing density approximately equal to that under traffic) must be utilized when compacting these samples.

The GSI determined during compaction with the Gyratory Testing Machine was shown to be a good indicator of mixes that had rutted under traffic. Based on the results of this study, a maximum GSI value of 1.1 is recommended when compacting samples with 1 degree angle, 120 psi, and 300 revolutions.

The Marshall flow appears to be a good indicator of rutting potential. A maximum flow of 16 is often specified for mix design and construction control and that appears to be a reasonable number from the data presented in this study. Mixes having flow values above 16 tended to have higher amounts of rutting.

Based on the test results obtained in this study, it appears that the Resilient Modulus and Indirect Tensile Strength values are not significantly related to rutting.

Stripping of the asphalt mixture had caused rutting to some extent at two of the sites. The amount of rutting at these two sites was small and at the time of sampling these pavements were performing satisfactorily.

Most of the rutting observed in this study had occurred in the top layers of asphalt concrete. These layers often contained fine aggregate gradations and high asphalt contents.

Asphalt mixes can be designed and constructed to carry todays traffic as shown by these mixes at site 4. Steps must be taken during mix design to ensure that the asphalt content is correctly selected for the mix being produced and that sufficient quality control tests be conducted to verify mix design and to provide data to make adjustments in mix proportions if needed.

RECOMMENDATIONS

One of the biggest causes of rutting is excessive asphalt content in asphalt mixtures. Steps should be taken to insure proper asphalt content is selected and provided during mix production. Compactive effort should be selected to provide a density equal to that which will be obtained under traffic (75 blow with manual hammer or Gyratory Testing Machine have been shown to be sufficient). The asphalt content should be selected to provide a void content of 4-5 percent in laboratory compacted mixtures for high traffic volume roads. Asphalt content should not arbitrarily be increased to facilitate compaction, to minimize segregation, or for any other reason except to provide satisfactory voids in the laboratory compacted asphalt mixture. The maximum Marshall flow should be specified to be 16. If a Gyratory Testing Machine is used the GSI should not exceed 1.1.

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Table 1. Site Traffic Information and Construction History

SITE	DATE CONSTRUCTED	PERCENT TRUCKS	TOTAL EQUIVALENT 18 KIP AXLE LOADS (millions)	TOTAL RUT DEPTH (INCHES)
SITE #1		50		1.500*
Overlay	1980		11.8	
Orig Pvmt	1968		26.5	
SITE #2		20		0.896
Overlay	1982		2.05	
Orig Pvmt	1961		5.48	
SITE #3		22		0.375
Overlay	1982		3.12	
SITE #4		12		0.250
Orig Pvmt	1972		2.74	
SITE #5		41		0.625
Overlay	1982		5.25	
Orig Pvmt	1967		13.3	

*Maximum rut depth" in inner wheel path. The maximum rut depth of 2.58 inches occured in the outer wheel path in a tapered pavement section.

Table 2. Sieve Analysis and Asphalt Content*

Sample	% AC	1	3/4	1/2	3/8	No 4	No 8	No 16	No 30	No 50	No 100	No 20
						Sieve Size Percent Passing						
SITE #1												
Surface	7.8		100	96	91	72	59	49	39	27	14	6.0
Binder	5.3	100	98	83	73	48	35	31	29	28	7	3.2
sand aspt	5.2						100	99	98	86	10	3.0
SITE #2												
Surface	7.2		100	98	93	74	60	49	36	21	12	6.6
Old surf	6.1		100	93	81	62	51	46	39	28	11	4.7
Binder	4.4	100	93	77	69	52	40	36	34	30	7	3.2
sand aspt	5.3							100	98	79	9	3.1
SITE #3												
Surface	6.0			100	93	68	51	43	30	12	4	2.1
Binder	5.5		100	84	73	48	35	29	21	10	4	2.3
SITE #4												
Surface	5.8		100	99	93	68	53	42	30	18	10	5.2
Binder	5.1	100	88	76	70	49	37	28	21	14	8	4.1
Binder	504	100	94	78	70	51	38	29	21	14	8	3.8
Base	5.6	100	88	73	69	54	44	34	25	17	9	4.5
Base	5.0	loo-	86	75	68	47	35	26	20	13	8	4.8
SITE #5												
Surface	6.6			100	95	66	49	39	31	21	12	6.2
Binder	7.0	100	99	85	74	50	38	31	25	17	10	5.3
Surface	7.2		100	98	93	71	57	48	39	27	15	6.9
Binder	5.5	100	96	90	80	53	40	34	28	18	10	4.2
Base	4.7	87	77	66	59	45	38	32	26	17	9	3.8

* Asphalt content does not include ash correction hence the numbers reporte are slightly high. All asphalt extraction tests reported here were conducted on asphalt mixtures after compaction with 30 revolutions on the GTM.

Table 3. In Place Mix Characteristics of Four Inch Diameter Cores

Sample	Core	Air Voids (%)	Rice's Specific Gravity	Marshall Stability (lbs)	Flow (0.01 inch)	Resilient Modulus (KSI)	Indirect Tensile (PSI)
SITE #1							
Surface	1 IWP	2.2	2.436			643	179
	3 IWP	0.3		1462	12		
	4 BWP	0.3				413	128
	6 BWP	0.8		2095	12		
	8 OWP	2.7				334	146
	9 OWP	1.9		1140	17		
Binder	1 IWP	2.4	2.485			872	258
	3 IWP	4.0		3604	11		
	4 BWP	4.7				668	275
	6 BWP	0.0		6616	10		
	8 OWP	1.5				229	156
	9 OWP	0.6		5992	7		
Sand Asphalt	1 IWP	26.1	2.426			216	61
	3 IWP	25.8		708	12		
	4 BWP	25.7				278	75
	6 BWP	24.3		691	14		
	8 OWP	22.7				233	75
	9 OWP	24.9		850	14		
SITE #2							
Surface	3 IWP	Core was cracked, testing not possible					
	6 BWP	4.2*	2.420	2195*	14*		
	9 OWP	4.3*		2250*	13*		
	10 IWP	4.0				1250	205
	12 BWP	4.1				1102	212
	14 OWP	4.3				860	186
Old Surface	3 IWP	Core was cracked, testing not possible					
	6 BWP	4.2*	2.454	2195*	14*		
	9 OWP	4.3*		2250*	13*		
	10 IWP	4.9				718	197
	12 BWP	3.0				890	239
	14 OWP	8.0				348	133
Binder	3 IWP	Core was cracked, testing not possible					
	6 BWP	7.3	2.491	4925	15		
	9 OWP	5.7		2640	13		
	10 IWP	5.9				835	190
	12 BWP	6.7				963	226
	14 OWP	7.2				502	154
Sand Asphalt	3 IWP	Core was cracked, testing not possible					
	6 BWP	31.3	2.482	1105	14		
	9 OWP	30.7		880	15		
	10 IWP	31.1				313	65
	12 BWP	29.8				265	58
	14 OWP	31.7				278	55

*Both surface layers utilized for testing
IWP = Inner wheel path, BWP = Between wheel path, OWP = Outerwheelpath

Table 3. (cont.)

Sample	Core	Air Voids (%)	Rice's Specific Gravity	Marshall Stability (lbs)	Flow (0.01 inch)	Resilient Modulus (KSI)	Indirect Tensile (PSI)
SITE #3							
Surface	3 IWP	5.5	2.445	1120	10		
	6 BWP	5.8		1110	10		
	9 OWP	6.7 *		1050*	10*		
	13 IWP	6.2				757	167
	14 BWP	5.7				517	152
	15 OWP	6.8				508	128
Binder	3 IWP	3.5	2.451	1370	12		
	6 BWP	Insufficient material for testing					
	9 OWP	Insufficient material for testing					
	13 IWP	4.4				776	155
	14 BWP	Insufficient material for testing					
	15 OWP	4.1				778	118
SITE #4							
Surface	3 IWP	3.1	2.432	4360	12		
	6 BWP	5.2		3545	11		
	9 OWP	3.3	Insufficient material for further testing				
	13 IWP	3.4				643	218
	14 BWP	4.8				637	188
	15 OWP	2.7				1048	234
Binder	3 IWP	3.6	2.463	3420	17		
	6 BWP	4.8		3520	19		
	9 OWP	3.8		3700	19		
	13 IWP	3.6				875	233
	14 BWP	3.8				874	214
	15 OWP	2.9				854	262
Binder	3 IWP	5.4	2.477	2600	21		
	6 BWP	4.2		3375	20		
	9 OWP	5.6		3105	21		
	13 IWP	3.8				907	217
	14 BWP	4.2				937	193
	15 OWP	4.4				1070	208
Base	3 IWP	5.5	2.475	3675	16		
	6 BWP	4.2		4160	18		
	9 OWP	5.2		3270	17		
	13 IWP	6.1				923	224
	14 BWP	6.0				908	222
	15 OWP	6.4				830	219
Base	3 IWP	6.1	2.437	2440	13		
	6 BWP	4.3		2855	23		
	9 OWP	5.2		3260	24		
	13 IWP	5.5				1045	222
	14 BWP	5.5				928	186
	15 OWP	5.4				880	172

* Surface and friction course utilized for test
IWP = Inner wheel path. BWP = Between wheel path, OWP = Outer wheel path

Table 3. (cont.)

