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<b>16. Abstract</b> <p>Surface irregularities causing a rough ride on an asphalt concrete pavement may be contributable to equipment related problems as well as to mix related problems. Problems relating to the laydown equipment can cause such irregularities as surface waves, ripples, tearing of the mat, screed marks, nonuniform texture and surface shadows.</p> <p>Surface shadows can be defined as areas of discoloration on the surface of the mat. In the past the surface shadows have been called auger shadows as they were thought to be related to overloading the augers on the paver with the asphalt concrete mix -- burying the augers. This study presents a discussion of the mixture variables as well as equipment variables which influence the presence and severity of surface shadows.</p> <p>The problem of surface shadows exists throughout the state of Texas. It is not restricted to any one type of mix, although mixture properties do influence the development of the phenomenon. A study of 11 hot mix projects in District 2 of the Texas State Department of Highways and Public Transportation is presented. This study examines equipment, construction and equipment variables. Based on the results of the study of the 11 selected projects in District 2, a field construction investigation was accomplished to create surface shadows "on demand" by varying selected parameters related to the paver and the paver operation. The field test project consisted of operations at three sites within Texas. The results of this evaluation are presented and analyzed. Suggestions are made by which to prevent or decrease the intensity and frequency of surface shadows based on the results of the field evaluation.</p>			
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**EFFECT OF EQUIPMENT AND MIX VARIABLES  
ON SURFACE SHADOWS IN ASPHALT CONCRETE MATS**

by

James A. Scherocman, Mary Anne Rodriguez

and

Dallas N. Little

Research Report 1134-1F  
Research Study 2-8-89/9-1134

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# METRIC (SI\*) CONVERSION FACTORS

## APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
in	inches	2.54	centimetres	cm
ft	feet	0.3048	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km

### AREA

in <sup>2</sup>	square inches	645.2	centimetres squared	cm <sup>2</sup>
ft <sup>2</sup>	square feet	0.0929	metres squared	m <sup>2</sup>
yd <sup>2</sup>	square yards	0.836	metres squared	m <sup>2</sup>
mi <sup>2</sup>	square miles	2.59	kilometres squared	km <sup>2</sup>
ac	acres	0.395	hectares	ha

### MASS (weight)

oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg

### VOLUME

fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft <sup>3</sup>	cubic feet	0.0328	metres cubed	m <sup>3</sup>
yd <sup>3</sup>	cubic yards	0.0765	metres cubed	m <sup>3</sup>

NOTE: Volumes greater than 1000 L shall be shown in m<sup>3</sup>.

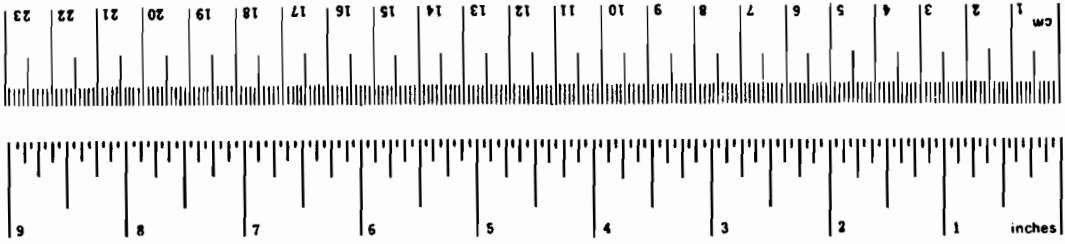
### TEMPERATURE (exact)

°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C
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## APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi

### LENGTH



### AREA

mm <sup>2</sup>	millimetres squared	0.0016	square inches	in <sup>2</sup>
m <sup>2</sup>	metres squared	10.764	square feet	ft <sup>2</sup>
km <sup>2</sup>	kilometres squared	0.39	square miles	mi <sup>2</sup>
ha	hectares (10 000 m <sup>2</sup> )	2.53	acres	ac

### MASS (weight)

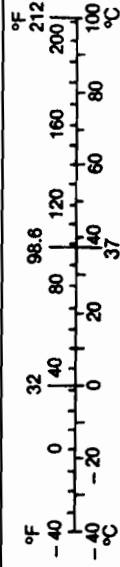
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1 000 kg)	1.103	short tons	T

### VOLUME

mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m <sup>3</sup>	metres cubed	35.315	cubic feet	ft <sup>3</sup>
m <sup>3</sup>	metres cubed	1.308	cubic yards	yd <sup>3</sup>

### TEMPERATURE (exact)

°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F
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These factors conform to the requirement of FHWA Order 5190.1A.

\* SI is the symbol for the International System of Measurements



## IMPLEMENTATION STATEMENT

The findings of this study demonstrate that surface shadows are the result of paver operations and secondarily mixture properties. The reason for the development of surface shadows is based on a highly complex interaction between mixture characteristics and paver operations.

Reduction of surface shadows can be achieved by careful attention to the following paver equipment parameters: (1) head of material in the auger chamber, (2) position of the screed, (3) paver speed, (4) height of the tow point, (5) location of the pre-strikeoff, (6) height of the augers and (7) condition of the screed. Mixture design and mixture temperature are also important.

This report suggests a technique for quantifying the workability of mixtures using the Texas gyratory compactor. The technique is simple and easy to perform. However, the criteria by which to judge adequate workability have not been developed and will probably have to be developed by each individual district or using agency based on the types of material available in the region and on the expectations of the mix.

The suggestions on how to minimize surface shadows presented in this report are ready for implementation.

## **DISCLAIMER**

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification or regulation.



## ACKNOWLEDGEMENT

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**CHAPTER 1**  
**INTRODUCTION**

**SCOPE AND PURPOSE**

The objectives of this study as originally proposed were to (a) improve methods by which high stability mixes are placed and (b) suggest methods to improve workability and compactibility of asphalt concrete mixes without sacrificing stability. However, when the proposal for this study was reviewed by those responsible for submitting the original problem statement (District 2, Fort Worth District of the State Department of Highways and Public Transportation (SDHPT)), the primary objective was changed to determine the causes of surface shadows in surface asphalt concrete mats and suggest ways to eliminate these surface shadows. A secondary objective was to determine the degree and nature of the surface shadow problem and whether or not it poses a structural or long term performance threat. Thirdly, the problem of workability of the mix was to be addressed as time and resources permitted so as to determine if mixture workability played a significant role in the surface shadow problem.

The term surface shadow was adopted in lieu of auger shadow during the progress of this study. The reason for this change in terminology will be discussed latter. Henceforth, in this report, the phenomenon will be referred to as surface shadow.

Several meetings were held between Texas Transportation Institute (TTI) personnel and SDHPT personnel from District 2 to plot a course of action for this research project. These early meetings with SDHPT personnel clearly identified the surface shadow problem as primarily an equipment and construction problem and secondarily a materials problem. It was clear from

the outset that the problem statement being addressed by this research project did not require additional study in mixture design, mixture workability or the effects of moisture on mixture performance. These studies abound in the literature. Therefore, the direction taken in this research was to address the problem statement submitted by District 2 in the most direct way possible.

### PROBLEM STATEMENT

Due to increases in traffic level, truck loads, and tire pressures (as well as tire contact pressures), Texas has responded to the need for improving design and construction practices by building asphalt concrete pavements with greater stability and durability. These mix design modifications include changing aggregate gradations by using more crushed instead of rounded aggregate and adding additives in an attempt to improve the properties of the asphalt cement binder. Some of these needed improvements, however, can cause a mix to be "harsh" and less workable than the mixes used in the past. In addition, the stiffer mixes may be more difficult to place and compact which may lead to a rougher riding pavement surface.

Most of the mixes currently being produced and placed in Texas, however, are relatively tender--they tend to shove and check under the compaction equipment during construction and have a tendency to rut under heavy traffic. These mixes are often characterized by the use of a high amount of rounded field sand in the asphalt concrete mix and by low voids in mineral aggregate and low air voids contents in the mixes.

Surface irregularities causing a rough ride on an asphalt concrete pavement may also be attributable to equipment related problems as well as

to mix related deficiencies. Problems relating to the laydown equipment can cause such irregularities as surface waves, ripples, tearing of the mat, screed marks, nonuniform texture, and surface shadows.

### RESEARCH APPROACH

The workplan for accomplishing this research project was originally divided into eight tasks. Task 1 was to investigate the extent and essence of the problem of surface shadows. This task included two subtasks. The first was to perform a thorough study of the literature. The second subtask was to contact paver equipment manufacturers in order to determine the extent of the surface shadow problem across the country. To aid in this most critical task, TTI hired Mr. James A. Scherocman as a consultant and member of the research team. Mr. Scherocman was retained because of his experience and familiarity with the paver equipment manufacturers. With the help of Mr. Scherocman, three paver manufacturers were contacted and their expertise was used extensively to research the extent and severity of the surface shadow problem. These manufacturers are Barber-Greene (a division of Astec Industries), Blaw Knox (a division of White Consolidated Industries) and Cedarapids (a division of Raytheon).

Representatives of Barber-Greene and Blaw Knox formed an integral part of the research team, not only in the initial phase of problem assessment but throughout the project. Barber-Greene and Blaw Knox representatives gave willingly of their time and expertise on three field projects which were designed with their input to assess the problem of surface shadow. Barber-Greene, Blaw Knox and Cedarapids representatives participated in the evaluation and assessment of the results of the field operations.

With the input of the expert team a definition of surface shadows was

developed. This definition included a discussion of the effects of surface shadows on the appearance, surface texture, surface roughness and ultimate durability of the pavement structure. Secondly, the two primary causes of surface shadows were articulated.

Task 2 of the proposal was a study of selected paving projects in Texas where surface shadow had been clearly defined as a distress problem. With the aid of SDHPT District 2 personnel, 11 projects were identified in the Fort Worth District.

Following the collection and review of the data discussed above, it was ascertained that the surface shadow problem could not be clearly associated with any specific paver type, mix type, contractor, location, time of year of the paving operation, asphalt plant type or other specific equipment or mixture parameters. In addition other sections of the state were evaluated. Engineers in Districts 15, 17, 19, 20, 8, 14, 5, 13 and 16 were contacted as well as State Highway and Transportation Departments in other states. The problem is not a regional problem. The solution to the problem was not evident in the published literature nor in the design and construction records of the projects evaluated. Based on this discovery, it was decided to move forward with a series of planned field trials within the State of Texas.

Task 3 was to construct a limited number of test sections or field experiments. Ultimately, it was decided to perform three field experiments: one in District 2 - - SH 183 frontage roads, and two in District 12 -- FM 1488 and FM 2920. These field experiments will be discussed in detail in chapter three of this report. The purpose of the test section construction was to determine what factors had the most effect on the occurrence of

surface shadows. On each job, it was attempted to create surface shadows "on demand". It was felt that if the shadows could be produced under certain paver operating conditions, then the optimum set of conditions could be found to reduce or eliminate the occurrence of the shadows. A number of different paving variables were tested on each job in order to attempt to produce and change the intensity of the surface shadows that occurred.

Task 4 in the original proposal was entitled assessment of direction. It was decided that following tasks 1, 2, and 3 a general meeting should be held among consultants, interested SDHPT personnel, paver manufacturers and TTI researchers to decide whether to expand, if possible, the field experiments (the experiments themselves and/or the analysis of the experiments) or to continue with laboratory investigations of mixture workability and compatibility from a materials standpoint.

The direction of the project was determined early when it was decided that the surface shadow problem was primarily one of equipment and technique. The secondary material problem, consequently, was relegated a secondary role in the research effort. The aspects of mixture workability and their influence on the surface shadow problem and mat surface distress were evaluated based on limited laboratory testing and an extensive literature review. This activity is discussed in detail in chapter two.

### **REPORT ORGANIZATION**

This report consists of four chapters. The first chapter is the introduction which includes four subsections: scope and purpose, statement of the problem, research approach and report organization. The second chapter is a succinct literature review which highlights the definitions of surface shadow and discusses paver operations which may potentially contribute to surface shadows and asphalt mixture design considerations

which may also contribute to surface shadows. In addition, a literature survey of workability and compatibility and its influence on mat surface defects is included in chapter two. The third chapter is a thorough assessment of the field investigations and the construction of the test sections. This chapter contains a detailed discussion of the construction of the test sections and an analysis of the results including an analysis of the roughness measurements. This chapter is the essence of this research study. Finally, the fourth chapter presents the conclusions and recommendations of this study.

Two appendices support this report. The first appendix contains a summary of the profilometer data from the three test sections; International Roughness Indices were calculated and plotted for each test section. The second appendix contains examples of the Blaw-Knox roughness measurements.

## CHAPTER 2

### SURVEY OF LITERATURE AND PRACTICE

#### DEFINITION OF SURFACE SHADOWS

Surface shadows, shown in Figures 1 and 2, can be defined as areas of discoloration on the surface of an asphalt concrete pavement. These shadows occur at a relatively constant distance apart in the longitudinal direction. In the transverse direction, the shadows may appear to be completely across the width of the lane being paved or may extend only part of the way across the pavement width. In some cases, the shadows may be present on both sides of the paved lane centerline but do not extend across that centerline or to either edge of the lane.

Surface shadows are not present on the surface of most asphalt concrete pavements. The occurrence of the shadows seems to be related to unique combinations of mix design factors and the operation of the paving equipment. In the past, surface shadows have often been called "auger shadows" because it was believed that the surface discoloration was caused primarily by overloading the augers on the paver with the asphalt concrete mix--burying the augers.

Surface shadows can typically be seen only under certain conditions of sunlight. When the sun is low on the horizon and a person is looking directly into the sun, the surface shadows can most easily be seen, if they are present. The shadows normally can not be seen when the sun is at the back of the individual looking at the pavement surface. Rarely can the shadows be seen when the sun is directly overhead or when the sun is at right angles to the longitudinal direction to the roadway. The shadows can sometimes be seen under the headlights of a vehicle that is driving down the

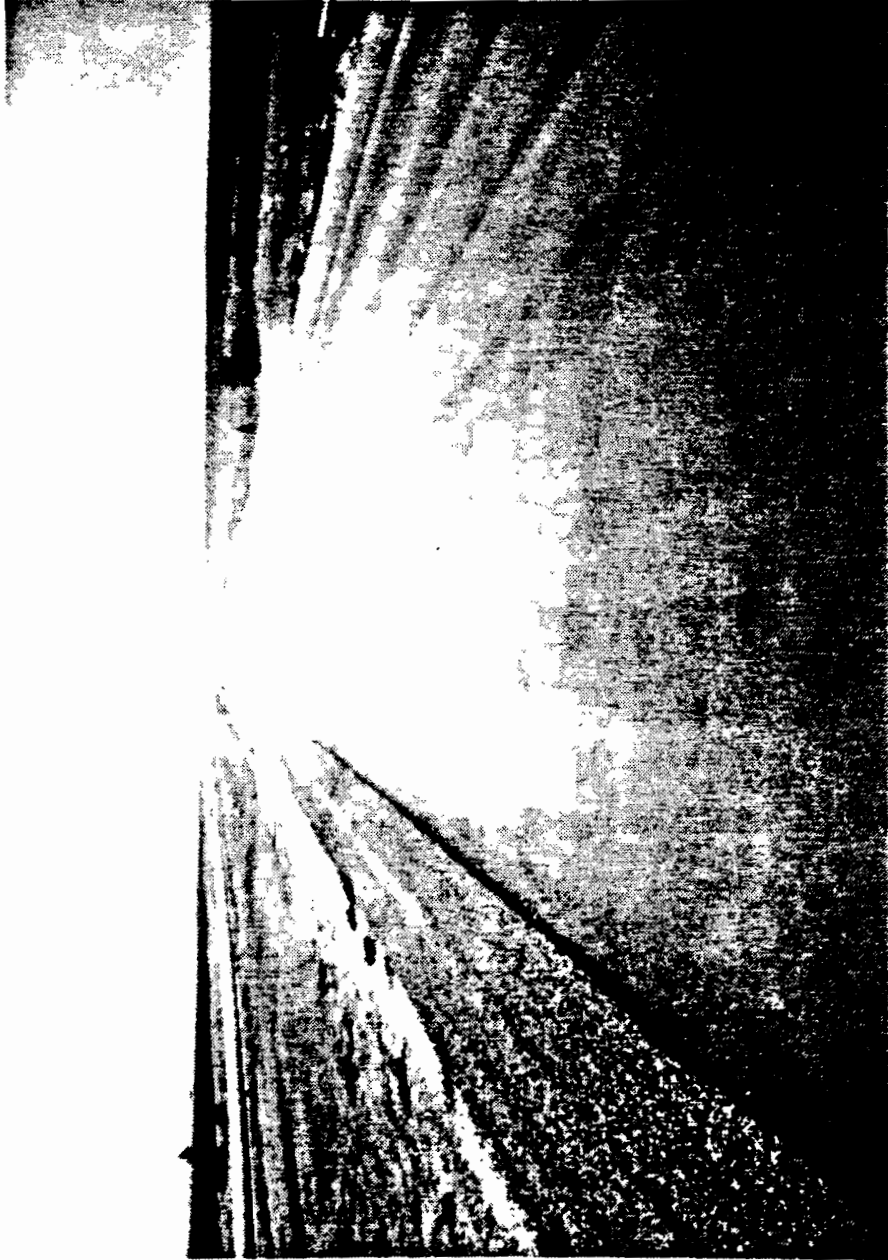


Figure 1. Surface Shadows on a Texas Interstate Highway.



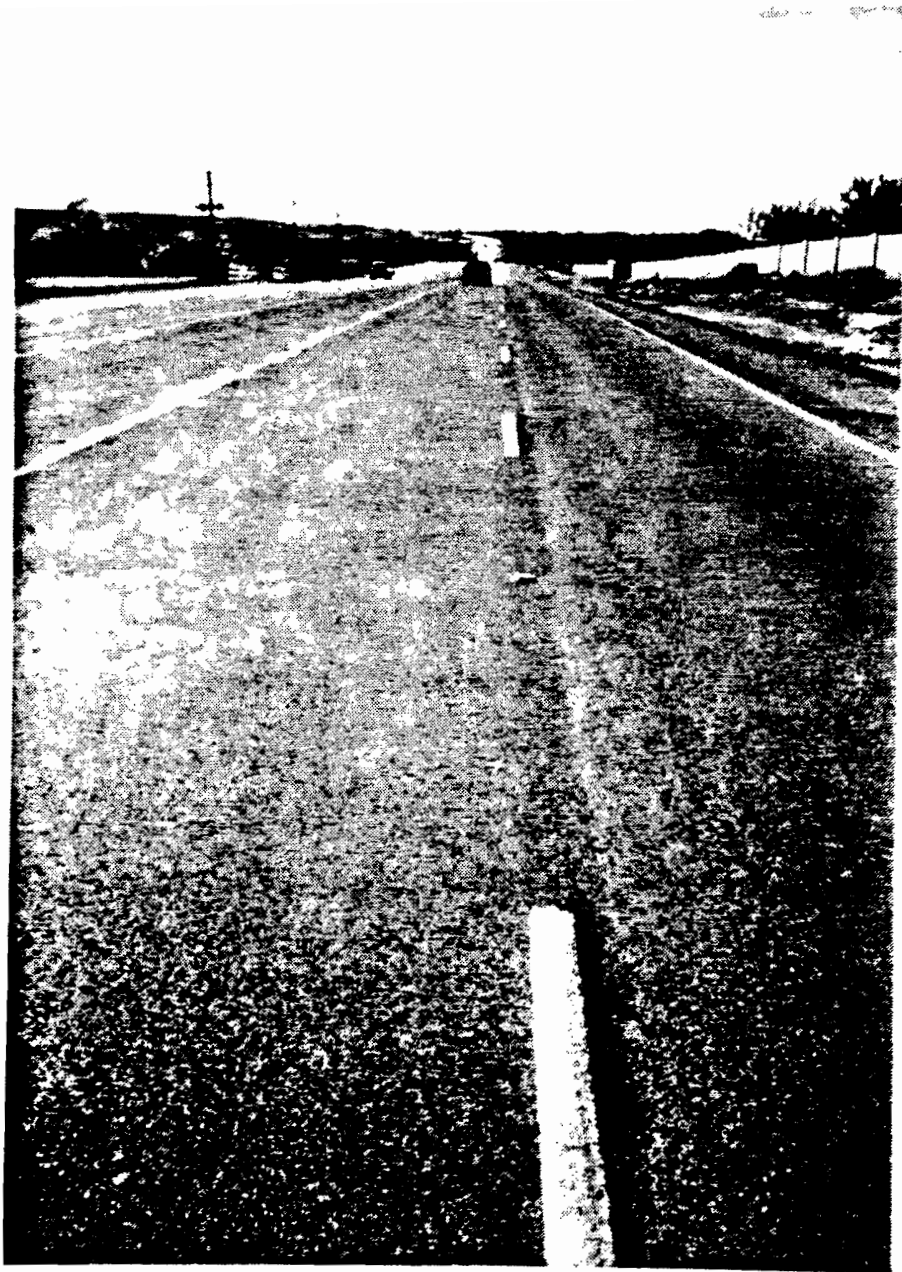


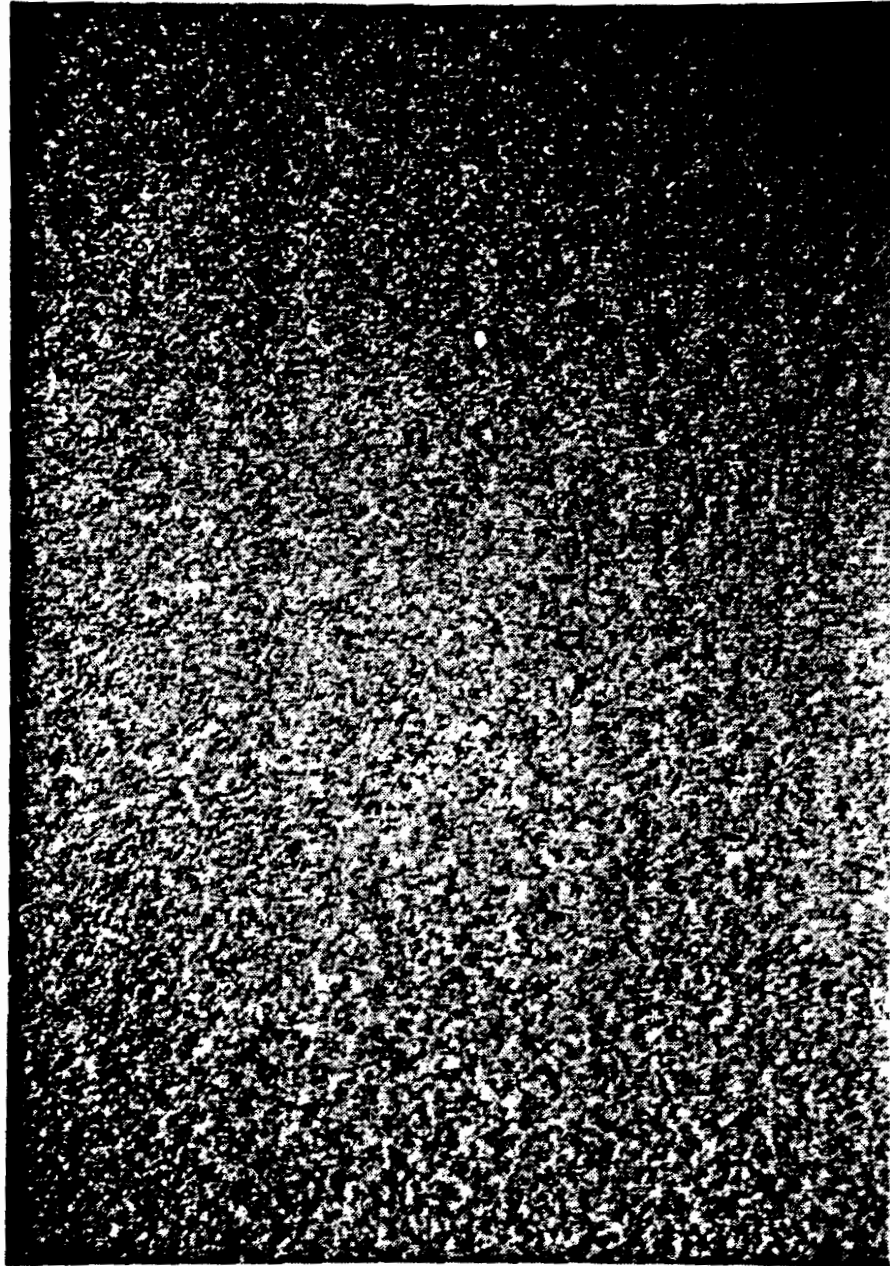
Figure 2. Surface Shadows on a Rural Highway.

roadway at night, although they normally are not visible in the headlights of a stopped vehicle.

A damp pavement surface is also conducive to viewing surface shadows. When the surface is dry, the shadows are usually difficult to see, even under conditions with the sun low on the horizon. If the pavement surface is damp, however, the shadows are much easier to find. If the pavement surface is wet, occasionally the intensity of the shadows is enhanced but the shadows normally can not be seen if there is standing water on the surface.

In the longitudinal direction, the pattern of surface shadows is relatively constant for a particular paving project. The shadows on some jobs may be as close together as three feet. On other projects, however, the shadows may be six or seven feet apart. In most cases, the shadows appear to be four to five feet apart looking down the roadway. Figures 3 and 4 illustrate the longitudinal location of two surface shadows on the pavement surface--a coin was placed on top of different shadow areas; each shadow area was located by a person looking at the shadows from a distance down the pavement.

In the transverse direction, the shadows are typically seen on both sides of the centerline of the paving lane. If the paver is placing mix twelve feet wide, the shadows most often occur on each half of the lane, but generally do not extend across the middle portion of the mat. Rarely do the shadows extend all the way to the edge of the mat. In general, the surface shadows seem to be concentrated at the quarter points of the lane width--for a twelve foot wide lane, from two to five feet from the edge of the course and also from seven to ten feet from the same edge. These distances,



**Figure 3. Coins Marking the Location of the Surface Shadows.**



**Figure 4. Coins Marking the Location of the Surface Shadows.**

however, vary from project to project.

Surface shadows are thought to be caused by the buildup and then the release of fines from the screed on the paver. Fines from the mix--part of the fine aggregate and mineral filler in each mix--collects on the front of the paver screed and on the bottom of the screed itself. As the angle of attack of the screed changes, the collected fines break loose from the bottom of the screed. These fines cause minute (unmeasurable) changes in the surface texture of the mix behind the paver due to the very small changes in the screed angle of attack as the screed attempts to remain in equilibrium with the forces acting on it. The presence of the fines also causes a change in the color of the pavement surface in the area where the fines are present--in the shadow locations.

### EFFECT OF SURFACE SHADOWS

#### Surface Appearance

The surface shadows are usually a darker color compared to the surrounding pavement surface. The shadows can only be viewed from a distance and at an angle to that surface. It is relatively easy, during periods of time when the sun is low on the horizon, for one person to direct another person to walk down the roadway and to stand directly on an area that is darker in color than the rest of the pavement area. When the individual that has been directed to stand over the shadow looks down at the pavement surface, however, no difference in the color of the pavement surface can normally be detected. The coloration difference can be seen only when viewed from an angle and not when looking vertically down at the pavement surface.

Surface shadows make the pavement surface look "blotchy" and

non-uniform. In addition, the shadows make the surface appear to be rough. If the shadows are intense and if the sun is at the correct angle on the horizon, it may appear that the surface of the pavement is like a roller coaster with a series of small waves spreading out in front of the driver of a vehicle.

### Surface Texture

In most cases, there is no significant difference in the texture of the area where the shadow is visible and the surrounding pavement surface, even though the texture of the shadow area appears to be rougher when viewed from a distance and at an angle. Again, when a person is directed to stand directly over a shadow area by another person located some distance away who can see the shadow, the individual at the shadow location, when looking downward, normally can not detect any major difference in the surface texture of supposed shadow area and the adjacent pavement surface.

In the past, the sand patch test has been used to attempt to measure any differences in surface texture between the shadow area and the surrounding area. The results have not been meaningful in most cases. There have been no major changes in the size of the area covered by the sand in the shadow locations compared to the areas where the shadows could not be seen. Thus, although the surface texture of the asphalt concrete mix looks to be rougher in the area where the shadow can be seen, there is generally not any visible or measurable difference in the surface texture of the mix when looking directly at the shadow location from vertically above the area.

### Surface Roughness

When riding on a pavement surface that is covered with surface shadows,

it appears that the surface is very rough. As a person drives down the road, with the sun directly ahead and low on the horizon or when the pavement surface is damp, the roughness can normally be "felt". If the surface looks rough by visual inspection, it is generally perceived to be rough by the other human senses. In actuality the surface may not be rough, it only appears to be rough.

If two sections of pavement, one with surface shadows and one without surface shadows, are ridden over with eyes open, it will usually be perceived that the pavement section with the surface shadows will be the rougher project. If the same two sections are ridden over with eyes closed, however, the roughness (or smoothness) of the two projects will generally be perceived to be the same, assuming that the two sections have equal roughness as measured by a profilometer or some other roughness measuring device. It seems to be the visual perception of roughness caused by the presence of the surface shadows that makes the ride seem rougher even though it may not be.

When measured by a California style profilometer or by a response type measuring system such as a Mays Ride Meter, the roughness of a paving project which contains surface shadows is typically the same as the roughness of a similar project that does not have surface shadows. This comparison, of course, assumes that the condition of the existing pavement on each job was approximately the same and that the same amount of asphalt concrete overlay was used on each project. Generally the measured roughness of the pavement course with the surface shadows is not significantly different than the roughness of a pavement layer that does not contain the shadows.

The roughness of some pavements that contained surface shadows was "measured" with a stringline. The string was stretched in a longitudinal direction across the shadow area and across the surrounding pavement. The distance between the bottom of the string and the top of the pavement surface was determined at multiple locations along the string. It was found that the string was just as tight to the surface of the pavement in the shadow area as in the adjacent pavement locations. No dip or depression, or bump, was found in the area where the shadow was located.

#### Pavement Durability

No evidence exists that shows that the presence of shadows on the surface of an asphalt concrete pavement affects, in any meaningful way, the ultimate durability of that pavement layer under traffic. Although the shadows are visible under certain conditions of sunlight and when the pavement surface is damp, the aesthetic difference in the pavement appearance seems to be the primary "problem" with the occurrence of the shadows.

In general, the texture of the area where the shadows can be seen is similar to the texture of the adjacent pavement surface. The roughness of a pavement section which contains the shadows is essentially the same as the roughness of other asphalt concrete pavements which do not have the shadows. Thus the main defect caused by the occurrence of the shadows is a visual one--the shadows are unsightly to look at but probably do not affect the service life of the asphalt concrete pavement layer in which they are found.



## CAUSES OF SURFACE SHADOWS--PAVER OPERATIONS

One of the primary causes of surface shadows is the operation of the paver used to place the asphalt concrete mixture. The factors that have an affect on the occurrence of the shadows include: the paver speed, the head of material in front of the paver screed, the position of the paver screed, the height of the tow points on the paver screed, the location of the pre-strikeoff, the height of the augers, and the condition of the paver screed plate.

### **Functions of the Asphalt Paver**

An asphalt paver consists of two major parts. The first part is the tractor unit; this unit is the prime mover section of the paver. It incorporates a receiving hopper which accepts mix from the haul vehicle and, using twin drag slat conveyors, the tractor unit carries the asphalt concrete mix to the rear of the machine through a set of metering (flow) gates and then deposits the mixture directly in front of the paver screed. The material is then transported transversely across the width to be paved by a pair of screw conveyors or augers. The tractor unit, equipped with its own engine, contains all the necessary mechanisms to power and control the mix receiving, conveying, and distributing systems. The primary components of the paver are illustrated in Figure 5.

The screed unit, illustrated in Figures 6 and 7, is towed by the tractor unit with the towing point pivotally mounted to the tractor by a pin that eliminates any ability to transmit torque. The screed is self-leveling and has the ability to establish an equilibrium attitude (angle of attack) based on the forces applied to it. As the asphalt concrete mix passes under the heated, flat screed plate, the screed floats on the mix, determining

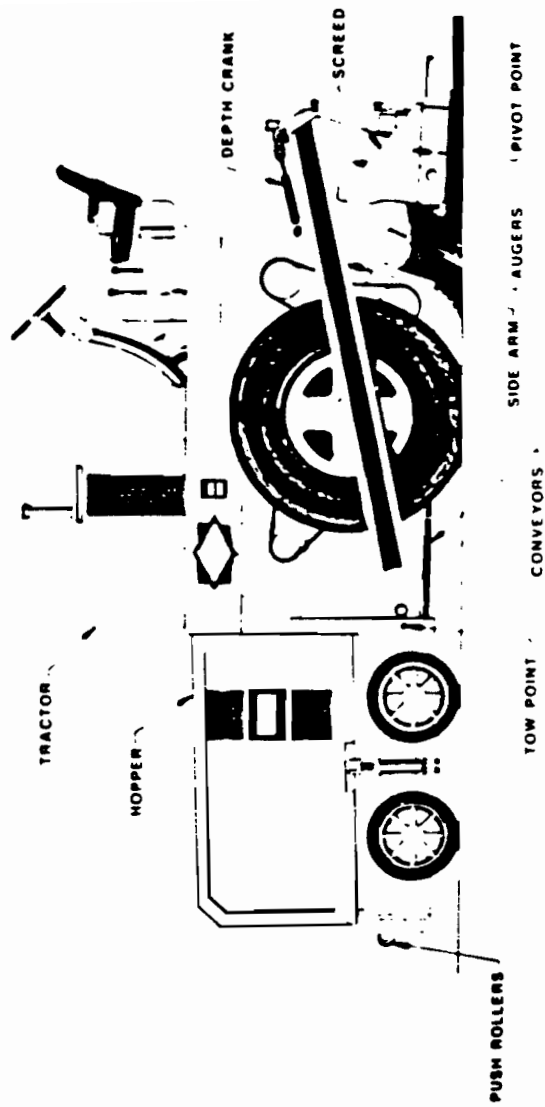


Figure 5. Major Components of an Asphalt Paver.

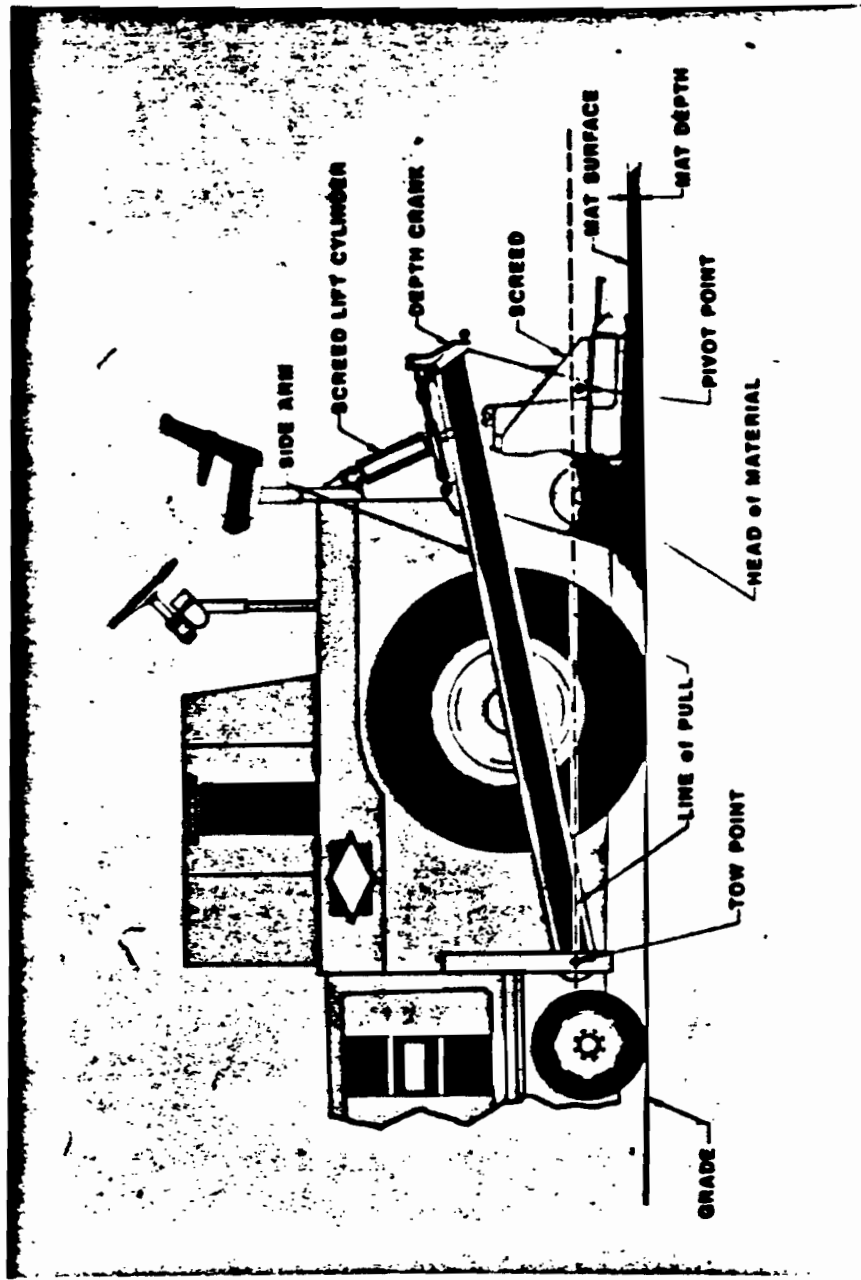


Figure 6. Components of the Paver Screed.

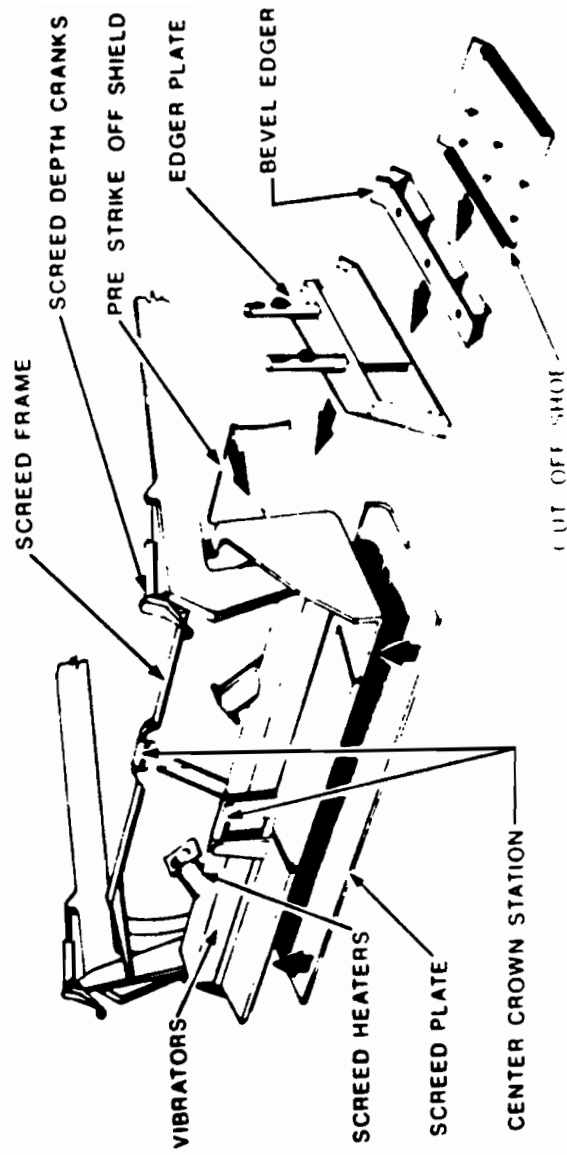


Figure 7. Components of the Paver Screed.

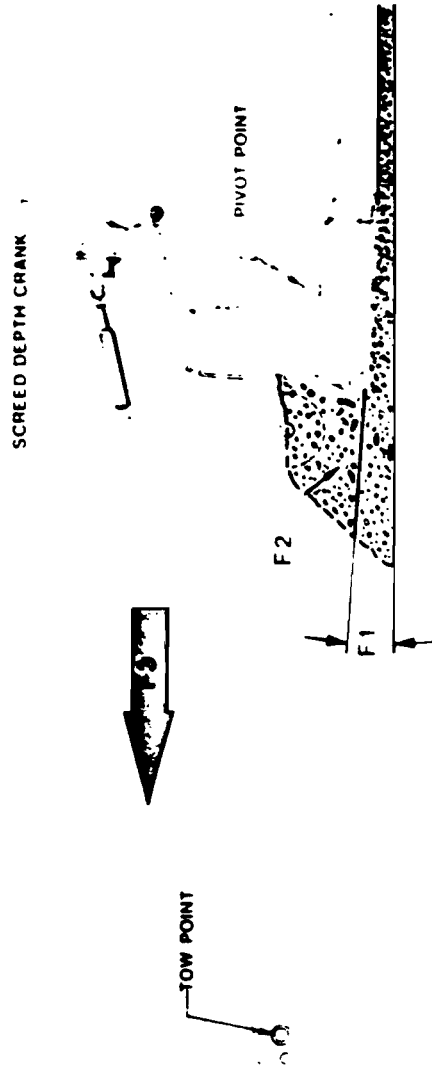


Figure 8. Forces Acting on the Paver Screed.

both the mat thickness and texture and providing some degree of initial compaction to the asphalt concrete mix.

### **Forces on the Screed**

As shown in Figure 8, several different forces act on the screed. These factors are (a) the towing force of the paver (paver speed), (b) the material force (head of material) against the screed as the screed pushes the excess mix ahead of it, (c) the frictional force that is created between the screed plate and the mix passing under it, and (d) the weight of the screed itself. All of these factors must be in balance for the screed to remain at a constant level (angle) and provide a uniform thickness and texture to the asphalt concrete mix being placed.

### **Paver Speed**

The towing force of the paver will have a consistent affect on the screed when the paver moves forward at a constant rate of speed. Everything else being equal, as the speed of the paver increases, the angle of attack of the screed will decrease and less mix will pass under the screed. As a result, the thickness of the mat is reduced. If the paver slows down, with no other changes being made in the operation of the paver (no change in the rate of feed of the mix to the augers and under the screed), the thickness of the mat being placed will increase because the angle of attack of the screed will increase--the screed will rotate around its pivot point and take on a more upward attitude. Thus changes in paver speed have a significant affect on one of the primary forces that acts on the paver screed.

If the paver operator continually changes paver speed during the placement of a truckload of mix, the screed will react to the change in towing force on it. If the speed changes only slightly, from 20 to 25 feet

per minute or 60 to 65 feet per minute, for example, the effect of that change in paver speed on the angle of attack of the paver screed will be minimal. If, however, the paver operator changes speed from 20 to 60 feet per minute or from 80 to 40 feet per minute, the towing forces acting on the screed will change and the angle of attack of the screed will change. The change in the angle of attack of the screed in turn will affect the thickness of the mat. If the speed changes are significant enough and made often enough, ripples can be formed in the mat. Ripples are a severe form of surface shadows. Surface shadows can thus be caused by continual changes in the travel speed of the paver.

#### Head of Material

The other primary factor that greatly affects the equilibrium angle of attack of the screed is the amount of mix which is carried in the auger chamber on the paver. The mix which is directly in front of the screed, pushes against the screed (Figure 9). An increase in the force of the mix on the screed changes the equilibrium of the screed and causes the screed to rotate around its pivot point. The angle of attack of the screed increases, and the thickness of the mat being constructed also increases. If the force of the mix on the screed decreases, the angle of attack of the screed will decrease and the mat thickness will be reduced. In order to keep the angle of attack of the screed (and thus the mat thickness) constant, it is necessary to keep the head of material in front of the screed as consistent as possible. In general, this means that the amount of mix should be at a level near the center of the auger shaft, as shown in Figure 10. If the proper head of material (amount of mix) is maintained, it should not be possible to see the bottom of the augers when the augers

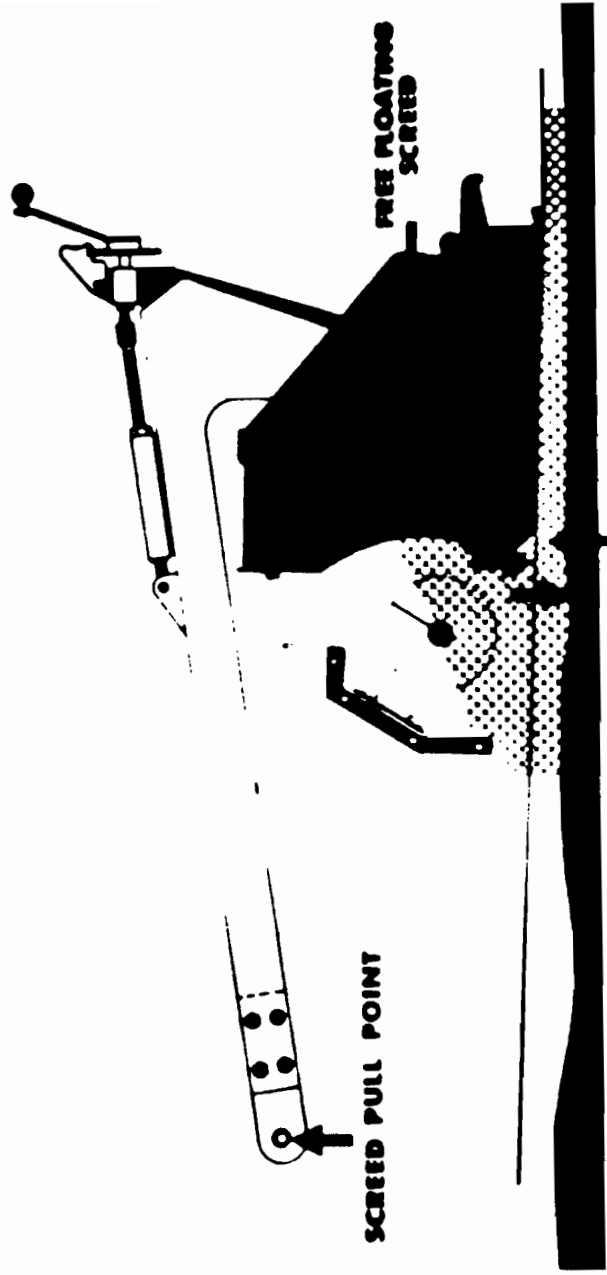


Figure 9. Head of Material in Front of the Paver Screed.





Figure 10. Proper Head of Material in the Auger Chamber.

are distributing mix across the width of the screed. Further, the top portion of the augers should always be visible when the augers are working. The auger should never be overloaded or buried. These conditions are shown in Figure 11.

As the amount of mix carried in the auger chamber changes, the force of the mix against the screed obviously also changes. If the amount of mix on the augers is small--the bottom of the augers are visible--the reduced head of material will decrease the force acting on the screed and the screed will rotate around its pivot point. The angle of attack of the screed will be reduced and the thickness of the mat will be decreased. If the amount of mix carried on the augers is great--the top of the augers are covered or barely visible--the increased head of material will significantly increase the force acting on the screed. This increase in force will cause the screed to rotate around its pivot point and the angle of attack of the screed will be increased, resulting in a greater mat thickness.

If the paver operator does not control the rate of flow of mix through the paver to the augers and the screed, the head of material in the auger chamber will continually change. The flow rate is governed by the position of flow gates at the back of the paver hopper, shown in Figure 12. If the flow gates are wide open, the slat conveyors and augers are turned on to deliver mix back to the screed (Figure 13). A large mass of mix is pulled back through the tractor unit and dumped in front of the screed. This mass of material causes the augers to be overloaded, changes the head of mix in front of the screed, and causes the screed to rotate around its pivot point, increasing the thickness of the mat being placed. When too much mix is available in the auger chamber, the slat conveyors and augers turn off and

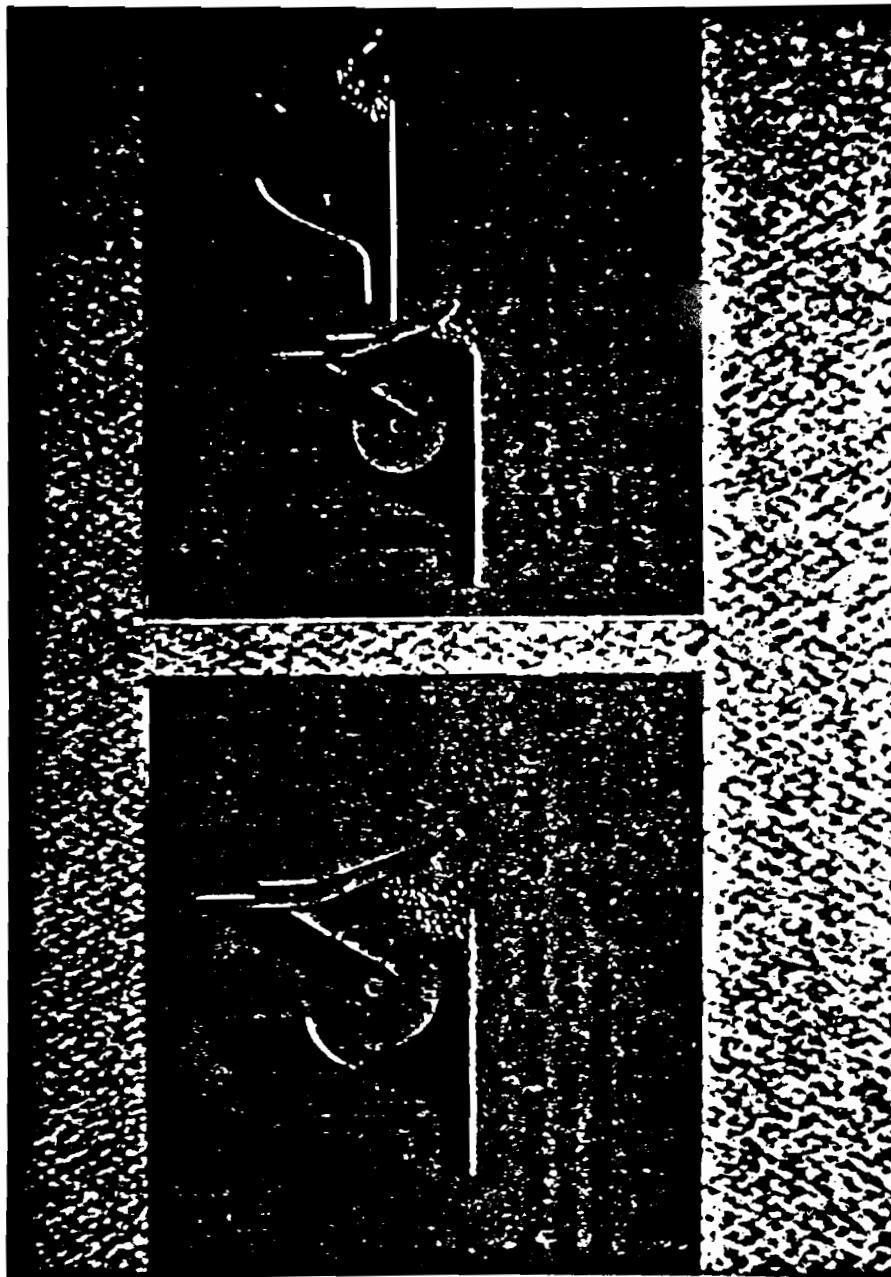


Figure 11. Head of Material in Front of the Paver Screed.

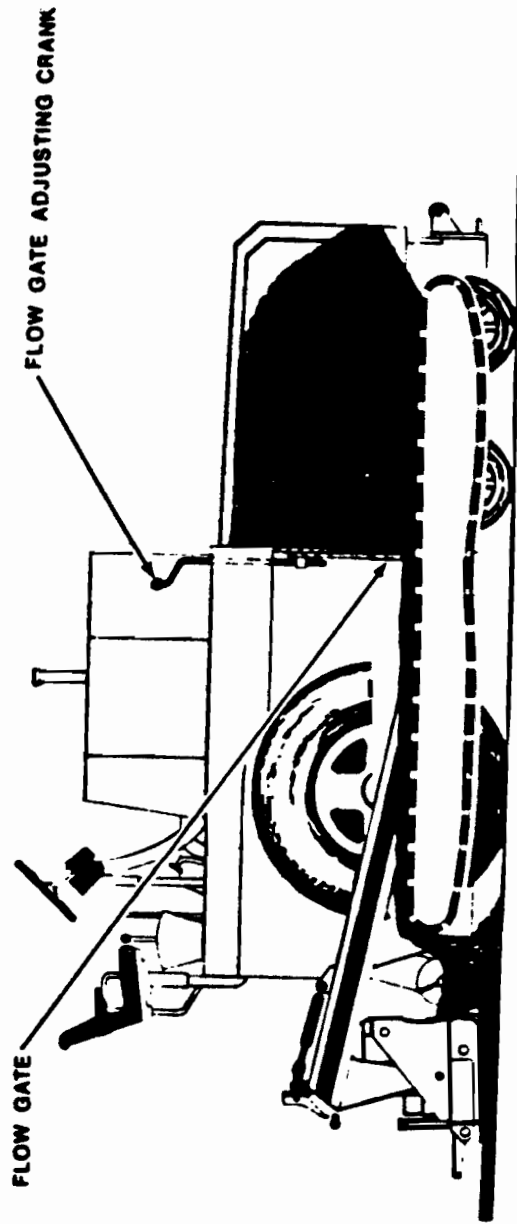


Figure 12. Location of the Paver Hopper Flow Gates.

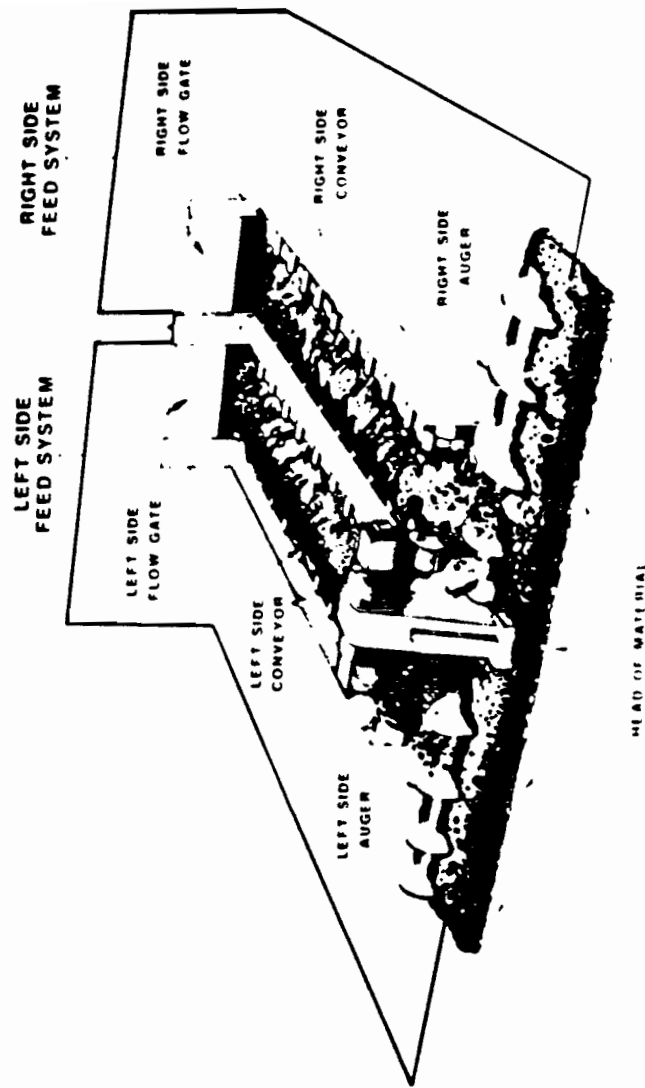


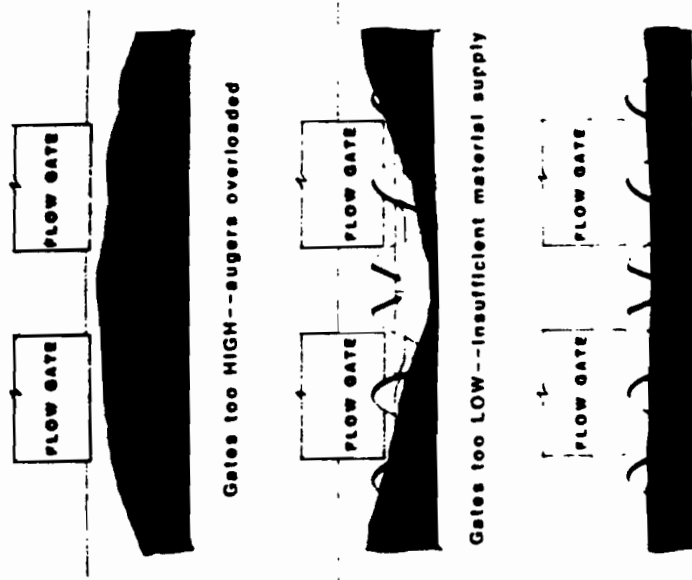
Figure 13. Illustration of Flow Gates, Slat Conveyors and Augers.

the head of material is allowed to fall as the mix passes out under the screed. When too little mix is in the auger chamber, the slat conveyors and augers are turned on once again and another mass of material is pulled back to the auger chamber. These conditions are shown in Figure 14.

This on-off cycle for the slat conveyors and augers continually changes the head of material in front of the paver screed. This change in force causes the screed to hunt--rotate constantly around its pivot point. This change in force is a major factor in the generation of surface shadows.

In order to control the amount of mix in the auger chamber, the flow gates at the back of the paver hopper must be set at a level to keep the slat conveyor and auger on each side of the machine running at all times. A constant level of mix is accomplished by lowering the height of the flow gates and restricting the amount of mix that can pass under the gates. In order to deliver enough mix to the screed without starving the screed, the gates should be lowered to the point in which the slat conveyors and augers run 100% of the time. The key to a constant head of material in front of the screed is the delivery of a constant amount of mix from the paver hopper. When the slat conveyors and augers continually turn on and off, the amount of mix deposited in front of the screed must vary. If the slat conveyors and augers run continuously, a consistent amount of mix is placed in front of the screed and the head of material is constant. Thus the force on the screed is constant and the screed maintains a constant angle of attack. The system used to deliver mix to the screed is illustrated in Figure 15.

