TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No. FHWA/TX-88/448-1F	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle DESIGN AND CONSTRUCTION OF MULTIPLE SEAL COATS		5. Report Date November 1988
		6. Performing Organization Code
7. Author(s) Cindy K. Estakhri and Miguel A. Gonzalez		8. Performing Organization Report No. Research Report 448-1F
9. Performing Organization Name and Address Texas Transportation Institute The Texas A&M University System College Station, Texas 77843		10. Work Unit No.
		11. Contract or Grant No. Study No. 2-9-85-448
12. Sponsoring Agency Name and Address Texas State Department of Highways and Public Transportation; Transportation Planning Division P. O. Box 5051 Austin, Texas 78763		13. Type of Report and Period Covered Final - September 1985 August 1988
		14. Sponsoring Agency Code

15. Supplementary Notes

Research performed in cooperation with DOT, FHWA
Research Study Title: Multiple Seal Coat Design and Construction

16. Abstract

The primary objectives of this study were to establish design and construction guidelines for multiple seal coats for the Texas State Department of Highways and Public Transportation. A multiple seal coat is a bituminous surface that results from two or more successive alternating applications of bituminous binder and cover aggregate to an existing paved surface, usually with the smaller aggregate sizes used in each successive layer.

From a thorough review of the literature, it was concluded that the key to executing an effective design for multiple seal coats was in the ability to measure the available void space in multiple stone layers that could be filled with binder. A design method developed by the NITRR of South Africa which included a test procedure (Modified Tray Test) for measuring the void content and effective thickness of a stone layer was chosen for further field and laboratory investigation.

Based on a statistical analysis of a number of samples, the Modified Tray Test was found to be repeatable. It was also determined that a single sample of stone, as tested by means of the Modified Tray Test, gives a good indication of the overall void content and effective layer thickness for a particular type and grade of stone. The Modified Tray Test was also used to determine the void content and effective layer thickness of double seals made up of different combinations of four aggregate grades. A relationship was found between the effective layer thickness of a double seal and the sum of the bottom and top layers separately.

The design method was tested by fabricating multiple seal coats in the laboratory and field and, with modifications, was found to produce satisfactory performance.

17. Key Words Seal coat, multiple seal coat, surface treatment, double seal coat, double surface treatment, design guidelines, field performance, chip seal	18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service 5285 Port Royal Road Springfield, Virginia 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	176	

Form DOT F 1700.7 (8-69)

Design and Construction of Multiple Seal Coats

by

Cindy Estakhri

and

Miguel A. Gonzalez

Research Study Number 2-9-85-448

Multiple Seal Coat Design and Construction

Report No. 448-1F

Sponsored by the

Texas State Department of

Highways and Public Transportation

in cooperation

with the

United States Department of Transportation

Federal Highway Administration

Texas Transportation Institute

Texas A&M University

College Station, Texas 77843

November 1988

METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

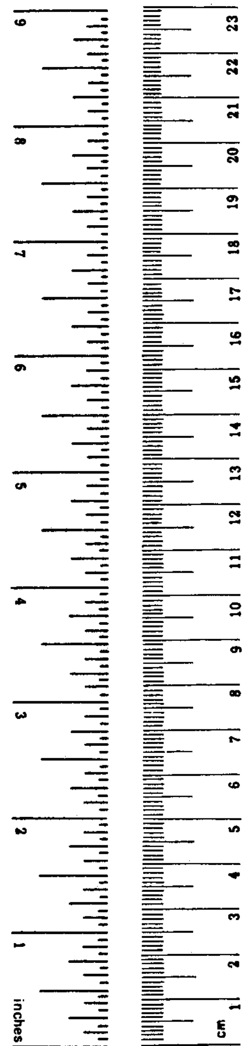
Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
in	inches	2.54	millimetres	mm
ft	feet	0.3048	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
	AREA			
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.0929	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
mi^2	square miles	2.59	kilometres squared	km^2
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^3	cubic feet	0.0328	metres cubed	m^3
yd^3	cubic yards	0.0765	metres cubed	m^3

NOTE: Volumes greater than 1000 L shall be shown in m^3.

TEMPERATURE (exact)

°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

* SI is the symbol for the International System of Measurements

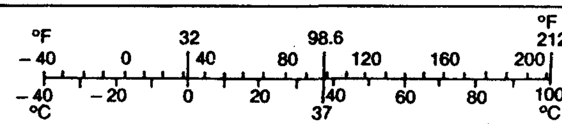


APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
	AREA			
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
km^2	kilometres squared	0.39	square miles	mi^2
ha	hectores (10 000 m^2)	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^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3

TEMPERATURE (exact)

°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



These factors conform to the requirement of FHWA Order 5190.1A.

SUMMARY

The primary objectives of this study were to establish design and construction guidelines for multiple seal coats for the Texas State Department of Highways and Public Transportation. A multiple seal coat is a bituminous surface that results from two or more successive alternating applications of bituminous binder and cover aggregate to an existing paved surface, usually with the smaller aggregate sizes used in each successive layer.

From a thorough review of the literature, it was concluded that the key to executing an effective design for multiple seal coats was in the ability to measure the available void space in multiple stone layers that could be filled with binder. A design method developed by the NITRR of South Africa which included a test procedure (Modified Tray Test) for measuring the void content and effective thickness of a stone layer was chosen for further field and laboratory investigation.

Crushed limestone that met the Texas specifications for grades 2,3,4 and 5 seal coat aggregate was used to evaluate the suitability of the Modified Tray Test for use in designing multiple seal coats. Based on a statistical analysis of a number of samples, the Modified Tray Test was found to be repeatable. It was also determined that a single sample of stone, as tested by means of the Modified Tray Test, gives a good indication of the overall void content and effective layer thickness for a particular type and grade of stone. The Modified Tray Test was also used to determine the void content and effective layer thickness of double seals made up of different combinations of four aggregate grades. A relationship was found between the effective layer thickness of the double seal and the sum of the bottom and top layers separately.

The design method was tested by fabricating multiple seal coats in the laboratory as well as in the field and, with some modifications, was found to produce satisfactory field performance.

IMPLEMENTATION

Implementing the results of this study will require the Texas State Department of Highways and Public Transportation to apply two new test procedures: the Modified Tray Test and the Ball Penetration Test. Both test procedures require inexpensive equipment and can be performed with little or no training by personnel. A step-by-step procedure outlining the tests,the design procedure and construction guidelines discussed in this report will be prepared in the form of a Laboratory/Field Manual for use by laboratory and field engineers with the cooperation of the Department's Research Division.

DISCLAIMER

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

CHAPTER I

INTRODUCTION

A multiple seal coat or multiple chip seal is a bituminous surface that results from two or more successive alternating applications of bituminous binder and cover aggregate to an existing paved surface, usually with smaller aggregate sizes used in each successive layer of the system. A multiple surface treatment is a similar bituminous surface but applied to a prepared pavement base such as compacted gravel, crushed limestone or a stabilized soil.

In Texas, seal coats are used as the principal maintenance tool on farm to market pavements and much of the state and U.S. facilities. This means potentially half of all the pavements maintained by the State Department of Highways and Public Transportation receive seal coats to extend pavement life.

The relatively high quality possible with multiple seal coats if properly designed and constructed means that pavement life should be extended well beyond that expected with single seal coats, and that in some circumstances multiple seals may be substituted for asphalt concrete overlay construction.

Although design and construction of single seal coats is well documented, less information is available for multiple seal coats. As the use of multiple seal coats increases in Texas, an objective procedure is necessary for design and construction of these systems.

The objectives of this study were to develop design and construction guidelines for building multiple seal coats and to identify those circumstances where multiple seal coats can be more effective than single seal coats. However, before establishing a design procedure for multiple seals, it is necessary to have a good understanding of the design principles and guidelines already established for single seal coats as many of these will apply to multiple seal coats, as well.

During the early development of surface treatments or seal coats, no formal design method was available, and the success of the treatment was due largely to the fact that this type of work has been handled, in general, by field engineers having considerable background and experience.

Hanson (1), a New Zealand engineer, was the first engineer to make a scientific study of the performance and design of single surface treatments. All subsequent contributions have followed Hanson's basic principles. He stated that the rate of application of both stone and binder are controlled by the average least dimension (ALD) of the single-size stone. He also emphasized that the voids in a single layer of stone determine the quantity of binder to be applied. (1)

Hanson's findings are, however, in some dispute today, mainly because he developed his basic principles using a rather soft aggregate which crushed under the action of the steel-wheel rollers used during the construction of the treatment and under traffic. This factor has caused his findings to be limited to the aggregate and construction techniques used in New Zealand in the early 1930's.

Important laboratory work has been done through the years towards the establishment of a rational relation between the amount and size of the cover aggregate and the quantity of binder to be applied. Considerable progress has been made. However, because of the many additional factors that can affect the performance and behavior of seal coats and surface treatments, it is probable that substantial modifications will have to be made in any selected method in order to meet the final desired quality.

Presently, the application of seal coats in the United States is more of an art than a science. Many of these "artists" who have many miles of experience do a reasonably good job. However, there is often a lack of consistency in the seal quality. A rational design method with strict adherence to sound engineering principles probably will have the greatest potential to provide serviceable cost-effective seals for high traffic volume pavements. One of the newest and most innovative rational design methods was developed by Dr. C.P. Marais in 1981 (2,3,4) and recently modified by C.J. Semmelink in 1985. (5,6)

Marais' proposed method differs from any previous design method in that it provides for a way of directly measuring the void volume in a layer of stone and it analyzes from first principles, the factors which effect a change in the void volume in a single layer of stone in shoulder-to-shoulder contact. These quantities are used to determine the rate of binder application.

This design method and the theory behind it as well as other methods were reviewed quite extensively under this study and a discussion of the results of this research follow in Chapters II through V.

After a thorough review of all design methods and the basic principles involved in designing multiple seal coats, Marais' method was chosen for further investigation. The Modified Tray Test as developed by Marais was thoroughly investigated and found to be a suitable method for measuring the void content of a layer of stone and the effective thickness of that layer. This research was also extended to multiple layers of stones. The Modified Tray Test also was found to be suitable for determining the void content and effective thickness of multiple layers of stone. The ability to measure the void content and effective thickness of multiple stone layers was felt to be the key in executing an effective design for multiple seal coats. The design method was tested by fabricating multiple seal coats in the laboratory as well as in the field and, with some modifications, was found to produce satisfactory field performance.

CHAPTER II

FACTORS INFLUENCING THE PERFORMANCE OF SEALS

A. GENERAL

The performance of both single and multiple seal coats is influenced by and depends on the following:

a. The properties of the bituminous binder and the stone;
b. The amount of stone and bituminous binder used along with the uniformity of their application;
c. The development of good adhesion initially which must be maintained throughout the expected life of the seal;
d. The development of a dense interlocking of stone;
e. The construction techniques used;
f. The strength of the base and flexural properties of the pavement;
g. The amount and type of traffic;
h. The environmental and drainage conditions; and
i. The type and condition of the existing road surface.

Even under the most favorable conditions, the effects of traffic and the environment will cause distress to the point where maintenance eventually needs to be performed on the seal coat to restore skid resistance, to seal a cracked surface or to repair a surface that is disintegrating or that has worn excessively.

Although engineers in the United States have long recognized that the above factors play an important role in the long- and short-term performance of seal coats, they have not attempted to take all of them into account in their seal coat design methods (7,8,9), since most of the factors are interrelated and a practical method of separation or consideration of the variables is difficult to develop. The most important factors affecting the performance of both single and multiple seal coats will be briefly discussed in the following.

B. FACTORS RELATED TO THE AGGREGATE

The aggregates used should be resistant to traffic abrasion and should have sufficient strength not to crush under rolling and traffic forces. In addition, the aggregate should have a single-size gradation, a cubical rather than an elongated shape, and a low dust content.

1. Amount of Aggregate

The predominant criteria among engineers dealing with the design of seal coats is that the quantity of cover aggregate should be the "amount of aggregate required to form a blanket one stone in depth when the aggregate is placed so that the least dimension is in an upward position." (1,7,8,9,10) In most of the existing design methods, two different quantities are determined. One is the exact amount of aggregate that is needed to cover the road surface, known as the design or correct spread rate. The other quantity, known as the field spread rate, is the amount of aggregate that must be spread on the road. The amount of aggregate that must be spread on the road surface should be slightly greater than the amount needed to just cover the surface. This increase is to account for construction factors such as inaccuracy of spreading and loss of aggregate due to whip-off.

The way engineers calculate the design spread rate varies according to the design method used. One of the most direct methods for determining the design quantity of cover aggregate in a seal coat is Kearby's board-test. (7,9) This is the method predominantly used by most districts in Texas for determining spread rate. Some engineers prefer an indirect method for determining the design quantity of cover aggregate needed. This quantity is based on the average size of the aggregate. The average size of the aggregate may be determined by a number of different procedures. Hanson (1) using a caliper measured the smallest dimension of at least 100 particles of cover aggregate and averaged the results. Most other investigators (7,8,10) used the sieve analysis as the basis for determining the aggregate average size. Obviously, since the average size of the aggregate is determined in different manners, the quantity of cover aggregate computed will vary accordingly.

In calculating the field spread rate, whip-off is the main factor that is considered. The magnitude of the additional quantity of cover stone to be used in the field varies from 5 to 20 percent of the design spread rate (to allow for whip-off and construction loss) calculated by any of the existing seal coat design methods. (1,7,8,9,10,11)

Single seal coats have the longest life when the stone particles are tightly packed together with shoulder-to-shoulder contact. (1) The orientation of the stone particles through rolling and traffic action causes them to lie with their least dimensions vertical, reaching their position of maximum stability. In their final position, the thickness of the stone layer is assumed to be equal to the least dimension of the aggregate. (1,7,10)

2. Gradation

It is generally agreed that the most satisfactory aggregates for seal coats and surface treatments are those having a single-size gradation. (12) A one-size aggregate not only performs better in seal coats, but also provides several advantages related to the design and construction of the seals.

Herrin et al. (12) states that one of the most important advantages of using a one-size aggregate in a surfacing operation is that maximum contact is obtained between the tire and the surface. This increases the frictional area, and thus, there is better skid resistance, provided that the correct quantity of binder is used.

A one-size aggregate usually develops interlocking qualities that are better than those developed with nonuniform aggregates. (12) This development of the dense interlocking mosaic of stone provides lateral support to the adjacent particles, preventing aggregate displacement under traffic.

Seal coats that are constructed with graded cover aggregates are likely to be less uniform, to be inferior in appearance, and to have a shorter service life than those built with the one-size cover stone. (10) Nevertheless, large mileages of seal coats are likely to continue to be constructed with graded cover aggregate, primarily because the graded aggregate can be produced at a much lower cost than the one-size aggregate. (10)

3. Size

The size of the one-size cover aggregate is one of the factors that must be given detailed consideration due to its marked influence on the performance and appearance of seal coats and surface treatments.

As the aggregate size is decreased, the possibility of applying too much bitumen is increased. This possibility results from errors that could occur in construction procedures, through poor operation of the bituminous distributor, or through allowable tolerances. Regardless of the cause, the result is flushing and subsequent blackening of the surface which is an undesirable condition. (12)

On the other hand, too large an average size aggregate is also undesirable. Predominantly coarse aggregates provide few points of contact, and the wear is concentrated on the projections of the aggregate. These projections will soon be smooth and slippery due to traffic, decreasing the resistance to skidding, especially in wet weather environments.

McLeod (10) reports that 75 percent of the seal coats and surface treatments that have been constructed by the Country Roads Board of Victoria, Australia, contain cover aggregate of size 1/2 to 3/4 in. In the majority of the cases, good results have been obtained. There may be a tendency to conclude that one should always use the largest size aggregate readily available. This is not so because of other factors desired in the finished surface such as comfortable riding surface, little noise between the tires and the surface, and ease of maintenance. To obtain these qualities, a maximum size of 3/4 in. is normally used by most seal coat designers. (12)

The way in which the size of the aggregate is defined varies with different design methods. (1,4,5,7,10) Hanson (1) introduced an important contribution to the design of seal coats and surface treatments when he observed that after considerable traffic, particles of cover aggregate tend to lie on their flattest sides, with their shortest dimension vertical. Hanson recognized that this means that the average thickness of a surface treatment or seal coat is equal to the average of the smallest dimension of the cover aggregate particles, which he termed the "Average Least Dimension" or ALD.

It is believed by many authors that the average least dimension of the cover aggregate is the most important single value which adequately defines the aggregate performance. The ALD not only affects the quantity of binder to be applied, but also the spread rate of the aggregates. A method of test for measuring the ALD of a cover aggregate is described in Appendix A. (10)

4. Shape

The shape of the aggregate particles used in a surface treatment or seal coat greatly affects the interlocking qualities of the particles, and thus, the stability of the seal. (12) The best interlocking qualities can be obtained using angular particles. These particles have many points in contact with one another and therefore do not have a tendency to shift their position easily.

Although engineers have noted that the shape of the aggregate influences the amount of bituminous binder needed, it appears that few design methods take this aggregate characteristic into account. Kearby (9) stated that the amount of flat and elongated particles should not exceed 10 percent of any gradation requirement when used in surface treatment purposes. He defined flat aggregate as one having a thickness less than one-half the average width of the particle and elongated as those particles with length greater than twice the other minimum dimension. The same guidelines could apply to seal coats as well. If enough asphalt is used to hold the cubical particles, the flat and elongated particles may be completely covered. Aggregates approximating a uniform size provide a maximum of void space; therefore the binder application rates are less critical. Also the uniform aggregates usually develop better interlocking qualities.

The Country Roads Board of Victoria, Australia, and McLeod (10,13) consider the shape of the aggregate when calculating the Average Least Dimension of the aggregate. The tendency of an aggregate toward particle flatness is measured by the "Flakiness Index" (See Appendix A). (10) The Flakiness Index represents the percentage by weight of flat particles having a least dimension smaller than 60 percent of the mean size of each of one or more of the coarser sieve fractions. The lower the Flakiness Index for any sample of cover aggregate, the more nearly the aggregate particles approximate the cubical shape.

Rounded aggregate particles are sometimes used as a cover material; however, there is a sacrifice of stability, since contact between the particles occurs at only one spot. The rounded particles develop less strength due to interlock and have a tendency to push and roll under traffic stresses.

5. Adhesion

In seal coats and surface treatments, the aggregate is only partially embedded in the asphalt and therefore does not gain much support from other aggregate particles. Because of this situation, the aggregate must have good adhesion characteristics and these should be retained throughout the life of the seal in order to maintain a stable position under the action of traffic.

If there is dust in the stone, it adversely affects the adhesion between the stone and the binder. The presence of dust can result in a substantial loss of stone. Moist aggregate does not adhere well to binders (except bituminous emulsions), and if traffic is allowed to use the seal before adequate bonding occurs, excessive whip-off can occur.

Precoating of the aggregate improves adhesion and minimizes the problems associated with aggregate that is not free of dust and moisture. In Texas, the majority of precoating is done with AC-20 or AC-10. Special precoat oil, which is similar to SC-250, is also used fairly extensively. An SS-1, CSS-1 or 1h emulsion sometimes is used for precoating.

6. Durability

Surface treatment aggregate must be strong enough not to break excessively during rolling or under traffic. Since the aggregate particles are not completely covered by the protective bitumen, they must be more durable than the aggregate used in bituminous mixes.

Several testing devices are available that have been used to give an indication of the durability of the aggregate. The most common methods used for this purpose are the Los Angeles Abrasion Test (15) and the Sulfate Soundness Test. (16) Obtaining satisfactory results from one of these tests in the lab does not guarantee that the tested aggregate will have satisfactory durability in the field. This is because to forecast the durability of the aggregate subjected to natural degradation and traffic is almost an impossible task.

C. FACTORS RELATED TO THE BITUMINOUS BINDER

The service life and performance characteristics of a particular seal depend on good adhesion between the binder, the stone and the road surface. Adhesion is one of the paramount functions of the binder. Loss of the retention of the stone, the degree of stone whip-off and the durability of the seal coat are all influenced by adhesive forces developed by the binder, which depend primarily on the type, grade and amount of binder applied.

1. Amount of Binder

There is an optimum amount of binder that must be correctly applied during the construction of a seal coat for optimum performance. A minimum amount is required to hold the stone firmly in place and bind it to the underlying surface. On the other hand, there is also a maximum amount which, if exceeded, will overfill the voids in the compacted layer, cause bleeding and will result in low skid resistance.

The optimum bitumen content is influenced by many factors, and all should be taken into account in the design of the seals. These factors are primarily related to the volume of voids in the aggregate layer. This volume of voids is, in turn, related to the size and shape of the aggregate and the degree of compaction. The importance of the voids in a single layer of aggregate with shoulder-to-shoulder contact will be discussed in Chapter III.

2. Cohesive Strength and Adhesion

Prior to the opening of a new seal coat to traffic, the bitumen must have developed sufficient cohesive strength to prevent the aggregate from being dislodged by traffic. Much initial damage can be done to the new surface if the needed cohesion has not developed to a sufficient degree.

As mentioned before, the development of good adhesion between the aggregate and the binder is one of the key functions of the bituminous material. Adhesion will determine, in many respects, the service life and performance of the seal coat. A proper selection of the aggregate and binder materials will ensure an adequate adhesion development.

To fulfill the two functions, development of a good adhesion and cohesive strength, the perfect binder should be quite fluid initially to allow time for placing and wetting of the aggregate, and then it must harden rapidly to facilitate the opening of the road to traffic. Proper precautions should be exercised during the construction in order to achieve satisfactory results.

3. Uniformity of Binder Application

The very best materials and design can go into a bituminous seal coat or surface treatment and the results still may be unsatisfactory, unless the binder is evenly distributed to the proper depth. Poor control of the binder application could result in streaking, excessive loss of cover aggregate, bleeding, and in fact, almost any of the types of failures common in seal coats. Since this control is of utmost importance in the construction of seal coats regardless of the physical characteristics of the aggregate or binder, the natural elements, or the traffic, it is a factor of major concern for those responsible for the construction and performance of the seal coats.

4. Durability

The weathering of the bituminous binder and its deterioration with age is of great importance because it has resulted in the replacement of many surfaces which had otherwise been performing satisfactorily. Good durability or resistance to deterioration under service conditions is essential for prolonged service life and good performance of any pavement(12). Hardening and brittleness of a bituminous material may be caused by one or all of the following processes: (a) oxidation, (b) loss of oils by evaporation, and (c) a change in the physical structure of the material. Most of the hardening of the bituminous material is due to the oxygen attack or to volatilization of the oils after the initial curing period. As the age of the pavement increases, the amount of oxidation and volatilization increases at a decreasing rate. Also, as the thickness of the treatment increases, the influence of the oxygen attack decreases.

D. OTHER FACTORS

Several important factors pertaining to the constituent materials of a typical seal coat or surface treatment have been discussed previously in this chapter. These are not the only factors which must be considered to obtain a seal coat that will perform satisfactorily. The condition of the underlying surface, the climatic conditions and the volume and type of traffic also have an important influence in the performance. These factors, which are not related to the aggregate or the binder are discussed in the following.

1. Traffic

There is no doubt that the amount of traffic plays a very important part in the performance of seal coats, and therefore, it is necessary to predict or measure the traffic volume as accurately as possible.

The volume of traffic that a road carries and is likely to carry during the service life of the seal coat is a major factor affecting the quantity of binder to be applied and the size of the stone selected.

From observations of seal coat performance, it is clear that the usual equivalency factors used in structural pavement design for converting light axle loads (cars) to heavy axle loads (trucks) do not apply to seal coat design. Light traffic, such as cars, is of no consequence in structural pavement design, but plays an important part in the design and performance of seals. (3,4) There is only a limited amount of quantitative data available with regard to the equivalent effect on a seal of a truck (maximum legal loading) in terms of cars. Marais (3) suggests that one heavy vehicle can be equated to 25 cars. The NITRR (14) assumes that one loaded truck is equivalent to 20 light vehicles (cars).

2. Underlying Surface

Since the thickness of most surface treatments or seal coats is relatively small, no appreciable strength is added to the structure by the application of such treatments. The underlying surface must possess initially all of the strength required to satisfactorily support the expected vehicular loads. An adequate base will greatly reduce maintenance costs and will make possible the construction of relatively thin and economical surfaces that will have good performance qualities.

The quantity and the type of asphalt material and the size and quantity of the aggregate cover material to be used are affected by the condition of the underlying surface. Because of this, quantity allowance should be made for the existing surface.

3. Climatic Conditions

The weather conditions of a particular region greatly affect the procedures used in the construction of a seal coat as well as its service life. Many of these climatic conditions are difficult to take into account because there is no readily available method of evaluation.

Extremely hot weather is detrimental to the finished seal coat because at high temperatures, most bituminous binder materials approach a liquid state. When this occurs, the cohesion is reduced and damage occurs under traffic. Cold weather is also detrimental because at low temperatures the binder becomes brittle and often breaks under the impact of traffic which can cause stones to dislodge.

The amount of precipitation in conjunction with varying temperatures also affects the performance of the seal coat. In areas of high precipitation and low temperatures, the seal will be subjected to repeated cycles of freezing and thawing, leading to early breakup and subsequent short service life.

CHAPTER III

VOIDS IN SEAL COAT AGGREGATES

A. GENERAL

In the design of seal coats, perhaps the most important factor to be computed is the amount of bituminous material required to fill the voids between the aggregate to an optimum depth. This simple and logical principle was first stated by Hanson (1) in his scientific study of the performance and design of single surface treatments. Since there is a direct relationship between the void space and the amount of bituminous material needed, it is essential to have a good indication of the actual void content in a layer of aggregate with shoulder-to-shoulder contact in order to execute an effective design.

B. VOIDS AS USED IN EXISTING METHODS OF DESIGNING SEALS

Hanson (1) found that one-size cover aggregate in a loose spread condition are oriented in random directions (Figure 1A). (10) In this state, the volume of voids between the aggregate particles is approximately 50 percent. He observed that after some rolling and traffic compaction, the aggregate particles tend to become oriented in a position so that they lie on their flattest side with their least dimension normal to the road surface (Figure 1B). (10) Under these conditions, Hanson reported that the voids between the aggregate were approximately 20 percent. This void space of 20 percent is independent of the size of the one-size cover aggregate. It is thought by some investigators that the volume of voids in the surface treatment aggregate is only related to the position or orientation of the aggregate and not by the size or type of the aggregate.

The Country Roads Board of Victoria, Australia, and McLeod (10,13), whose methods of designing surface treatments and seal coats are based principally on Hanson's work, indirectly consider the shape of the aggregate by varying the amount of bituminous material needed to fill the aggregate voids to an optimum amount according to the type of aggregate to be used.

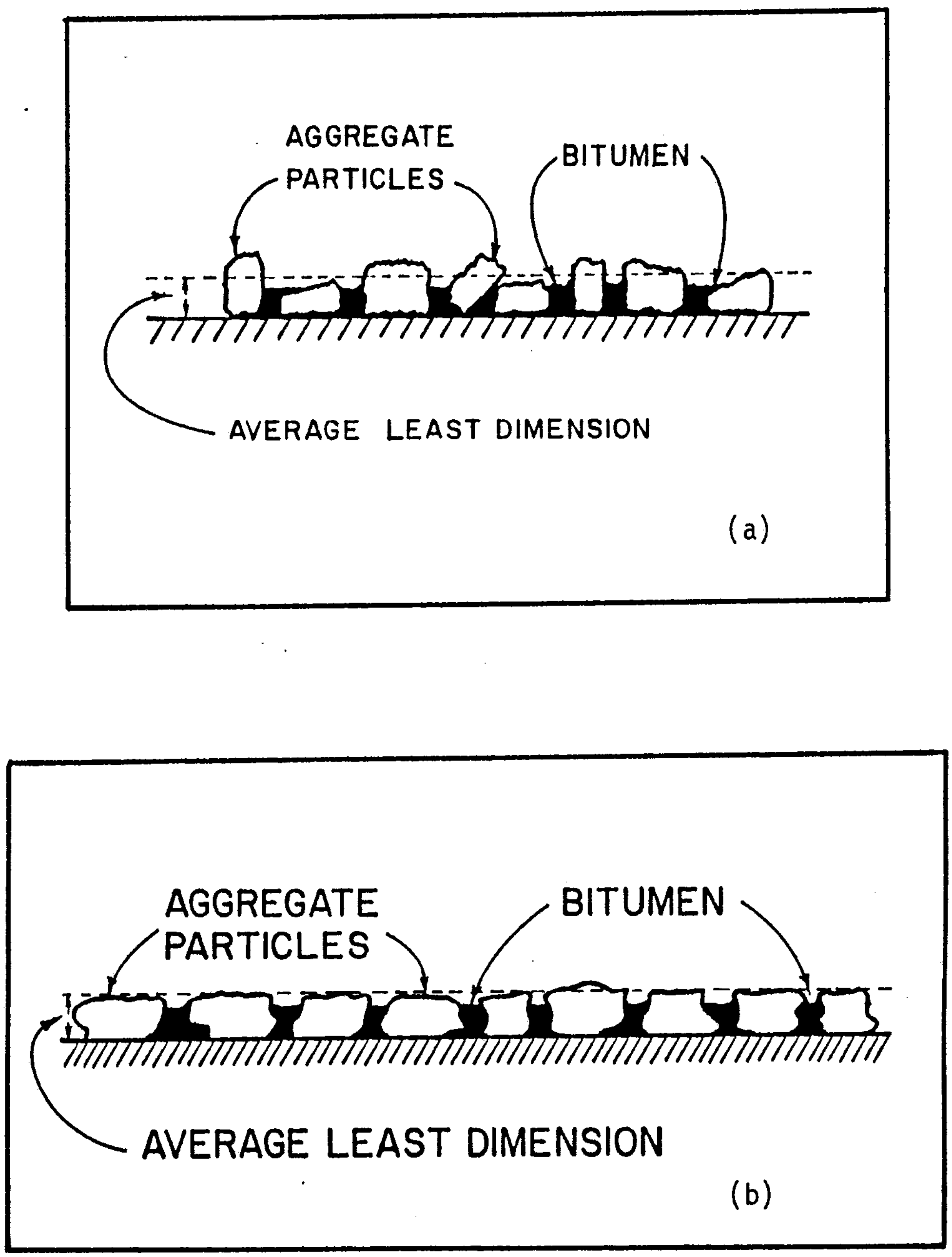


Figure 1. Illustration of a Seal Coat or Surface Treatment Cover Aggregate Particles: a) Immediately after Application from a Stone Chip Spreader and b) After Compaction and Considerable Traffic when the Aggregates are in their Final Position (Adapted from McLeod) (10).