Sample	Core	Air Voids (%)	Rice's Specific Gravity	Marshall Stability (lbs)	Flow (0.01 inch)	Resilient Modulus (KSI)	Indirect Tensile (PSI)
SITE #5							
Surface	3 IWP	2.2	* 2.443	3660*	13*		
	6 BWP	2.4	*	1710*	21*		
	9 OWP	2.1	*	2950*	16*		
	13 IWP	3.8				756	163
	14 BWP	4.0				242	111
	15 OWP	2.7				618	178
Binder	3 IWP	2.2	* 2.454	3660*	13*		
	6 BWP	2.4	*	1710*	21*		
	9 OWP	2.1	*	2950*	16*		
	13 IWP	3.3				476	130
	14 BWP	3.3				242	93
	15 OWP	3.8				365	118
Old Surface	3 IWP	1.8	2.421	3110	10		
	6 BWP	0.9		2630	11		
	9 OWP	0.9		3260	11		
	13 IWP	0.9				357	159
	14 BWP	0.9				446	148
	15 OWP	0.1				597	163
Binder	3 IWP	2.5	2.553	3340	13		
	6 BWP	4.2		2770	13		
	9 OWP	4.0		2885	17		
	13 IWP	5.0				656	197
	14 BWP	4.4				570	203
	15 OWP	3.2				707	195
Base	3 IWP	5.4	2.549	2540	16		
	6 BWP	-7.2		2245	13		
	9 OWP	5.6		2415	16		
	13 IWP	4.9				616	178
	14 BWP	6.7				350	72
	15 OWP	4.5				656	169

*Both layers utilized for testing
IWP = Inner wheel path
BWP = Between wheel path
OWP = Outer wheel path

Table 4. In-Place Air Void Contents for 6 Inch Diameter Cores

	Core 1	Core 2	Core 3	Core 4	Core 5	Core 6	20th Percentile
SITE #1							
Surface	3.8	101	2.4	0.3	0.5	3.2	0.8
Binder	2.9	5.9	2.2	1.0	1.9	N/A	1.4
Sand A.	26.0	26.2	25.4	25.1	19.8	23.9	22.6
SITE #2							
Surface	3.7	3.4	3.5	4.2	4.9	N/A+	3.5
Surface	5.7	3.4	4.6	4.6	4.0	8.8	3.7
Binder	7.8	6.1	7.2	7.2	5.8	7.5	6.3
Sand A.	30.3	30.1	31.1	30.4	30.3	32.7	30.1
SITE #3							
Friction	12.8	11.0	11.0	12.1	12.3	N/A+	11.2
Surface	7.9	5.8	5.3	6.5	6.0	N/A+	5.6
Binder	4.6	3.8	3.2	5*1	3.1	2.8	3.1
SITE #4							
Surface	5.6	2.7	4*9	3.6	3*4	7.3	3.3
Binder	4.8	3.3	3.7	3.8	3,3	3.3	3.3
Binder	4.8	4.4	3,7	4.2	4.8	5.7	4.1
Base	6.5	6.3	5.1	5.2	5.8	6.1	5.4
Ease	6.2	5.1	5.5	4.9	4.5	5.4	4.8
SITE #5							
Surface	3.2	4.3	N/A*	3*7	3.0	5.7	3.2
Binder	2.8	3.0	N/.4*	3.3	N/A*	5.9	2.7
Surface	1.6	0.5	3.3	2.0	2.6	N/A*	1.1
!3inder	3.4	3.1	4.6	2.9	2.8	8.8	2.5
Base	6.7	6.0	5.5	5.3	6.2	8.9	5.4

N/A = Layer Missing
N/A+ = Stripped
N/A* = Damaged

Table 5.Properties of Recompacted Samples

LAYER	COMP METHOD	GSI (MAX)	VMA (%)	AIR VOIDS (%)	MARSHALL STABILITY (lbs)	FLOW (0.01in)
SITE #1						
Layer 1	50 Blow M	N/A	20.3	1.8	3061	18
Surface	GTM(30)	1.14	20.0	1.4	3155	18
	GTM(100)	1.37	19.3	0.6	3412	20
Layer 4	50 Blow M	N/A	18.2	5.9	3375	12
Binder	GTM(30)	1000	18.2	6.0.	2651	12
	GTM(400)	1.03	16.1	3.5	3743	13
Layer 5	50 Blow M	N/A	33.5	24.0	1209	12
Sand A.	GTM(30)	1.00	34.8	25.5	[illegible]	15
	GTM(300)	1.01	31.4	21.6	1372	14
SITE #2						
Layer 2	75 Blow M	N/A	19.8	3.1	2269	13
Surface	GTM(30)	1.00	21.8	5.5	1488	12
	GTM(300)	1.31	19.2	2.4	1856	16
Layer 3	75 Blow M	N/A	19.5	5.5	3456	14
Old	GTM(30)	1000	18.9	4.8	302-4	12
Surface	GTM(300)	1.20	17.2	2.8	4586	17
Layer 4	75 Blow M	N/A	17.7	7.7	4033	14
Binder	GTM(30)	1.00	18.2	8.2	2830	11
	GTM(300)	1.00	15.7	5.5	5084	11
Layer 5	75 Blow M	N/A	36.3	26.7	1237	15
Sand A.	GTM(30)	1.00	37.6	28.3	1038	18
	GTM(300)	1001	35.2	25.5	1365	18
SITE #3						
Layer 2	75 Blow M	N/A	19.8	6.1	2350	10
Surface	GTM(30)	1*00	21.7	8.3	1090	10
	GTM(300)	1.00	19.8	6.1	1638	11
Layer 3	75 Blow M	N/A	16.2	3.2	2453	11
Binder	GTM(30)	1.00	17.4	4.7	1269	10
	GTM(300)	1.07	15.3	2.3	, 2162	10

Table 5. (Cent)

LAYER	COMP METHOD	GSI	VMA (%)	AIR VOIDS (%)	MARSHALL STABILITY (lbs)	FLOW (0.01in)
SITE #4						
Layer 1	75 Blow M	N/A	17.2	3.8	5338	15
Surface	GTM(30)	1*00	19.1	5.9	3122	17
	GTM(300)	1.04	16.5	2.9	4563	16
Layer 2	75 Blow M	N/A	14.9	2.8	5375	16
Binder	GTM(30)	1.00	16.5	4.6	3264	17
	GTM(300)	1.13	14.4	2.2	4574	17
Layer 3	75 Blow M	N/A	12.6	3.7	3961	15
Binder	GTM(30)	1.00	13.8	5.1	2937	18
	GTM(300)	1.11	11.2	2.2	4797	16
Layer 4	75 Blow M	N/A	16.5	3*3	6172	17
Base	GTM(30)	1.00	18.5	5.5	3536	18
	GTM(300)	1.07	16.5	3.3	4925	18
Layer 5	75 Blow M	N/A	13,9	2.1	5012	16
Base	GTM(30)	1000	13.5	3*9	2914	22
	GTM(300)	1.11	12.3	0.3	5192	18
SITE #5						
Layer 2	75 Blow M	N/A	17.4	1.7	3600	20
Surface	GTM(30)	1.00	19.7	4.5	2294	17
	GTM(150)	1.27	17.9	2.3	3058	20
Layer 3	75 Blow M	N/A	18.0	1.2	2796	22
Binder	GTM(30)	1.04	19.0	2.4	2202	15
	GTM(150)	1.37	17.9	1.1	2709	17
Layer 4	75 Blow M	N/A	19.1	2.3	3487	15
Old	GTM(30)	1.00	20.3	3.6	2313	14
Surface	GTM(300)	1*30	18.4	1.4	3471	18
Layer 5	75 Blow M	N/A	1'7.1	3.7	4613	14
Binder	GTM(30)	1.00	19.3	6.3	2313	15
	GTM(300)	1.07	17.8	4.6	3741	16
Layer 6	75 Blow M	N/A	15.6	4.3	4152	17
Base	GTM(30)	1*00	18.1	7.0	2083	15
	GTM(300)	1*01	15.6	4.2	4012	16

Table 6. Rut Depth per Layer

SAMPLE	TYPE MIX	MAXIMUM RUT DEPTH	TOTAL RUT DEPTH TOP OF LAYER	TOTAL RUT IN LAYER	RUT PERCENT OF TOTAL RUT	AVERAGE THICKNESS LAYER	RUT PERCENT LAYER THICKNESS
SITE #1		1.500					
Layer 1	Surface		1.500	1.000	67	2.432	41
Layer 4	Binder		0.500	0.000	0	3.250	0
Layer 5	Sand Asphalt		0.500	0.500	33	7.966	6
SITE #2		0.8956					
Layer 1	Friction		0.896	0.167	19	0.800	21
Layer 2	Surface		0.729	0.458	51	1.275	36
Layer 3	Old Surface		0.271	0.083	9	1.163	7
Layer 4	Binder		0.188	0.042	5	4.600	1
Layer 5	Sand Asphalt		0.146	0.146	16	8.513	2
SITE #3		0.375					
Layer 1	Friction		0.375	0.125	33	0.693	18
Layer 2	Surface		0.250	0.250	67	1.568	16
Layer 3	Binder		0.000	0.000	0	2.431	0
SITE #4		0.250					
Layer 1	Surface		0.250	0.000	0	1.182	0
Layer 2	Binder		0.250	0.100	40	2.205	5
Layer 3	Binder		0.150	0.000	0	2.500	0
Layer 4	Base		0.150	0.025	10	2.261	1
Layer 5	Base		0.125	0.125	50	4.807	3
SITE #5		0.625					
Layer 1	Friction		0.625	0.125	20	0.767	16
Layer 2	Surface		0.500	0.313	50	1.205	26
Layer 3	Binder		0.188	0.125	20	1.551	8
Layer 4	Old Surface		0.063	-0.063	-10	1.659	-4
Layer 5	Binder		0.125	0.000	0	2.352	0
Layer 6	Base		0.125	0.125	20	4.994	3

Table 7. Comparison of Densities (PCF) Measured from Mix Design, In-Place and Recompacted Samples

Location	Layer	Job Mix	In-Place 20th Pct'l	75 Blow Marshall	30 Rev GTM	300 Rev GTM
SITE #1	1 Surface	143.1	149.1	149.3	149.8	151.1
SITE #2	2 Surface	143.7	145.0	146.3	142.6	147.4
	3 Surface	146.2	146.8	144.8	145.8	148.9
SITE #3	2 Surface	145.5	143.0	143.2	139.8	143.3
SITE #4	1 Surface	144.4	146.4	146.1	142.8	147.3
	2 Binder	150.5	148.3	149.3	146.6	150.3
	3 Binder	150.5	148.0	148.8	146.7	151.3
SITE #5	2 Surface	145.8	147.1	149.8	145.6	148.9
	3 Binder	149.8	148.6	151.3	149.5	151.4