Flow control devices are used to control the amount of mix delivered from the hopper to the auger chamber. These devices are of two types:



**Figure 14. Flow Gate Settings.**

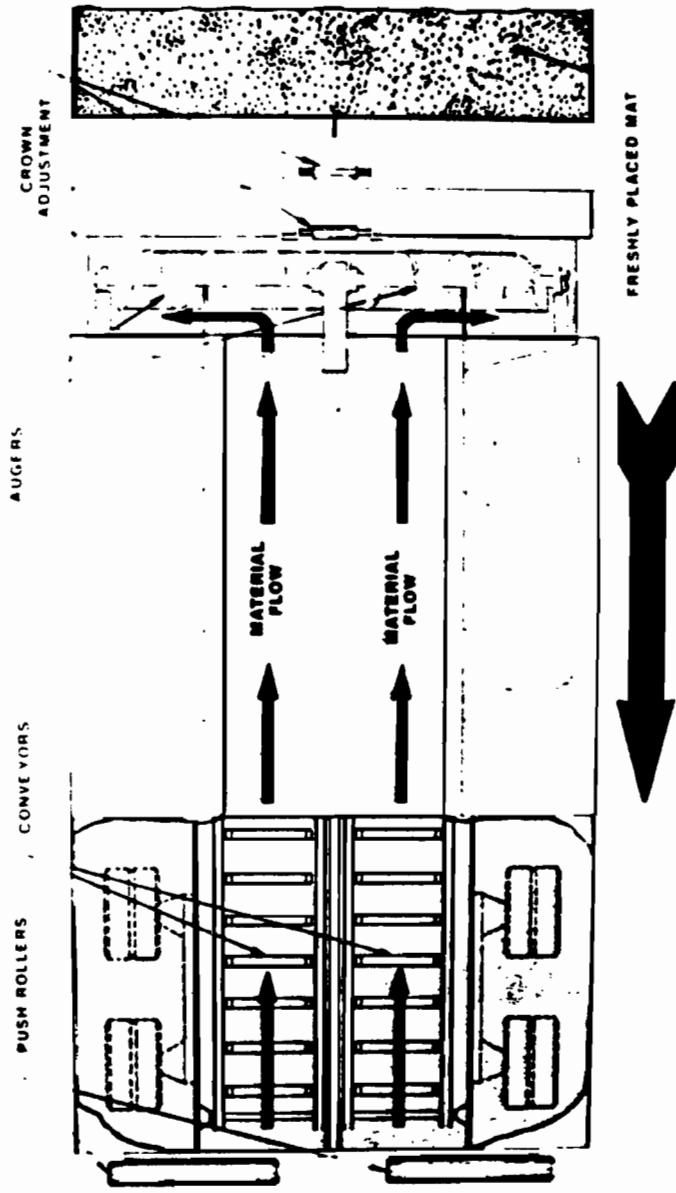


Figure 15. Delivery of Mix to the Paver Screed.



on-off switches and proportional speed sensors. For the on-off type flow control sensor, the amount of material in the auger chamber is determined by the position of the flow control device. Too much mix in front of the screed and the delivery of the mix is stopped. Too little mix in the auger chamber and the flow control device causes the slat conveyors and augers to begin delivery of the mix from the hopper. For the flow control device to operate properly, however, and keep the slat conveyors and augers operating 100% of the time, the flow gates on the back of the hopper must be set at a level to restrict the amount of mix pulled back through the tractor unit. When the flow gates are at the correct level, the slat conveyors and augers will run all the time, keeping the head of material in front of the screed constant.

Proportional flow control devices are available to increase or decrease the speed of the slat conveyors and augers as more or less mix, respectively, is needed in the auger chamber. If the paver is being used to place a variable thickness of mix (leveling course), the amount of mix needed at the screed will change with the condition of the existing pavement surface. If the paver is equipped with proportional flow control devices and if more mix is needed in the auger chamber because a low point is present in the underlying pavement, the automatic controls will increase the speed of the slat conveyors and augers. As a result, more mix is pulled from the hopper back to the screed. This action provides more mix for filling in the low spots in the existing surface. If a high point in the existing surface is found, less mix will need to be place. In this case, the proportional feed control device will reduce the speed of the slat conveyors and augers and less mix will be deposited in front of the screed.

The primary purpose of the flow control device is to keep the amount of mix (head of material) in front of the screed constant. A constant head of material is accomplished by keeping the slat conveyors and augers running 100% of the time. Even with automatic flow control sensors, the flow gates at the back of the paver hopper must be set at a level to restrict the delivery of the mix to the auger chamber. If the flow gates are not properly set, the flow control sensors will not be able to function properly. Keeping a constant head of material in front of the screed is absolutely necessary to control the formation of surface shadows.

#### Position of the Screed

The position of the screed, in relation to the tow point on the paver and thus the augers on the paver, can be changed to a limited degree (Figure 16). In most paving situations, the screed is in the forward position. In this position, the screed is as close to the augers as possible--the distance between the augers and the front of the screed is at the minimum. On most pavers, the screed can slide backwards up to four inches. This screed position is reached by unbolting a section of the tow arms, setting the screed on the ground, driving the tractor unit forward a few inches, and rebolting the screed in place on the tow arms. This operation, of course, increases the distance between the screed and the augers.

The paver is normally operated with the screed in the forward position, keeping the head of material in front of the screed to a minimum. If a mix which contains large size aggregate is to be placed by the paver, the screed is sometimes changed to the back position in order to permit the large size aggregate to be moved more easily by the augers and to pass under the screed without tearing of the mat. In the back position, however, more mix is

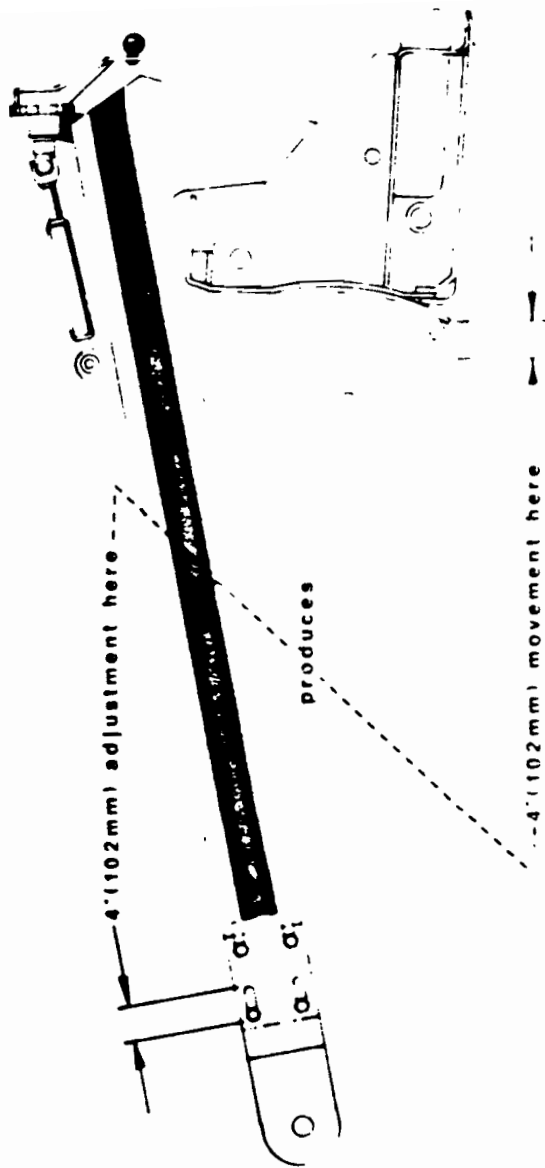


Figure 16. Variable Positions of the Paver Screed.

carried in the auger chamber, and the force of the mix on the screed is increased.

With the screed in the back position, changes in the head of material in the auger chamber have a greater affect on the forces acting on the screed. As the amount of mix delivered to the augers decreases, the force of the mix on the screed is reduced even more than when the screed is in the forward position because there is more mix in the auger chamber for any level of mix on the augers. With a low level of mix in the auger chamber, the screed will rotate around the pivot point and the angle of attack of the screed will decrease. As the amount of mix delivered to the augers increases (when the slat conveyors and augers are turned on and mix is pulled back from the paver hopper), the force on the screed (head of material) increases, and the angle of attack of the screed increases. The screed rotates around its pivot point and the thickness of the mat becomes greater.

In the back position, therefore, the angle of attack of the screed is more significantly affected by a change in the head (amount) of material in front of it than when the screed is in a forward position. This effect is due simply to the greater volume of mix in the auger chamber when the screed is farther away from the augers. It would be expected that surface shadows might be more intense when the screed was in the back position compared to the standard front position, all other factors being equal. Changes in the head of material with the screed in the back location cause more significant changes in the angle of attack of the paver screed and thus the potential for surface shadows.

### Other Factors

There are several other secondary factors that affect the forces on the paver screed and thus may have an affect on the occurrence of surface shadows. Among those other factors are the height of the tow points on either side of the paver, the location of the pre-strikeoff on the front of the screed, the height of the augers, and the condition of the screed plate.

Height of the tow points The paver screed is attached to the tractor unit at only one point on each side of the machine. This point is called the tow point or pull point, and is shown in Figure 17. When automatic grade and slope controls are used on the paver, the elevation of the tow point is kept constant as the paver tractor unit moves upward and downward over the existing pavement surface. As the tractor unit travels downward into a dip on the pavement surface, the hydraulic cylinder (shown in Figure 17) on the end of the tow arms raises the arms and keeps the elevation of the tow point constant in regard to the reference being used (stringline or mobil ski). The screed thus maintains a consistent angle of attack. In a similar fashion, as the tractor unit moves upward over a high point in the pavement surface, the elevation of the tow point is automatically lowered by the grade and slope control devices, keeping the angle of attack of the screed constant. Keeping the angle of attack of the screed constant permits the paver to place less mix at the high point and thus level up the pavement surface.

When the screed tow point is set near the midpoint of the length of travel of the hydraulic tow point cylinder, the screed generally rests directly on the asphalt concrete mix over its full length, from front to back (nose to tail). The weight of the screed, one of the forces acting on

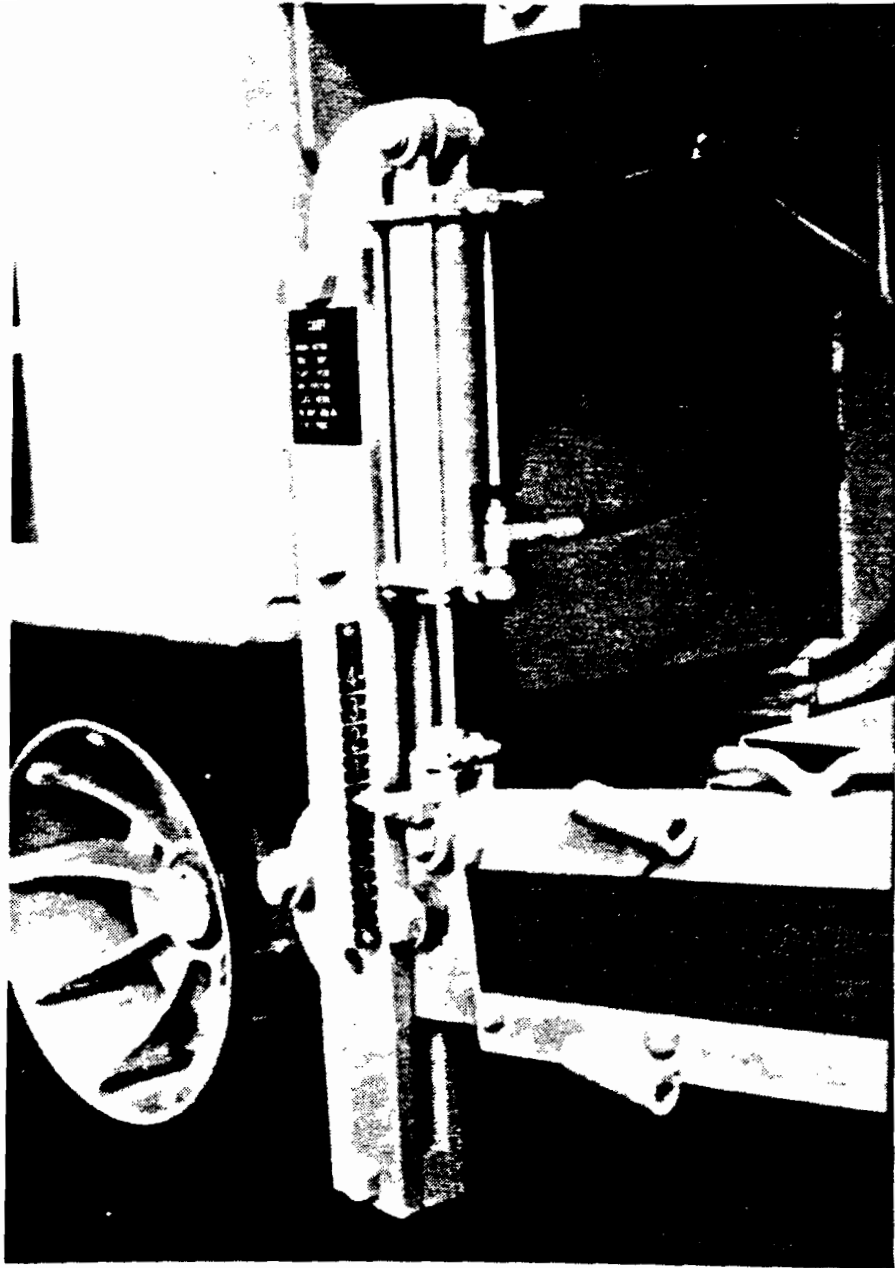
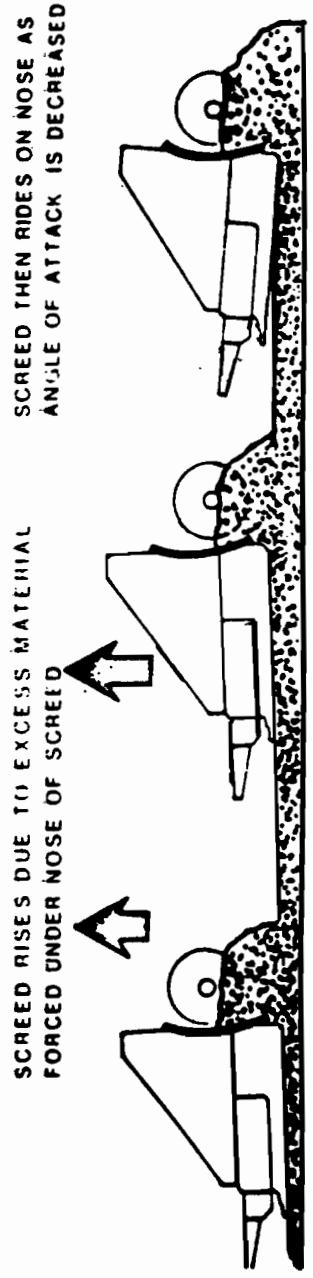


Figure 17. Hydraulic Cylinder and Paver Tow Point.

the screed, is thus evenly distributed over the whole area of the screed plate, and the screed is uniformly supported. When the elevation of the tow point is artificially raised--set at a level above the midpoint of the length of travel of the hydraulic cylinder--the screed has a tendency to ride on its nose. When the elevation of the tow point is artificially lowered--set a level below the midpoint of the length of travel of the hydraulic cylinder--the screed has a tendency to ride on its tail.

If it is correct that surface shadows are caused in part by the release of fine material from the bottom of the screed, then a screed which rides on its nose will have less screed plate in contact with the mix and may experience a lesser degree of fines buildup than will a screed that is in full contact with the mix being placed. A screed which is set too low at the tow point and which rides on its tail may still create surface shadows, however, as more fines will tend to collect on the trailing edge of the screed compared to the front edge. Although allowing a screed to ride on its nose may reduce the intensity of surface shadows, uneven wear on the leading edge of the screed will be a problem and non-uniform texture of the mat being constructed will result. Significant costs will be incurred in replacing the worn screed plate.

Location of the pre-strikeoff When the pre-strikeoff on the screed is set at the correct level for the stiffness of the mix being placed, the screed will ski at the proper angle of attack, and the screed will be uniformly in contact with the mix passing under it. If the pre-strikeoff is set too low, as shown in Figure 18, the screed will rotate around its pivot point and the angle of attack will increase. As a result the screed will tend to ride on its tail--the whole length of the screed will not be in contact with the mix passing underneath it. This screed position will



**PRE-STRIKE-OFF SET TOO HIGH**

Figure 18. Location of Screed Pre-Strike Off.



tend to cause additional wear of the screed plate on the rear portion of the screed and will also tend to slightly increase the amount of buildup of fines on the screed. This condition may increase the intensity of the surface shadows with some asphalt concrete mixtures.

If the pre-strikeoff is set at too high a level for the particular mix being placed, the angle of attack of the screed will be decreased and the screed will tend to ride on its nose. This screed position causes an increase in the wear on the screed plate on the front portion of the screed because the weight of the screed is being carried on a lesser area. This condition, however, may reduce the occurrence of surface shadows, since less fines from the mix will build up on the nose of the screed compared to the tail of the screed. For uniform surface texture and reduced screed plate wear, the pre-strikeoff should be set at a position where the whole screed plate is in contact with the mix beneath it.

Height of the augers A few pavers are equipped with a device that allows the position of the augers to be changed in a vertical direction. One of the primary causes of surface shadows is the amount of mix carried on the augers (head of material). Raising the height of the augers should reduce the intensity of the surface shadows since there will be less tendency to overload the augers with mix if the augers are further above the existing pavement surface.

Condition of the screed plate A screed plate (bottom of the screed) that is in good condition (smooth) will have less tendency to catch and hold fine aggregate from the asphalt concrete mix. A screed plate which is uneven or worn will have a tendency to briefly hold mix and release the fines periodically. It is believed that surface shadows can be increased in intensity if the screed plate on the paver screed is worn.

## **CAUSES OF SURFACE SHADOWS--ASPHALT CONCRETE MIX DESIGN**

The other primary cause of surface shadows is related to the characteristic of the materials used to manufacture the asphalt concrete mixture. Aggregate properties such as gradation, shape and surface texture, and absorption all can have an effect on the occurrence of the shadows. Properties of the asphalt cement, such as the grade of the binder, the temperature susceptibility of the material, and any additives used in the asphalt cement, may all affect in some manner both the presence of the shadows as well as the intensity of the surface shadows. In addition, the characteristics of the asphalt concrete mix itself, particularly the tenderness of the mix and the void content (voids in mineral aggregate and air voids) may affect the severity of the surface shadow problem.

### **Aggregate Characteristics**

A number of characteristics of the coarse and fine aggregate in the asphalt concrete mix can have an affect on the occurrence and intensity of the surface shadows that may be present in the pavement surface. Among those properties are the aggregate gradation, aggregate shape and texture, and absorption.

#### **Gradation**

The gradation of the combined coarse and fine aggregate employed in the mix can have a significant affect on the stiffness of the asphalt concrete mix. A very uniform gradation--one which parallels and is very close to the Texas gradation reference line (modified maximum density line) will provide for a mix which has a very low voids in mineral aggregate (VMA) content and also a very low air void (AV) content. This mix is very sensitive to small changes in fluid content--asphalt cement content and/or moisture content.

If too much binder material and/or moisture is present in the mix, the asphalt concrete material will become tender and may shove under the compaction equipment and rut under traffic. If too little asphalt cement is used in the mix, the asphalt concrete will lack cohesion and tend to ravel under the applied traffic loads.

An aggregate gradation which has a disproportionate amount of fine aggregate in the mix, particularly between the No. 40 and the No. 80 sieves (a hump in the fine aggregate portion of the gradation curve), can also provide for a mix which is tender. An asphalt concrete mix made with such a gradation, particularly if the amount of aggregate passing the No. 40 sieve is above the Texas gradation reference line and the amount of aggregate passing the No. 80 sieve is below that gradation reference line, will have reduced stiffness and will tend to shove under the compaction equipment and rut under traffic.

In both cases, the asphalt concrete mix that incorporates either of these two gradations will have a tendency to separate some of the fines from the rest of the mix. These fines can hang up on the screed of the paver and contribute to the development of surface shadows. In addition, if the mix contains some moisture, the tendency of the fines to cling to the front of the screed and the screed plate will be increased. An aggregate gradation that provides for adequate VMA and AV will have less tendency to produce a mix that will suffer from surface shadows.

#### Shape and Texture

In general, the more angular the aggregate incorporated in the mix, the stiffer the asphalt concrete mixtures, all other factors being constant. This effect is true for both coarse and fine aggregate. In addition, the rougher the surface texture of the aggregate, the stiffer the mix. Crushed

limestone is more angular and has a rougher surface texture than does a rounded gravel aggregate. A mix made with crushed limestone coarse aggregate will generally be stiffer than a mix made with rounded river gravel coarse aggregate. If manufactured sand is used in lieu of natural sand as a portion of the fine aggregate in the mix, the resulting asphalt concrete mix will also be stiffer.

There is some indication that the intensity of surface shadows will increase as the tenderness of the mix increases (as the stiffness of the mix decreases). In addition, surface shadows might be more prevalent in a mix that has an increased sand content since more fines can collect in front of and under the paver screed. Stiffer mixes are generally less susceptible to segregation and to separation of the fines from the remainder of the mix.

#### Absorption

A mix that contains aggregate that is highly absorptive may generally be more susceptible to a separation of the fines than will a mix that is made with non-absorptive aggregate unless an adjustment is made in the effective asphalt content of the mix. Enough asphalt cement must be added to the mix to account for the binder material that is absorbed into the aggregate. If that modification in the asphalt content is not made and the mix is lean on binder, the mix will have a greater tendency to lose its fines at the paver screed than will a mix that has an adequate asphalt content.

#### **Asphalt Cement Characteristics**

The grade of the asphalt cement, the temperature susceptibility of the binder material, and the use of additives in the asphalt cement may all have an effect the amount and the intensity of the surface shadows that might be present in an asphalt concrete surface course mix.

### Grade of Asphalt Cement

The grade of the asphalt cement incorporated into the mix may have an affect on the intensity of the surface shadows that can occur in the asphalt concrete mix. The stiffer the asphalt cement--the higher the viscosity grade or the lower the penetration grade-- the less likely the fines in the mix will separate from the other aggregate and cause surface shadows. A mix made with an AC-30 asphalt cement generally may have less surface shadows than the same mix made with an AC-10 binder material. Similarly, a mix that incorporates an 85-100 penetration grade binder material will be less stiff and may be more susceptible to the occurrence of surface shadows than a mix with the same aggregate type and gradation that is made with a 60-70 penetration graded asphalt cement.

### Temperature Susceptibility

An asphalt cement that is highly temperature susceptible--the viscosity of the asphalt cement changes significantly with a change in temperature--will typically produce an asphalt concrete mixture that is more tender (less stiff) than an asphalt cement that incorporates a less temperature susceptible binder material. Two AC-10 viscosity graded asphalt cements can have different temperature susceptibilities and can produce mixes that have different degrees of tenderness. The mix made with the more temperature susceptible binder will generally have a tendency to have the fines separate from the mix and increase the intensity of any surface shadows that are produced by the paving equipment.

### Use of Additives

Additives that increase the stiffness of the asphalt concrete mixture will usually reduce the occurrence of surface shadows. This occurrence is

related, however, to the stiffness of the mixture at laydown temperature and not necessarily to the stiffness of the mix after compaction by the rollers and under traffic. Materials such as anti-strip additives may or may not change the stiffness of the asphalt cement. Some liquid anti-strip materials will significantly reduce the viscosity of the binder material. Others will increase the stiffness of the asphalt cement at the mixing temperature. Thus the effect of anti-strip additives depends on the characteristics of each individual additive.

If hydrated lime is used as an anti-strip additive, the use of the lime will generally stiffen the mix to some degree. Typically, this stiffening effect will reduce the tendency of the fines in the mix to separate from the other aggregates and collect on the paver screed, causing surface shadows.

Polymer modified asphalt cements have various effects of the stiffness of the asphalt concrete mix at laydown temperatures. Some of these materials greatly stiffen the mix at both the mixing temperature and the laydown and compaction temperatures. If this is the case, the separation of the fines in the mix as the mix passes under the paver screed should be minimal. If the polymer modified material, however, is significantly less viscous than the unmodified material at the laydown and compaction temperatures, the occurrence of surface shadows in the mix may be enhanced.

Additives that increase the "stickiness" of the mix at laydown temperatures can increase the separation of the fines from the mix and affect the intensity of the surface shadows that develop. Latex modified asphalt concrete mixes may be especially susceptible to the occurrence of this defect in the pavement surface since the working temperature range for this type of mix is relatively narrow. These mixes are produced at the

batch or drum mix plant at elevated temperatures compared to standard (unmodified) asphalt concrete mixtures. The mixes cool quickly, and the viscosity of the modified binder changes significantly with the change in the temperature. The cool latex modified mixes are sticky and tend to cling to the front of the screed (the pre-strikeoff) and to the screed itself. This stickiness enhances the separation of the fines in the mix from the other aggregate and increases the development of surface shadows.

### **Asphalt Concrete Mix Characteristics**

The workability or tenderness of the asphalt concrete mix and the void characteristics of the mix can all have an affect on the number and the intensity of the surface shadows that occur in the mix. Factors that affect the characteristics of the aggregates and the asphalt cement incorporated in the mix also directly affect the properties of the resulting asphalt concrete mixture.

#### Workability and Tenderness

Workability is a characteristic of an asphalt concrete mixture that changes with many variables and particularly with temperature. In many cases, workability is equated with temperature susceptibility and/or with tenderness of the mix. Workability depends on the factors that affect the stiffness of the mix. Aggregate properties and asphalt cement properties that reduce the stiffness of the mix can increase the workability of the mix and thus make it easier for the some of the fines in the mix to separate from the other aggregate. Aggregate and asphalt cement properties that decrease the workability of the mix--increase the mix stiffness--should reduce the susceptibility of the mix to surface shadows. Workability is discussed in detail in the following section.

The tenderness of an asphalt concrete mixture can not really be defined or measured. Tender mixes, however, seem to be particularly prone to the development of surface shadows. These mixes tend to segregate during production--when delivered into the haul truck--and during laydown--when discharged from the truck into the paver hopper and placed by the paver. Since segregation is the separation of the coarse aggregate particles in the mix from the finer aggregate in the mix, the occurrence of segregation in the mix and the occurrence of surface shadows is related to some degree.

#### Mix Void Content

Both the voids in mineral aggregate (VMA) content of the mix and the air void (AV) content of the mix affect the possibility of the occurrence of surface shadows. Mixtures that are low in VMA, in general, are tender during laydown and compaction. The aggregate gradation which produces the low VMA mix is generally one that is parallel to and very close to the modified maximum density line (the Texas gradation reference line) on 0.45 power graph paper, or a gradation that has a hump in the fine aggregate gradation at the No. 40 sieve.

Asphalt concrete mixtures that can be compacted to a low air void content in the laboratory during the mix design phase are generally quite tender and workable. If the mix can also be compacted to a low air void content with minimum effort by the compaction equipment, it is an indication that the mix is also very workable. In both cases, the tender mix provides a mix that is typically susceptible to segregation and separation of the fines from the other aggregate in the mixture.

Surface shadows appear to be enhanced when the mix is tender--has a low VMA content and/or a low AV content. Mixes that have adequate voids in



mineral aggregate and air void content are usually stiffer and less susceptible to the fines clinging to the paver screed.

#### **APPROACH TO ANALYSIS OF WORKABILITY AS RELATED TO SURFACE SHADOW**

Workability is commonly used to describe the ease of mixing, laying and, most importantly, compacting a bituminous material. Less workable mixtures are less mobile during the placement process, influencing the height of the screed plate. Less workable mixtures are liable to lift the screed plate leaving the surface with longitudinal ridges, transverse cracks or ripping of the mat, or waves in the mat (either closely spaced or widely spaced) or transverse auger shadows.

The workability of a mixture can be increased by the following alterations to the mixture composition:

- a. Increase the asphalt binder content,
- b. Increase the moisture content of the mixture (resulting in an increase in the total fluids content of the mixture),
- c. Use an aggregate with less surface texture, less angularity and hence less internal friction,
- d. Induce a "hump" in the gradation curve moving from the coarse side of the 0.45 power (maximum theoretical density) curve to the fine side of the curve in the medium to fine sand-size range of the gradation band,
- e. Use an additive to serve as a lubricant of the mixture, such as silicone or
- f. Increase the temperature of the mixture.

Of course, it is not practicable to increase the binder content of the

mixture in order to improve workability; such a move would be disastrous in terms of stability of the mixture and resistance to rutting. Improving workability through increasing the total fluids in the mixture by maintaining a higher moisture content in the mixture was tried in the early 1970's when drum plants tried to produce mixtures at lower temperatures (near or slightly above the boiling point of water) than in traditional batch or continuous plants. The workability of the mixtures coming from the drum plants was achieved from the moisture escaping from the aggregate. This moisture lubricated the mixture and reduced the mixture stiffness and, hence, improved workability. The down side of this experiment was that the moisture retained in the mixture presented mat problems, durability problems and mixture stability problems.

Improvements in workability by means of aggregate manipulation have proven successful to some extent. Minor aggregate alterations such as moving to a somewhat finer mixture, moving from the maximum theoretical density 0.45 power curve without the proverbial "hump" and adding a small percentage of natural sand (rounded to subrounded) have proven successful. However, as with any portion of mixture design, this too is a give and take operation. Improvements in workability mean a reduction in resistance to deformation of the mixture.

Massive alteration of the mixture such as inducing a hump in the gradation band across the 0.45 power curve from the coarse to fine side of the 0.45 gradation band or by replacing significant quantities of crushed screening or manufactured sand with rounded river sand or field and have generally proven to be fatal flaws in the mixture in terms of stability and long-term performance. Texas Transportation Institute Report 1121-1F [1]

presents a detailed discussion of the steps required in mixture design to minimize rutting potential.

Excessive filler content can also affect workability [1]. The portion of the filler with particles thicker than the film of asphalt contributes to the interlocking of the aggregate. The other portion of the filler, with particles smaller than the thickness of the asphalt film, is suspended in the asphalt and constitutes the binder in the mixture. The mineral filler which is suspended may cause two types of stiffening effects. A relatively small stiffening effect may result from the volume displacement of the filler, and a relatively large stiffening effect may result from the physicochemical interaction between the asphalt and surfaces of the mineral filler [2]. These physicochemical stiffening effects can cause apparent changes of 100-1,000 fold in the viscosity of the binder, producing an asphalt concrete that is very stiff and difficult to compact.

Mixtures characterized by shoving (displacement in the longitudinal direction during compaction) are referred to as tender mixes which can be too unstable to place and compact properly. They are often caused by a shortage of mineral filler, excessive medium-sized sand, smooth, rounded aggregate particles and/or excessive fluids (asphalt or moisture) in the mix. Small top-sized aggregate will also contribute to tenderness. Shoving can be particularly prevalent when a sand mix is placed in a thick layer.

Although not normally a major contributor to workability problems, asphalt does have an effect on workability. Because temperature of the mix affects the viscosity of the asphalt, insufficient temperature will decrease workability; whereas, excessive temperature may produce tenderness in certain aggregate gradations. Softer asphalt grades will contribute to

tenderness as will excessive amounts of binder. Insufficient amounts of asphalt cement and harder asphalt cements will, of course, produce a stiff mix with poor workability. Additives such as antistripping agents, antifoam agents and polymers will affect binder viscosity and/or mass viscosity of the mix.

Additives such as silicone have been used in low concentrations to improve mixture workability especially during the laydown operation. The use of silicone in asphalt in concentration of 1-6 ppm [3] produces beneficial results in the laydown, storing and transportation of certain asphalt concrete mixtures. Silicone has no apparent effect on asphalt cement properties in these low concentrations and even in concentrations slightly higher. The greatest benefit of silicone in the hot mix as it pertains to this study is in the prevention of tearing and snagging of certain problem mixtures during the laydown operation. It has been proposed [4] that silicone coats the screed and makes it slide over the mix without tearing. A film of silicone acting as a barrier has been suggested as the cause of reduction of asphalt hardening in hot mix storage facilities. In this situation, the surface film conceivably acts to limit passage of oxygen to the asphalt. This mechanism is questioned because silicones do not reduce skinning on hot asphalt storage tank surfaces. The effects of silicone were not explored in this study as the concentration was placed on equipment operations and not mixture properties.

There is always a great temptation to increase the temperature of the mixture in order to accommodate the demands of workability of the mixture. However, as researchers have demonstrated [2], increasing the mixing temperature markedly accelerates the rate of bitumen oxidation resulting in

an increase in bitumen viscosity. It has been shown that every 10°C temperature increase above 100°C doubles the oxidation rate. Figure 19 shows that for every 5.5°C increase in mixing temperature, the softening point of the bitumen increases 1°C. Thus a significant proportion of the apparent reduction in viscosity achieved by increasing the mixing temperature will be lost as a result of additional bitumen oxidation, which may also adversely affect the long-term performance of the material.

Thus, although it may not be prudent to heat mix above normal mixing temperature requirements in order to improve workability, it is essential to maintain a certain degree of heat within the mat in order to properly compact the mat. All asphalt concrete mixtures stiffen when they cool. The increasing stiffness of a mix on cooling results from the increasing viscosity of the bitumen. The rate at which a mix cools is a function of:

- a. Environmental concerns, such as substrate temperature, solar radiation, air temperature and wind speed,
- b. Thickness of the mat,
- c. Thermal conductivity of the layer and the difference in temperature between the layer and that of the air and substrate,
- d. Temperature susceptibility of the bitumen and
- e. Application rate of the mat.

All of the above factors are external factors to the mixture itself.

The California Division of Highways [5] developed a grading chart which illustrates grading specifications established to avoid undesirable conditions in the mat (Figure 20). This chart confirms some of the discussion presented in the preceding paragraphs and concentrates on the

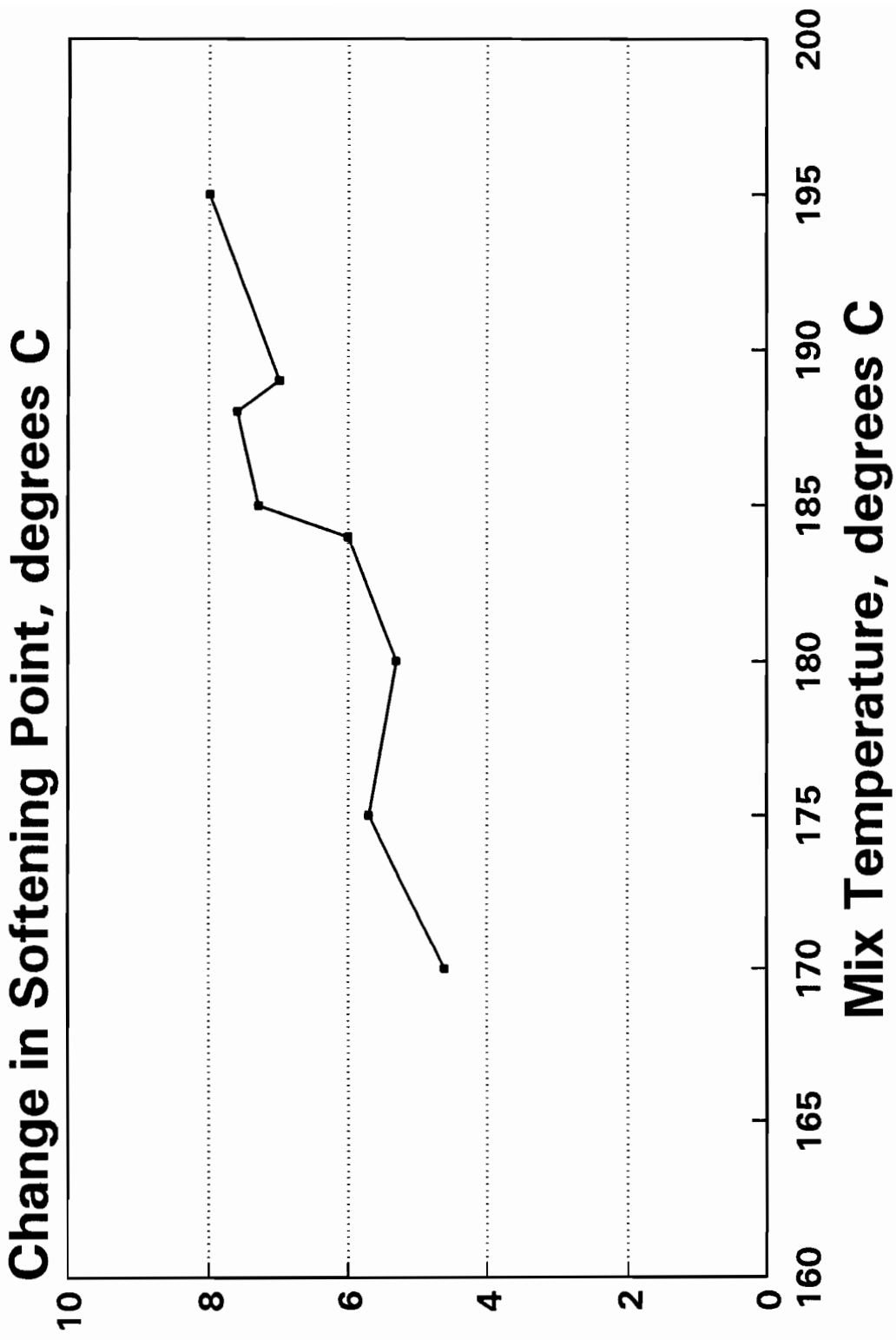


Figure 19. Relationship Between Mixture Temperature and Increase in Softening Point.

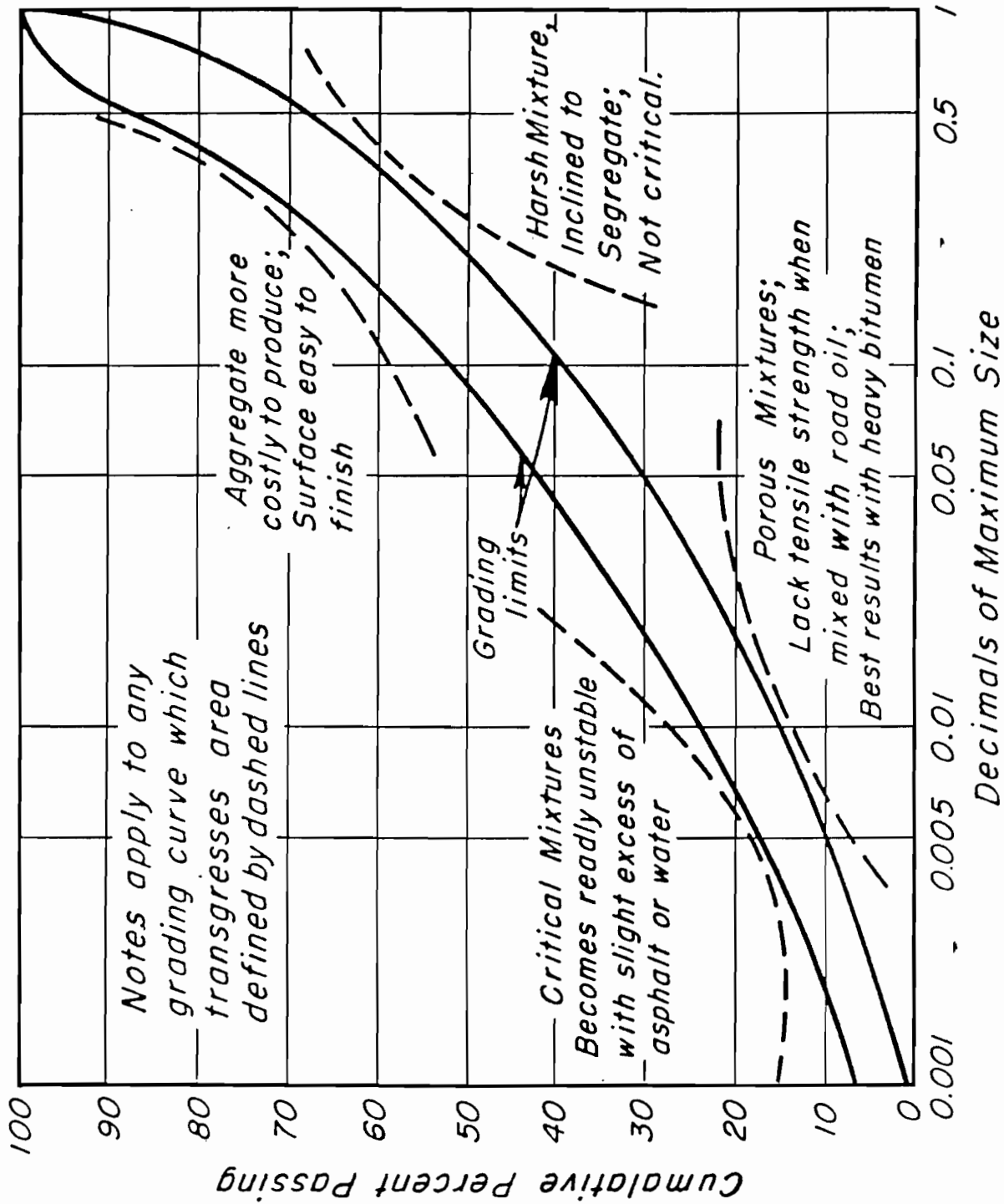


Figure 20. Identification of Mixture Workability as a Function of Gradation.

aspects of aggregate type, aggregate gradation, binder content and binder grade.

In summary, poor workability can be viewed as a series of causes and effects:

<u>Causes</u>	<u>Effects</u>
Large max.-sized particles	Rough surfaces, difficult to place
Excessive amounts of coarse aggregate	May be difficult to compact
Low mix temperature	Uncoated aggregate, not durable, rough surface, hard to compact
Too much medium-sized sand	Mix shoves under rollers and remains tender
Low mineral filler content	Tender mix, highly permeable
High mineral filler content	Mix may be dry or gummy, hard to handle, not durable

#### **Components of Mixture Resistance to Internal Movement**

Researchers [2] have identified three components which dictate the resistance of an asphalt concrete mixture to internal movement: (a) cohesion of the bitumen, which is influenced by the type and amount of added filler, (b) internal friction from the mineral aggregate, such as grading, shape, surface area and surface texture and (c) mix viscosity influenced by the viscosity of the bituminous binder and internal friction provided by the included filler and mineral aggregate.

In order to define the workability of a mixture, it is desirable to account for the three components of cohesion, internal friction and mass viscosity. In fact a procedure able to assess the components of resistance to internal movement - cohesion, internal friction and mass viscosity -



would be a fundamental measure of workability. This workability measure would have to account for temperature, however, as the mixture will stiffen upon cooling. Hence, a profile of workability with temperature would be necessary.

## **A Fundamental Measure of Workability of Asphaltic Materials**

### General Concepts

Nageint and Fordyce [6] have proposed a method to measure the three fundamental properties of internal resistance-cohesion, internal friction and mass viscosity. Two material parameters which include the three fundamental material properties are used to describe two phases in a material's resistance to internal movement. They are limiting internal resistance (LIR) and mix viscosity ( $VIS_m$ ).

The nature of the resistance of asphalt concrete mixtures to movement is a result of the specific nature of the bituminous binder. The properties of the binder are temperature dependent. Profiles of limiting initial resistance and mix viscosity over a temperature range where workability is an applicable property of the densification of an asphalt material layer are therefore of interest.

Nageint and Fordyce [6] quantified profiles of limiting initial resistance and mix viscosity by axially loading a laboratory prepared sample in a closed-system triaxial apparatus. The closed-system triaxial procedure employed to define limiting initial resistance is a modified version of the triaxial cell used in soil mechanics testing. Material samples are cylinders of uniform material density 4-inches in diameter and 8-inches in height. A sample has a specific voids content, and is contained in a heated

oil bath.

The triaxial cell is double-lined. The outer annulus is oil-filled and contains a heating coil. The sample is located in the inner cylinder. The inner cylinder is filled with oil during a test. The oil within the inner cylinder is heated by the oil in the outer annulus. The outer cylinder is insulated. The sample is orientated with its long axis in the direction of the vertical plane and is protected during a test by an easily adaptable rubber membrane. The pressure of the oil surrounding the sample can be increased using a hand operated pump; the oil pressure is measured using a bourdon gauge. The sample is stressed vertically by an externally applied load through a shaft.

Any vertical deformation of the sample is measured by the movement of the shaft. Limiting initial resistance is defined as achieving a state of static equilibrium with a sample subjected to a triaxial stress system. Viscous resistance is defined as achieving a state of dynamic equilibrium with a sample subjected to a triaxial stress system.

Using this procedure, samples can be tested in the device at various levels of confining pressure. An axial stress is applied to the sample under the specific level of confining pressure. Static equilibrium is defined as occurring when the rate of deformation of the specimen is 0.025 mm/min. This definition of static equilibrium has also been used by other researchers [7]. As the sample deforms, the confining pressure increases. At the defined level of static equilibrium, the major and minor principal stresses are measured. This process is repeated at different confining pressures until a series of Mohr circles are identified. The tangent to the Mohr circles may then be drawn to define the envelope of static equilibrium.

The intercept of the static equilibrium envelope and the vertical axis (shear stress) is defined as the cohesive intercept or the limiting initial resistance (LIR). This cohesive intercept is defined at various temperatures, providing a profile of LIR versus temperature.

The parameter of mix viscosity can be identified using the same triaxial apparatus. In this test the oil which applies the confining pressure is bled off until the desired rate of vertical deformation is achieved. This is done for several rates of deformation (called dynamic states of equilibrium). During the bleed down, the vertical (major) and confining (minor) principal stresses can be measured. These data are used to produce a series of Mohr circles which, in turn, define the mix viscosity. This is true as viscosity is defined as the quotient of shear stress (defined by the Mohr circle envelope) and rate of deformation (defined by the rate of bleed down selected). Thus to determine the mix viscosity, the shear strength as defined by the Mohr circle failure envelope is plotted versus the rate of deformation. If several rates of deformation are used, the slope of the shear strength versus rate of deformation relationship can be determined as the mix viscosity.

#### A Workability Index

Nageint and Fordyce [6] have proposed a workability index defined as the quotient of the mix viscosity and LIR at the temperature at which the quotient is minimized. Since the units of mix viscosity are Pa sec and the units of LIR are  $N/m^2$ , the units of the workability index are seconds.

If one plots the quotient of mix viscosity and LIR versus temperature a concave upward relationship is found to exist as demonstrated in Figure 21. The workability index is defined as the quotient of mix viscosity and

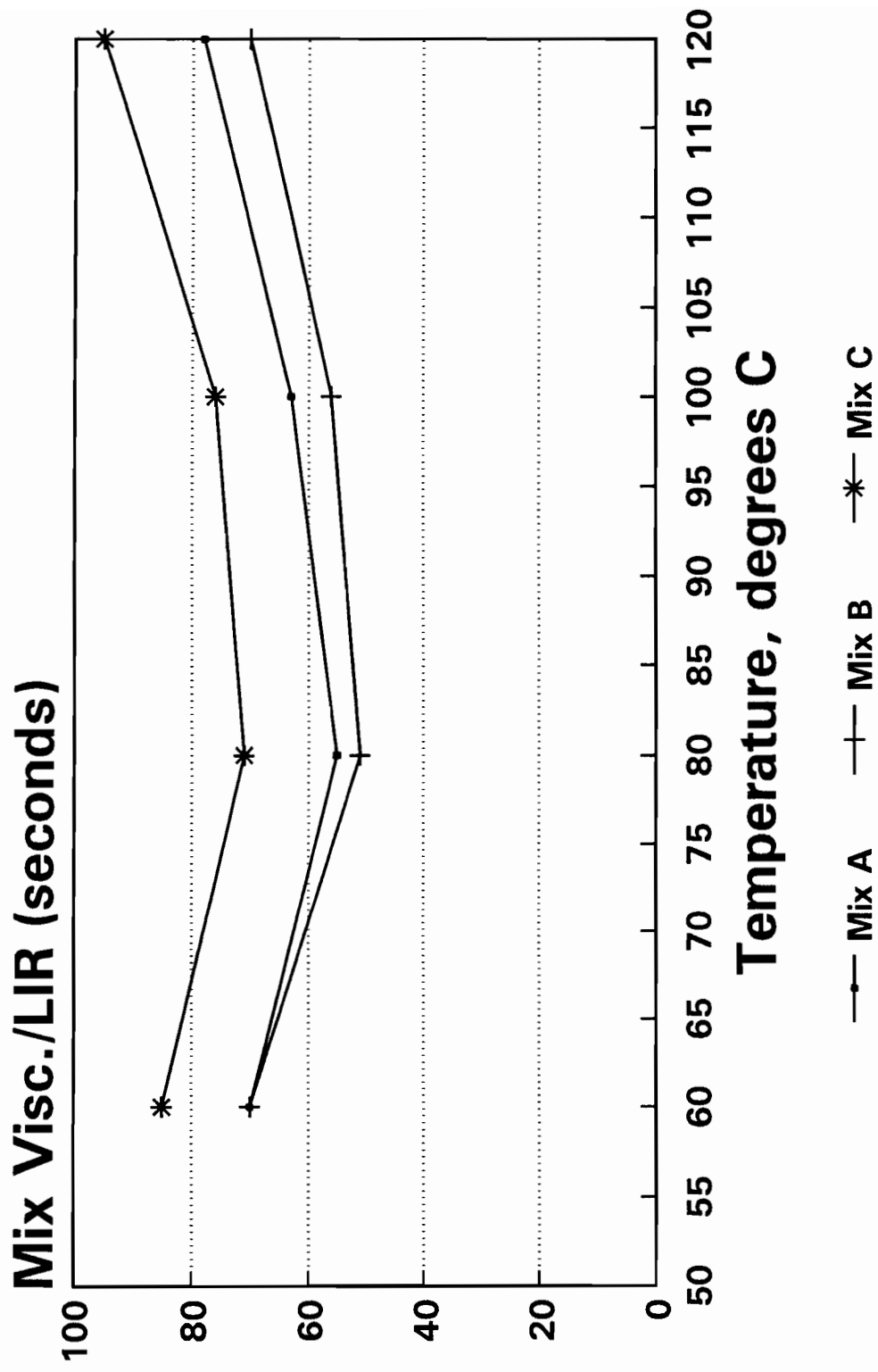


Figure 21. Profiles of Mix Viscosity and Limiting Initial Resistance.

LIR at the turning point of this relationship. The temperature corresponding to the turning point is the transition temperature for the rates of gain of the components influencing mixture resistance to deformation.

When the two parameters used to determine the workability index are plotted separately, over a common range of temperatures, the relative influence of each parameter can be distinguished (Figure 22). As the mixture illustrated in this figure cools from 120°C to the transition temperature, LIR is gaining in value more rapidly than mix viscosity. As the mix cools from the transition temperature to 60°C, mix viscosity is gaining more rapidly in value than LIR. In essence this illustrates that the LIR is the more significant parameter above the transition temperature and the mix viscosity is the more important parameter below the transition temperature.

Thus the information defining the workability of a mixture as it is being densified may be given by not one but two values: the workability index and the transition temperature at which this workability index occurs.

Evaluation of Selected Mixtures Using Workability Index and Transition Temperature

Nageint and Fordyce [6] evaluated three mixtures for workability using the concepts discussed in the preceding paragraphs. These mixtures will be briefly discussed. Mix A was a moderate mix with a moderate binder content, moderate filler-binder ratio and a moderate Marshall quotient (ratio of Marshall stability to Marshall flow). Mix B had a low binder content, a high filler-binder ratio and the highest Marshall quotient among the mixtures. Mix C had the highest binder content, the lowest filler-binder

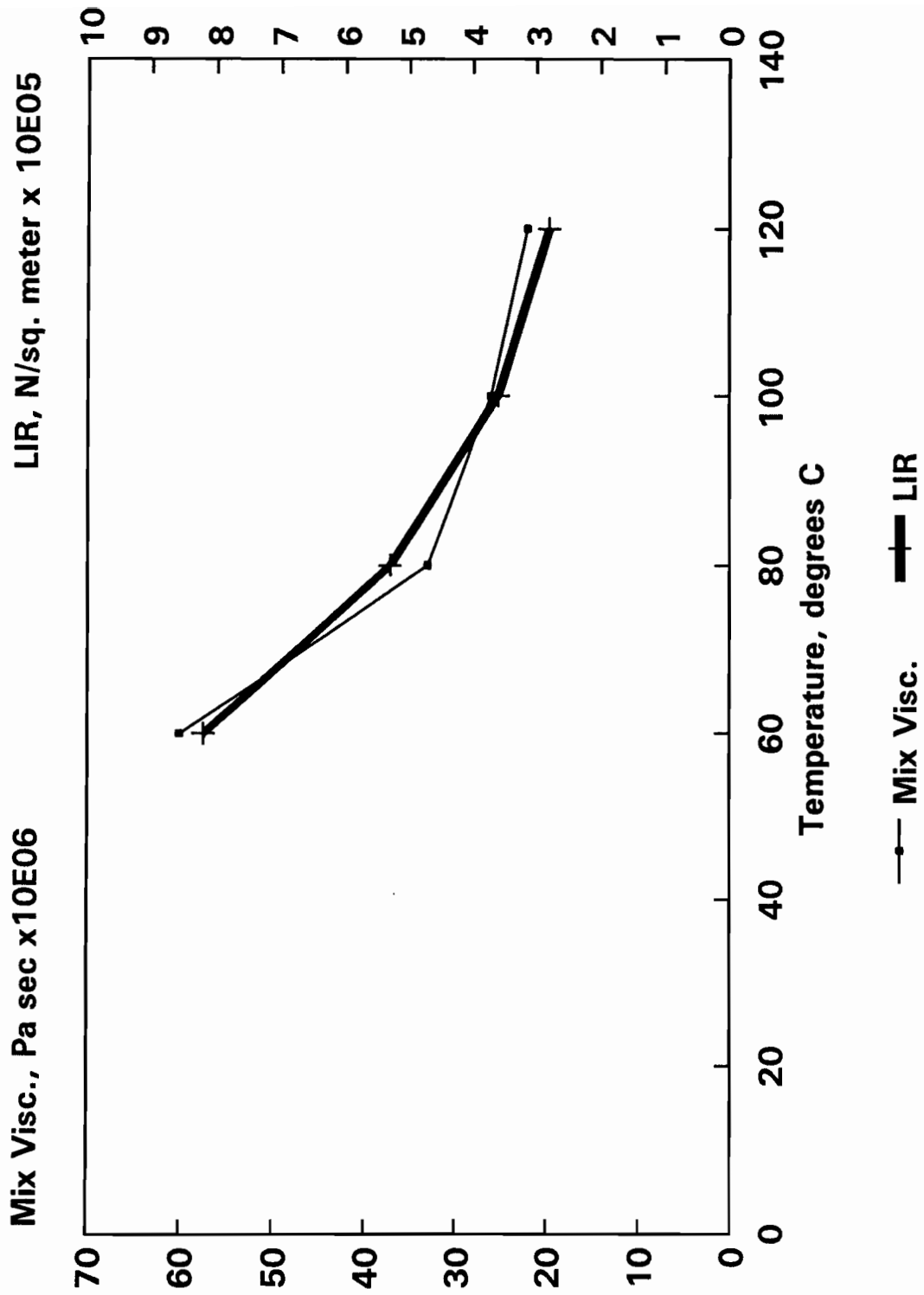


Figure 22. Mixture Viscosity and LIR as a Function of Temperature.

ratio and the lowest Marshall quotient among the mixtures. All three mixtures used the same asphalt cement and essentially the same coarse and fine aggregate. All three mixtures were evaluated at air void contents of 3, 6 and 9 percent. The 3 percent mixture was representative of a compacted wearing course mix. The 9 percent mix was representative of a mix following laydown and the 6 percent mix was representative of density following field compaction.

The LIR versus temperature and mix viscosity versus temperature relationships were determined for each mix at each air void content. The air void content was found not to influence the rank order of the LIR or mix viscosity of the mixtures.

Based on the workability index (ratio of mix viscosity to LIR at the transition temperature) and the value of the transition temperature, the rank order of the mixtures from most workable to least workable is:

	<u>Mix Workability Index</u>	<u>Trans. Temp., °C</u>	<u>Filler-Binder Ratio</u>
C	67	83	0.88
A	55	85	1.00
B	50	83	1.36

The Nageint-Fordyce approach to mixture workability is interesting and offers great promise. However, by their own admission [6] the procedure is not complete and is still under development. The value of the workability index at the transition temperature may be too simplistic a parameter upon which to define the workability of the mixture across the range of temperatures encountered in mixing paving and compaction. Perhaps the greatest value of the data collected in the Nageint-Fordyce procedure is that illustrated in Figures 21 and 22. These data demonstrate the

transition temperature of a particular mix at which compaction becomes essentially ineffective because of the rapid increase in both mix viscosity and LIR below this temperature. Above the transition temperature, the difference between mix viscosity and LIR increases with increasing temperature (ratio of mix viscosity to LIR becomes greater). The increase in this ratio above the transition temperature is indicative of the loss of the resistance to internal movement of the mixture caused by the aggregate matrix. The mix viscosity begins to level off above the transition temperature as it becomes a function of the volume concentration of the aggregate within the binder and the intrinsic nature of the binder itself. On the otherhand, the LIR is a function of the nature of the interactive aggregate particles. Thus the greater the difference between mix viscosity and LIR at and above the transition temperature (greater the workability index), the more workable the mixture at and above this temperature.

#### **Other Approaches to Evaluate Workability**

The Nageint-Fordyce approach to the evaluation of mixture workability is very promising and the most complete as well as complex approach found in the literature. The approach is promising in terms of its potential to identify mixture resistance to deformation under high pavement temperatures (104°F to 150°F) through a process similar to the octahedral shear stress analysis as reported in TTI report 2452-3F [8]. However, the approach is still in the developmental stage and is complex and expensive to perform at this stage. It also requires new and fairly complex and expensive triaxial testing equipment.

Based on the need to develop a simple procedure using currently available testing equipment (to the Texas SDHPT), other approaches were



evaluated. The approach selected is based on the Asphalt Aggregate Mixture Analysis System (AAMAS) approach. This approach was selected for the following reasons:

- a. It is based on the AAMAS approach developed partially at TTI for the NCHRP. The AAMAS approach will form the basis of the mixture design and analysis approach to be used by AASHTO and to be followed by SHRP.
- b. The procedure used the Texas gyratory shear compactor (Texas Test Method TEX 206E).
- c. The approach is simple and expedient.

Marvillet and Bougault [9] quantified the effects of a number of mixture parameters on workability using a workability meter. The mixture parameters considered were binder grade, binder content and sand shape. The workability meter was developed in France and consists of a chamber connected to a rigid frame into which the test mix is introduced and a speed controller which drives a blade in the mix. The speed controller features a rotor imparting uniform rotary motion to the blade within the mix, and a stator which moves about its shaft. The stator is connected to the fixed frame of the instrument by a spring whose tension offsets the resistance moment produced by the mix in reaction to the rotation of the blade. The equilibrium position is observed by means of a potentiometer whose spindle is integral with the stator. The electrical signal is converted into a value which can be recorded. The term "workability" is applied to the reciprocal of the resistance moment produced in the mix against the rotation of the blade:

$M = 1 / (\text{moment of spring tension/axis of rotation}).$

Experiments of Marvillet and Bougault [9] examined the effects of bitumen grade involved in the measurement of the variation in workability as a function of temperature and penetration. They discovered a very clear relationship between workability and viscosity at the same temperature for eleven bitumen grades.

A higher bitumen content in the mix makes it easier for an operator preparing mixes in the laboratory. Therefore, Marvillet and Bougault made a quantified comparison of workability with varying binder contents. Binder content was varied from 5.3 to 6.0 percent. No direct proportionality was found between workability and binder content.

An increase in the content of fine material in a mix, i.e., filler, produces a higher rigidity which was quantified. Filler content was varied from 7.9 to 16 percent by weight, keeping the binder content constant. This effect is shown in Figure 23. It was not possible to measure the workability of the mix containing 16 percent filler, which was too rigid and rotated as a single mass with the blade.