Several engineers take into consideration the shape of the aggregate by determining the volume of the voids to be filled by first placing the aggregate in a large cylinder. Kearby (9) and later Benson and Gallaway (11) computed the percent voids from the loose unit weight of the aggregate. In these cases, it is assumed that the aggregate in the one-stone-thick layer on the road surface will have the same arrangement and voids as it will have in the cylinder. This assumption is very likely not true. (16,17,18)

All of the surface treatment and seal coat design methods presently being used in the United States assume that the volume of voids in a single layer of stone varies linearly with depth. No design method considers the fact that voids within the aggregate layer vary nonlinearly with depth.

Saner and Herrin (17) were the first engineers to conclude from their research study on voids in one-size surface treatment aggregates that the linear relation assumed in the seal coat design methods was not true and that a curvilinear relationship exists. Their study revealed that although the curvilinear relationship varies for different aggregate sizes, it has the same basic shape. They also concluded that aggregate samples of different shape have significant differences in percent voids and that a suitable shape factor needs to be developed for design purposes to relate the volume of voids to the shape of the aggregate.

Marais (3,4) was the first engineer to incorporate the variation of the void volume with depth within a single layer of stone into a design method. His proposed method differs from any previous design method in that it analyzes, from first principles, the factors which affect a change in void volume in a single layer of stone with shoulder-to-shoulder contact between particles in order to determine the rate of binder application.

In his rational approach, Marais expressed the volume of voids as a percentage of the Average Least Dimension (ALD) volume of the aggregate. He analyzed how the voids, expressed as a percentage of the ALD volume, change due to embedment, wear, and degradation in order to calculate the available voids remaining to be filled with binder. Semmelink states that the equation derived by Marais to measure the void content as a function of the Average Least Dimension had a low correlation factor which pointed to a very wide scatter of values, sometimes as much as 80 percent of the actual measured value. (5) This was confirmed by reports from practice that indicated that some seals designed according to this method tended to have too much binder.

Considering the need to improve their seal coat performance in the field, the National Institute for Transport and Road Research (NITTR) developed a modification of Marais' Tray Test. (5,6) The Modified Tray Test (see Appendix B [14] for description) determines the actual void content as a function of the Effective Layer Thickness (ELT). The Modified Tray Test measures the volume displaced by the aggregate plus the voids in the tray. The relative density of the aggregate is required to determine the void content in the layer. The Effective Layer Thickness (ELT) is the average thickness of the layer of aggregate and is determined by dividing the volume displaced by the aggregate plus void space by the area of the tray.

Based on the above concepts, Marais' rational design method for single seals was modified to take into account the correct amount of binder required to fill the actual void space. A seal coat can now be designed more accurately because the true void content is known which should virtually eliminate the possibility of a fatty surface, if the seal coat is properly constructed.

C. CHANGE IN VOID VOLUME

A certain amount of empty space is present in a seal coat layer. A portion of these voids is lost during the life of the seal because of the effect of traffic on (a) the embedment of the aggregate at the bottom of the seal layer, and (b) the wear and degradation of the aggregate at the top of the seal coat layer. (5) Also, a certain portion of the voids must be left unfilled with binder to ensure good skid resistance.

The void volume that must therefore be filled with binder is the balance of this void volume that remains after the estimated amount of loss that results from embedment and wear, and the amount required for good skid resistance, have been subtracted.

It is clear that a better knowledge of the actual void content in a seal coat or surface treatment layer is essential to execute an effective design. This is an area in which problems have been experienced in the past because most design methods assume a fixed equation for the void content in relation to the Average Least Dimension (ALD) of the aggregate or a fixed value for the void content regardless of the ALD value.

For a proper design procedure the following factors have to be considered.

1. Embedment

For seals, the embedment of the layer of stone in contact with the road surface is of particular importance in the subsequent performance of the seal coat or surface treatment. The embedment is independent of the thickness of the binder film and refers to the gradual immersion of the stone into the underlying road surface due to traffic compaction. (2,3,4)

It is believed that insufficient attention to embedment results in the majority of single seal coat and surface treatment failures in practice. Some embedment is necessary to ensure that the seal is bonded well with the existing road surface. However, excessive embedment can result in premature bleeding of the seal coat. Researchers (7,10) have recognized to a limited extent that embedment of the surfacing stone is desirable, but they have not quantified the amount of embedment that is likely to occur in practice and have merely left it to the judgement of the designer.

Embedment is by far the most important factor to be considered in the reduction of the volume of voids that takes place in a single layer of stone in shoulder-to-shoulder contact (3), and therefore it requires special consideration. Careful measurements have shown that embedment does occur and that the amount of embedment is dependent on the intensity of traffic and the hardness of the underlying surface. (3,18) Research done by Potter and Church (18) revealed that traffic has a greater effect on embedment than does the hardness of the underlying surface (except for PCC surface). It was also shown that the reduction in the effective voids due to embedment is quite marked after only three months of service.

The big question that arises is, "How long does embedment continue to increase?" It seems likely that the bulk of the embedment will have occurred in the first 12 months under normal traffic. (18) In areas subjected to freezing, the time of the year in which the seal is completed could have a bearing on the rate of embedment. The accurate measurement of the embedment of the stone into the underlying surface is a serious practical problem. Studies (3,18) have been undertaken to assess the amount of embedment under known traffic. It seems to be a fact that the embedment is a gradual process which is considered to have reached equilibrium condition after three years; even so, this period of time is affected by the amount of traffic and by the temperature of the road surface (when reseals are considered). A higher rate of embedment occurs under high road surface temperature.

2. Wear and Degradation

Wear of the aggregate in a single seal coat or surface treatment occurs due to the action and the intensity of traffic. Observations have shown that the wear of the aggregate takes place at the topmost (exposed) face of the stone layer and is more noticeable with weak than with strong aggregates. Studies done by Marais (3) revealed that after five years of service, the stone dimension changed in a manner to produce a more spherical shape. For even longer service life, it was observed that the effects of wear under heavy traffic can reduce stones into flat particles, increasing the aggregate Flakiness Index. The wearing of the stone in a single seal coat or surface treatment reduces the available voids to be filled with asphalt.

Degradation of the stone takes place mainly during the construction phase, particularly when steel-wheel rollers are used. (3) Due to this fact, these rollers are not recommended and the pneumatic type roller is preferred. The net effect of degradation is that it changes the grading of the stone, producing smaller sized particles. This change in the grading of the cover aggregate decreases the available voids either by filling the existing voids (acting as a wedge between larger stones) or through the reduction of the overall size of the original particles (lowering the ALD).

3. Skid Resistance

The skid resistance of highway pavements, particularly when wet, is a serious problem of increasing concern to highway engineers and researchers. As traffic speeds and traffic densities continue to rise, the chances of skidding accidents and their consequences are growing at an alarming rate each year. For these reasons, control of pavement slipperiness has extremely high priority in the continuing campaign to reduce traffic accidents.

The term skid resistance, as commonly used, refers to the characteristics of pavement surfaces that inhibit skidding, that is, the sliding of a tire or a vehicle in an uncontrolled manner.

Nearly all pavement surfaces that are economically feasible to construct lose their high initial skid resistance with the exposure to today's traffic. While the skid resistance of dry pavements is generally good and nearly independent of speed, wet pavements often have poor skid resistance even at low speeds. Past improvements in vehicle and tire performance have unfortunately been largely offset by higher speed so that there has been no net gain in safety margins. For this reason, highway engineers are faced with a continuing problem of building pavements with higher and more long-lasting skid resistance. To deal with the problem rationally and objectively, the engineer and researcher needs to understand the multitude of complex and interrelated factors that make for good, long-lasting skid resistance. These factors are extensively covered in the literature. (19,20,21,22,23,24,34)

The texture in a seal coat surface is most significantly influenced by the aggregate size. Texture generates resistance to sliding via the hysteresis effects in the tread rubber and facilitates the expulsion of water from the tire-pavement interface. Hysteresis reflects the energy loss that occurs as the rubber is alternately compressed and expanded (the lost energy appears as heat). Thus, as the tire slides over the irregularities of the textured surface, resistance develops even if the surface is perfectly lubricated.

Surface texture is beneficial to the generation of friction, but its most important function is to provide channels by which the water can escape from under the tire so that the tread rubber can make contact with the pavement. Providing and maintaining a skid resistant surface is a very important factor in the performance of any highway, and one of the primary purposes for applying a seal coat is to improve the skid resistance characteristics of an existing asphalt concrete pavement.

In the design of seal coats or surface treatments, the macrotexture of the aggregate is taken into account to ensure good skid resistance. Most of the existing design methods (7,8,10) indirectly considered the texture of the aggregate by selecting the aggregate size. The most recent design methods (4,5) take into account a portion of the aggregate surface texture depth (void space not to be filled with binder) to ensure satisfactory skid resistance properties in wet weather and to prevent hydroplaning.

A literature review (20) revealed that there are around 26 methods for measuring road surface texture. A brief discussion of the two most popular methods used to measure the surface texture of the roads is given below:

The Sand Patch Test was developed at the British Road Research Laboratory (19) and was one of the first methods used to evaluate surface texture. This rather simple test involves the spreading of a known volume of fine, dry sand over a circular area until the sand is flush with the aggregate tips of the pavement surface. The area of the patch is determined from the average of several diameter measurements. The average texture depth which is the ratio of volume to area is then calculated.

The Silicone Putty Test was developed by researchers at the Texas Transportation Institute (21) to evaluate macrotexture. It is, in principle similar to the Sand Patch Test. A known volume of silicone putty is formed into an approximate sphere and placed on the pavement surface. A recess in a plate is centered over the putty, and the plate is pressed down in firm contact with the surface. The average diameter of the deformed putty is recorded. When tested on a smooth, flat surface with no texture, the silicone putty will completely fill the recess. A decrease in the diameter of the deformed putty is associated with an increase in texture depth. This is a rapid, simple method for measurement of surface texture.

The effect of providing a surface of specified surface texture depth for skid resistance purposes is to calculate the void volume within the stone mat which is available for the binder. The texture depth specifications as mentioned before are obtained by dividing a given volume (sand or putty) by the area which is being covered. Therefore, if the texture depth required is known, it can then be converted to a quantity of binder expressed in liters/square meter or gallons/square yard.

Engineers in general agree that an increase in the quantity of binder is required to allow for the existing road surface texture. Some adjustments to the cold binder volume calculation is then necessary to allow for the existing texture of the road to be sealed. For this purpose, the methods described above are used.

CHAPTER IV

RATIONAL APPROACH TO THE DESIGN OF SEAL COATS AND SURFACE TREATMENTS

A. GENERAL

The accumulated knowledge and research findings of various engineers and researchers, along with the data and results obtained from several full-scale and small-scale surface treatment road experiments constructed by the National Institute for Transport and Road Research, (NITRR), (26,27,28,29) have been integrated by Claude P. Marais with the objective of developing a rational method of design for single surface treatments.

Marais' proposed method (3,4) differs from any other previous design method in that it analyzes, based on sound engineering principles, the factors which are considered to influence the performance of single seals under various climatic and traffic conditions. Attention is focused on the factors that have been recognized by engineers as affecting the performance of seals, but have not <u>all been taken into account</u> in the existing seal coat design methods. These factors are:

a) the embedment of chippings <u>in the underlying surface</u> of the road,

b) the surface texture of the final surfacing which must provide adequate skid-resistance in wet weather, even at high speeds (50 to 80 mph),

c) degradation and wear of the cover aggregate due to rolling under construction, and

d) the condition and texture of the surface to be treated.

In the following section, Marais' basic principles will be summarized. His findings and design method are discussed in detail in References 2,3,4, and 14.

B. AGGREGATE SPREAD RATE

The approach adopted for the determination of the rate of spread of the cover aggregate is an extension of previous studies done in South

Africa. For this purpose, the Tray Test developed by R. N. Walker (30) is used.

In his laboratory study, Walker found that when the aggregate is spread over a known area in a single layer with the individual stone particles in shoulder-to-shoulder contact and with the ALD's in a vertical position, there is little difference in the packing properties of the stones with a high flakiness index and those that are more cubical in shape if they have the same Average Least Dimension (ALD). He then concluded that the predominant factor which affects the packing of single-sized aggregate is their ALD and not their physical characteristics.

Based on the above concept, Marais expressed the voids in a single layer of stone as a fraction of the ALD in order to quantify the volume of these voids. In his study, he found that the voids in a single layer of stone are not constant but are related to the ALD of the stone. This relationship is shown in Figure 2. (2) Marais also found out that the voids in a loose volume of stone are dependent on the shape of the stone as defined by the Flakiness Index. The results from both laboratory and field measurements are shown in Figure 3. (2) These two concepts are radical departures from Hanson's principles (1) where he states that the volume of voids in any loose volume of stone are 50 percent of the total volume occupied by the stone and that these volumes were independent of the size and shape of the stone.

Assuming that the average compacted depth of the stone is equal to the ALD, (the Potter and Church study [18] revealed that, after traffic compaction, the average depth of the layer is reduced to 1.23 ALD), and that in practice there will be some wastage of stone, Marais came up with the following relationship (4):

$$SR = \left[3.3 + \frac{883.3}{ALD} \right] \left[\frac{100 - V1}{100 - V2} \right]$$

Where

SR = practical spread rate (sq.mt/cu.mt)
ALD = average least dimension of stone (mm)
V1 = void volume in loose bulk expressed as a percent of the total volume occupied by stone (Figure 3)
V2 = void volume in a single layer of stone expressed as a percent of the ALD volume (Figure 2)

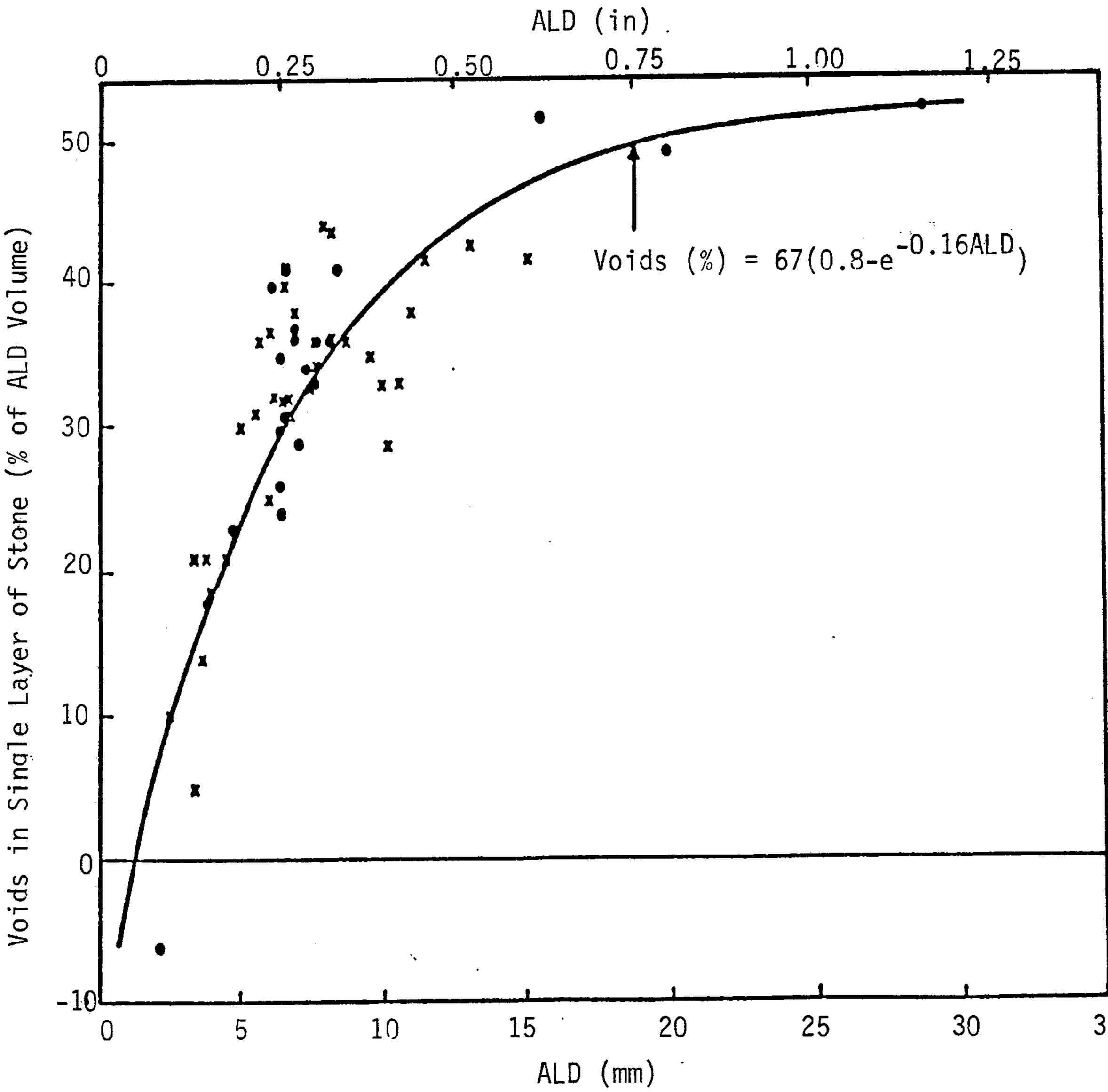


Figure 2. Void Distribution in a Single Layer of Stone as Percentage of ALD Volume (2).

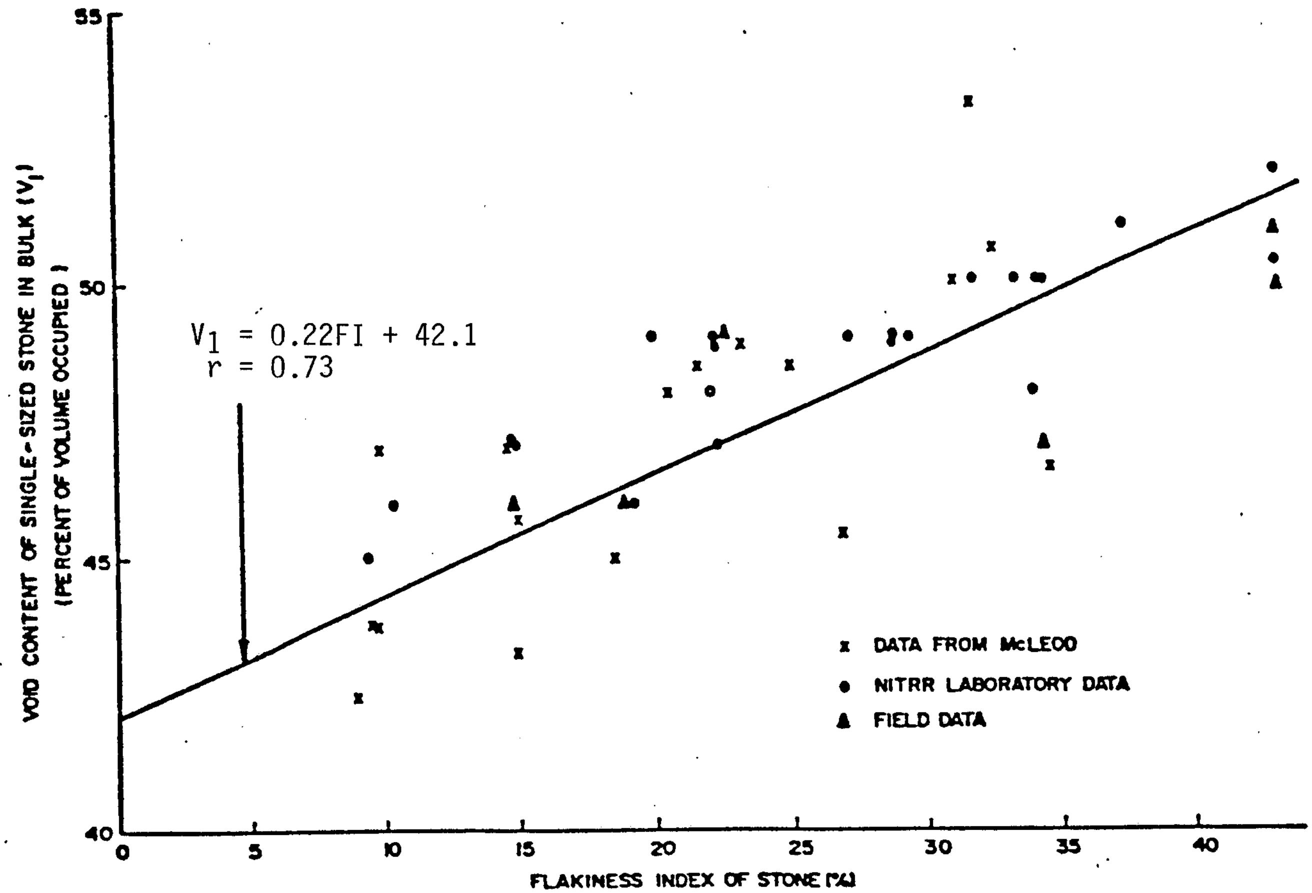


Figure 3. Relationship Between Flakiness Index and Void Content of Single-Size Stone in Bulk (2).

C. BINDER QUANTITY

There is no doubt that the most important factor to be computed in the design of seal coats and surface treatments is the amount of binder required to fill the voids between the aggregate layer to an optimum depth. Since the amount of binder required is related to the volume of voids, it is of paramount importance for the designer to know what this void content is.

In his rational approach, Marais takes into account the factors that reduce the actual void content within a single layer of aggregate in order to calculate the remaining voids to be filled with binder. These factors (embedment, wear and degradation) have already been discussed in Chapter III. In this section, we will describe how these factors are measured and taken into account by Marais to calculate the correct quantity of binder to be applied in a single surface treatment.

1. Volume of Voids

To execute an effective design, it is clear that a good indication of the <u>actual void content</u> in a seal layer is essential. For this purpose, Marais used the Tray Test (30) to calculate the existing relationship between the voids in a single layer of stone spread in shoulder-to-shoulder contact over a known area (1 sq.mt.) and the ALD of the aggregate. In calculating the volume occupied by the stone, the mass of the stone covering the tray unit area is converted to volume by using the bulk density of the stone. In this way, the correct stone volume (including the internal pores) is obtained. The equation derived by Marais has the following form (3):

$$\text{Voids (\% of ALD volume)} = 100 \times \left(1 - \frac{W}{ALD \times SG}\right)$$

where

W = stone coverage per sq.mt. (kg/sq.mt.)
ALD = average least dimension (m)
SG = ASTM bulk density at 25° c (kg/cu.mt.)

Quantitative data were plotted and the relationship obtained is shown in Figure 2. The actual void content is then calculated from this relationship.

In order to calculate the correct amount of binder to be applied, Marais analyzed how the actual voids change due to embedment, wear and degradation. He also estimates the amount of voids required to ensure good skid resistance.

2. Embedment

In an attempt to quantify or measure the amount of embedment that will likely occur, Marais developed the Ball Penetration Test (3) for surfacing seals (see Appendix C (31) for test description). In this test, a standard 19 mm diameter steel ball bearing is forced to penetrate the old road surface to be sealed under a standard effort (one blow of a Marshall hammer). The road surface temperature at the time of test is recorded and the penetration value is converted to a standard temperature for that location. In this test, Marais assumes that the measured penetration of the ball at the standard road temperature is directly proportional to the final embedment of the stone.

Figure 4 (3) suggests a possible relationship between the Ball Test value, traffic and embedment. The embedment values obtained from Figure 4 include the initial embedment during construction.

3. Wear and Degradation

It has been observed that wear and degradation of the stone seems to be directly related to the strength of the aggregate. Degradation takes place mainly during the construction process (rolling), while wear is due to the effect of traffic.

In the Republic of South Africa, the crushing strength of the aggregate is measured by a method known as the 10 percent Fines Aggregate Crushing Test (FACT). (32) A tentative relation between the Los Angeles Abrasion value (LAA) and the 10 percent FACT value in kilonewtons could be calculated with the following equation (2):

$$\text{10 percent FACT} = \left(\frac{34 - 0.65\ \text{LAA}}{0.80}\right) 8.9$$

Results obtained from a small-scale road experiment (29) have shown that after five years of service, the physical dimensions of the

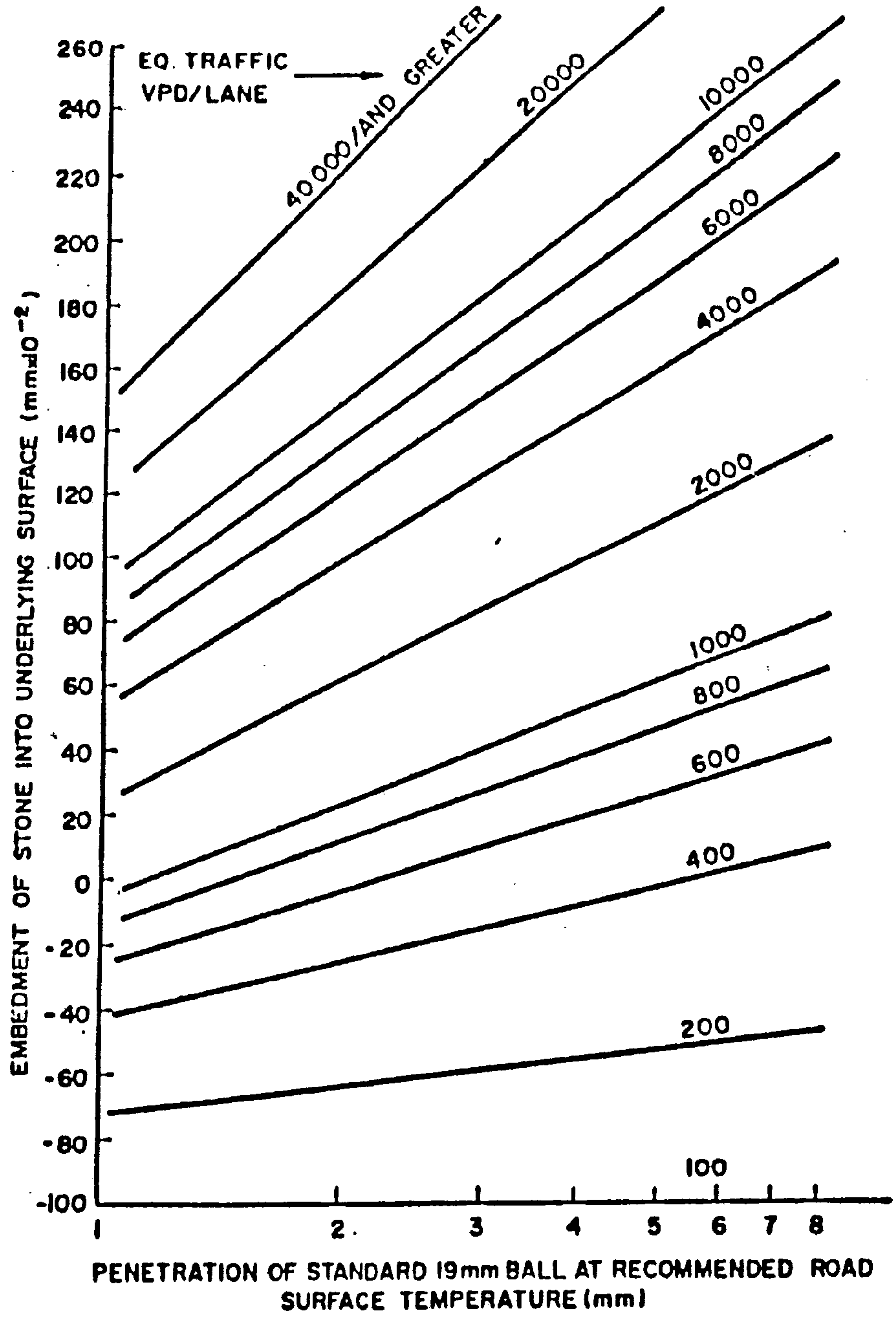


Figure 4. Relationship Between Penetration of Standard Ball, Traffic and Embedment of Stone into Underlying Surface of Road (3).

aggregates used have changed significantly. The original ALD and the Flakiness Index of the aggregate used in the test road were reduced.

Based on the above study, values for the total degradation and wear that is thought to take place under various traffic intensities over the expected life of a seal (10 years) were estimated and are given in Table 1. (3,4)

4. Texture Depth

The texture depth of the surfacing plays a very important role in providing resistance to skidding under wet conditions. An intensive study on skid resistance done by the Road Research Laboratory in the United Kingdom (19) revealed that the drop-off in the coefficient of skid resistance from 50 km/hr (30 mph) to 130 km/hr (80 mph) was limited to less than 25 percent when the surface texture depth was greater than 0.64 mm (0.025 in.) as measured by the Sand Patch Test, provided that the stone had an acceptable polished stone value (PSV).

A final texture depth of 0.64 mm or greater is easily provided by aggregates having a reasonably large ALD (>1/4 in.), but it is virtually impossible to obtain with aggregates of a small ALD. (2) For the cases where aggregates with a small ALD are used, a surface texture depth requirement of 10 percent of the aggregate ALD is suggested.

As mentioned earlier, in the Sand Patch Test, the texture depth is calculated by dividing a given volume of material (sand) by the area it covers. Knowing the texture depth, it can then be converted to a quantity of binder expressed in lt/sq.mt. by simply multiplying the texture depth in mm by its unit (i.e, 0.64 mm of texture depth = 0.64 lt/sq.mt.) or multiplying by 4.6875 to get gal/sq.yd. providing that the texture depth is in inches.

5. Surface Texture of the Existing Surface

Engineers, in general, agree that the quantity of binder to be applied is affected by the texture of the existing surface. This surface hunger is higher on surfaces with coarse textures than those with smooth textures. Therefore an adjustment for the quantity of additional binder required to allow for the road surface hunger should be taken into account

Table 1. Estimated Degradation and Wear Under Construction Rolling and Traffic (10-Year Life) (3).