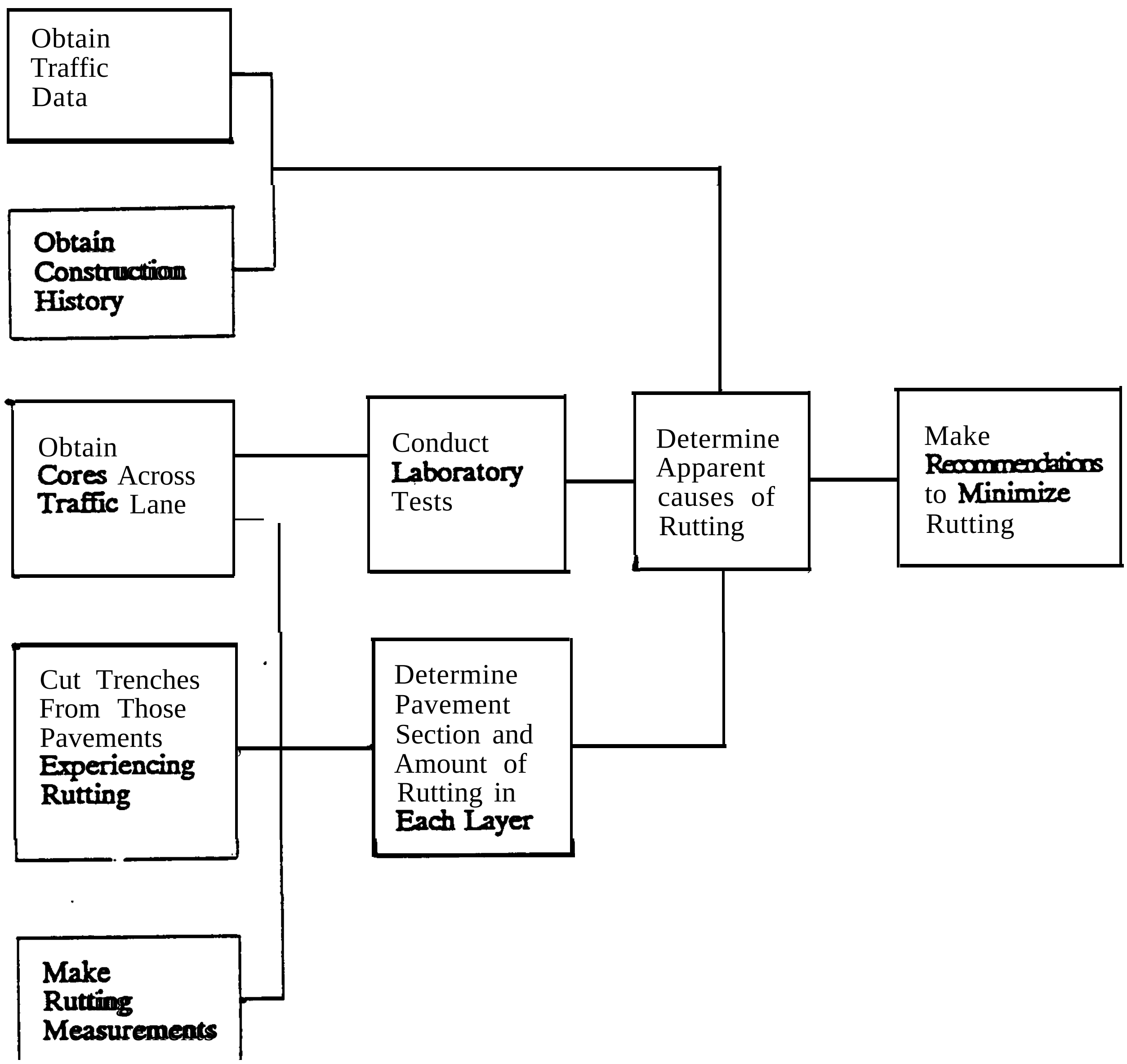


Figure 1. Overall Test Plan.

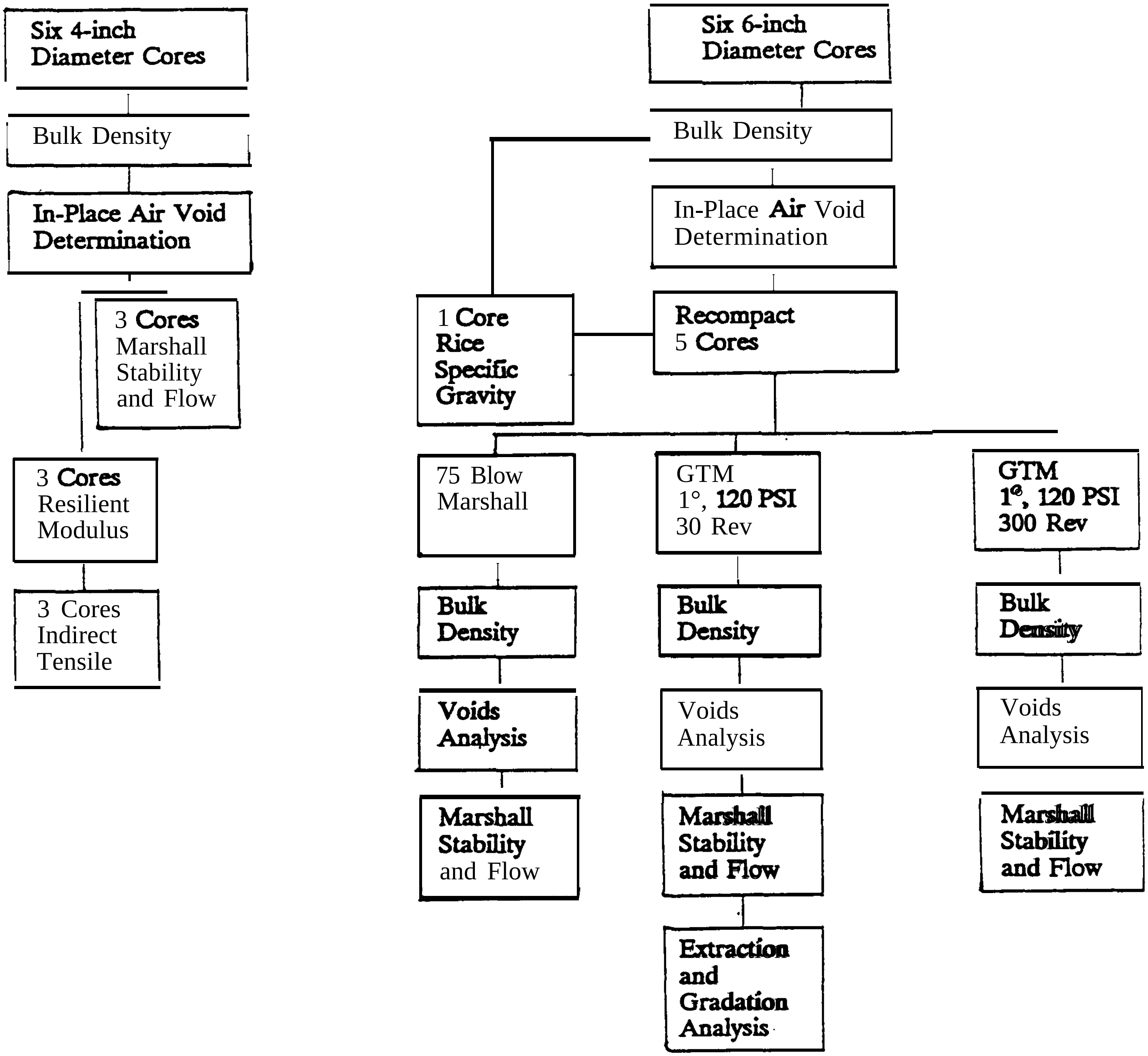


Figure 2 Laboratory Test Plan

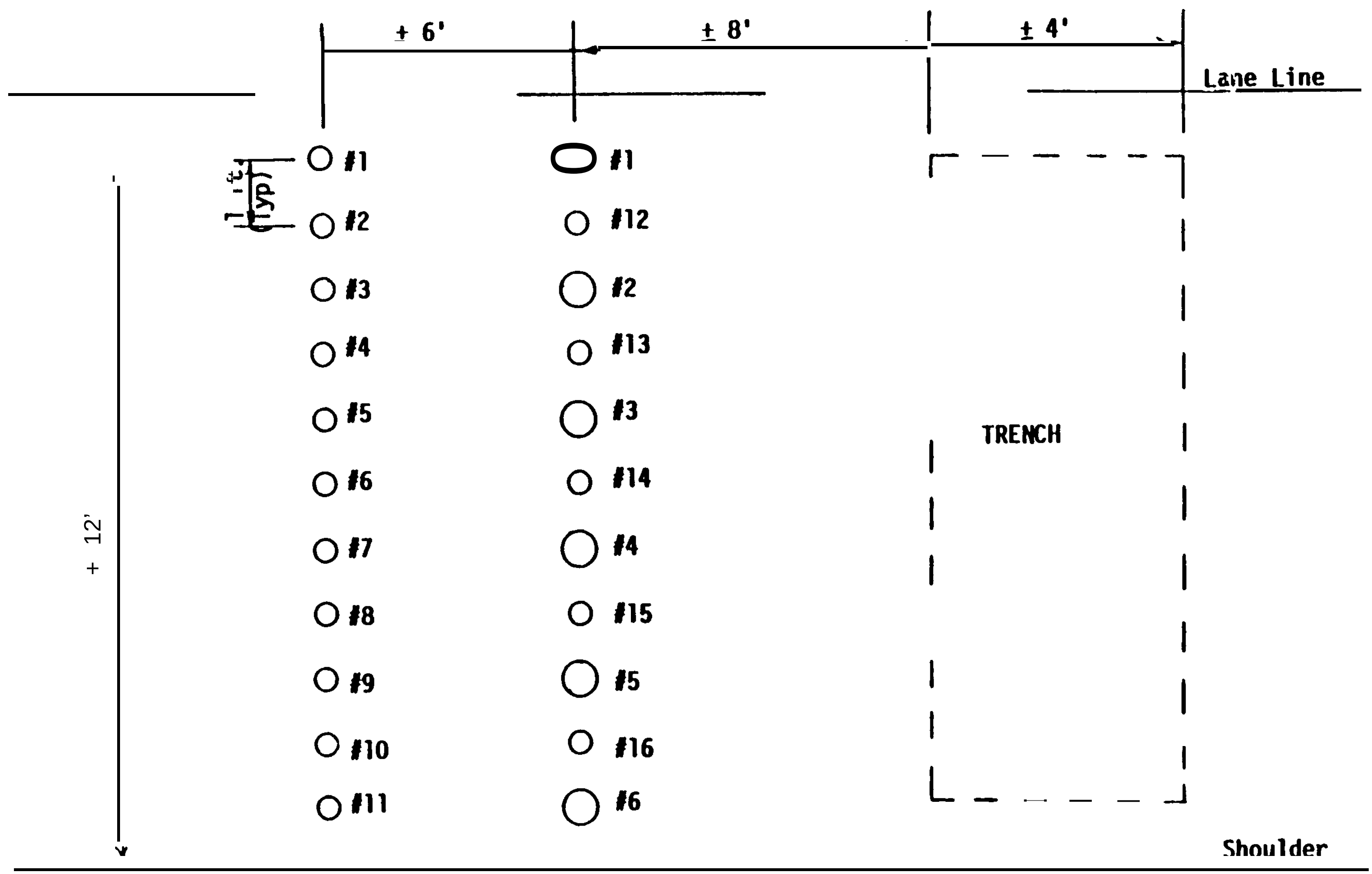
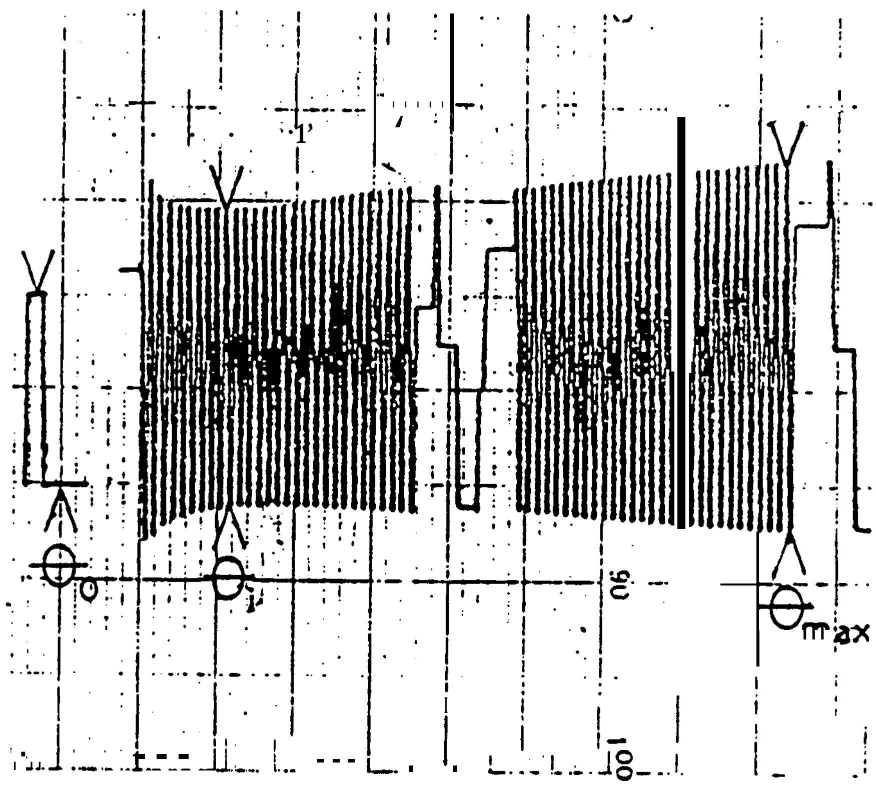