Round and subrounded, smooth-surfaced sands reduce the coefficient of internal friction of the mixes. Asphaltic concretes, which contain only crushed particles with high coefficients of friction are sometimes difficult to place owing to poor workability and compactibility. The addition of 10 to 15 percent round sand to these mixes can lower their coefficient of internal friction sufficiently to improve workability and compactibility. Marvillet and Bougault [9] used their workability meter to evaluate numerically the increase in workability produced by the addition of rounded sand. The difference in workability between a mix containing no round sand

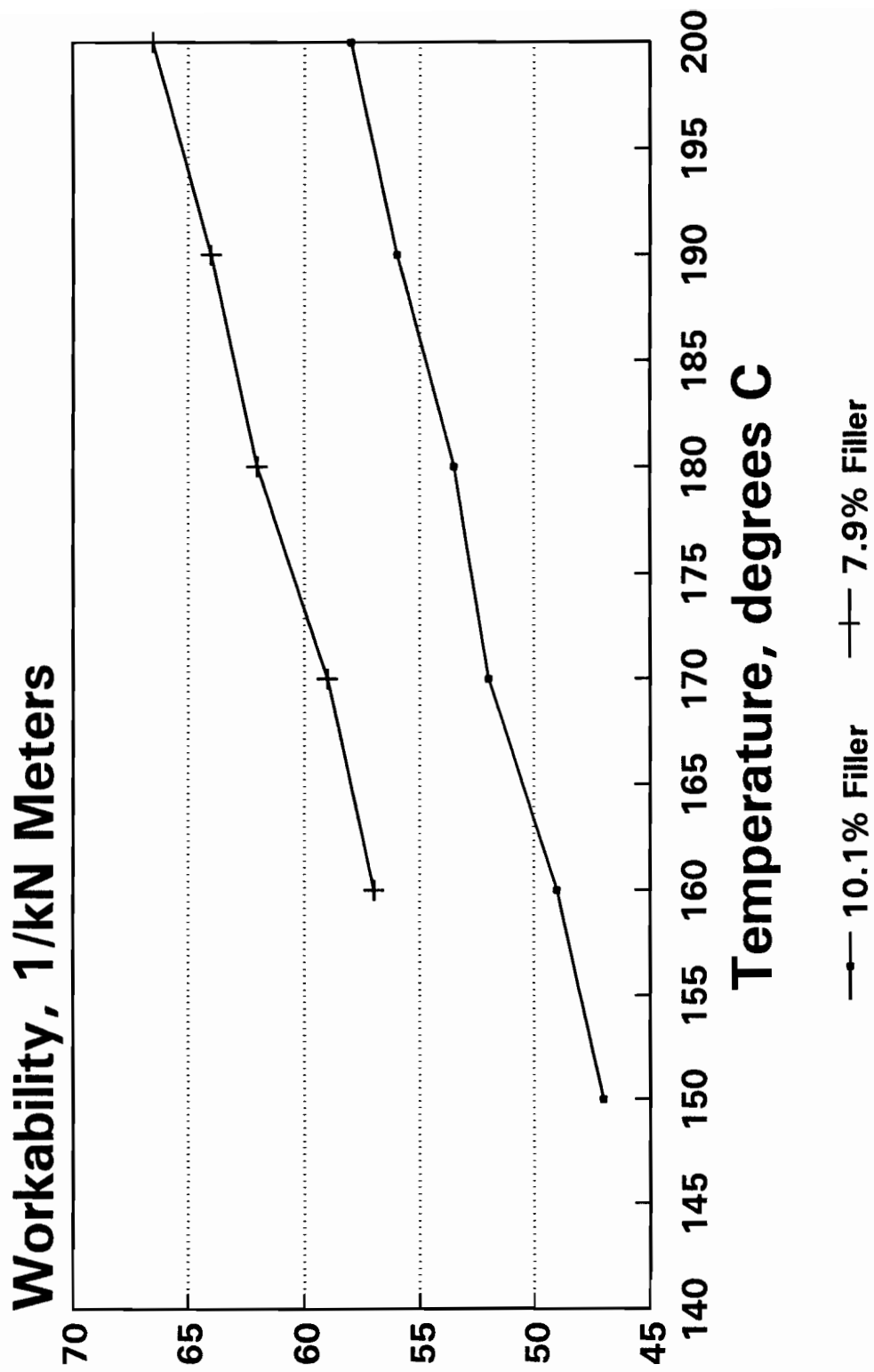


Figure 23. Mixture Workability as a Function of Mineral Filler.

and one containing 5 percent round sand was not significant; when the round sand content reached 10 percent, however, the workability increased sharply and appeared to be at an optimum influence at this level for their particular mixture.

#### Discussion of AAMAS Approach

Asphalt mixtures that can be easily densified under the compaction equipment are said to be "workable". Asphalt mixtures that are difficult to compact and lay are said to be "harsh". Thus the degree or workability of a mixture is a factor of the ability of the contractor to achieve the proper density and air void content of the mix.

For the purposes of AAMAS [10], workability was defined simply as the ease of densification of the asphalt concrete mixture under some given compactive effort. Mathematically speaking, workability could be defined as the area under the compactive effort curve (compactive effort versus air void content). Densification relationships for the five different compaction devices evaluated in the AAMAS study were mathematically expressed as follows [10]:

$$V_{ni} = Ae^{niB} (V_o - V_u) + V_u$$

where:  $V_n$  = air voids of the compacted specimen using n compactive efforts.

$V_o$  = air voids of the loose mixture, without any compactive effort.

$V_u$  = ultimate air voids of the mixture.

$n_i$  = number of compactive efforts applied by a single device, such as the number of gyrations of the gyratory

compactor.

A, B = regression coefficients.

This equation simply represents the reduction in air voids with an increase in compactive effort for each of the compaction devices used in the compaction study of AAMAS [10].

Five compaction devices were included in the AAMAS study. The purpose of the study was to determine which compaction devices best duplicated the effects of field compaction in terms of the degree of densification achieved and the ability of the lab compaction technique to produce mixes with material properties similar to those from field compacted mixes. The compaction devices evaluated were: (a) the Marshall hammer to represent an impact type compaction apparatus, (b) the California kneading compactor to simulate a kneading type compaction, (c) the Texas gyratory shear compactor to simulate gyratory-kneading action, (d) the Arizona vibratory/kneading compactor to simulate the use of vibratory type compaction and (e) the steel wheel simulator to simulate a rolling type compaction.

Five field projects were identified to form the basis of this study. Loose mixtures from these projects were compacted in the TTI lab to simulate the air void content achieved in the field under the rolling patterns used. The lab mixtures were then tested along with cores from the field for diametral resilient modulus (over a wide range of temperatures), indirect tensile strength and strain at failure (over a wide range of temperatures) and indirect tensile creep.

Based on a detailed statistical analysis of the results it was concluded that the Texas gyratory and rolling wheel simulation compaction best duplicated actual field compaction. The basis of this decision was

that these compaction devices produced mixtures with material properties most like the material properties from field cores. The California kneading compactor also did a reasonable job of simulating field compacted mixtures based on the same criteria. However, the Marshall hammer did not produce mixtures with mixture properties acceptably similar to the field compacted mixtures.

The importance of the results of the AAMAS evaluation to this study is that the Texas gyratory shear compactor does an acceptable job of simulating actual field compaction. Thus, it is reasonable to believe that the Texas gyratory compactor can be used as a reasonable indicator of workability of a mixture over a range of compactive efforts.

The Texas gyratory shearing action applied to a mixture at low initial pressures allows orientation of the aggregate particles. Specimens are compacted to simulate the density, aggregate degradation, particle orientation and structural characteristics achieved in the field. A pressure of 50 psi is established in the mold, and the sample is gyrated at an established angle three times during the time the pressure diminishes. The sample height is then reduced by 0.02-inches with one full stroke of the pump handle; the process is repeated until one full stroke of the pump causes the pressure to surge to 150 psi or more. This indicates that proper densification has been achieved. It is reasonable that a measure of mixture workability could be based on the compaction energy required to densify a mixture from a void content of  $V_o$  to  $V_u$ . This was achieved in the AAMAS study for the five mixtures studied and verified in this study.

The five mixtures analyzed in the AAMAS study are identified as follows:

<u>Mixture</u>	<u>Coarse Aggregate</u>	<u>Fine Aggregate</u>	<u>Type and % AC</u>
Colorado	30% pit run crushed gravel	70% pit run crushed gravel	AC-10, 5.5% 0.4% pave bond
Michigan	39% 5/8-in. gravel chips	25% crushed sand 16% blend sand 20% concrete sand	85-100 pen, 5.6%
Texas	35% 3/4-in. limestone (LS)	15% limestone screenings (LSS) 33% 3/8-in. LS	AC-20, 5.5% 17% field sand (FS)
Virginia	65% trap rock	20% crushed fines 15% natural sand	AC-20, 4.5% 0.6% ACRA 1000
Wyoming	40% RAP	20% fine gravel 40% blend of crushed rock and gravel	AC-20, 2.75% 1.0% hydrated lime

Thus five very different mixtures were included in the study. From a standpoint of workability, the suite of mixtures falls short as variables such as fines content, filler-binder ratio, binder content, effects of additives, etc. were not accounted for. However, a careful evaluation of the mixture information coupled with a visual evaluation of the mixtures allows one to predict the order of workability. Based on this visual and preliminary analysis, one would rank the Virginia mix as the least workable because of its relatively low level of natural sand (15 percent) and because of the angularity and rough surface texture of the crushed trap rock. The Texas mixture would probably be ranked next in terms of its resistance to internal movement based on the relatively high percentage of crushed

aggregate (limestone) with a rough surface texture and relatively low level of natural sand (17 percent). The Colorado mix would probably be ranked as a mixture of intermediate workability based on its gradation and the nature of the aggregates involved. The mixture with the least resistance to internal movement and, consequently the highest degree of workability would be the Michigan mixture because of the high total percentage of uncrushed sand (36 percent) and the relatively high binder content of the mix (5.6 percent). The workability of the recycled Wyoming mix would appear to be intermediate to workable based on a preliminary evaluation. This judgement would be based on the nature of the recycled material and the addition of 20 percent uncrushed fine gravel.

The Wyoming, Colorado and Michigan mixtures are densely graded while the Virginia mix gradation is slightly concave downward indicating a slightly fine-grained mixture. The Texas mixture is the only mixture that departs substantially from the dense, 0.45 power gradation. The Texas mix possesses a significant hump in the curve between the No. 10 and No. 80 sieve sizes.

### Results of AAMAS Study

The five laboratory compaction devices were used in the AAMAS study to compact the five field mixtures from  $V_o$  to  $V_u$ . In this exercise it was found that as the compactive effort applied to each compaction device was increased, the density was increased and that the area under the compactive effort versus density curve represents a quantification of the workability of the mixture. To calculate the area under the compaction curve for each mixture and each device, the maximum compactive effort value was set as the



practical limit for each device. The relationship of compactive effort versus change in air void content for each mixture and each device is presented in Figures 24 through 28.

The smallest area beneath the compactive effort curve for each of the compaction devices was the Michigan mix, whereas, the greatest area beneath the compactive effort curves occurred consistently for the Virginia mix, with the exception for the California kneading compactor. Thus, for the most part, the different compaction devices provide a similar relative measure or ranking of workability for different mixtures.

The compactibility of the five mixtures under actual field compaction was determined based on the rate of densification in the field with passes of the rollers (breakdown and finishing). Based on this relationship between decrease in air voids during field compaction and passes of the rollers, and based on the lab-derived compaction energy versus densification relationships, the following ranking of mixture workability was ascertained:

<u>Project</u>	<u>Field</u>	<u>Kneading</u>	<u>Marshall Hammer</u>	<u>Texas Gyratory</u>	<u>Rolling Wheel Simulator</u>	<u>Arizona Vibratory</u>
VA	1*	2	1	1	1	1
TX	2	1	2	2	3	2
CO	3	3	3	3	2	3
WY	4	4	4	4	4	4
MI	5	5	5	5	5	5

Because the Texas gyratory compactor fabricated lab-compacted mixtures that were most representative of field-compacted mixtures in terms of selected mixture properties, and because the Texas gyratory compactor is available to the Texas State Department of Highways and Public Transportation, it was selected as the tool by which to measure workability in this study.

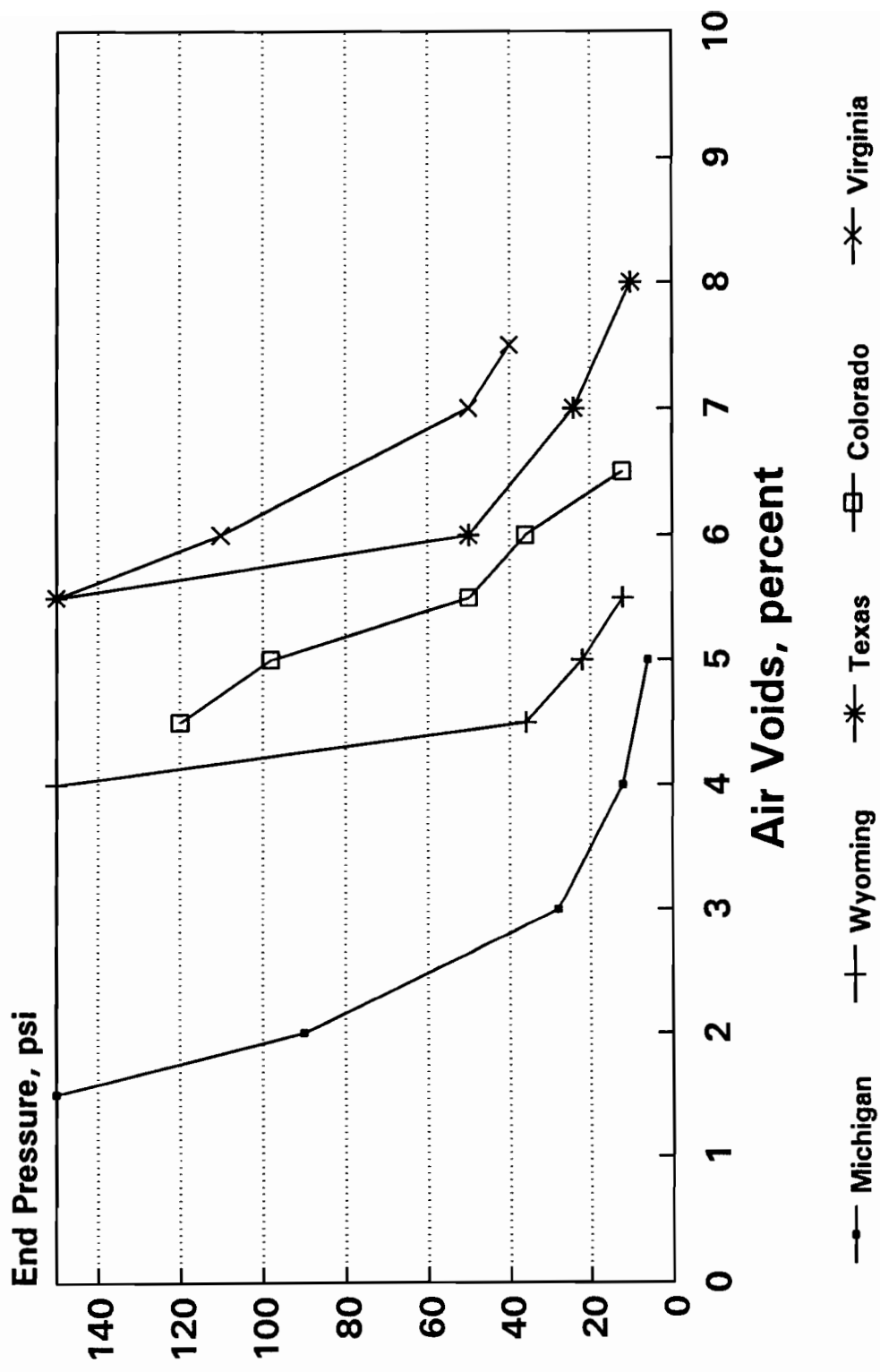


Figure 24. Compactive Effort Curves Developed For Each Mix Using Texas Gyrotory Compactor.

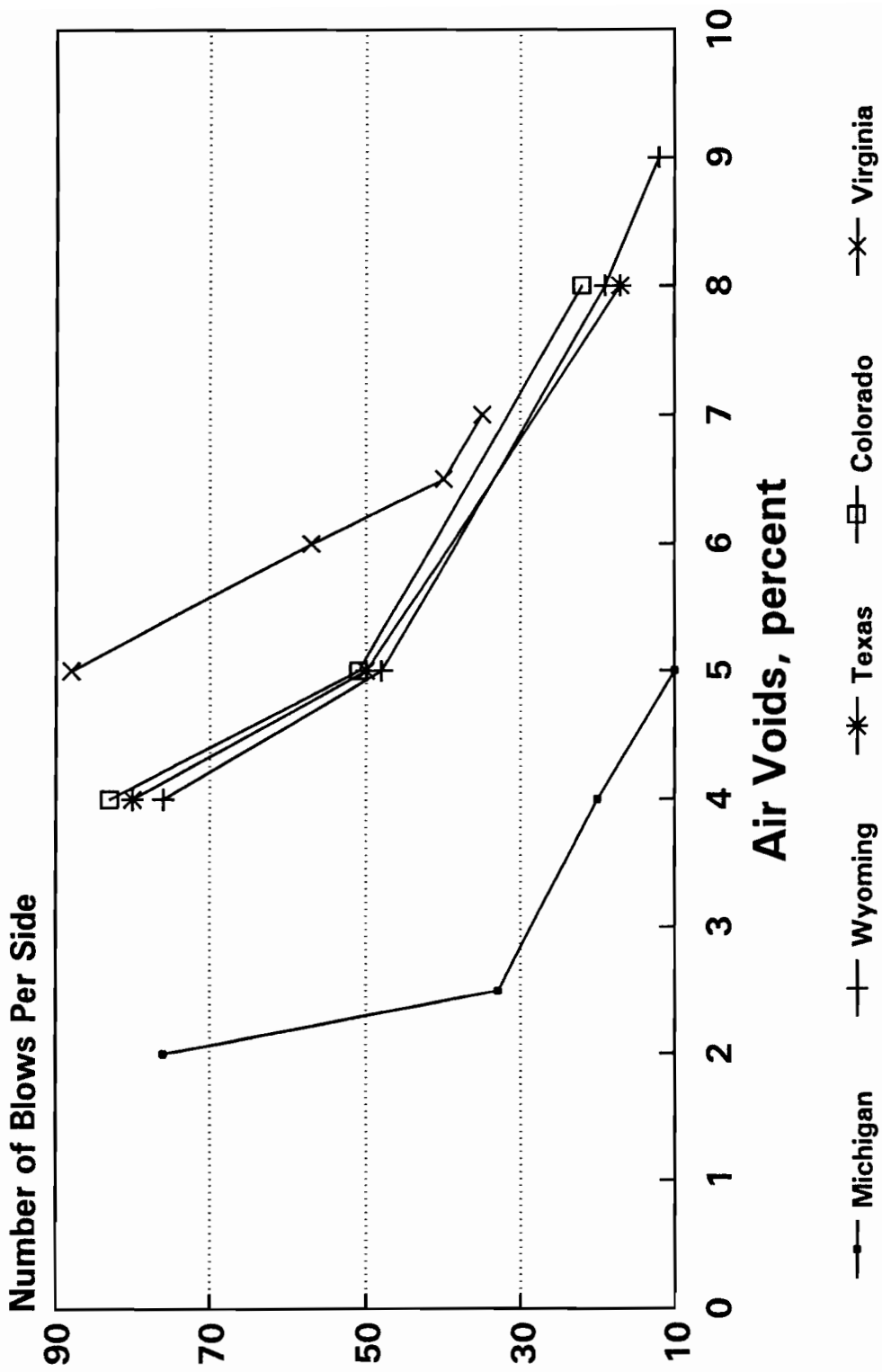


Figure 25. Compactive Effort Curves Developed For Each Mix Using the Marshall Hammer.

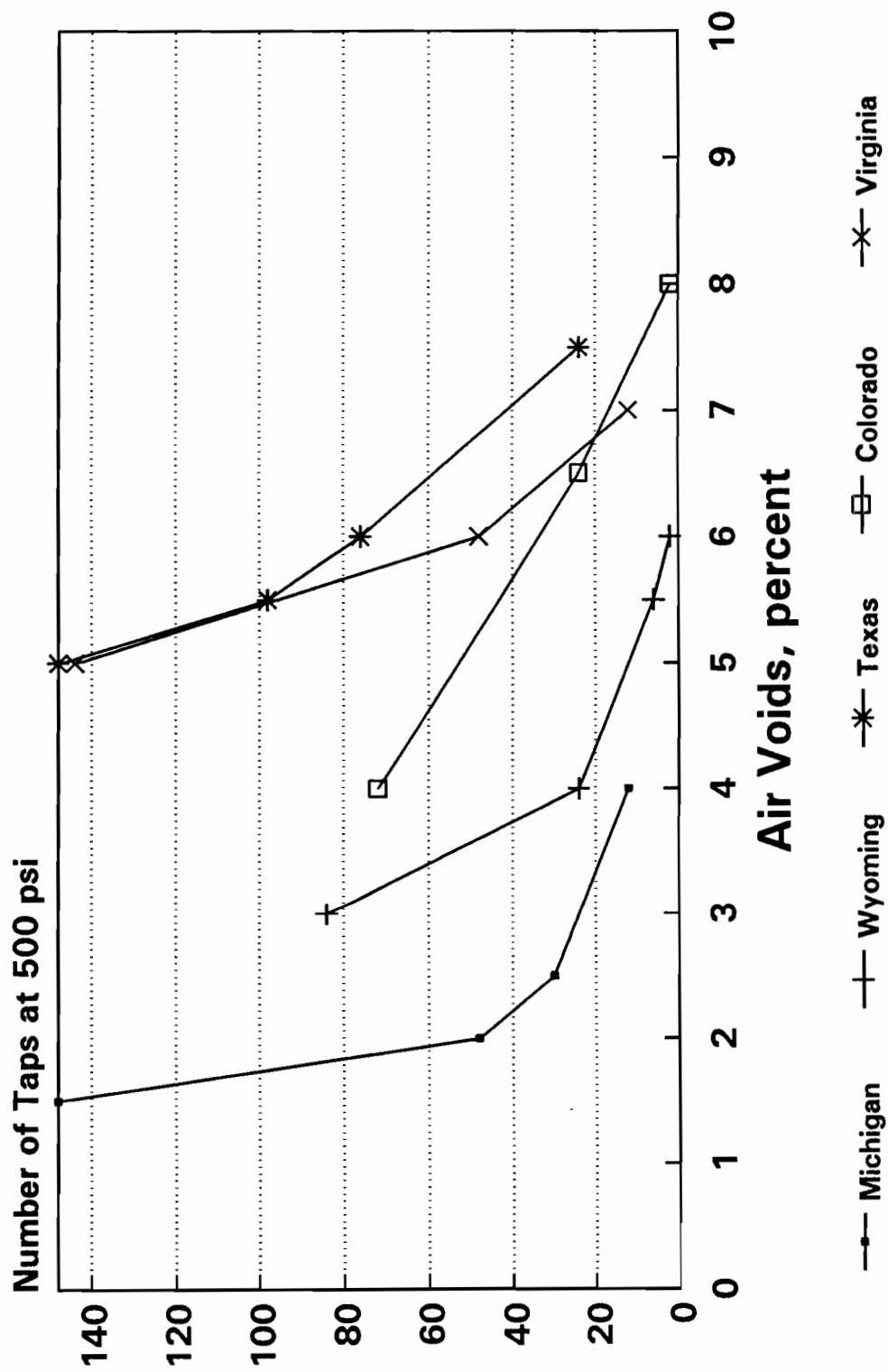


Figure 26. Compactive Effort Curves Developed for Each Mixture Using California Kneading Compactor.

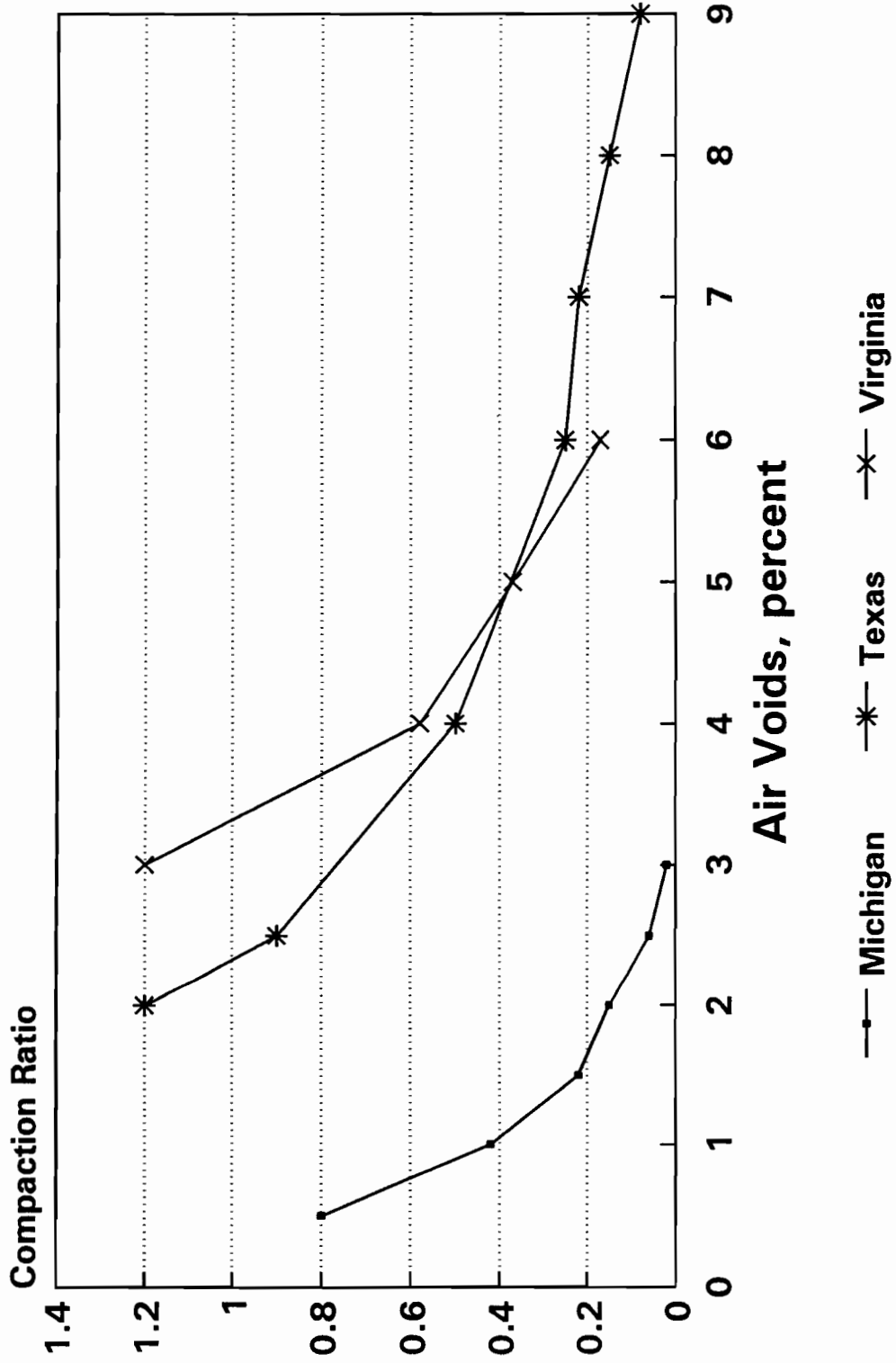


Figure 27. Compactive Effort Curves Developed For Each Mix Using the Arizona Vibratory Kneading Compactor.

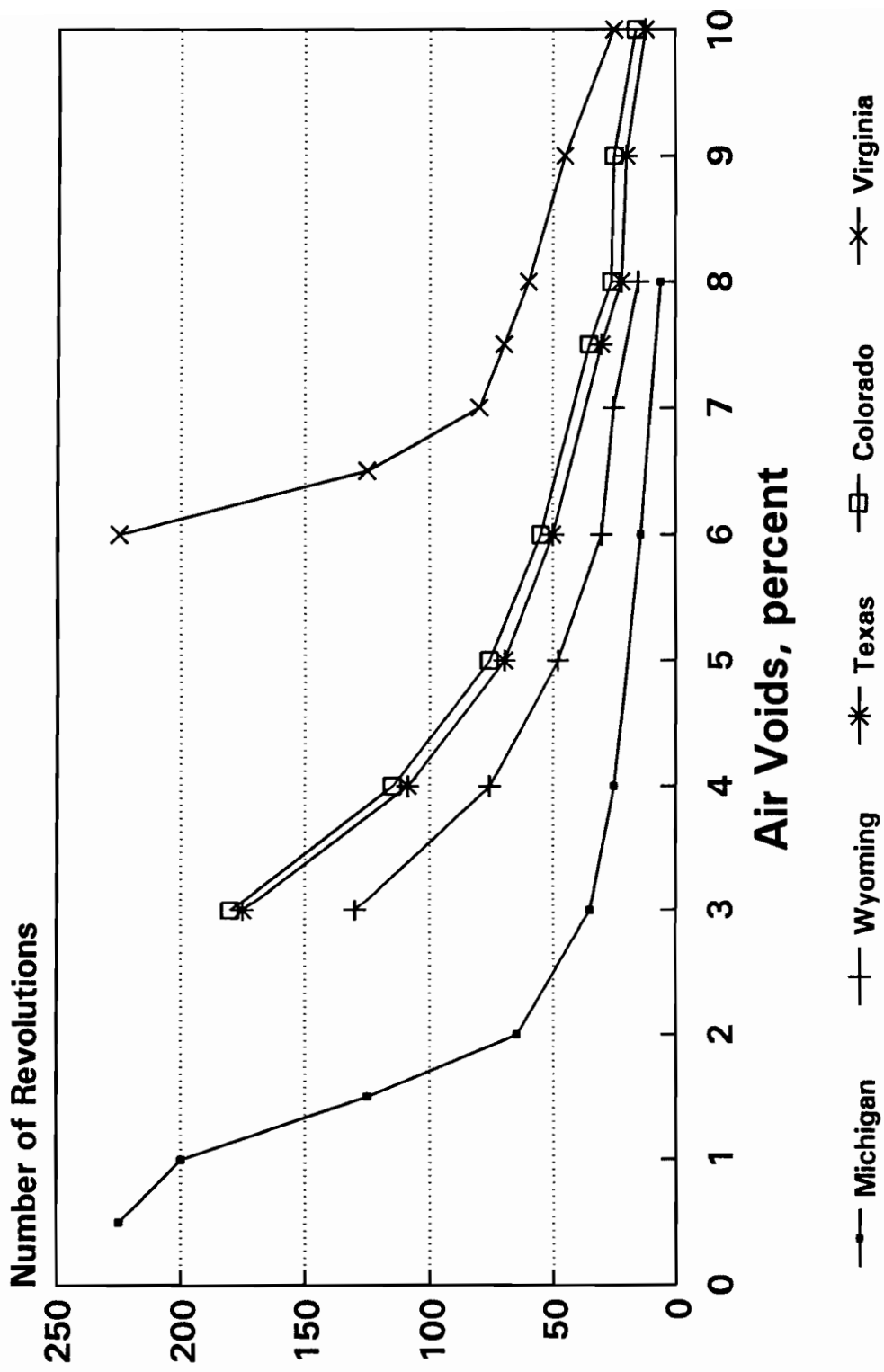


Figure 28. Compactive Effort Curves for Each Mix Using the Mobile Steel Wheel Roller Simulator.

All laboratory specimens prepared with the gyratory compactor were prepared in accordance with ASTM D 4013-87, "Preparation of Test Specimens of Bituminous Mixtures by Means of Gyratory Shear Compactor". The ASTM D 4013 procedure had to be modified to reproduce the air void level measured from field cores. To determine the amount of compactive effort required to match an equivalent air void level of the field cores, many of the laboratory compaction variables had to be varied for each of the mixes. These were number of gyrations, gyration pressure, or end pressure.

Initially, the number of gyrations were to be increased to define the compactive effort to simulate the air voids of the field cores. Unfortunately, three gyrations (the minimum that can be used in the Texas device) resulted in significantly lower air voids than occurred in the field cores (under construction densification). Therefore, gyration and end pressures were varied for the minimum three gyrations to determine the compactive effort for reproducing the average air void measured in the field cores. Figure 24 shows the reduction or change in air void as a function of gyration pressure. It should be pointed out that, for purposes of simply measuring workability and not trying to simulate field air void contents, either number of gyrations, end pressure or gyration pressure could have been varied. However, variation of end pressure, as is illustrated in Figure 24, is probably the most effective method for development of mixture workability curves.

As seen in Figure 24, the end pressure of 150 psi was set as the practical compaction limit. This, together with the mathematical expression of the decrease in air voids upon compaction (equation 1), was used to determine the area under the compaction energy curve versus air void content

for the five mixtures. In this case the value of  $n_i$  in equation 1 is equal to the end pressure in lieu of the number of gyrations. Using this approach for the five mixtures, the following workability values and coefficients for equation 1 and extreme air void parameters were determined for the five mixtures (workability is in units of end pressure times air voids or area):

<u>Project</u>	<u>Workability</u>	<u>A</u>	<u>B</u>	<u>V<sub>o</sub></u>	<u>V<sub>u</sub></u>
CO	1017	0.31	0.01992	13.0	5.0
MI	457	0.29	0.00707	8.0	1.0
TX	1192	0.14	0.00891	13.0	5.4
VA	1344	0.32	0.01160	14.0	5.2
WY	826	0.12	0.00811	11.0	3.6

In order to verify the results of the AAMAS study performed at TTI the workability of a series of mixtures used in studies 1170 and 1121 were determined in the way described above. The test matrix consisted of mixtures with a gradation very close to the 0.45 power maximum density configuration. The top size aggregate was 3/8 inch. The coarse fraction (plus No. 40 sieve size) for each mix was crushed limestone. The minus No. 40 sieve to plus No. 100 sieve size fraction was varied in 10 percent increments from 100 percent crushed or manufactured sand to 100 percent rounded field or natural sand. The filler-binder ratio remained constant for each mixture. The results of the testing demonstrated that the workability as quantified by the area under the compaction energy versus void content curve decreased consistently as increasing amounts of field sand were replaced with increasing amounts of crushed or manufactured sand.



In addition, one subset test was done within the matrix in which the filler-binder ratio was varied from 0.9 to 1.3 for the aggregate blend of 80 percent crushed sand and 20 percent natural sand. The increase in filler-binder ratio resulted in a marked effect on workability, a substantial reduction in workability with increase in filler-binder ratio.

#### **Proposed Procedure to Quantify Mixture Workability**

The recommended approach to determine and quantify mixture workability is to reduce the air void content of the mixture in question from  $V_o$  to  $V_u$  through the increase in compactive effort by means of increase in end pressure of the gyratory compactor. This operation will be done at two temperatures to define a workability profile. The two temperatures will be 280°F (the upper limit temperature) and 200°F (the lower limit temperature). The upper limit of end pressure will be 150 psi. This value will define ultimate void content,  $V_u$ .

The idea of the lower temperature limit (200°F) is to establish a temperature near the lower limit temperature at which a mixture would be compacted in the field. This lower limit could as easily be lower than or greater than 200°F. The upper temperature represents a reasonable approximation of the upper temperature at which most mixtures are compacted in situ. Once the compaction energy versus densification plots are prepared at the two temperatures, Figure 29, the values of workability are determined. These values can now be plotted versus temperature to develop a workability profile.

A profile connecting the values of workability at the two temperature extremes defines how a material stiffens with reducing temperature. The

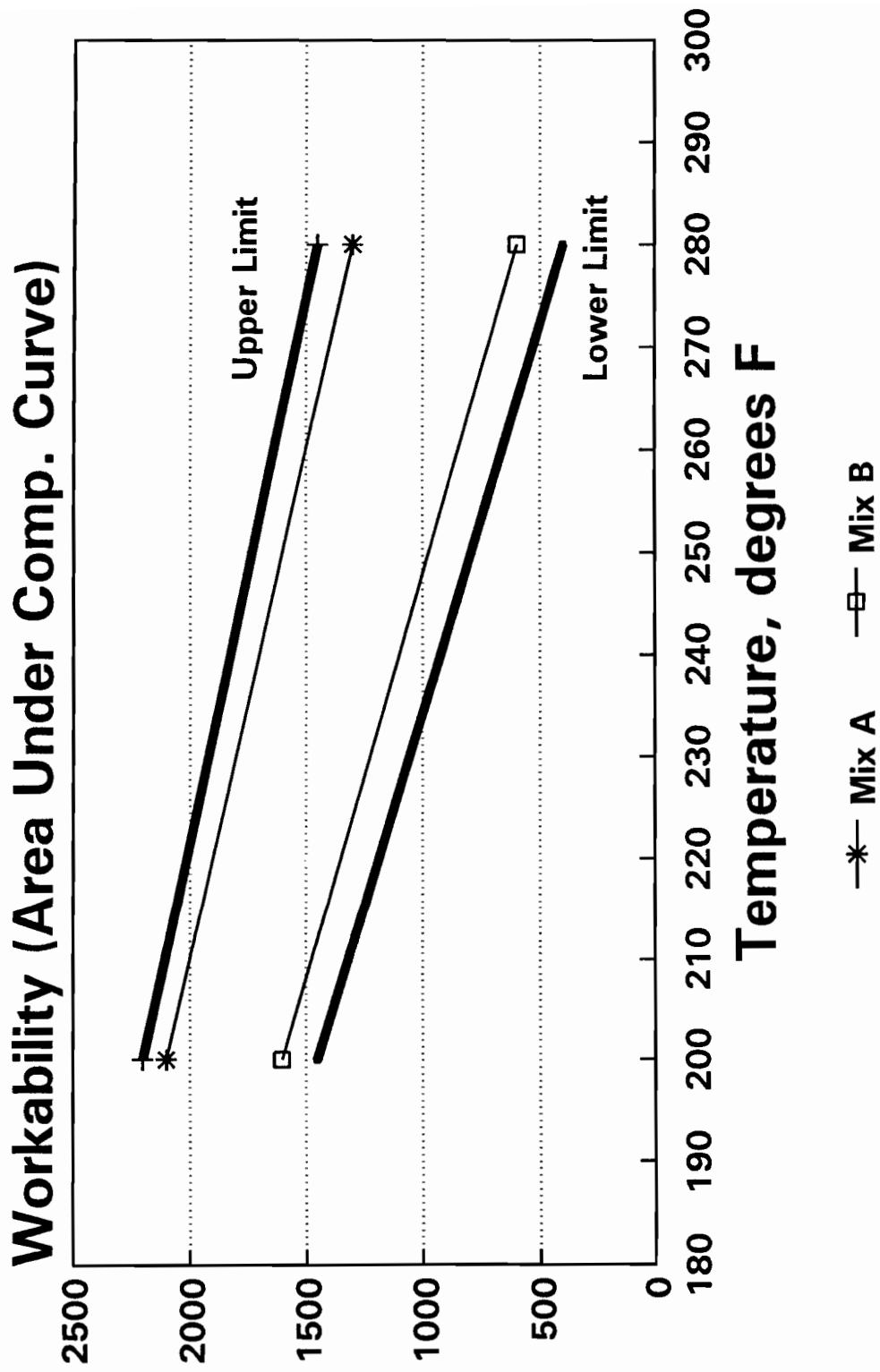


Figure 29. Workability Profile and Illustrative Boundary Limits.

magnitudes of the workability values at the two temperature extremes as well as the slope of the line connecting the two values of workability provide the information upon which to decide whether or not the workability level of the mixture is acceptable.

The decision criteria about whether or not a mixture is acceptable in terms of workability may be based on a window of acceptability shown schematically in Figure 29. This acceptability window must be based on field experience for various mixtures. This is beyond the scope and outside the direction of this current study. However, Figure 29 illustrates how this criteria window might appear with real data from two very different mixtures. Mixture A is a densely graded, 100 percent crushed limestone with a binder content of 5.0 percent, an air void content of 4.0 percent, a VMA of 14 percent and a filler-binder ratio of 1.3. Mixture B is a 100 percent river gravel mixture (uncrushed) with a binder content of 4.7 percent, and air void content of 4.2 percent, a VMA of 13 percent and a filler-binder ratio of 1.1 percent.

#### **Influence of Moisture on Workability**

In the original proposal, Task 5.0 was to establish the relationship between mixture strength and resilient modulus as a function of moisture loss (ranging from a higher than normal amount of moisture to an acceptable level). In addition this task was to determine the rate of moisture loss of the mixture during the laydown and compaction operation. It was hoped that for selected atmospheric and environmental conditions, a relatively high moisture content (high total fluids content) might be possible during laydown and compaction promoting workability. However, with moisture loss during the laydown and compaction process, it was hoped that the residual

moisture content would diminish to a tolerable level. This task was abandoned for several reasons. First, the idea of retaining rather high levels of moisture to promote workability has been tried before during the early years of the drum plants. The idea was abandoned due to problems in the mats and in mixture durability. Second, the literature is filled with evidence that high residual moisture contents in the mixture result in poor performance of the mixture structurally and from a durability standpoint, and the risk of high residual moisture is not worth the benefits of improved workability. Finally, other, more sensible means of improving mixture workability exist, the most important of which is better, more efficient laydown and compaction equipment and techniques.

As a powerful illustration of the deleterious effects of high residual levels of moisture on mixture stiffness (pavement structural aspects) and mat problems, a brief review of certain aspects from the literature in this area are presented.

Schmidt and Graf performed an experiment consisting of vacuum saturating an asphalt concrete sample to a moisture content of 5.6 percent and leaving it saturated for 80 days. The sample was then dried to a moisture content of 0.3 percent. The resilient modulus of the sample was monitored during the process of cycling wetting and drying. Schmidt and Graf discovered that as the sample was saturated from a dry state, the resilient modulus decreased by 50 percent. A further decrease in resilient modulus of about 30 percent occurred as the sample remained saturated for 80 days. However, when the sample was dried to a moisture content of 0.3 percent, the resilient modulus approached 100 percent of its original, dry resilient modulus. This process is illustrated in Figure 30.

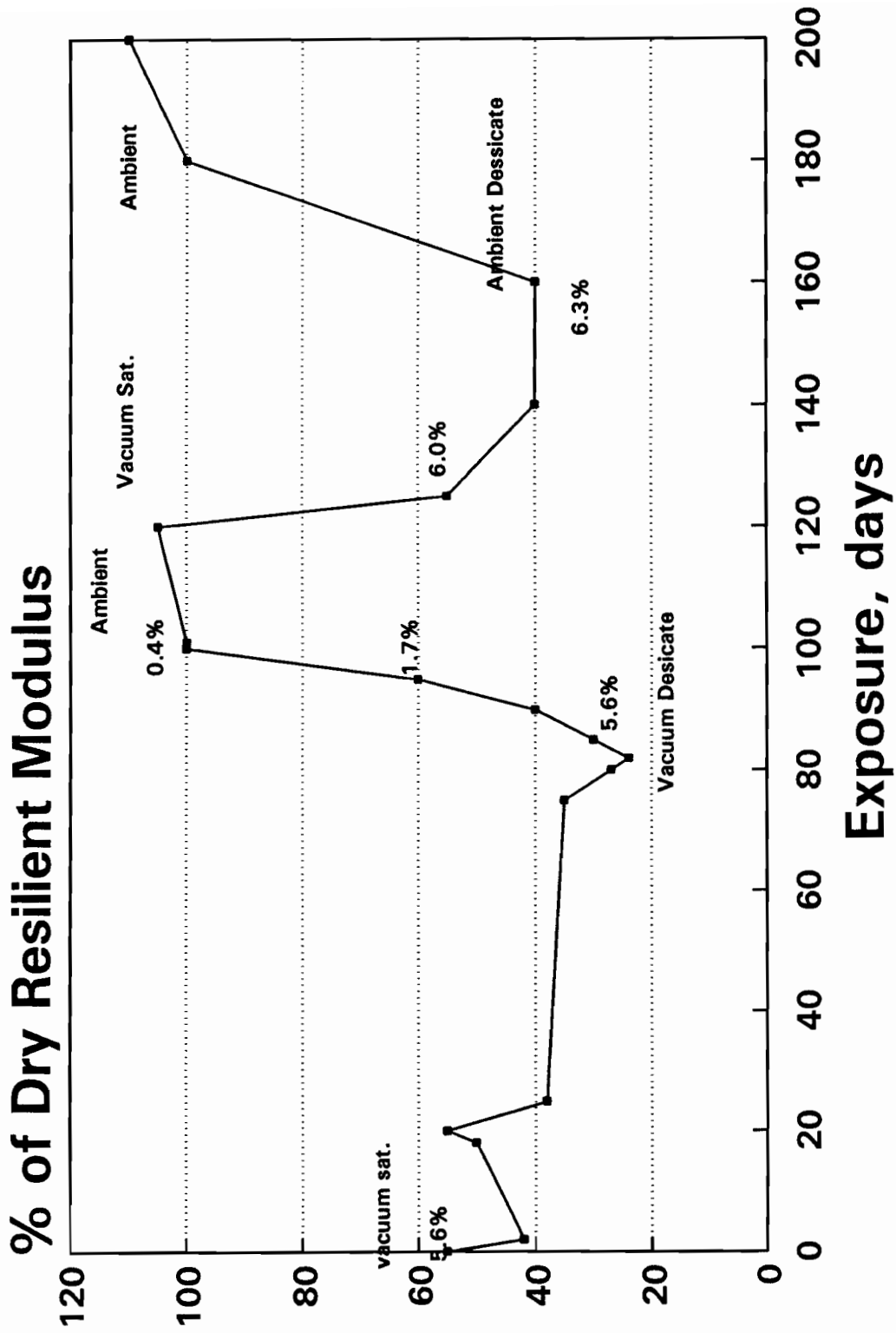


Figure 30. Fluctuation of Mixture Stiffness as a Function of Moisture Content.

Further work by Schmidt [11] demonstrated that it is necessary to reduce the moisture content of the mixture below about 0.5 percent to achieve full structural benefit of the mixture. Upon drying from a saturated condition, the mixture does not begin to achieve a substantial increase in the resilient modulus until the moisture content of the mixture is reduced to below the 0.5 percent level. Schmidt [11] also demonstrated that residual moisture contents within the mixture above 0.5 percent aggravated susceptibility to moisture damage and freeze-thaw potential.

High residual moisture contents within the mixture following laydown and compaction result in mat distress. Fat spots in an asphalt concrete mixture are isolated areas where asphalt cement has come to the surface of the mix during the laydown and compaction operation. These spots can occur very erratically and irregularly, or they may be numerous and in a fairly regular pattern. Bleeding of an asphalt concrete mixture occurs when the asphalt cement flows to the top of the mix surface under the action of traffic. Bleeding usually is characterized as two flushed longitudinal streaks in the wheelpath of the roadway.

Fat spots are primarily caused by excessive moisture in the mix. The problem is more prevalent in mixtures that contain high percentages of fine aggregate (oversanded mixtures) and in mixtures that contain aggregates of high porosity. If all the moisture in the coarse and fine aggregate is not removed during the drying and mixing operation at the asphalt batch or drum plant, the moisture will pull asphalt cement to the surface of the mix behind the paver as the moisture escapes from the mixture and evaporates.

The cause of bleeding can normally be divided into two categories. The first cause is related to an excess of fluids in the asphalt concrete

mixture, either asphalt cement or moisture or both. Under traffic, the extra moisture in asphalt will be pulled to the surface by the suction of the vehicle tires. This bleeding phenomenon occurs usually on new mats and during hot weather when the viscosity is at its lowest level. Bleeding can also accompany pavement rutting. If, during construction, adequate density is not achieved in the mixture, traffic will cause densification and rutting in the mix with time. This traffic compaction process will decrease the air void content of the mix and may, in turn, squeeze asphalt cement out of the mix and onto the surface of the roadway. The extra asphalt will appear at a longitudinal fat spot throughout the length of each wheelpath. A wide fluctuation in the asphalt concrete mix temperature is an indication that the moisture content of that mix is also variable. This latter phenomenon can contribute to both the generation of fat spots in the mix during construction and bleeding of the mix later under traffic. It is important, therefore, that the aggregate used in the mix be dry and that the moisture content of the mix, upon discharge from the asphalt plant, be as low as possible and not more than 0.5 percent. Extra care in drying needs to be exercised when producing mixtures that incorporate highly absorptive aggregate. Bleeding problems caused by excess asphalt cement in the mix can most easily be solved by reducing the asphalt content of the mix, consistent with other mixture properties such as air voids, voids in the mineral aggregate and stability. Bleeding problems that occur in conjunction with pavement rutting may only be solved, however, by a complete redesign of the asphalt concrete mixture with emphasis on the air void content and the voids in the mineral aggregate criteria.

Fat spots in the mix, if there are only a few of them, should not

affect the ultimate durability of the mixture to a significant degree. A great number of fat spots or bleeding in the wheel path does affect pavement performance because of variable asphalt and air void contents in different parts of the mix. In addition, other mix problems, such as shoving and rutting, can occur in a mix that contains many fat areas or bleeding in the wheelpath. Design of the asphalt concrete mixture, the operation of the asphalt batch or drum mix plant (more complete removal of the moisture), or both should be checked to assure adequate pavement performance under vehicular loading.



## CHAPTER 3

### ANALYSIS OF FIELD SECTIONS

#### DISTRICT TWO PROJECTS-FIELD INVESTIGATION

The second task under this contract was to review selected paving projects that had been completed in the Fort Worth District of the Texas State Department of Highways and Public Transportation during the 1985, 1986, 1987, and 1988 paving seasons. A number of projects were chosen for study which exhibited shadows on the finished surface of the roadway. It was desired to determine if there was any relationship between the contractor who did the paving, the equipment used, and/or the paving operating techniques and the occurrence of surface shadows.

The projects reviewed were selected by engineering personnel from the District 2 Office. The purpose of the selection process was to obtain a variety of projects located throughout the district that had been paved by different contractors using different brands of asphalt pavers. After a analysis of the projects completed during the time period of interest, a total of eleven jobs were chosen for an in-depth review.

The plans and specifications for each project were examined. Information was gathered on the location of each job, the name of the contractor that did the paving work, the type of asphalt concrete mix used on each job (Type D mix or Type D modified with latex), and the Mays meter reading of the finished surface course. In addition, each contractor was then contacted in order to gain data on the make and model of the paver used on project, the primary paving width used, the type of extensions used on the paver (rigid or hydraulically extendable), the use of automatic grade and slope control equipment, and the use of automatic mix feed controls.

The information obtained from the survey of the District 2 records and phone contacts with the various paving contractors revealed the following data:

SH 121, Tarrant County, from Trinity River Bridge to IH 820.

Placed: 7/85. Contractor: Austin Paving Co.

Paver: Blaw-Knox PF 500 track machine with rigid screed extensions.

Paving Width: 12 feet, variable.

Controls: Automatic grade control on both sides. Automatic mix feed control.

Mix Type: Latex modified.

Mays Meter Reading: 3.6

Watanga Road, Tarrant County, from US 377 to Rufe Snow Road.

Placed: 12/85-1/86. Contractor: Austin Paving Co.

Paver: Cedarapids BSF 400 track machine with rigid screed extensions.

Paving Width: 11 and 12 feet.

Controls: Automatic grade control on both sides. Automatic mix feed control.

Mix Type: Type D, unmodified.

Mays Meter Reading: 2.9

SH 121, Tarrant County, from IH 820 to SH 10.

Placed: 7/86. Contractor: APAC-Texas, Inc.

Paver: Blaw-Knox PF 180H rubber tire paver with rigid extensions.

Paving Width: 12' and 14'.

Controls: Automatic grade control on both sides. Automatic mix feed control.

Mix Type: Latex modified.

Mays Meter Reading: 3.7

US 67, Johnson County, from Pendell Street in Cleburne to Lake Bridge.

Placed: 7/86. Contractor: Southwestern Contracting Co.

Paver: Barber-Greene SB 140 rubber tire machine with rigid screed extensions.

Paving Width: Variable.

Controls: Automatic grade and slope control. Automatic mix feed control.

Mix Type: Latex modified:

Mays Meter Reading: 3.4.

US 377, Tarrant County, from IH 20 to west of FM 2871.

Placed: 8/86. Contractor: Austin Paving Co..

Paver: Blaw-Knox PF 500 track machine with rigid extensions.

Paving Width: 18 feet.

Controls: Automatic grade and slope control. Automatic mix feed control.

Mix Type: Latex modified.

Mays Meter Reading: 3.7

US 281, Jack County, from SH 199 to SH 59.

Placed: 9/86. Contractor: Herzog Construction Co.

Pavers: Cedarapids BSF 531 rubber tire machine with hydraulic extensions and Barber-Greene BG 260 rubber tire machine with hydraulic extensions.

Paving Width: 10', 12', and 14'.

Controls: Automatic grade and slope control. Automatic mix feed

control.

Mix Type: Latex modified.

Mays Meter Reading: 3.5

US 180, Parker County, from US 80 to T&P Railroad.

Placed: 10/86. Contractor: APAC-Texas, Inc.

Paver: Blaw-Knox PF 180H rubber tire machine with rigid screed extensions.

Paving Width: 12 feet.

Controls: Automatic grade control. Automatic mix feed control.

Mix Type: Latex modified.

Mays Meter Reading: 3.7

US 377, Hood County, from Loop 426 west of Granbury to Brazos River Bridge.

Placed: 7/87. Contractor: Duininck Brothers, Inc.

Paver: Barber-Greene SA 140 track machine with hydraulic extensions.

Paving Width: Variable.

Controls: Automatic grade and slope control. Automatic mix feed control.

Mix Type: Latex modified.

Mays Meter Reading: 3.6.

Spur 496, Tarrant County, from Berry Street to Rosedale Street.

Placed 7/87. Contractor: APAC Texas, Inc.

Paver: Blaw-Knox PH 180H rubber tire machine with rigid screed extensions.

Paving Width: 12 feet.

Controls: Automatic grade control. Automatic mix feed control.

Mix Type: Latex modified.

Mays Meter Reading: 3.0.

SH 144, Hood and Somervell Counties, from US 377 to US 67.

Placed: 9/87. Contractor: Zack Burkett Co.

Paver: Barber-Greene SB 245B track machine with hydraulic screed extensions.

Paving Width: 16 and 18 feet.

Controls: Automatic grade and slope control. Automatic mix feed control.

Mix Type: Latex modified.

Mays Meter Reading: 3.5

FM 1187, Tarrant County, from IH 35W to Spur 496.

Placed: 7/88. Contractor: APAC-Texas, Inc.

Paver: Blaw-Knox PF 180H rubber tire machine with rigid screed extensions.

Paving Width: 18 feet.

Controls: Automatic grade control. Automatic mix feed control.

Mix Type: Latex modified.

Mays Meter Reading: 3.4.

### **COMPARISON OF PROJECT CHARACTERISTICS**

Data from the above eleven projects indicates that many variations existed in the companies that completed the paving work, in the type of paving equipment used to place the asphalt concrete mix, and in the roughness of the surface after the paving was completed. The only factor in common on all of the projects was the presence of surface shadows on the roadway.

For the eleven projects, six different contractors were involved in the

construction process: APAC-Texas--four projects; Austin Paving--three projects; Duinick Brothers--one project; Southwestern Contracting--one project; Herzog Construction--one project; and Zack Burkett--one project. The presence of surface shadows does not seem to be related to the work done by a specific contractor in the Fort Worth District.

The paving projects reviewed were constructed in four different years. Two jobs were done in 1985, five jobs in 1986, three jobs in 1987, and one job in 1988. The occurrence of surface shadows seems to be a continuing problem over a period of time.

The type and model of paver used by the different contractors varied significantly and included three different makes of machine: Blaw-Knox--six projects; Barber-Greene--four projects; and Cedarapids--two projects. It is noted that on one job (US 281 in Jack County) two different makes of pavers were used on the same project (Barber-Greene and Cedarapids). From this information, it can be concluded that the development of surface shadows is not caused by one particular make of paving machine.

The type of suspension/propulsion system used on the paver was also varied and did not appear to be related to the occurrence of surface shadows. For the Blaw-Knox pavers, four of the machines were rubber tire models and two of the units were track machines. For the jobs that employed Barber-Greene equipment, three of the pavers were supported on tracks and one of the machines was on rubber tires. For the two Cedarapids pavers, one was a track machine and the other was mounted on rubber tires. Thus five of the pavers were track machines and seven of the machines were rubber tire units.

Eight of the pavers were equipped with rigid screed extensions. This

setup included all three types of pavers--Blaw-Knox, Barber-Greene, and Cedarapids. The rigid extensions were used on both track and rubber tire machines. The other four pavers were equipped with hydraulically extendable screeds. All of these latter screeds were rear-mounted (Barber-Greene and Cedarapids). No front-mounted screeds (used only on Blaw-Knox pavers) were used on any of these eleven projects. Three of the rear-mounted hydraulic extensions were used on rubber tire pavers (Barber-Greene and Cedarapids) and one on a track paver (Barber-Greene). From this information, surface shadows do not appear to be related to the type of screed extension used on the paver--either rigid or hydraulically extendable.

The width of paving varied from a minimum of 10 feet to a maximum of 18 feet. The most common paving width, as would be expected, was 12 feet. All of the projects studied had surface shadows visible on the pavement surface. From this limited data, the presence of surface shadows does not seem to be related to the width of the asphalt concrete mix being placed.

Automatic grade control or automatic grade and slope control was used on all of the twelve pavers used on the eleven projects. According to the information gathered from the paving contractors, none of the machines was run manually in terms of grade and slope control. In addition, all of the pavers were equipped with automatic mix feed control systems. It is not known, however, how the feed controls were set or what proportion of the time the augers on the paver were actually turning.

On all projects except one (Watauga Road), the asphalt concrete mix placed was an Item 340, Type G, Grade 2 material that was modified with the addition of latex. On the Watauga Road job, the asphalt concrete mix was standard Item 340, Type D material without any latex additive. Surface

shadows occurred in both the one standard mix and in all of the ten latex modified Type G asphalt concrete mixes.

The rideability of the completed pavement surface was measured through the use of the Mays Ride Meter. The range of Mays Meter readings was from 2.9 to 3.7. One project was rated at 2.9, one at 3.0, two at 3.4, two at 3.5, two at 3.6, and three at 3.7. The condition of the pavement surface before overlay was not determined as part of this study, and the amount and the distribution of mix used to level the existing surface was also not determined. Thus the Mays Meter readings may, in part, reflect the condition of the existing pavement surface before overlay as well as the effect of the overlay in reducing the pavement roughness.

#### SUMMARY

Only a very limited number of paving projects in the Fort Worth District were sampled as part of the initial investigation for this project. The purpose of the limited study was to determine if the occurrence of surface shadows could be related to the workmanship of one particular paving contractor, the use of a particular make or model of paver, the paver mounted on rubber tires or tracks, the use of rigid or hydraulic extensions on the paver, the differences in the paving widths, or in the use of automatic grade and slope controls and/or automatic mix feed controls.

It was initially believed that surface shadows are a common enough problem that a significant relationship would not be found between any of the variables examined and the occurrence of surface shadows on the roadway. Although the data reviewed from eleven paving projects in the Fort Worth District are extremely limited and a statistical analysis can not be carried out, it does not appear that the presence of surface shadows can be related



to any of the above factors. The workmanship of any one contractor or the make and model of paver used to place the asphalt concrete mixture does not appear to have a strong correlation to the occurrence of surface shadows.

### **FIELD TEST SECTIONS**

The third phase of this study consisted of construction of roadway test sections to try to create surface shadows under various field project conditions. A series of meetings were held to determine those variables which might affect the severity of the surface shadows.

The first meeting was held at the Texas Transportation Institute (TTI) on March 23, 1989. In attendance at that session were representatives of the Texas State Department of Highways and Public Transportation (SDHPT) and TTI. The primary purpose of this initial meeting was to develop a list of factors that might have a significant affect on the occurrence of surface shadows. The list that was compiled included the following factors:

- A. Head of material in front of the paver screed.
- B. Forward travel speed of the paver.
- C. Use of automatic mix feed controls on the paver.
- D. Use of automatic grade and slope control on the paver.
- E. Asphalt concrete mix design.
- F. Asphalt concrete mix temperature, and
- G. The temperature of the asphalt concrete mix.

### **SH 183 Frontage Road Test Section Construction**

#### **Test Section Variables**

A meeting was then held on April 26, 1989 at the Fort Worth District office of the Texas SDHPT. Twelve people were in attendance at that

meeting. They represented TTI, the Texas SDHPT, three different paving contractors in the Fort Worth area, and the paver service managers of two different paver equipment manufacturing companies. The group was supplied with a summary of the information that had been gathered on eleven paving projects that had been completed in the district in the last several years. As discussed in detail above, it was pointed out that there did not seem to be a relationship between the occurrence of surface shadows and the contractor that paved the roadway, the make and model of paver used, the use of rigid or hydraulic screed extensions, the paving width, or the type of mix placed (standard Type D or latex modified Type G).