10% FACT of stone (kN)	Degradation and wear of stone mat (mm x 10^{-2})									
	Equivalent traffic (vpd/lane)									
	>4,000	4,000	3,000	2,000	1,000	800	600	400	200	100
130 - 180	100	92	86	78	66	66	58	52	44	37
181 - 220	90	86	80	72	60	58	54	48	40	34
221 - 270	80	78	74	68	56	54	50	46	38	32
271 - 310	75	72	68	62	52	48	46	42	36	30
311 - 350	70	68	62	56	48	46	42	38	32	28

in the design process. In his design procedure, Marais uses a suggested relationship between the texture depth, traffic intensity and the additional quantity of cold binder required to properly satisfy the surface hunger of the existing road surface. This relationship is given in Figure 5. (3)

Allowance for bleeding surfaces is not explicitly accounted for by Marais in his design procedure. However, a reduction in the binder content to indirectly account for bleeding surfaces has been taken into consideration when the embedment value was calculated. Possible binder absorption is also not accounted for in Marais' design procedure because he states that "the viscosity of the binder at the time of spraying is so high, that it is extremely doubtful that absorption could take place." (3) In extreme cases where it is known that the aggregate is highly absorptive, Marais suggests a bituminous prime coat or a pretreatment prior to the placing of the seal.

6. Minimum Quantity of Cold Binder

It has been proven that a minimum quantity of binder film thickness, determined by the size of the stone or ALD, is required in order to effectively retain the cover aggregate, withstanding the combined effects of traffic and weather. Laboratory studies done in South Africa have revealed that this required binder thickness is the quantity which will occupy just 50 percent of the total volume between a single layer of stone.

In practice, under the action of the rolling process during the construction of the seal, an initial embedment of the stone may take place. Marais estimates that this embedment is equal to a third of the embedment given by the Ball Penetration Test. (3) In order to calculate the minimum quantity of cold binder required to hold the aggregate in place, the above condition is taken into account by Marais, along with the quantity of extra binder required to satisfy the existing road surface texture (surface hunger).

Taking all the previous mentioned factors (embedment, wear and degradation, texture depth and surface hunger), which in one way or another largely influence the amount of binder required to be used in a surface treatment or seal coat design, Marais calculates the design

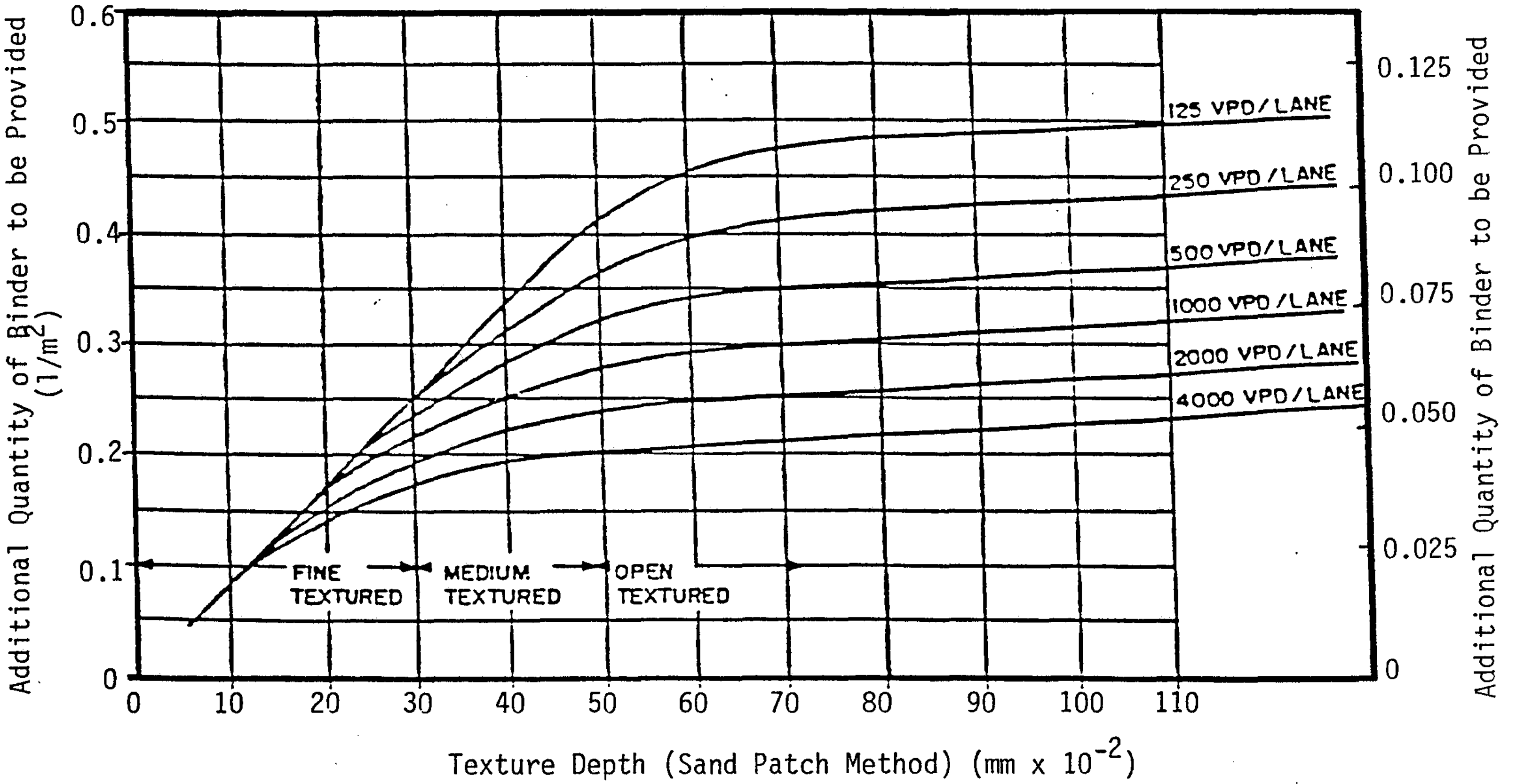


Figure 5. Additional Quantity of Binder Required to Allow for Texture Depth of Existing Surface (3).

quantity of binder that should be sprayed in order to have a successful seal coat performance.

CHAPTER V

THE MODIFIED TRAY TEST METHOD

A. GENERAL

A recent study conducted by the National Institute for Transport and Road Research (NITRR) (5) revealed that the equation that was derived by C. P. Marais for the calculation of the actual void content as a function of the average least dimension of the stone (Figure 2) had a low correlation factor which pointed to a very wide scatter of values, sometimes as much as 80 percent of the actual measured value. This was confirmed by reports from practice that indicated that some seals designed according to this method tended to have too much binder.

In an attempt to measure more accurately the actual void content of a single layer of stone in shoulder-to-shoulder contact, the NITRR devised a very simple test known as the Modified Tray Test. (5,6,14,33) The Modified Tray Test was developed to determine the true layer void content and the Effective Layer Thickness (ELT) of the aggregate layer.

B. DESCRIPTION OF THE METHOD

The test equipment essentially consists of a circular tray and a shoulder piece which fits snugly on top of the tray. The shoulder piece has the same internal diameter as the tray and is fitted to a loose-fitting cloth membrane. The purpose of the membrane is to prevent the "density sand" from flowing into the voids between the stone.

The test is performed by packing the stone in the tray in a single layer with their least dimension vertical. The stone should be packed shoulder to shoulder (Figure 6). The shoulder with the membrane is then placed on top of the tray and the membrane is smoothed out without disturbing the stone (Figure 7 and 8). This entire mass is determined.

The space above the stone is then filled with "density sand" in one smooth pour (Figure 9). The tray should be overfilled (Figure 10) and the excess sand scraped off with a straight edge (Figure 11). This mass is then determined. The aggregate sample used in the tray is then poured into a plastic measuring cylinder and the average volume is read off in

Figure 6. Packing of Stone in Modified Tray.

Figure 7. Placing of Shoulder with Cloth Membrane on Tray.

Figure 8. Modified Tray with Membrane in Place.

Figure 9. Pouring of Density Sand into Tray.

Figure 10. Tray Overfilled with Density Sand.

Figure 11. Scraping Off of Excess Density from Tray.

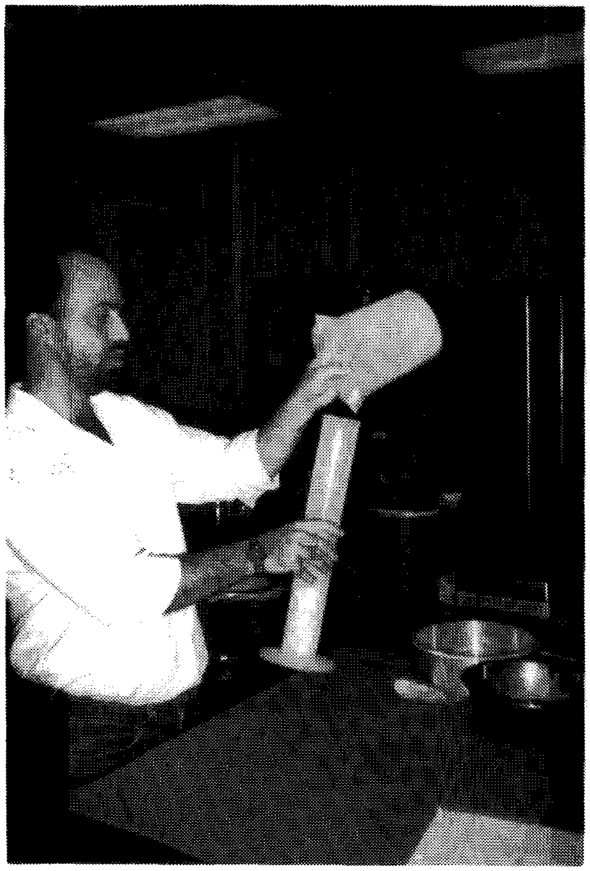


Figure 12. Pouring of Aggregate from Tray into Measuring Cylinder to Determine Spread Rate.

milliliters (Figure 12). This quantity is used to determine spread rate of the aggregate.

C. BINDER QUANTITY

Based on the schematic illustration of the Modified Tray (Figure 13), the total void space that is occupied by the aggregate sample plus the voids in the layer is determined as follows (14):

$$V3 = V_{s1} - V_{s2}$$
$$= \frac{M1 - M2}{BDS}$$

where

V3 = volume of the aggregate plus the voids between the aggregate (ml),
V_{S1} = volume of the density sand required to fill the tray without the aggregate (ml),
V_{S2} = volume of the density sand required to fill the tray with the aggregate (ml),
M1 = mass of the density sand required to fill the tray without the aggregate sample (g),
M2 = mass of the density sand required to fill the tray with aggregate sample (g), and
BDS = bulk density of the density sand (g/ml).

The ELT in millimeters is determined as follows (14):

$$ELT = 10 \times V3/A$$

where

A = area of the tray (sq.cm.)

The true layer void content V1 is determined as follows (14):

$$V1 = (V3 - Va)/V3 \times 100\%$$
$$= (V3 - (Ma/RDa))/V3 \times 100\%$$

where

Va = volume of the aggregate sample required to cover the tray area (ml),
Ma = mass of the aggregate sample required to cover the tray area (g), and
RDa = relative density of the aggregate sample.

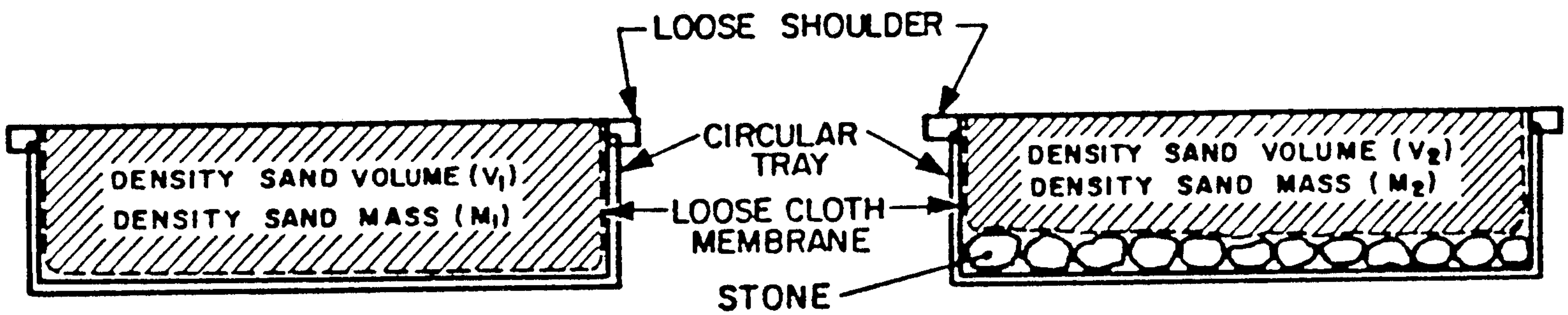


Figure 13. Schematic Illustration of the Modified Tray Test. (5)

A step-by-step procedure to determine the numerical values of the variables involved in the above formula is contained in Appendix B. (14)

The ELT calculated by means of the Modified Tray Test differs from the ALD as used in Marais' rational design in that it gives a better average value for the layer thickness of the aggregate. (5,33) In the case of the ALD, only the highest points of the least dimension of the aggregate particles are measured.

Even though the ELT gives an overall average of the layer thickness and the ALD gives the average of the highest points of the stones on their flattest side, a good correlation between them was found (see Figure 14) (6). However, a poor correlation was found between the layer void content (Vl) and the effective layer thickness (ELT) (see Figure 15). (6) This fact bears out why the use of just the ELT or ALD alone cannot be used to determine the quantity of cold binder required for an optimum seal coat performance. The void content must be considered as well. (5,33)

Marais' rational design method (4) was modified, taking into account the ELT and the true void content Vl calculated by means of the Modified Tray Test, in order to calculate the required cold binder quantity. The fractional void losses as the result of embedment, wear and degradation, as well as the required voids to ensure good skid resistance, are calculated following Marais' approach using the Ball Penetration Test (embedment), the 10 percent FACT value of the aggregate (wear), the Sand Patch Test (to ensure skid resistance and to measure surface texture) and the average daily traffic per lane expressed in equivalent light vehicles. A complete design procedure along with the tables to calculate the embedment due to traffic as determined by the Ball Penetration Test, the estimated wear under construction rolling and traffic, the fractional loss due to embedment, wear, and the additional cold binder required to satisfy surface hunger are contained in Appendix E. (14)

C. AGGREGATE SPREAD RATE

In a layer of stone lying shoulder-to-shoulder with a specific layer thickness (ELT), only a portion of the space in the layer is occupied by the stone particles. The balance of the space in the layer consists of the true void (Vl). Similarly, in a loose bulk volume of the stone, only

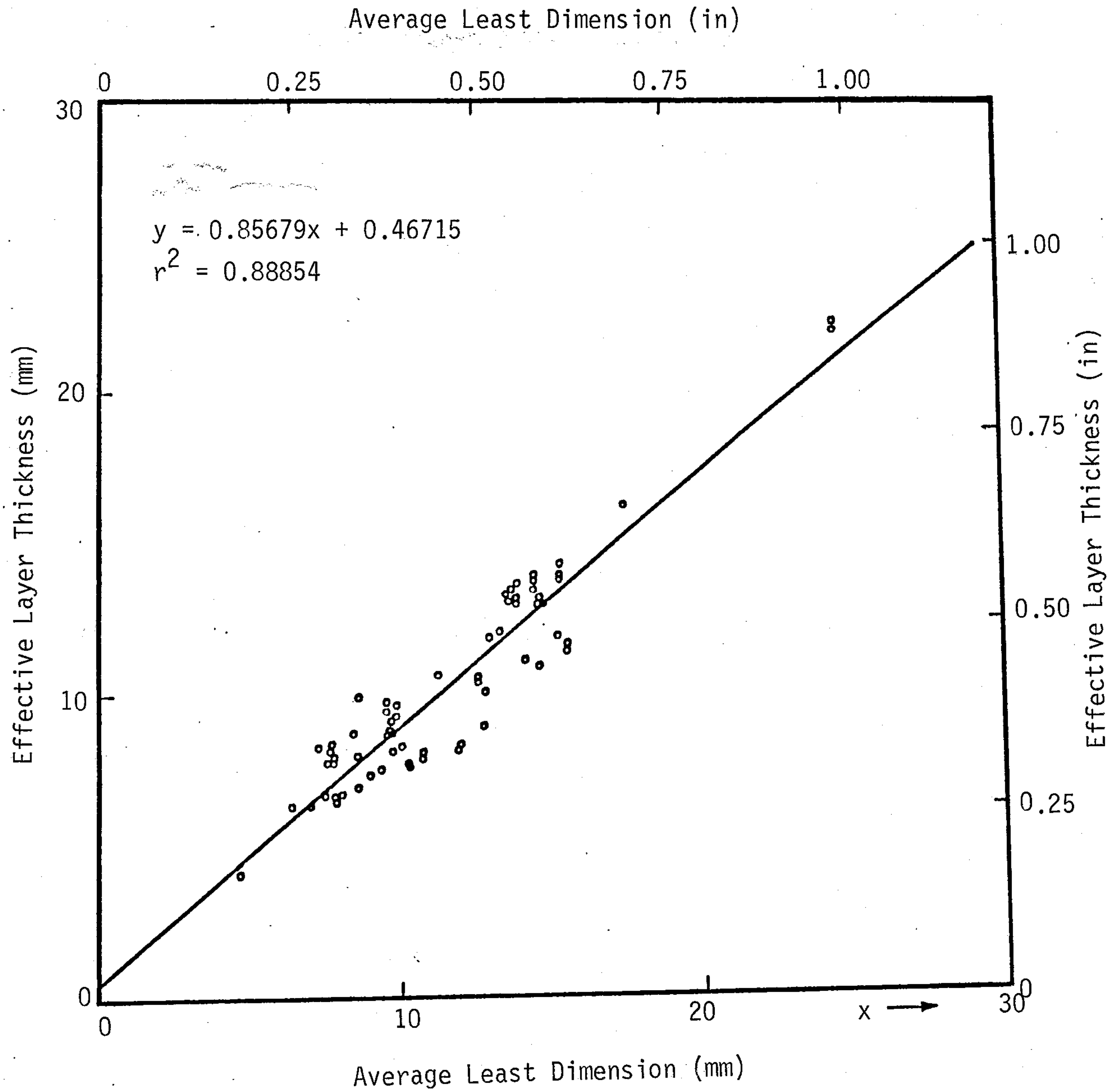


Figure 14. Relation Between the ALD and ELT. (6)

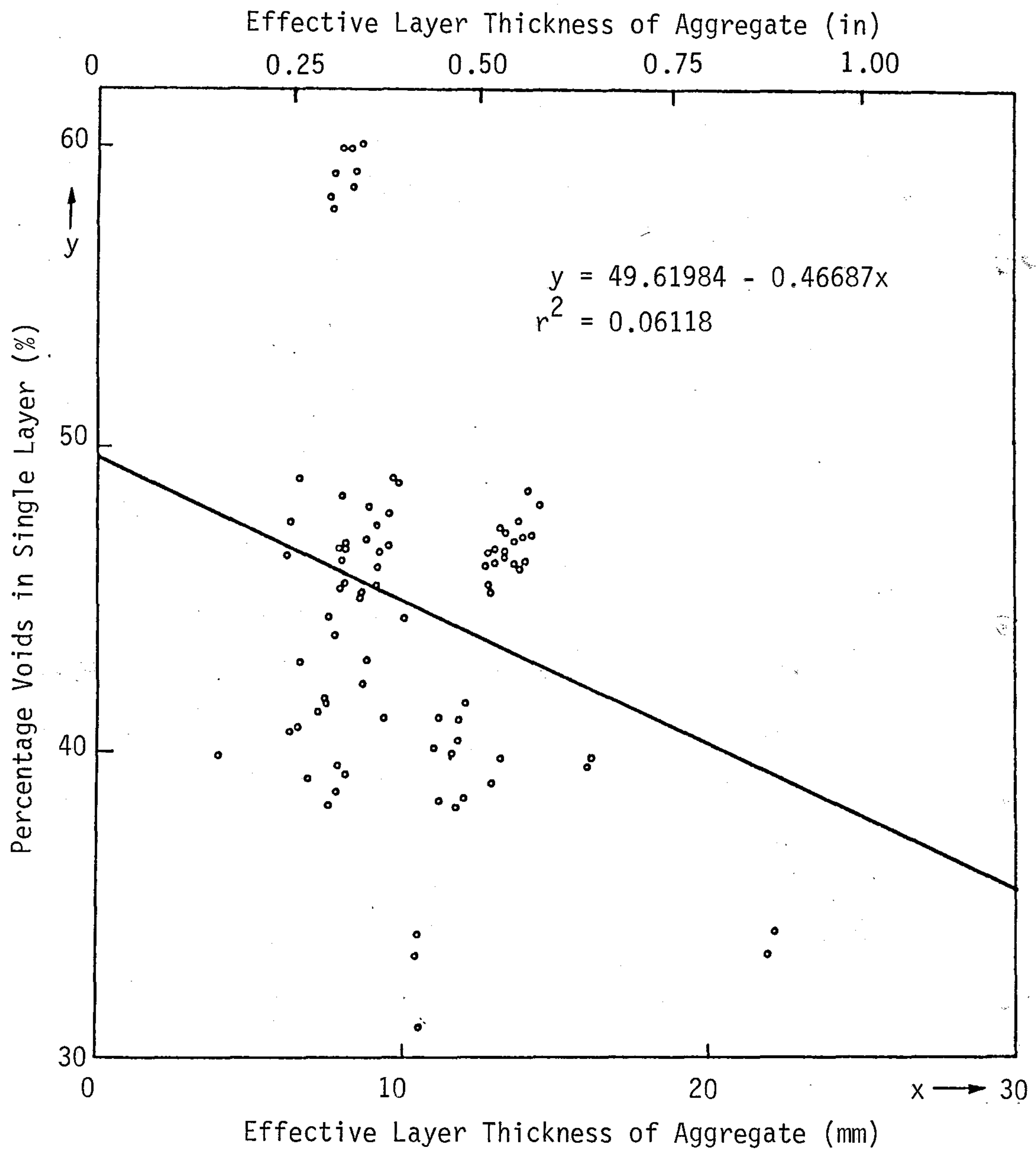


Figure 15. Relation Between the ELT and Void Content in a Single Layer of Aggregate. (6)

a portion of the space is occupied by the stone particles while the remaining bulk volume consists of the bulk void space Vb.

From the above, it could be stated theoretically that the number of square meters that should be covered by one cubic meter of loose aggregate (A*), is equal to the volume of the solids in one cubic meter of aggregate divided by the volume of the solids in one square meter of aggregate lying shoulder-to-shoulder. Therefore:

$$A^* = \frac{(\ 1000 \times (100 - Vb)\ )}{(\ ELT \times (100 - Vl)\ )} \qquad \text{Reference 33}$$

where

ELT = effective layer thickness (mm),
Vb = void content in bulk volume (%), and
Vl = true void content in a single layer of stone lying shoulder-to-shoulder (%),

If the theoretical spread rate Qt is expressed as a fraction of cubic meter per square meter, then

$$\begin{aligned} Qt &= 1/A^* \\ &= \frac{(ELT \times (100 - Vl)\ )}{(1000 \times (100 - Vb)\ )} \times 1000 \times 10^{-3} \\ &= \frac{ELT \times (100 - Vl)}{(100 - Vb)} \times 10^{-3} \ \text{(cu.mt./sq.mt)} \qquad \text{Reference 33} \end{aligned}$$

where

10^{-3} cubic meter = 1 liter

The procedure to calculate the bulk void content (Vb) of the aggregate is given in Appendix B. (14)

CHAPTER VI

LABORATORY STUDY ON MODIFIED TRAY TEST

A. RESEARCH APPROACH

The Modified Tray Test was evaluated in the laboratory to determine the following:

1. The repeatability of the test,
2. The variation in results from sample to sample for the same stone,
3. The accuracy of the test in measuring ELT (effective layer thickness),
4. Suitability of the Modified Tray Test for multiple seals, and
5. Spread rate as determined from the Modified Tray Test.

B. MATERIALS

The aggregate used to evaluate the Modified Tray Test was a crushed limestone from Texas Crushed Stone in Georgetown, Texas. Four gradations of this aggregate were used which met Texas SDHPT Specifications Item 302 for Grades 2,3,4, and 5. These gradations are shown in Figures 16 through 19. Other material properties for this aggregate are presented in Table 2. One 55-gallon container of each aggregate grade was obtained from the aggregate stockpiles.

C. LABORATORY EVALUATION

1. Repeatability of the Modified Tray Test

One of the questions which needed to be answered regarding the test procedure was, "Could the test be repeated on the same sample of stone with similar results?" To evaluate the repeatability of the test, ten representative samples of each aggregate grade (2,3,4 and 5) for a total of forty samples were obtained. Each 55-gallon container of aggregate was quartered according to AASHTO T248. (35) Then a mechanical splitter was used to further reduce the aggregate sample size to obtain ten samples of each aggregate grade for a total of forty samples. The ELT and void

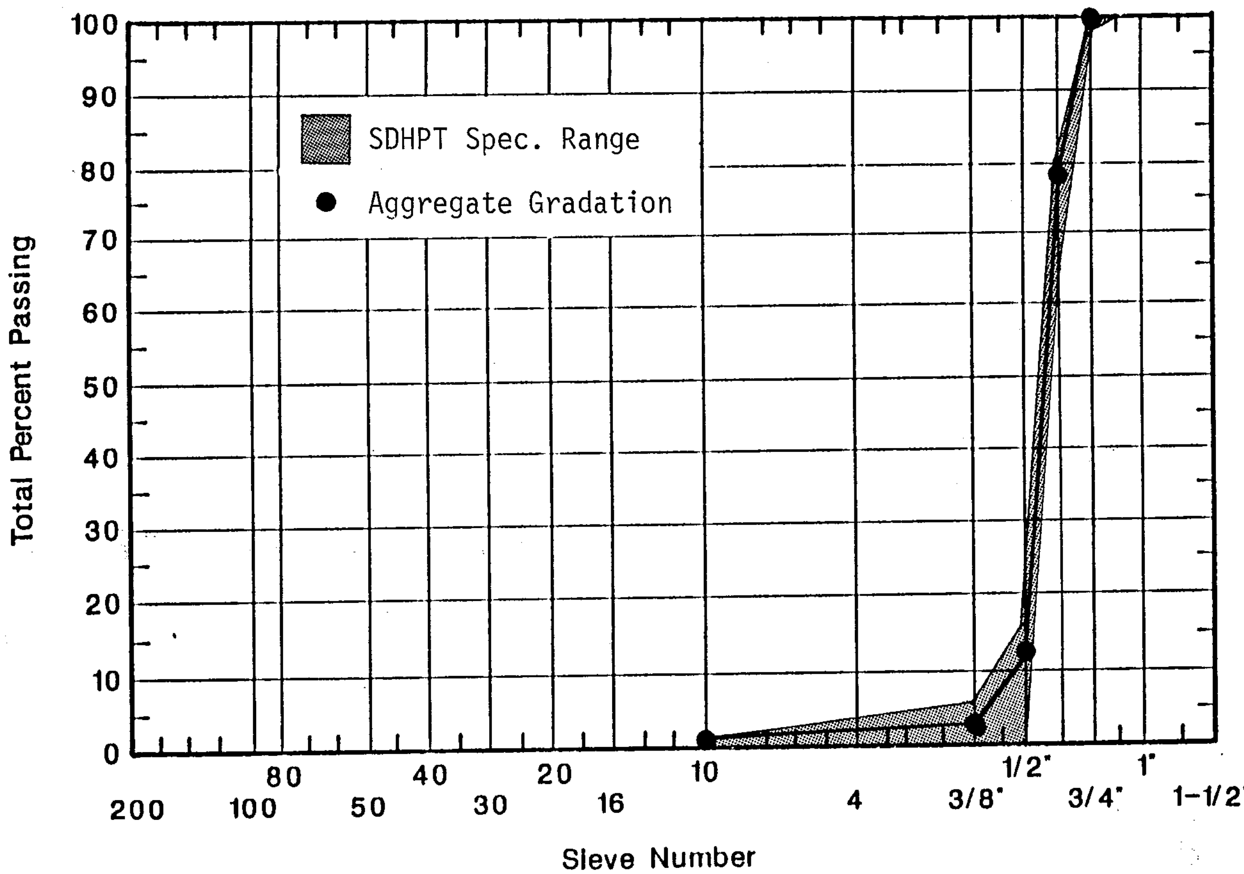


Figure 16. Aggregate Gradation for Grade 2 Crushed Limestone (Texas Crushed Stone).