Figure 3. Core Sampling Pattern

Figure 4. Trench Cut at Site #5.



$$GSI = \Theta_{max}/\Theta_i$$

Figure 5. Determination of GSI from Typical Gyrograph

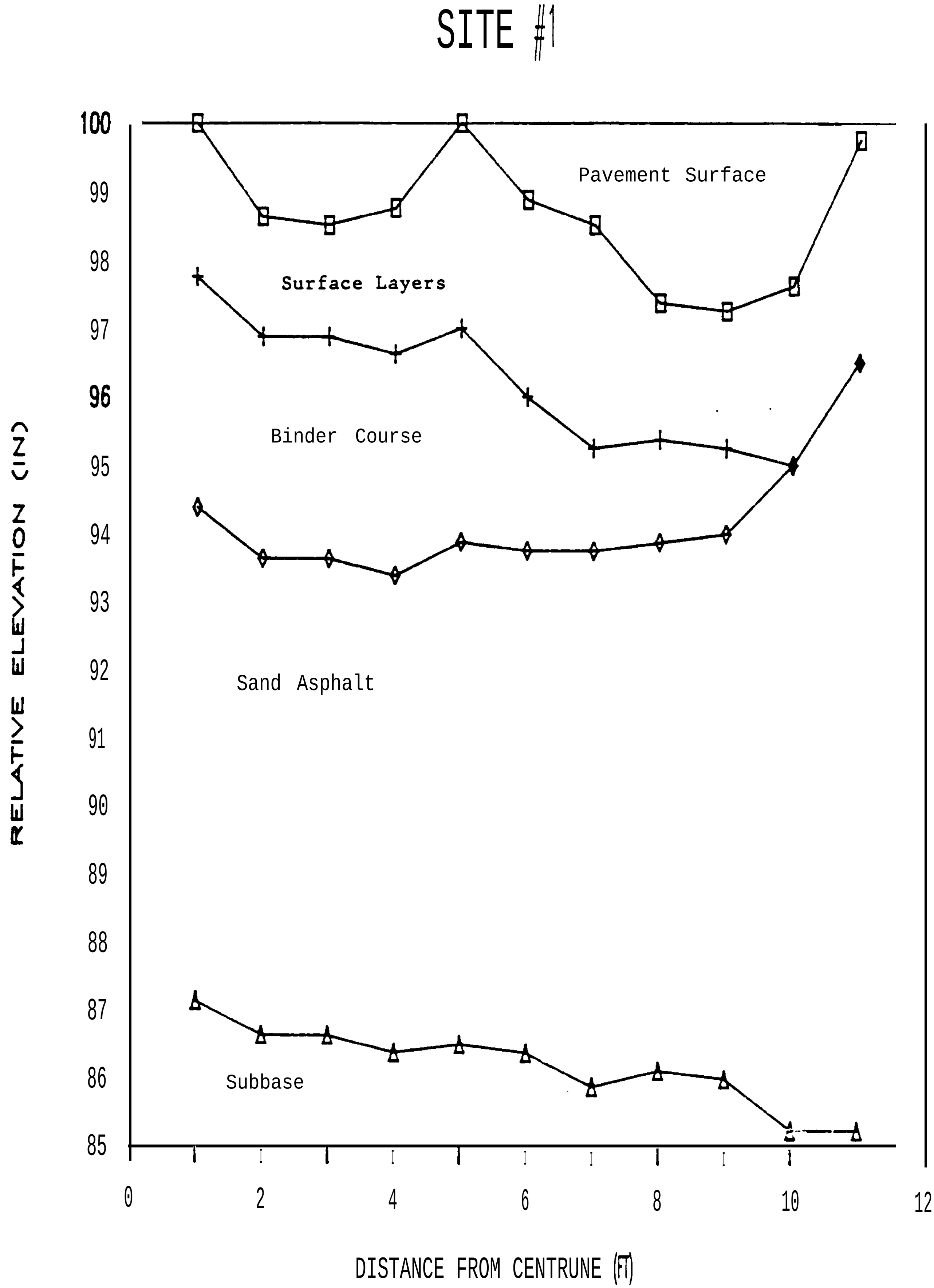


Figure 6. Relative layer elevation vs. distance from centerline for Site #1

Figure 7. Typical Rutting at Site #1.