The group discussed at length the various factors that might contribute to the occurrence of surface shadows. Possible causes were listed and ranked by the group according to the probability of being a significant factor. The ranking system assigned a low, medium, and high probability to each of the variables, as given below:

- A. Use of automatic grade and slope controls: Low.
- B. Head of material in front of the paver screed:
  - 1. Use of automatic mix feed controls: High.
  - 2. Auger speed: High.
  - 3. Percent of time that the augers are turning: High.
  - 4. Auger height: High.
  - 5. Distance of screed from augers: High.
  - 6. Build up of fines on the screed strike-off: High.
- C. Mix characteristics: Medium.
- D. Paver speed: Medium.
- E. Mix temperature:

1. Constant temperature: Low.
2. Proper temperature for stiffness of mix: High.

F. Layer Thickness: Low.

It was decided to build multiple field test sections of asphalt concrete surface course mix that would take into account as many of the above variables as possible. The following matrix was developed.

Screed position Two locations--forward and back. The screed is normally in the forward or "front" position, as illustrated in Figure 31. In this position the screed is as far forward as possible--as close to the augers as possible. In the "back" position, shown in Figure 32, the screed is moved backwards on the paver tow arms and the distance between the augers and the screed is increased. In most cases, the back position increases the distance between the augers and the screed by four inches compared to the distance between the augers and the screed when the screed is in the forward position.

Auger "On-Off" time Two different auger "on-off" times were selected for the test program. The first time was 70% on and 30% off time. At this timing, the flow gates on the paver would be set at a height so that the augers would run only about 70% of the time. By positioning the flow gates at the back of the paver hopper at a greater height than necessary, more asphalt concrete mix would be pulled back through the paver by the drag slat conveyors and carried onto the augers. This setup would tend to "flood" the augers and significantly increase the amount of mix carried in the auger chamber of the paver, thus also increasing the forces on the paver screed. The second "on-off" time was to be 100% on and 0% off. At this timing the

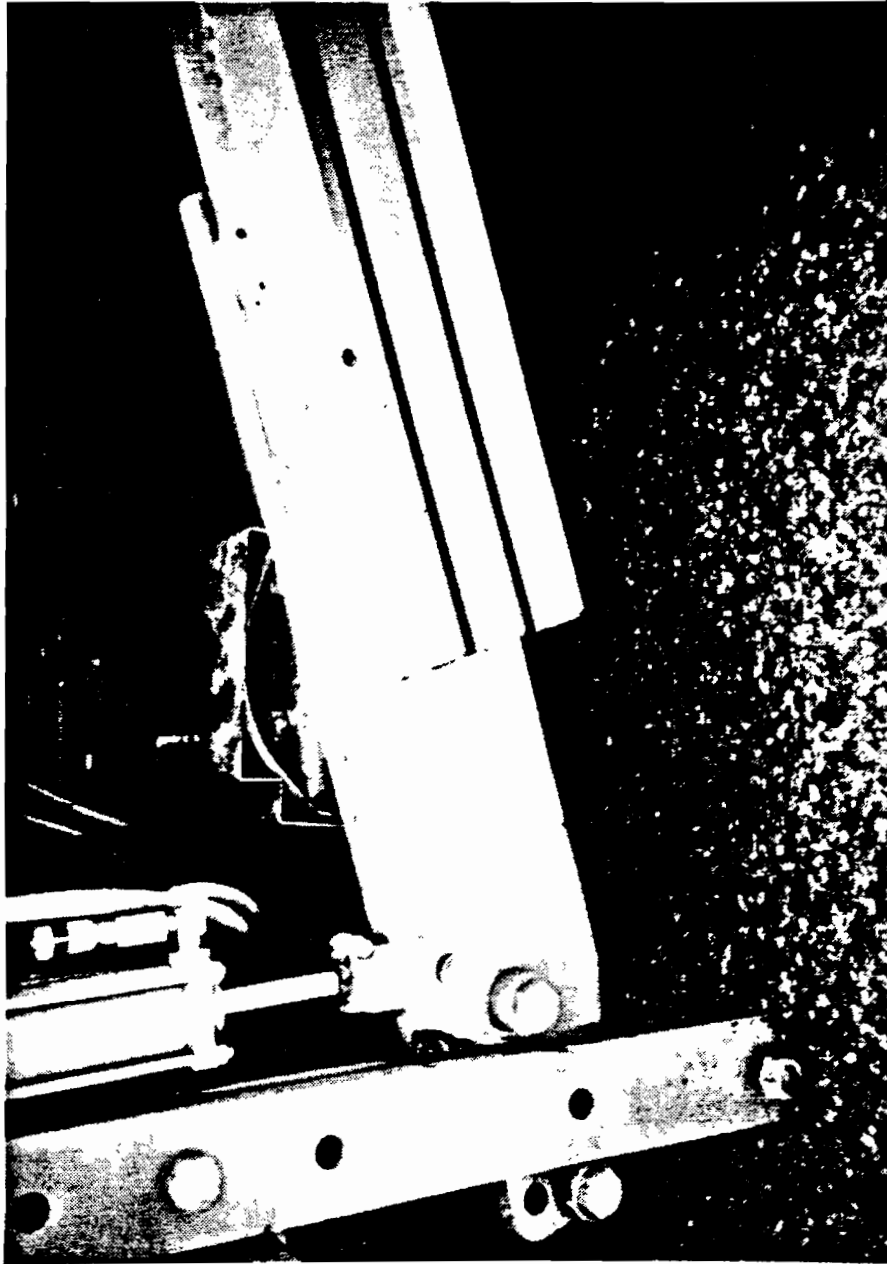


Figure 31. Paver Screed in the Forward (Normal) Position.

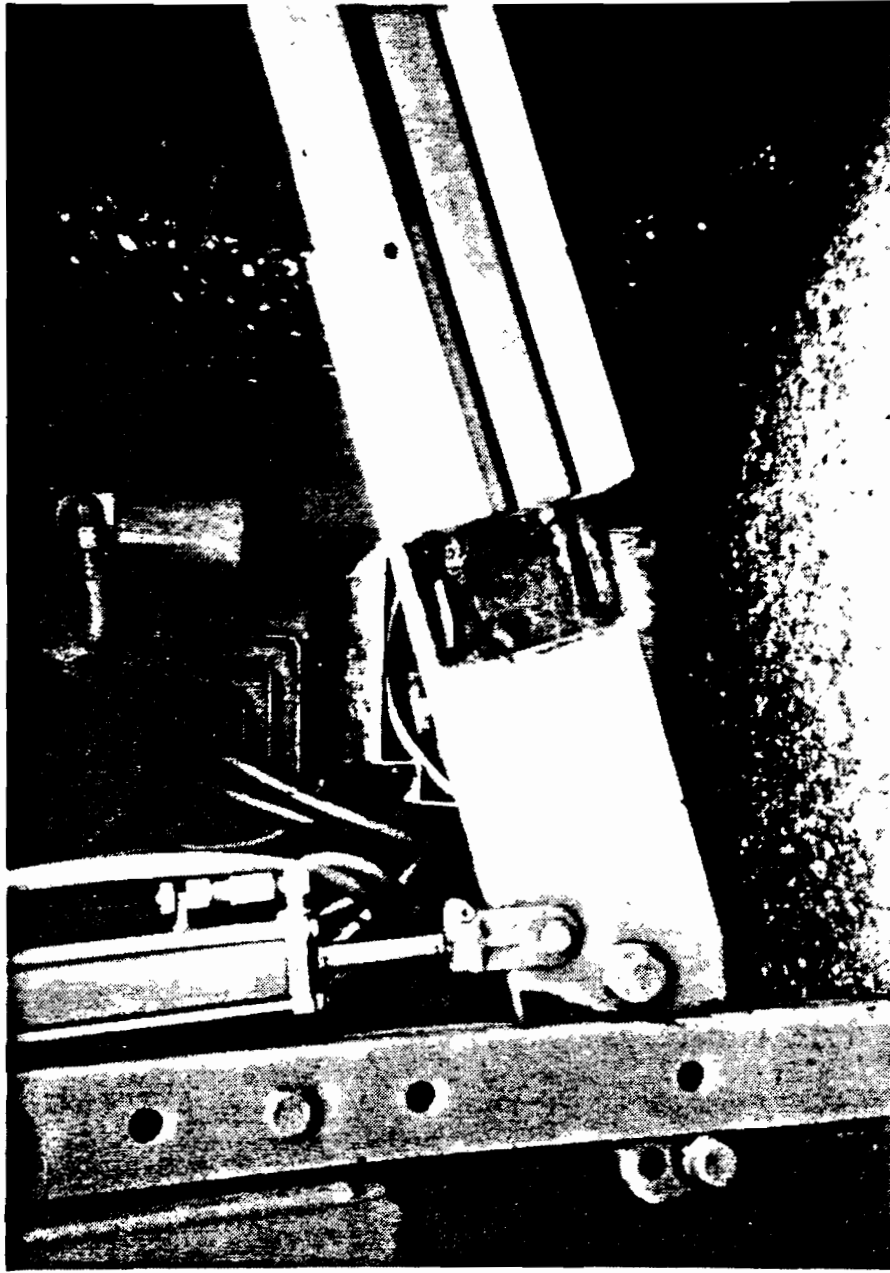


Figure 32. Paver Screed in the Back Position, Moved Backward Four Inches on the Screed Tow Arm.

flow gates at the back of the paver hopper would be set to the height that the delivery of mix to the augers would be restricted and the drag slat and augers on each side of the paver would have to run as much of the time as possible (close to 100% of the time) in order to deliver the proper amount of mix to the screed and provide the proper thickness of the mat being placed.

Mix temperature Fort Worth District primarily uses latex modified asphalt concrete surface course mixtures. This type of mix (Type G) is typically placed at elevated temperatures compared to normal Type D asphalt concrete mix. At high temperatures, the mix is relatively fluid because the viscosity of the modified asphalt cement binder is low. As the mix temperature decreases and the mix cools, the mix becomes stiffer and less workable. It is known that a stiff mix increases the force on the screed and causes the screed to change angle of attack. Two different levels of mix temperature were selected for use on the first trial project. Those two temperatures were 15°F above and below the "optimum" mix temperature which was determined to be 325°F. Thus two different mix temperatures were selected for use: 310°F and 340°F.

Height of the head of material in front of the screed This factor was determined to be the most important variable to be investigated in the field test sections project. Three different levels of mix in the auger chamber (on the augers in front of the screed) were chosen for the test program. The three heights were at the bottom of the augers (low), at the center of the auger shaft (middle), and at the top of the augers (high, or an overloaded condition). These three conditions are illustrated in Figures 33, 34, and 35, respectively. When the mix level is at the bottom of the

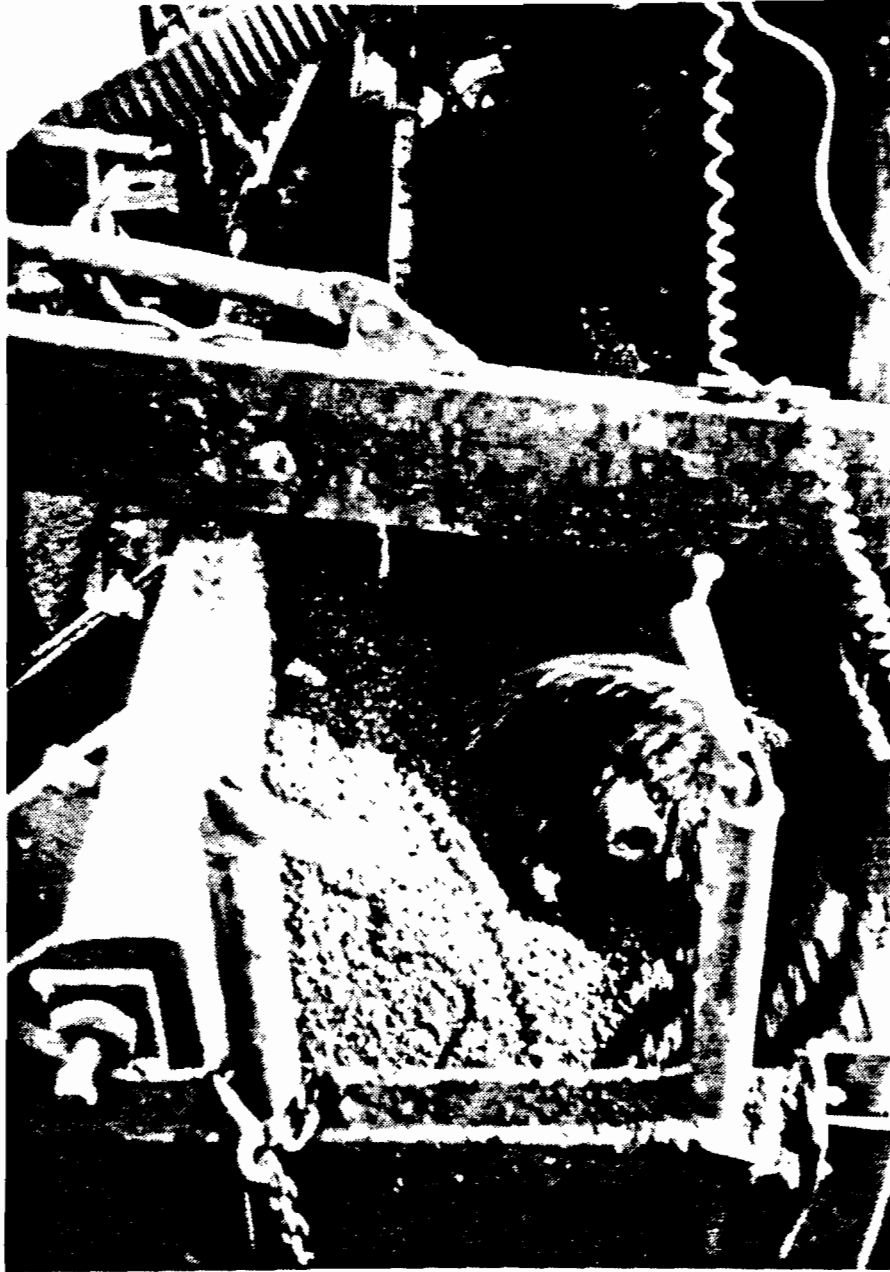
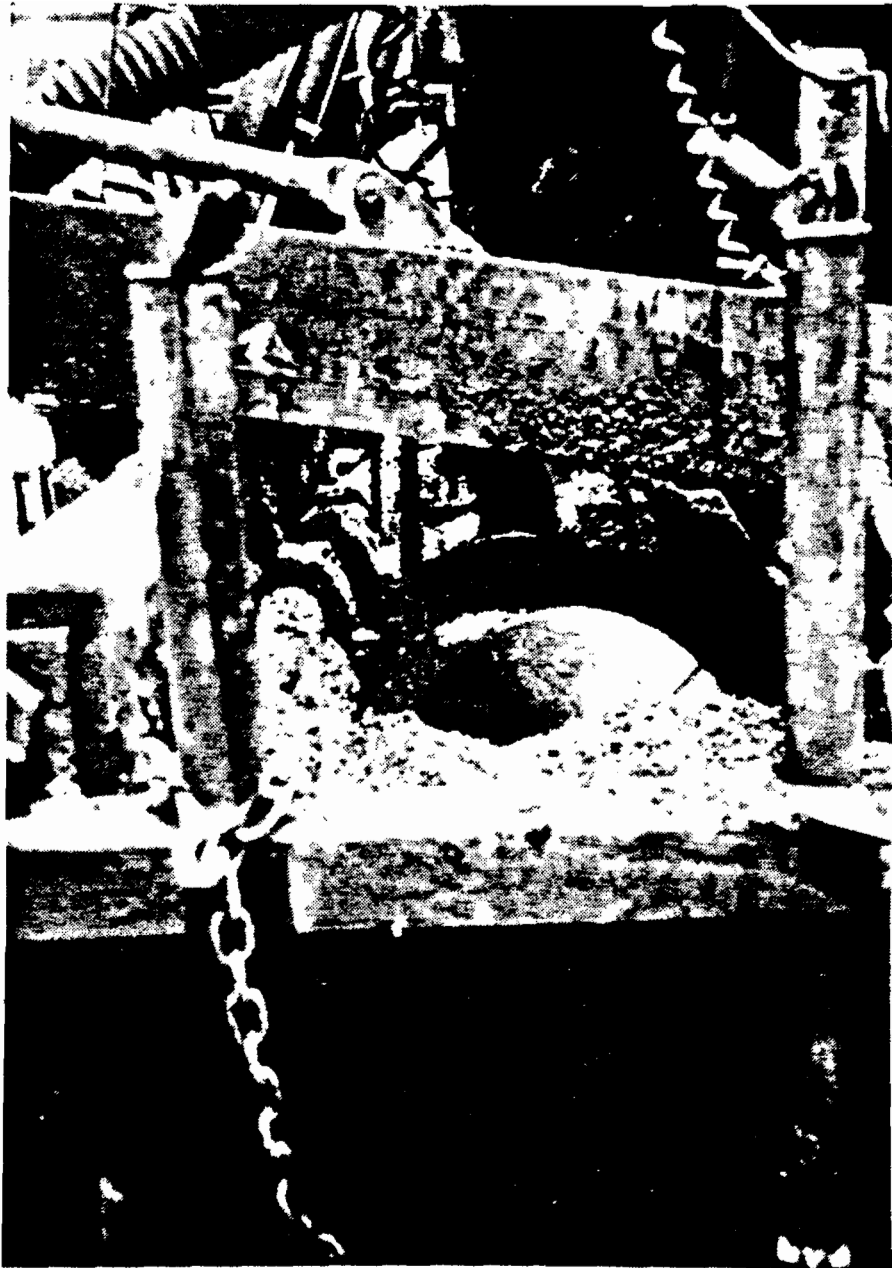


Figure 33. Low Level of Mix in Auger Chamber, Low Head of Material.



**Figure 34. Mix Near Center of Auger Shaft, Middle and Correct Head of Material.**



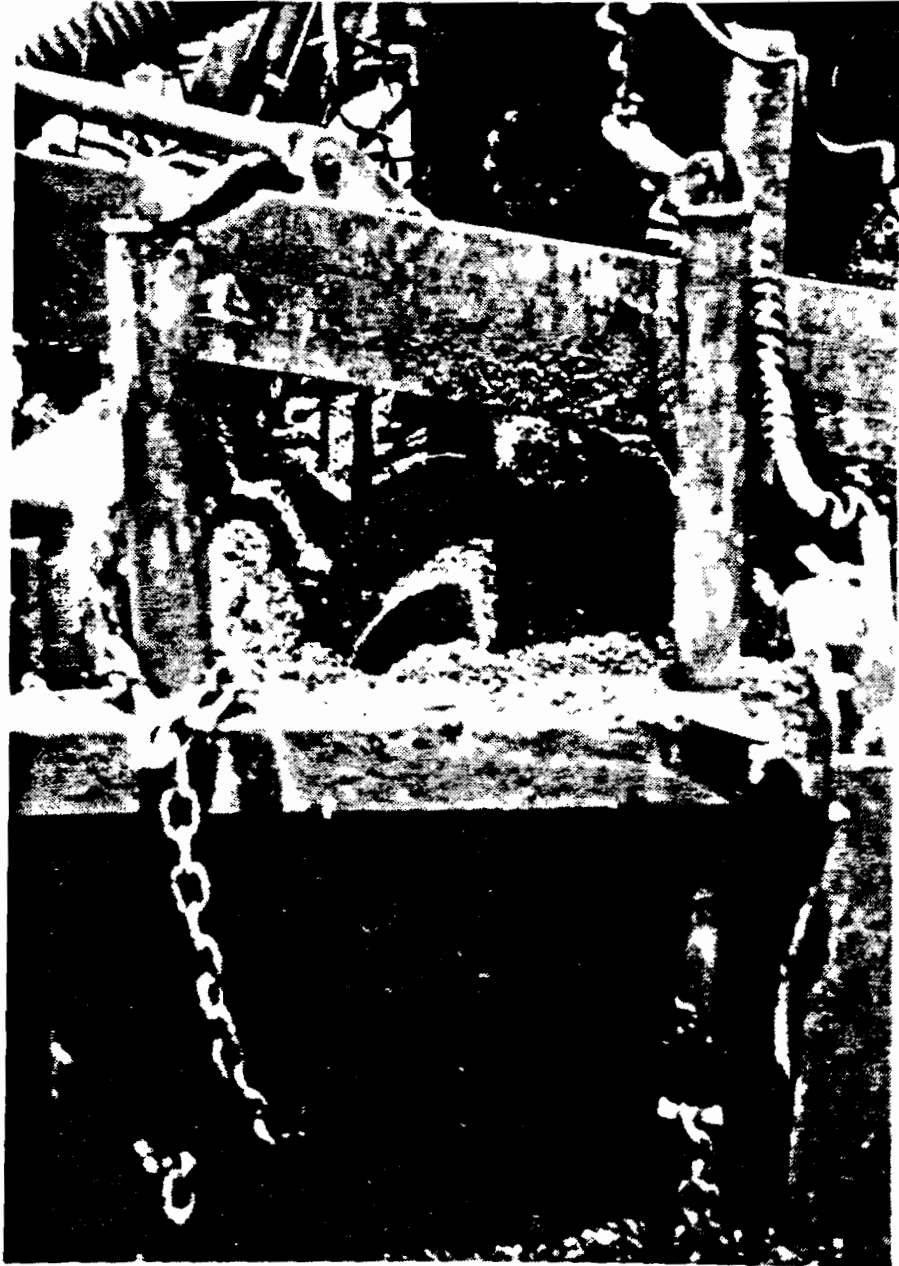


Figure 35. High Level of Mix in Auger Chamber, Augers Overloaded.

augers, the amount of asphalt concrete mix carried in front of the screed is minimal (Figure 33). With the mix at this level, the force on the screed is small. When the level of mix is at the center of the auger shaft (middle position, Figure 34), a proper amount of mix is carried in front of the screed. In this condition, the force on the screed is constant and correct. When the augers are overloaded (high mix level, Figure 35)--almost completely covered with mix--the force on the screed is great and the screed reaction time is significantly altered.

The four variables described above were set out in a matrix to attempt to determine a schedule for the construction of the required test sections. Twenty-four sections were needed to completely test all of the variables: two levels of screed position, two levels of auger "on-off" time, two levels of mix temperature, and three levels of head of material in front of the screed (2 X 2 X 2 X 3 matrix = 24 test sections). The paver speed was to be the same and held constant at approximately 40 feet per minute for all of the test sections. This matrix for the proposed test sections is shown in Figure 36.

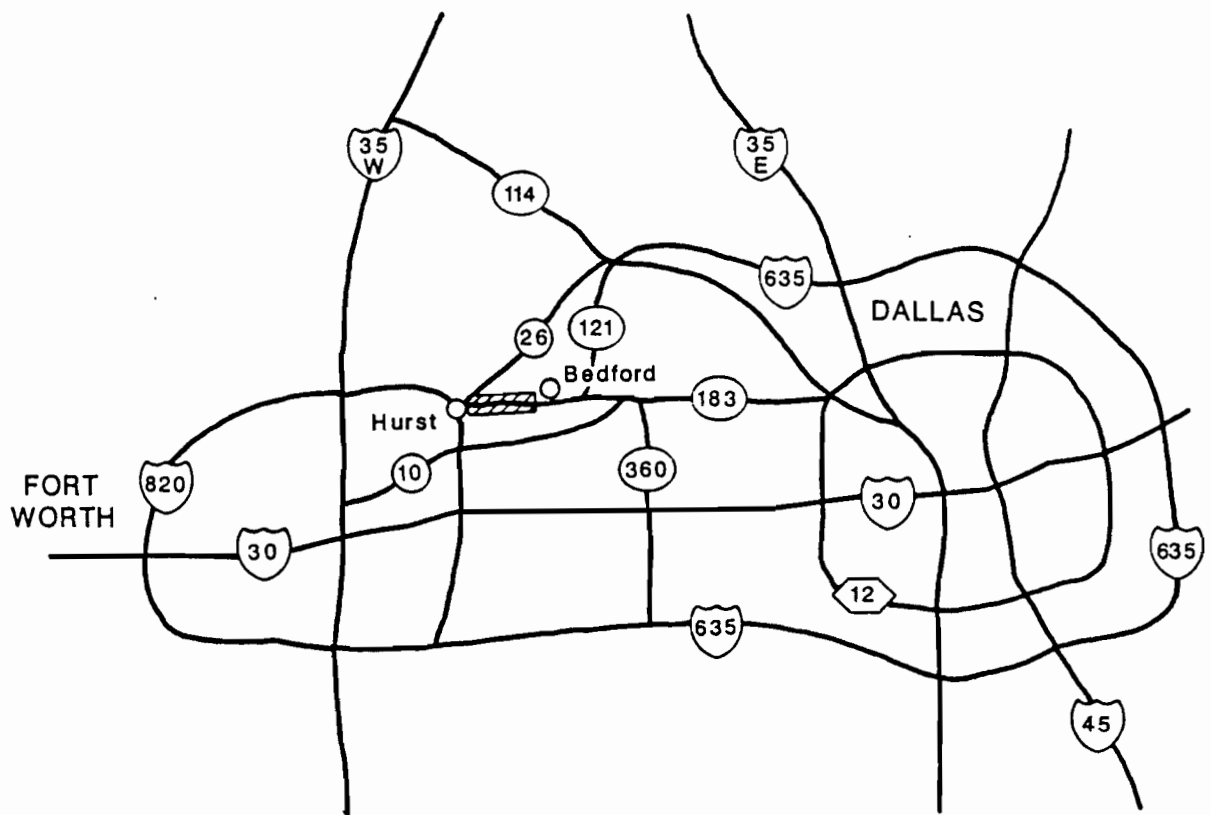
#### Test Section Construction

Project Location The first field trial was constructed on the south and north frontage roads for State Highway 183 in the Fort Worth District, in the cities of Bedford and Euless in Tarrant County in July 1989. Only fifteen test sections were constructed. Four of those sections are on the eastbound service road (south service road) between FM 157 and Ector Drive. The remaining eleven sections were built on the westbound (north) service road between FM 157 and Murphy/Westpark Way. Figure 37 shows the location of the test sections.

Head Material	Mix Temperature	Auger Time (Percent "On")	Screed Position	FORWARD		BACK	
				70%	100%	70%	100%
				Low	340°F	5	2
310°F	17	14	20		23		
Middle Center of Shift	340°F	4	1	7	10		
	310°F	16	13	19	22		
High Overloaded	340°F	6	3	9	12		
	310°F	18	15	21	24		

Note: Paver Speed is Constant at 40 ft/min.

Figure 36. Proposed Test Section Matrix for SH 183 Frontage Roads.



Location of SH 183 Site

Figure 37. Location of Test Sections on SH 183 Frontage Roads.

Personnel The paving contractor for these test sections was APAC-Texas, Inc, Fort Worth Division. The manager in charge of the project for APAC was Doug Shock, Vice President. The Blaw-Knox Construction Equipment was represented by Tom Skinner, Parts and Service Manager. Jack Farley, Vice President, Product Support, and John Guzman, Regional Sales Manager were at the site for the Barber-Greene Company. Texas SDHPT personnel involved in the test section construction included Carl Utley, District Construction Engineer; Dave Bass, District Materials Engineer; and Bob Julienne, Assistant District Construction Engineer. From TTI, the people participating in the project were Dallas Little, Professor of Civil Engineering and Principle Investigator for the study; Mary Anne Rodriguez, Engineering Research Associate; and Jim Scherocman, Consulting Engineer.

Pavement Cross-Section The overlay consisted of a 1-3/4 inch layer of Item 340, Type G, Grade 2, latex modified asphalt concrete surface course. A fabric underseal was placed beneath the surface course layer. On 7/6/89, the average rate of mix placement was 168.4 pounds per square yard. On 7/7/89, the average rate of mix placement was only 138.6 pounds per square yard.

Mix Design The aggregate used in the Type G mix consisted of 46% lightweight coarse aggregate from TXI-Streetman, 44% washed screenings from TXI-Bridgeport, and 10% natural sand from Harston Sand and Gravel-Azel. The asphalt cement was an AC-10 material modified with 3% latex solids and was supplied by Cosden Asphalt. An antistripping additive, Adhere, was also included in the mix. The binder content was 7.6% by weight of aggregate.

The average extracted aggregate gradations and asphalt contents during construction on the dates of 7/6/89 and 7/7/89 are shown in the last column

of Table 1. Also included in that same table are the Texas specification requirements for the Type G mix and the job mix formula for the combined aggregates. In general, the extracted aggregate gradation is relatively close to the job mix formula gradation. The average extracted asphalt content is 7.3% compared to a design asphalt content of 7.6%.

The mix temperature on 7/6/89, when the high temperature mix was being placed, was 342°F at the mix plant and 335°F at the paver. On 7/7/89, the mix temperature was lowered from normal and averaged 313°F at the plant and 310°F at the paver. The average laboratory density was 95.7% on 7/6/89 and 96.% on 7/7/89.

Equipment The paver used to place the mix was a Blaw-Knox PF 180H rubber tire paver. This piece of machinery was in poor mechanical condition. Test section construction was delayed for 1-1/2 days in order to correct some of the mechanical problems with the laydown machine. Paver speed, which was supposed to be held constant for each of the test sections, varied from 15 to 60 feet per minute. The average paver speed was just under 45 feet per minute. Figure 38 shows the mix being placed by the Blaw-Knox PF 180H paver.

Three rollers were used to compact the latex modified asphalt concrete mix. The first or breakdown roller was a Dynapac model CC 42A double drum vibratory roller. A Galion 3500A pneumatic tire roller was used in the intermediate position. The finish roller was a Galion tandem static steel wheel roller.

Test Section Layout Due to mechanical problems with the paver, no test sections were placed on 7/5/89, and only four test sections were able to be constructed on 7/6/89. Figure 39 shows the layout of the test sections and

Table 1. Mix Design for SH 183 Frontage Roads.

Sieve Size	Texas SDHPT Specifications	JMF Combined Gradations	Average Extracted Gradations
-1/2	0	0.0	0
-3/8	0 - 13	2.3	1.0
3/8 - 4	15 - 45	27.7	29.3
4 - 10	10 - 30	23.3	23.8
+10	42 - 62	53.3	52.4
10 - 40	10 - 45	24.3	21.2
40 - 80	10 - 40	15.6	15.3
80 - 200	5 - 40	5.4	7.5
Pass 200	0 - 6	1.5	1.9
AC Content		7.6	7.3

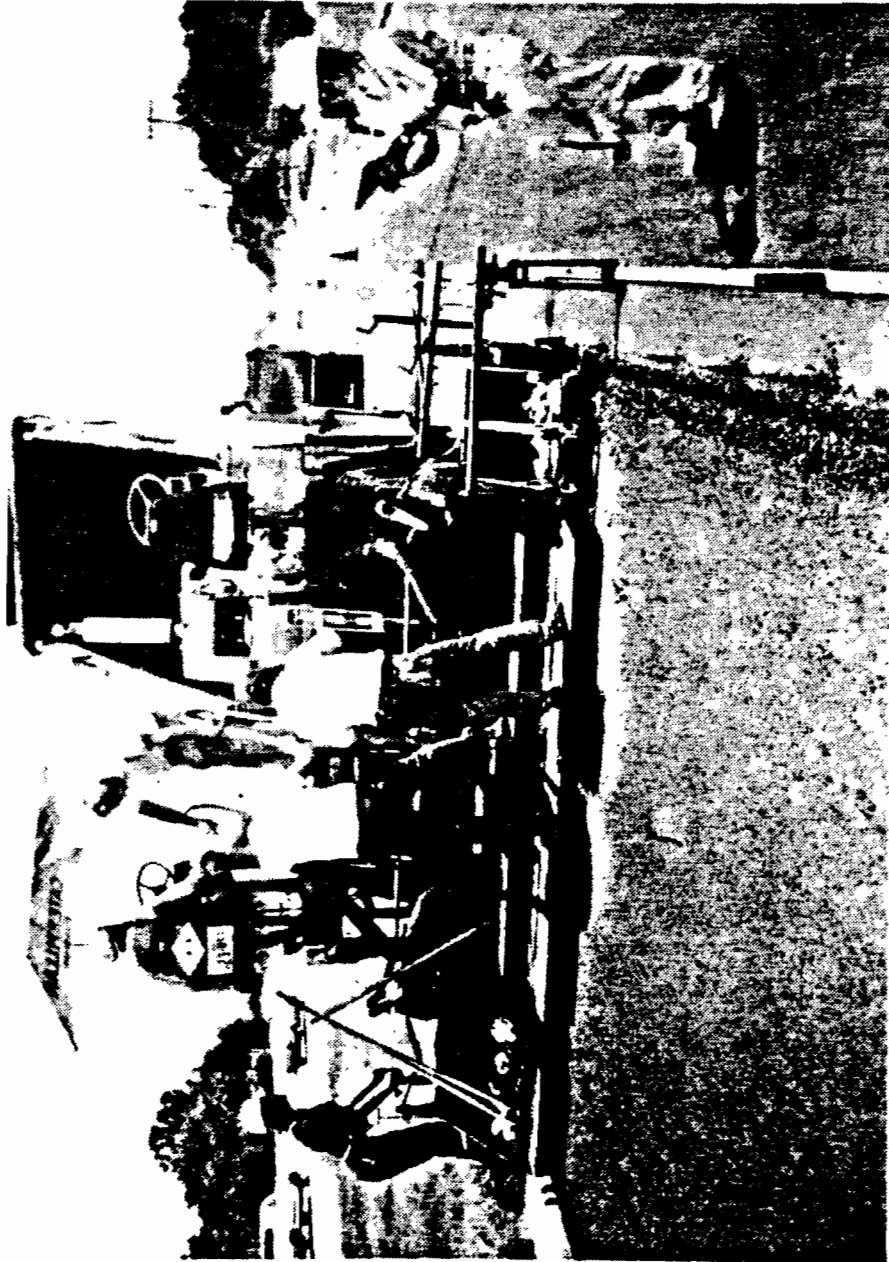
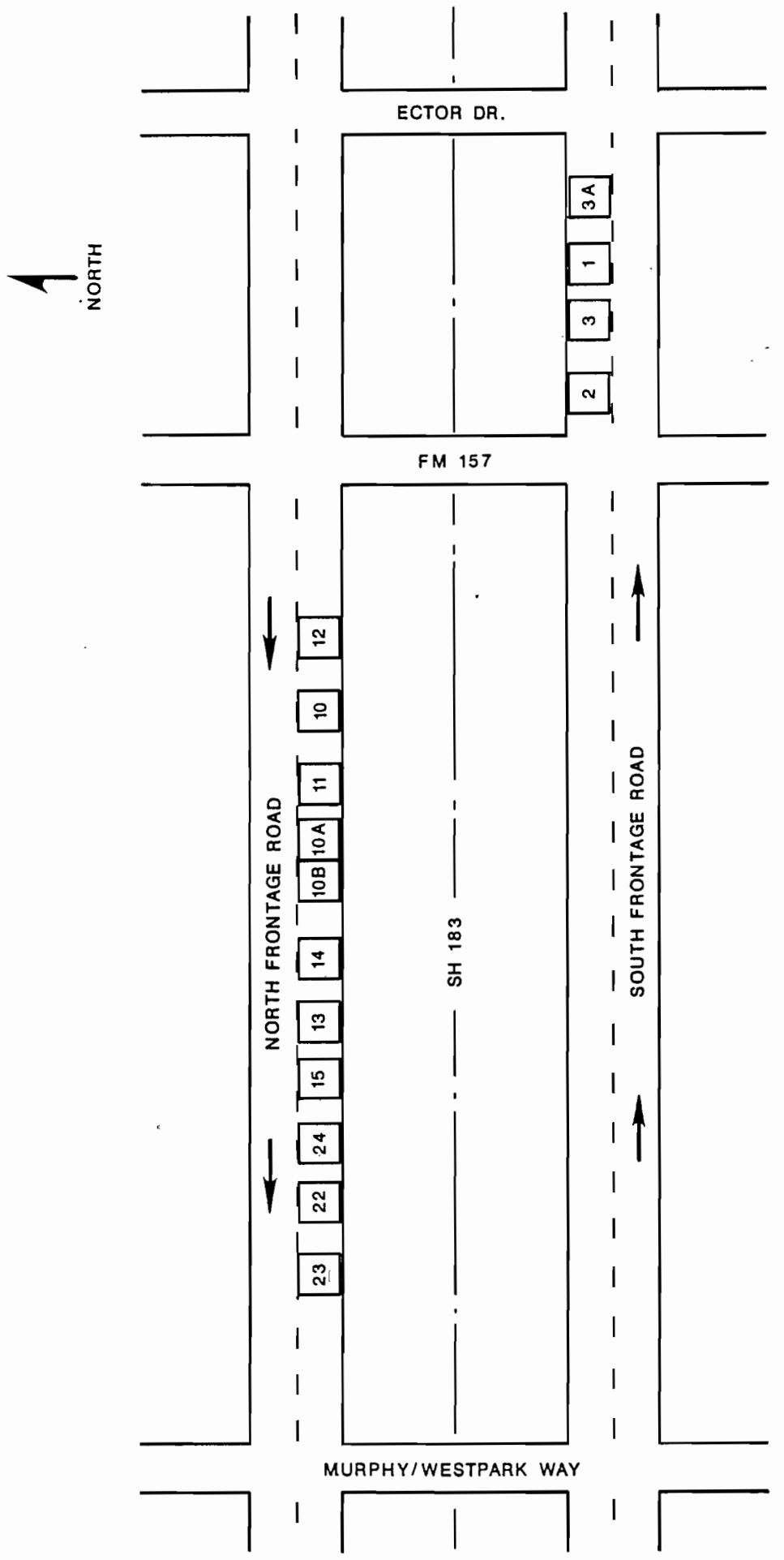


Figure 38. Blaw-Knox PF 180H Paver on SH 183 Frontage Road.





SH 183 TEST SECTIONS  
 (TEST SECTIONS ARE 400 FEET LONG)  
 Not to Scale

Figure 39. Layout of Test Sections for SH 183 Frontage Roads.

Table 2 shows the stations numbers of the test section locations. The mix temperature at the paver for these sections was low--between 289°F and 298°F degrees F. The mix temperature at the paver should have been approximately 310°F. Paver speed varied between 15 and 38 feet per minute, but was supposed to be 40 feet per minute. In each case, the paver screed was forward--or in the normal paving position--and therefore, as close to the screed as possible. The amount of mix in the auger chamber--the head of material against the screed--was varied from low (section 2) to high (section 3) to middle (section 1) and back to high again (section 3a).

Because of the difficulty in regulating the speed of the paver, it was decided not to attempt to vary the "on-off" time of the augers. For all of the test sections completed on this project, the augers were kept running as close to 100% of the time as possible. No test sections were built with the augers running only 70% of the time.

On the following day, 7/7/89, the mix temperature was increased, but not to the required level. High mix temperature was supposed to be used--15° higher than the nominal mix temperature of 325°F. Instead of this temperature (340°F), however, the mix was delivered to the paver in the range of 302°F to 317°F, as shown in the table. Paver speed, which was supposed to be 40 feet per minute, ranged from a low of 36 feet on one section to a high of 60 feet per minute on another section. Consistency in the laydown operation was not accomplished by the contractor. The augers on the paver were left at the 100% "on" condition, and the flow of mix from the paver hopper was controlled by an automatic flow control device.

For the eleven test sections constructed on the westbound service road, the screed was in the back position for the first five sections and also for

Table 2. Test Section Variables for SH 183 Frontage Roads.

Section	Location		Screed Position	Material Height	Average Paver Speed ft/min	Average Mix Temperature °F
	Start Station	End Station				
2	337+60	341+65	forward	low	34.0	295
3	343+08	347+12	forward	high	38.0	282
1	347+58	351+62	forward	middle	36.0	298
3a	352+62	356+62	forward	high	15.0	289
12	325+29	321+25	back	high	52.0	306
10	319+06	315+00	back	middle	60.0	313
11	313+75	309+71	back	low	36.0	317
10a	309+34	306+79	back	middle	55.0	313
10b	306+79	305+51	back	middle	55.0	312
14	303+92	299+95	forward	low	30.0	306
13	299+38	295+41	forward	middle	58.0	302
15	294+53	290+54	forward	high	51.0	304
24	289+36	285+32	back	high	50.0	305
22	284+32	280+32	back	middle	60.0	-
23	277+45	273+54	back	low	42.0	306

the last three sections. It was thought that this position would be a more critical position for the screed due to the greater amount of material carried in the auger chamber in front of the screed. The screed was in the forward or front position for three of the test sections, as illustrated in the table. The level of mix in the auger chamber was varied for the construction of the westbound service road test sections. The height of mix in front of the screed was varied from low to middle to high for each screed position.

Due to a lack of time and the inconsistency of the contractor's paving operation, it was decided to delete the construction of the remaining test sections that were scheduled to be built. Thus, instead of 24 distinct test sections, only 12 different test sections were constructed. In addition, replicate test sections were built for three of the sections, as shown in Table 2, for a total of 15 test areas.

### Observations

During Construction Observations were made during the mix placement process as to the presence of shadows in the surface of the mix behind the paver--before compaction by the rollers. In some cases, surface shadows were slightly visible in the mix. On other test sections, surface shadows could not be observed at the time of construction. In all cases, where the shadows were visible directly behind the paver, the shadows "disappeared" after the mix was compacted by the rollers.

On the eastbound service road, the surface shadows were most visible in test section 3 where the screed was forward and the amount of mix carried in front of the screed was high--the augers were overloaded (Figure 40). The surface shadows were not as intense in test section 3a, which was a

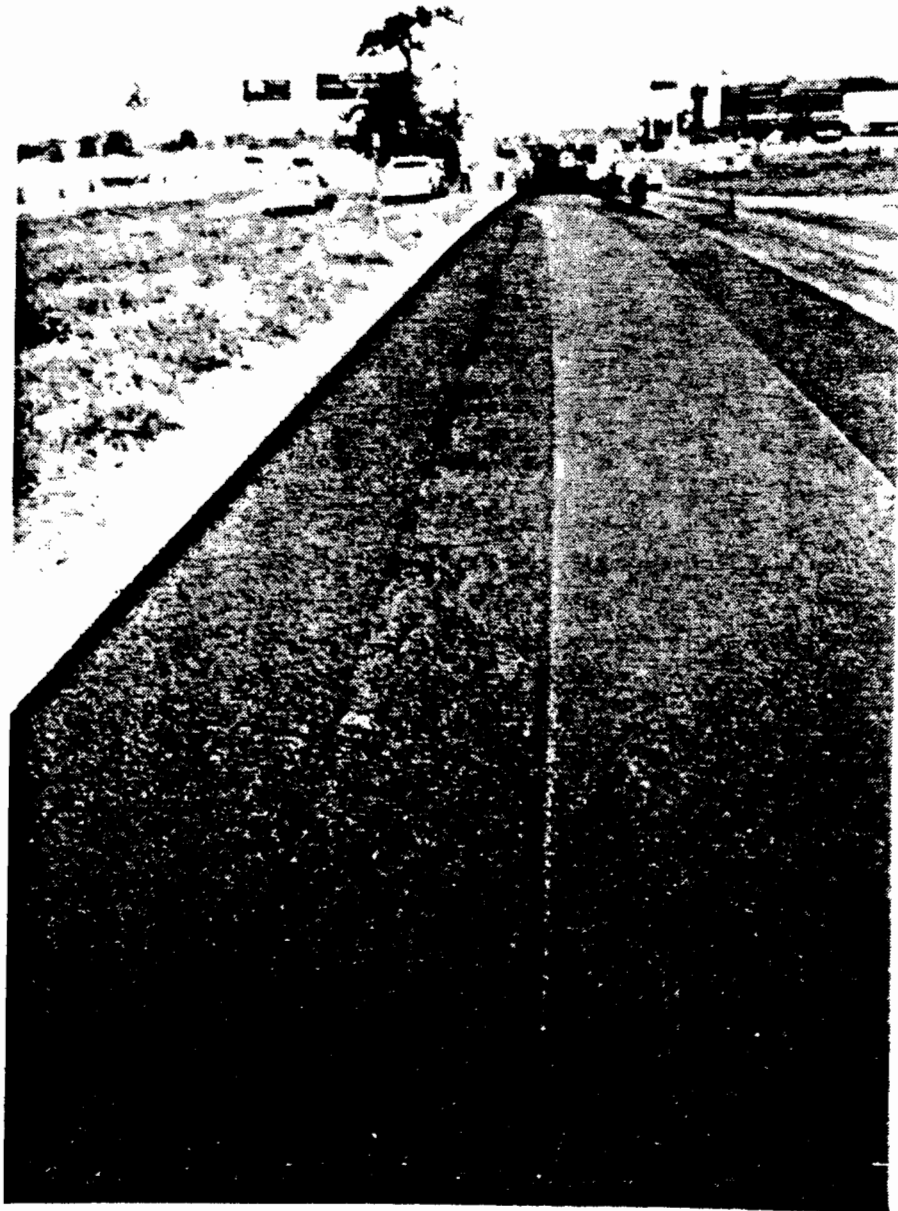


**Figure 40. Surface Shadows on SH 183 Frontage Roads, Paver Screed Forward.**

replicate section to section 3. This result may have been due to the fact that the paver speed was very slow for section 3a. Very faint surface shadows were visible in section 2 during laydown of the mix.

On the westbound service road, slight surface shadows were visible during the construction of the first three test sections--with the screed in the back position. The shadows could be seen even when the head of material in front of the screed was low--at the bottom of the paver augers. Surface shadows were visible in test section 15 at the time of construction. For this area, the paver screed was forward, and the level of mix in front of the screed was high. No shadows were seen in sections 14 and 13. When the paver screed was moved back for the placement of sections 24, 22, and 23, surface shadows were particularly visible in section 24 where the level of mix in the auger chamber was high (Figures 41 and 42). Less visible but still significant shadows were observed in sections 22 and even 23 where the head of material in front of the screed was at the middle of the auger shaft and at the bottom of the augers, respectively. As for the eastbound service road, the surface shadows were not visible after the mix had been compacted by the rollers.

After Construction The test sections on the SH 183 service roads have been inspected several times since construction. Surface shadows are essentially not visible in any of the test sections, even the ones that were built with the paver screed in the back position and with the head of material in front of the screed at the high level. This phenomenon may be due in part to the fact that surface shadows are often not visible except when the sun is very low in the sky and shining directly along the longitudinal axis of the roadway. Although surface shadows can usually be



**Figure 41. Surface Shadows on SH 183 Frontage Roads, Paver Screed Back.**



Figure 42. Surface Shadows on SH 183 Frontage Roads, Paver Screened Back.



observed when the pavement surface is wet, none of the inspections were conducted after a rainfall. The sections that contained the most visible surface shadows at the time of mix placement--directly behind the paver screed--did not appear to have surface shadows when inspected up to one and a half years after initial construction.

## **FM 1488 Test Section Construction**

### Test Section Variables

The second project to attempt to create surface shadows "on demand" was built in November 1989 with a different set of test variables than the SH 183 project. For this job, the screed was still placed in two different positions--forward or as close to the augers as possible and back--four inches farther away from the augers. Three levels of head of material in the auger chamber were also used--low, middle, and high or overloaded. For this test section, which used a straight Type D mix, the mix temperature was held constant and was not a variable. The paver speed was to be controlled at three different levels--40, 60, and 80 feet per minute.

With the screed in the forward position, two different paver speeds, approximately 80 and 60 feet per minute were used, each with three different levels of the head of material in front of the screed. With the screed in the back position, the three different levels of the head of material were used at a paver speed of approximately 60 feet per minute. For paver speeds of both 40 and 80 feet per minute, only the middle and the high levels of the head of material were employed to construct test sections. Replicate sections were constructed for the 40 foot per minute paver speed test sections with the screed in the back position.

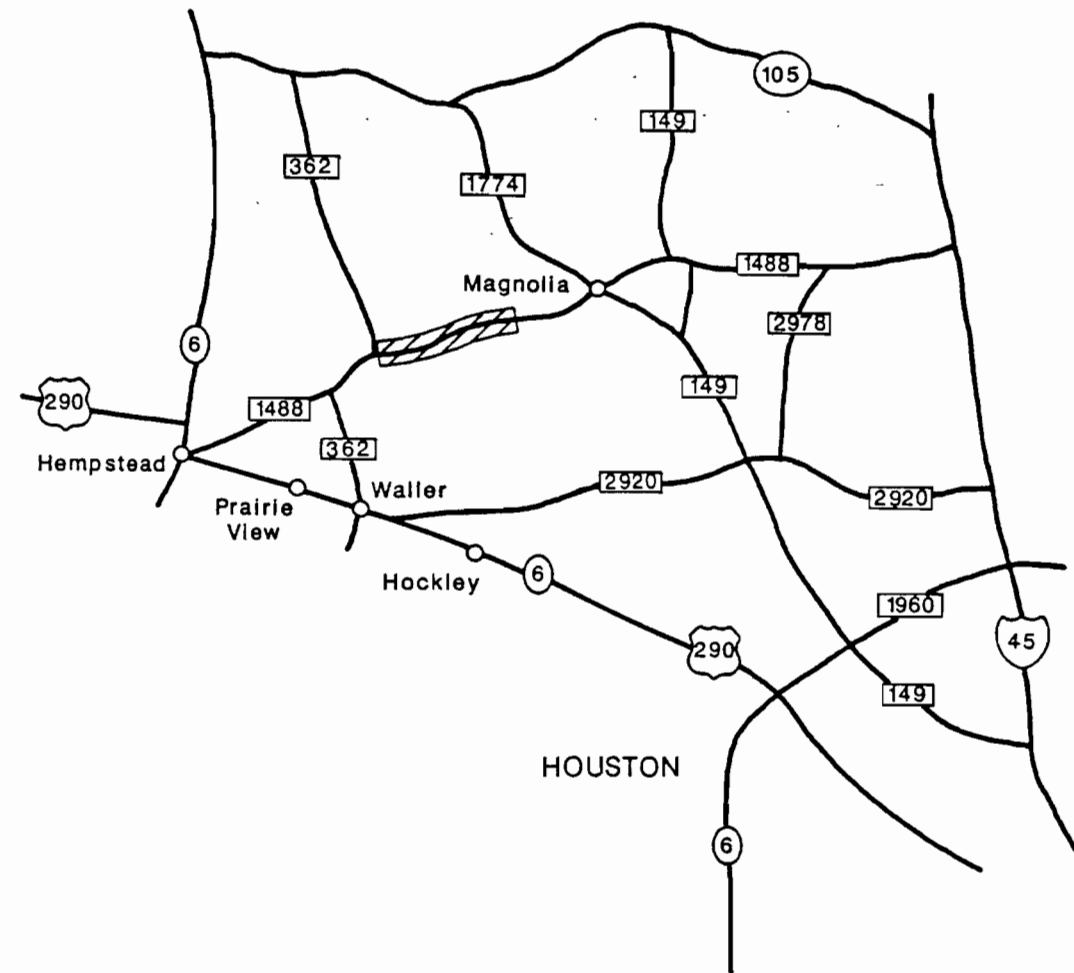
### Test Section Construction

Project location The second surface shadow test project was located approximately 45 miles northwest of Houston. The job was built on FM 1488 in Waller County, west of the town of Magnolia. The test sections in the eastbound lane begin approximately 1.65 miles east of the intersection of FM 362 North with FM 1488 and end (test section 6) about 2.73 miles east of the same intersection, as illustrated in Figure 43. In the westbound lane, test section 7 begins about 4.28 miles east of the junction of FM 362 North, and test section 15 ends approximately 5.19 miles east of the same point. For reference, Sheffield Road is located approximately 3.5 miles east of FM 362 North, and Rice Road intersects FM 1488 about 5.4 miles east of FM 362 North. The project is located in District 12 of the Texas SDHPT.

Personnel The mix on this project was placed by Duinick Bothers. The Quality Control officer for the contractor was Dallas Krepps. Personnel from both Barber-Greene and Blaw-Knox were also present during construction. Jack Farley, Vice President, Product Support; John Guzman, Regional Sales Manager; and Tom Dittmer, Regional Product Support Manager represented Barber-Greene. Stan Lamb, Field Service Representative, was on the project for Blaw-Knox.

Texas SDHPT personnel included Walter Torres, Assistant Construction Engineer; Steve Simmons, Supervising Resident Engineer; and Kathy Rust, Laboratory Supervisor. From the Texas Transportation Institute, the people on the job during mix placement included Mary Anne Rodriguez, Engineering Research Associate; and Bill Jones, Paving Consultant.

Pavement Cross-Section The overlay of the mainline pavement consisted of 1-1/2 inches of Type D surface course mix on top of 4 inches of asphalt



Location of FM 1488 Site

Figure 43. Location of Test Sections on FM 1488.

stabilized base course material. The shoulder pavement consisted of the same thickness of surface and asphalt stabilized base course mix built on top of 8 inches of new flexible base course material (Item 249). The average rate of surface course mix placement on 11/16/89 was 152.8 pounds per square yard. For the Type D mix placed on 11/17/89, the average rate of mix laydown was 163.6 pounds per square yard.

Mix Design The Type D mix did not contain any latex additive. The aggregate used in the mix consisted of 28% coarse aggregate from Delta Materials-Drock, 32% coarse aggregate from Parker Brothers-Drock, 18% screenings from Parker Brothers, and 22% natural sand from Montgomery Base-Montgomery. The asphalt cement incorporated in the mix was AC-20 from Exxon, and the asphalt content was 5.0 percent by weight of the aggregate. An antistrip additive, Permatrac Plus, was also added to the mix.

The surface shadow test sections were constructed on two different days. The average extracted aggregate gradations and asphalt contents during those two days are shown in Table 3 together with the specifications for the Type D mix and the job mix formula values proposed by the contractor at the time of initial mix design approval. In general, the extracted aggregate gradations are close to the job mix formula values. The average extracted asphalt content matched the required mix design value of 5.0%.

The mix temperatures on both days at the plant were very consistent, varying from 295°F to 305°F. At the laydown site, the mix temperature was somewhat more variable, ranging from 285°F to 300°F. The density of the mix on the roadway was 95.4% of lab density on 11/16/89 and 94.7% on the following day.

Equipment A Barber-Greene model 265 track paver, shown in Figures 44

Table 3. Mix Design for FM 1488.

Sieve Size	Texas SDHPT Specifications	JMF Combined Gradations	Average Extracted Gradations
-1/2	100	0.0	0
-3/8	85-100	7.3	7.9
3/8 - 4	21-53	36.2	37.8
4 - 10	11-32	16.8	16.5
+10	54-74	60.3	62.1
10 - 40	6-32	13.5	13.8
40 - 80	4-27	10.7	8.5
80 - 200	3-27	11.4	10.5
Pass 200	1-8	4.0	5.1
AC Content		5.0	5.0

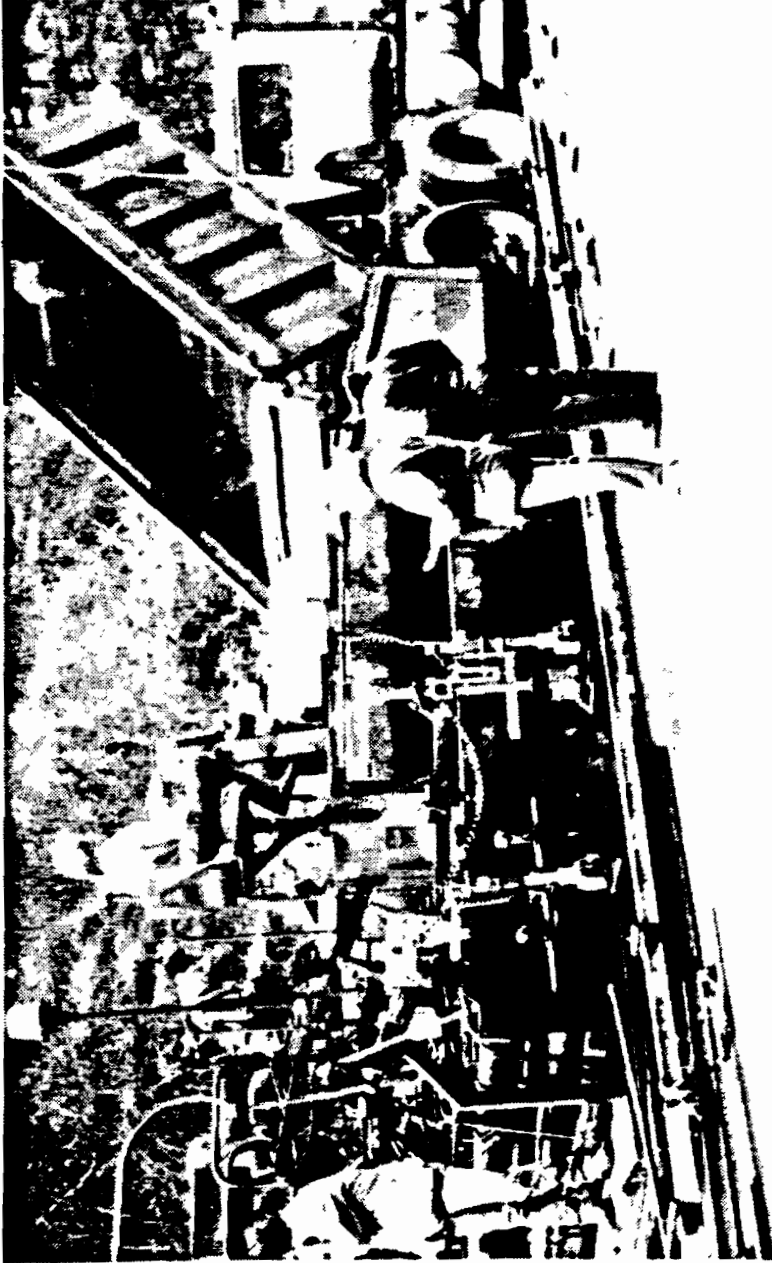


Figure 44. Barber-Greene SB 265 Paver on FM 1488.

and 45, was used to place the mix by Duininck Brothers. The paver was equipped with a hydraulically extendable screed. For grade control, a 30 foot long multifooteed mobile ski was attached to the paver (Figure 45).

Also attached to the mobile ski was a Blaw-Knox device which measured the movement of the ski in relation to the pivot point of the screed. The device consisted primarily of two sensors which rode on the mobile ski (in addition of the sensor used for normal grade control). One of the sensors was located in front of the pivot point of the screed and the second sensor was located behind the screed pivot point, as shown in Figure 46. This dual location for the sensors permitted changes in the angle of attack of the screed to be measured when a change was made in the head of material in front of the screed. The purpose of the Blaw-Knox device, then, was to determine what the reaction of the screed was to a change in the level of mix carried on the augers.

The contractor used a Dynapac CC 50 double drum vibratory roller in the breakdown position. Intermediate compaction was accomplished by a Dynapac CC 27 pneumatic tire roller. Finish rolling was completed by a Ferguson SP 266A double drum vibratory roller operated in the static mode.