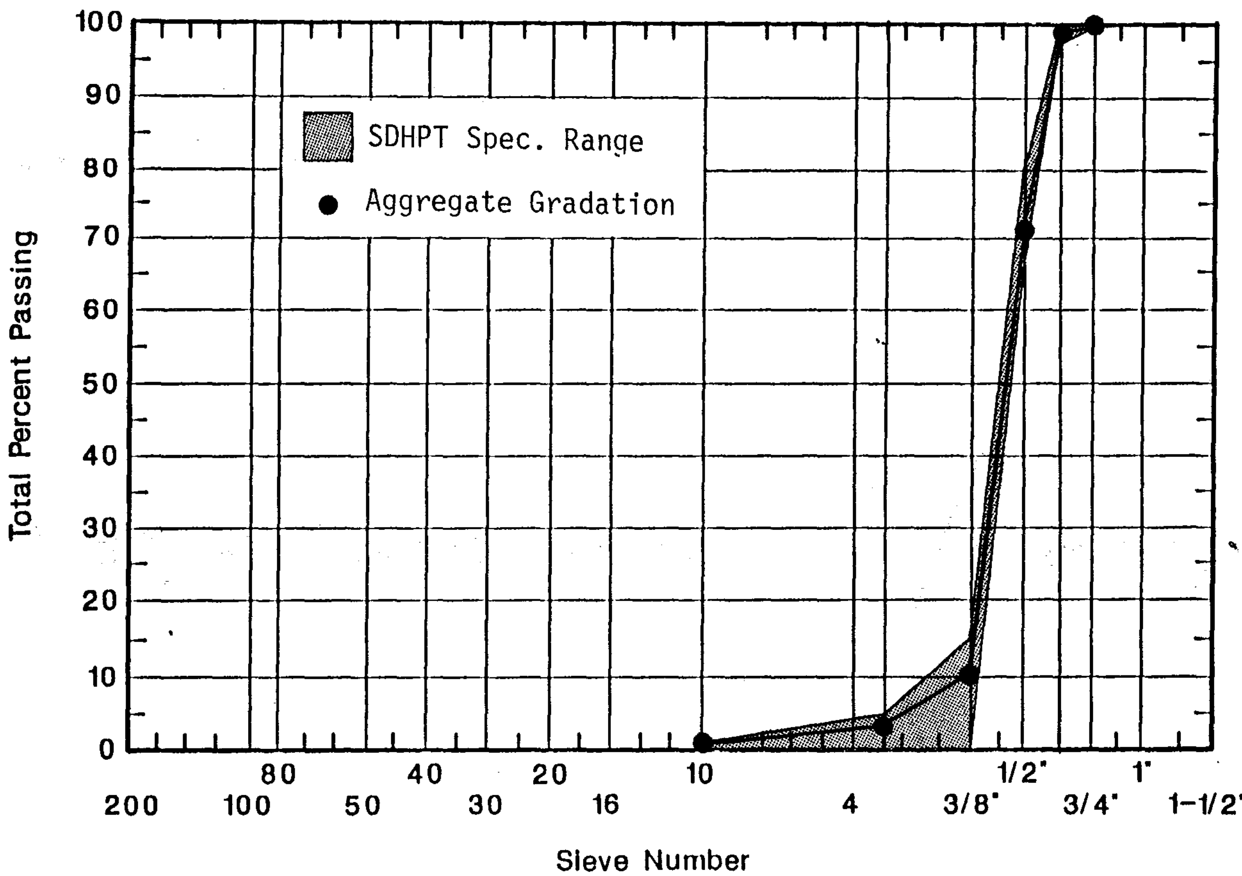


Figure 17. Aggregate Gradation for Grade 3 Crushed Limestone (Texas Crushed Stone).

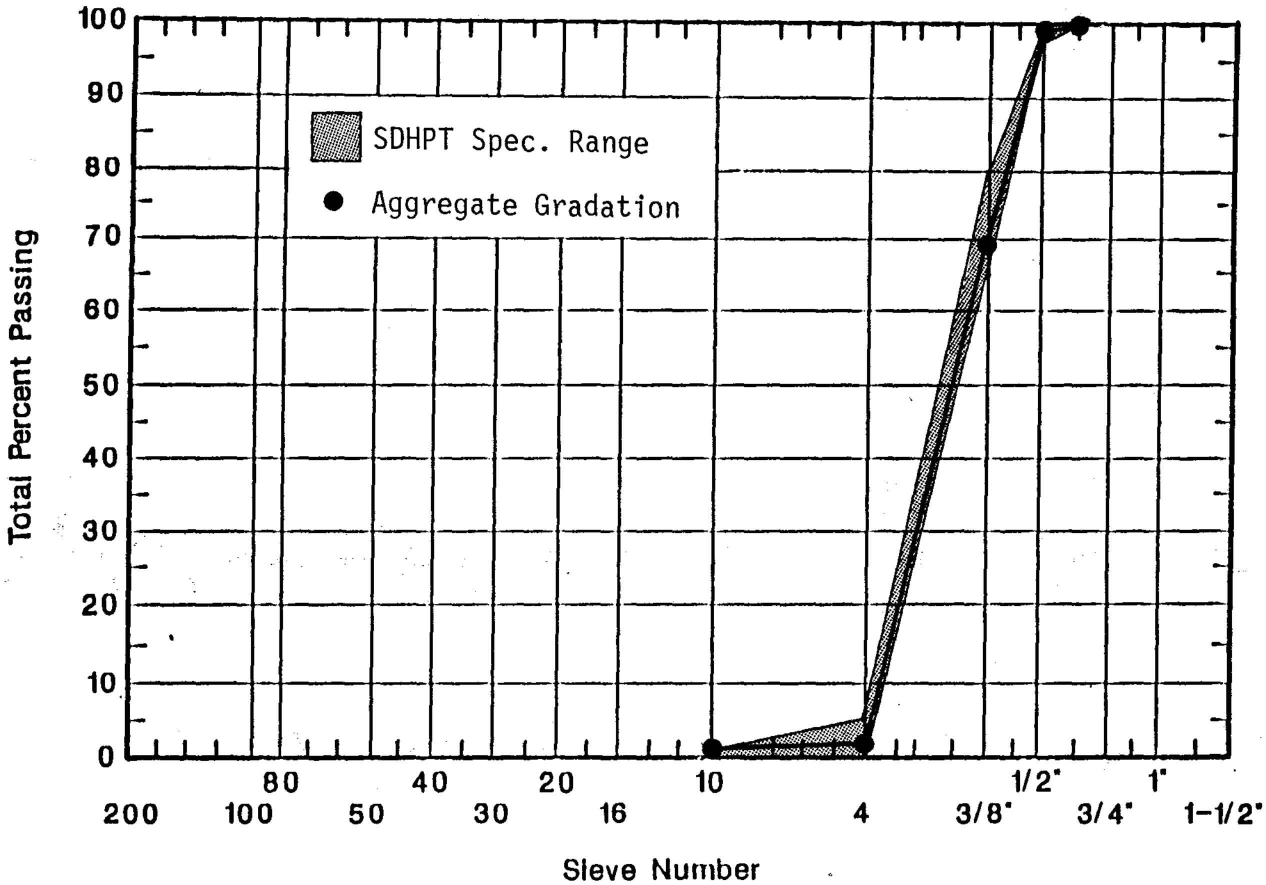


Figure 18. Aggregate Gradation for Grade 4 Crushed Limestone (Texas Crushed Stone).

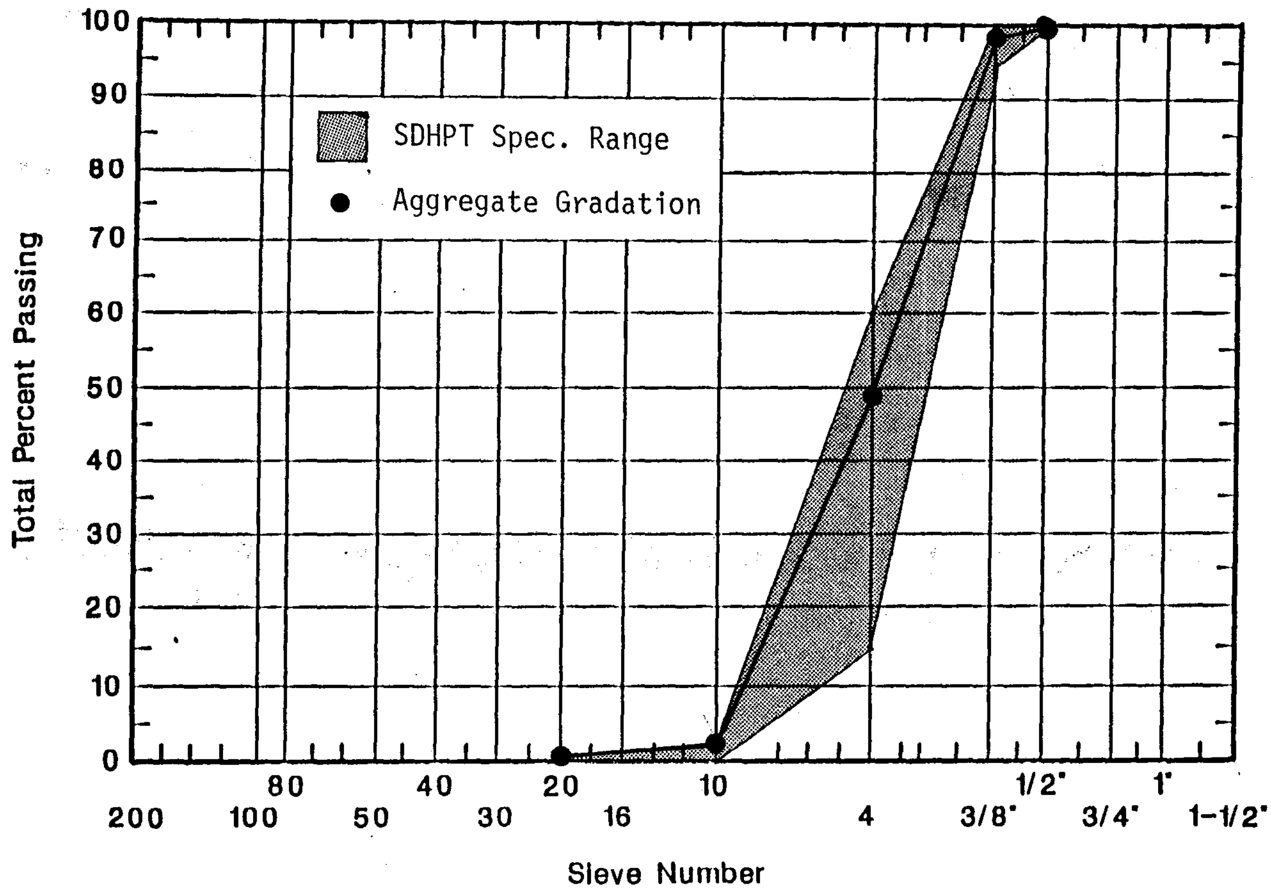


Figure 19. Aggregate Gradation for Grade 5 Crushed Limestone (Texas Crushed Stone).

Table 2. Properties of Crushed Limestone Used in Laboratory Study.

Aggregate Grade	Bulk Specific Gravity	Bulk Specific Gravity(SSD)	Apparent Specific Gravity	Flakiness Index
Grade 2	2.380	2.450	2.560	10
Grade 3	2.382	2.457	2.576	18
Grade 4	2.430	2.501	2.615	7
Grade 5	2.387	2.481	2.633	14

content of each sample was obtained using the Modified Tray Test. The test was performed three times on each sample and the variability in these three tests was evaluated for each sample. The ELT results are shown in Tables 3 through 6. The void contents are shown in Tables 7 through 10. The standard deviation and coefficient of variation are tabulated for each set of three tests. The coefficient of variation is simply the standard deviation expressed as a percentage of the mean. For data from different populations or, in this case, different aggregate grades, the mean and standard deviation often tend to change together so that the coefficient of variation is relatively stable or constant.

The average coefficients of variation for the four different aggregates are summarized as follows:

Grade	Cv (ELT)	Cv (Voids)
2	2.59%	3.54%
3	4.48%	5.19%
4	5.17%	5.67%
5	8.38%	6.42%

As shown above, there appears to be an increase in test variability as the size of the aggregate decreases. This may possibly be attributed to the fact that as we go from Grade 2 to Grade 5, the stone tends to be less one-sized. As the stone becomes less one-sized, there may be more variability in the test results.

The overall average coefficient of variation for all forty samples is 5.2% for both ELT and void contents. Therefore, it is concluded that the Modified Tray Test gives repeatable results.

2. Variability of Test Results from Sample to Sample

A second objective in testing the ten samples of each aggregate was to determine if a single sample of stone gave a reasonable indication of the ELT and true void content or whether it varied a lot from sample to sample. These results are shown in Tables 11 through 14. The standard deviation and coefficient of variation was calculated for the ten samples of each aggregate grade to evaluate the variability in results from sample to sample. The Cv's are summarized as follows:

Table 3. Effective Layer Thickness (ELT) of Grade 2 Aggregate As Obtained From Average of Three Modified Tray Tests Performed On Each Sample.

Sample No	Effective Layer Thickness, mm Trial 1	Trial 2	Trial 3	Average ELT, mm x	Standard Deviation S	Coefficient of Variation Cv, %
2A	8.94	9.88	9.30	9.37	0.47	5.02
2B	9.44	9.58	9.68	9.57	0.12	1.25
2C	9.23	9.44	9.36	9.34	0.11	1.18
2D	10.04	9.67	9.35	9.69	0.35	1.14
2E	10.07	10.20	10.43	10.23	0.18	1.76
2F	9.92	10.15	10.49	10.19	0.29	2.84
2G	9.86	9.83	9.83	9.84	0.02	0.20
2H	9.30	9.38	9.17	9.28	0.11	1.18
2I	9.20	8.23	8.76	8.73	0.49	5.61
2J	8.73	8.60	9.54	8.96	0.51	5.69
					Avg. S = 0.27	Avg. Cv = 2.59%

Table 4. Effective Layer Thickness (ELT) of Grade 3 Aggregate As Obtained From Average of Three Modified Tray Tests Performed On Each Sample.

Sample No.	Effective Layer Thickness, mm Trial 1	Trial 2	Trial 3	Average ELT, mm x	Standard Deviation S	Coefficient of Variation Cv, %
3A	7.71	6.84	7.75	7.43	0.51	6.86
3B	7.06	7.33	7.05	7.14	0.16	2.24
3C	7.35	7.46	7.28	7.36	0.09	1.22
3D	7.31	7.49	6.90	7.23	0.30	4.15
3E	7.30	7.93	7.85	7.69	0.34	4.42
3F	7.74	7.57	6.69	7.42	0.41	5.52
3G	7.02	6.84	7.79	7.22	0.51	7.06
3H	7.27	7.52	6.91	7.23	0.30	4.10
3I	7.25	6.91	7.79	7.30	0.41	5.62
3J	7.75	7.25	7.33	7.44	0.27	3.63
					Avg. S = 0.33	Avg. Cv = 4.48 %

Table 5. Effective Layer Thickness (ELT) of Grade 4 Aggregate As Obtained From Average of Three Modified Tray Tests Performed On Each Sample.

Sample No.	Effective Layer Thickness, mm Trial 1	Trial 2	Trial 3	Average ELT, mm x	Standard Deviation S	Coefficient of Variation Cv, %
4A	6.80	6.71	6.51	6.51	0.43	6.61
4B	5.73	6.42	6.48	6.21	0.42	6.76
4C	5.89	6.11	7.11	6.37	0.65	10.20
4D	6.36	6.27	6.67	6.43	0.21	3.27
4E	6.80	7.78	7.43	7.33	0.50	6.82
4F	5.55	6.06	5.84	5.82	0.26	4.47
4G	6.62	6.91	7.22	6.77	0.21	3.10
4H	6.34	6.27	6.14	6.25	0.10	1.60
4I	6.40	5.98	6.34	6.24	0.23	3.69
4J	6.27	6.36	6.90	6.51	0.34	5.22
				Avg. S = 0.34		Avg. Cv = 5.17%

Table 6. Effective Layer Thickness (ELT) of Grade 5 Aggregate As Obtained From Average of Three Modified Tray Tests Performed On Each Sample.

Sample No.	Effective Layer Thickness, mm Trial 1	Trial 2	Trial 3	Average ELT, mm x	Standard Deviation S	Coefficient of Variation Cv, %
5A	3.24	3.84	3.15	3.41	0.38	11.14
5B	3.57	3.59	4.09	3.75	0.29	7.73
5C	4.99	3.84	4.07	4.30	0.61	14.19
5D	3.84	3.94	4.26	4.01	0.22	5.49
5E	3.69	3.60	3.72	3.67	0.06	1.63
5F	3.72	3.51	4.10	3.78	0.30	7.94
5G	3.62	4.06	3.19	3.62	0.43	11.88
5H	4.03	3.15	3.32	3.50	0.47	13.43
5I	3.69	3.95	3.87	3.84	0.13	3.38
5J	5.30	5.05	4.61	4.99	0.35	7.01
				Avg. S = 0.32		Avg. Cv = 8.38%

Table 7. Void Content of Grade 2 Aggregate As Obtained From Average of Three Modified Tray Tests Performed On Each Sample.

Sample No.	Void Content, % Trial 1	Trial 2	Trial 3	Mean Void Content,% x	Standard Deviation S	Coefficient of Variation Cv,%
2A	41.45	42.35	42.96	42.2	0.76	1.80
2B	44.65	44.48	44.48	44.54	0.10	0.22
2C	45.78	46.48	47.68	46.65	0.96	2.05
2D	47.08	40.86	44.42	44.12	3.12	7.07
2E	42.01	47.52	44.27	44.60	2.77	6.21
2F	43.07	43.52	42.25	42.95	0.64	1.49
2G	47.42	45.42	43.54	45.46	1.94	4.27
2H	43.73	45.03	46.80	45.19	1.54	3.41
2I	41.52	40.62	46.46	42.87	3.14	7.32
2J	41.80	43.06	42.61	42.49	0.64	1.51
					Avg. S = 1.56	Avg. Cv = 3.54%

Table 8. Void Content of Grade 3 Aggregate As Obtained From Average of Three Modified Tray Tests Performed On Each Sample.

Sample No.	Void Content, % Trial 1	Trial 2	Trial 3	Avg. Void Content,% x	Standard Deviation S	Coefficient of Variation Cv,%
3A	50.55	44.29	50.83	48.56	3.69	7.60
3B	43.49	45.53	43.37	44.13	1.21	2.74
3C	47.54	48.26	47.01	47.60	0.63	1.32
3D	44.90	46.20	41.63	44.24	2.36	5.33
3E	43.89	48.35	47.87	46.70	2.45	5.25
3F	48.54	47.44	42.79	46.26	3.05	6.59
3G	46.50	45.12	51.83	47.82	3.54	7.40
3H	45.22	47.03	42.43	44.89	2.32	5.17
3I	45.89	43.25	49.27	46.14	3.02	6.55
3J	49.61	46.15	46.69	47.48	1.86	3.92
					Avg. S = 2.41	Avg. Cv = 5.19%

Table 9. Void Content of Grade 4 Aggregate As Obtained From Average of Three Modified Tray Tests Performed On Each Sample.

Sample No.	Void Content, % Trial 1	Trial 2	Trial 3	Avg. Void Content,% x	Standard Deviation S	Coefficient of Variation Cv,%
4A	52.02	51.39	45.70	49.70	3.48	7.00
4B	41.59	47.86	48.34	45.93	3.76	8.19
4C	43.35	45.39	53.05	47.26	5.11	10.81
4D	46.65	45.90	49.12	47.22	1.68	3.56
4E	51.33	57.48	55.46	54.76	3.13	5.72
4F	41.75	46.68	44.67	44.37	2.48	5.59
4G	49.06	51.22	53.30	51.19	2.12	4.14
4H	45.80	45.16	43.98	44.98	0.92	2.05
4I	48.47	44.80	47.99	47.09	1.99	4.23
4J	46.50	47.24	51.38	48.37	2.63	5.44
				Avg. S = 2.7		Avg. Cv = 5.67%

Table 10. Void Content of Grade 5 Aggregate As Obtained From Average of Three Modified Tray Tests Performed On Each Sample.

Sample No.	Void Content, % Trial 1	Trial 2	Trial 3	Avg. Void Content,% x	Standard Deviation S	Coefficient of Variation Cv,%
5A	48.95	56.95	47.53	51.14	5.08	9.93
5B	51.70	51.90	57.76	53.79	3.44	6.40
5C	67.48	57.67	63.92	63.02	4.97	7.89
5D	53.58	54.79	58.21	55.52	2.40	4.32
5E	56.49	55.43	56.83	56.25	0.73	1.30
5F	53.36	50.63	57.69	53.89	3.56	6.61
5G	55.60	60.42	49.70	55.24	5.37	9.72
5H	60.36	49.29	51.97	53.87	5.77	10.71
5I	52.48	55.66	54.65	54.26	1.62	2.99
5J	64.32	62.56	58.99	61.96	2.71	4.37
				Avg. S = 3.57		Avg. Cv = 6.42%

Table 11. Test Results from Different Samples of the Same Stone as Determined with the Modified Tray Test (Texas Grade 2).

Sample	ELT $\bar{X}$ (mm)	Voids $\bar{X}$ (%)
2A	9.57	42.25
2B	9.84	44.54
2C	10.23	46.65
2D	8.73	44.12
2E	9.37	44.60
2F	9.28	42.95
2G	9.69	45.46
2H	10.19	45.19
2I	8.96	42.87
2J	9.34	42.49
$\bar{X}$	9.52	44.11
$S_{\bar{X}}$	0.4873	1.4466
C_V	5.12%	3.28%

$\bar{\bar{X}}$ = The mean of the sample mean values.

$S_{\bar{X}}$ = Standard deviation of the sample mean value.

C_V = Coefficient of variation = $S_{\bar{X}}/\bar{\bar{X}}$.

Table 12. Test Results from Different Samples of the Same Stone as Determined with the Modified Tray Test (Texas Grade 3).

Samples	ELT $\bar{X}$ (mm)	Voids $\bar{X}$ (%)
3A	7.43	48.56
3B	7.14	44.13
3C	7.36	47.60
3D	7.23	44.24
3E	7.69	46.70
3F	7.42	46.26
3G	7.22	47.82
3H	7.23	44.89
3I	7.30	46.14
3J	7.44	47.48
$\bar{\bar{X}}$	7.35	46.38
$S_{\bar{X}}$	0.1589	1.5478
C_V	2.16%	3.34%

$\bar{\bar{X}}$ = The mean of the sample mean values.

$S_{\bar{X}}$ = Standard deviation of the sample mean values.

C_V = Coefficient of variation = $S_{\bar{X}}/\bar{\bar{X}}$.

Table 13. Test Results from Different Samples of the Same Stone as Determined with the Modified Tray Test (Texas Grade 4).

Samples	ELT $\bar{X}$ (mm)	Voids $\bar{X}$ (%)
4A	6.51	49.70
4B	6.21	45.93
4C	6.37	47.26
4D	6.43	47.22
4E	7.33	54.76
4F	5.82	44.37
4G	6.77	51.19
4H	6.25	44.98
4I	6.24	47.09
4J	6.51	48.37
$\bar{\bar{X}}$	6.44	48.09
$S_{\bar{X}}$	0.3985	3.1161
C_V	6.18%	6.48%

$\bar{\bar{X}}$ = The mean of the sample mean values.

$S_{\bar{X}}$ = Standard deviation of the sample mean values.

C_V = Coefficient of variation = $S_{\bar{X}}/\bar{\bar{X}}$.

Table 14. Test Results from Different Samples of the Same Stone as Determined with the Modified Tray Test (Texas Grade 5).

	ELT	Voids
Samples	$\bar{X}$ (mm)	$\bar{X}$ (%)
5A	3.41	51.14
5B	3.75	53.79
5C	4.30	63.02
5D	4.01	55.52
5E	3.67	56.25
5F	3.78	53.89
5G	3.62	55.24
5H	3.50	53.87
5I	3.84	54.26
5J	4.99	61.96
$\bar{\bar{X}}$	3.89	55.89
$S_{\bar{X}}$	0.4631	3.7429
C_V	11.91%	6.70%

$\bar{\bar{X}}$ = The mean of the sample mean values.

$S_{\bar{X}}$ = Standard deviation of the sample mean values.

C_V = Coefficient of variation = $S_{\bar{X}}/\bar{\bar{X}}$.

Grade	Cv (ELT)	Cv (Voids)
2	5.12%	3.28%
3	2.16%	3.34%
4	6.18%	6.48%
5	11.91%	6.70%

The overall average Cv for the ELT is 6.3% and 5.0% for the void contents. This confirms results from the NITRR (5) that a single sample of stone as tested by means of the Modified Tray Test, gives a good indication of the overall void content for a particular type and grade of stone.

3. Accuracy of the Modified Tray Test in Measuring ELT

A random sample of each aggregate grade was selected to determine the average least dimension (ALD). Since aggregate particles in a seal coat eventually lie on their flattest side, the average thickness of a seal coat is determined from the overall average smallest dimension of the aggregate particles. Three different methods were used to measure this average least dimension: (1) ALD as determined using McLeod's (10) test procedure, (2) ELT as determined using the Modified Tray Test, and (3) ALD as determined from calipering individual stones.

A rapid method for determining the average least dimension of seal coat aggregate was developed in Australia (10). First a grading analysis is made and plotted on a grading chart. The 50 percent passing size determined from the grading curve is called the "median" size of the aggregate. Each size passing one sieve and retained on the next is then tested particle by particle on appropriate slotted sieves to determine the Flakiness Index (Appendix A). The Median Size and the Flakiness Index are then used to determine the Average Least Dimension from the graph in Appendix A.

Another rapid method of determining the average least dimension of a particular aggregate is with the Modified Tray Test. The ELT or effective layer thickness as obtained with the Modified Tray Test is essentially a measure of the average least dimension.

Measuring the average least dimension by means of the caliper procedure was done with a vernier gage. Each stone as used in McLeod's ALD test and the Modified Tray Test was individually calipered with a vernier gage. For grades 2,3 and 4, three-point readings were taken for each stone and averaged. For the Grade 5 aggregate, a one-point reading was obtained for each stone (See Figure 20). Calipering each individual stone is, of course, the most accurate way of determining the average least dimension of a particular aggregate; however, it is extremely tedious and completely impractical. Therefore, there is a definite need for a more rapid way of determining the average least dimension of a representative sample of aggregate such as McLeod's ALD test or the Modified Tray Test.

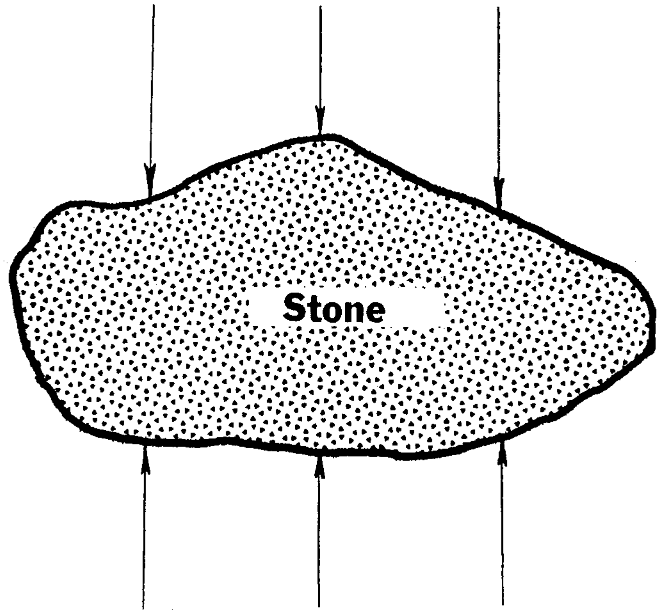
A comparison of the results obtained for each grade between the ELT, the ALD using McLeod's method and the ALD using the vernier gage is shown in Table 15 and in Figure 21. The results obtained with the Modified Tray Test are very close to those obtained using the calipers. The ALD obtained using McLeod's method appears to be significantly higher than the calipered method. Therefore, it is concluded that using the Modified Tray Test to measure the ELT of a sample gives a very good indication of the actual average least dimension for a particular aggregate.

4. Suitability of the Modified Tray Test for Multiple Seals

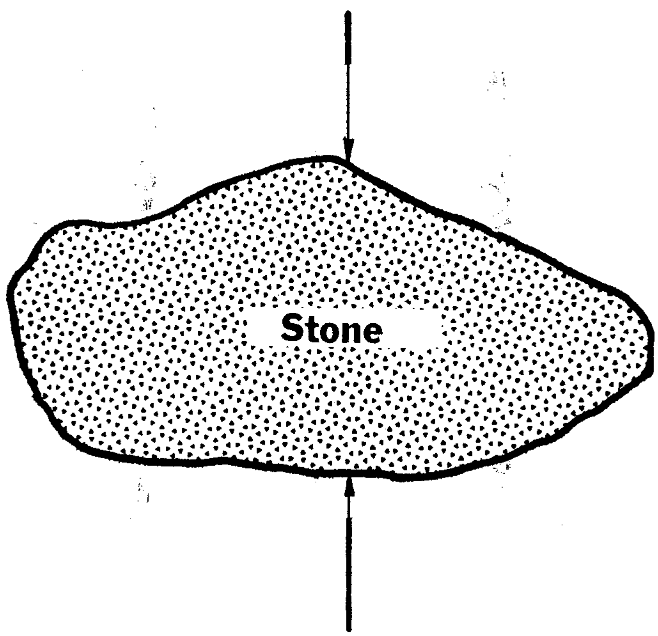
The NITRR (5) first decided to extend the rational design method for single seals to accommodate double seals. It was, therefore, necessary to know the true void content and ELT of a double seal, as in the case of a single seal. The suitability of the Modified Tray Test for double seals was verified in TTI's laboratory by using the stone samples used in the initial evaluation of the Modified Tray Test. The Modified Tray Test was used to determine the true void content and ELT of double seals made up by different combinations of these stones.

The NITRR (5) also determined that there was a good relationship between the void content of a double seal and the void contents of the bottom and top stone layers separately. A relationship was also found between the ELT of the double seal and the sum of the ELTs of the bottom and top layers (5). This was evaluated in TTI's laboratory using the same stone samples used in the previous experiments.

The following combinations of stone layers were used to evaluate the Modified Tray Test for double seals:



Three-Point Reading



One-Point Reading

Figure 20. Three-Point and One-Point Readings as Taken with Vernier Gage.

Table 15. Comparison of Results Using Calipered ALD, ELT as Determined from Modified Tray Test, and ALD Determined by McLeod's Method.