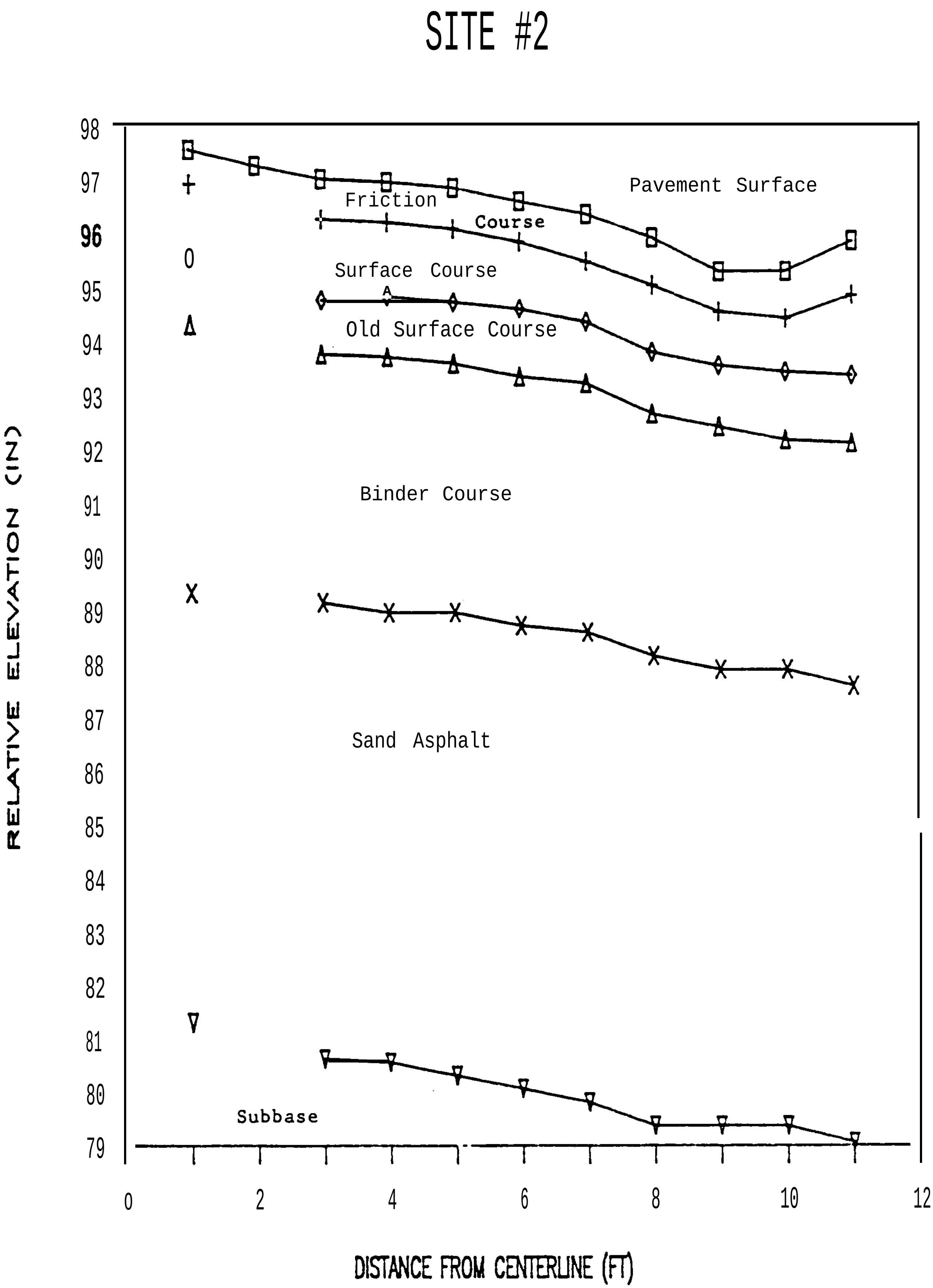


Figure 8. Relative layer elevation vs. distance from centerline for Site #2

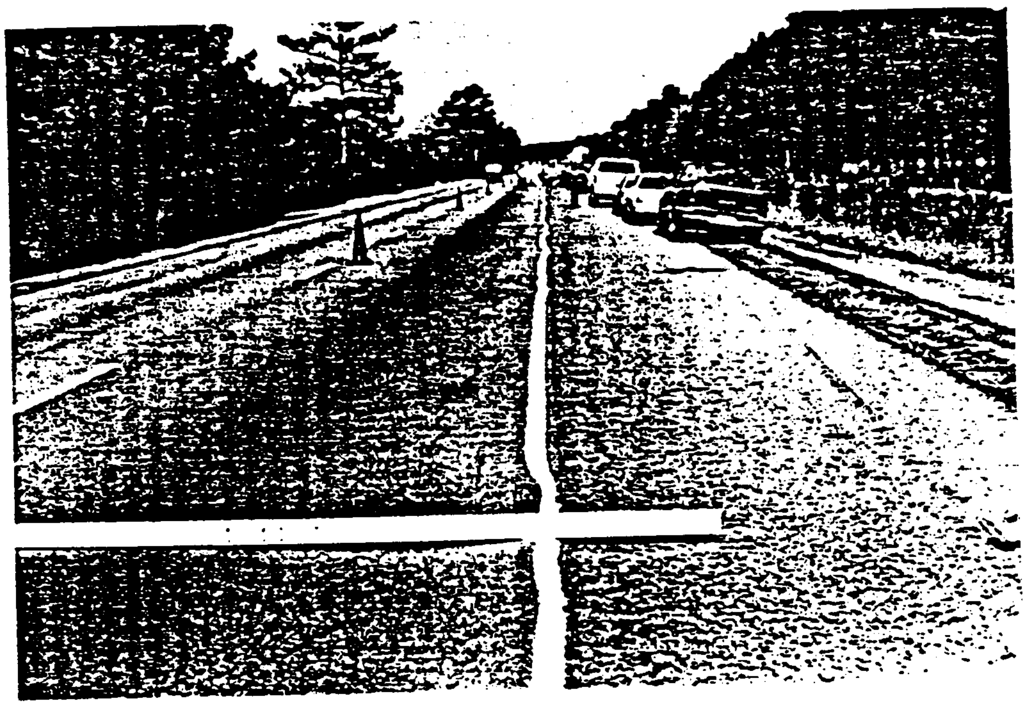


Figure 9. Typical Rutting at Site #2

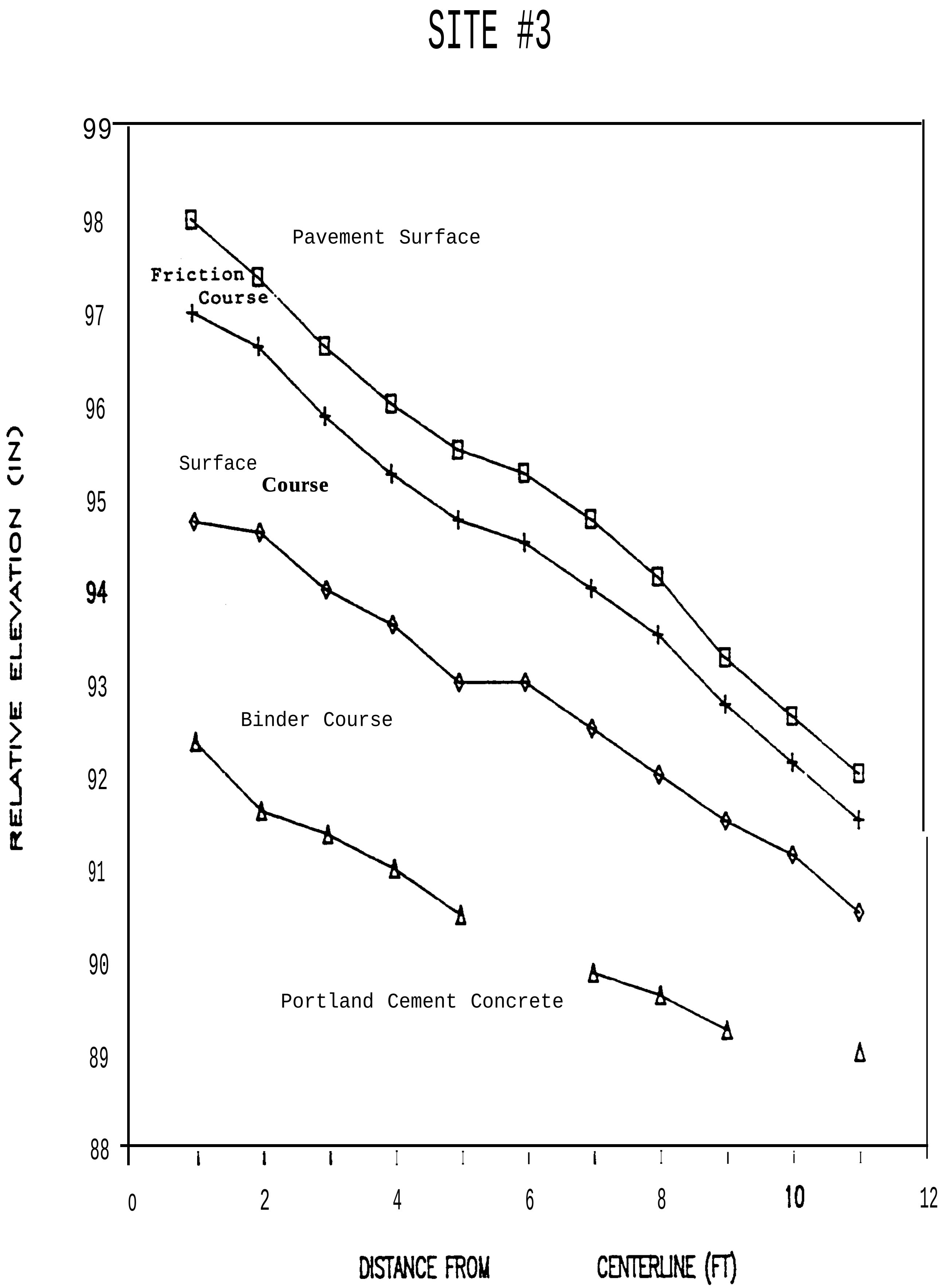


Figure 10. Relative layer elevation vs. distance from centerline for Site #3

Figure 11. Typical Rutting at Site #3.

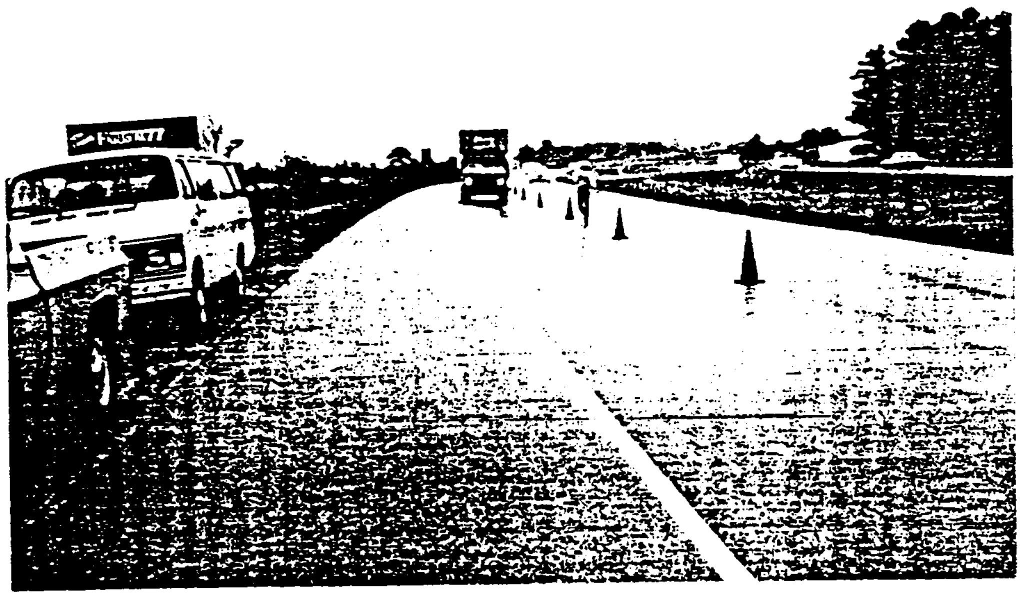


Figure 12 Asphalt Mix with Excellent Performance at Site #4.