Test Section Layout Figure 47 shows the layout for the test sections for FM 1488. Table 4 provides information on the station location of the various test sections. Six test sections were placed in the eastbound lane on 11/16/89. For all of these sections, the screed was located in the forward position. The head of material was increased from the low level to the middle level to the high level for the first three test areas (sections 1, 2, and 3, respectively). The paver speed for these sections was supposed to be approximately 80 feet per minute. The paver speed for the first

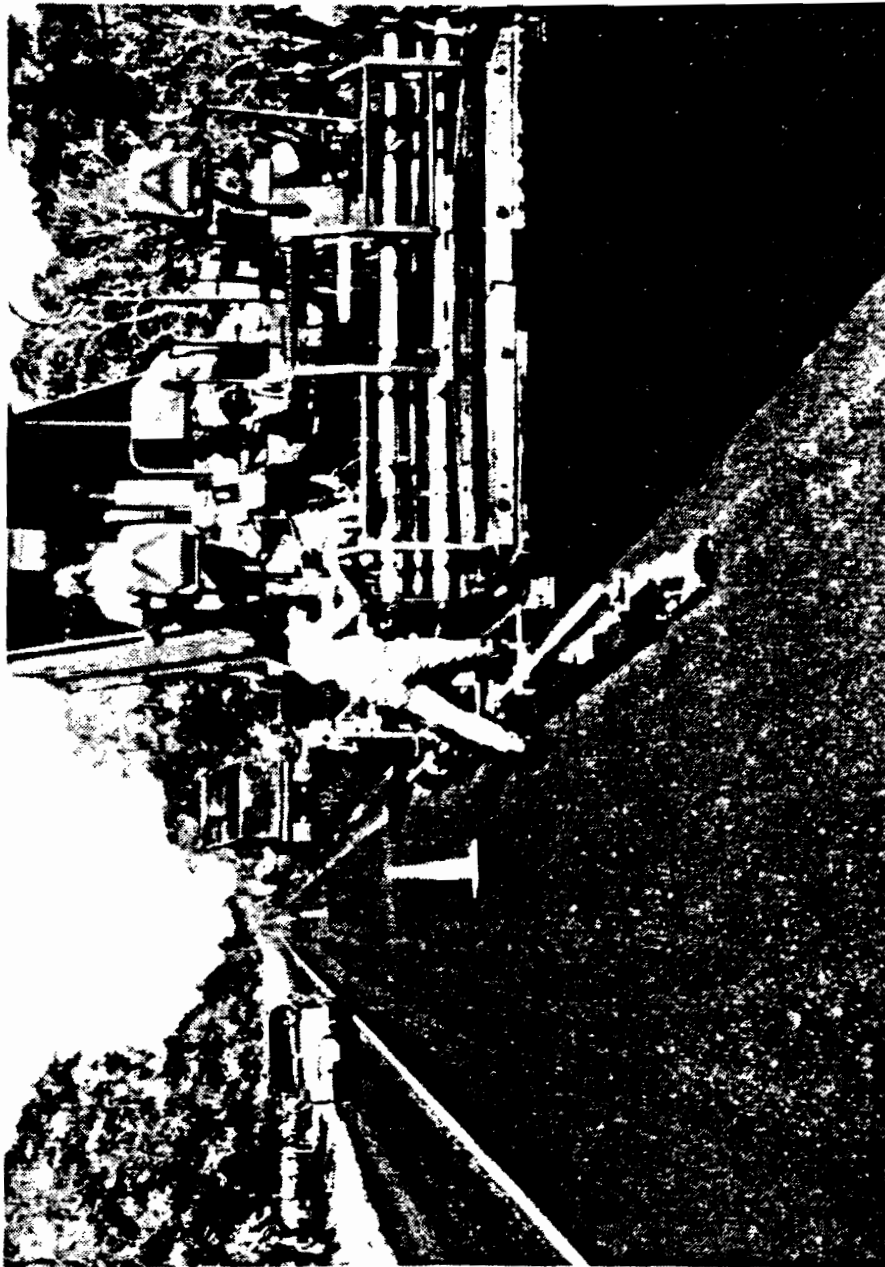


Figure 45. Mix Behind Barber-Greene SB 265 Paver on FM 1488.



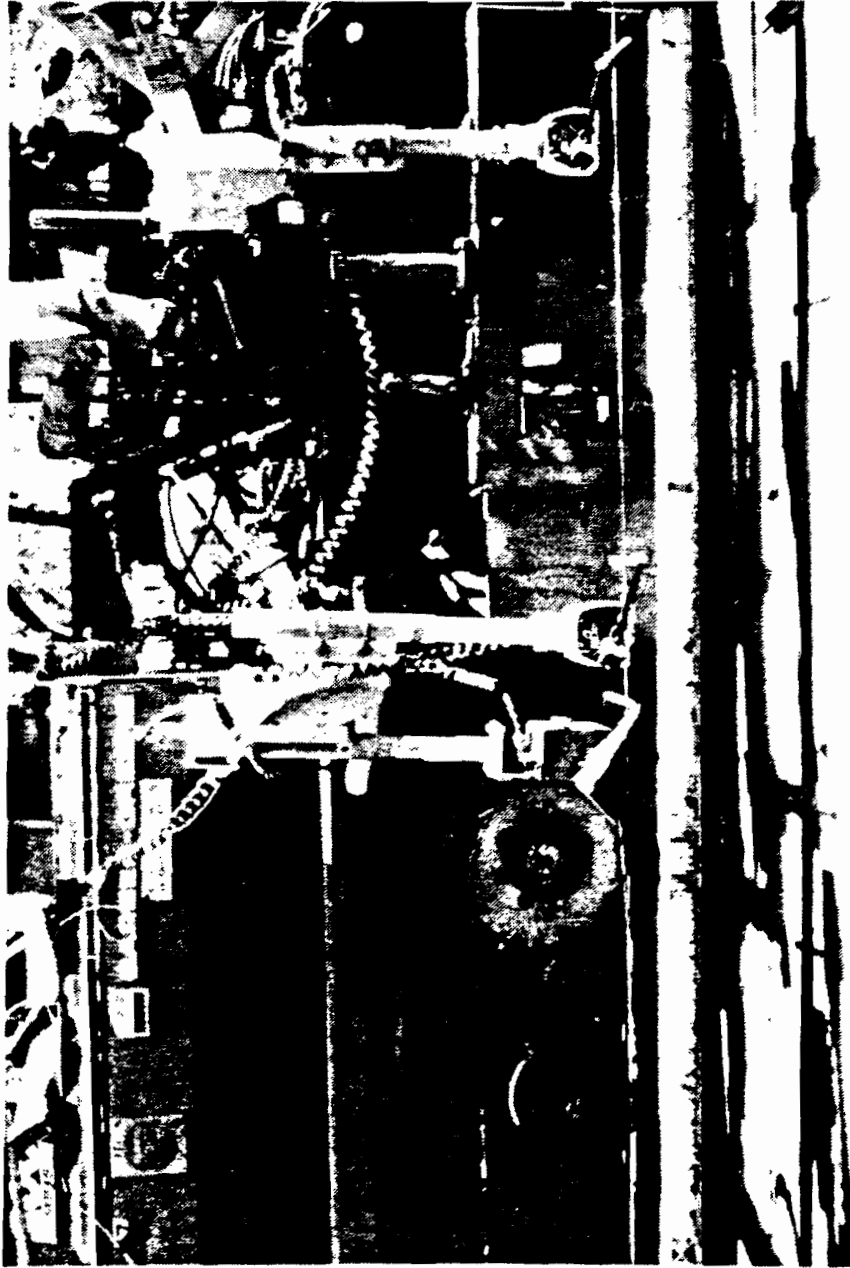
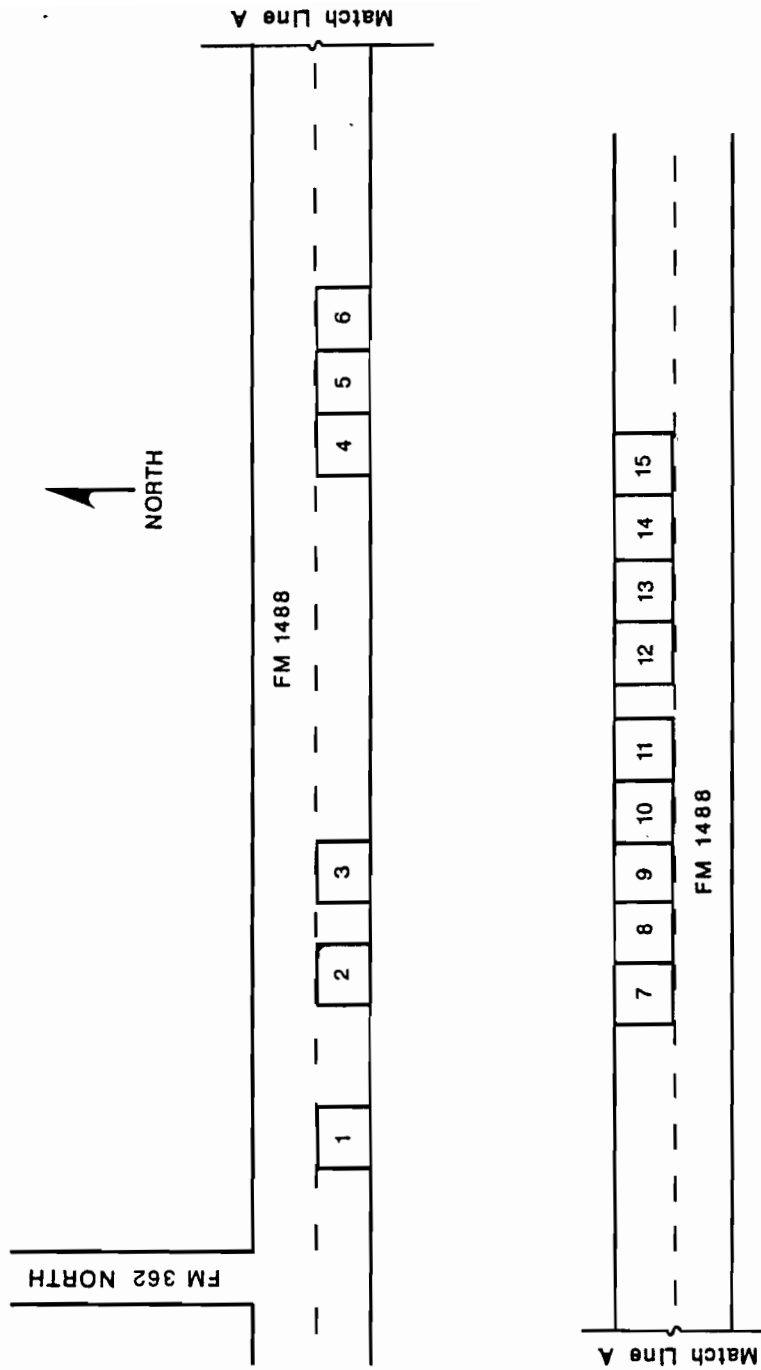


Figure 46. Normal Grade Control Sensor and Two Additional Blaw-Knox Screed Angle of Attack Sensors on Barber-Greene SB 265 Paver.



**FM 1488 TEST SECTIONS**

(TEST SECTIONS ARE 400 FEET LONG)

Not to Scale

Figure 47. Layout of Test Sections for FM 1488.

Table 4. Test Section Variables for FM 1488.

Section	Location		Screed Position	Material Height	Average Paver Speed ft/min	Average Mix Temperature °F
	Start Station	End Station				
1	87+00	91+00	forward	low	56.0	321
2	97+00	101+00	forward	middle	88.4	307
3	104+00	108+00	forward	high	74.2	301
4	132+00	136+00	forward	low	54.7	325
5	136+00	140+00	forward	middle	66.2	324
6	140+00	144+00	forward	high	66.9	299
7	226+00	230+00	back	low	59.8	303
8	230+00	234+00	back	middle	60.0	305
9	234+00	238+00	back	high	60.0	-
10	238+00	242+00	back	middle	38.8	313
11	242+00	246+00	back	high	41.0	298
12	258+00	262+00	back	middle	84.0	307
13	262+00	266+00	back	high	80.6	302
14	266+00	270+00	back	middle	41.5	308
15	270+00	274+00	back	high	39.5	307

section, however, was only 56 feet per minute. For the next three sections, a paver speed of about 60 feet per minute was used, with the head of material at all three levels--low, middle, and high. Mix temperature varied from a low of 299°F to high of 325°F for the six sections.

On the following day, nine different test sections were constructed. For all of these areas, the paver screed was in the back position--four inches farther away from the augers on the paver. Three different levels of mix were carried in the auger chamber--low, middle, and high. A low head of material was used only in section 7 since it was felt that the low level of mix in front of the screed would cause the least amount of movement of the screed. For sections 7, 8, and 9, the head of material was low, middle, and high, respectively. The paver speed was about 60 feet per minute for these sections. A paver speed of 40 feet per minute was used to construct test sections 10 and 11, with the head of material at the middle and the high level, respectively. For sections 12 and 13, the paver speed was increased to approximately 80 feet per minute using two different levels for the head of material--middle and high. Finally, the last two test sections, 14 and 15, were replicates of sections 10 and 11, however, with a paver speed was about 40 feet per minute and two different levels of mix were carried on the augers. The mix temperature for the nine sections constructed on 11/17/89 ranged from 298°F to 313°F.

### Observations

During Construction Observations were made of the mat behind the paver during the construction of the fifteen test sections. No surface shadows were seen in any of the test sections. Both TTI and Texas SDHPT personnel walked the roadway and looked at the mix behind the screed but no

discoloration or blemishes were observed in the pavement surface between the paver and the breakdown roller or after the compaction was completed.

After Construction The test sections on FM 1488 were observed several months after the construction was completed--in the spring of 1990. Surface shadows were present in all of the test sections, with the most significant shadows present in the westbound lane sections. The number and intensity of the surface shadows in the eastbound lane, (with the paver screed in the forward or front position), shown in Figure 48, are essentially similar throughout the six test sections. The shadows are faint enough to be visible only when the pavement surface is wet or the sun is very low on the horizon.

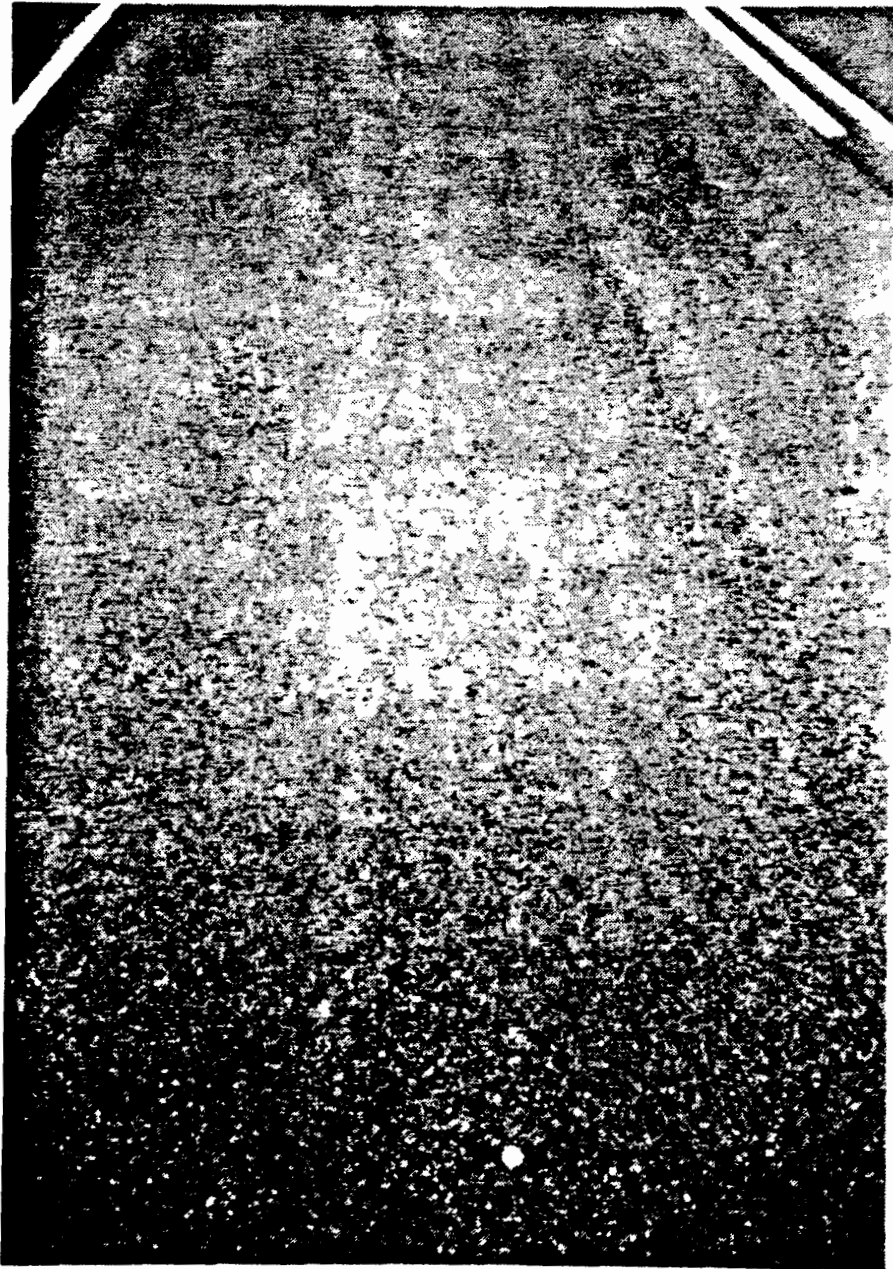
The shadows in the eastbound lane are not nearly as intense as the shadows in the westbound lane. For these latter nine sections, constructed with the screed in the back position, the shadows are easily visible, even in daylight, in all of the areas. Under wet pavement conditions, the surface of the roadway is covered with shadows, as seen in Figure 49. It is not possible, however, to differentiate visually between the intensity of the shadows in the different test sections.

Additional observations have been made of these test sections in the nine months following construction. Depending on the lighting conditions at the time of the inspection, the intensity of the shadows seems to have decreased with time and traffic, but the shadows are still visible, especially in the test sections in the westbound lane.

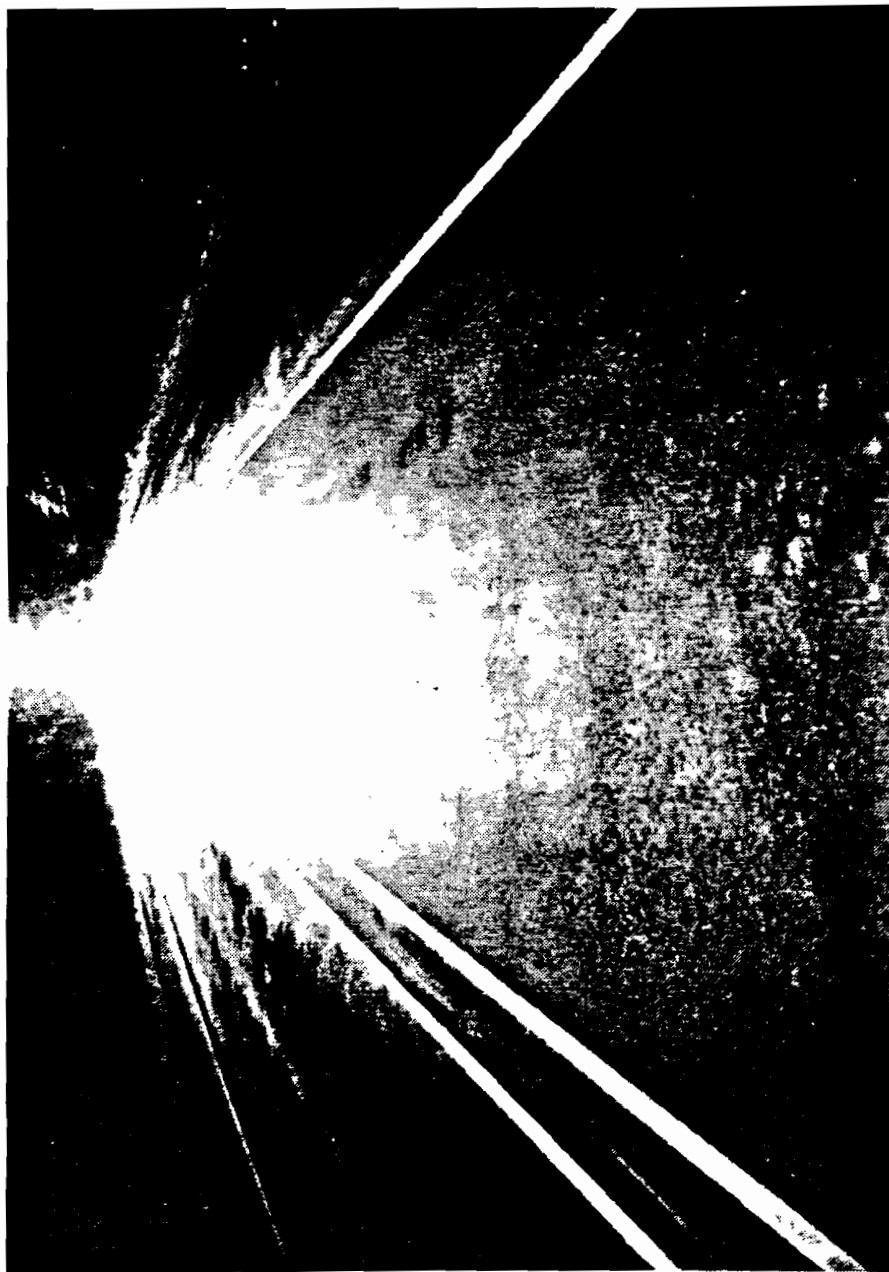
## **FM 2920 Test Section Construction**

### Test Section Variables

A third trial project was constructed in July 1990 on FM 2920. The



**Figure 48. Surface Shadows on FM 1488, Screed Forward.**



**Figure 49. Surface Shadows on FM 1488, Paver Screenshot Back.**





variables used on this set of test sections were similar to those employed on FM 1488 except that the effect of paver speed was not a primary factor. One major variable was the position of the paver screed. Two positions were used--forward, or the normal location for the screed in relation to the tow point of the screed with the tractor unit, and back--with the screed four inches farther away from the augers. Three levels of mix in front of the screed were again selected to control the head of material and thus the forces on the screed. Those three levels of mix were low--at the bottom of the augers, middle--at the center of the auger shaft, and high--with the augers almost covered with mix or overloaded.

The speed of the paver was essentially held constant at approximately 50 feet per minute except for two test sections: one where the screed was forward and the paver speed was slow and one where the screed was back and the paver speed was greater than normal. Replicate sections were constructed for most of the test areas to see if the intensity of the surface shadows could be successfully duplicated at different locations under similar paving conditions. The temperature of the Item 340, Type D mix, modified with a polymer type additive, was kept essentially constant.

A total of 15 test sections were constructed. Although the sections are numbered from one to sixteen, the results of test section number 6 were not included in the analysis due to a problem with the paver during the construction of that test section.

#### Test Section Construction

Project Location This series of surface shadow test sections was also located in District 12 of the Texas SDHPT. The project is in Harris County, approximately 42 miles northwest of Houston, just east of US 290 near the

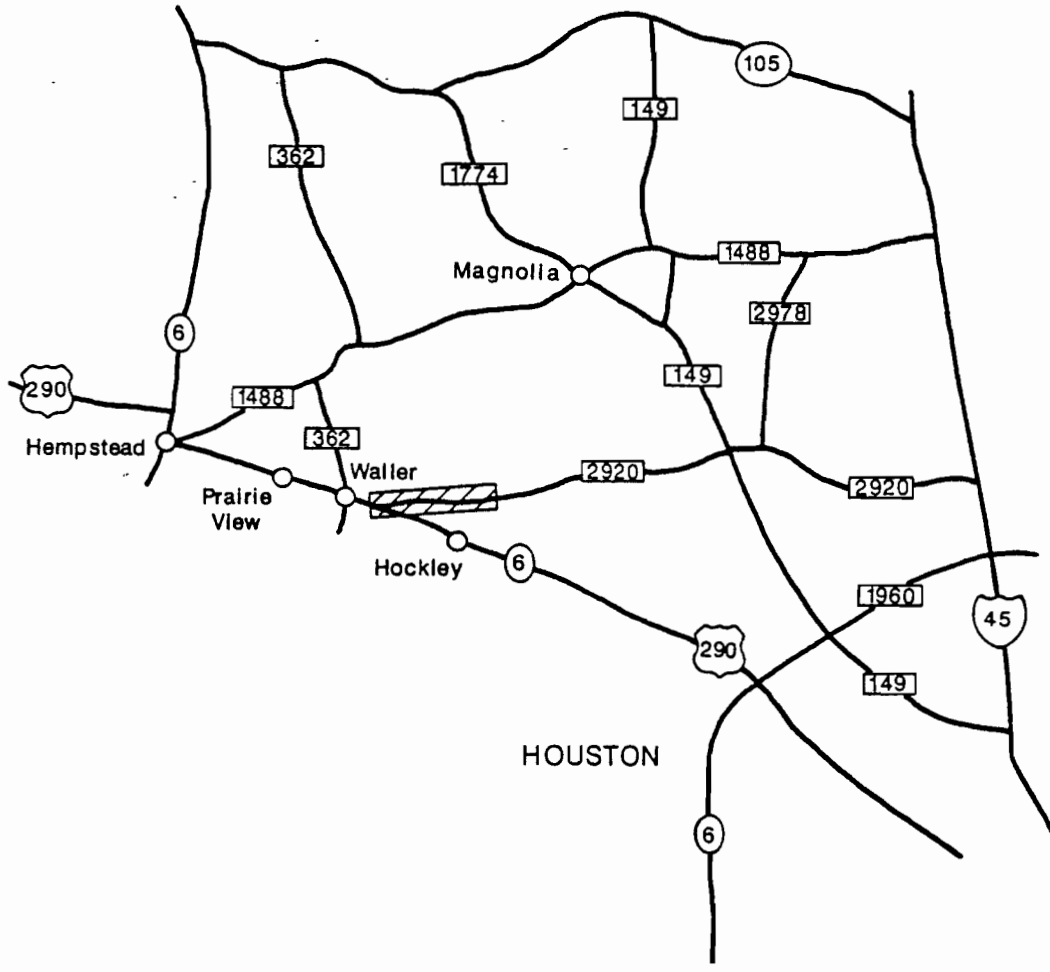
town of Waller. Figure 50 shows the location of the test sections. The test sections were placed in both the eastbound and westbound lanes of the two lane roadway, as seen in Figure 51. Test section number 1 begins in the eastbound lane approximately 0.44 miles east of the junction with US 290. Section 9, also in the eastbound lane, ends about 1.42 miles east of the same junction. In the westbound lane, which was paved from east to west similar to the eastbound lane, the first test section (number 10) is located 0.12 miles east of US 290. The last test section (number 16) ends approximately 0.66 miles east of the US 290 intersection.

#### Personnel

The contractor for the FM 2920 paving project was Jones G. Finke, Inc. The personnel involved in the job for the contractor were David Baker, Vice President and Otto Duesthofer, Project Supervisor. Stan Lamb, Field Service Representative, was on the job site for the Blaw-Knox Construction Equipment Company.

For the Texas SDHPT, the District 12 was represented by Walter Torres, Assistant Construction Engineer; Steve Simmons, Supervising Resident Engineer; Kathy Rust, Laboratory Supervisor; and Robert Farley, Project Manager. At the site for the Texas Transportation Institute were Mary Anne Rodriguez, Engineering Research Associate; and Jim Scherocman, Consulting Engineer.

Pavement Cross-Section The existing pavement consisted of a surface treatment over 2-1/4 inches of asphalt concrete surface course on top of 8 inches of asphalt stabilized base course. The overlay placed consisted of 1-1/2 inches of Item 340, Type D modified asphalt concrete mix. The mix was placed over both of the twelve foot wide travel lanes and the three foot



Location of FM 2920 Site

Figure 50. Location of Test Sections for FM 2920.

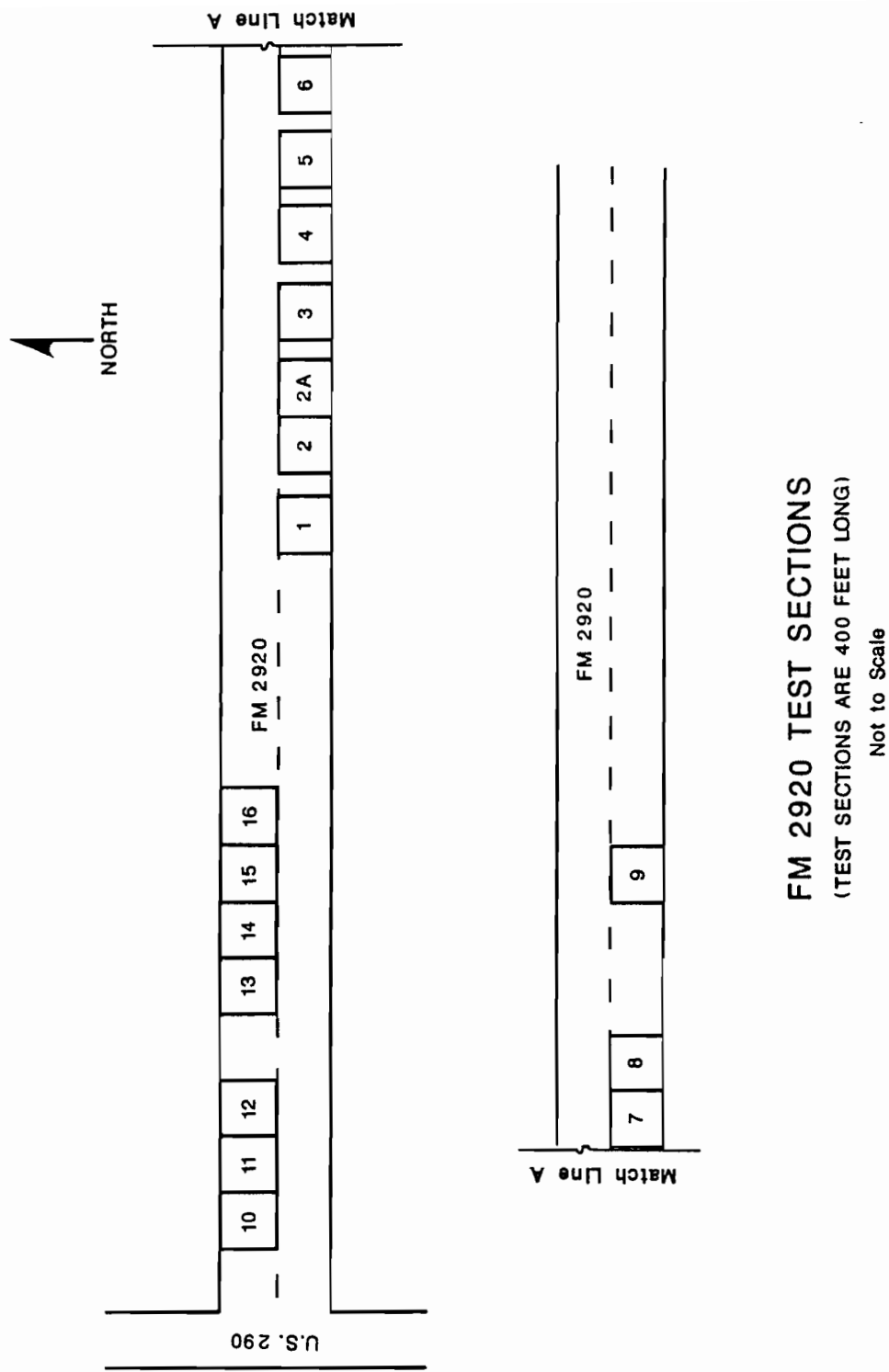


Figure 51. Layout of Test Sections for FM 2920.

wide outside shoulders in both directions.

Mix Design The aggregate incorporated into the Type D mix consisted on 22% coarse aggregate from Gifford Hill-Carter Pit, 14% coarse aggregate from Redland Worth (D rock), 23% coarse aggregate from Redland Worth (F rock), 19% screenings from Redland Worth, and 22% natural sand from Prairie View. The asphalt cement used was a polymer modified AC-30P binder supplied by Star Enterprises. The asphalt content was set at 5.1% by weight of aggregate. An antistripping agent, Permatac Plus, was also added to the asphalt cement binder.

The surface shadow test sections were all constructed on the same day. The specifications for the Type D mix as well as the job mix formula for the mix are shown in Table 5. Also given in that same table are the average extracted gradations for the mix for the day of paving. It can be seen that the extracted gradations are reasonably close to the job mix formula values. The average extracted asphalt content of 5.5%, however, is greater than the design asphalt content of 5.1%.

The mix temperature at the mix production plant averaged 305°F on the day that the sections were built. On the roadway, the mix temperatures ranged from a low of 275°F to a high of 305°F. The average density of the mix, compared to the laboratory density, was 97.9%.

Equipment A Blaw-Knox PF 200 rubber tire paver, equipped with a hydraulically extendable screed, was used to place the polymer modified Type D mix. The machine, shown in Figure 52, was equipped with a 30 foot long multifooteed mobile ski for use in controlling the grade and cross-slope of the mix being placed (Figure 53).

Also attached to the screed was a Blaw-Knox device which measured the

Table 5. Mix Design for FM 2920.

Sieve Size	Texas SDHPT Specifications	JMF Combined Gradations	Average Extracted Gradations
-1/2	100	0.0	0
-3/8	85-100	4.2	5.0
3/8 - 4	21-53	29.7	28.9
4 - 10	11-32	26.9	29.2
+10	54-74	60.8	63.1
10 - 40	6-32	10.8	8.3
40 - 80	4-27	8.2	6.9
80 - 200	3-27	16.8	16.6
Pass 200	1-8	3.3	4.7
AC Content		5.1	5.5

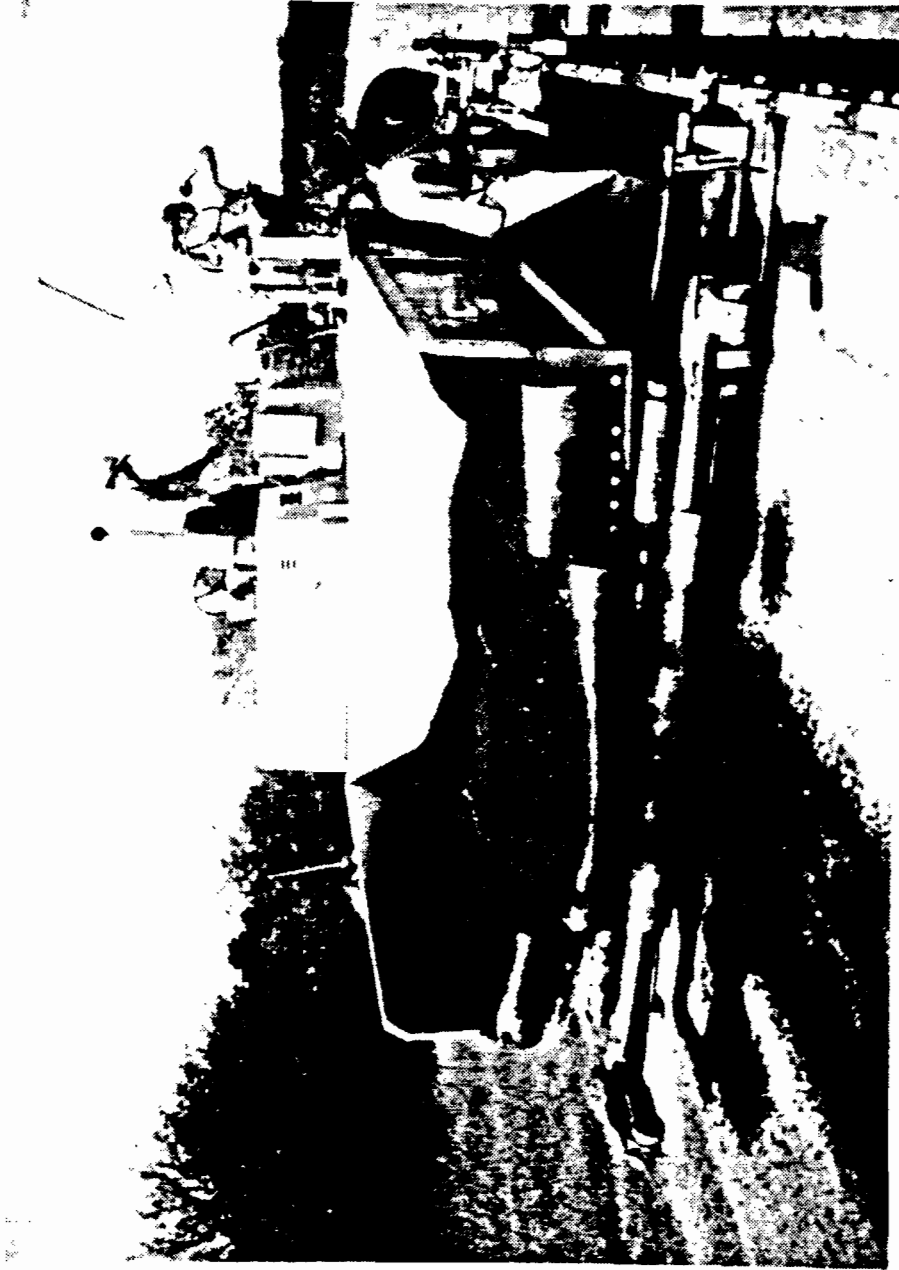


Figure 52. Blaw-Knox PF 200 Paver on FM 2920.



Figure 53. Grade Control Ski on Blaw-Knox PF 200 Paver on FM 2920.

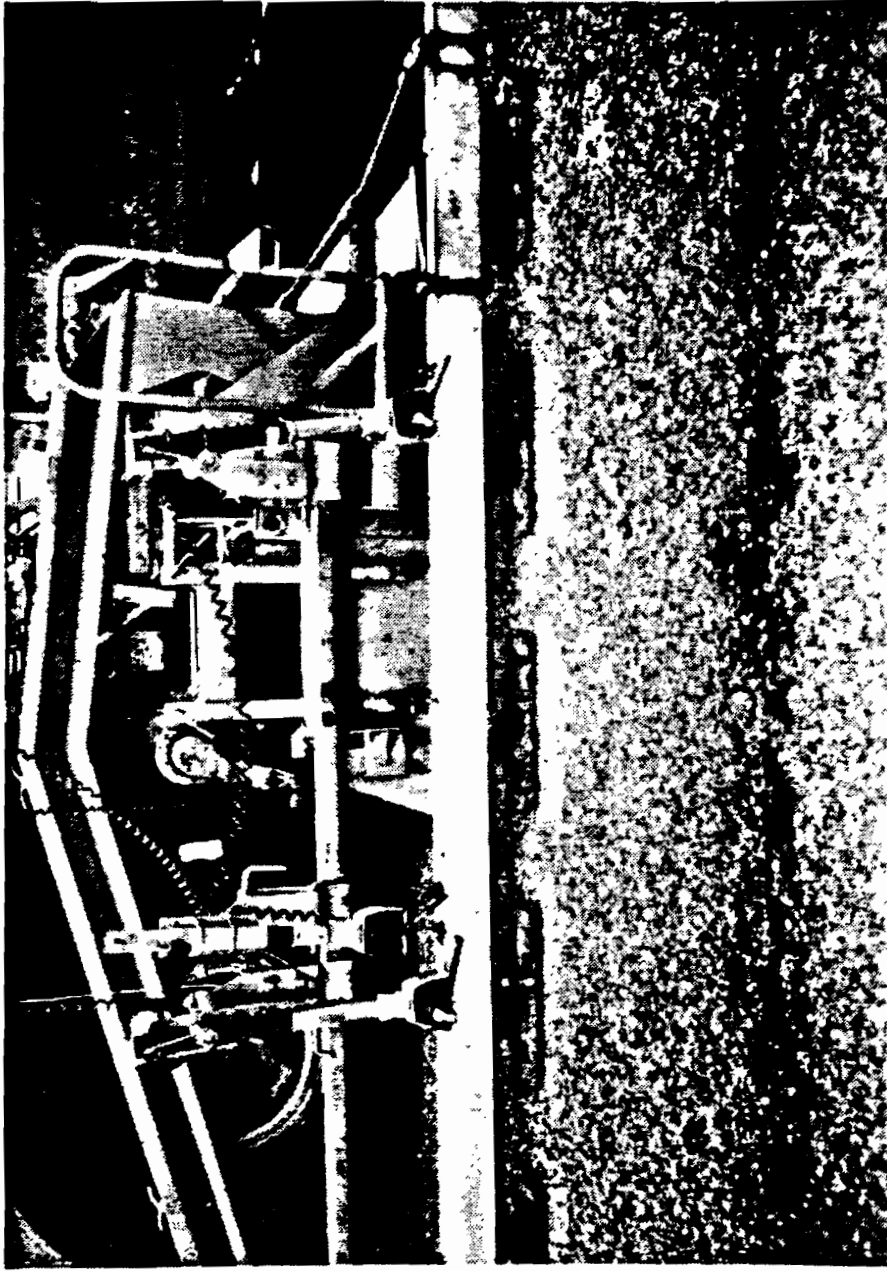


movement of the ski in relation to the pivot point of the screed. This equipment was the same equipment that had been used on the Barber-Greene paver on the FM 1488 test sections. The device, shown in Figure 54, consisted on two additional sensors which rode on the mobile ski (in addition to the normal sensor used for grade control). One of the sensors was located in front of the pivot point of the screed and the second sensor was located behind the screed pivot point. This dual location provided the opportunity to measure the reaction of the screed (changes in the angle of attack) to changes in the forces acting on the screed--head of material and paver speed, primarily.

The mix was initially compacted by a Raygo Ranger double drum, articulated, vibratory roller. The intermediate and finish roller was a Dynapac CC 27 pneumatic tire machine. No static steel wheel roller was used.

Test Section Layout Table 6 provides information as to the relative location of the fifteen test sections constructed on the FM 2920 project. All of the sections were constructed on 7/19/90. The first seven sections were built in the eastbound lane with the paver screed in the front or forward position--normal paving mode. The last section in this lane as well as all of the seven test sections constructed in the westbound lane were built with the paver screed moved to the back position--four inches farther away from the augers.

Test section 1 was built with the paver running at normal speed (for this contractor on this project, 65 feet per minute). The head of material was kept at the center of the auger shaft--in the middle position of the mix height. The head of material was varied for the next six sections--2



**Figure 54. Normal Grade Control Sensor and Two Additional Blaw-Knox Screed Angle of Attack Sensors on Blaw-Knox PF 200 Paver.**

Table 6. Test Section Variables for FM 2920.

Section	Location		Screed Position	Material Height	Average Paver Speed ft/min	Average Mix Temperature °F
	Start Station	End Station				
1	934+00	930+00	forward	middle	65.5	290
2	929+00	926+00	forward	low	58.0	295
2a	926+00	922+00	forward	low	50.3	290
3	921+00	917+00	forward	high	48.0	305
4	916+00	912+00	forward	middle	47.0	300
5	911+00	907+00	forward	low	47.4	298
7	899+00	894+00	forward	high	52.9	-
8	894+00	891+00	forward	high	14.0	300
9	883+00	879+00	back	middle	59.3	295
10	951+00	947+00	back	low	50.7	275
11	947+00	943+00	back	middle	46.2	298
12	943+00	939+00	back	high	45.0	285
13	938+00	934+00	back	low	42.4	285
14	934+00	930+00	back	middle	43.4	278
15	930+00	926+00	back	high	41.4	285
16	926+00	922+00	back	high	77.5	275

through 7 (except that section 6 was not constructed). Three different levels of mix were used: low, middle, and high. Paver speed was kept relatively constant, ranging from 47 to 58 feet per minute. Section 8 was built with the screed in the forward position and the mix at the top of the augers (high level), but the paver was run at a speed of only 14 feet per minute.

After the completion of section 8, the paver screed was moved to the back position by sliding the screed backward on the tow arm. Section 9 was then constructed in the eastbound lane with the screed in the rear position, the head of mix at the center of the paver shaft (middle level) and a paver speed of 59 feet per minute. At this point in time, just after mid-day, the contractor needed to cease paving in the eastbound lane and move back to the start of the paving in order to bring both lanes up to the same end point at the end of the day. Thus, the remaining test sections were constructed in the westbound lane with the paver moving in the eastbound direction.

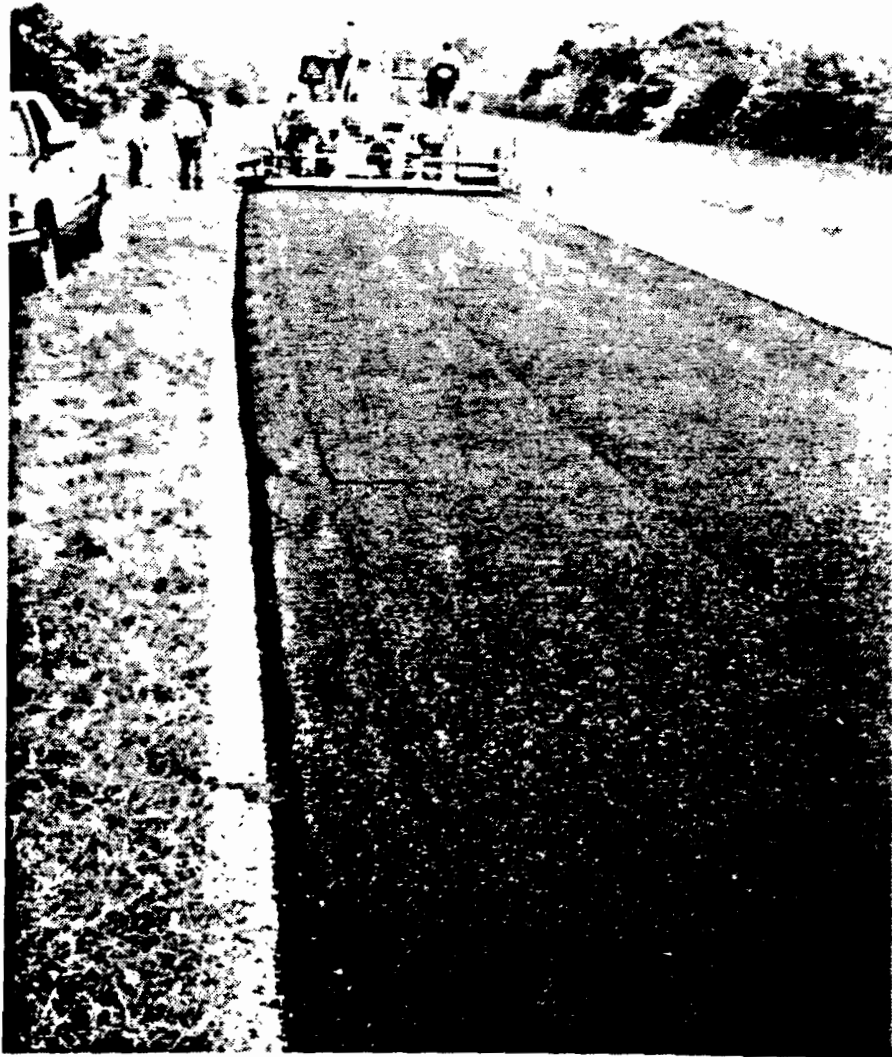
All of the seven sections placed in the westbound lane were done with the paver screed in the back position. Three different levels of mix in the auger chamber were employed--low, middle, and high. For the first six sections (numbers 10 through 15), the paver speed was kept relatively constant at about 45 feet per minute (the target speed was 50 feet per minute). For the last section, number 16, the paver speed was increased to 77 feet per minute to determine the effect of the greater speed on the intensity of the surface shadows. For this latter test section, the head of material in front of the screed was kept at the high level.

### Observations

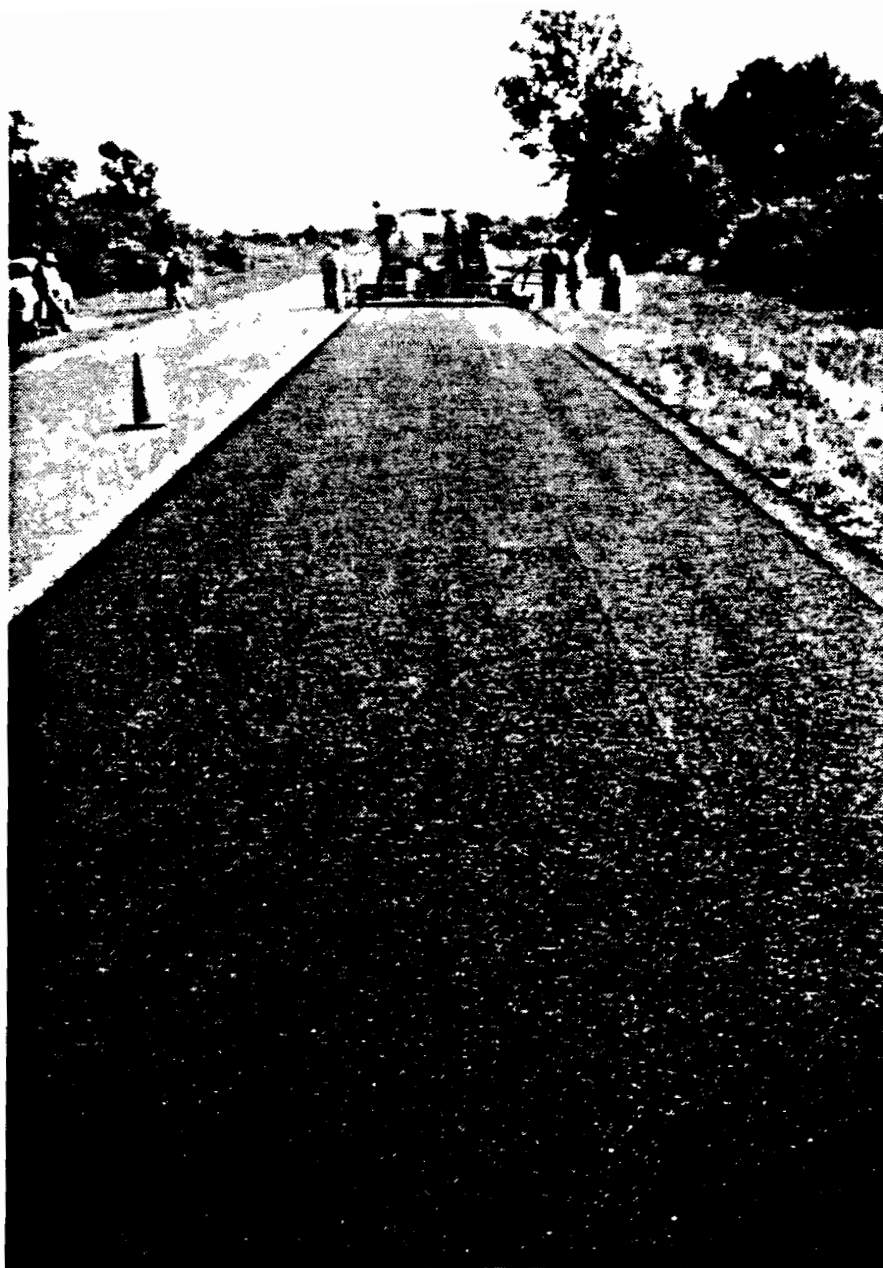
During Construction An inspection was made of the condition of the

asphalt concrete mat at the time it was placed in the various test sections by the Blaw-Knox PF 200 paver. Surface shadows were observed in some of the sections, both with the screed in the forward position and with the screed in the back position, as shown in Figures 55, 56, and 57. In general, the intensity of the shadows appeared to be greater when the head of material in the auger chamber was at the high level, with the augers overloaded with the asphalt concrete mix. Further, the intensity of the shadows seemed to be greater with the screed in the back position--with more mix in the auger chamber.

After Construction Only one inspection has been made of the test sections on FM 2920 since the time of mix placement. That inspection, early in 1991, did not show any shadows present on the surface of the pavement on any of the test sections. At the time of this inspection, however, the sun was relatively high in the sky and the pavement surface was dry. Under these lighting and environmental conditions, surface shadows often are not visible even though the shadows may be very visible under conditions of low light (the sun on the horizon) and a damp pavement surface.



**Figure 55. Surface Shadows on FM 2920 Paver Screed Forward.**



**Figure 56. Surface Shadows on FM 2920, Screed Back.**



**Figure 57. Surface Shadows on FM 2920, Paver Screed Back.**



## **ROUGHNESS MEASUREMENTS**

Two different types of roughness measurements were made on the surface shadow test section projects. On all three of the jobs, the profile measurement of each of the test sections was determined by a response-type profilometer owned by the Texas SDHPT. The description of this equipment and its operation are given below. In addition, on two of the projects--FM 1488 and FM 2920, a second method, developed by the Blaw-Knox Construction Equipment Company, was employed to measure the reaction of the paver screed to changes in the forces acting on the screed. The measurements made with both devices were used to rank the roughness of each test section on each of the projects. A comparison was then made between the rankings for the two different methods for the last two of the projects.

The purpose of the roughness measurements was to determine if the variables that were used on each job to control the operation of the paver had any affect on the amount of roughness obtained in relation to the movement of the paver screed or the profile measurement of the compacted pavement surface.

### **Profilometer Measurements**

#### **International Roughness Index**

Road roughness is a major factor in determining the ride quality and overall condition of a pavement. Primarily, three scales of road roughness have been used in major studies of road deterioration and road user costs: 1) the Bump Integrator Trailer of the Transport and Road Research Laboratory; 2) the Quarter-Car Index; and 3) the Serviceability Index [12,13]. The Bump Integrator, expressed in units of mm/km, was used in studies conducted in Kenya, the Caribbean and India. The Quarter-Car Index

was used in a study conducted in Brazil; it is expressed in units of counts/km. In North America, Serviceability Index (established during the AASHO Road Test) has been used as a measure of road roughness and riding comfort. Many roughness measures are used worldwide. Most measures are produced from response-type measuring systems mounted in a passenger car or on a trailer. Generally, the relative axle-body displacement of the rear axle is measured. Examples of these roughness measuring methods include the Bump Integrator, Mays Ride Meter, and Cox Meter.

In 1982 the World Bank set up the International Road Roughness Experiment in order to develop a common quantitative basis with which to relate the major roughness scales to one another [14]. This experiment resulted in the development of the International Roughness Index (IRI). The International Roughness Index is a profile-related index used as a reference scale for all profilometric and response-type systems that measure road roughness.

The International Roughness Index determines the longitudinal surface profile of the road in a wheeltrack. This profile represents the vibrations induced in a typical passenger car by road roughness. The International Roughness Index is defined as the ratio of the accumulated suspension motion to the distance traveled by a standard quarter-car traveling at a speed of 80 km/h. The International Roughness Index is computed from surface elevation data collected by either a mechanical profilometer or a topographical survey and is expressed in m/km.

As stated previously, the Serviceability Index (SI) function is used in North America (including Texas) as a measure of road roughness and riding comfort. The Serviceability Index function was established from panel

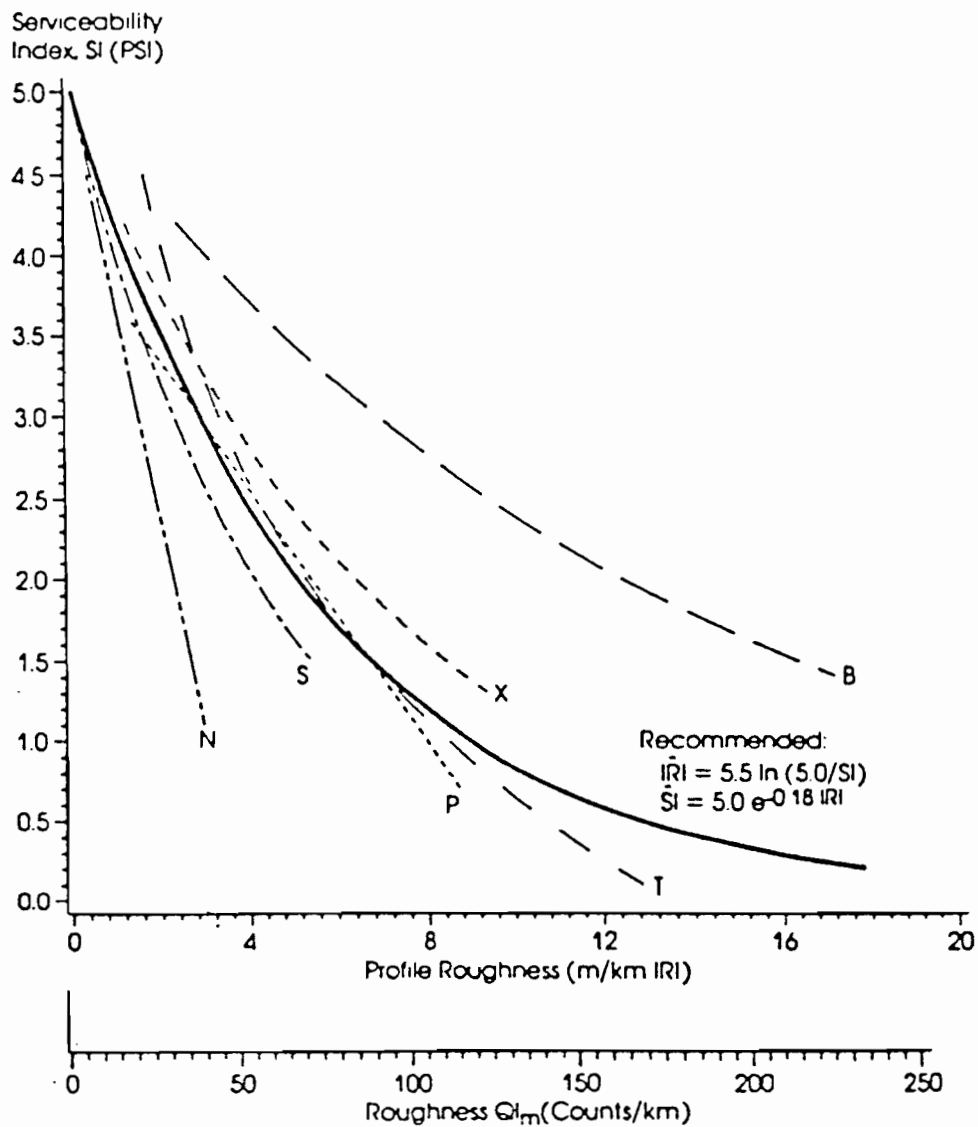
ratings of pavement serviceability at the AASHO Road Test. One component of the SI function defined roughness by a slope variance statistic. Some attempts have been made to calibrate vehicles to slope variance in order to relate roughness to serviceability. More commonly, agencies have been relating roughness to local Panel Ratings of Serviceability (PSR). Now as a result of the International Road Roughness Experiment, different measures of road roughness can be directly related by the IRI. Relationships between Serviceability Index, Quarter-Car Index, and IRI roughness scales are given in Figure 58. In addition, Figure 59 shows an IRI scale relationship for different pavement types and conditions.

This study used the International Roughness Index as a measure of road roughness. The IRI values for each test section were computed from profilometer readings taken with the 690D Surface Dynamics Profilometer, property of the Texas State Department of Highways and Public Transportation. A summary of the IRI values for the test sections can be found in the Appendix.

#### 690D Surface Dynamics Profilometer Measurements

Profilometer measurements were taken using the Texas SDHPT 690D Surface Dynamics Profilometer (SDP). The Surface Dynamics Profilometer has been used for several years by the Texas SDHPT for road profile measurements. The Surface Dynamics Profilometer is considered as the standard equipment for road roughness measurements in Texas. In addition, Serviceability Index roughness measurements, obtained from the SDP, are used for calibrating the Mays Ride Meter.

The Surface Dynamics Profilometer uses a non-contact probe to measure the road profile: the Selcom Laser Optocator. The basic operation of the



Legend: X - - - Texas      B ——— Brazil  
 N - - - NCHRP228      S - - - South Africa  
 P - - - PennDOT      T ——— TRDF

Figure 58. Approximate Relationships Between AASHO Serviceability Index, PSI, and the  $Q_{Im}$  and IRI Roughness Scales.