Aggregate Grade	Calipered ALD, mm	Modified Tray Test ELT, mm	McLeod's ALD, mm
2	9.21	9.52	11.94
3	7.31	7.35	8.38
4	6.31	6.44	7.37
5	3.34	3.89	4.32

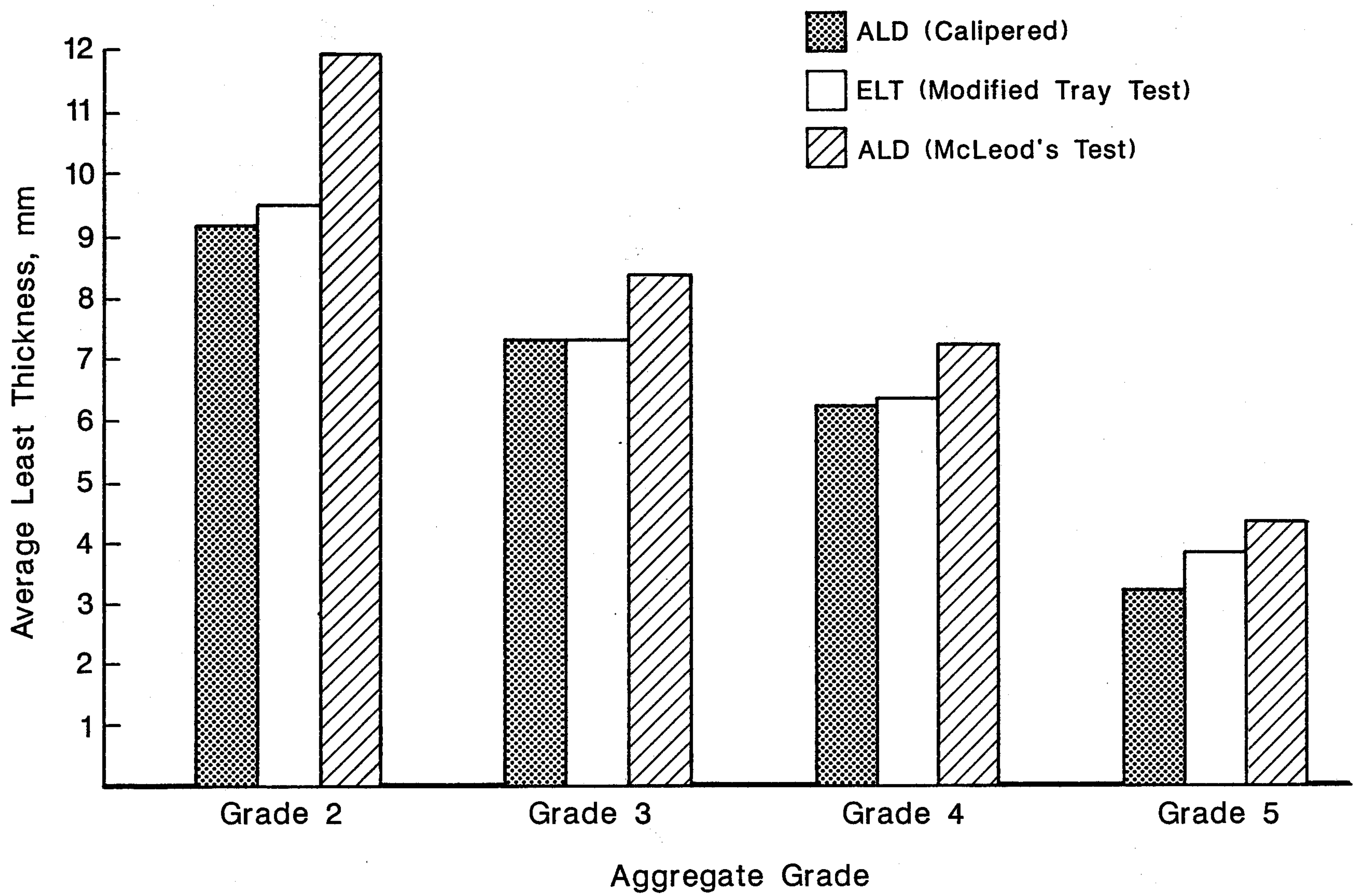


Figure 21. Comparison of Effective Layer Thickness (ELT) as Measured with Modified Tray Test, ALD Using McLeod's Method(10), and ALD Using Vernier Calipers.

Top Layer	Bottom Layer
Grade 5	Grade 2
Grade 4	Grade 2
Grade 3	Grade 2
Grade 2	Grade 2
Grade 5	Grade 3
Grade 4	Grade 3
Grade 3	Grade 3
Grade 5	Grade 4
Grade 4	Grade 4
Grade 5	Grade 5

These results are tabulated in Appendix C. The sum of the ELTs of the separate layers is plotted against the ELTs of the double layers in Figure 22. A very good relationship was found to exist between the two as shown in Figure 22. This also compares well to the relationship developed by the NITRR (5) as shown by the dashed line in Figure 22. The coefficient of determination (R^2) for the regression line established by the NITRR is 0.98.

The void contents in the double seals were also measured and compared with a "calculated" void content. The voids were calculated as follows:

$$\text{Voids}_d = \frac{[\text{ELT}_b\ (\text{Voids}_b) + \text{ELT}_t\ (\text{Voids}_t)]\ \text{ELT}_d}{(\text{ELT}_b + \text{ELT}_t)^2}$$

where ELT_b = ELT of the bottom stone layer,

ELT_t = ELT of the top stone layer,

ELT_d = ELT of the double stone layer,

Voids_b = Void content of the bottom stone layer,

Voids_t = Void content of the top stone layer, and

Voids_d = Void content of the double stone layer.

The ELT of the double layer used in this calculation was that measured in the Modified Tray Test. These results are plotted in Figure 23. A good relationship was found here, also. The dashed line in Figure 23 represents the regression line established by the NITRR (5) which has a coefficient of determination of 0.77.

A comparison was also made between the measured voids in a double layer and the calculated void content using a calculated ELT_d. This ELT_d was calculated using the regression equation developed from Figure 22. This relationship is shown in Figure 24. The dashed line in Figure 24 is

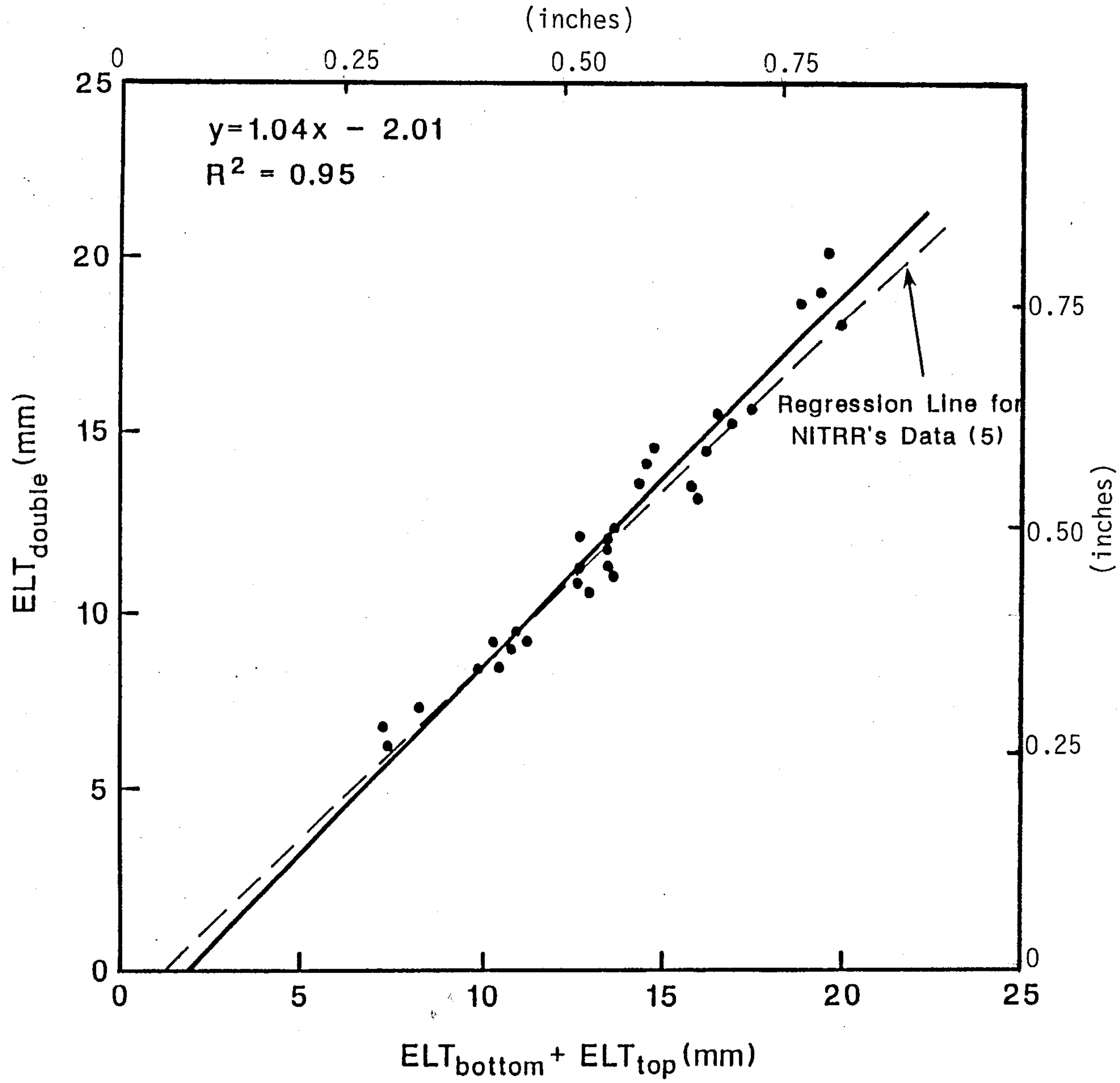


Figure 22. The Sum of the Elt's of the Bottom and Top Stone Layers Versus the ELT of the Double Stone Layer.

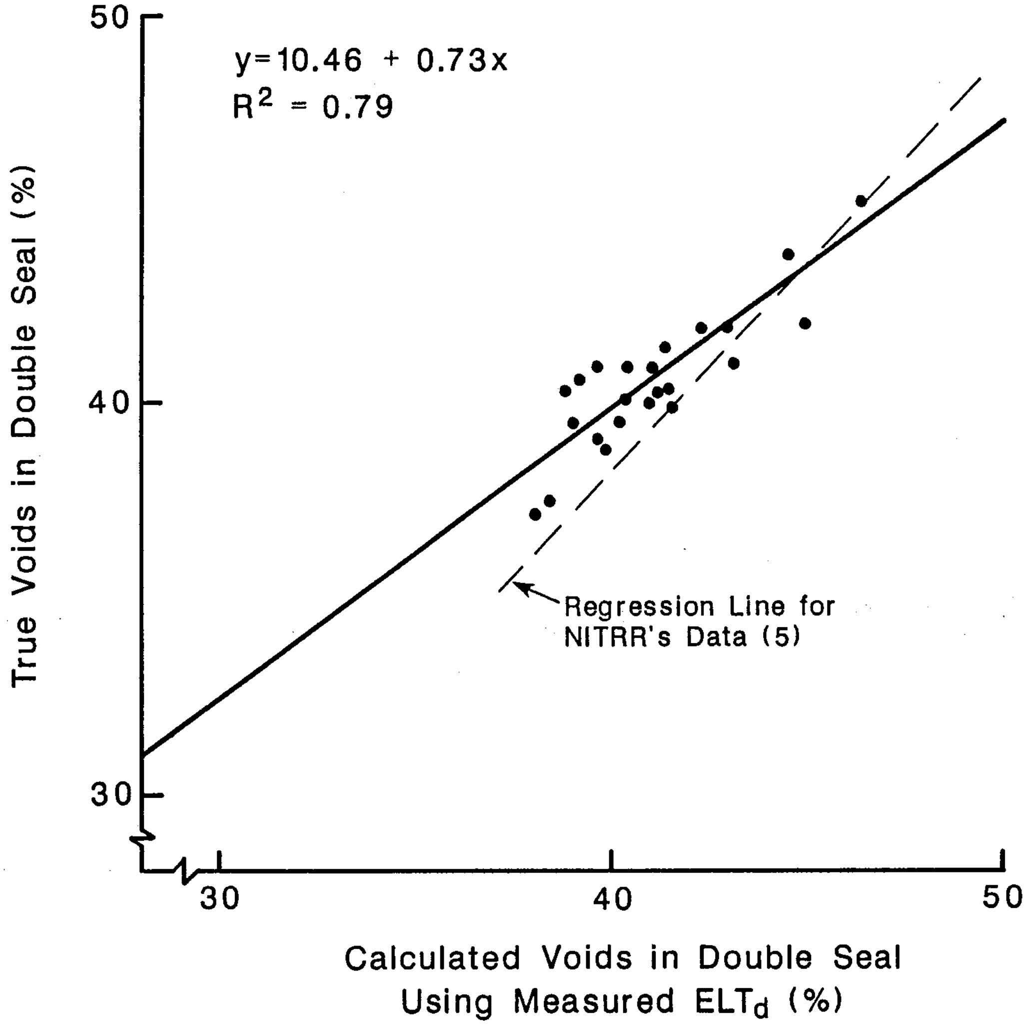


Figure 23. Calculated Voids Using Measured ELT Versus Voids as Measured for Double Stone Layer.

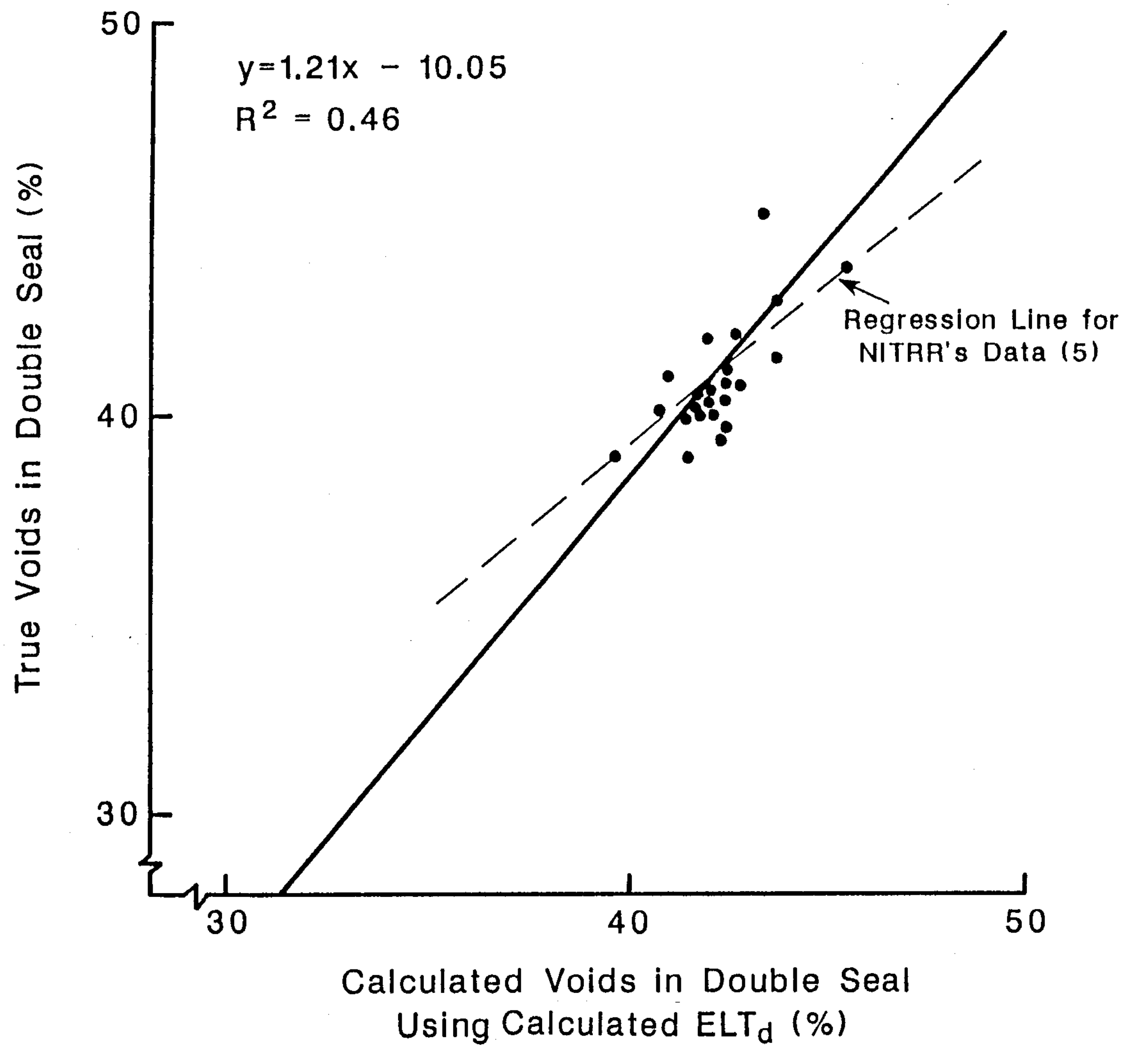


Figure 24. Calculated Voids Obtained Using Calculated ELT Versus Measured Voids in a Double Stone Layer.

the regression line established by the NITRR (5), which has a coefficient of determination of 0.82. The data presented by the NITRR (5) for the relationship between the calculated and measured voids produced a better fit to the regression equations than that presented by TTI in Figures 23 and 24. However, the data produced by the NITRR represented a much larger variety of aggregates which exhibited a wider range in void contents. The TTI experiment involved four sizes of aggregates from only one source. Therefore, the relationships developed by the NITRR (5) which were supported by this experiment were used for the design procedure.

Based on these results, it is concluded that it is possible to determine good estimates of the ELT and void content of a double seal by using the properties (ELT and void content) of the separate layers as determined with the Modified Tray Test.

5. Spread Rate as Determined from the Modified Tray Test

To determine the spread rate (Q) of the aggregate, the same stone samples used in the initial evaluation of the Modified Tray Test were used once the ELT and void content of a stone layer had been determined from the Modified Tray Test. The stone sample was poured directly from the tray into a two-liter plastic measuring cylinder and the bulk volume occupied by the stone plus voids was read off the cylinder. This procedure was repeated five times (per stone sample) to get an average of the bulk volume and the variability associated with it. The test was performed on all 40 samples mentioned previously and the results are shown in Table 16. The spread rate, Q (in m^3/m^2), can be calculated by the following equation (14):

$$Q = V_b/A_1 \times 10^{-3}$$

where Vb = bulk volume of aggregate sample (liters)

A_1 = area of the tray (sq. meters).

The spread rates for all forty samples are presented in Table 17. The coefficients of variation shown in Table 17 for each aggregate grade are very low, indicating that one sample as used in the Modified Tray Test can give a good indication of the spread rate for that particular aggregate type.

Table 16. Average Bulk Volume of Samples (5 readings) as Measured by Means of the Plastic Measuring Cylinder.

Bulk Volume of Sample V2 (liters)				
Sample	Grade 2	Grade 3	Grade 4	Grade 5
A	.476	.337	.275	.135
B	.472	.356	.280	.139
C	.474	.342	.271	.136
D	.427	.357	.270	.143
E	.439	.348	.275	.140
F	.458	.360	.269	.136
G	.457	.329	.270	.134
H	.488	.351	.274	.130
I	.442	.349	.277	.142
J	.464	.343	.279	.138
$\bar{\bar{X}}$	.460	.347	0.274	0.137
$S_{\bar{X}}$	0.019	.010	0.004	0.004
C_v	4.1%	2.8%	1.4%	2.9%

$\bar{\bar{X}}$ = The mean of the sample mean values.

$S_{\bar{X}}$ = Standard deviation of the sample mean values.

C_v = Coefficient of variation = $S_{\bar{X}}/\bar{\bar{X}}$.

Table 17. Spread Rate as Determined with the Modified Tray Test and Volumetric Measuring Cylinder.

	Aggregate Spread Rate (yd^2/yd^3)			
Sample	Grade 2	Grade 3	Grade 4	Grade 5
A	79	112	137	279
B	80	105	134	271
C	79	110	139	277
D	88	105	139	263
E	86	108	137	269
F	82	105	140	277
G	82	114	139	281
H	77	107	137	289
I	85	108	136	265
J	81	110	135	273
$\bar{\bar{X}}$	82	108	137	274
$S_{\bar{X}}$	3	3	2	8
C_V	3.7%	2.8%	1.5%	2.9%

$\bar{\bar{X}}$ = The mean of the sample mean values.

$S_{\bar{X}}$ = Standard deviation of the sample mean values.

C_V = Coefficient of variation = S_X/X.

CHAPTER VII

FABRICATION OF SEAL COATS IN THE LABORATORY

A. RESEARCH APPROACH

The objective of this portion of the research study was to evaluate the design procedure by fabricating multiple seal coats in the laboratory. Seal coats built in the laboratory were evaluated for embedment depth, aggregate retention and surface texture.

B. MATERIALS

The aggregate used to build the laboratory seal coats was the same as used in the previous experiment to evaluate the Modified Tray Test: Grades 2, 3, 4 and 5 of a crushed limestone from Texas Crushed Stone in Georgetown, Texas. The binder used for this portion of the study was an emulsion: HFRS-2 supplied by Texas Emulsions. An emulsion was used rather than an asphalt cement due to laboratory equipment constraints and for safety reasons. The emulsion could be sprayed at a much lower temperature than an asphalt cement.

C. LABORATORY PROCEDURE

1. General

Seal coats were fabricated in the laboratory on boards with a surface area of one-half square yard. The asphalt was applied with a small laboratory distributor utilizing standard distributor nozzles in much the same manner as would be used in the field. Cover stone was spread and brushed by hand; rolling was accomplished with a small pneumatic-tire roller. The laboratory procedure normally consisted of the steps listed below.

1. Preparation of the boards to receive the binder.
2. Application of the binder to the boards.
3. Application of the cover stone to the binder.
4. Rolling and brushing the stone.

5. Allow seal coat to cure overnight in 104°F temperature chamber.

6. Determination of the amount of stone retained by the binder.

7. Determination of the stone embedment depth into the binder.

8. Determination of the surface texture of the seal coat by the sand patch method.

9. Steps 2 through 8 were repeated for successive seal coat layers.

2. Equipment for Application of the Binder

The apparatus used for distributing the binder was designed and built by Benson and Gallaway (11) and is shown in Figure 25. Benson and Gallaway state that the operation of this machine is similar to that of the regular asphalt distributor which is used in commercial seal coat work. The tank, composed of a short section of ten-inch pipe (capacity of about 5 gallons), is charged through the large opening that may be seen to the left of the pressure gage. An asbestos gasket is used to effect a seal between the cover and the tank. A thermowell and thermometer are located just to the left of the pressure gage. The thermowell extends to within one-fourth inch of the bottom of the tank. In this laboratory distributor, air pressure is used to replace the pump used on the commercial machine. This regulator also provided an effective means of removing any moisture from the air.

The binder flows under pressure from the tank through a 1 1/4-inch pipe and plug valve to the spray bar as may be seen in Figure 25. The tank and spray bar are heated by means of electrical heating tapes. The spray bar is equipped with four standard distributor nozzles. Locomotion of the distributor was effected by means of the apparatus shown in Figure 26. This consists of an electric motor, pulley and a small cable on a drum. A speed of travel from 2 mph to 5 mph is obtainable.

3. Procedure Used in Applying the Binder

The heated binder was applied under pressure to paper covered boards with the apparatus described. For ease of handling and calculating, these boards were made of such size as to yield one-half square yard of area. The masonite board is completely hidden by the paper which is

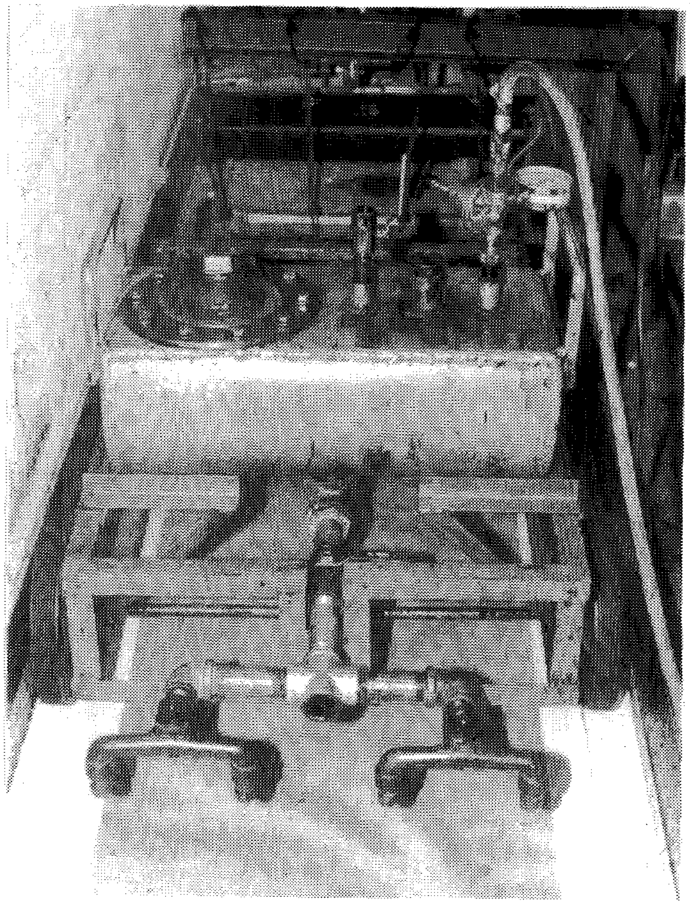


Figure 25. Laboratory Asphalt Distributor.

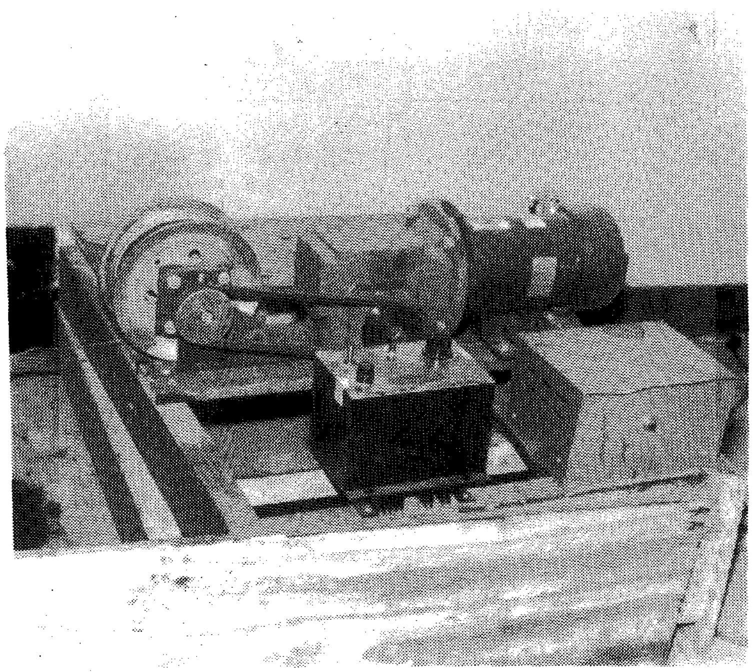


Figure 26. Apparatus Used to Pull Laboratory Distributor.

taped to the board. The tape is effective in preventing the binder from flowing between and under the boards at the time of shooting.

After the boards were prepared as described above they were weighed and placed in the "run" as shown in Figure 27. The "run" or track served to guide the distributor over the boards and to protect the operator from splattering asphalt. The "run" was covered with paper which was removed after each shot minimizing the cleaning problem. Early removal of the protective paper from the run is important since the binder, given time, will soak through the paper and create an undesirable situation.

The emulsion was heated in the distributor to approximately 135°F. The spray bar delivery pipe and valve were also thoroughly heated to ensure free flow of the binder. The air pressure in the distributor tank was then adjusted to the value desired for the particular quantity to be applied. The range of air pressures used was from 15 to 35 psi. The distributor was started at one end of the run, the valve being opened before the first board was reached and closed after the last board was passed. Figure 28 shows the distributor in operation. Immediately after the asphalt was shot, a preweighed quantity of aggregate was applied to the boards.

4. Procedure Used in Applying Cover Stone

It was found desirable to establish a standard operating procedure as to time and sequence of the different steps. In this standard procedure, five minutes were allowed between the shooting operation and the beginning of the application of the cover stone. A predetermined quantity of cover stone was applied by hand.

5. Procedure Used in Rolling the Stone

The stone was rolled 30 minutes after spraying the binder. All of the rolling was accomplished with a small pneumatic roller as shown in Figure 29. It has a tread width of 2 1/4 inches for each of three tires with a total width of 10 1/2 inches and was loaded to a total weight of 350 pounds. A tire pressure of 40 pounds per square inch was used. The procedure used in rolling is described as follows:

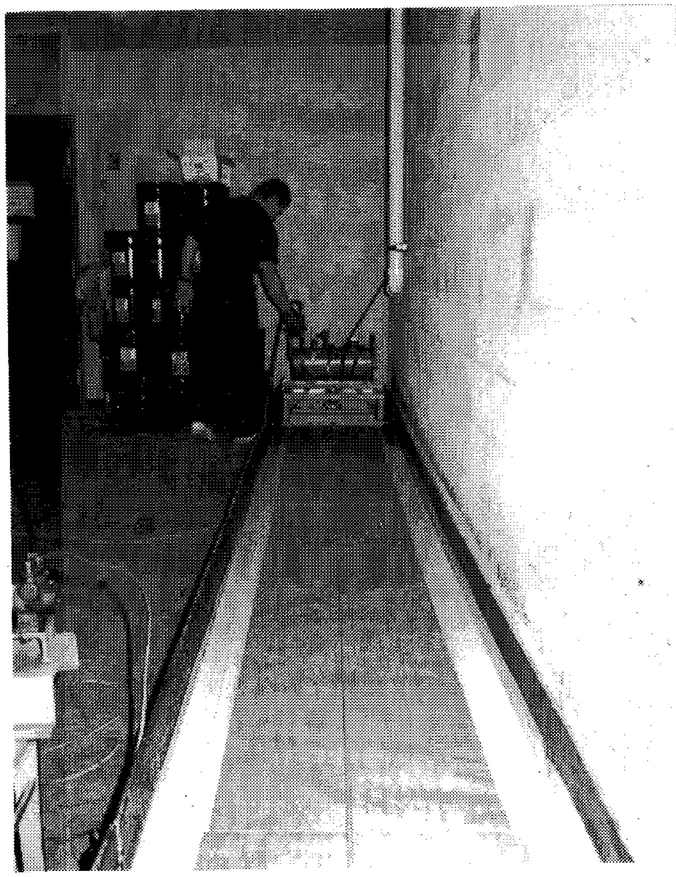


Figure 27. Paper-Covered Boards Placed in Track.

Figure 28. Laboratory Distributor in Motion.