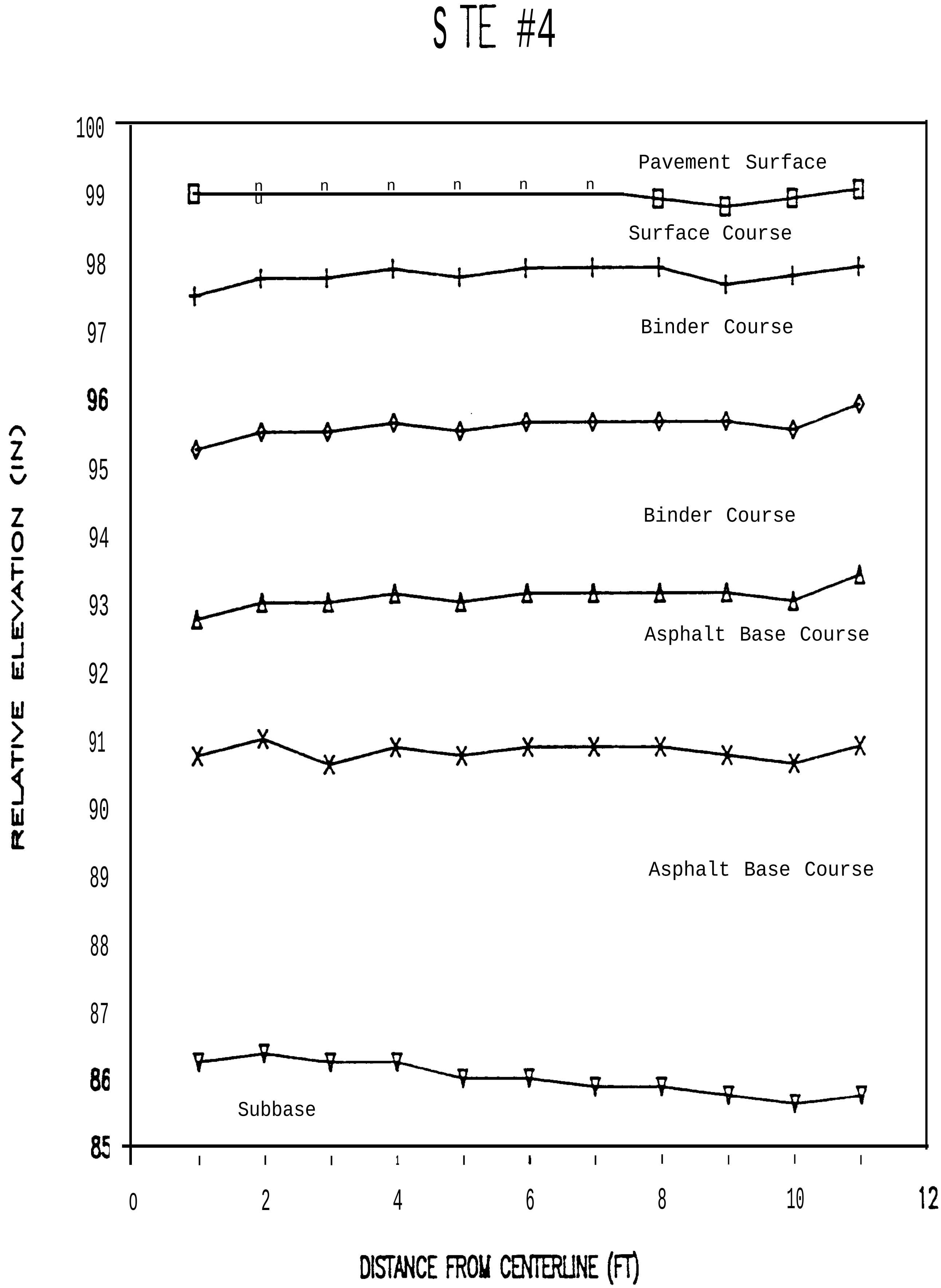


Figure 13. Relative layer elevation vs. distance from centerline for Site #4

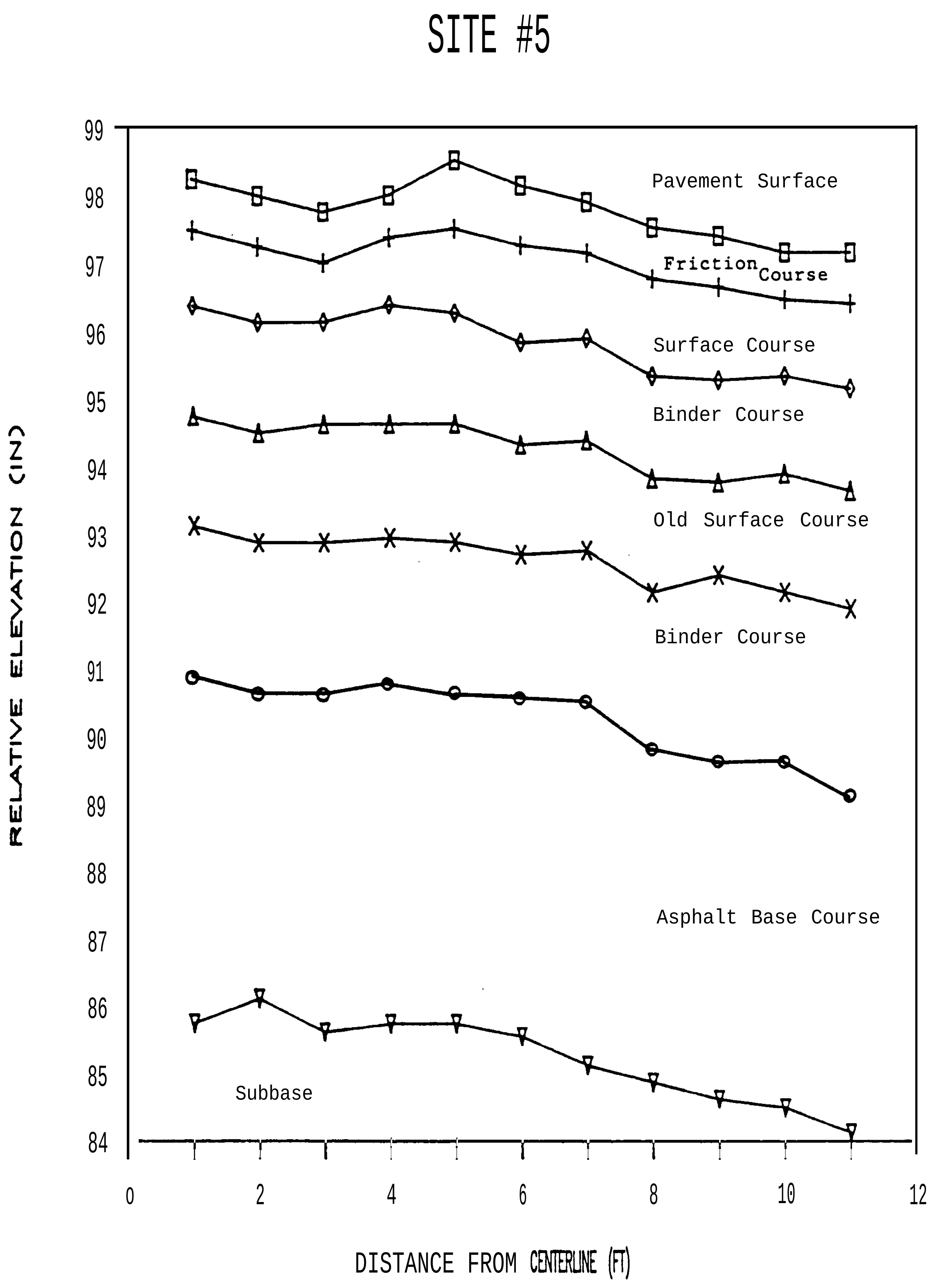


Figure 14. Relative layer elevation vs. distance from centerline for Site #5

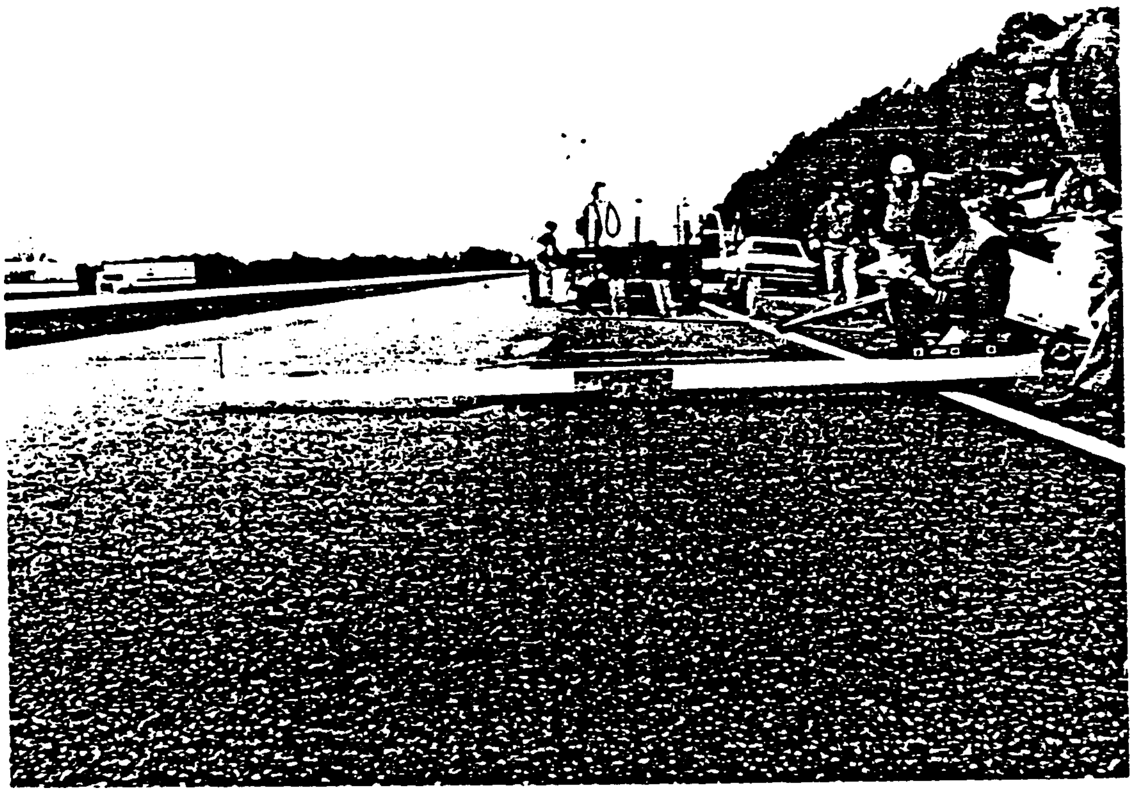


Figure 15. Typical Rutting at Site #5.