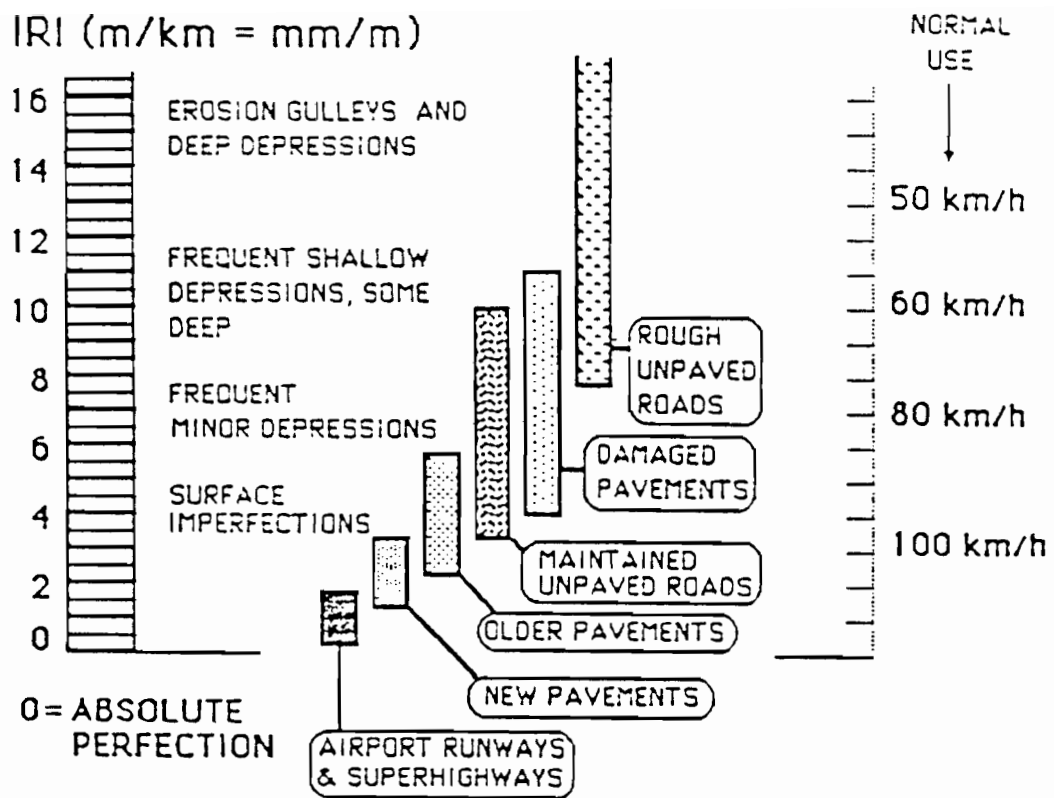


Figure 59. International Roughness Index Roughness Scale.

Selcom Optocator is shown in Figure 60. The laser light reflected by the road surface is focused on a detector, and the position of the light on the detector surface is used to calculate the distance from the detector to the road surface. A Compaq 286 computer receives and processes the readings from the Selcom Optocator to provide a profile for the left and right wheel paths of the roadway. The analysis of this data can be found in the following sections.

#### SH 183 Frontage Road Data

The profile measurements were made in both the right hand and the left hand wheel paths of each of the test sections. In addition, profile measurements were also made outside of the wheelpaths in each lane. Thus, for each test section, the profile was determined in four different longitudinal lines--outside the left wheelpath, in the left wheelpath, outside the right wheelpath, and in the right wheelpath.

The data presented in Table 7 shows the International Roughness Index ranking for the profile for each of the four longitudinal lines for each test section on the frontage roads on SH 183. In addition, the sixth column provides the average IRI index rating for all four of the profile readings for each section. For this project, from the data illustrated in this table, test section number 1 had the lowest IRI rating (was the smoothest) and section number 22 was the roughest.

The three smoothest sections were numbers 1, 24, and 12. The screed position for these three sections, as shown in Table 8, was forward, back, and back, respectively. For these same three sections, the head of material was middle, high, and high, respectively. For the three roughest sections, numbers 10a, 2, and 22, the screed location was back, forward, and back,

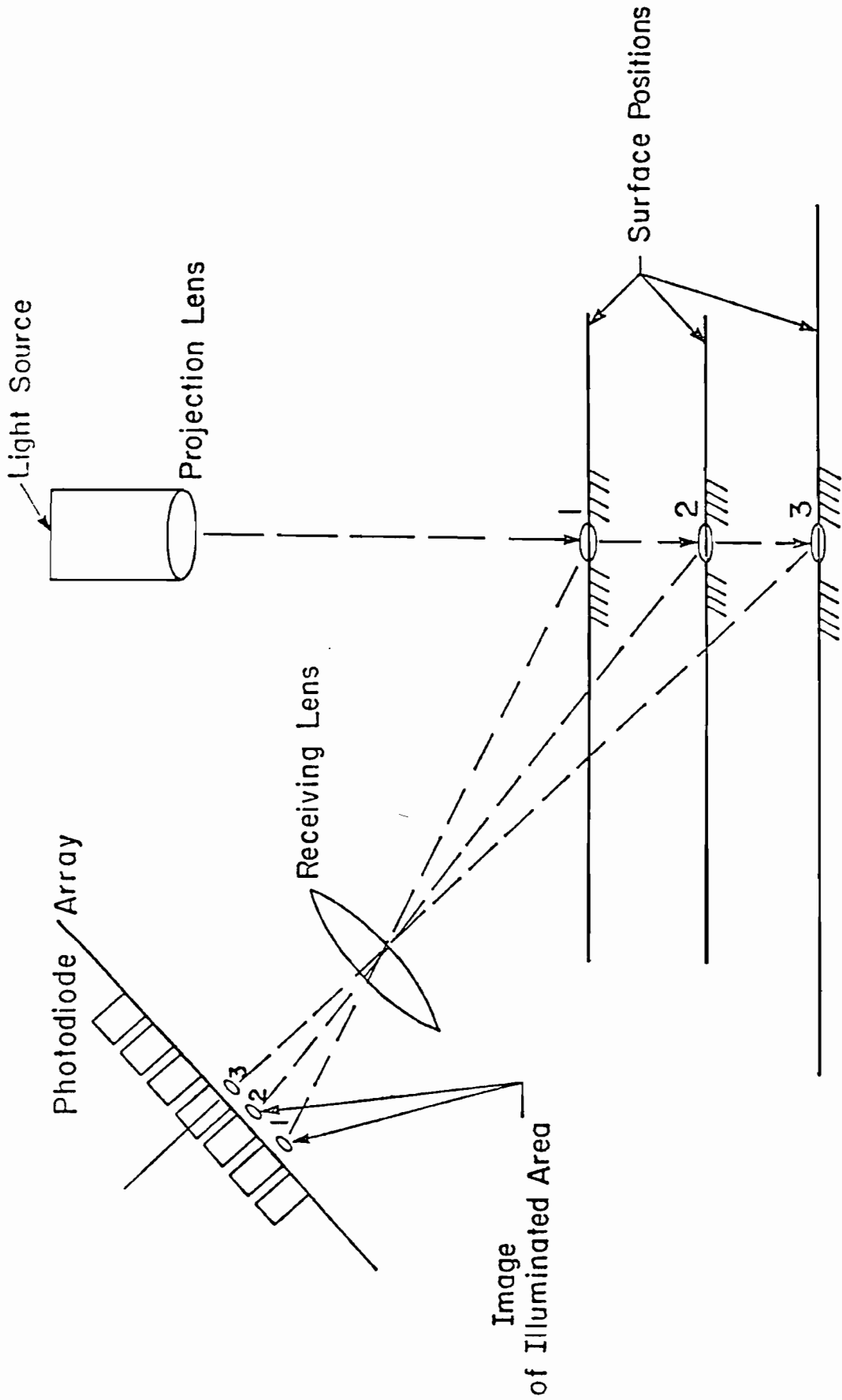


Figure 60. Operation of the Selcom Optocator.

Table 7. International Roughness Index Ranking for SH 183 Frontage Roads

Section	Eastbound Right Wheelpath	Eastbound Right Not Wheelpath	Eastbound Left Wheelpath	Eastbound Left Not Wheelpath	Average
2	15	14	14	14	14
3	10	9	2	1	4
1	3	1	3	2	1
3a	4	3	9	11	10
Section	Westbound Right Wheelpath	Westbound Right Not Wheelpath	Westbound Left Wheelpath	Westbound Left Not Wheelpath	Average
12	8	2	4	8	3
10	7	10	7	3	7
11	12	13	12	10	12
10a	13	12	13	12	13
10b	9	5	5	5	5
14	2	8	10	7	8
13	6	6	8	9	9
15	5	7	6	6	6
24	1	4	1	4	2
22	14	15	15	15	15
23	11	11	11	13	11



Table 8. Test Section Variables for SH 183 Frontage Roads.

IRI Rank	Section	Screed Position		Head of Material			Paver Speed ft/min
		Forward	Backward	Low	Middle	High	
1	1	X			X		36.0
2	24		X			X	50.0
3	12		X			X	52.0
4	3	X				X	38.0
5	10b		X		X		55.0
6	15	X				X	51.0
7	10		X		X		60.0
8	14	X		X			30.0
9	13	X			X		58.0
10	3a	X				X	15.0
11	23		X	X			42.0
12	11		X	X			36.0
13	10a		X		X		55.0
14	2	X		X			34.0
15	22		X		X		60.0

respectively, while the head of material was middle, low, and middle. From this data, there is little correlation between the location of the screed or the height of the head of material in front of the screed and the amount of roughness measured by the 690D Surface Dynamic Profilometer.

#### FM 1488 Data

The same type of information is presented in Table 9 for the fifteen test sections that were constructed on FM 1488. The smoothest three sections--the ones with the lowest IRI scores were numbers 14, 7, and 10. For these sections, the screed positions were all in the back location. The head of material in the auger chamber was middle, low and middle, respectively. For the roughest three sections (numbers 9, 5, and 6), the screed position was back, front, and front, respectively; the height of mix in front of the screed was high, middle, and high, respectively, as shown in Table 10.

For these test sections, there is little relationship between the position of the screed and the resulting pavement roughness. There does seem to be correlation, however, between the head of material and roughness--with the lesser amount of mix in the auger chamber related to a smoother ride and a greater amount of mix in the auger chamber associated with a rougher pavement surface.

#### FM 2920 Data

Sixteen test sections were built on FM 2920. The road profile was measured for the same four longitudinal lines in each test section as for the other two projects. The data obtained is shown in Table 11. The three smoothest sections were numbers 5, 4, and 7. For these three locations, the screed position, as shown in Table 12, was all forward. The head of

Table 9. International Roughness Index Ranking for FM 1488

Section	Eastbound Right Wheelpath	Eastbound Right Not Wheelpath	Eastbound Left Wheelpath	Eastbound Left Not Wheelpath	Average
1	8	9	6	6	8
2	7	10	5	4	6
3	9	6	7	10	9
4	4	8	2	8	4
5	14	14	14	14	14
6	15	15	15	15	15
Section	Westbound Right Wheelpath	Westbound Right Not Wheelpath	Westbound Left Wheelpath	Westbound Left Not Wheelpath	Average
7	3	2	4	5	2
8	6	7	3	11	7
9	13	13	12	7	13
10	2	4	9	2	3
11	12	11	13	13	11
12	5	5	10	9	10
13	10	3	8	3	5
14	1	1	1	1	1
15	11	12	11	12	12

Table 10. Test Section Variables for FM 1488.

IRI Rank	Section	Screed Position		Head of Material			Paver Speed ft/min
		Forward	Backward	Low	Middle	High	
1	14		X		X		41.5
2	7		X	X			59.8
3	10		X		X		38.8
4	4	X		X			54.7
5	13		X			X	80.6
6	2	X			X		88.4
7	8		X		X		60.0
8	1	X		X			56.0
9	3	X				X	74.2
10	12		X		X		84.0
11	11		X			X	41.0
12	15		X			X	39.5
13	9		X			X	60.0
14	5	X			X		66.2
15	6	X				X	66.9

Table 11. International Roughness Index Ranking for FM 2920

Section	Eastbound Right Wheelpath	Eastbound Right Not Wheelpath	Eastbound Left Wheelpath	Eastbound Left Not Wheelpath	Average
1	10	8	13	11	10
2	3	7	1	7	4
2a	8	4	5	4	6
3	9	10	7	8	8
4	6	6	2	2	2
5	1	3	3	1	1
7	4	1	9	3	3
8	14	14	8	9	12
9	5	16	4	12	9
Section	Westbound Left Wheelpath	Westbound Left Not Wheelpath	Westbound Left Wheelpath	Westbound Left Not Wheelpath	Average
10	16	12	15	15	15
11	11	15	11	10	13
12	12	9	10	13	11
13	13	13	16	16	16
14	15	11	14	14	14
15	7	2	12	5	7
16	2	5	6	6	5

Table 12. Test Section Variables for FM 2920.

IRI Rank	Section	Screed Position		Head of Material			Paver Speed ft/min
		Forward	Back	Low	Middle	High	
1	5	X		X			47.4
2	4	X		X			47.0
3	7	X				X	52.9
4	2	X		X			58.0
5	16		X			X	77.5
6	2a	X				X	51.4
7	15		X			X	41.4
8	3	X				X	48.0
9	9	X			X		65.5
10	1	X				X	14.0
11	12		X		X		46.2
12	8		X			X	45.0
13	11		X		X		59.3
14	14		X		X		43.4
15	10		X	X			42.4
16	13		X	X			50.7

material in the auger chamber was low, low, and high, respectively. For the three roughest test sections, numbers 14, 10, and 13, the screed was in the back position. The height of mix in front of the screed was center, low, and low, respectively.

From the data in the latter table, there appears to be some relationship between the position of the screed and IRI roughness value--the smoother pavements were generally built with the paver screed in the forward position. There does not seem to be any strong correlation between the head of material and roughness except a smoother pavement layer was constructed when the head of material was high.

### Discussion

In general, the data for the International Roughness Index measured on these three projects did not correlate well with either the screed position or the amount of mix in the auger chamber in front of the screed. This result is not unexpected since the profilometer readings were taken after the pavement layer had been compacted by the rollers. In addition, traffic was permitted to use each roadway for a period of time before the profile measurements were taken, particularly for the frontage roads on SH 183.

### **Blaw-Knox Screed Measurements**

#### Screed Sensor Device

The primary purpose of the Blaw-Knox roughness detection device was to measure very minute changes in the angle of attack of the paver screed as the forces acting on that screed changed. On both the FM.1488 project and the FM 2920 projects, the paver was equipped with a mobil ski to control the grade of the layer being placed on the inside (centerline) side of the machine. Each paver was also equipped with a pendulum type device to

control the cross-slope of the screed and thus the grade of the new pavement course on the outside (shoulder) side of the paver.

The grade on the inside of the paver was determined by a sensor which rode on the mobil ski device. Changes in the elevation of the existing pavement were detected by the sensor as the ski moved up and down over the existing surface. This data was input to the grade controls to keep the elevation of the tow point of the paver screed constant as the tractor unit traveled over the roadway. The basic operation of the automatic grade and slope controls was not altered by the use of the additional Blaw-Knox screed measuring equipment.

Two additional grade type sensors were mounted on the mobil ski, as shown in Figure 46. One of these sensors was placed just in front of the pivot point of the screed and measured the movement of the mobil reference, similar to the normal grade sensor. The data (electrical signal) from this sensor was printed out on a strip chart recorder that was located on the top of the paver. This setup provided information on the movement of the ski reference in regard to the movement of the screed. The second sensor was attached directly to the paver screed. It was used to measure the changes in the angle of attack of the screed as the forces on the screed changed. The data from this screed sensor was also printed out on a strip chart recorder.

#### FM 1488 Data

A visual, manual count was made of the peak roughness points for the strip chart recording for each test section. Examples of the strip chart recording can be found in the Appendix. A blanking band width of 5 mm was used, according to the instructions from Blaw-Knox. Only roughness peaks



that exceeded that minimum value were thus counted. For example, a "0" count was obtained for test section 9 because none of the roughness peaks exceeded the width of the blanking band (See Appendix). A considerably different pattern is seen, however, for test section 11 on FM 1488. Using the same blanking band width, this section contained 282 "counts" or roughness peaks greater than the width of the blanking band. While section 9 was extremely smooth--little change in the angle of attack of the screed, section 11 was extremely rough--many changes in the angle of attack of the screed.

Table 13 shows the screed movement data for all of the fifteen test sections on FM 1488. The data provided in the table lists the section number, the number of counts (peaks) in each section, and the ranking for each section in regards to screed movement. The two smoothest sections were numbers 7 and 9. For section 7, the screed was in the back position and the head of material was low in the auger chamber. For section 9, the screed was also in the back position but the head of material was high--the augers were overloaded. The two roughest sections were numbers 11 and 5. For section 11, the screed was in the back position and the head of material was high. For section 5, the screed was in the forward position while the head of material was at the middle--at the center of the auger shaft.

From the data gathered by the Blaw-Knox device, there does not appear to be any direct correlation between the position of the screed and the number of roughness counts determined by the screed sensor. Furthermore, there does not seem to be any direct correlation between the amount of asphalt concrete mix in the auger chamber (low, middle, or high) and the number of counts of roughness--changes in the angle of attack of the paver

Table 13. Blaw-Knox Screed Movement Counts for FM 1488.

Section	Counts	Count Rank
1	40	11
2	72	13
3	46	12
4	35	9
5	92	14
6	30	8
7	0	1
8	15	6
9	0	2
10	7	3
11	282	15
12	12	4
13	37	10
14	13	5
15	25	7

screed.

#### FM 2920 Data

The screed sensor data from the Blaw-Knox PF 200 paver used on FM 2920 is shown in Table 14. The strip chart developed on this project indicated that seven of the test sections had a "0" roughness count--none of the roughness peaks were greater than the width of the blanking band. The screed was in the forward position for four of the sections and in the back position for the other three sections. For the same seven "0" counts sections, the head of material in the auger chamber was low for three sections, middle for another three sections, and high for one of the sections. For the locations that have the least change in the angle of attack of the paver screed, there does not seem to be any relationship between the position of the screed or the head of material in front of the screed and the reaction of the screed.

The roughest two sections--the sections with the most changes in the angle of attack of the paver screed--were sections 13 (102 counts) and 3 (70 counts). For section 13, the screed was in the back position and the head of material was low. For section 3, the screed was in the forward position and the head of material in the auger chamber was high. Again, there does not appear to be any correlation between the position of the screed and/or the amount of mix in front of the screed and the number of changes in the angle of attack of the screed.

#### Discussion

It was hoped that a relationship would be found between the changes in the angle of attack of the paver screed and both the position of the screed as well as the amount of mix in the auger chamber--head of material in front

Table 14. Blaw-Knox Screed Movement Counts for FM 2920.

Section	Counts	Count Rank
1	0	1
2	33	13
2a	5	9
3	70	15
4	0	2
5	0	3
7	0	4
8	26	11
9	27	12
10	0	5
11	0	6
12	4	8
13	102	16
14	0	7
15	21	10
16	35	14

of the screed. Conventional wisdom would dictate that the screed should change angle of attack more often when it is in the back position--when more mix is being carried in the auger chamber. Furthermore, it is believed that the angle of attack of the screed should be more sensitive to a high head of mix in front of the screed. The more mix in the auger chamber, the greater the force on the screed, and the more movement (change in the angle of attack) of the screed with small changes in the amount of mix against the screed.

Conventional wisdom did not prove to be fact in the case of the measurement of the angle of attack of the screed on either the Barber-Greene paver used on FM 1488 or the Blaw-Knox paver employed on FM 2920. It is not known if this deficiency is due to the screed sensor not really measuring the changes in the angle of attack or if the sensor and strip chart system were not sensitive enough to measure the very minute changes in angle of attack that actually took place. No reason is known at this time why a better relationship was not obtained between the screed angle of attack, the screed position, and the head of material in front of the screed.

### **Comparison of Test Section Rankings**

A comparison was made between the rankings for the test sections using both the International Roughness Index values and the Blaw-Knox screed sensor numbers. This comparison was done for both the test sections on FM 1488 as well as for the sections on FM 2920. That comparison is presented below.

The IRI rankings and the Blaw-Knox rankings are compared in Table 14 for the fifteen test sections constructed on FM 1488. From this data, it can be seen that there is essentially no correlation between the rankings



for the two measurement methods. Although test section number 5 was ranked #14 by both methods and test section number 10 was ranked #3 by both methods, there was only slight correlation between the ranking of the other sections.

Table 15 shows the two sets of rankings for the set of sixteen test sections built on FM 2920. The two different methods--profilometer and Blaw-Knox--ranked section number 4 the same (rank = 2) and section number 8 the same (rank = 10). The ranking of the other fourteen test sections, however, is relatively random. There is a definite lack of correlation between the rankings of the test sections by the two different methods.

Table 15. FM 1488 and FM 2920 Roughness Ranking.

FM 1488			FM 2920		
Section	Blaw Knox Count By Section	IRI Roughness By Section	Section	Blaw Knox Count By Section	IRI Roughness By Section
1	11	8	1	1	7
2	13	6	2	13	13
3	12	9	2a	9	11
4	9	4	3	15	9
5	14	14	4	2	15
6	8	15	5	3	16
7	1	2	7	4	14
8	6	7	8	11	5
9	2	13	9	12	8
10	3	3	10	5	2
11	15	11	11	6	4
12	4	10	12	8	6
13	10	5	13	16	1
14	5	1	14	7	3
15	7	12	15	10	10
-	-	-	16	14	12



## CHAPTER 4

### SUMMARY

#### OCCURRENCE OF SURFACE SHADOWS

The results of the construction of the test sections on the three projects--SH 183 frontage roads, FM 1488, and FM 2920--were inconclusive in regard to determining an exact cause or causes for surface shadows. The shadows were seen during construction on two of the jobs--SH 183 and FM 2920. The shadows were not visible in the mix during laydown on the FM 1488. After construction, however, the surface shadows can not be seen on either the SH 183 or the FM 2920 jobs. The surface shadows, however, are readily seen on the pavement on FM 1488.

On both the SH 183 and the FM 2920 jobs, the surface shadows that could be seen behind the paver were most intense when the screed on the paver was in the back position. In addition, the shadows were also more visible when the head of material in the auger chamber was high--when the augers were overloaded. On both projects, the shadows were very faint or not seen when the screed was in the forward position except when the augers were overloaded--the head of material in front of the screed was high.

Further, on both the SH 183 and the FM 2920 projects, the shadows that were visible behind the paver before compaction were not present after the rollers had passed over the mix. The difference in color between the area of the shadow and the surrounding pavement, while noticeable before rolling, was not visible after the compaction process had been completed. In addition, the difference in texture that was present behind the screed before compaction was not longer seen once the rollers had passed over the surface.

The opposite occurrence happened on the FM 1488 project. At the time of laydown, no shadows could be seen behind the paver on any of the test sections, both before and after the pavement layer had been compacted by the rollers. After use by traffic for a period of time, however, the surface shadows could easily be seen on all of the test sections and on the pavement adjacent to the test sections.

The mix on each of the three projects was different. A latex modified asphalt concrete mix was placed on the frontage roads to SH 183. A standard, unmodified Type D mix was used on FM 1488. The mix laid on FM 2920 contained a polymer modified asphalt cement. Whether the type of mix used on the project had an affect on the presence or on the intensity of the surface shadows is unknown.

Since surface shadows are typically only visible when the sun is low on the horizon and in line with the longitudinal direction of the roadway or when the pavement is damp, it is possible that some surface shadows exist in both the SH 183 frontage roads and in FM 2920 roadway. The post-construction inspections of these two projects may not have been carried out under the most favorable conditions to observe the surface shadows, if indeed they are present.

#### **REDUCTION OF SURFACE SHADOWS**

As a result of the information gained during this research effort, the following comments can be made as ways to possibly reduce the occurrence of shadows on the surface of an asphalt concrete pavement layer.

a. Head of Material Keep the head of material in the auger chamber near the center of the auger shaft. Do not overload the augers.

b. Position of the Screed Keep the screed in the forward position--as close to the augers as possible.

c. Paver Speed Keep the paver speed constant. Although the speed of the paver probably does not affect the occurrence of surface shadows, speed may have some affect on the spacing of the shadows, with the faster paver speed causing the shadows to be somewhat farther apart.

d. Height of the Tow Point Raising the height of the tow point of the paver screed will cause the screed to ride on its nose and may reduce surface shadows to some degree. (Allowing the screed to ride on its nose, however, can cause other problems such as non-uniform mat texture, excessive wear of the screed plate, and reduced compactive effort by the screed.)

e. Location of the Pre-Strikeoff If the pre-strikeoff on the screed is set too high, the screed will also ride on its nose. This setup may reduce the intensity of the shadows.

f. Height of the Augers If the vertical position of the augers can be changed on the paver, the augers should be raised (the distance from the ground should be increased) to reduce the chance of overloading the augers and increasing the head of material in front of the screed.

g. Condition of the Screed A worn screed plate should be replaced. A worn plate increases the opportunity for the fines in the asphalt concrete mix to cling to the screed and thus causes surface shadows.

h. Mix Design Shadows are more visible on surface courses that contain more fine aggregate. Coarse graded surfaces or open graded asphalt concrete mixtures normally do not exhibit surface shadows. If the presence of surface shadows is aesthetically unacceptable, the amount of coarse aggregate in the mix can be increased and the amount of fines in the mix

(amount of material passing the No. 200 sieve) can be decreased.

i. Mix Temperature In general, the hotter the mix and the less viscous the asphalt cement material (either unmodified or modified), the less tendency for fines to build up on the paver screed.

#### RECOMMENDATIONS FOR FUTURE RESEARCH

In some cases, this research effort produced more questions than it answered. On each of the three projects used in this investigation, the construction of the surface shadow test sections was incidental to the normal paving work on the job. The sections were built only through the cooperation of the contractor and the state district personnel. A lack of control, however, existed over some of the primary variables that may have had a significant affect on the ability to cause the shadows.

It is suggested that two additional paving projects be selected to attempt to create surface shadows "on demand". For both of these jobs, it would be necessary to have additional personnel on the project during construction to assure that the mix temperature at the plant is at the desired level and that the temperature remains as constant as possible. Further, closer control of the paver speed and the rate of feed of the mix through the paver would be necessary. This operation would require some education of the paver operator before the test section construction began.

For the three test section projects, the services of personnel and equipment from both the Barber-Greene Company and the Blaw-Knox Construction Equipment Company was donated by the two firms. Some funds need to be set up in any future research contract to reimburse these companies for some of their out-of-pocket costs. This reimbursement would help assure that these

personnel maintain an interest in the research study and make their expertise available both at the planning stages for the jobs as well as during the actual mix placement.

It is also recommended that a seminar be held with a limited number of people to review the results of this investigation and to make suggestions as to the variables to be controlled for any future test section construction. In particular, it should be determined if there is a method available to measure the surface texture of the surface shadow if it is visible behind the paver before compaction of the mix by the rollers. In addition, it would be desirable to determine if it is possible to measure any roughness and/or surface texture differences in the area of the shadows when they are visible after the roadway has been under traffic for a period of time.

Although the objective of this research project was to be able to reduce or eliminate the occurrence of surface shadows by understanding the factors that contribute to the cause of those shadows, that objective was not fully accomplished. The surface shadows were not able to be created completely "on demand". To be able to eliminate surface shadows, one must know how to cause them. Thus, it is recommended that two additional field paving projects be selected in an attempt to better isolate the factors that contribute to the occurrence of surface shadows.



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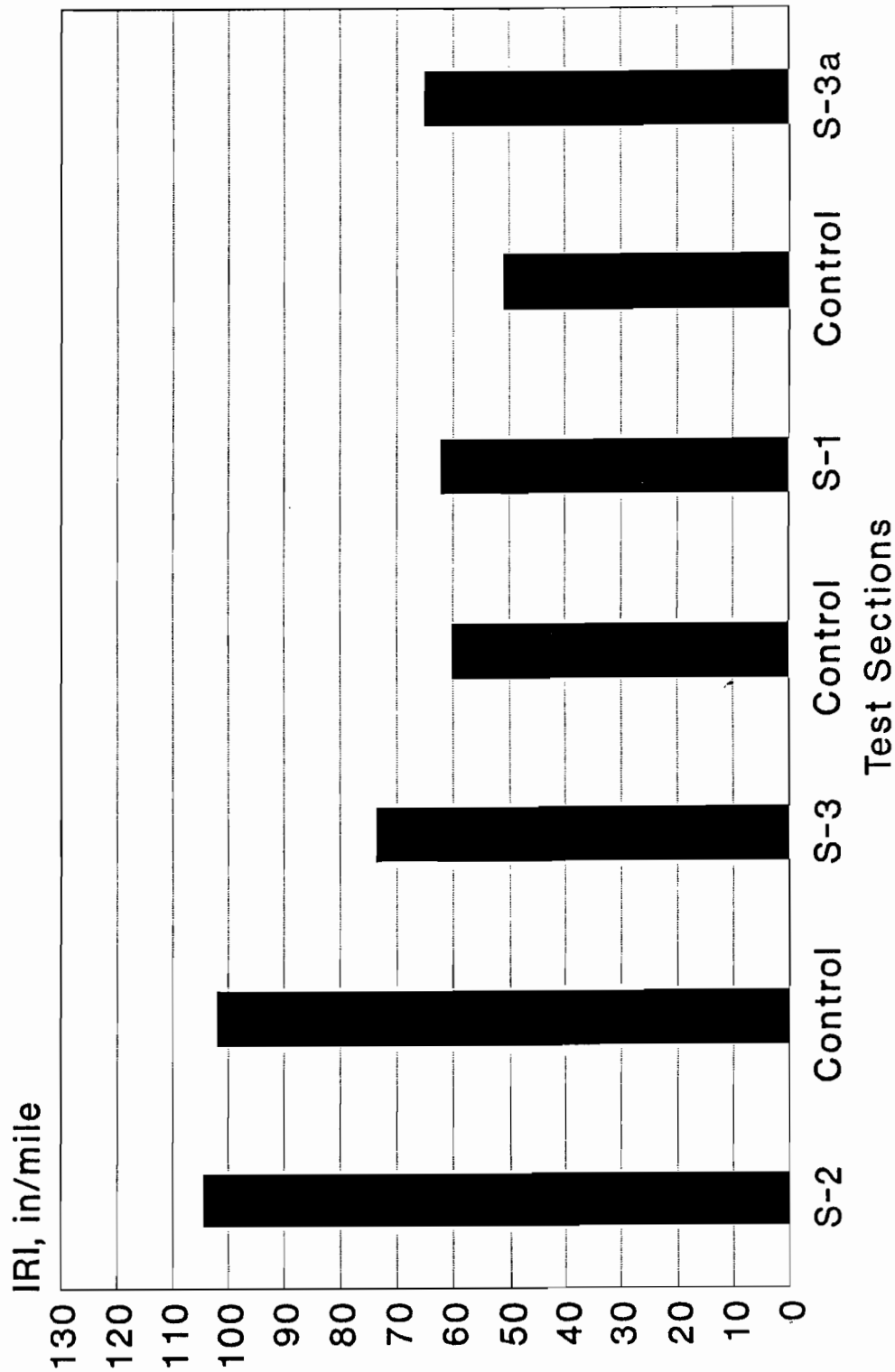
**APPENDIX A**

**Summary of International Roughness  
Indices for the Test Sections**



# International Roughness Index (IRI)

## SH 183 Eastbound Right Wheelpath



Test Section - S-2  
 Screed Position - forward  
 Head of Material - low  
 Mix Temperature - 295°F  
 Paver Speed - 34.0 ft/min

Test Section - S-3  
 Screed Position - forward  
 Head of Material - high  
 Mix Temperature - 282°F  
 Paver Speed - 38.0 ft/min

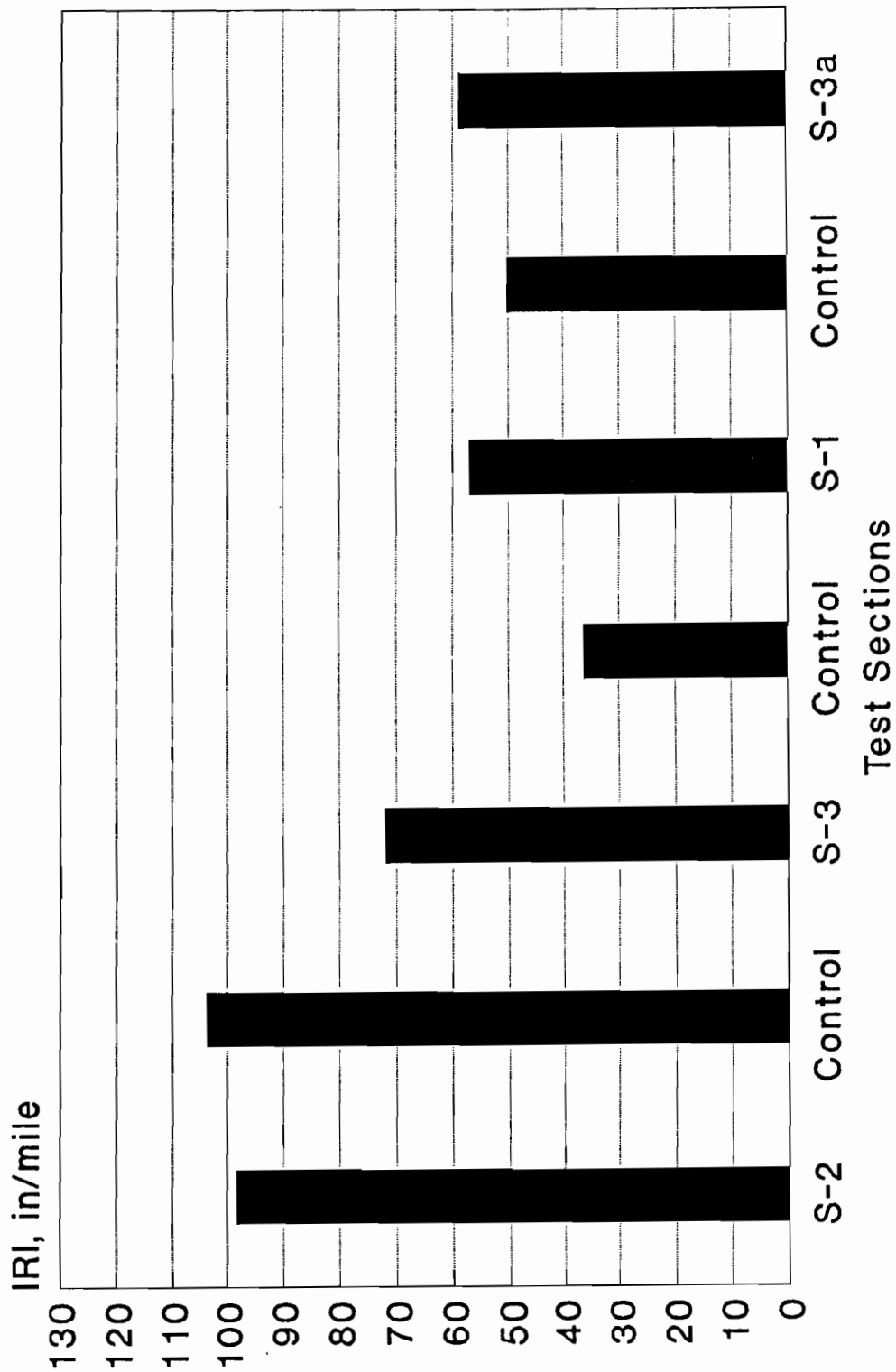
Test Section - S-1  
 Screed Position - forward  
 Head of Material - middle  
 Mix Temperature - 298°F  
 Paver Speed - 36.0 ft/min

Test Section - S-3a  
 Screed Position - forward  
 Head of Material - high  
 Mix Temperature - 289°F  
 Paver Speed - 15.0 ft/min

Figure A-1.

# International Roughness Index (IRI)

## SH 183 Eastbound Right Not Wheelpath



Test Section - S-2  
 Screed Position - forward  
 Head of Material - low  
 Mix Temperature - 295°F  
 Paver Speed - 34.0 ft/min

Test Section - S-3  
 Screed Position - forward  
 Head of Material - high  
 Mix Temperature - 282°F  
 Paver Speed - 38.0 ft/min

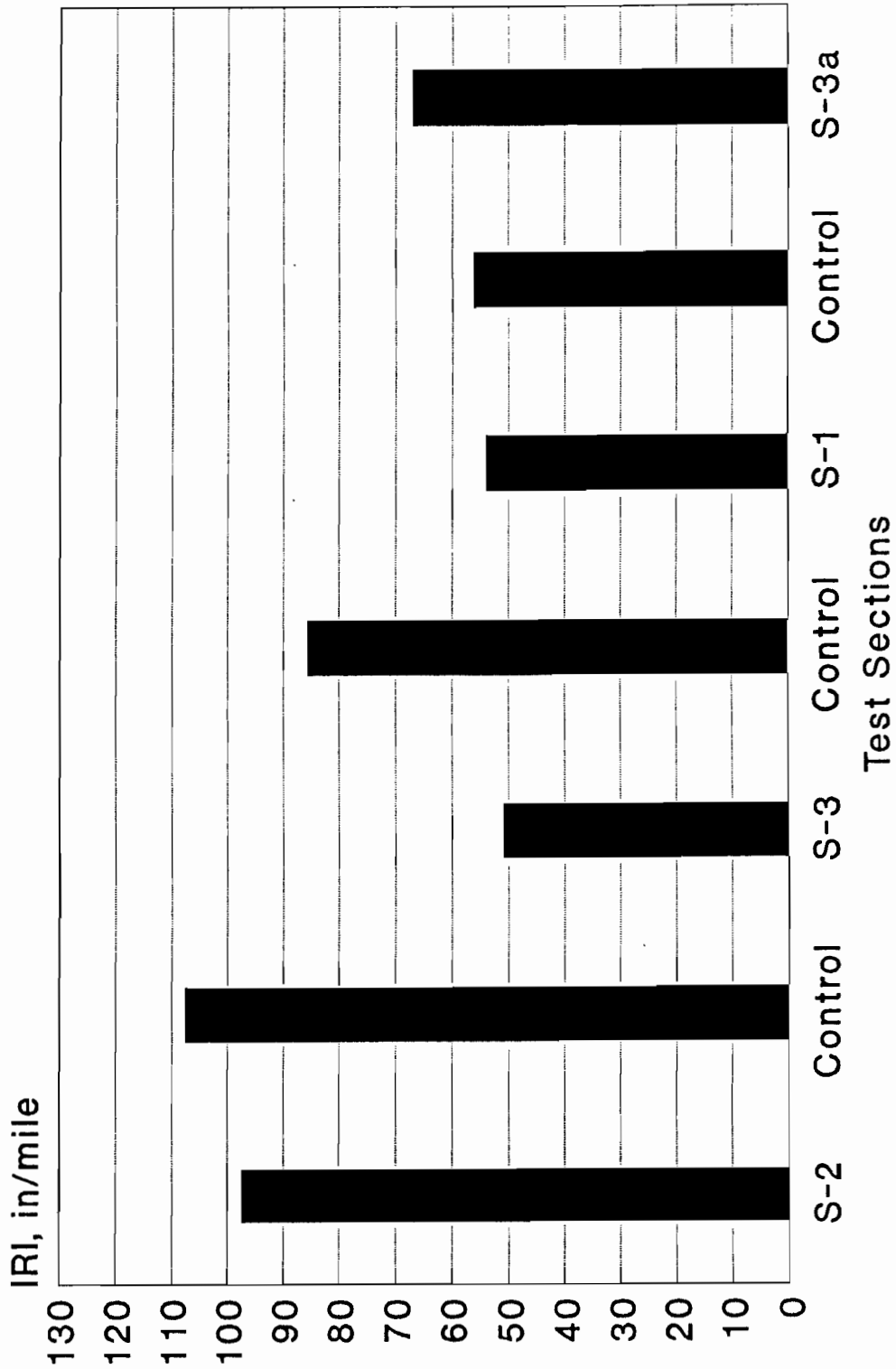
Test Section - S-1  
 Screed Position - forward  
 Head of Material - middle  
 Mix Temperature - 298°F  
 Paver Speed - 36.0 ft/min

Test Section - S-3a  
 Screed Position - forward  
 Head of Material - high  
 Mix Temperature - 289°F  
 Paver Speed - 15.0 ft/min

Figure A-2.

# International Roughness Index (IRI)

## SH 183 Eastbound Left Wheelpath



Test Section - S-2  
 Screed Position - forward  
 Head of Material - low  
 Mix Temperature - 295°F  
 Paver Speed - 34.0 ft/min

Test Section - S-3  
 Screed Position - forward  
 Head of Material - high  
 Mix Temperature - 282°F  
 Paver Speed - 38.0 ft/min

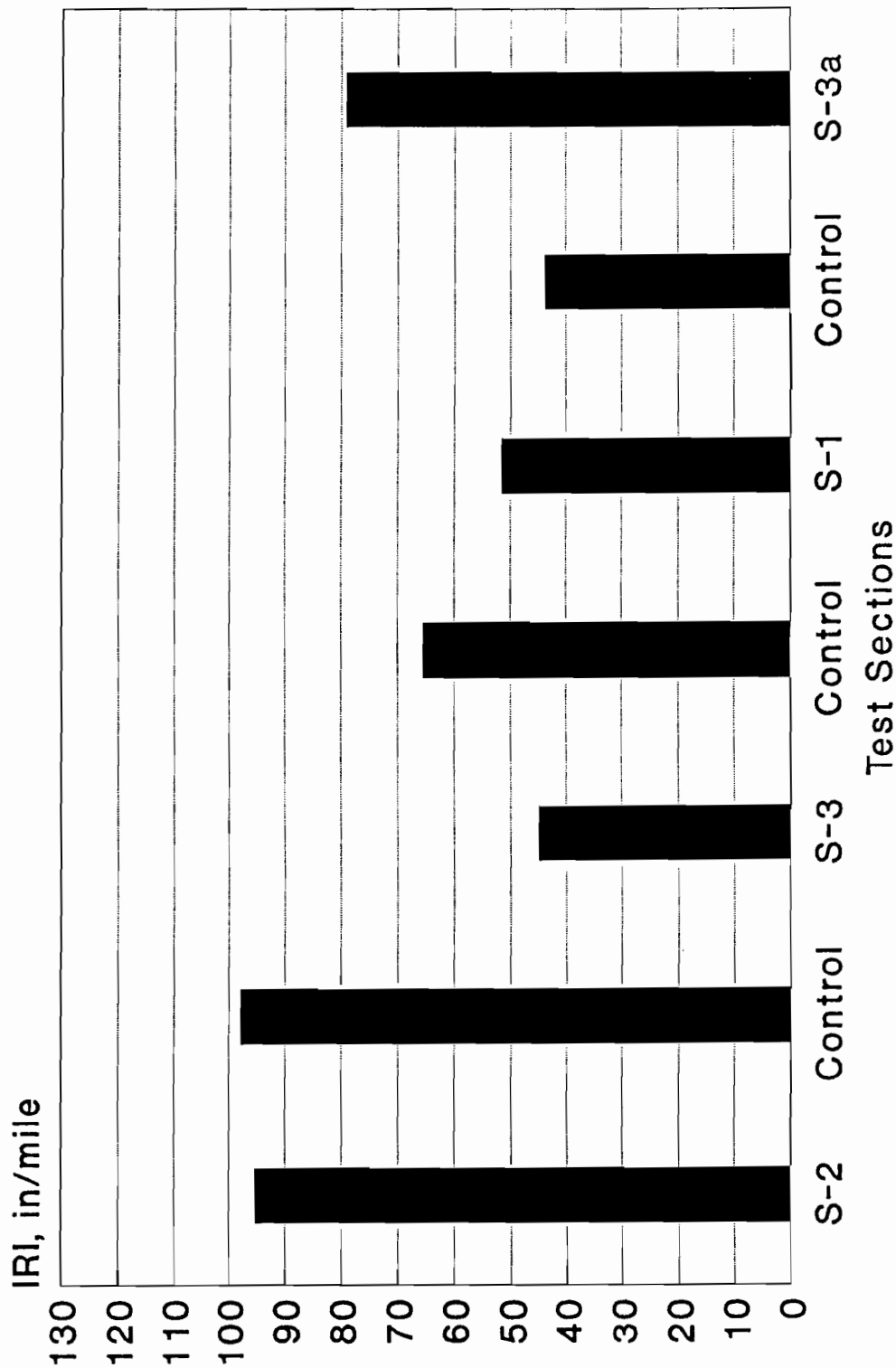
Test Section - S-1  
 Screed Position - forward  
 Head of Material - middle  
 Mix Temperature - 298°F  
 Paver Speed - 36.0 ft/min

Test Section - S-3a  
 Screed Position - forward  
 Head of Material - high  
 Mix Temperature - 289°F  
 Paver Speed - 15.0 ft/min

Figure A-3.

# International Roughness Index (IRI)

## SH 183 Eastbound Left Not Wheelpath



Test Section - S-2  
 Screed Position - forward  
 Head of Material - low  
 Mix Temperature - 295°F  
 Paver Speed - 34.0 ft/min

Test Section - S-3  
 Screed Position - forward  
 Head of Material - high  
 Mix Temperature - 282°F  
 Paver Speed - 38.0 ft/min

Test Section - S-1  
 Screed Position - forward  
 Head of Material - middle  
 Mix Temperature - 298°F  
 Paver Speed - 36.0 ft/min

Test Section - S-3a  
 Screed Position - forward  
 Head of Material - high  
 Mix Temperature - 289°F  
 Paver Speed - 15.0 ft/min

Figure A-4.

# International Roughness Index (IRI)

## SH 183 Westbound Right Wheelpath

Test Section - S-12  
 Screed Position - back  
 Head of Material - high  
 Mix Temperature - 306°F  
 Paver Speed - 52.0 ft/min

Test Section - S-10  
 Screed Position - back  
 Head of Material - middle  
 Mix Temperature - 313°F  
 Paver Speed - 60.0 ft/min

Test Section - S-11  
 Screed Position - back  
 Head of Material - low  
 Mix Temperature - 317°F  
 Paver Speed - 36.0 ft/min

Test Section - S-10a  
 Screed Position - back  
 Head of Material - middle  
 Mix Temperature - 313°F  
 Paver Speed - 55.0 ft/min

Test Section - S-10b  
 Screed Position - back  
 Head of Material - middle  
 Mix Temperature - 312°F  
 Paver Speed - 55.0 ft/min

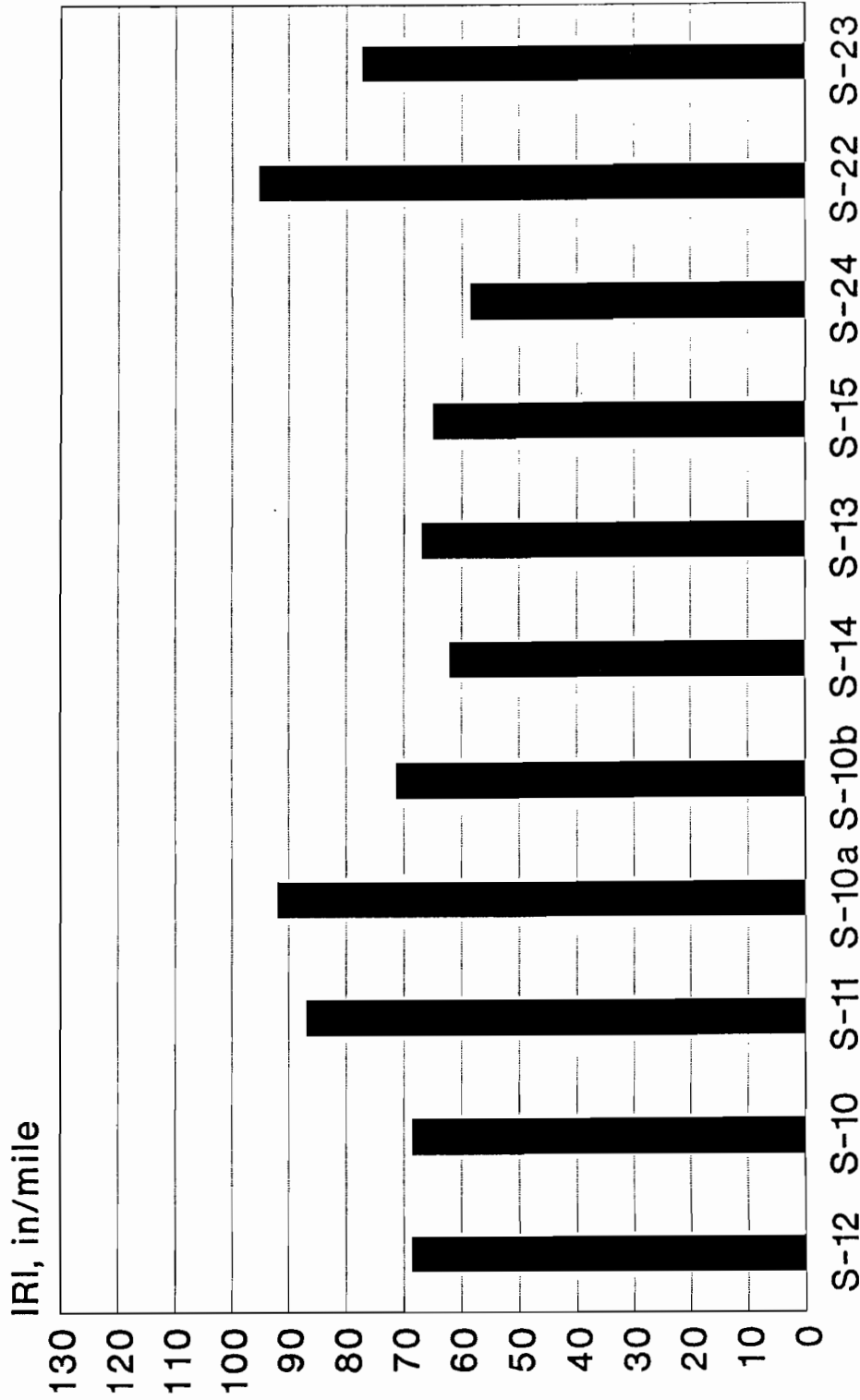
Test Section - S-14  
 Screed Position - forward  
 Head of Material - low  
 Mix Temperature - 306°F  
 Paver Speed - 30.0 ft/min

Test Section - S-13  
 Screed Position - forward  
 Head of Material - middle  
 Mix Temperature - 302°F  
 Paver Speed - 58.0 ft/min

Test Section - S-15  
 Screed Position - forward  
 Head of Material - high  
 Mix Temperature - 304°F  
 Paver Speed - 51.0 ft/min

Test Section - S-24  
 Screed Position - back  
 Head of Material - high  
 Mix Temperature - 305°F  
 Paver Speed - 50.0 ft/min

Test Section - S-22  
 Screed Position - back  
 Head of Material - middle  
 Mix Temperature - none  
 Paver Speed - 60.0 ft/min



Test Sections

Figure A-5.

Test Section - S-23  
 Screed Position - back  
 Head of Material - low  
 Mix Temperature - 306°F  
 Paver Speed - 42.0 ft/min

Test Section - S-12  
 Screed Position - back  
 Head of Material - high  
 Mix Temperature - 306°F  
 Paver Speed - 52.0 ft/min

Test Section - S-10  
 Screed Position - back  
 Head of Material - middle  
 Mix Temperature - 313°F  
 Paver Speed - 60.0 ft/min

Test Section - S-11  
 Screed Position - back  
 Head of Material - low,  
 Mix Temperature - 317°F  
 Paver Speed - 36.0 ft/min

Test Section - S-10a  
 Screed Position - back  
 Head of Material - middle  
 Mix Temperature - 313°F  
 Paver Speed - 55.0 ft/min

Test Section - S-10b  
 Screed Position - back  
 Head of Material - middle  
 Mix Temperature - 312°F  
 Paver Speed - 55.0 ft/min

Test Section - S-14  
 Screed Position - forward  
 Head of Material - low  
 Mix Temperature - 306°F  
 Paver Speed - 30.0 ft/min

Test Section - S-13  
 Screed Position - forward  
 Head of Material - middle  
 Mix Temperature - 302°F  
 Paver Speed - 58.0 ft/min

Test Section - S-15  
 Screed Position - forward  
 Head of Material - high  
 Mix Temperature - 304°F  
 Paver Speed - 51.0 ft/min

Test Section - S-24  
 Screed Position - back  
 Head of Material - high  
 Mix Temperature - 305°F  
 Paver Speed - 50.0 ft/min

Test Section - S-22  
 Screed Position - back  
 Head of Material - middle  
 Mix Temperature - none  
 Paver Speed - 60.0 ft/min

# International Roughness Index (IRI)

## SH 183 Westbound Right Not Wheelpath

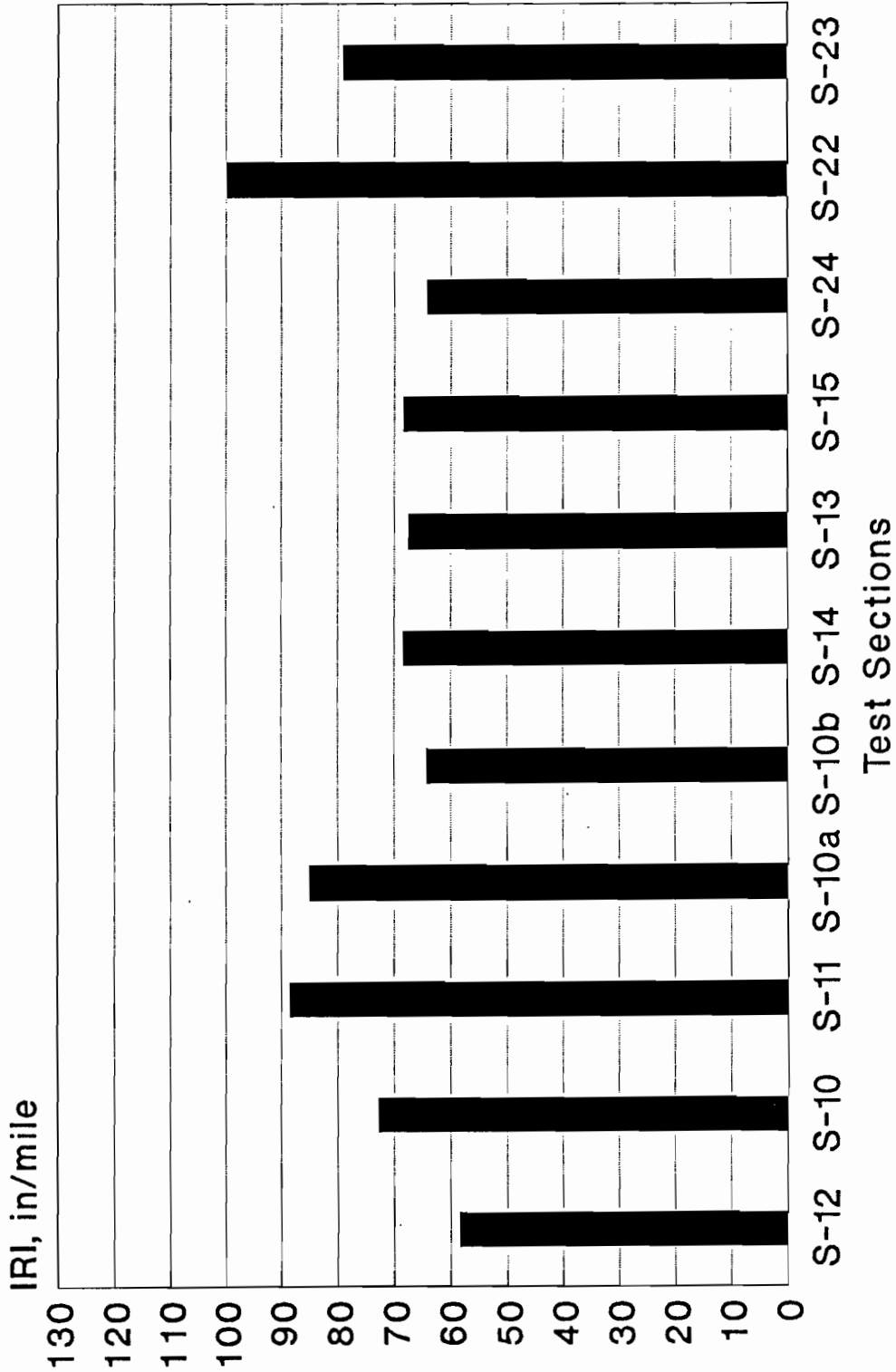


Figure A-6.

Test Section - S-23  
 Screed Position - back  
 Head of Material - low  
 Mix Temperature - 306°F  
 Paver Speed - 42.0 ft/min



Test Section - S-12  
 Screed Position - back  
 Head of Material - high  
 Mix Temperature - 306°F  
 Paver Speed - 52.0 ft/min

Test Section - S-10  
 Screed Position - back  
 Head of Material - middle  
 Mix Temperature - 313°F  
 Paver Speed - 60.0 ft/min

Test Section - S-11  
 Screed Position - back  
 Head of Material - low  
 Mix Temperature - 317°F  
 Paver Speed - 36.0 ft/min

Test Section - S-10a  
 Screed Position - back  
 Head of Material - middle  
 Mix Temperature - 313°F  
 Paver Speed - 55.0 ft/min

Test Section - S-10b  
 Screed Position - back  
 Head of Material - middle  
 Mix Temperature - 312°F  
 Paver Speed - 55.0 ft/min

Test Section - S-14  
 Screed Position - forward  
 Head of Material - low  
 Mix Temperature - 306°F  
 Paver Speed - 30.0 ft/min

Test Section - S-13  
 Screed Position - forward  
 Head of Material - middle  
 Mix Temperature - 302°F  
 Paver Speed - 58.0 ft/min

Test Section - S-15  
 Screed Position - forward  
 Head of Material - high  
 Mix Temperature - 304°F  
 Paver Speed - 51.0 ft/min

Test Section - S-24  
 Screed Position - back  
 Head of Material - high  
 Mix Temperature - 305°F  
 Paver Speed - 50.0 ft/min

Test Section - S-22  
 Screed Position - back  
 Head of Material - middle  
 Mix Temperature - none  
 Paver Speed - 60.0 ft/min

# International Roughness Index (IRI)

## SH 183 Westbound Left Wheelpath

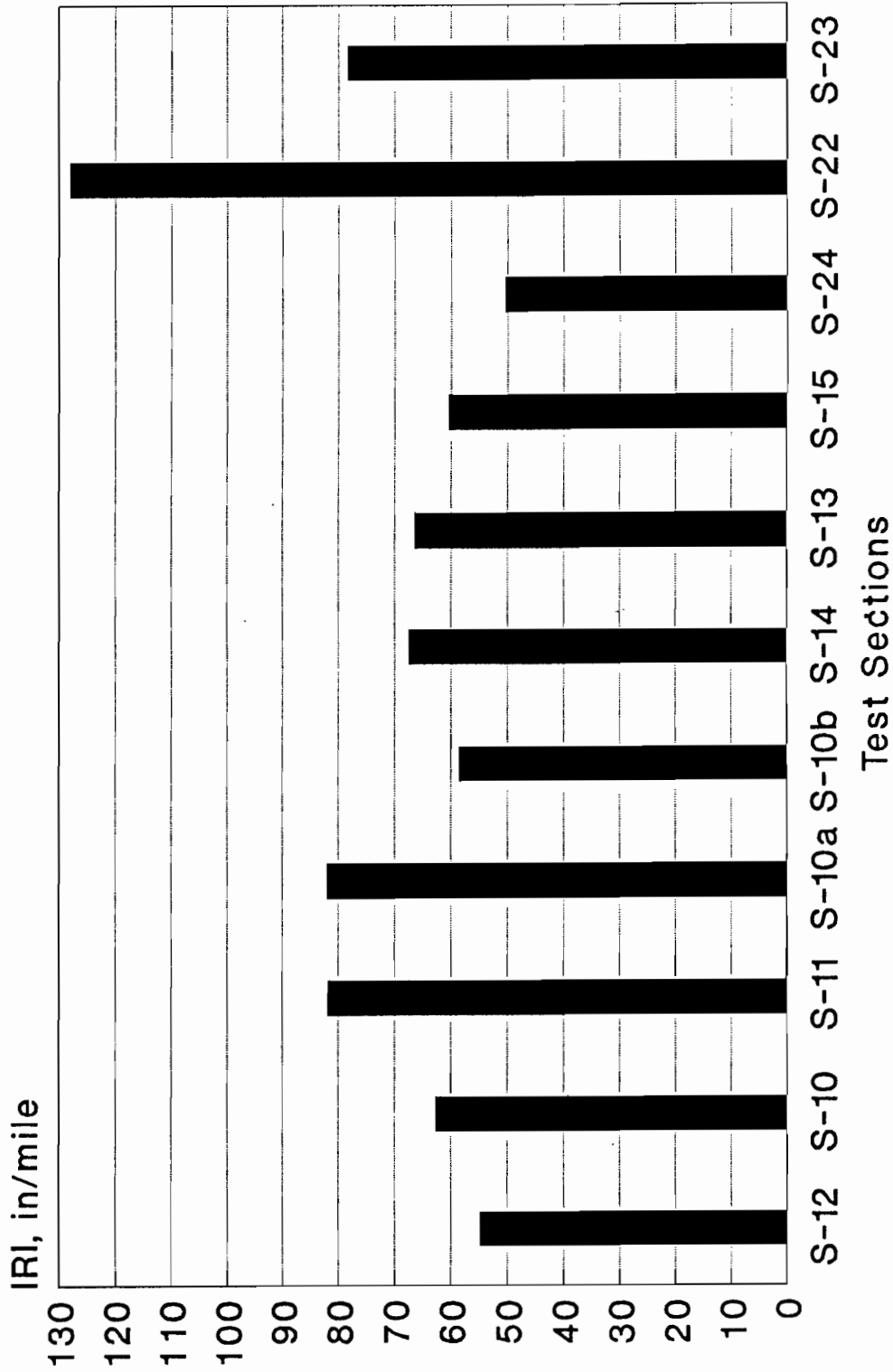


Figure A-7.