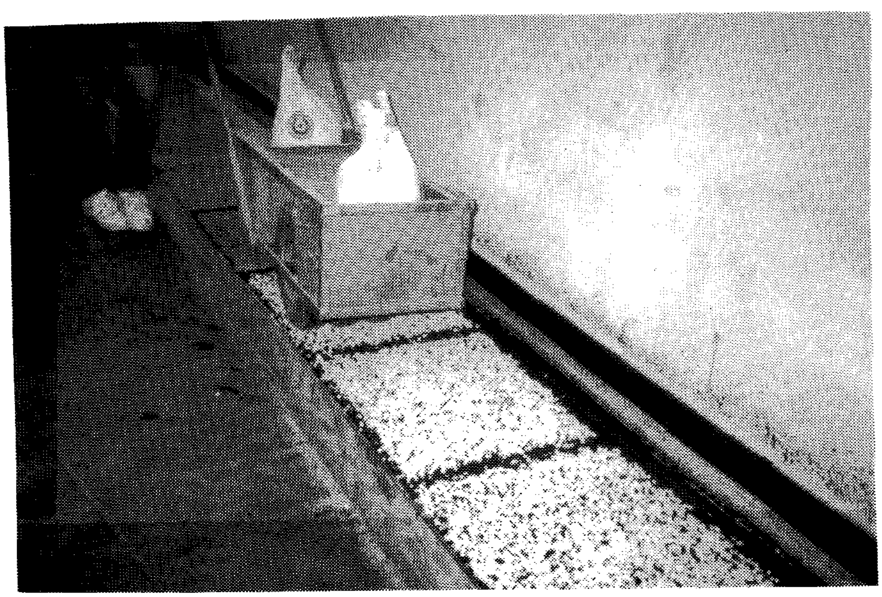


Figure 29. Laboratory Pneumatic Roller in Motion.

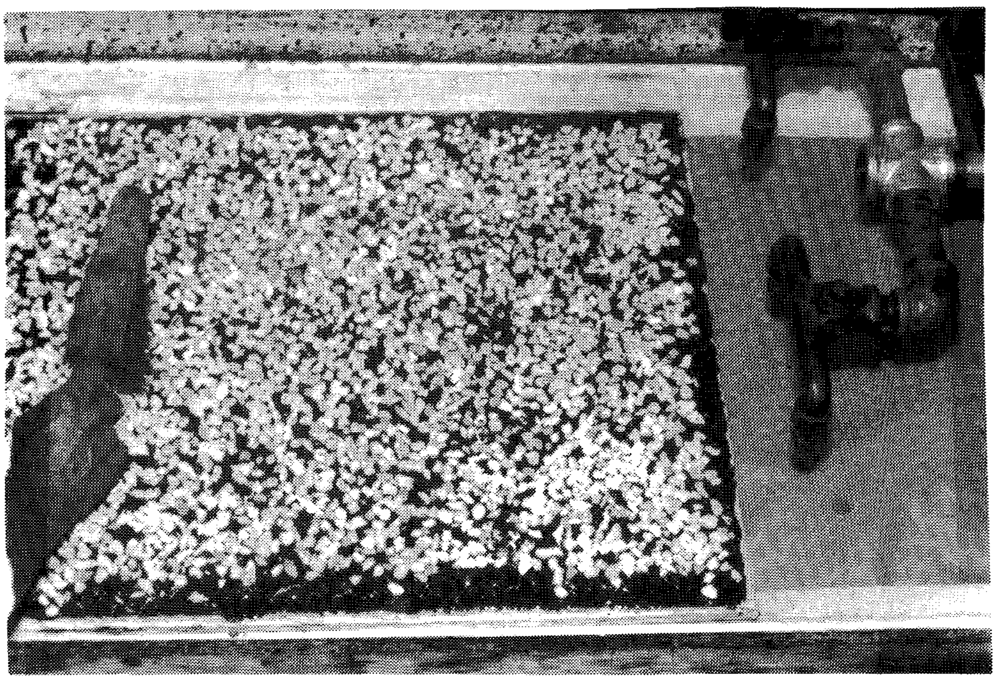


Figure 30. Brushing of Stone Between Rolling Passes.

1. The stone was lightly brushed to obtain uniform distribution. (See Figure 30)
2. The stone was rolled with two passes of the roller, a pass consisting of a trip back and forth.
3. The stone was again lightly brushed.
4. The stone was rolled with four additional passes of the roller.

6. Procedure Used to Cure the Emulsion Seal Coats

Once the cover stone was placed on the boards and rolled, the boards were removed from the track and placed in a 104°F temperature chamber for 24 hours. This was to allow sufficient time for the emulsion to "break" before weighing and applying a second seal coat layer. After this 24-hour period, the boards were weighed to determine the residual binder content. The boards were then placed back in the "run" and a second seal coat layer was applied. The seal coat boards were then cured again for 24 hours and the residual binder content was then determined for the second layer.

7. Procedure Used to Determine "Brush-off"

After the final 24 hour curing period, the quantity of stone which could be readily brushed off of the top seal coat layer was determined. The quantity of stone adhering to the asphalt could then be easily determined by difference.

The boards were placed on a jig to incline them 75° with the horizontal as shown in Figure 31. They were then brushed with a medium soft bristle brush, one pass across and one pass down covering the entire board. For the brush used in this work, four strokes in each direction were required to cover the board. The ideal procedure was to brush the boards so as to remove all loose stone and also that loosely attached by asphalt. An approximately one-pound force was exerted between the brush and the stone during the brushing operation. The stone removed was weighed to the nearest gram and the amount of stone retained was calculated by difference.

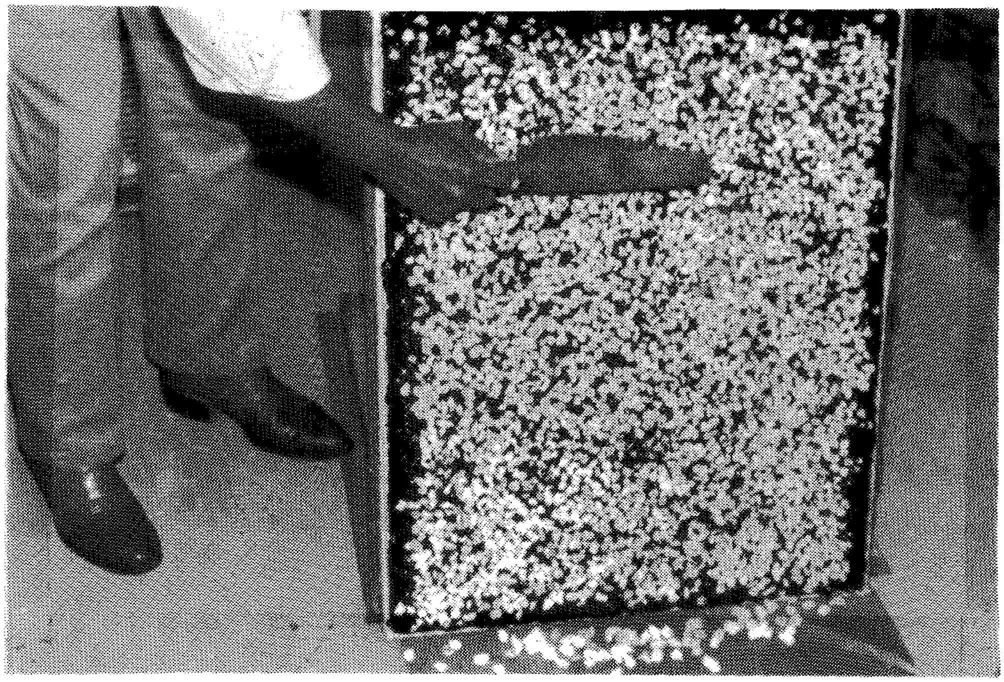


Figure 31. Procedure Used to Determine "Brush-Off."

8. Procedure Used to Determine Embedment Depth

The embedment depth of the aggregate in the binder was determined by randomly selecting ten stones from each board. The stones were removed from the binder and visually observed to estimate what percentage of the stone's vertical dimension was covered with asphalt. This percentage was the stone's estimated embedment depth. The embedment depth for all ten stones was averaged to obtain the embedment depth for each board.

9. Procedure Used to Determine Surface Texture

The Sand Patch Test was used to determine the surface texture of these laboratory fabricated seal coats. This rather simple test involves the spreading of a known volume of fine, dry sand over a circular area until the sand is flush with the aggregate tips of the surface. The area of the patch was determined from the average of three diameter measurements. The average texture depth, which is the ratio of volume to area, was then calculated. Two sand patch tests were performed on each board.

D. LABORATORY TEST RESULTS

1. General

Various combinations of Grades 2,3,4 and 5 aggregates were used to build seal coats in the laboratory using the procedure previously described. These test results were used to verify or modify the design pro-cedure described in Chapter IV and to provide preliminary target data for construction of field test sections.

The two main variables used in the laboratory experiment were (1) combination of aggregate gradings and (2) binder application rate. Ten different combinations of aggregate gradings and two different binder application rates were used. These are noted in Figure 32. The "design" application rate is that obtained using the design procedure as discussed in Chapter IV. It was desirable then to have application rates both higher and lower than the design rate; however, it was not possible to obtain an application rate significantly higher than the design with the laboratory distributor. Binder application rates higher than the design rates also appeared to be much too high to be worth considering. There-

		Aggregate Combination $\left(\frac{\text{Top Layer}}{\text{Bottom Layer}}\right)$									
		$\frac{5}{2}$*	$\frac{4}{2}$	$\frac{3}{2}$	$\frac{2}{2}$	$\frac{5}{3}$	$\frac{4}{3}$	$\frac{3}{3}$	$\frac{5}{4}$	$\frac{4}{4}$	$\frac{5}{4}$
Binder Appl. Rate	Low	- **	-	-	-	-	-	-	-	-	-
	Design	-	-	-	-	-	-	-	-	-	-

* Grade 5 on Grade 2

** "-" represents one laboratory seal coat built with noted aggregate gradings and binder application rate.

Figure 32. Experiment Design for Laboratory Fabrication of Multiple Seal Coats.

fore, the two binder application rates used were (1) the rate obtained by the design procedure and (2) a rate 30% lower than that obtained by the design procedure.

In this experiment, a total of twenty laboratory seal coats (10 stone combinations x 2 binder application rates) were built and evaluated for embedment depth, surface texture and aggregate retention. Each seal coat was a result of one "run" of the laboratory distributor and each "run" produced four seal coat boards. Therefore the data presented for embedment depth, surface texture and aggregate retention were obtained from an average of four samples (or boards). However, time did not permit replication of the experiment, so a statistical analysis was not performed. By definition, a replication would require a repetition of the entire basic experiment.

2. Aggregate Retention

The aggregate retention of each seal coat was determined using the "brush-off" procedure described previously. These results are shown in Table 18. Each tabulated retention percentage represents an average retention rate of four seal coat boards. Aggregate retention was good on all of the seal coats. Those seal coats with the design application rates had the highest retention and those with the lower rates had slightly less, but both were well within an acceptable range.

3. Surface Texture Results

The surface texture depth was measured on all of the laboratory seal coats using the Sand Patch Test as previously described. The texture depth for the surface layers is shown in Table 19, and each depth tabulated is an average of 8 readings (2 readings per board). The results were quite variable with the different stone combinations, and no correlations were developed that could be used for design purposes. One consistent trend was that the texture depth was greater with the lower asphalt application rate, as would be expected.

Gallaway, et al. (34) recommends that where longitudinal grades do not exceed 3% and drainage is not over three 12-foot lanes, the texture

Table 18. Aggregate Retained on Top Layer of Laboratory Fabricated Seal Coats.

Stone Layer Combination	% Aggregate Retained: Lower Asphalt Application Rate	% Aggregate Retained: Design Asphalt Application Rate
Grade 5 on Grade 2	96	100
Grade 4 on Grade 2	96	98
Grade 3 on Grade 2	95	97
Grade 2 on Grade 2	93	98
Grade 5 on Grade 3	95	99
Grade 4 on Grade 3	94	99
Grade 3 on Grade 3	93	98
Grade 5 on Grade 4	94	99
Grade 4 on Grade 4	95	100
Grade 5 on Grade 5	95	100
	X = 95	99
	S = 1	1
	C_v = 1.1%	C_v = 1.0%

Table 19. Surface Texture Depth of Top Layer of Laboratory Fabricated Seal Coats.

Stone Layer Combination	Surface Texture Depth, mm: Low Asphalt Application Rate	Design Asphalt Application Rate
Grade 5 on Grade 2	3.02	2.18
Grade 4 on Grade 2	3.42	3.56
Grade 3 on Grade 2	3.74	3.31
Grade 2 on Grade 2	*	*
Grade 5 on Grade 3	3.25	2.87
Grade 4 on Grade 3	3.81	3.16
Grade 3 on Grade 3	4.72	3.90
Grade 5 on Grade 4	2.39	2.03
Grade 4 on Grade 4	3.74	2.87
Grade 5 on Grade 5	2.31	1.73

* Surface Texture too deep to measure with Sand Patch Test

Table 20. Embedment Depth of Top Layer of Laboratory Fabricated Seal Coats.

Stone Layer Combination	Embedment Depth, %: Low Asphalt Application Rate	Embedment Depth, %: Design Asphalt Application Rate
Grade 5 on Grade 2	30	48
Grade 4 on Grade 2	33	39
Grade 3 on Grade 2	27	38
Grade 2 on Grade 2	26	42
Grade 5 on Grade 3	36	52
Grade 4 on Grade 3	29	43
Grade 3 on Grade 3	24	36
Grade 5 on Grade 4	34	42
Grade 4 on Grade 4	34	48
Grade 5 on Grade 5	32	47
	X = 31	X = 44
	S = 4	S = 5
	C_v = 12.9%	C_v = 11.4%

depth should not fall below 1.0 mm. In this experiment, all of the seal coats had texture depths well above 1.0 mm.

4. Embedment Depth Results

The percent aggregate embedment into the binder was obtained using the procedure described previously. These results are shown in Table 20. Each embedment depth tabulated represents an average of 40 readings (10 readings per board). The overall average embedment for the surface layers using the lower application rate was 31%. The percent embedment using the design application rate was 44%. This embedment depth should represent that obtained in the field immediately after construction and before traffic. According to Epps, et al. (7), the suggested embedment immediately after construction is 30% + 10%. This points to the low application rate as possibly being the more desirable.

CHAPTER VIII

FIELD STUDY

A. GENERAL

Four field test roads were constructed and monitored to evaluate the performance of multiple seals, to establish construction procedures, and to help establish and verify laboratory design procedures.

One test pavement was constructed in the Lubbock District on U.S. 82 between Plains and Brownfield. This pavement will be referred to as the "Lubbock Test Road." Another test pavement was constructed in the Brownwood District on the feeder road to Interstate 20 near Eastland, Texas. This pavement will be referred to as the "Eastland Test Road." The third test road was constructed in the Austin District on U.S. 290 between Paige and McDade, Texas, and will be referred to as the "Paige Test Road." The fourth test road was also constructed in the Austin District. This test pavement is located on State Highway 29 between Circleville and Georgetown and will be referred to as the "Circleville Test Road". See Figure 33 for locations.

B. LUBBOCK TEST ROAD

1. Objectives

This test road was constructed early in the research study before the design procedure had been evaluated. This project was a regular construction project for District 5 and it was monitored under this study in order to (1) evaluate and document the construction techniques for building multiple seals by a district which has been building successful multiple surface treatments for more than 20 years, (2) evaluate the performance of a multiple surface treatment, and (3) obtain samples from the construction site to begin evaluation of a laboratory design procedure which could be compared to actual field application quantities.

2. Construction of Test Road

The Lubbock Test Road was constructed the week of July 7, 1986. It is located on U.S. Highway 82 between Plains and Brownfield. It begins at the Yoakum County line and extends west to State Highway 214 for

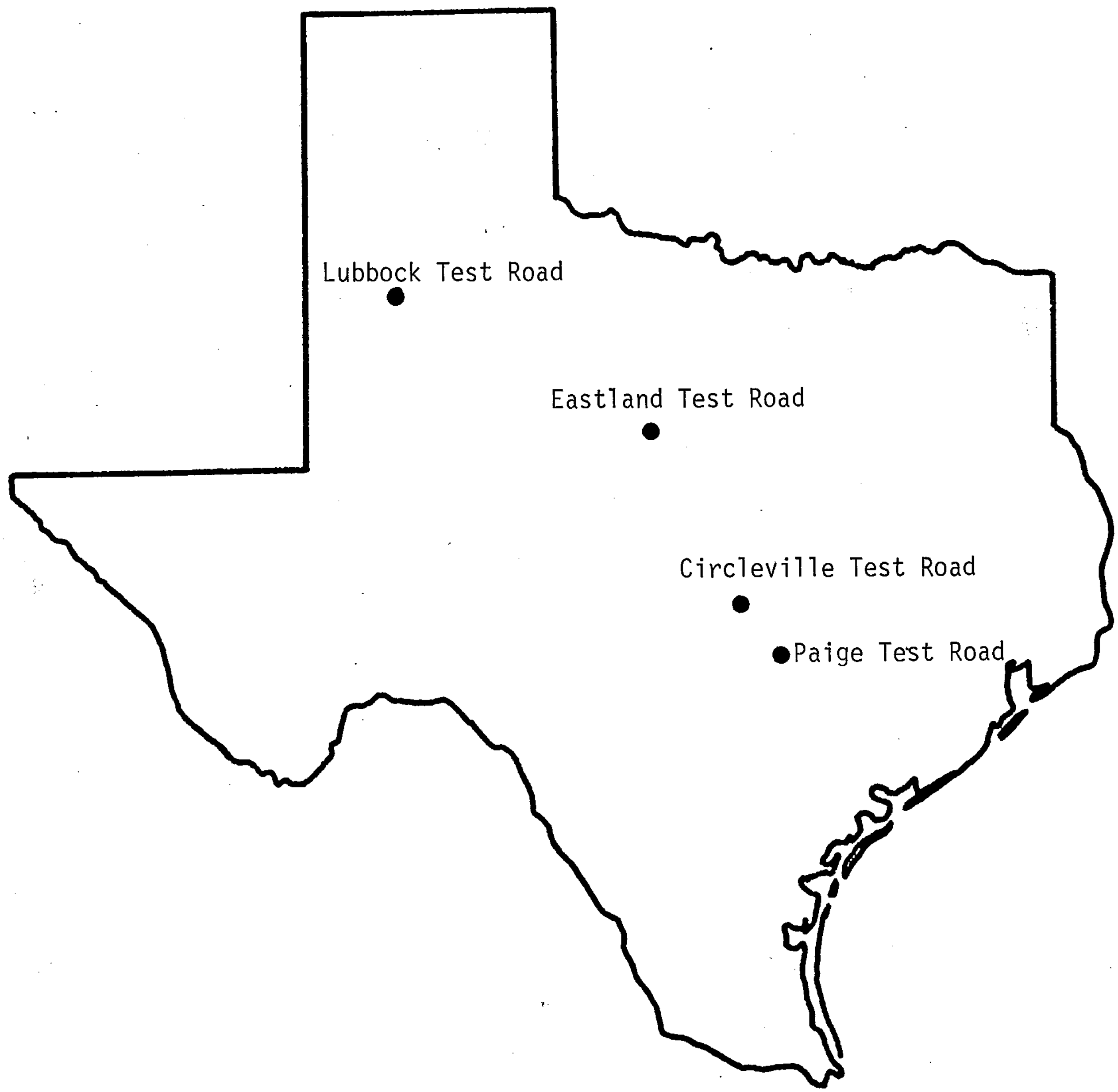


Figure 33. Field Test Road Locations.

approximately 12 miles of construction (See Figure 34). Traffic on the Lubbock Test Road consisted of an average daily traffic (ADT) of about 2000 vehicles per day in 1984.

The original pavement structure was scarified and reshaped, primed with 0.22 gallons per square yard of MC-30, and topped with a Grade 4, one-course surface treatment. This was the surface preparation before application of a triple surface treatment. This preparation is called the base preservative and was exposed to traffic several days before application of the triple surface treatment.

Materials. The aggregate used for construction of the triple surface treatment was as follows:

Bottom Course - Grade 1, Crushed Limestone,

Middle Course - Grade 4, River Gravel, and

Top Course - Grade 5, Precoated Crushed Limestone.

These aggregate gradation curves are shown in Figures 35, 36 and 37. The asphalt used for construction of all three layers was an AC-10. The application quantities of each of these materials is shown in Table 21.

Construction Procedure. This part of U.S. Highway 82 is a two-lane highway (one lane in each direction). All of the traffic was directed onto both shoulders of the highway during the construction process and traffic was not allowed back onto the main lanes until the third and final course was applied.

The asphalt distributor sprayed across both lanes of traffic at one time for a total width of 24 feet (Figure 38). The aggregate spreader covered one lane of traffic for a few hundred feet (Figure 39), then backed up to the beginning again, moved over and covered the other lane (Figure 40). The aggregate spreader was then immediately followed by the pneumatic rollers (Figure 41). This construction sequence was repeated until the third and final course was applied. The final course was then rolled with a lightweight steel-wheel roller (Figures 42). District personnel feel that the breakdown of any aggregate due to the steel wheels is minimal. Figure 43 is a close-up view of the final surface which is a precoated crushed limestone. From the white, powdery spots in the photograph, it appears that there may be some crushing involved here. This, however, was not significant enough to adversely affect the performance of the pavement, as it is still performing well today.

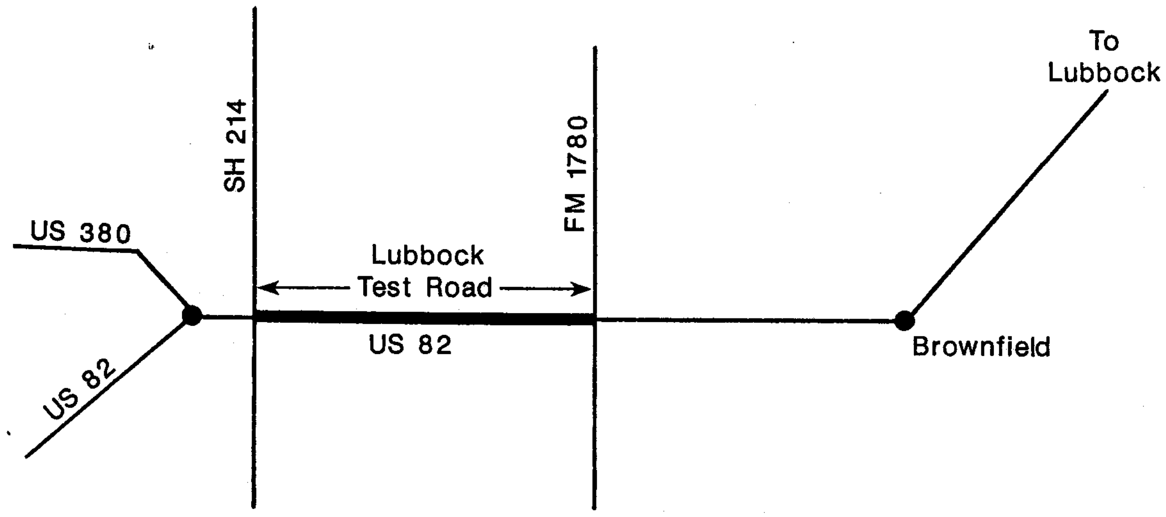


Figure 34. Location of Lubbock Test Road.

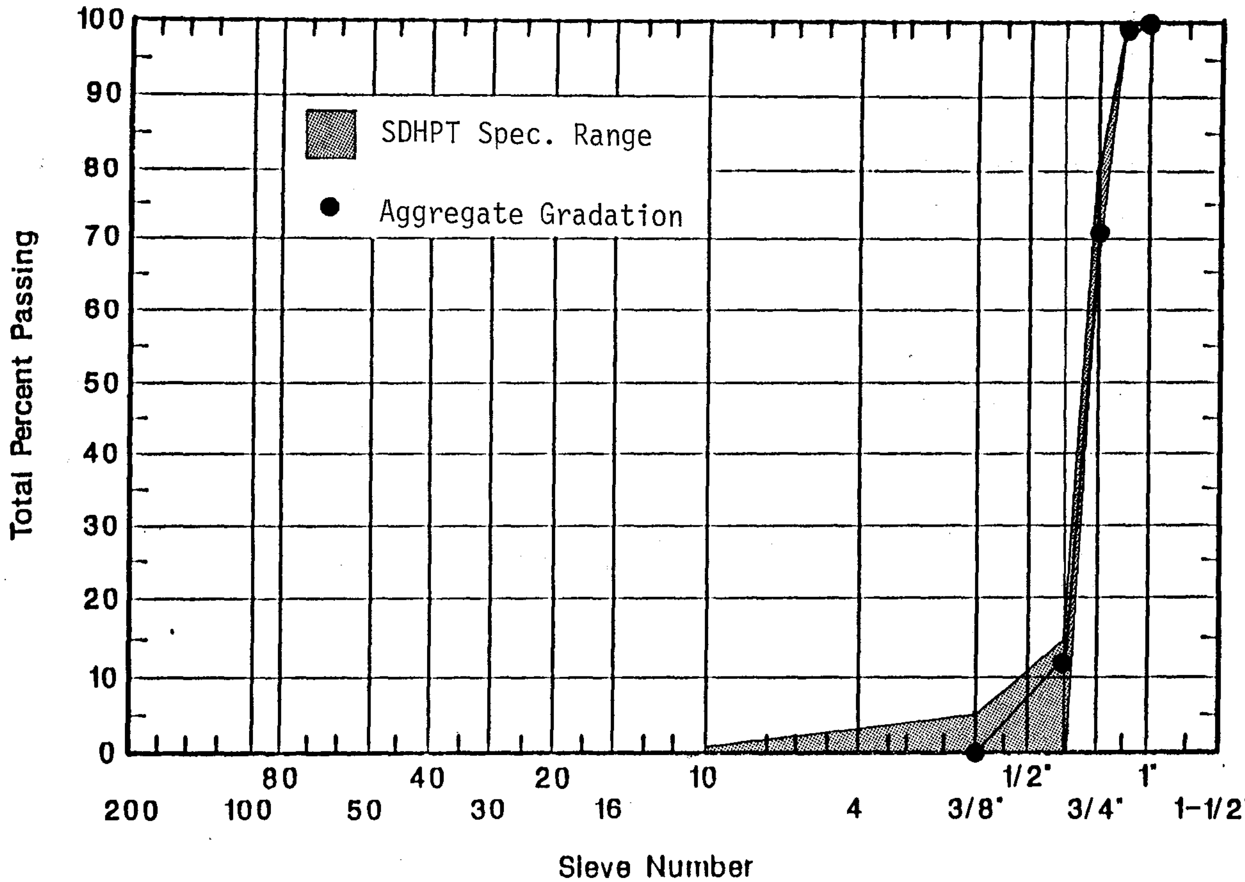


Figure 35. Aggregate Gradation for Grade 1, Crushed Limestone for Lubbock Test Road.

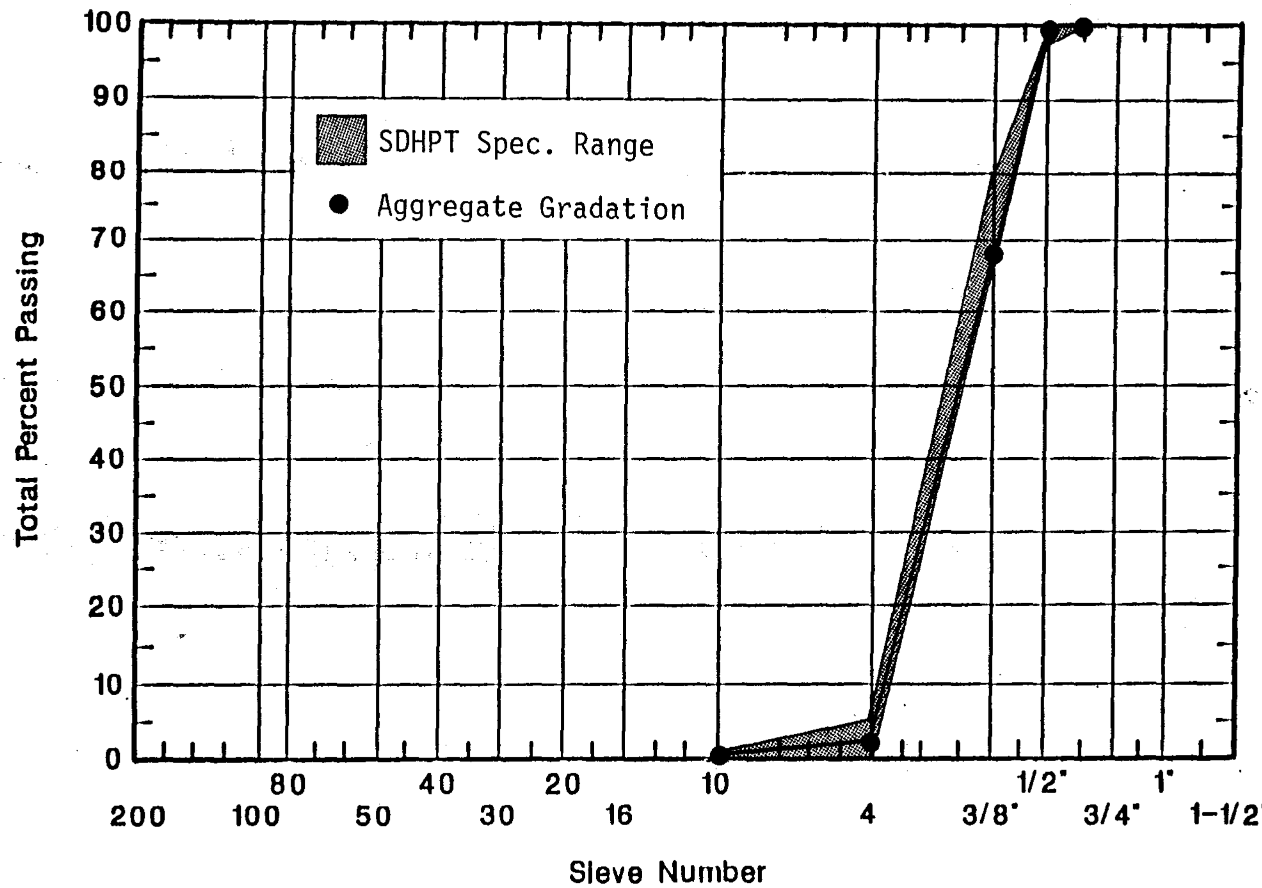


Figure 36. Aggregate Gradation for Grade 4, River Gravel for Lubbock Test Road.