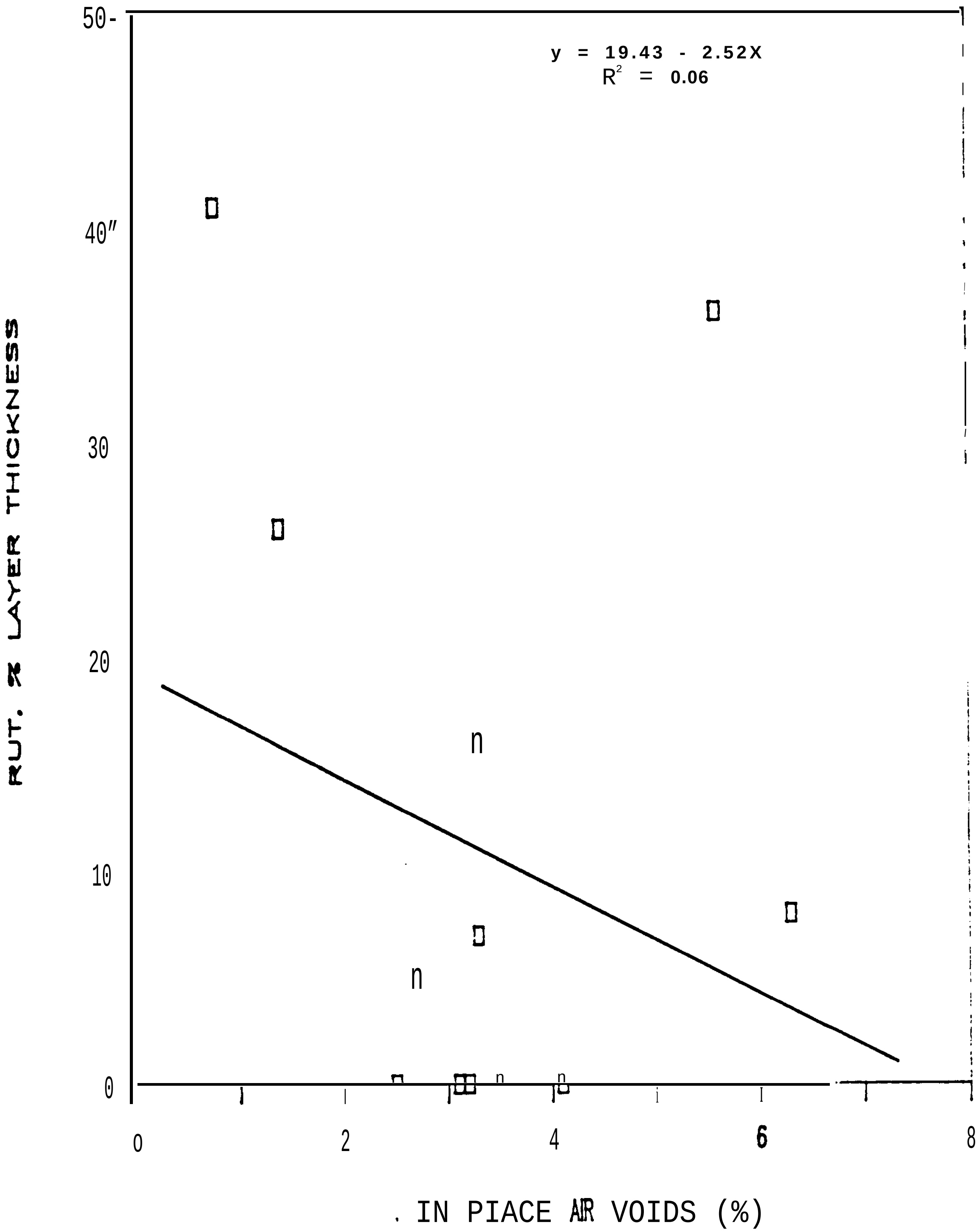


Figure 16. In-Place Air Voids vs. Layer Rutting

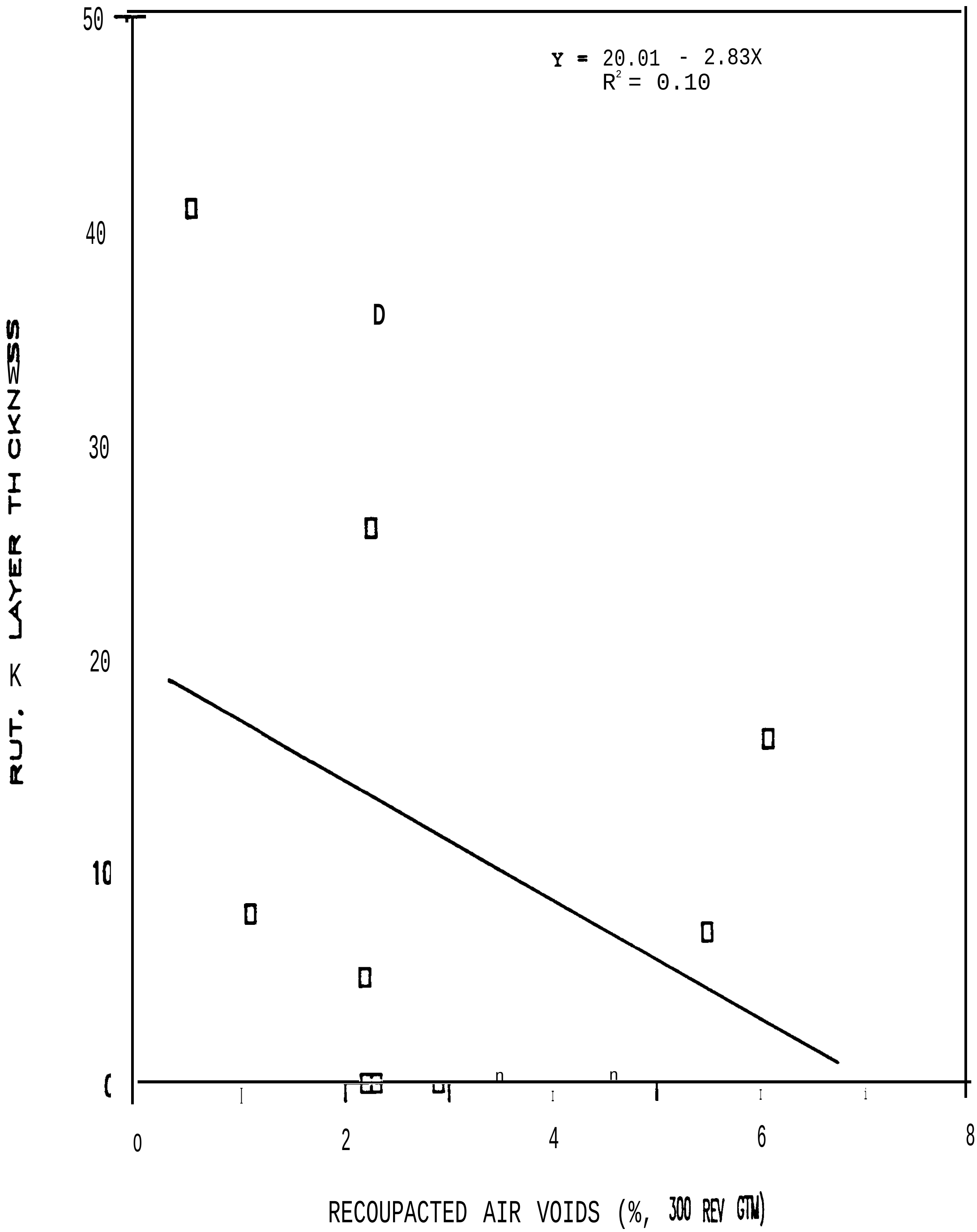


Figure 17. Recompacted Air Voids vs. Layer Rutting

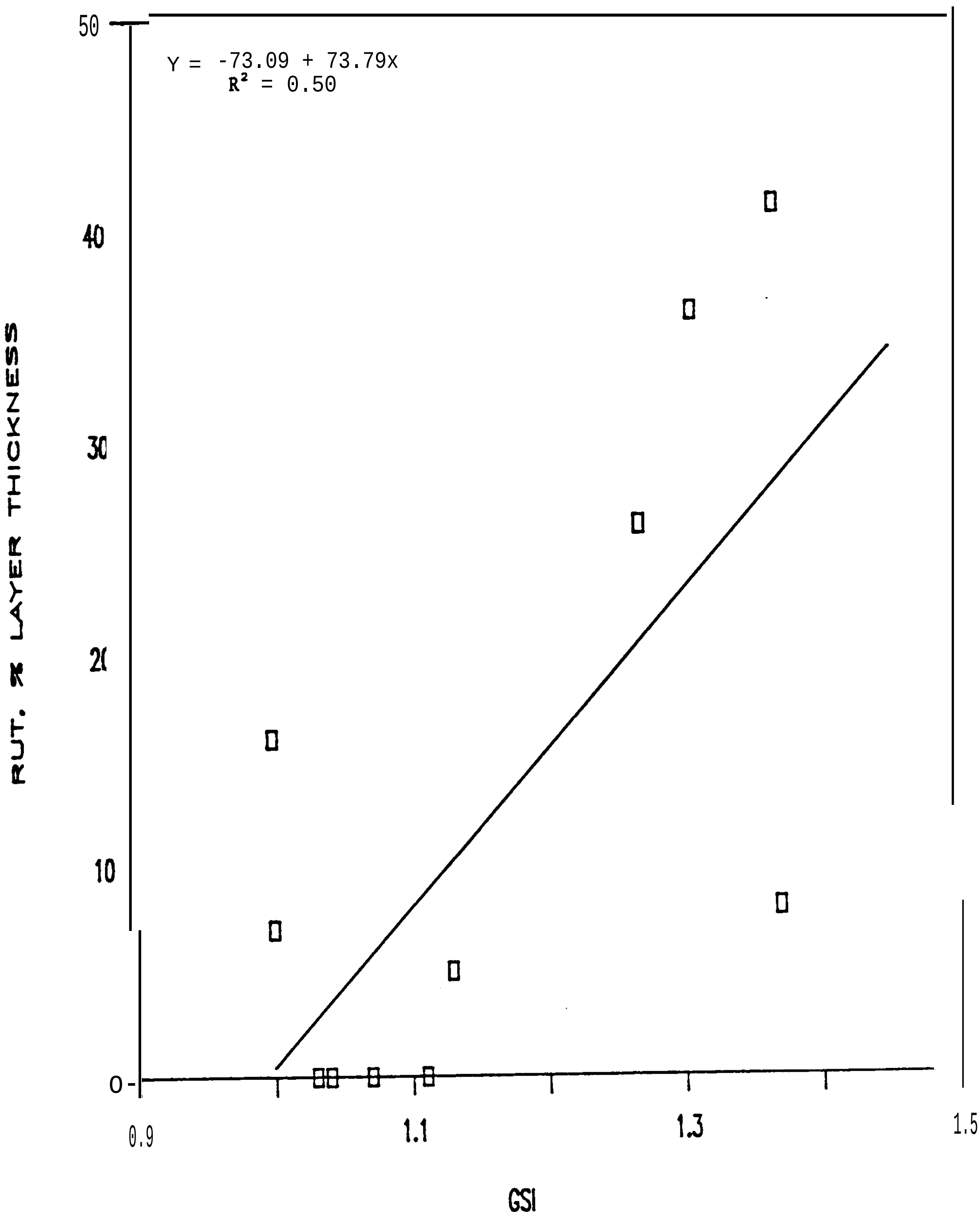


Figure 18. GSI VS. Layer Rutting