Test Section - S-23  
 Screed Position - back  
 Head of Material - low  
 Mix Temperature - 306°F  
 Paver Speed - 42.0 ft/min

# International Roughness Index (IRI)

## SH 183 Westbound Left Not Wheelpath

Test Section - S-12  
 Screed Position - back  
 Head of Material - high  
 Mix Temperature - 306°F  
 Paver Speed - 52.0 ft/min

Test Section - S-10  
 Screed Position - back  
 Head of Material - middle  
 Mix Temperature - 313°F  
 Paver Speed - 60.0 ft/min

Test Section - S-11  
 Screed Position - back  
 Head of Material - low  
 Mix Temperature - 317°F  
 Paver Speed - 36.0 ft/min

Test Section - S-10a  
 Screed Position - back  
 Head of Material - middle  
 Mix Temperature - 313°F  
 Paver Speed - 55.0 ft/min

Test Section - S-10b  
 Screed Position - back  
 Head of Material - middle  
 Mix Temperature - 312°F  
 Paver Speed - 55.0 ft/min

Test Section - S-14  
 Screed Position - forward  
 Head of Material - low  
 Mix Temperature - 306°F  
 Paver Speed - 30.0 ft/min

Test Section - S-13  
 Screed Position - forward  
 Head of Material - middle  
 Mix Temperature - 302°F  
 Paver Speed - 58.0 ft/min

Test Section - S-15  
 Screed Position - forward  
 Head of Material - high  
 Mix Temperature - 304°F  
 Paver Speed - 51.0 ft/min

Test Section - S-24  
 Screed Position - back  
 Head of Material - high  
 Mix Temperature - 305°F  
 Paver Speed - 50.0 ft/min

Test Section - S-22  
 Screed Position - back  
 Head of Material - middle  
 Mix Temperature - none  
 Paver Speed - 60.0 ft/min

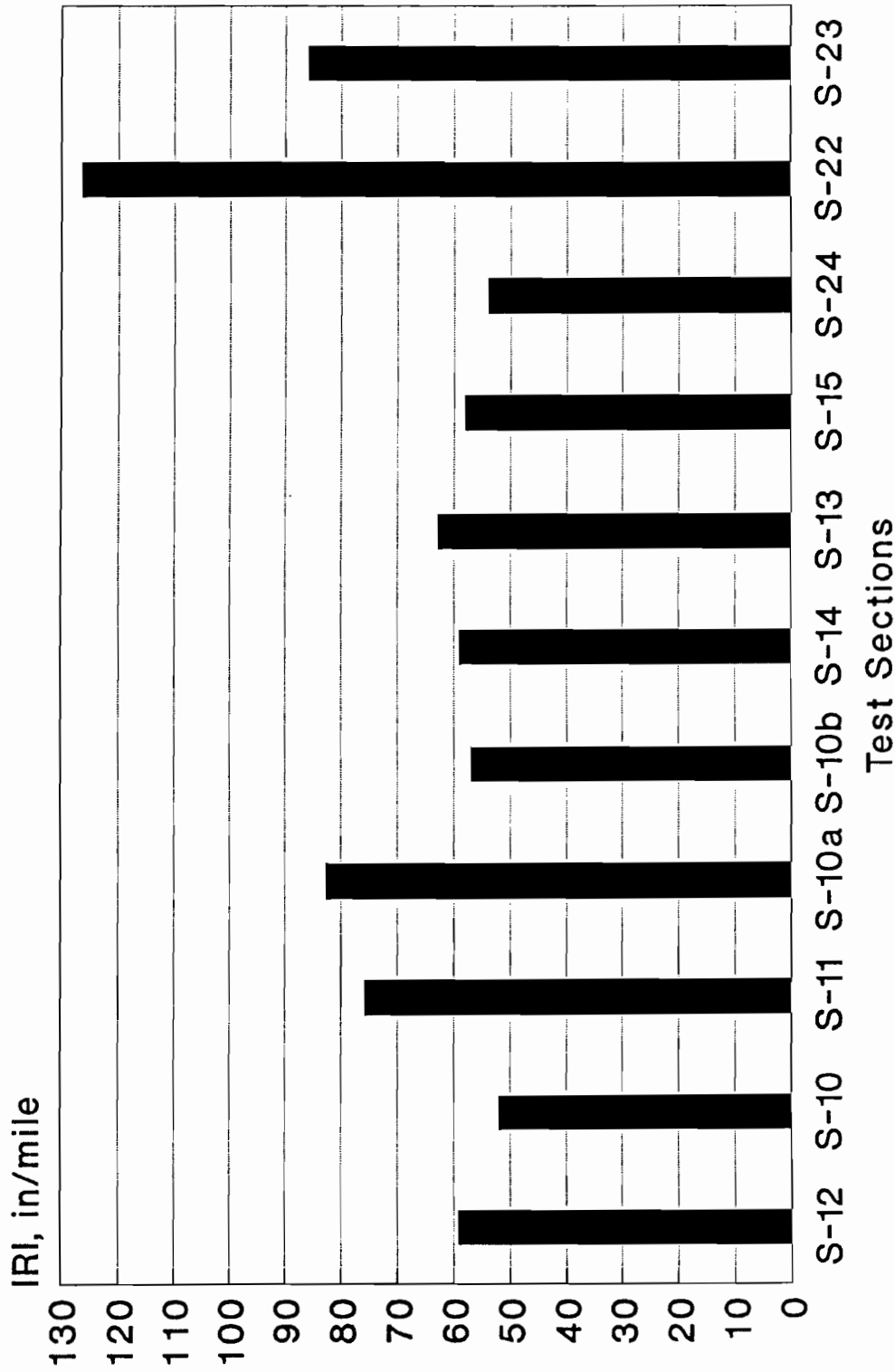
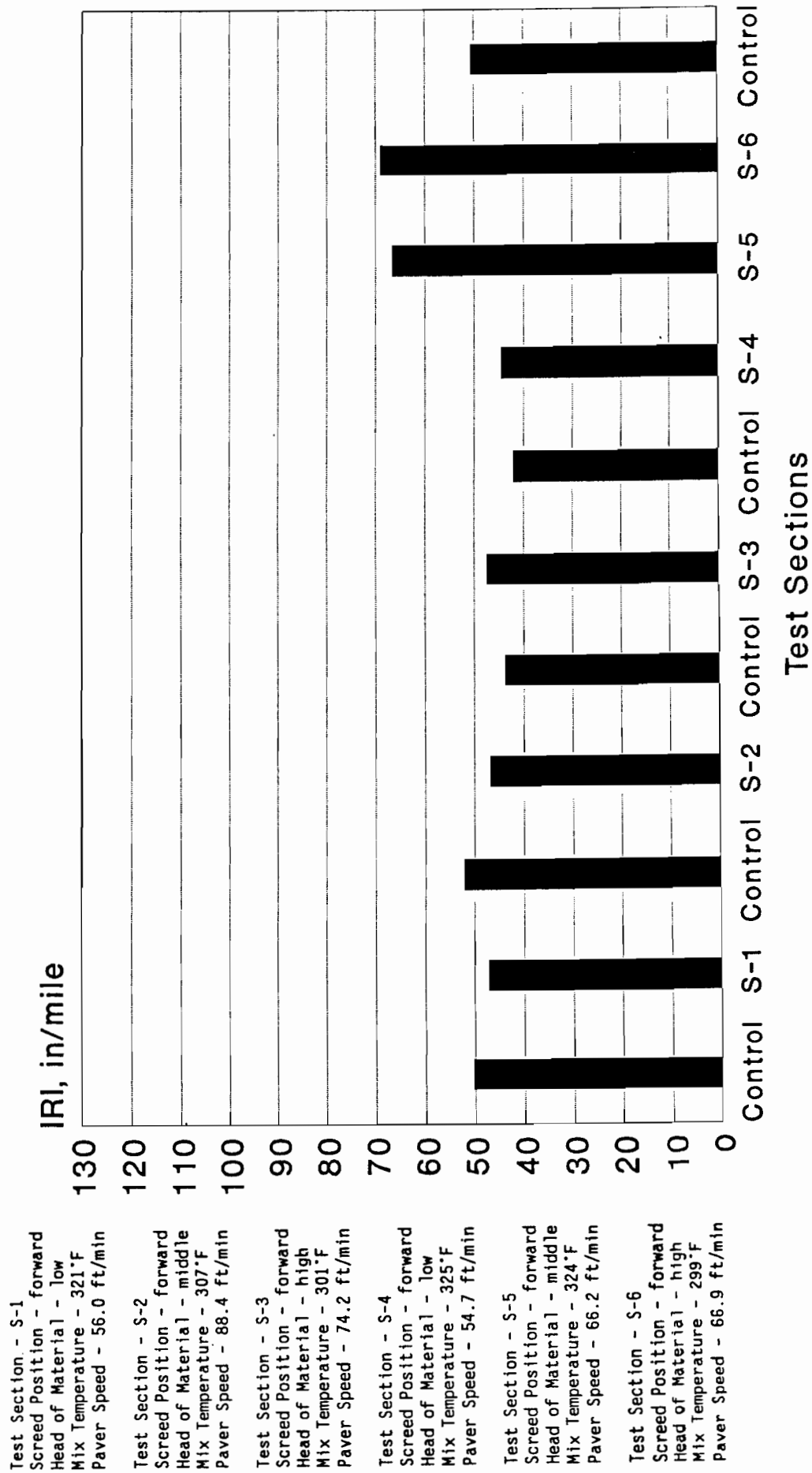


Figure A-8.  
 Test Section - S-23  
 Screed Position - back  
 Head of Material - low  
 Mix Temperature - 306°F  
 Paver Speed - 42.0 ft/min

# International Roughness Index (IRI)

## FM 1488 Eastbound Right Wheelpath



Test Section - S-1  
 Screed Position - forward  
 Head of Material - low  
 Mix Temperature - 321°F  
 Paver Speed - 56.0 ft/min

Test Section - S-2  
 Screed Position - forward  
 Head of Material - middle  
 Mix Temperature - 307°F  
 Paver Speed - 88.4 ft/min

Test Section - S-3  
 Screed Position - forward  
 Head of Material - high  
 Mix Temperature - 301°F  
 Paver Speed - 74.2 ft/min

Test Section - S-4  
 Screed Position - forward  
 Head of Material - low  
 Mix Temperature - 325°F  
 Paver Speed - 54.7 ft/min

Test Section - S-5  
 Screed Position - forward  
 Head of Material - middle  
 Mix Temperature - 324°F  
 Paver Speed - 66.2 ft/min

Test Section - S-6  
 Screed Position - forward  
 Head of Material - high  
 Mix Temperature - 299°F  
 Paver Speed - 66.9 ft/min

Figure A-9.

# International Roughness Index (IRI)

## FM 1488 Eastbound Right Not Wheelpath

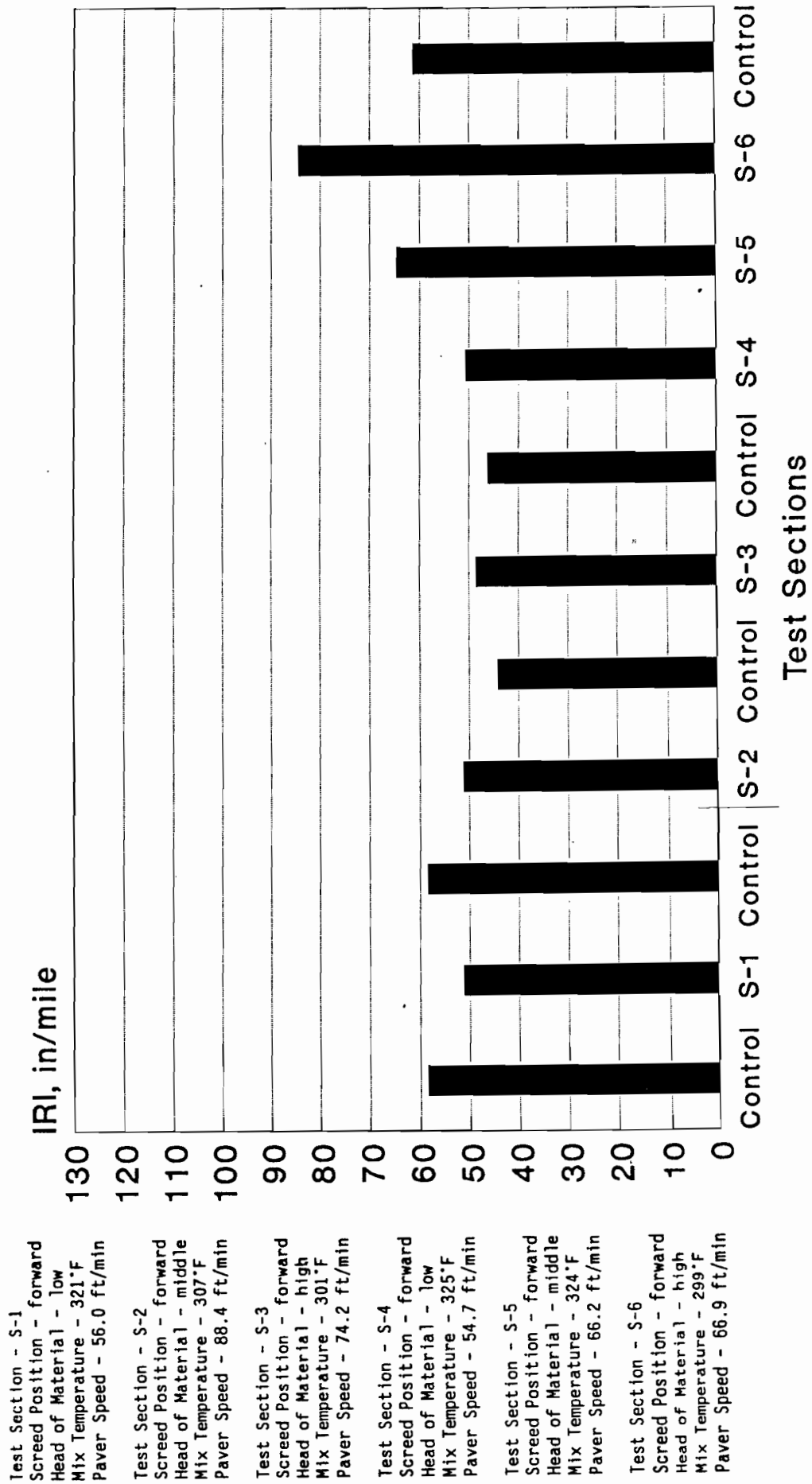


Figure A-10.

# International Roughness Index (IRI)

## FM 1488 Eastbound Left Wheelpath

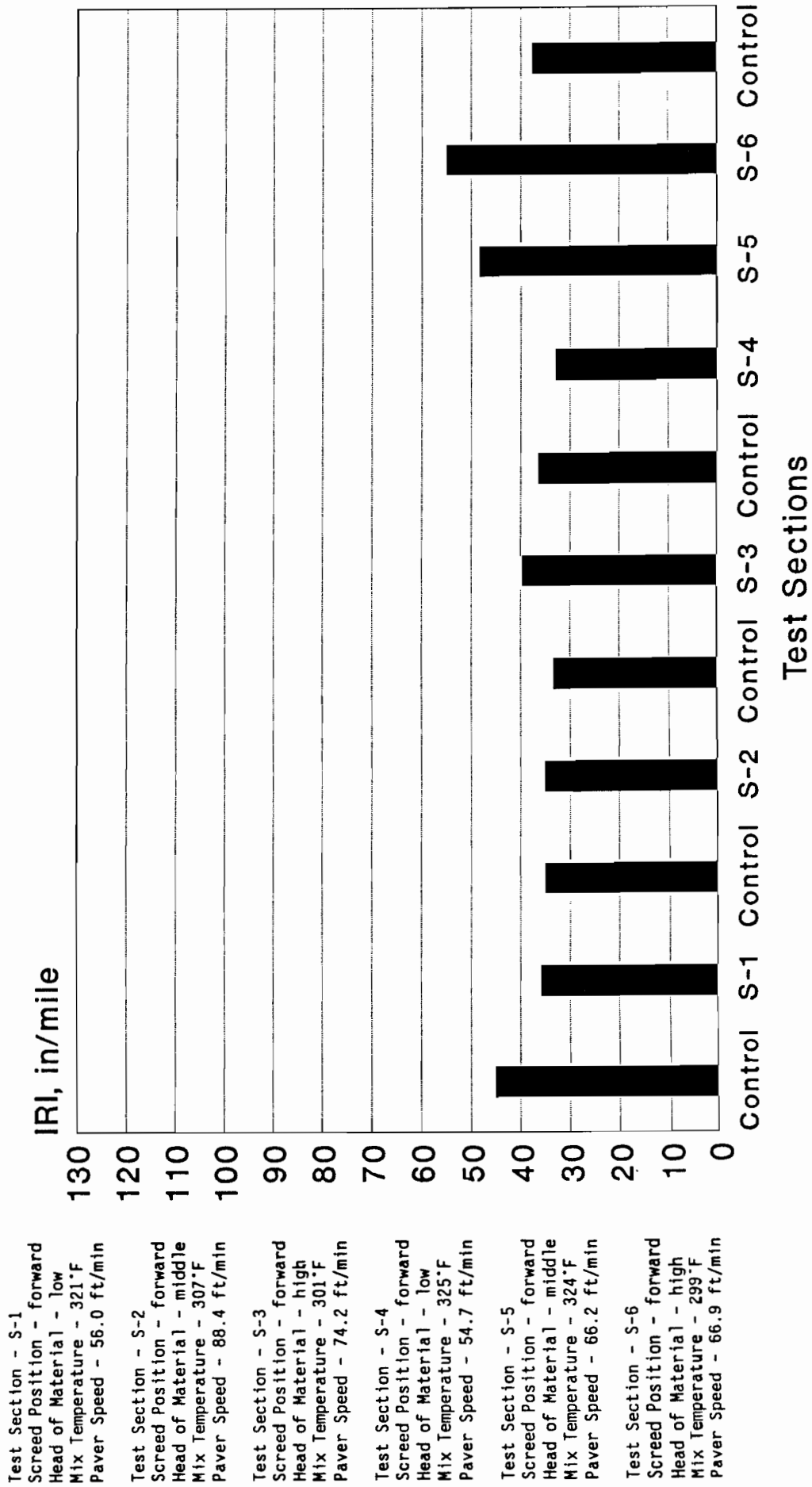


Figure A-11.

# International Roughness Index

## FM 1488 Eastbound Left Not Wheelpath

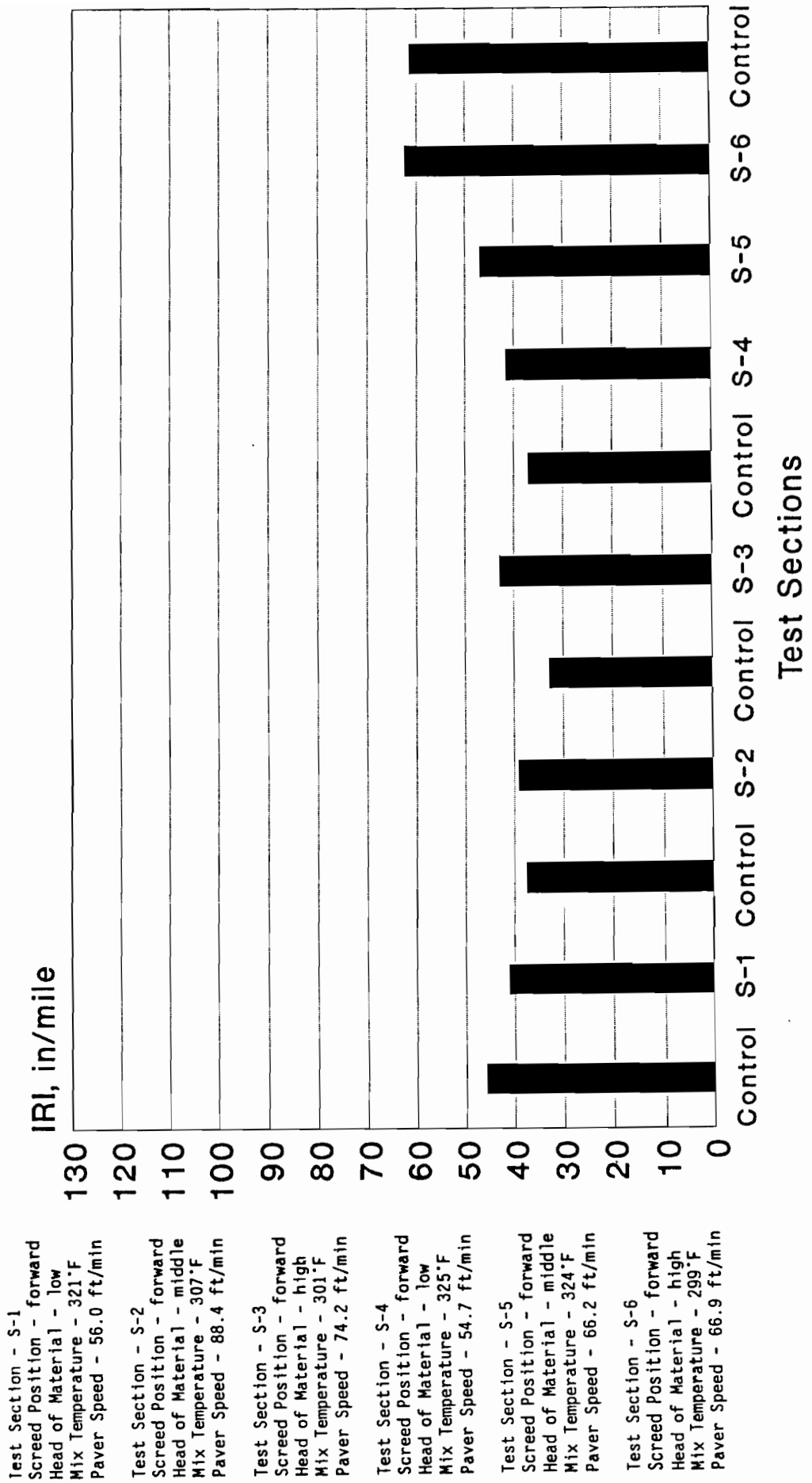


Figure A-12.

# International Roughness Index (IRI)

## FM 1488 Westbound Right Wheelpath

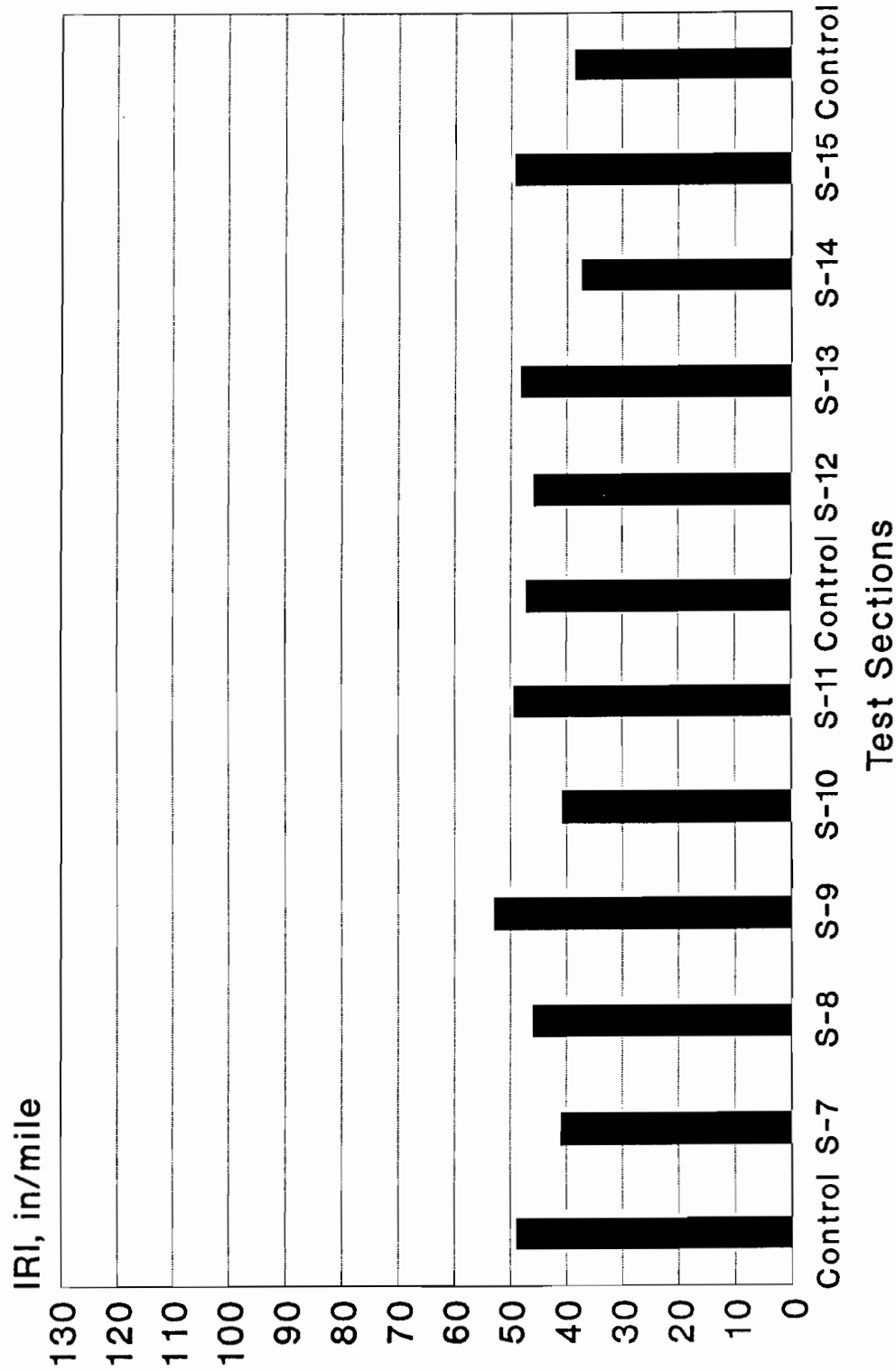


Figure A-13.

Test Section - S-7  
 Screed Position - back  
 Head of Material - low  
 Mix Temperature - 303°F  
 Paver Speed - 59.8 ft/min

Test Section - S-8  
 Screed Position - back  
 Head of Material - middle  
 Mix Temperature - 305°F  
 Paver Speed - 60.0 ft/min

Test Section - S-9  
 Screed Position - back  
 Head of Material - high  
 Mix Temperature - none  
 Paver Speed - 60.0 ft/min

Test Section - S-10  
 Screed Position - back  
 Head of Material - middle  
 Mix Temperature - 313°F  
 Paver Speed - 38.8 ft/min

Test Section - S-11  
 Screed Position - back  
 Head of Material - high  
 Mix Temperature - 298°F  
 Paver Speed - 41.0 ft/min

Test Section - S-12  
 Screed Position - back  
 Head of Material - middle  
 Mix Temperature - 307°F  
 Paver Speed - 84.0 ft/min

Test Section - S-13  
 Screed Position - back  
 Head of Material - high  
 Mix Temperature - 302°F  
 Paver Speed - 80.6 ft/min

Test Section - S-14  
 Screed Position - back  
 Head of Material - middle  
 Mix Temperature - 308°F  
 Paver Speed - 41.5 ft/min

Test Section - S-15  
 Screed Position - back  
 Head of Material - high  
 Mix Temperature - 307°F  
 Paver Speed - 39.5 ft/min

# International Roughness Index (IRI)

## FM 1488 Westbound Right Not Wheelpath

Test Section - S-7  
 Screed Position - back  
 Head of Material - low  
 Mix Temperature - 303°F  
 Paver Speed - 59.8 ft/min

Test Section - S-8  
 Screed Position - back  
 Head of Material - middle  
 Mix Temperature - 305°F  
 Paver Speed - 60.0 ft/min

Test Section - S-9  
 Screed Position - back  
 Head of Material - high  
 Mix Temperature - none  
 Paver Speed - 60.0 ft/min

Test Section - S-10  
 Screed Position - back  
 Head of Material - middle  
 Mix Temperature - 313°F  
 Paver Speed - 38.8 ft/min

Test Section - S-11  
 Screed Position - back  
 Head of Material - high  
 Mix Temperature - 298°F  
 Paver Speed - 41.0 ft/min

Test Section - S-12  
 Screed Position - back  
 Head of Material - middle  
 Mix Temperature - 307°F  
 Paver Speed - 84.0 ft/min

Test Section - S-13  
 Screed Position - back  
 Head of Material - high  
 Mix Temperature - 302°F  
 Paver Speed - 80.6 ft/min

Test Section - S-14  
 Screed Position - back  
 Head of Material - middle  
 Mix Temperature - 308°F  
 Paver Speed - 41.5 ft/min

Test Section - S-15  
 Screed Position - back  
 Head of Material - high  
 Mix Temperature - 307°F  
 Paver Speed - 39.5 ft/min

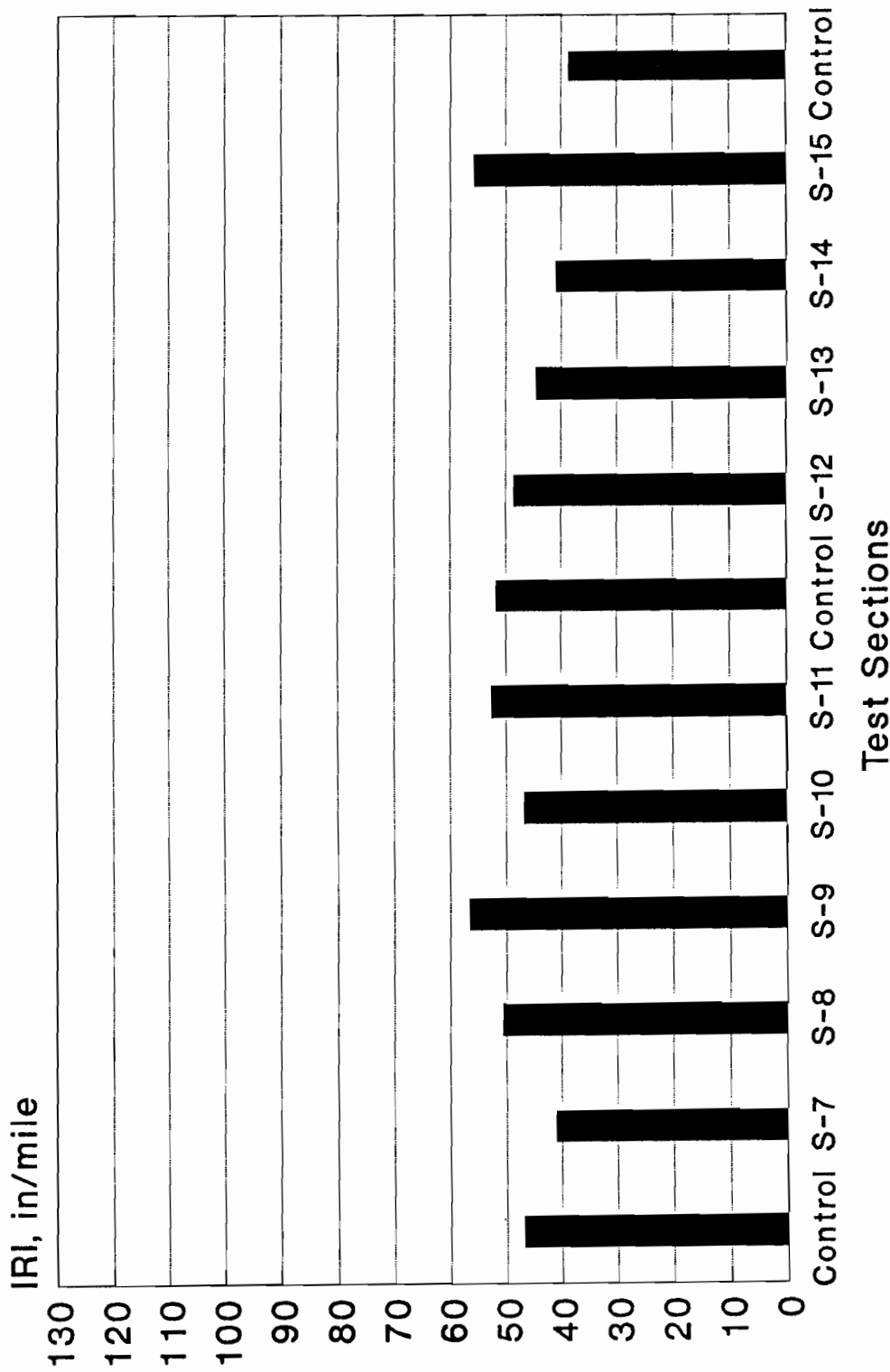


Figure A-14.



# International Roughness Index (IRI)

## FM 1488 Westbound Left Wheelpath

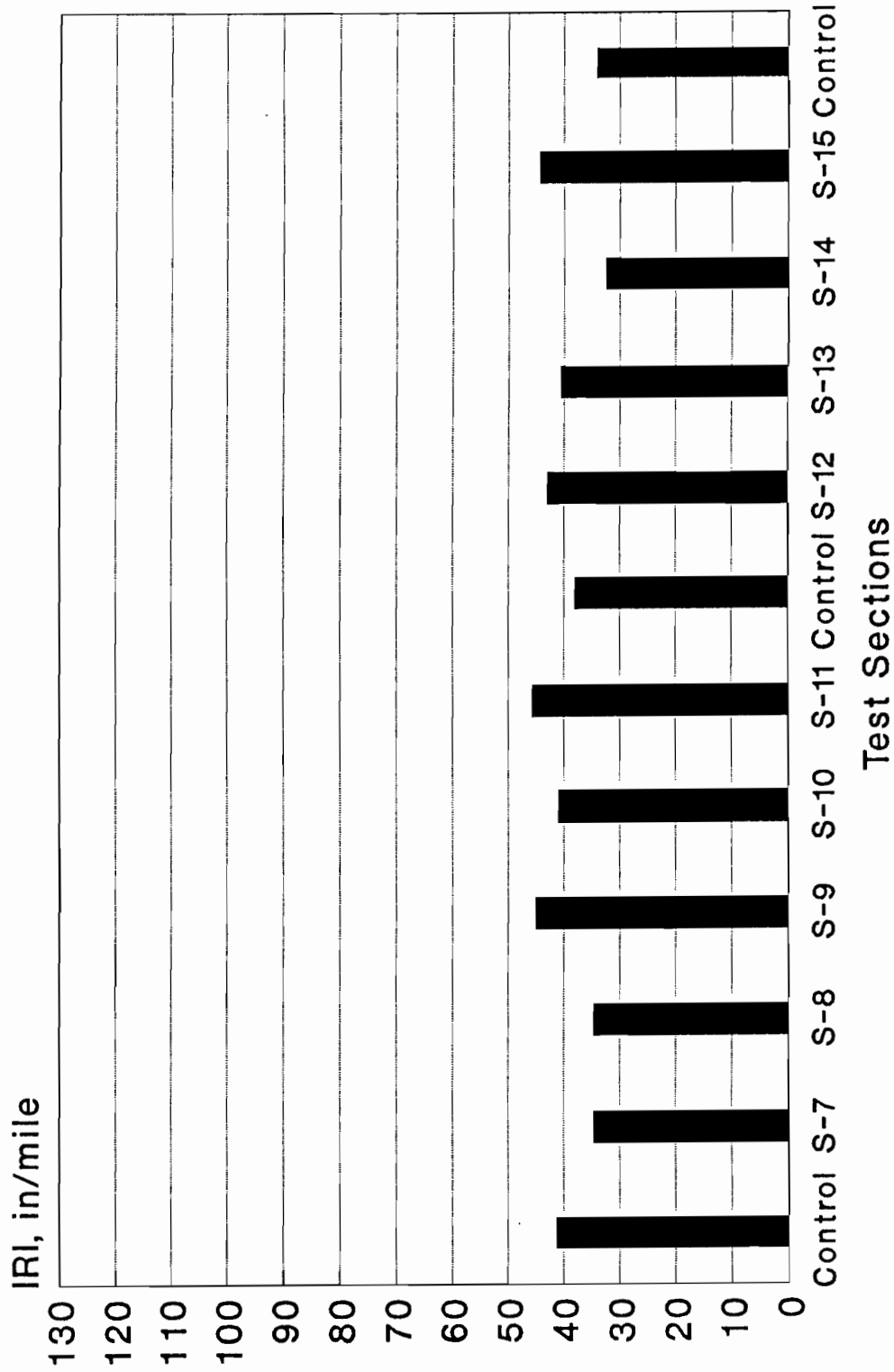


Figure A-15.

Test Section - S-7  
 Screed Position - back  
 Head of Material - low  
 Mix Temperature - 303°F  
 Paver Speed - 59.8 ft/min

Test Section - S-8  
 Screed Position - back  
 Head of Material - middle  
 Mix Temperature - 305°F  
 Paver Speed - 60.0 ft/min

Test Section - S-9  
 Screed Position - back  
 Head of Material - high  
 Mix Temperature - none  
 Paver Speed - 60.0 ft/min

Test Section - S-10  
 Screed Position - back  
 Head of Material - middle  
 Mix Temperature - 313°F  
 Paver Speed - 38.8 ft/min

Test Section - S-11  
 Screed Position - back  
 Head of Material - high  
 Mix Temperature - 298°F  
 Paver Speed - 41.0 ft/min

Test Section - S-12  
 Screed Position - back  
 Head of Material - middle  
 Mix Temperature - 307°F  
 Paver Speed - 84.0 ft/min

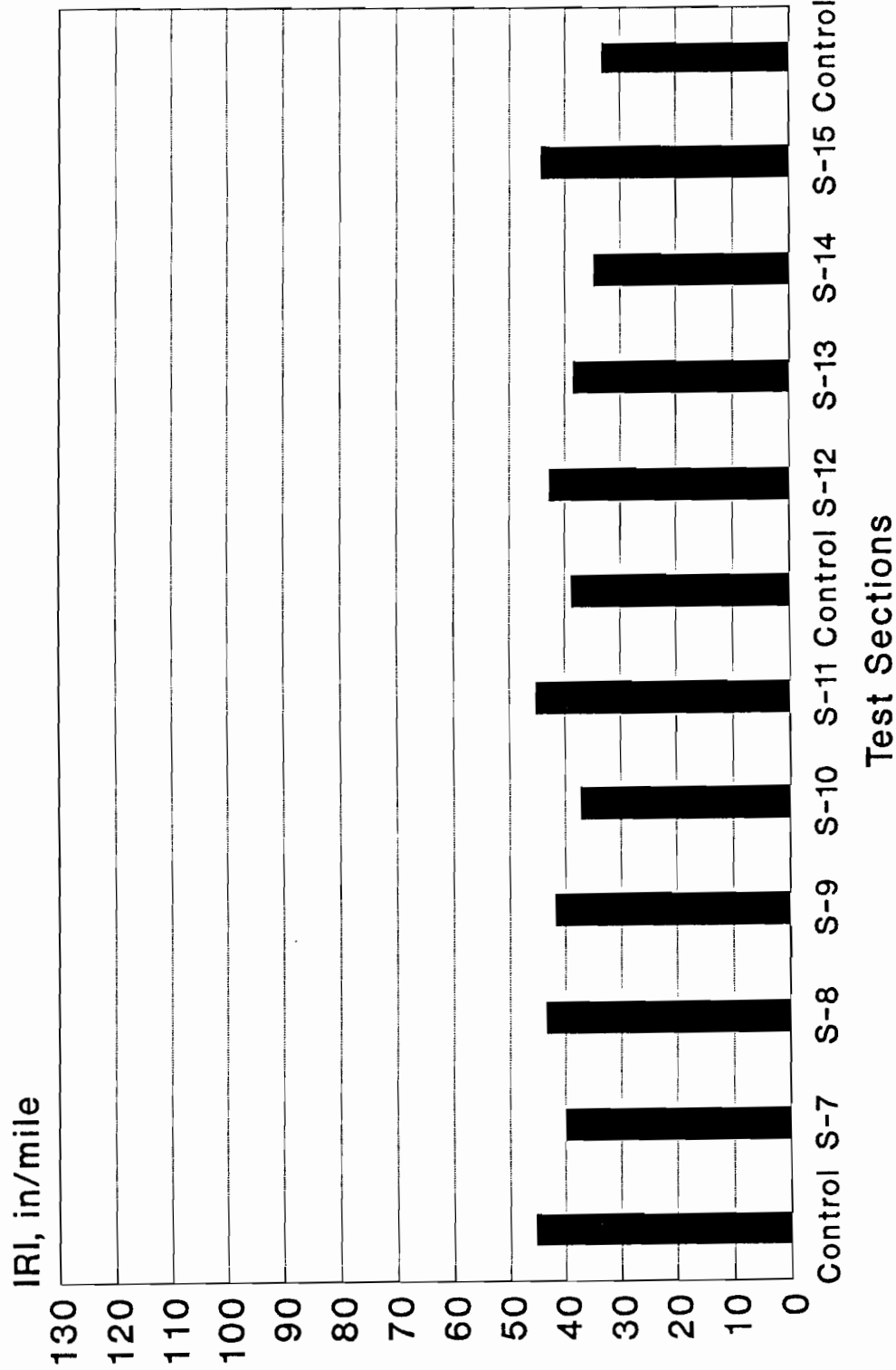
Test Section - S-13  
 Screed Position - back  
 Head of Material - high  
 Mix Temperature - 302°F  
 Paver Speed - 80.6 ft/min

Test Section - S-14  
 Screed Position - back  
 Head of Material - middle  
 Mix Temperature - 308°F  
 Paver Speed - 41.5 ft/min

Test Section - S-15  
 Screed Position - back  
 Head of Material - high  
 Mix Temperature - 307°F  
 Paver Speed - 39.5 ft/min

# International Roughness Index (IRI)

## FM 1488 Westbound Left Not Wheelpath



Test Section - S-7  
 Screed Position - back  
 Head of Material - low  
 Mix Temperature - 303°F  
 Paver Speed - 59.8 ft/min

Test Section - S-8  
 Screed Position - back  
 Head of Material - middle  
 Mix Temperature - 305°F  
 Paver Speed - 60.0 ft/min

Test Section - S-9  
 Screed Position - back  
 Head of Material - high  
 Mix Temperature - none  
 Paver Speed - 60.0 ft/min

Test Section - S-10  
 Screed Position - back  
 Head of Material - middle  
 Mix Temperature - 313°F  
 Paver Speed - 38.8 ft/min

Test Section - S-11  
 Screed Position - back  
 Head of Material - high  
 Mix Temperature - 298°F  
 Paver Speed - 41.0 ft/min

Test Section - S-12  
 Screed Position - back  
 Head of Material - middle  
 Mix Temperature - 307°F  
 Paver Speed - 84.0 ft/min

Test Section - S-13  
 Screed Position - back  
 Head of Material - high  
 Mix Temperature - 302°F  
 Paver Speed - 80.6 ft/min

Test Section - S-14  
 Screed Position - back  
 Head of Material - middle  
 Mix Temperature - 308°F  
 Paver Speed - 41.5 ft/min

Test Section - S-15  
 Screed Position - back  
 Head of Material - high  
 Mix Temperature - 307°F  
 Paver Speed - 39.5 ft/min

Figure A-16.

Test Section - S-1  
 Screed Position - forward  
 Head of Material - middle  
 Mix Temperature - 290°F  
 Paver Speed - 65.5 ft/min

Test Section - S-2  
 Screed Position - forward  
 Head of Material - low  
 Mix Temperature - 295°F  
 Paver Speed - 58.0 ft/min

Test Section - S-2a  
 Screed Position - forward  
 Head of Material - low  
 Mix Temperature - 290°F  
 Paver Speed - 50.3 ft/min

Test Section - S-3  
 Screed Position - forward  
 Head of Material - high  
 Mix Temperature - 305°F  
 Paver Speed - 48.0 ft/min

Test Section - S-4  
 Screed Position - forward  
 Head of Material - middle  
 Mix Temperature - 300°F  
 Paver Speed - 47.0 ft/min

Test Section - S-5  
 Screed Position - forward  
 Head of Material - low  
 Mix Temperature - 298°F  
 Paver Speed - 47.4 ft/min

Test Section - S-6  
 Screed Position - forward  
 Head of Material - high  
 Mix Temperature - 295°F  
 Paver Speed - 52.9 ft/min

Test Section - S-7  
 Screed Position - forward  
 Head of Material - high  
 Mix Temperature - none  
 Paver Speed - 52.9 ft/min

Test Section - S-8  
 Screed Position - forward  
 Head of Material - high  
 Mix Temperature - 300°F  
 Paver Speed - 14.0 ft/min

Test Section - S-9  
 Screed Position - back  
 Head of Material - middle  
 Mix Temperature - 295°F  
 Paver Speed - 59.3 ft/min

# International Roughness Index (IRI)

## FM 2920 Eastbound Right Wheelpath

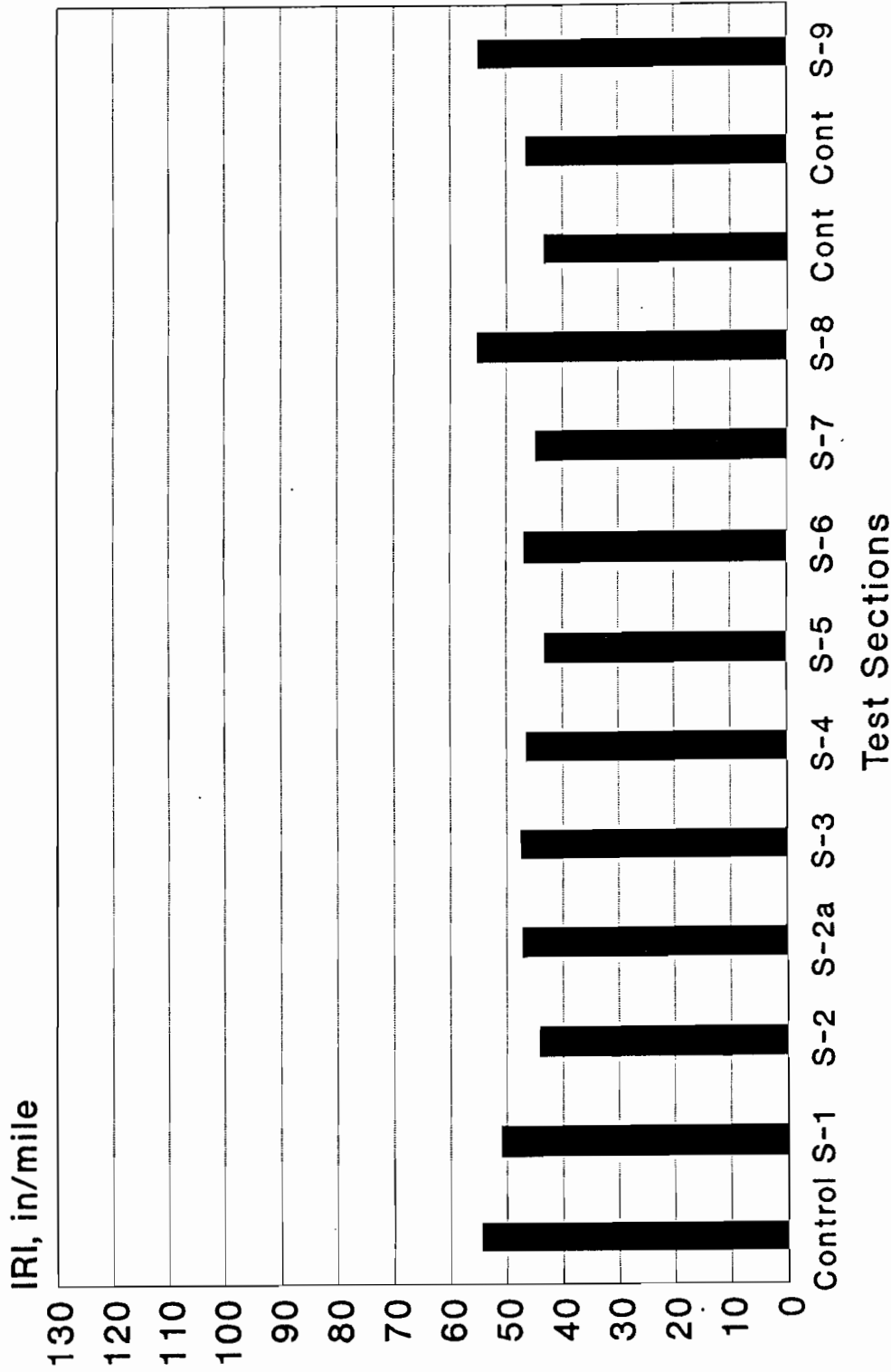


Figure A-17.

Test Section - S-1  
 Screed Position - forward  
 Head of Material - middle  
 Mix Temperature - 290°F  
 Paver Speed - 65.5 ft/min

Test Section - S-2  
 Screed Position - forward  
 Head of Material - low  
 Mix Temperature - 295°F  
 Paver Speed - 58.0 ft/min

Test Section - S-2a  
 Screed Position - forward  
 Head of Material - low  
 Mix Temperature - 290°F  
 Paver Speed - 50.3 ft/min

Test Section - S-3  
 Screed Position - forward  
 Head of Material - high  
 Mix Temperature - 305°F  
 Paver Speed - 48.0 ft/min

Test Section - S-4  
 Screed Position - forward  
 Head of Material - middle  
 Mix Temperature - 300°F  
 Paver Speed - 47.0 ft/min

Test Section - S-5  
 Screed Position - forward  
 Head of Material - low  
 Mix Temperature - 298°F  
 Paver Speed - 47.4 ft/min

Test Section - S-6  
 Screed Position - forward  
 Head of Material - high  
 Mix Temperature - 295°F  
 Paver Speed - 52.9 ft/min

Test Section - S-7  
 Screed Position - forward  
 Head of Material - high  
 Mix Temperature - none  
 Paver Speed - 52.9 ft/min

Test Section - S-8  
 Screed Position - forward  
 Head of Material - high  
 Mix Temperature - 300°F  
 Paver Speed - 14.0 ft/min

Test Section - S-9  
 Screed Position - back  
 Head of Material - middle  
 Mix Temperature - 295°F  
 Paver Speed - 59.3 ft/min

# International Roughness Index (IRI)

## FM 2920 Eastbound Right Not Wheelpath

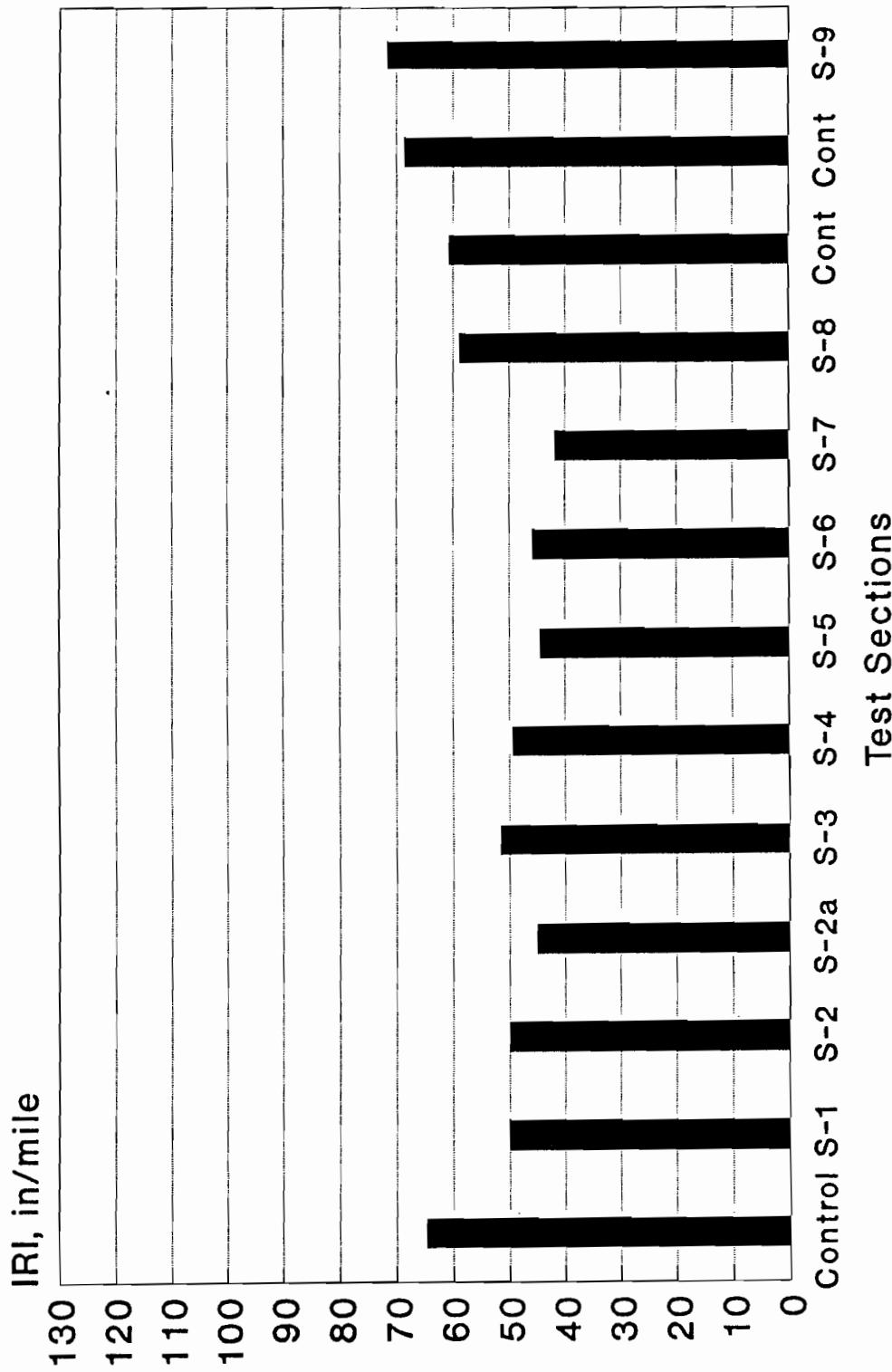


Figure A-18.

Test Section - S-1  
 Screed Position - forward  
 Head of Material - middle  
 Mix Temperature - 290°F  
 Paver Speed - 65.5 ft/min

Test Section - S-2  
 Screed Position - forward  
 Head of Material - low  
 Mix Temperature - 295°F  
 Paver Speed - 58.0 ft/min

Test Section - S-2a  
 Screed Position - forward  
 Head of Material - low  
 Mix Temperature - 290°F  
 Paver Speed - 50.3 ft/min

Test Section - S-3  
 Screed Position - forward  
 Head of Material - high  
 Mix Temperature - 305°F  
 Paver Speed - 48.0 ft/min

Test Section - S-4  
 Screed Position - forward  
 Head of Material - middle  
 Mix Temperature - 300°F  
 Paver Speed - 47.0 ft/min

Test Section - S-5  
 Screed Position - forward  
 Head of Material - low  
 Mix Temperature - 298°F  
 Paver Speed - 47.4 ft/min

Test Section - S-6  
 Screed Position - forward  
 Head of Material - high  
 Mix Temperature - 295°F  
 Paver Speed - 52.9 ft/min

Test Section - S-7  
 Screed Position - forward  
 Head of Material - high  
 Mix Temperature - none  
 Paver Speed - 52.9 ft/min

Test Section - S-8  
 Screed Position - forward  
 Head of Material - high  
 Mix Temperature - 300°F  
 Paver Speed - 14.0 ft/min

Test Section - S-9  
 Screed Position - back  
 Head of Material - middle  
 Mix Temperature - 295°F  
 Paver Speed - 59.3 ft/min

# International Roughness Index (IRI)

## FM 2920 Eastbound Left Wheelpath

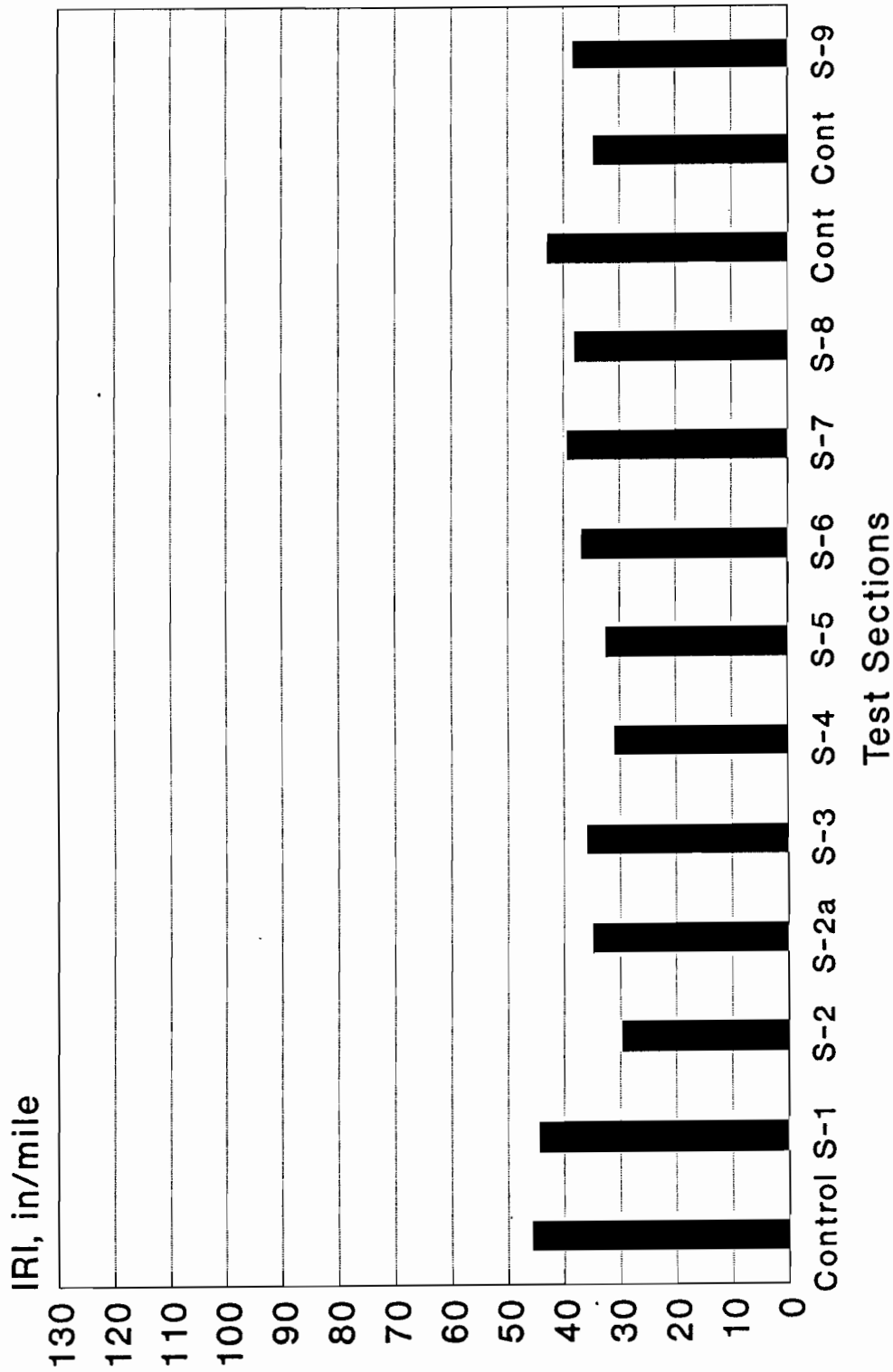


Figure A-19.