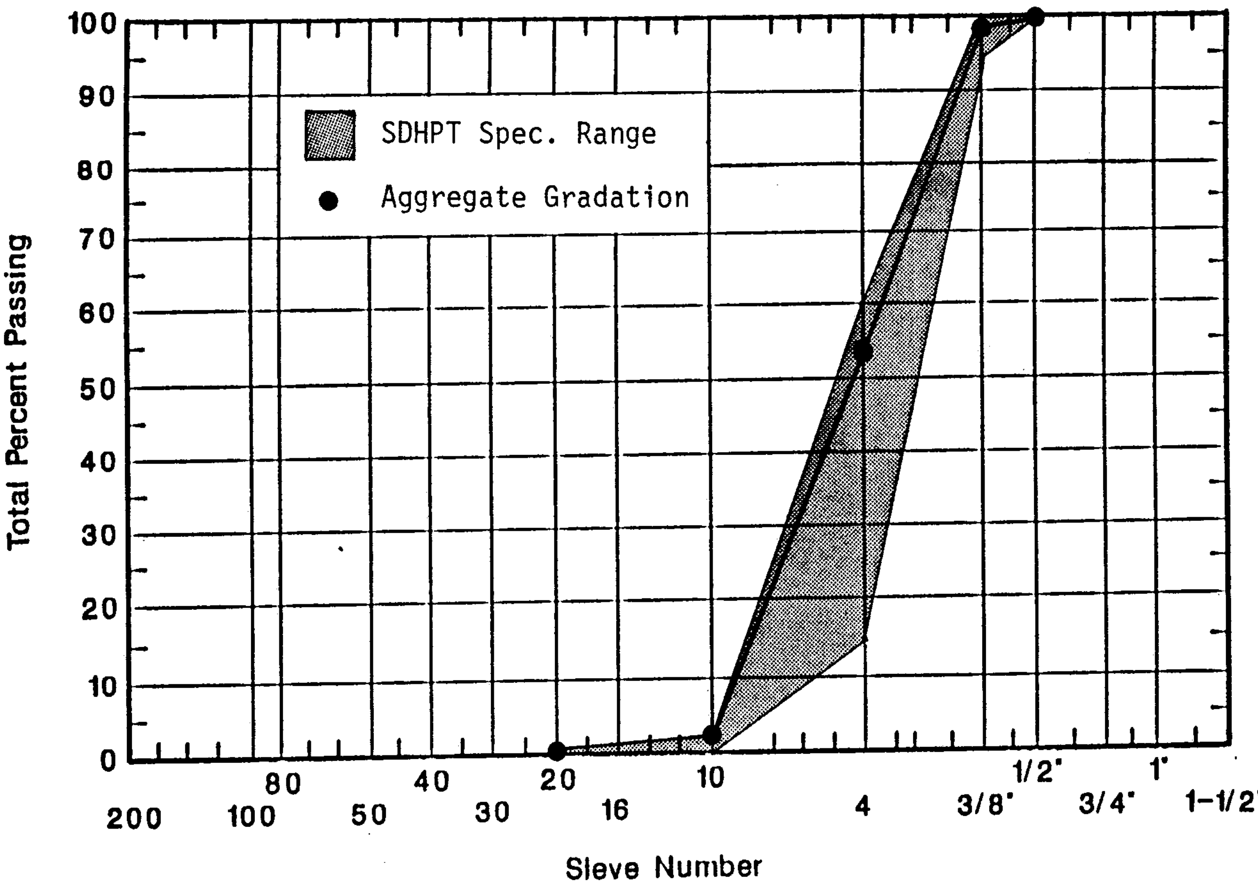


Figure 37. Aggregate Gradation for Grade 5, Precoated Crushed Limestone for Lubbock Test Road.

Table 21. Application Quantities for Three Course Surface Treatment on Lubbock Test Road.

	First Course	Second Course	Third Course (Top)
Aggregate Grade	1	4	5
Aggregate Spread Rate	50 sy/cy	100 sy/cy	150 sy/cy
Asphalt Shot Rate	0.24 gsy	0.35 gsy	0.35 gsy

Figure 38. Asphalt Distributor in Motion for Lubbock Test Road.

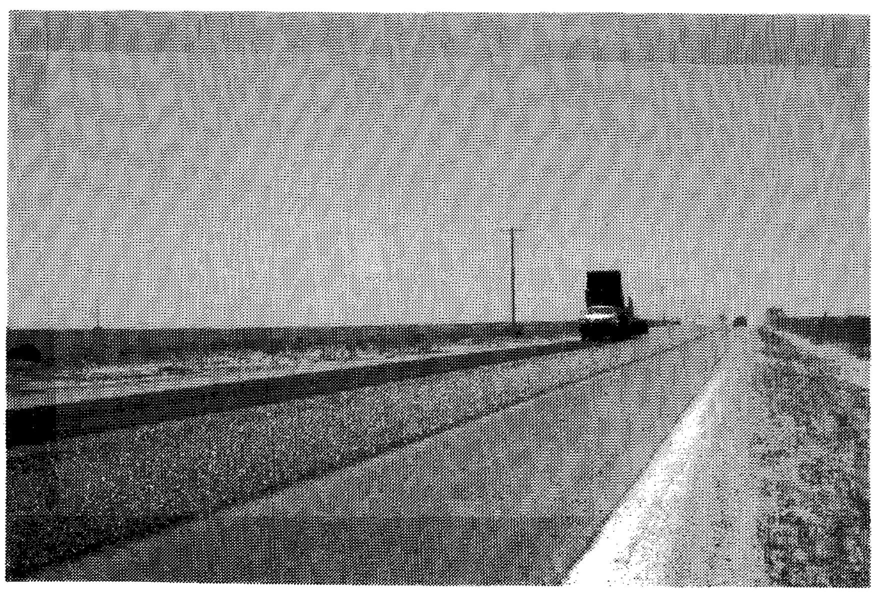


Figure 39. Aggregate Spreader in Motion for Lubbock Test Road.

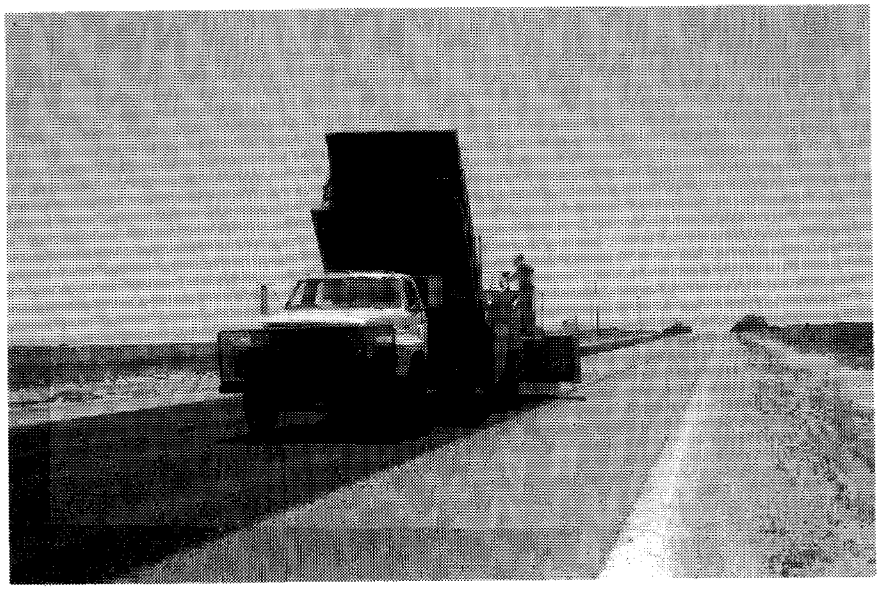


Figure 40. Aggregate Spreader in Motion for Lubbock Test Road.

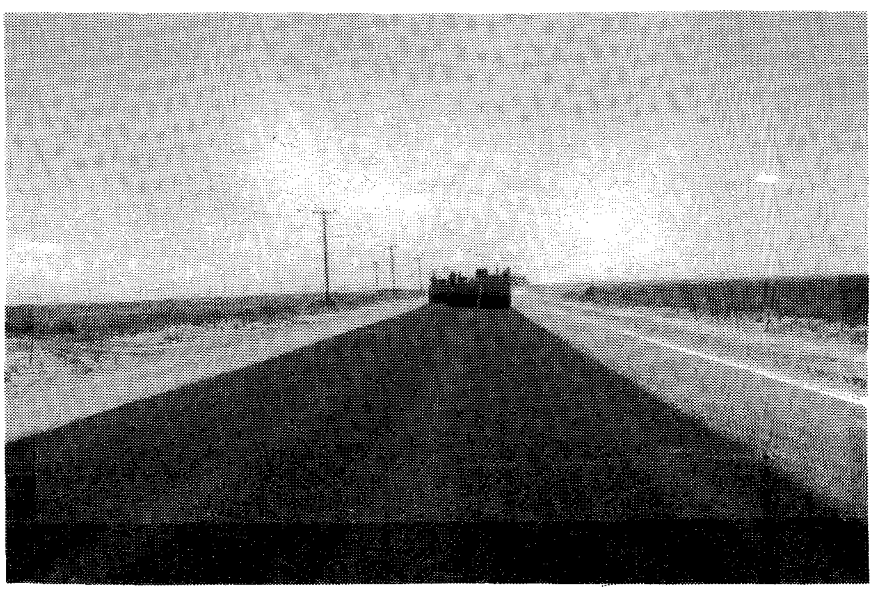


Figure 41. Pneumatic Rollers in Motion for Lubbock Test Road.

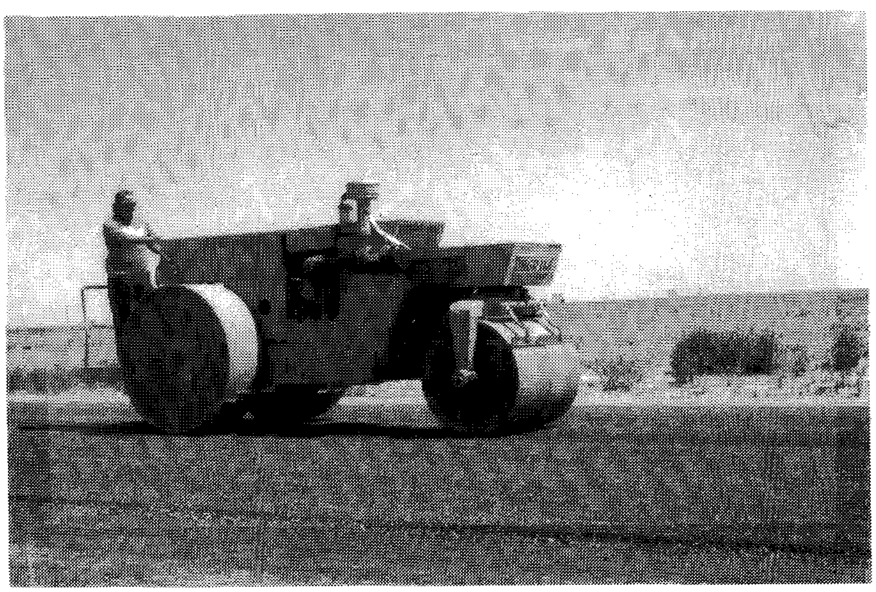


Figure 42. Lightweight Steel-Wheel Rollers in Motion for Lubbock Test Road.

Figure 43. Close-Up of Finished Surface on Lubbock Test Road.

C. PRECONSTRUCTION DATA

The following three test roads were constructed more specifically to evaluate the design procedure. Therefore, certain preconstruction field data measurements were obtained which were used in the design procedure. The sand patch test was performed on the existing surfaces to determine the surface texture and thereby estimate surface hunger. The Ball Penetration Test (3) was performed on the existing surface to evaluate the hardness of the existing surface and thereby estimate the future embedment of the stone into the underlying pavement surface.

The equipment required to perform the Ball Penetration Test consists of a circular tripod stand and cross bar, a steel ball, a depth gauge, a surface thermometer and a standard Marshall compaction hammer (Figure 44). The steel ball bearing is forced to penetrate the old road surface to be sealed under a standard effort (one blow of a Marshall hammer) and the depth of penetration is measured (Figure 45). The road surface temperature at the time of test is recorded and the penetration value is converted to a standard temperature for that location. The test procedure is described in detail in Appendix D.

D. EASTLAND TEST ROAD

1. Objectives

The objectives in construction of the Eastland Test Road were to (1) test the design procedure at predicting asphalt and aggregate quantities, (2) evaluate the use of different combinations of aggregate grades in the field, and (3) evaluate the field performance of multiple seals.

2. Test Road Construction

The Eastland Test Road is located on the north feeder road of Interstate 20 (See Figure 46). It begins at the intersection of I-20 and U.S. 80 and extends east for approximately one mile in the eastbound lane only. The existing road surface was an asphalt concrete pavement in relatively good condition with minimal cracking. The average daily traffic for this section is approximately 1000 vehicles per day.

<u>Materials</u>. Materials used for the construction of the Eastland Test Road consisted of a Grade 3, Grade 4, and Grade 5 lightweight aggregate from Ranger and the binder was an HFRS-2 from Texas Emulsions. Aggregate gradations are shown in Figure 47, 48, and 49. The Grade 3 sample as

Figure 44. Equipment Required for Ball Penetration Test.

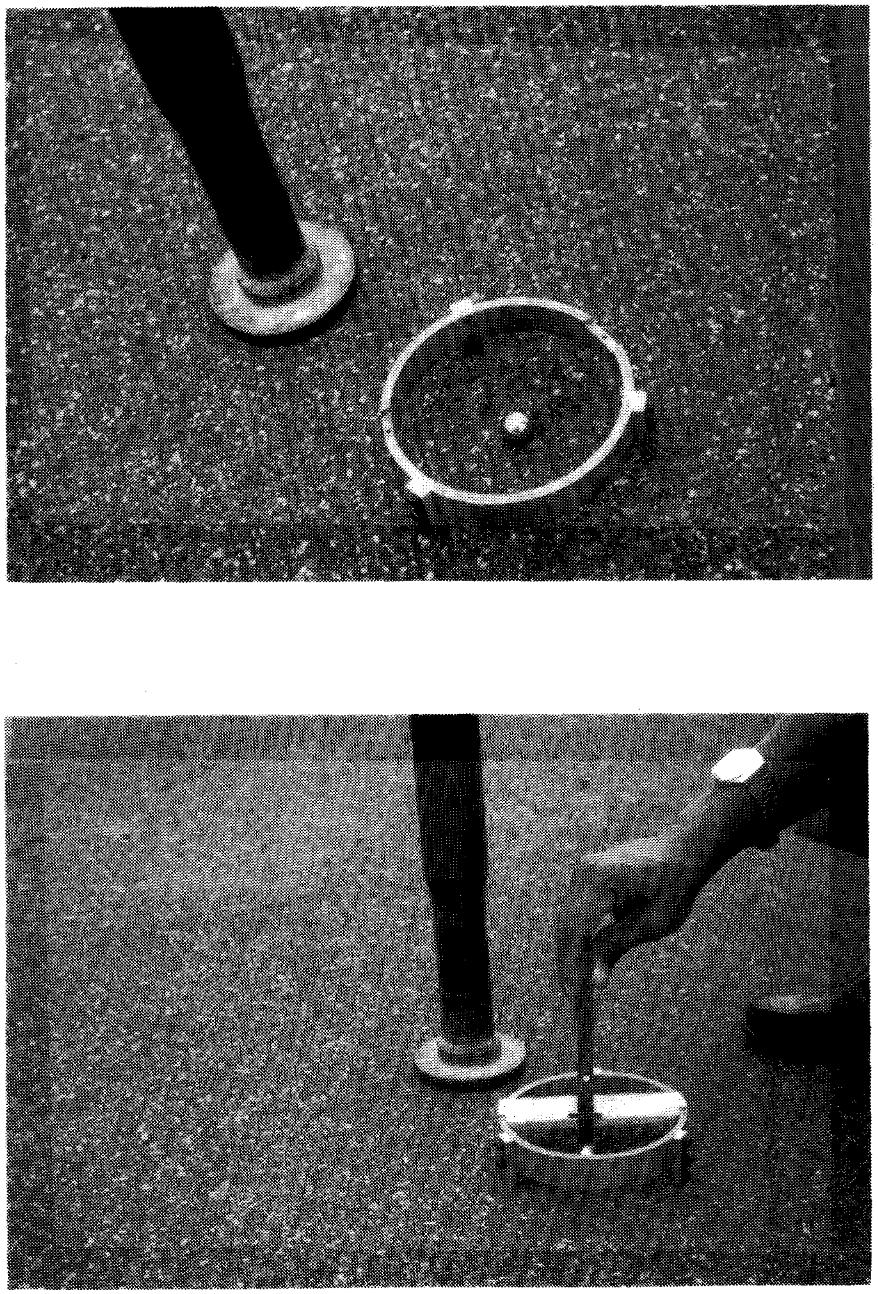


Figure 45. Measurement of Depth of Ball Penetration.

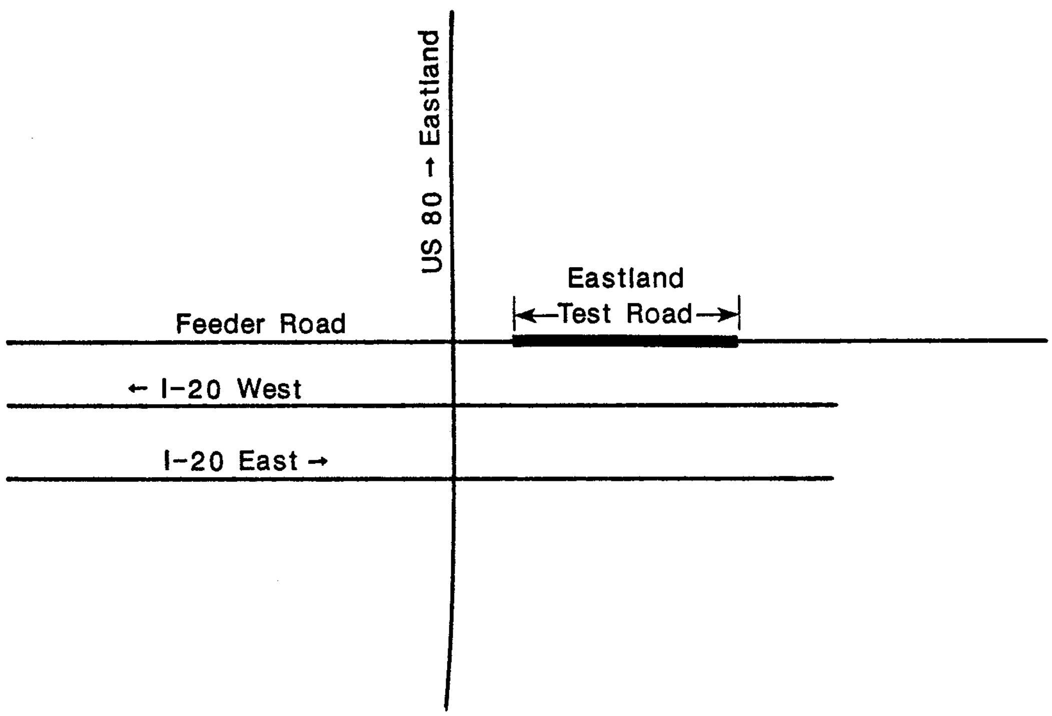


Figure 46. Location of Eastland Test Road.

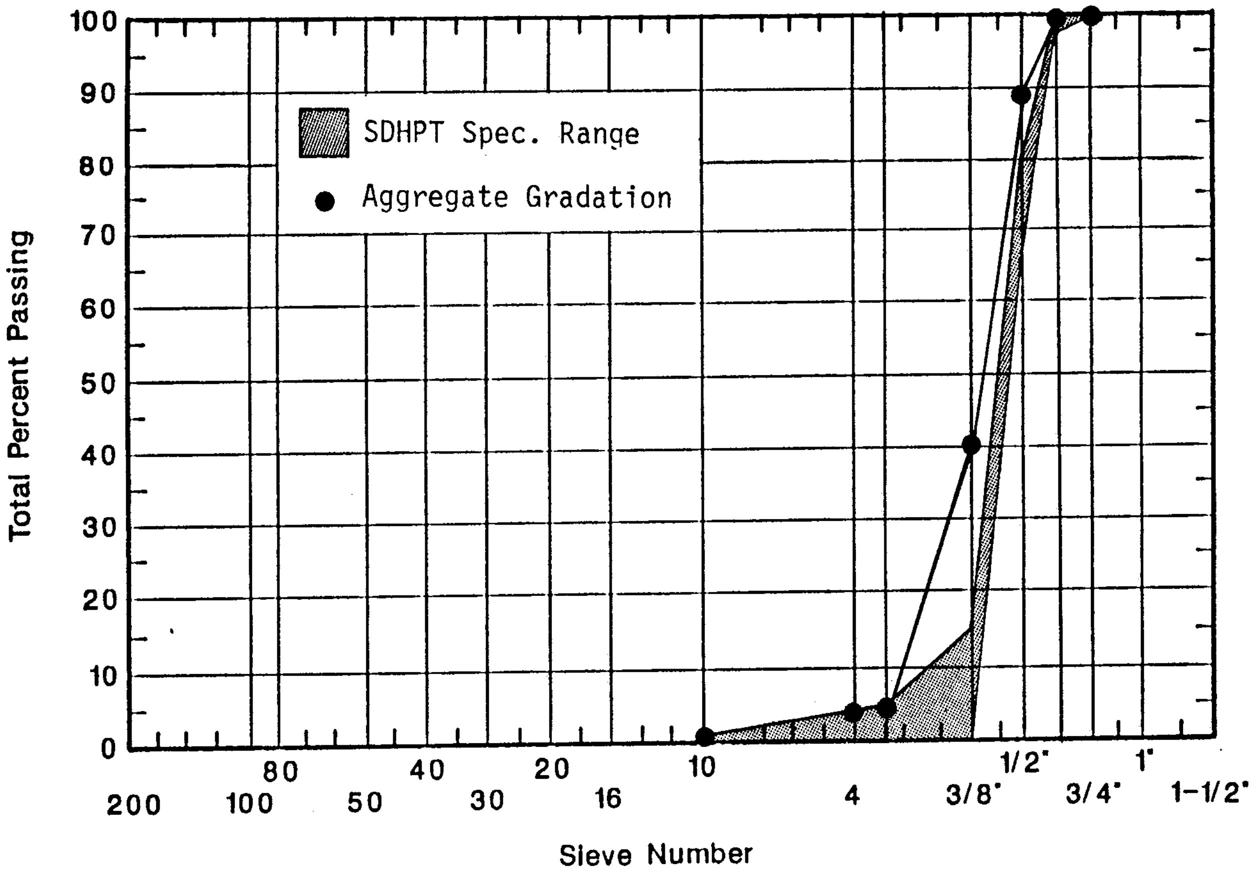


Figure 47. Aggregate Gradation for Grade 3, Lightweight for Eastland Test Road.

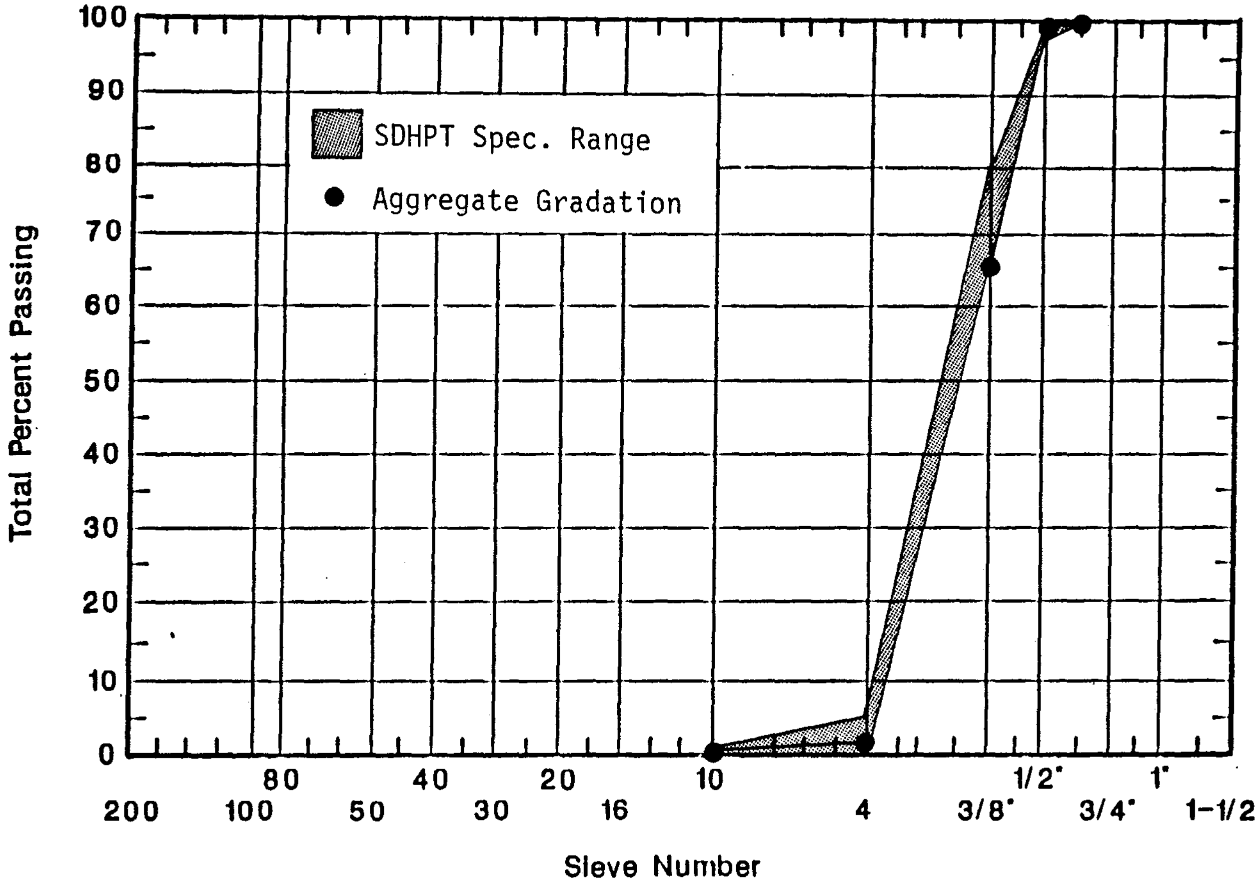


Figure 48. Aggregate Gradation for Grade 4, Lightweight for Eastland Test Road.

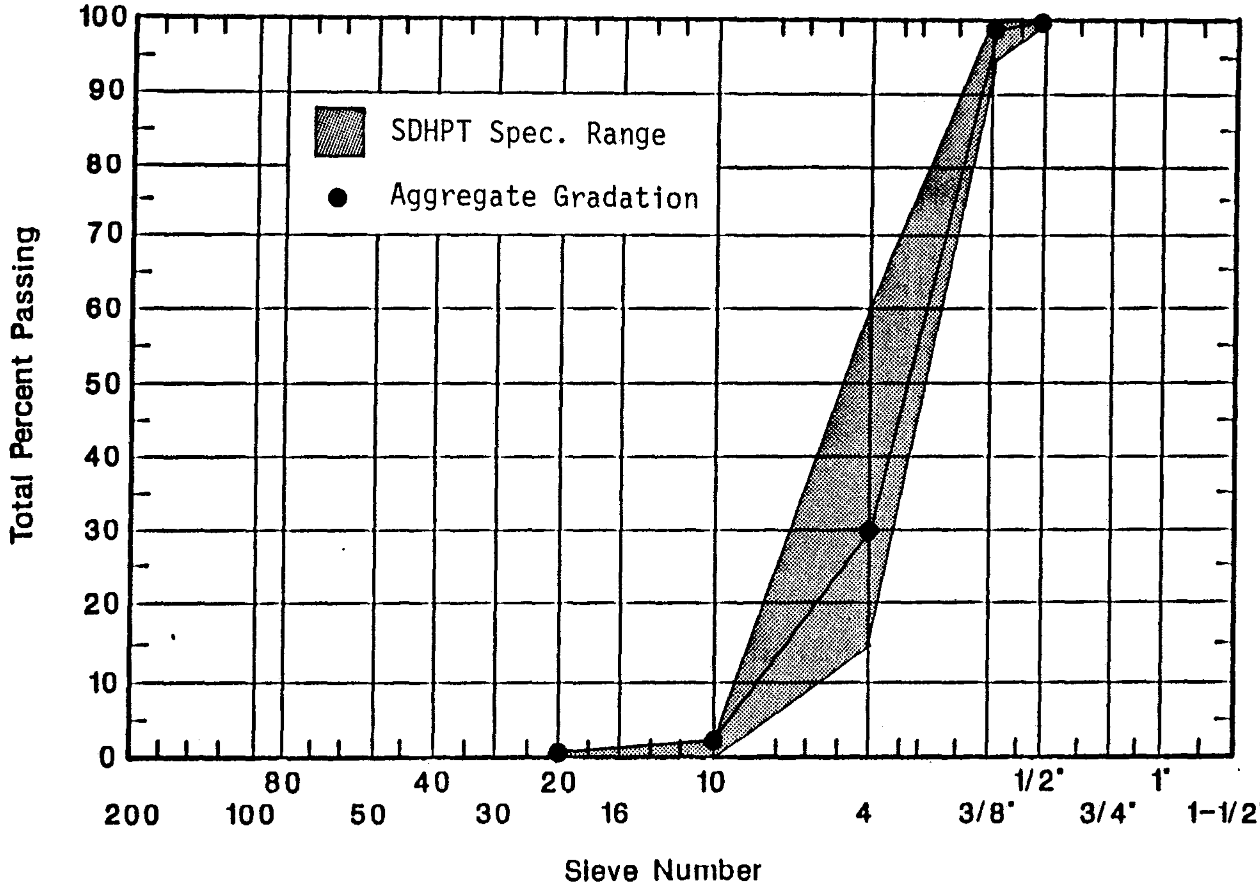


Figure 49. Aggregate Gradation for Grade 5, Lightweight for Eastland Test Road.

obtained by TTI did not conform to the gradation specifications for a Grade 3.