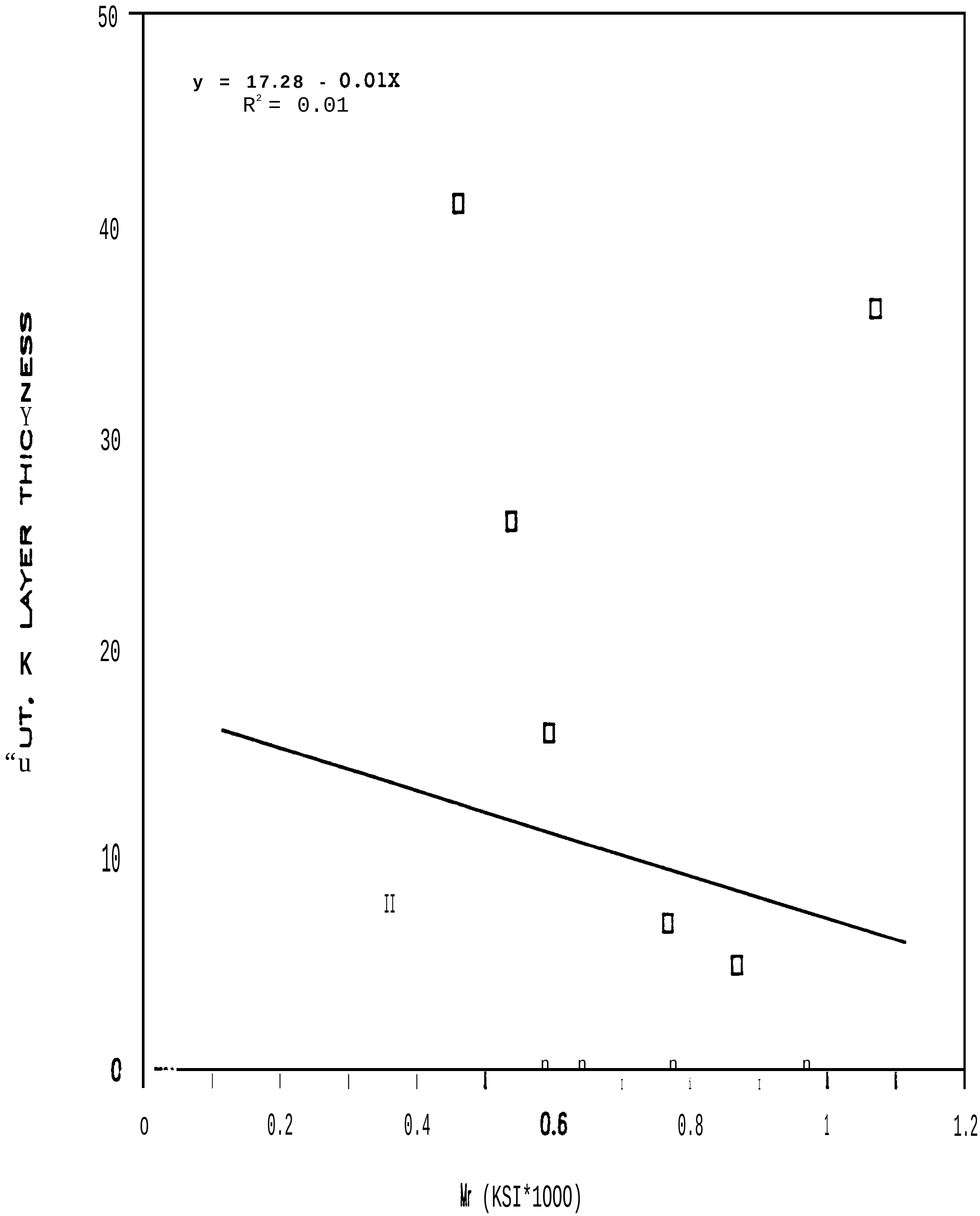


Figure 19. Resilient Modulus vs. Layer Rutting

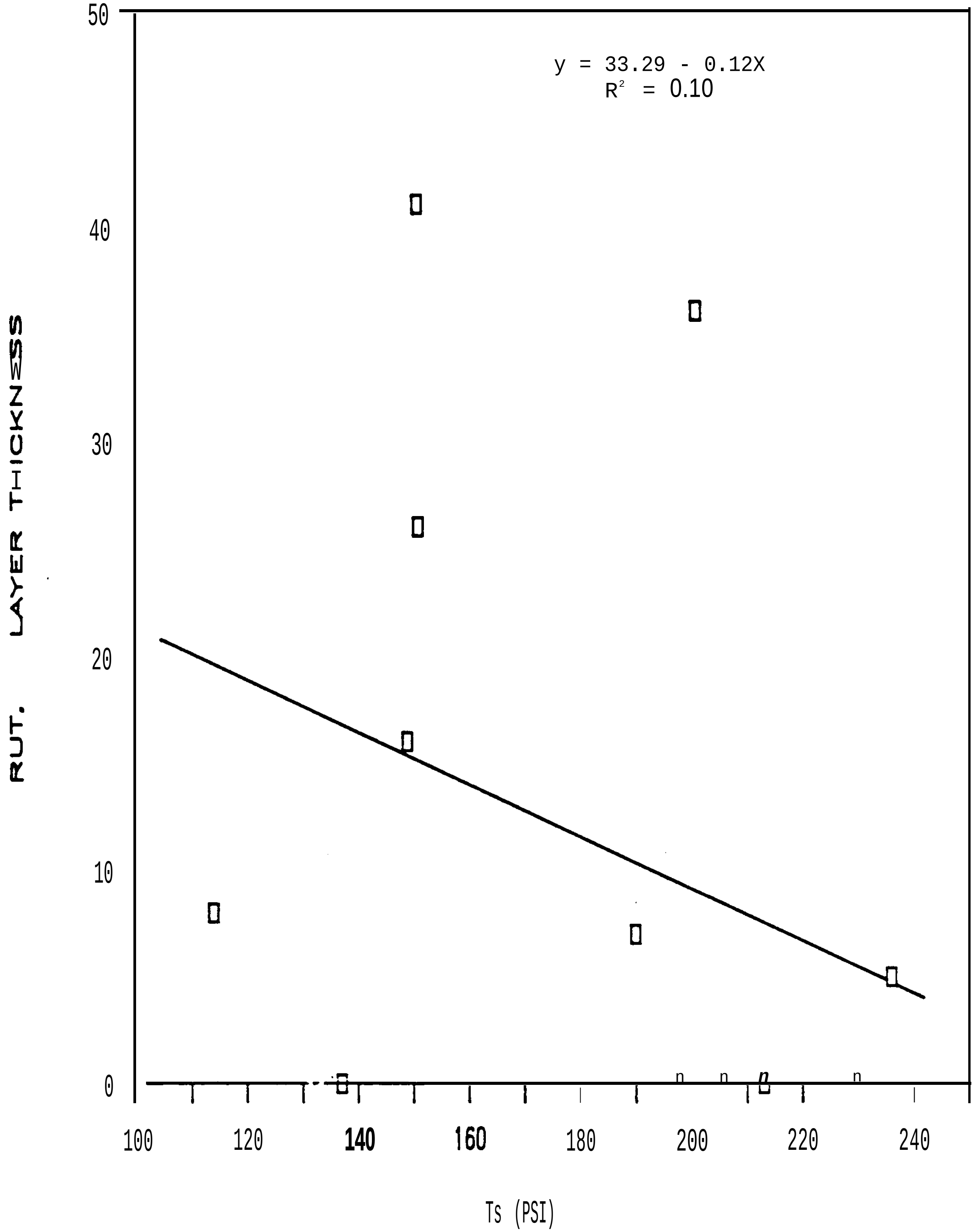


Figure 20. Indirect Tensile Strength vs. Layer Rutting

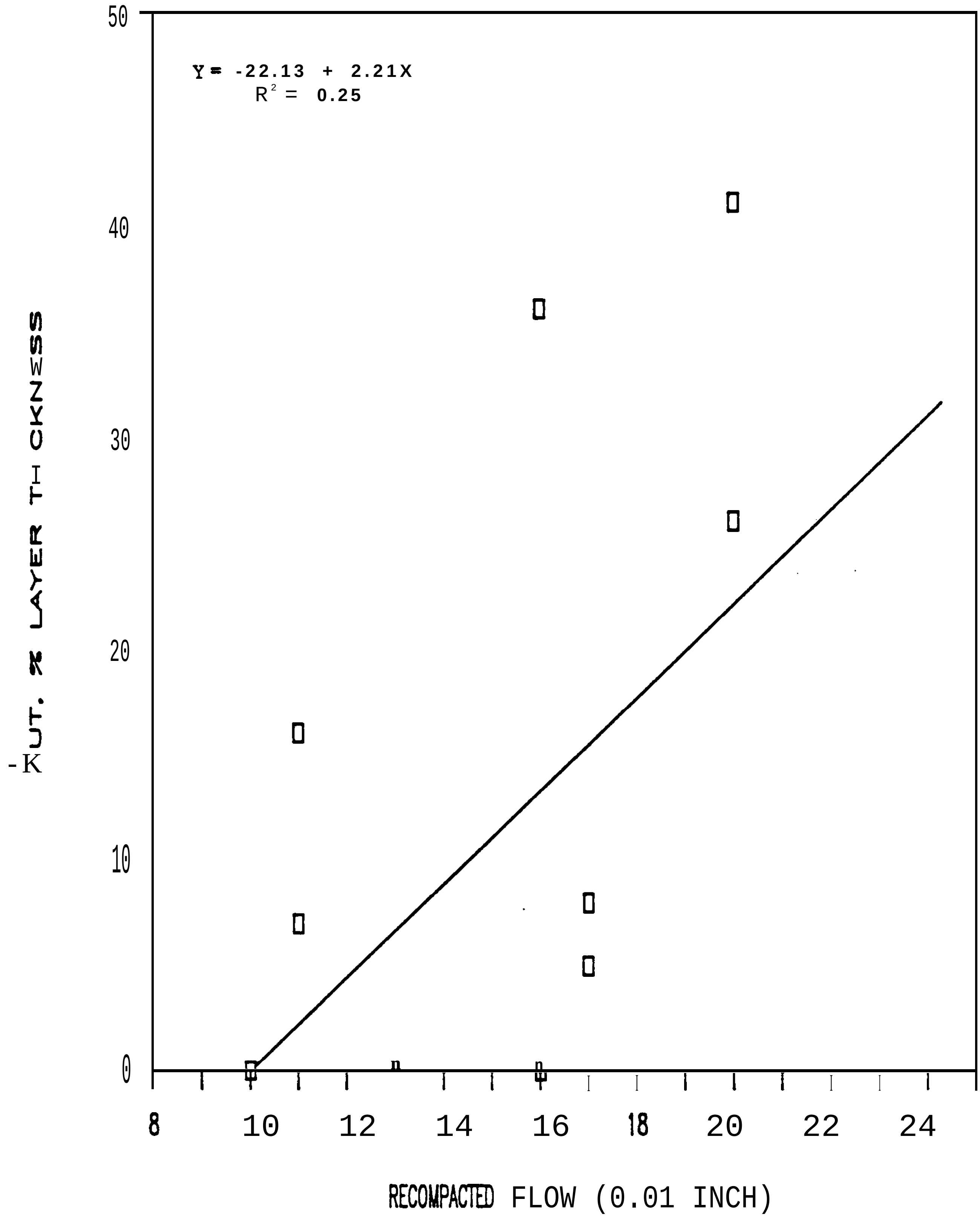


Figure 21. Marshall Flow vs. Layer Rutting