# International Roughness Index (IRI)

## FM 2920 Eastbound Left Not Wheelpath

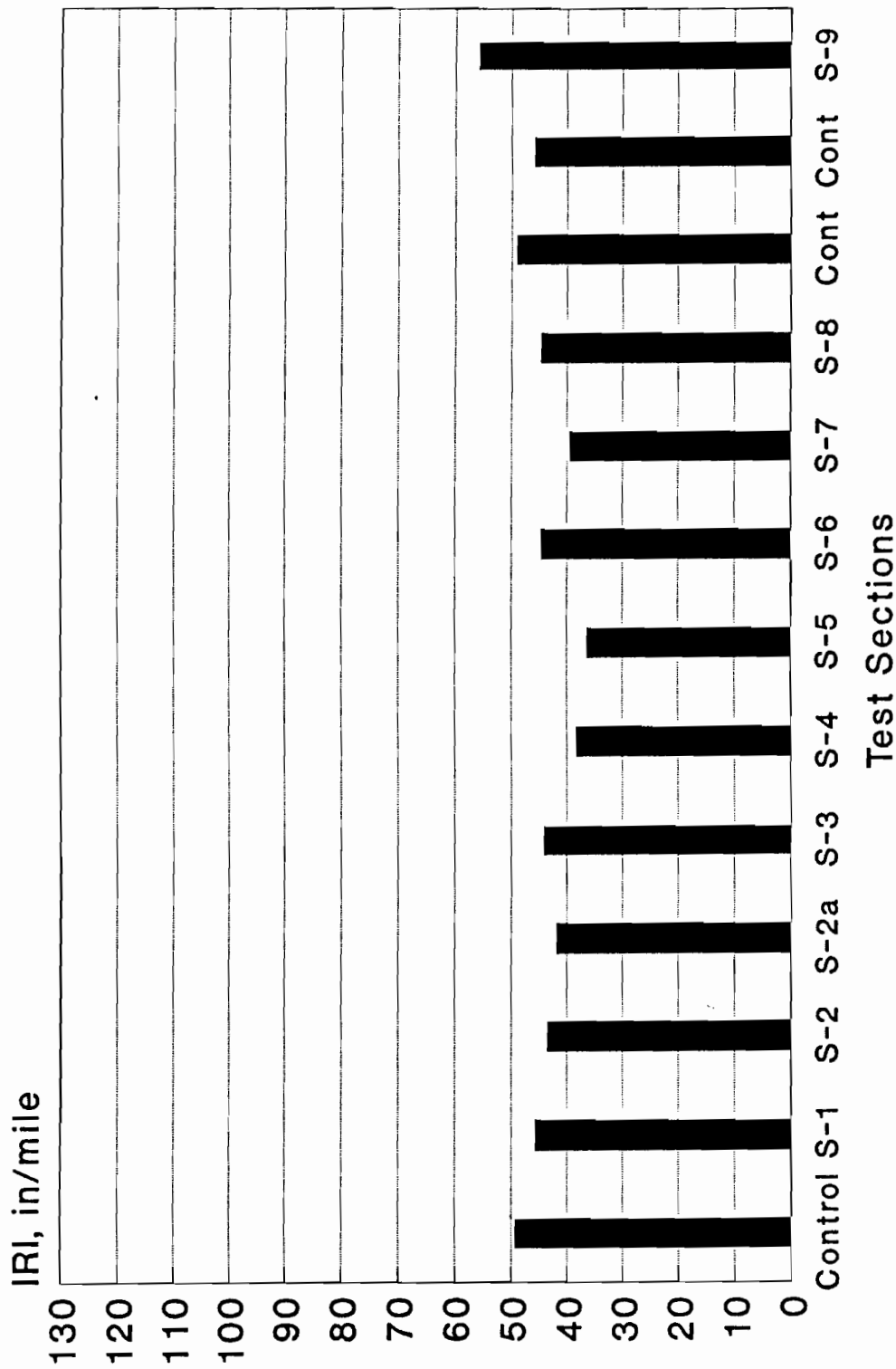


Figure A-20.

Test Section - S-1  
 Screed Position - forward  
 Head of Material - middle  
 Mix Temperature - 290°F  
 Paver Speed - 65.5 ft/min

Test Section - S-2  
 Screed Position - forward  
 Head of Material - low  
 Mix Temperature - 295°F  
 Paver Speed - 58.0 ft/min

Test Section - S-2a  
 Screed Position - forward  
 Head of Material - low  
 Mix Temperature - 290°F  
 Paver Speed - 50.3 ft/min

Test Section - S-3  
 Screed Position - forward  
 Head of Material - high  
 Mix Temperature - 305°F  
 Paver Speed - 48.0 ft/min

Test Section - S-4  
 Screed Position - forward  
 Head of Material - middle  
 Mix Temperature - 300°F  
 Paver Speed - 47.0 ft/min

Test Section - S-5  
 Screed Position - forward  
 Head of Material - low  
 Mix Temperature - 298°F  
 Paver Speed - 47.4 ft/min

Test Section - S-6  
 Screed Position - forward  
 Head of Material - high  
 Mix Temperature - 295°F  
 Paver Speed - 52.9 ft/min

Test Section - S-7  
 Screed Position - forward  
 Head of Material - high  
 Mix Temperature - none  
 Paver Speed - 52.9 ft/min

Test Section - S-8  
 Screed Position - forward  
 Head of Material - high  
 Mix Temperature - 300°F  
 Paver Speed - 14.0 ft/min

Test Section - S-9  
 Screed Position - back  
 Head of Material - middle  
 Mix Temperature - 295°F  
 Paver Speed - 59.3 ft/min

# International Roughness Index (IRI)

## FM 2920 Westbound Right Wheelpath

Test Section - S-10  
 Screed Position - back  
 Head of Material - low  
 Mix Temperature - 275°F  
 Paver Speed - 50.7 ft/min

Test Section - S-11  
 Screed Position - back  
 Head of Material - middle  
 Mix Temperature - 298°F  
 Paver Speed - 46.2 ft/min

Test Section - S-12  
 Screed Position - back  
 Head of Material - high  
 Mix Temperature - 285°F  
 Paver Speed - 45.0 ft/min

Test Section - S-13  
 Screed Position - back  
 Head of Material - low  
 Mix Temperature - 285°F  
 Paver Speed - 42.4 ft/min

Test Section - S-14  
 Screed Position - back  
 Head of Material - middle  
 Mix Temperature - 278°F  
 Paver Speed - 43.4 ft/min

Test Section - S-15  
 Screed Position - back  
 Head of Material - high  
 Mix Temperature - 285°F  
 Paver Speed - 41.4 ft/min

Test Section - S-16  
 Screed Position - back  
 Head of Material - high  
 Mix Temperature - 275°F  
 Paver Speed - 77.5 ft/min

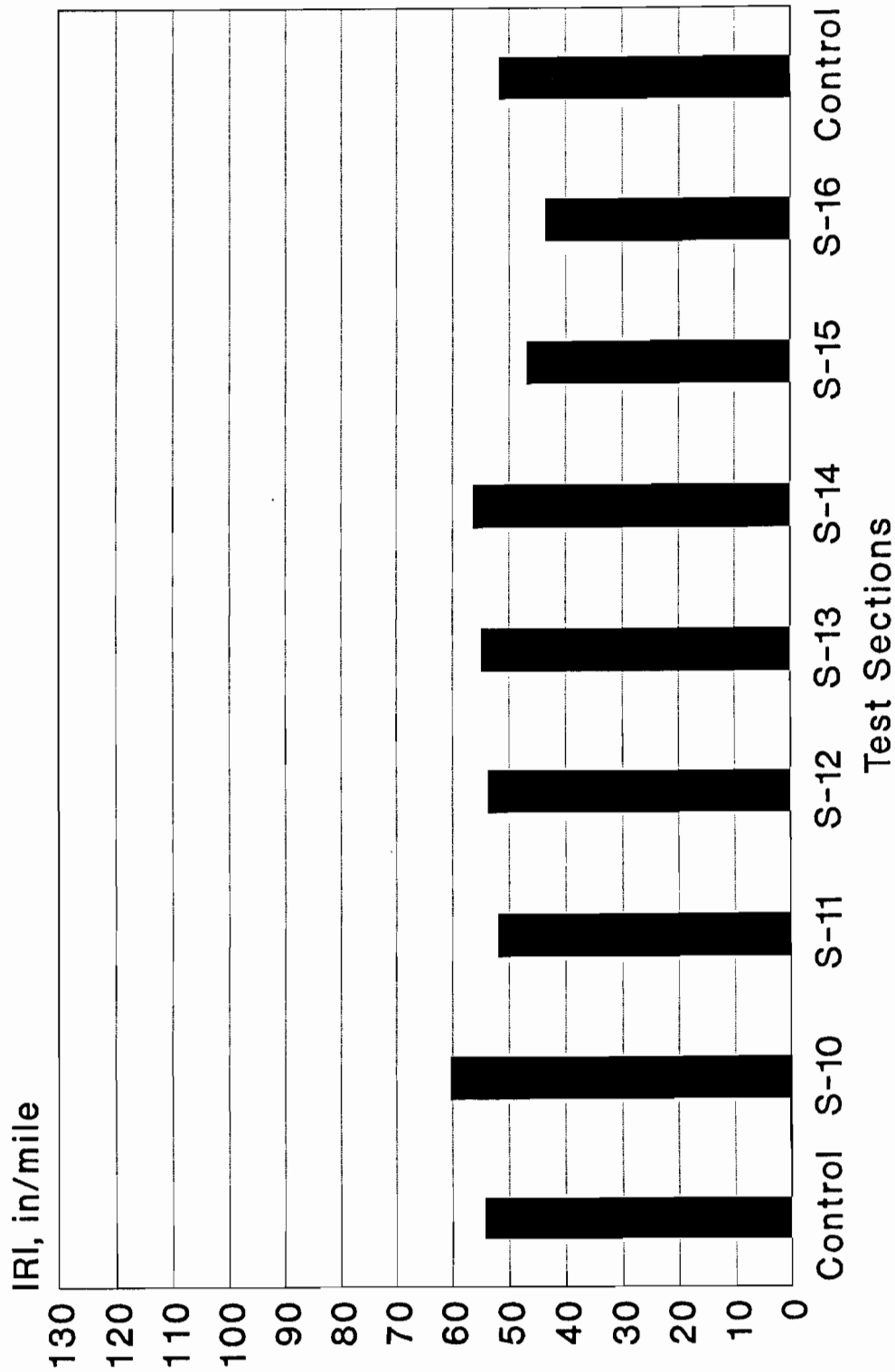


Figure A-21.

# International Roughness Index (IRI)

## FM 2920 Westbound Right Not Wheelpath

Test Section - S-10  
 Screed Position - back  
 Head of Material - low  
 Mix Temperature - 275°F  
 Paver Speed - 50.7 ft/min

Test Section - S-11  
 Screed Position - back  
 Head of Material - middle  
 Mix Temperature - 298°F  
 Paver Speed - 46.2 ft/min

Test Section - S-12  
 Screed Position - back  
 Head of Material - high  
 Mix Temperature - 285°F  
 Paver Speed - 45.0 ft/min

Test Section - S-13  
 Screed Position - back  
 Head of Material - low  
 Mix Temperature - 285°F  
 Paver Speed - 42.4 ft/min

Test Section - S-14  
 Screed Position - back  
 Head of Material - middle  
 Mix Temperature - 278°F  
 Paver Speed - 43.4 ft/min

Test Section - S-15  
 Screed Position - back  
 Head of Material - high  
 Mix Temperature - 285°F  
 Paver Speed - 41.4 ft/min

Test Section - S-16  
 Screed Position - back  
 Head of Material - high  
 Mix Temperature - 275°F  
 Paver Speed - 77.5 ft/min

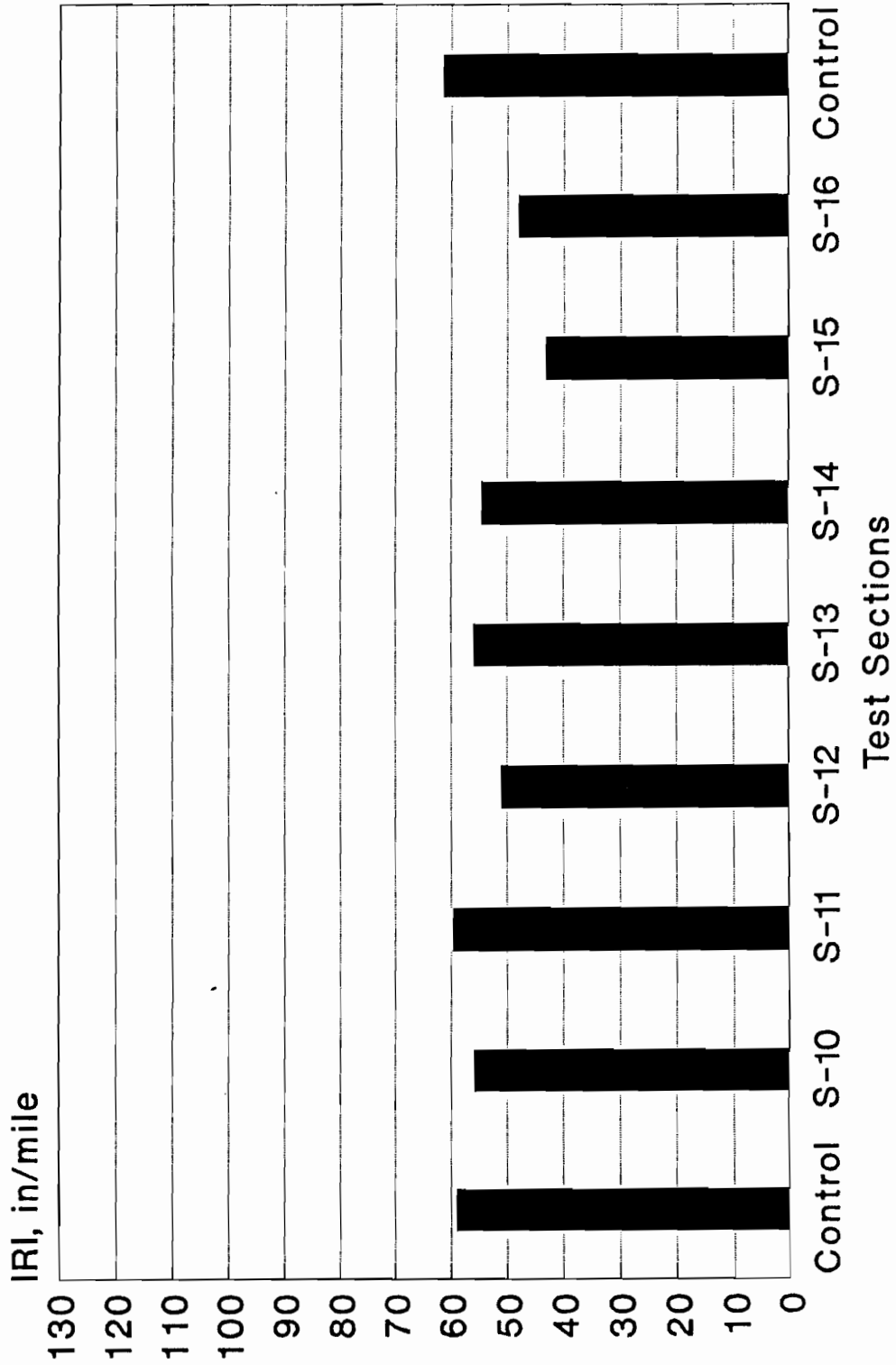


Figure A-22.



# International Roughness Index (IRI)

## FM 2920 Westbound Left Wheelpath

Test Section - S-10  
 Screed Position - back  
 Head of Material - low  
 Mix Temperature - 275°F  
 Paver Speed - 50.7 ft/min

Test Section - S-11  
 Screed Position - back  
 Head of Material - middle  
 Mix Temperature - 298°F  
 Paver Speed - 46.2 ft/min

Test Section - S-12  
 Screed Position - back  
 Head of Material - high  
 Mix Temperature - 285°F  
 Paver Speed - 45.0 ft/min

Test Section - S-13  
 Screed Position - back  
 Head of Material - low  
 Mix Temperature - 285°F  
 Paver Speed - 42.4 ft/min

Test Section - S-14  
 Screed Position - back  
 Head of Material - middle  
 Mix Temperature - 278°F  
 Paver Speed - 43.4 ft/min

Test Section - S-15  
 Screed Position - back  
 Head of Material - high  
 Mix Temperature - 285°F  
 Paver Speed - 41.4 ft/min

Test Section - S-16  
 Screed Position - back  
 Head of Material - high  
 Mix Temperature - 275°F  
 Paver Speed - 77.5 ft/min

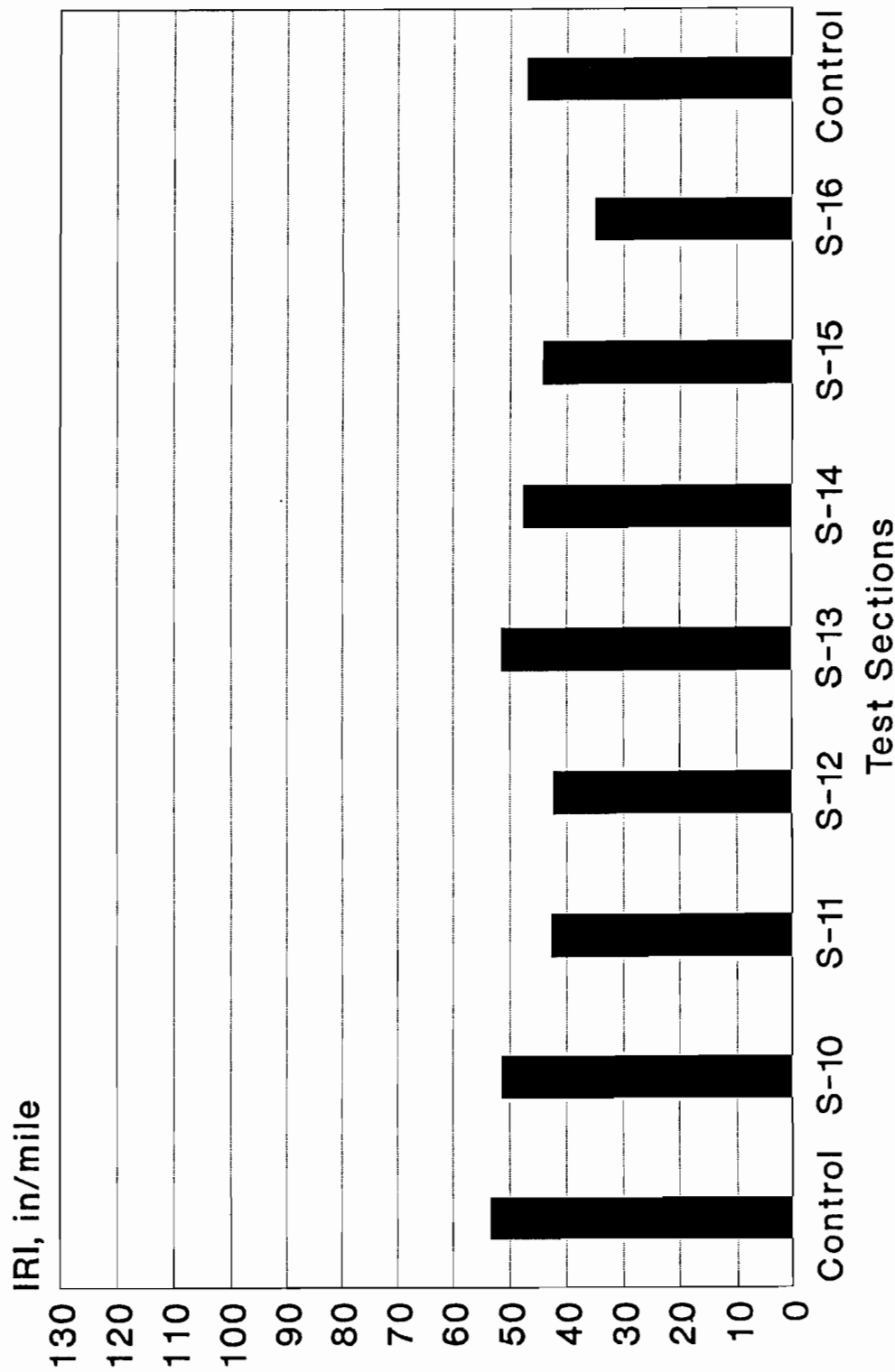


Figure A-23.

# International Roughness Index (IRI)

## FM 2920 Westbound Left Not Wheelpath

Test Section - S-10  
 Screed Position - back  
 Head of Material - low  
 Mix Temperature - 275°F  
 Paver Speed - 50.7 ft/min

Test Section - S-11  
 Screed Position - back  
 Head of Material - middle  
 Mix Temperature - 298°F  
 Paver Speed - 46.2 ft/min

Test Section - S-12  
 Screed Position - back  
 Head of Material - high  
 Mix Temperature - 285°F  
 Paver Speed - 45.0 ft/min

Test Section - S-13  
 Screed Position - back  
 Head of Material - low  
 Mix Temperature - 285°F  
 Paver Speed - 42.4 ft/min

Test Section - S-14  
 Screed Position - back  
 Head of Material - middle  
 Mix Temperature - 278°F  
 Paver Speed - 43.4 ft/min

Test Section - S-15  
 Screed Position - back  
 Head of Material - high  
 Mix Temperature - 285°F  
 Paver Speed - 41.4 ft/min

Test Section - S-16  
 Screed Position - back  
 Head of Material - high  
 Mix Temperature - 275°F  
 Paver Speed - 77.5 ft/min

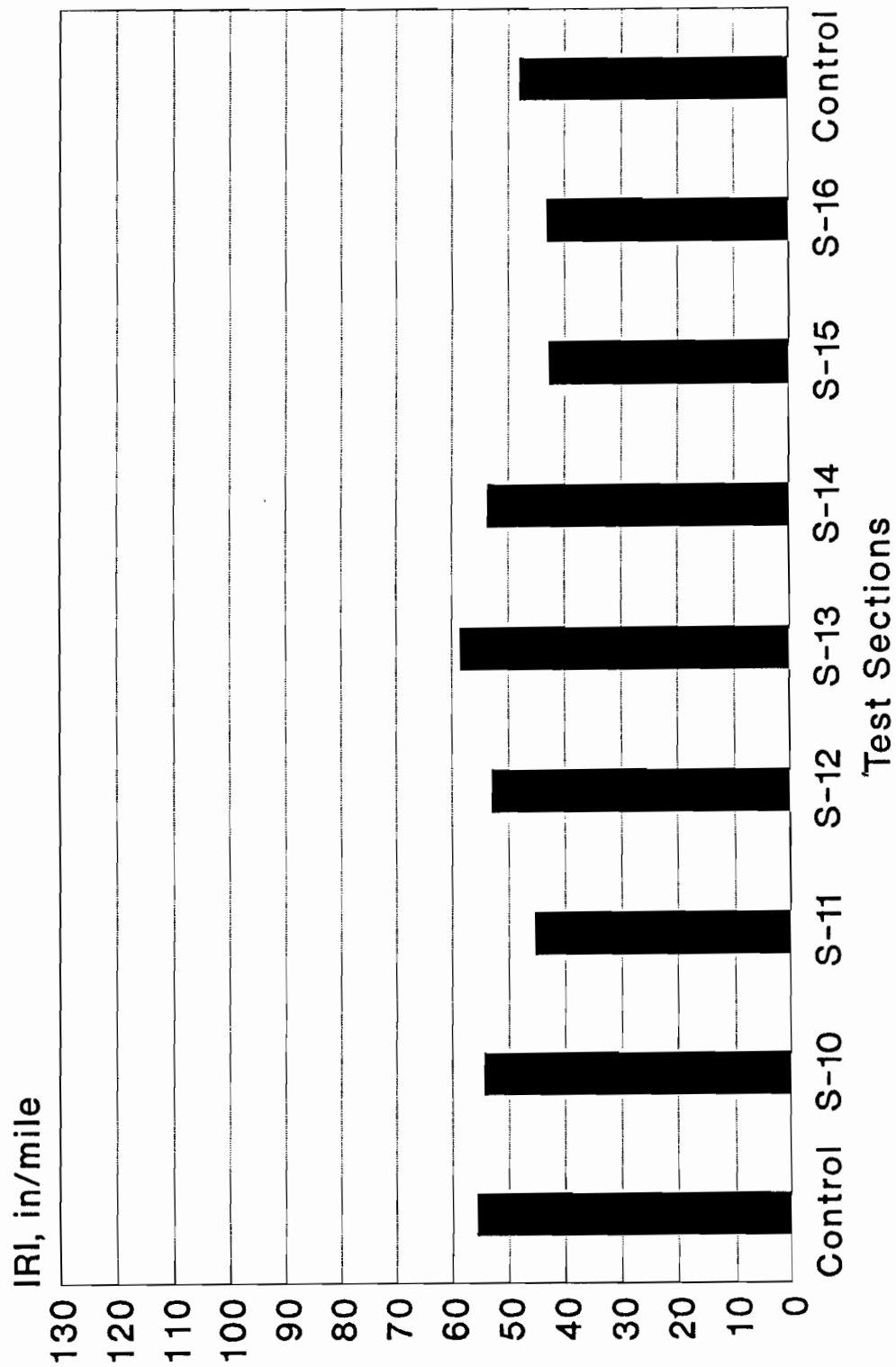


Figure A-24.

**APPENDIX B**  
**Examples of Blaw Knox**  
**Roughness Measurements**



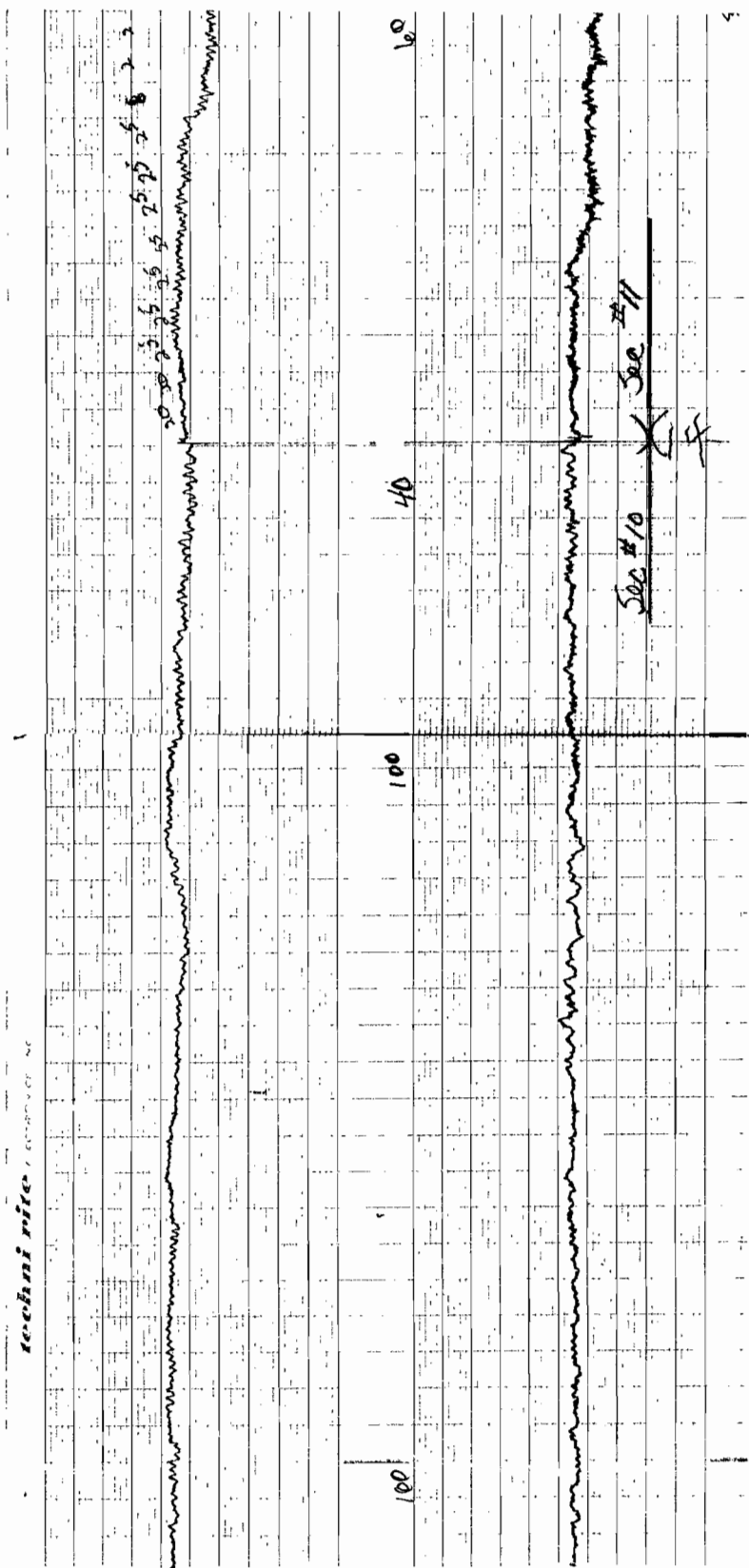


Figure B-1.

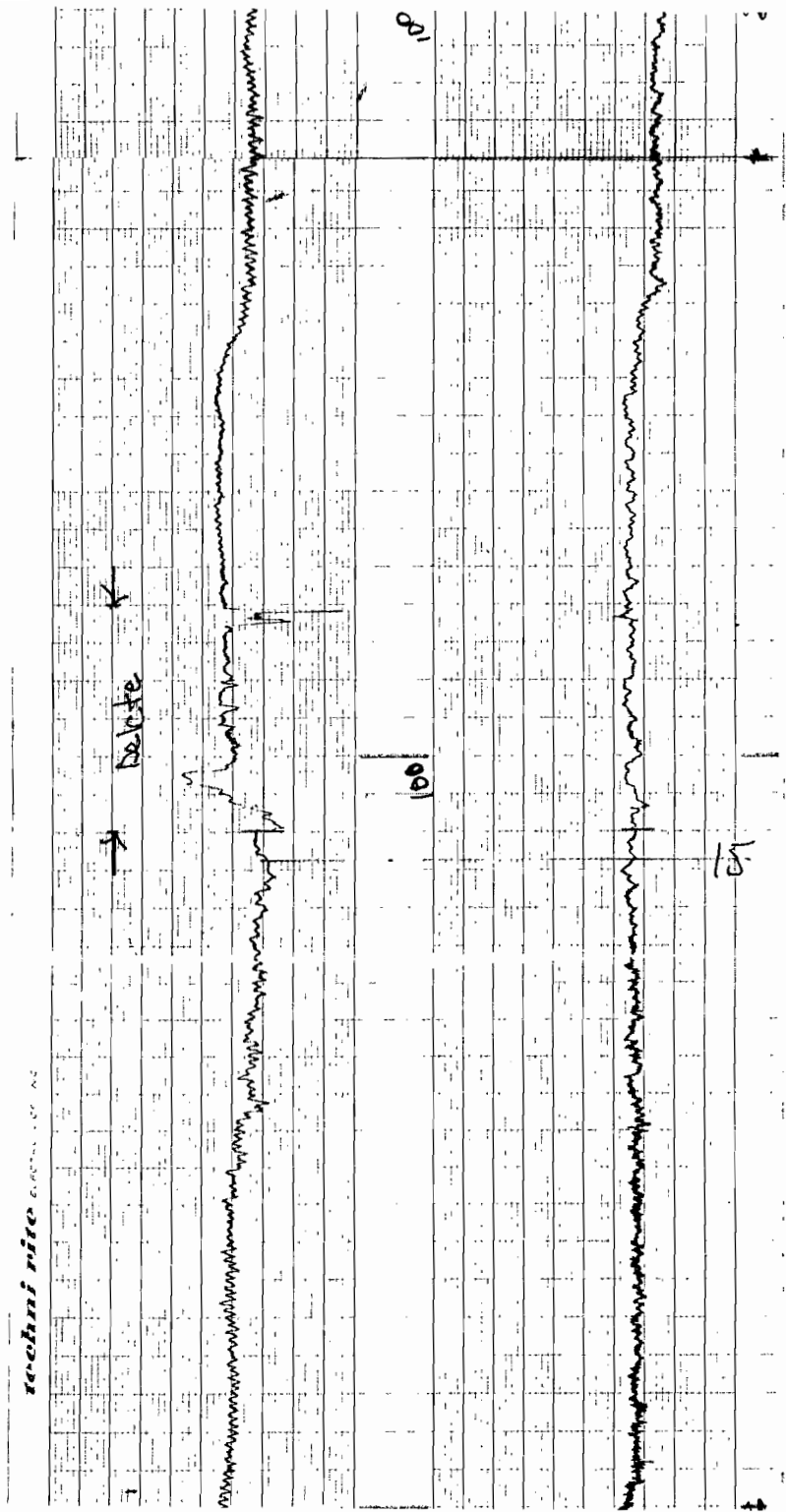


Figure B-2.

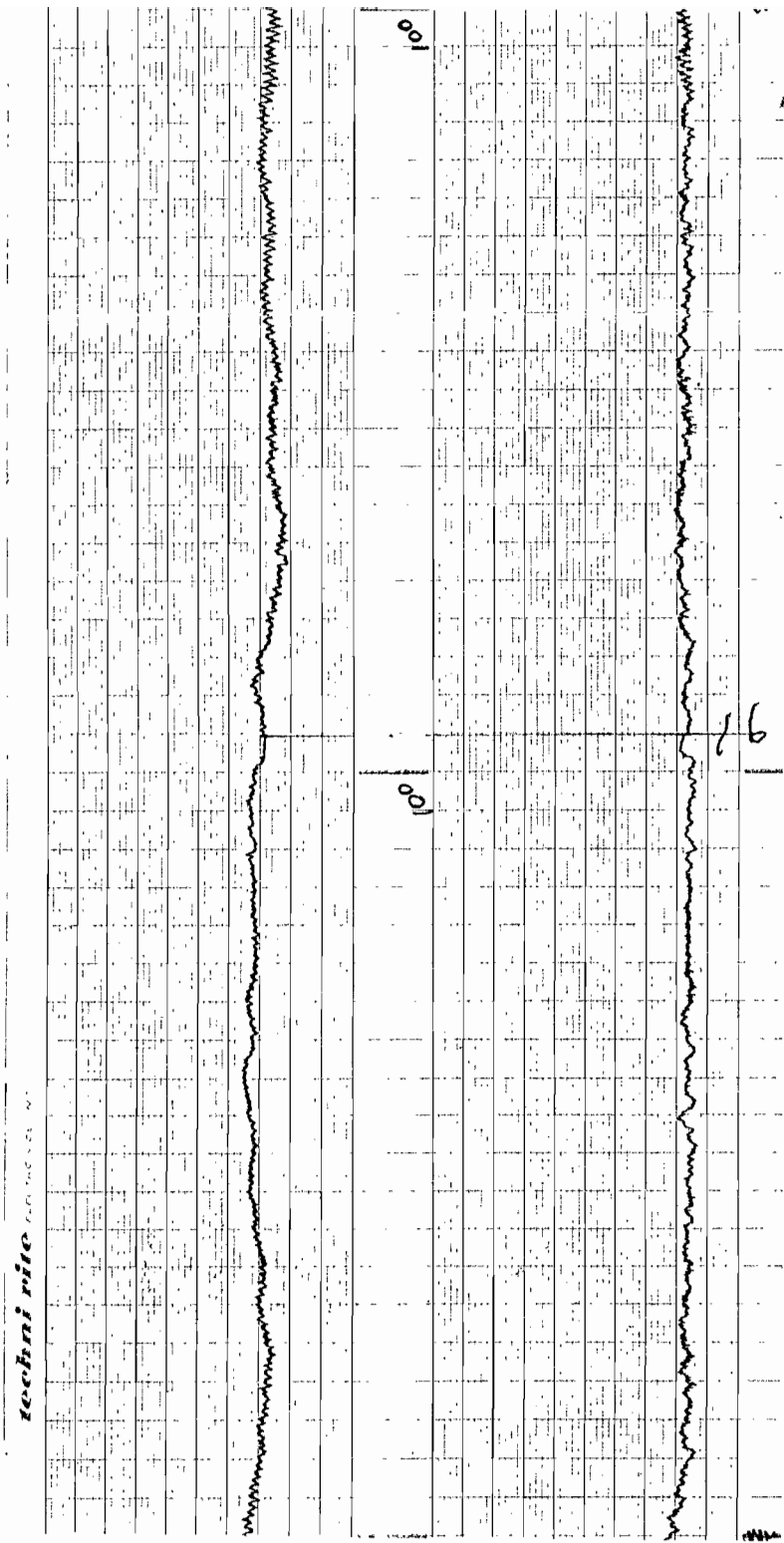


Figure B-3.

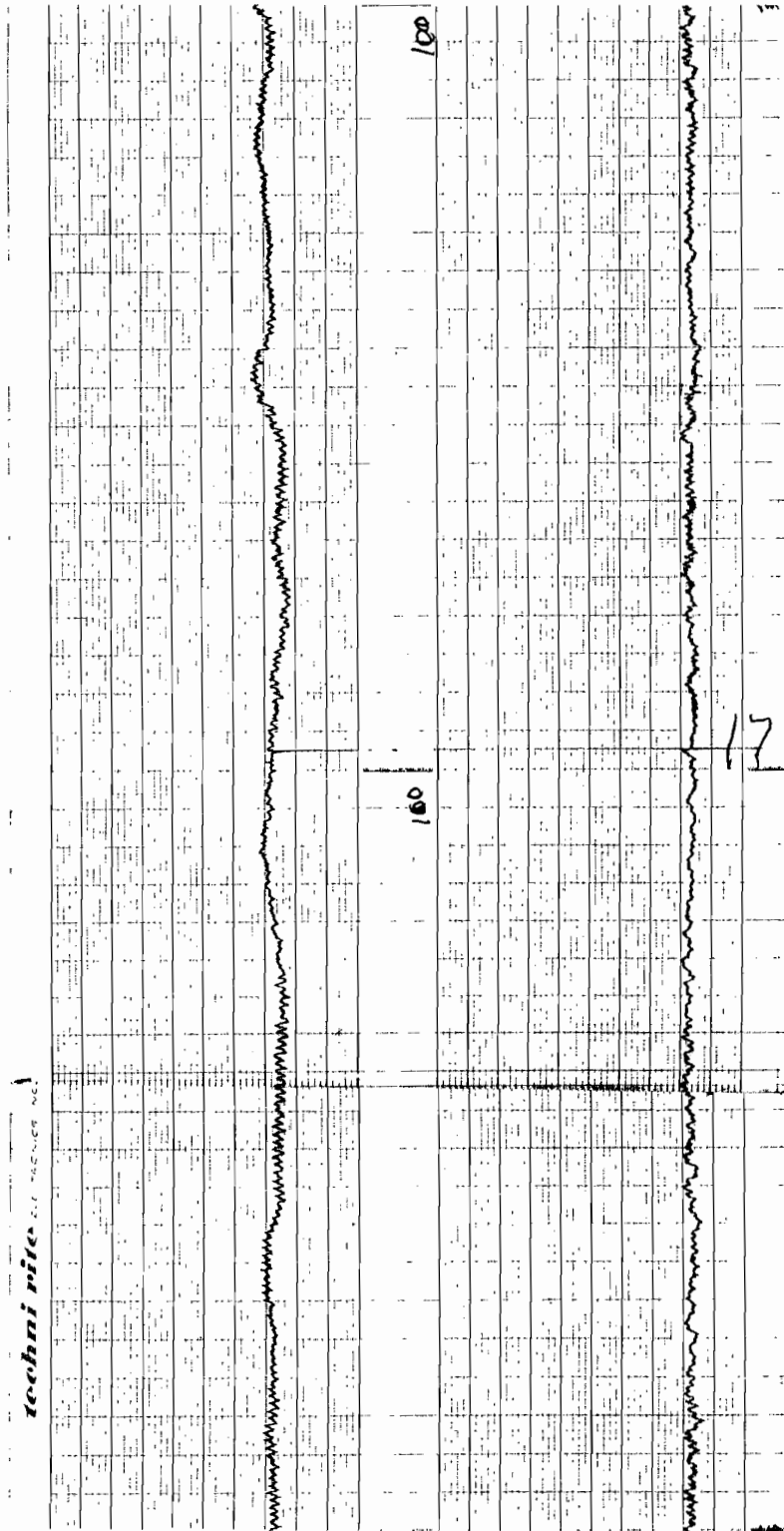


Figure B-4.



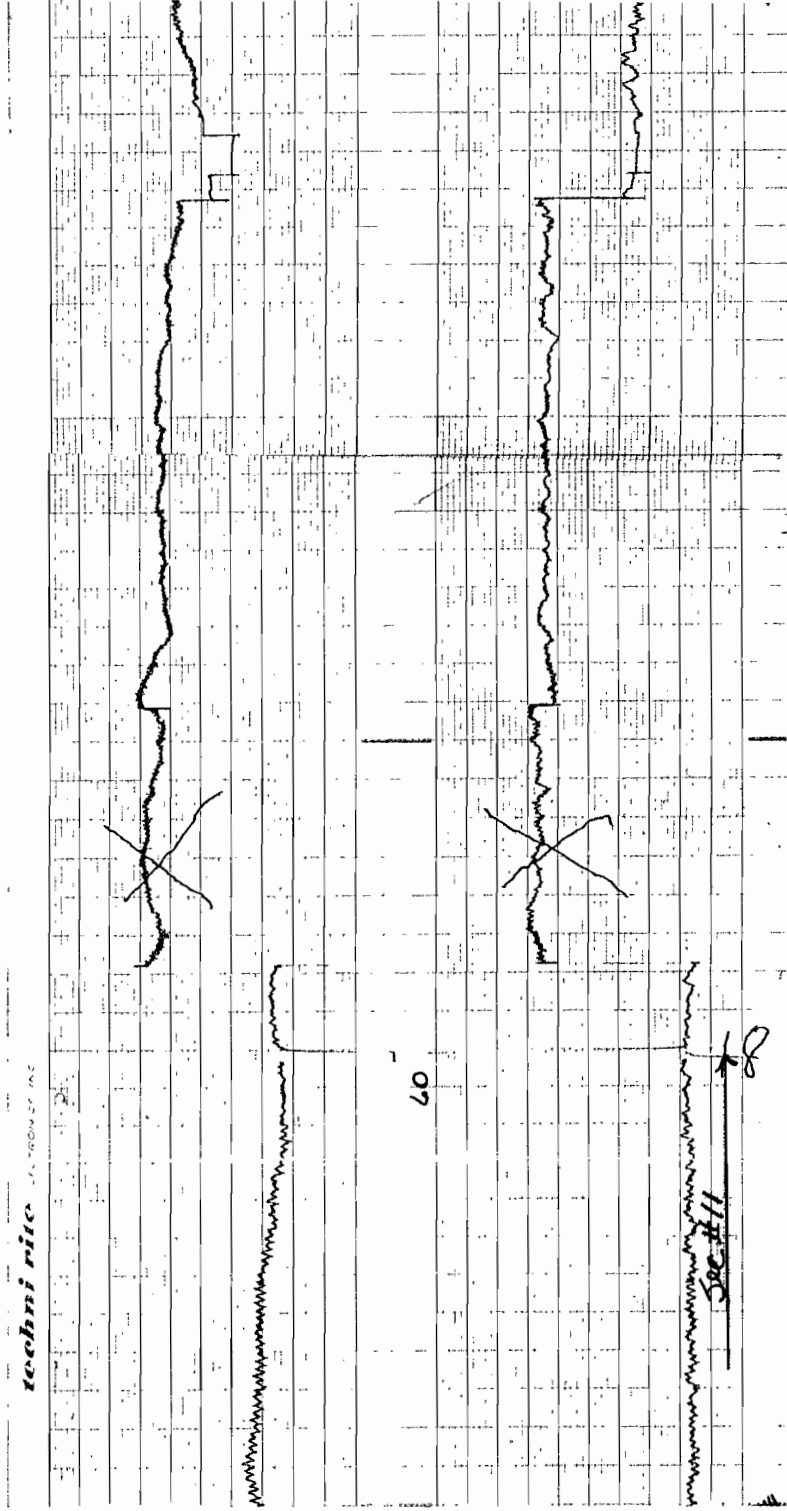


Figure B-5.

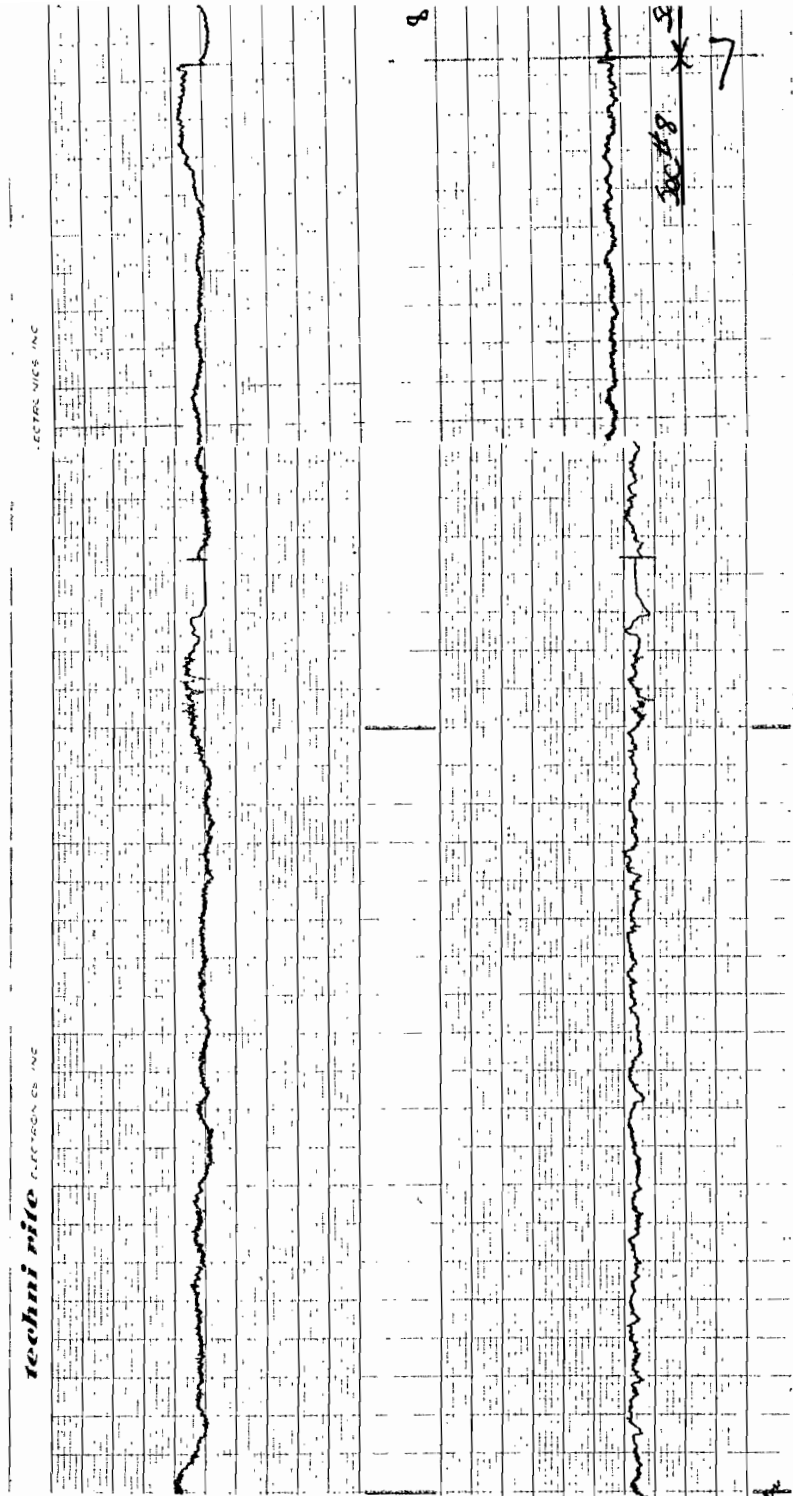


Figure B-6.

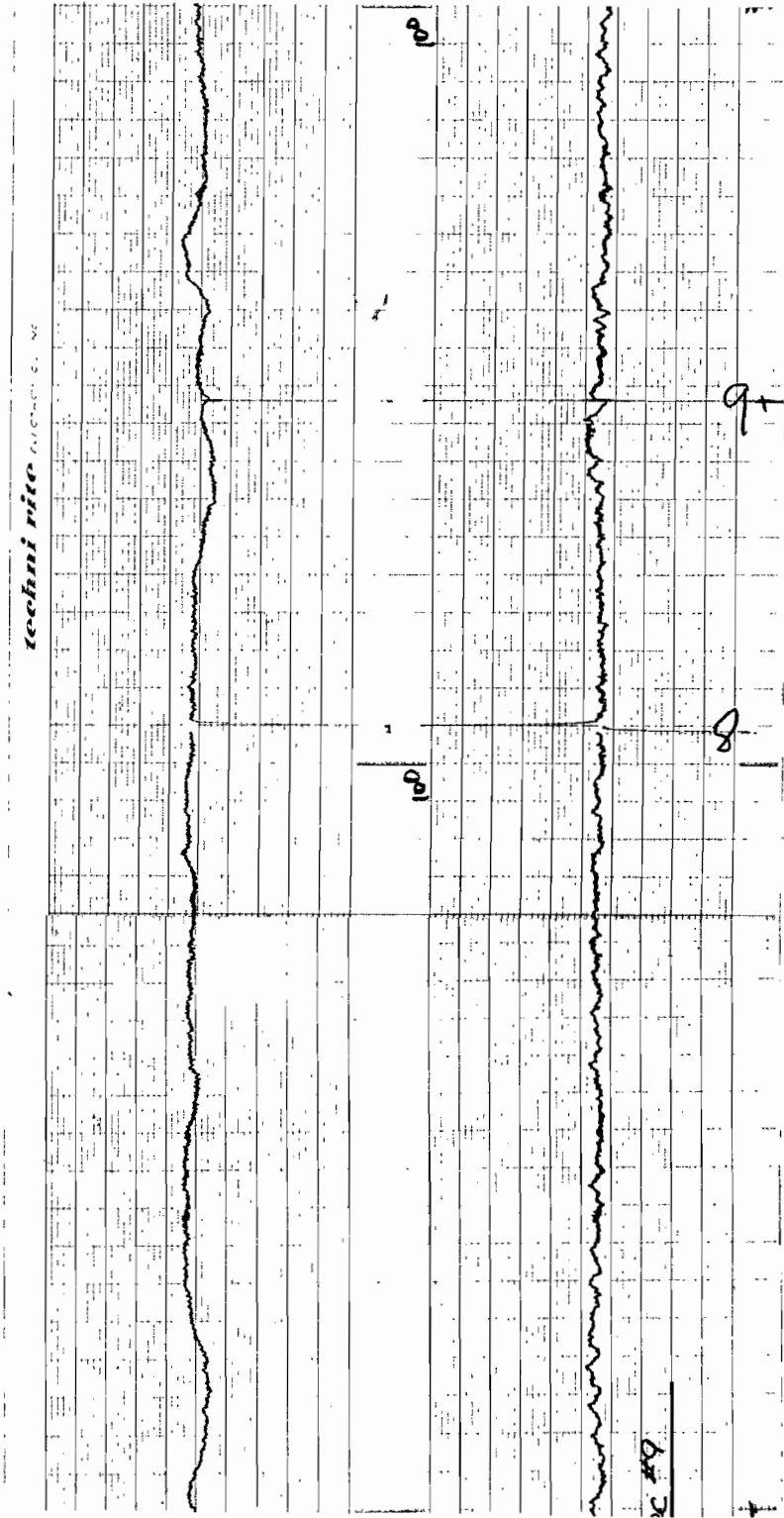


Figure B-7.

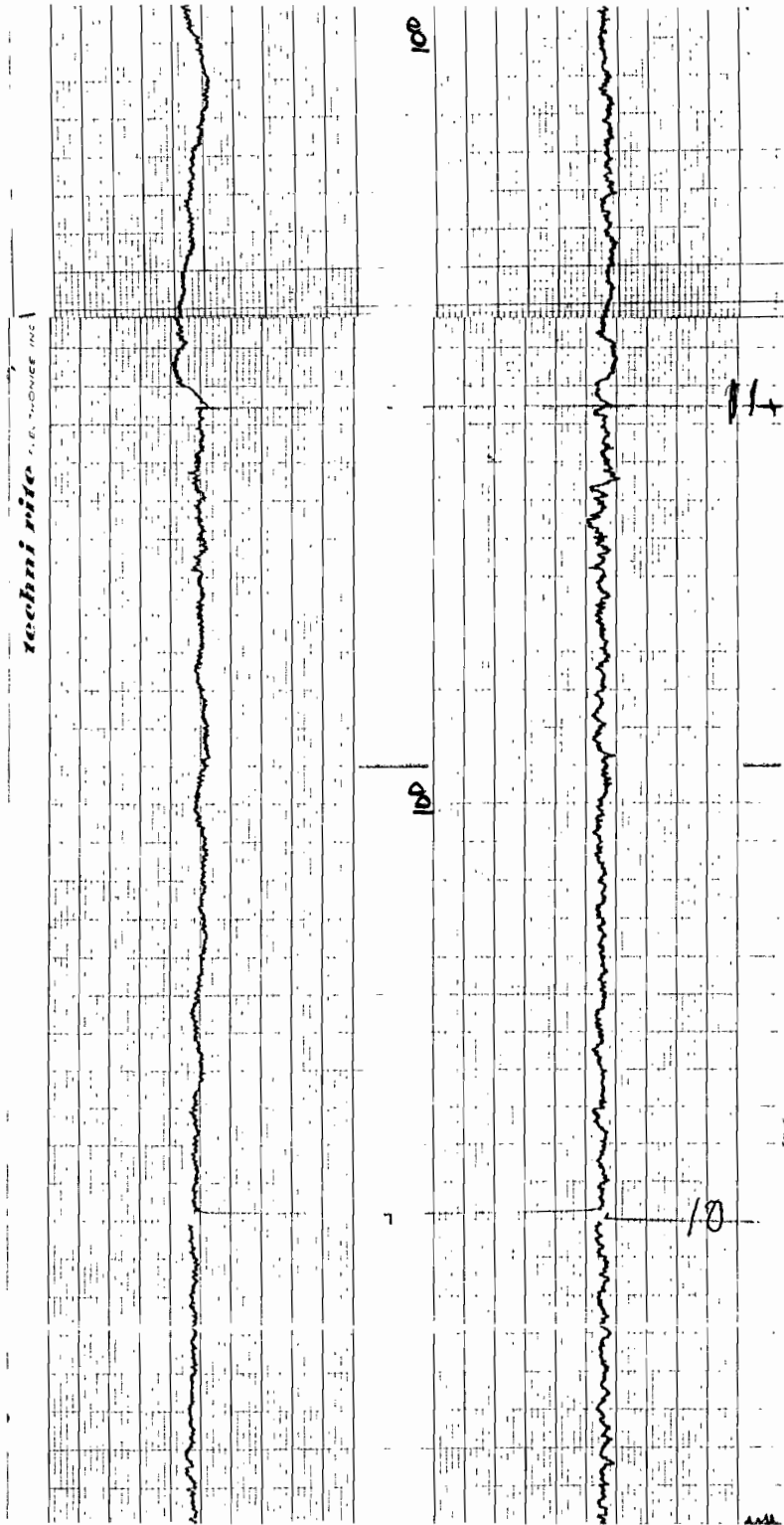


Figure B-8.

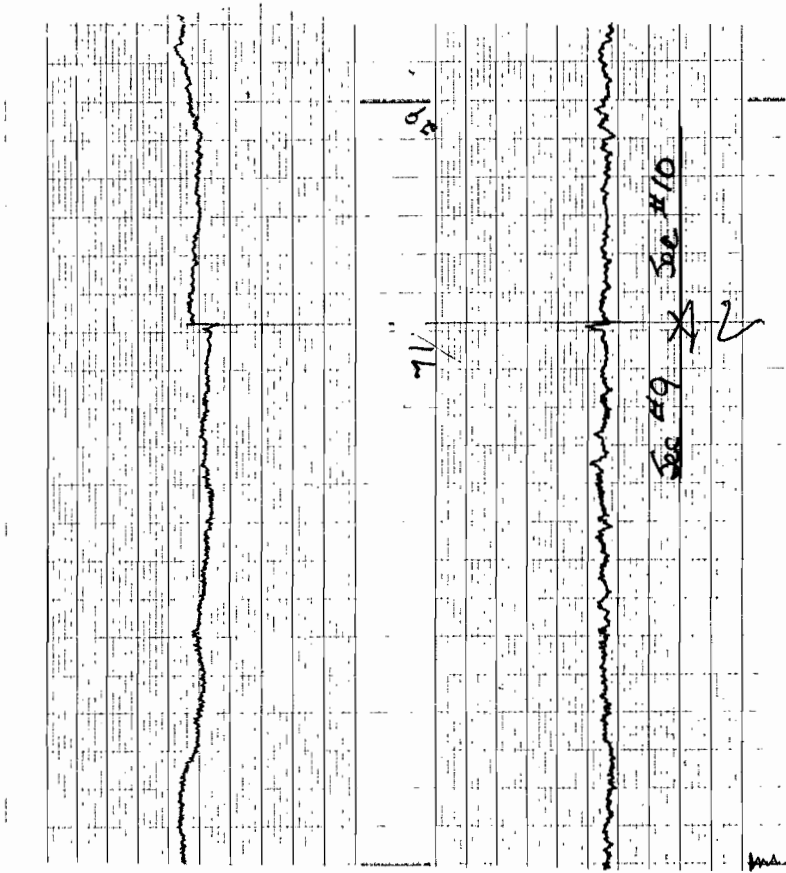


Figure B-9.