Test Section Layout. The test road consisted of four different sections constructed in the westbound lane, and each section was approximately 1000 feet in length. The first section was a Grade 4 aggregate on top of a Grade 3. The second section was a Grade 5 on top of a Grade 3. The third section was a Grade 5 on top of a Grade 4 and the fourth section was a single Grade 4 seal. The single Grade 4 seal was constructed based on the standard design procedure normally used by District 23. The test section layout is shown in Figure 50.

Construction. The test road was built by the maintenance forces of District 23 in August of 1987. Traffic was diverted to the eastbound lane until all four test sections were completed. Pneumatic rollers were used on each aggregate layer. The laboratory and field data used to calculate the design application quantities are shown in Table 22. The aggregate and binder quantities designed using the Modified Tray Test and those quantities actually used in the field are shown in Table 23.

3. Performance of Eastland Test Road

It has been recommended by others (5) that for multiple seals, each successive aggregate layer should have a stone size approximately half the size of the preceding layer. This was found to be a good recommendation after construction of this test road. The Grade 4 on 3 and the Grade 5 on 4 both appeared to be good combinations; however, the Grade 5 on 3 caused some problems during the construction process. Because the Grade 5 is much smaller than the Grade 3, all of the Grade 5 stones collect into the big voids of the Grade 3 leaving an exposed film of binder on the surface of the Grade 3 as illustrated in Figure 51. This causes problems during the rolling process and immediately after traffic has been allowed onto the surface. Because there is an exposed film of asphalt, the asphalt collects on the tires of the rollers and vehicles and then the tires begin to pick up the stones.

Based on visual observations immediately after construction, it appeared that the design binder quantities for the double seals may have been excessive. This confirmed results from the laboratory fabricated seal coats. Therefore, at this point, modifications were made to some of

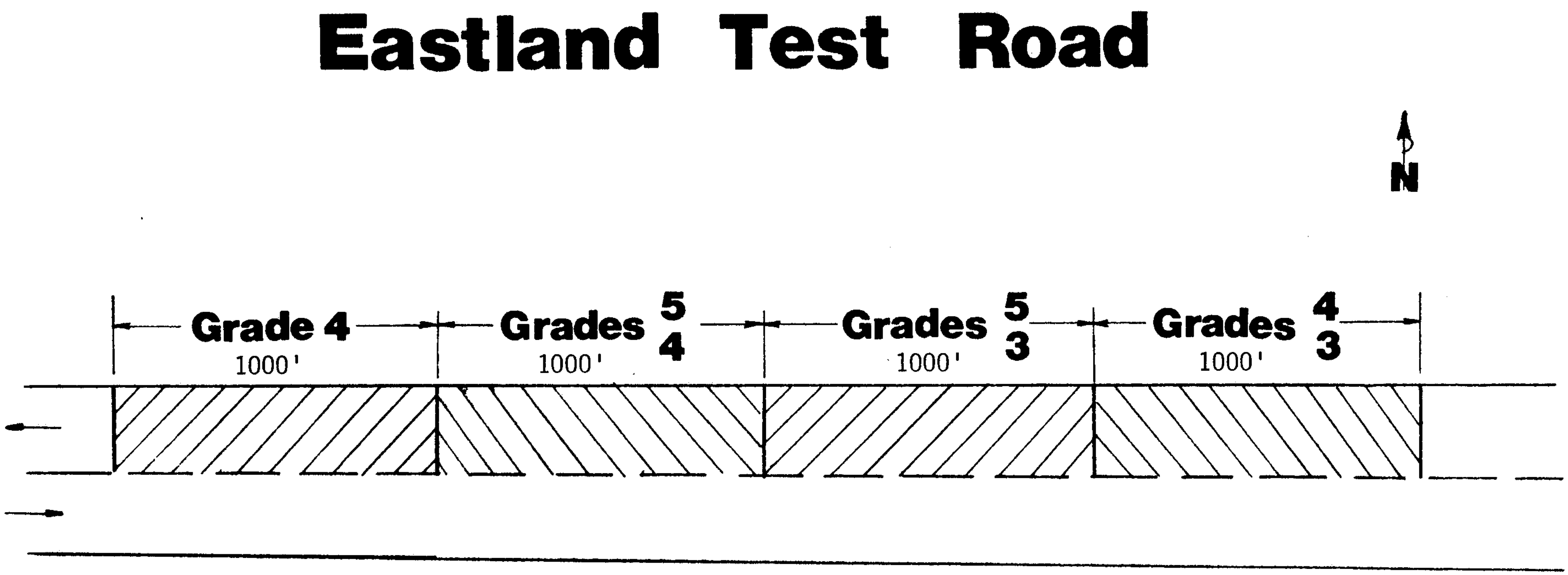


Figure 50. Eastland Test Road Test Section Layout.

Table 22. Laboratory and Field Data Used to Calculate Design Application Quantities for Eastland Test Road.

Aggregate	ELT, mm	Voids in Layer, %
Grade 3	7.87	50.6
Grade 4	7.00	56.1
Grade 5	4.59	55.4

Surface Texture = 0.89 mm

Corrected Ball Penetration Value = 2.7 mm

ADT = 2300 Equivalent light vehicles/day/lane

Los Angeles Abrasion Value = 25%

Table 23. Design and Actual Application Quantities for the Eastland Test Road.

Section	Layer	Aggregate Spread Rate, sy/cy		Residual Binder Application Rate, gsy	
		Design	Actual	Design	Actual
Grade 4 on 3	Grade 4	140	135	0.44	0.45
	Grade 3	126	120	0.30	0.30
Grade 5 on 3	Grade 5	223	210	0.37	0.35
	Grade 3	126	120	0.24	0.29
Grade 5 on 4	Grade 5	223	210	0.35	0.31
	Grade 4	140	135	0.24	0.22
Grade 4*	Grade 4	140	135	0.35	0.35

* The Grade 4 single seal was built according to District 23's standard design procedure.

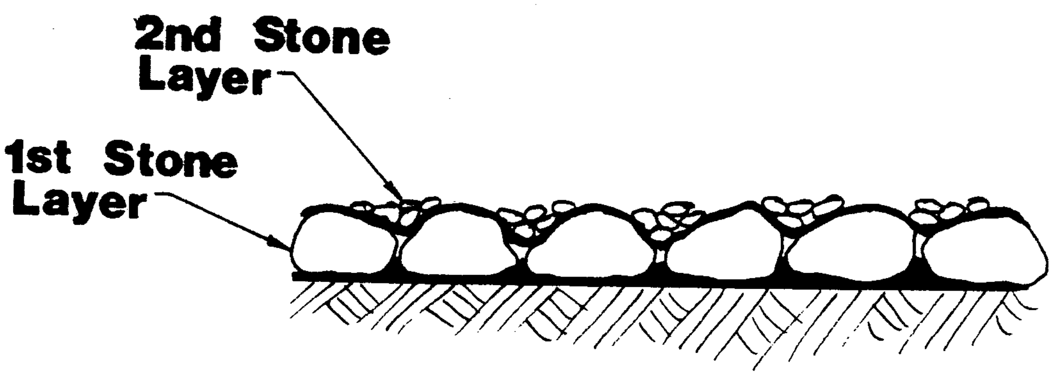


Figure 51. Illustration of a Grade 5 Aggregate Over a Grade 3 Aggregate Exposing a Film of Asphalt on the Surface.

the design parameters to more closely represent what happens in the field. No changes regarding the test procedure were made.

Based on a field evaluation of the test sections one year after construction, bleeding was observed in the wheel paths (Figure 52). This confirmed the previous conclusion that the binder quantities were excessive.

E. DESIGN PROCEDURE MODIFICATIONS

Two parameters in the design procedure were altered as a result of the laboratory study and the performance of the Eastland Test Road:

1. The final surface texture required for adequate skid resistance,
2. The minimum quantity of voids that must be filled to prevent initial stone loss.

The design procedure as developed by the NITRR requires a texture depth of the final surface of 0.64 mm. Gallaway et al. (34) recommends that the texture depth not fall below 1.0 mm; therefore, the required texture depth of the final surface was changed from 0.64 mm to 1.0 mm.

According to the design procedure as developed by the NITRR, it is recommended that, immediately after construction, the aggregate be covered at least halfway with binder to prevent initial stone loss due to whip-off. In the case of a double seal, 65% of the voids would have to be filled with binder to ensure that the top layer of aggregate is covered at least halfway. Figure 53 (5) shows a theoretical distribution of the voids in a double seal.

Based on recommendations by Epps, et al. (7) and on field reports by experienced engineers in the Department, the aggregate should be covered with binder approximately 30% (rather than 50% as recommended by the NITRR) immediately after construction to prevent initial stone loss. Suggested depths at which the aggregate should be covered with binder are as follows (7):

immediately after construction	30 $\pm$ 10%
start of cool weather (first year)	35 $\pm$ 10%
start of cold weather (first year)	45 $\pm$ 10%
after two years of service	70 $\pm$ 10%

Based on recommendations by Epps, et al.(7) and on field experience, the quantity of voids that have to be filled with binder to ensure that the

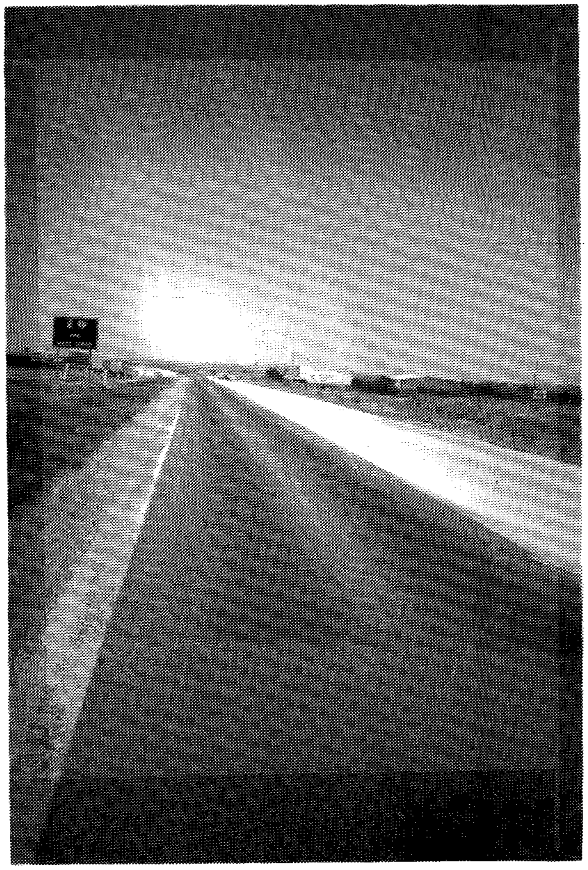


Figure 52. Eastland Test Road One Year After Construction.

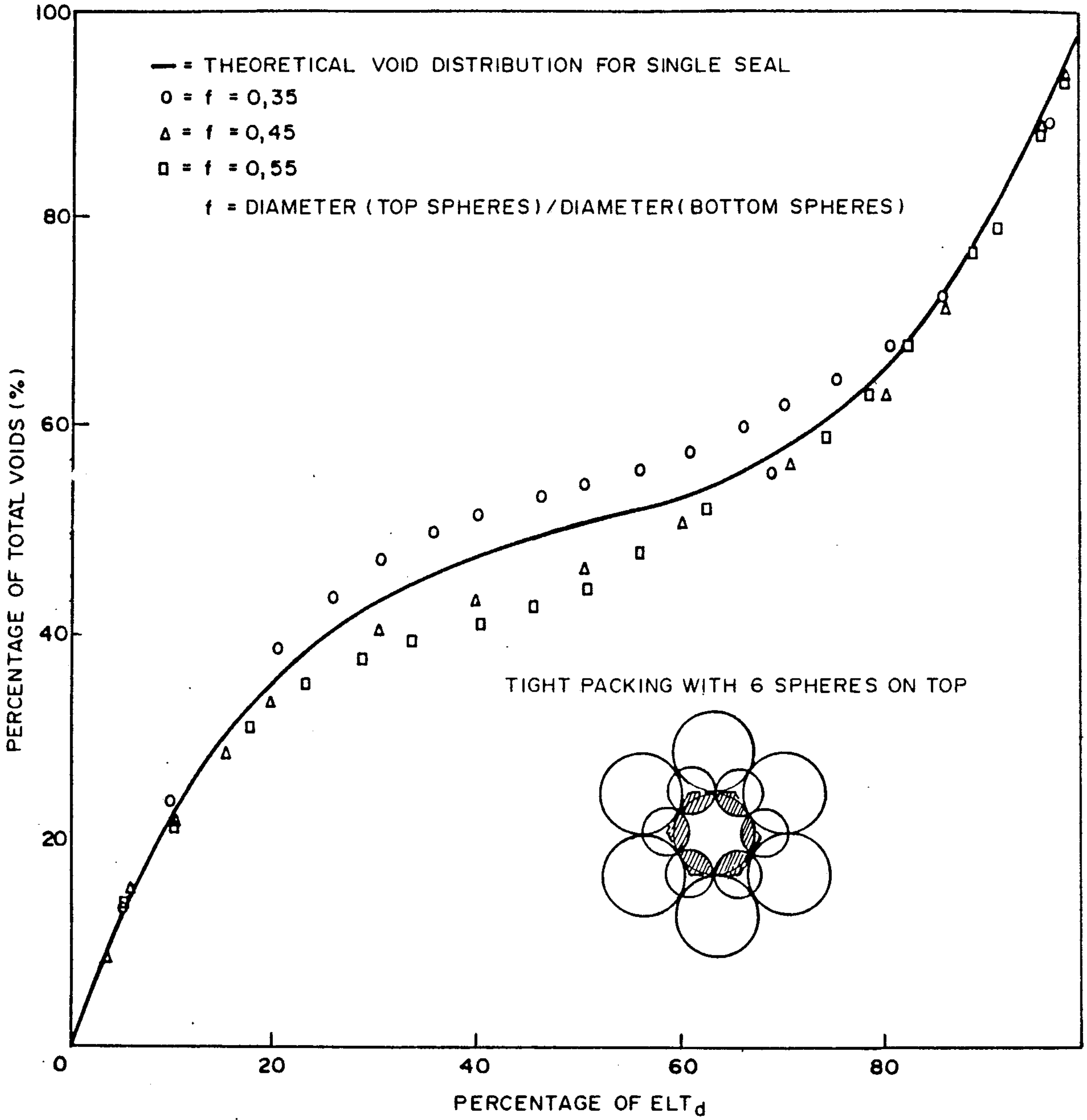


Figure 53. Theoretical Void Distribution in a Double Seal. (5)

top layer of aggregate is adequately covered to prevent initial stone loss was decreased from 65% to 55%.

E. PAIGE TEST ROAD

1. Objectives

The primary objective in construction of the Paige Test Road was to make a final evaluation of the design procedure after the above modifications were made. A secondary objective was to evaluate the performance of a multiple seal on a road with a relatively high traffic volume. Another objective was to observe the construction process used by District 14. District 14 builds multiple seals routinely and with great success.

2. Test Road Construction

The Paige Test Road was constructed the week of June 27, 1988. It is located between Paige and McDade on U.S. Highway 290 (Figure 54). This was a regular double seal construction project for District 14; however, for this research study, the residency agreed to supply a section of this project which could be used as a test section to test the design procedure. This section is located approximately 1 mile west of the Highway 21 overpass in the eastbound travel lane. Average daily traffic is approximately 7400 vehicles per day with 15% trucks.

Preconstruction. Prior to construction of the test road, an evaluation of the existing pavement was performed along with some field tests. The existing road surface was a Grade 3 limestone seal coat. The pavement was in relatively good condition with slight to moderate bleeding in the wheel paths. Samples of the aggregate were brought back to the laboratory to perform the Modified Tray Test and calculate design quantities. The results of the Modified Tray Test and other field and laboratory data are shown in Table 24.

Materials. The aggregate for construction of the first or bottom layer of the double seal was a Grade 3 limestone from Texas Crushed Stone in Georgetown. The top layer was constructed of a Grade 4 synthetic lightweight from TXI-Streetman. The aggregate gradations are shown in Figures 55 and 56. The binder was an emulsion: HFRS-2P from Gulf States.

Construction. The first layer of binder and aggregate was placed and then rolled with a lightweight steelwheeled roller. The first layer of

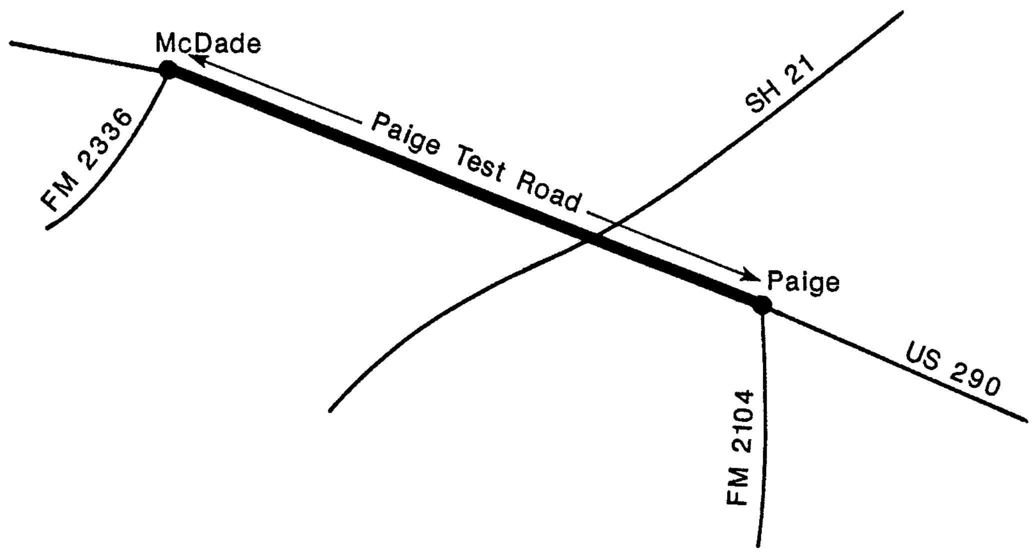


Figure 54. Paige Test Road Location.

Table 24. Laboratory and Field Data Used to Calculate Design Application Quantities for the Paige Test Road.

Aggregate	ELT, mm	Voids in Layer,%
Grade 3	8.25	58.91
Grade 4	7.38	51.62

Surface Texture = 0.58 mm

Corrected Ball Penetration Value = 1.05

ADT = 7100 Equivalent light vehicles/lane/day

Los Angeles Abrasion Value = 24%

Table 25. Design and Actual Application Quantities for the Paige Test Road.

Layer	Aggregate Spread Rate, sy/cy		Residual Binder Application Rate, gsy	
	Design	Actual	Design	Actual
Grade 3	95	92	0.27	0.28
Grade 4	123	120	0.40	0.38

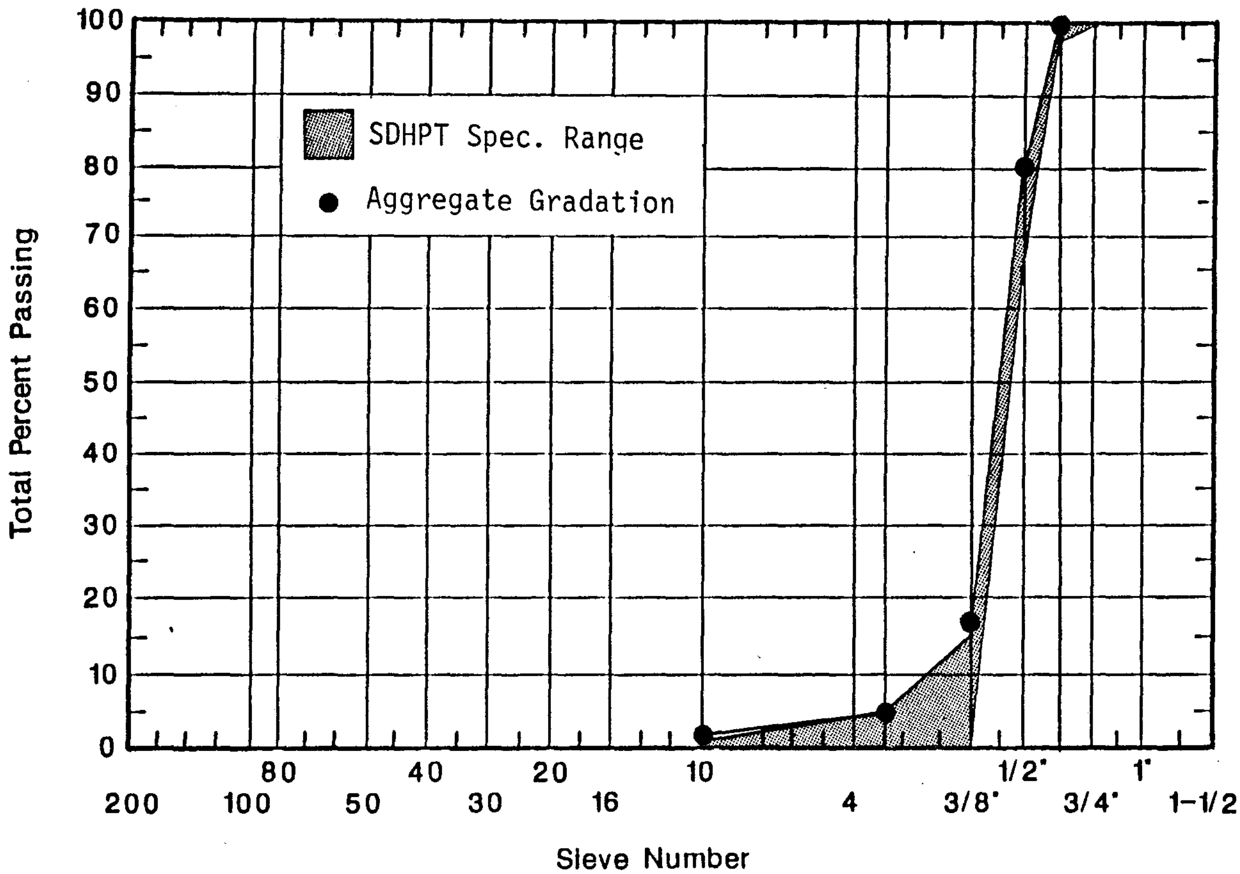


Figure 55. Aggregate Gradation for Grade 3, Crushed Limestone for Paige Test Road.

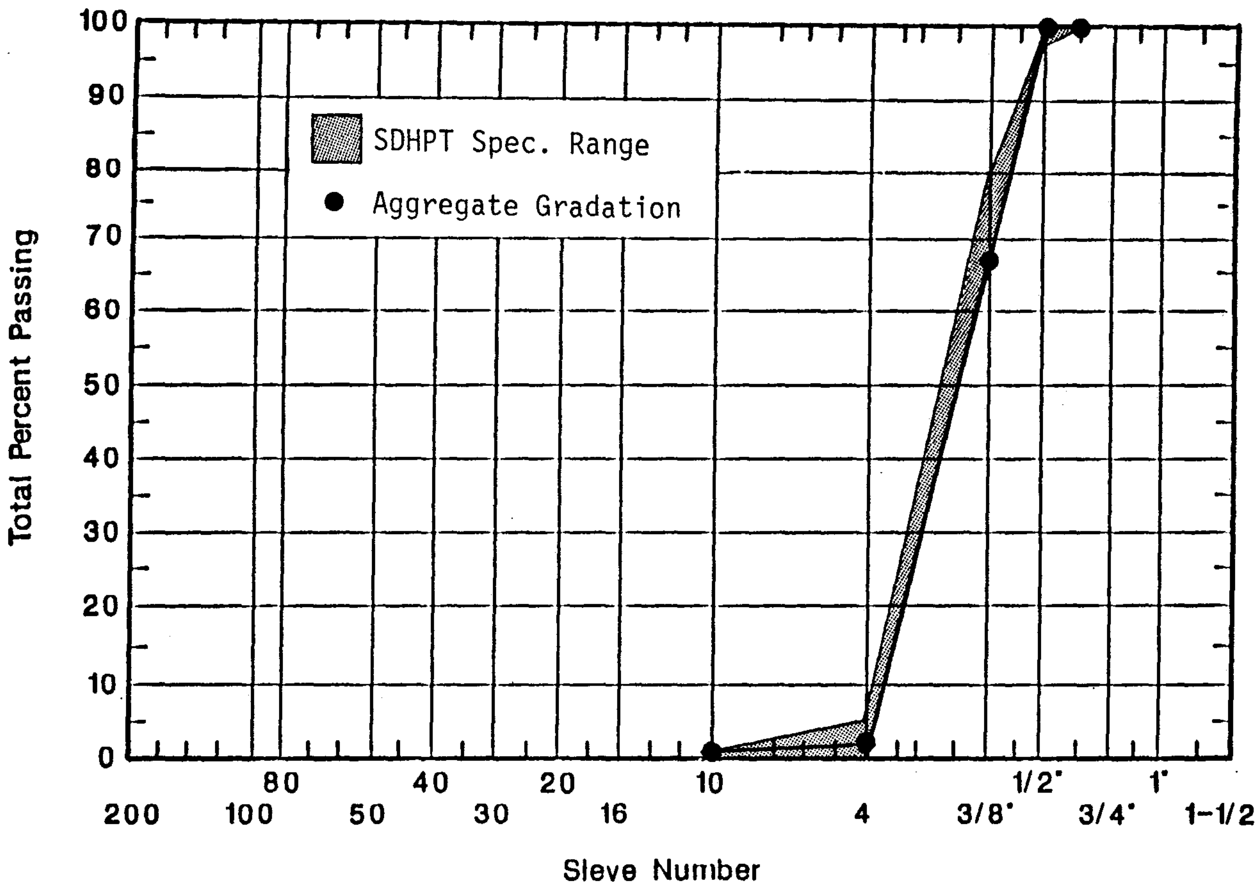


Figure 56. Aggregate Gradation for Grade 5, Lightweight for Paige Test Road.

the seal was placed during the morning and the second layer was placed in the afternoon. The second layer was then rolled with a medium pneumatic roller followed by a small pneumatic roller. Traffic was not allowed on the first seal coat layer. The design and actual binder and aggregate quantities applied are shown in Table 25.

3. Performance

Immediately after construction, the pavement surface appeared to be in good condition and the application quantities appeared to be the correct amount. One month after construction and at the end of this study, the surface was still in good condition and performing as would be expected.

F. CIRCLEVILLE TEST ROAD

1. Objectives

The objective in construction of the Circleville Test Road was essentially the same as for the Paige Test Road: to make a final evaluation of the design procedure by comparing the design quantities calculated with the field performance.

2. Construction of Test Road

The Circleville Test Road was constructed the week of July 6, 1988. It is located between Circleville and Georgetown on State Highway 29 (Figure 57). This was a regular double seal construction project for District 14; however, for this research study, the residency agreed to supply a section of this project which could be used as a test section. This section is approximately one mile in length and is located about 0.5 miles west of the SH 95 intersection. The pavement is a two-lane roadway and the test section is located in the eastbound lane. Average daily traffic is approximately 2000 vehicles per day with 8% trucks.

Preconstruction. Prior to construction of the test road, an evaluation of the exising pavement was performed along with some field tests. The existing road surface was a seal coat built with a sandstone aggregate. There was slight to moderate bleeding in the wheel paths but no signs of cracking or rutting. Samples of the aggregate were brought back to the laboratory to perform the modified tray test and to calculate

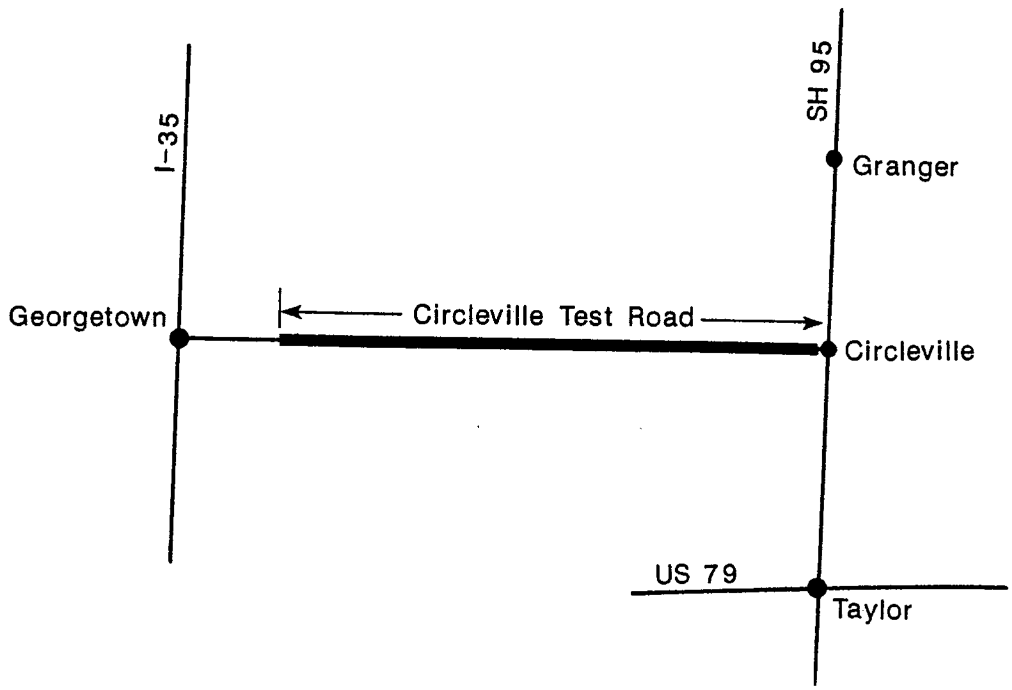


Figure 5-7. Circleville Test Road Location.

design quantities. The results from the Modified Tray Test and other laboratory and field data are shown in Table 26.

Materials. The aggregate used for construction of the first or bottom layer of the double seal was a Grade 3 - Modified limestone from Texas Crushed Stone. The top layer was constructed of a Grade 4 from Delta Materials. The gradation of the Modified Grade 3 is shown in Figure 58 and compared to the specification for a regular Grade 3. The Grade 4 sample as obtained by TTI did not conform to the specifications as shown in Figures 59. The binder was an HFRS-2p emulsion from Gulf States.

Construction. The first layer of binder and aggregate was placed and then rolled with a medium followed by a small pneumatic roller. The surface is then blade broomed and rolled with a lightweight steel wheel roller. The second layer was then rolled with the pneumatic rollers only. Since SH 29 is a two lane roadway, traffic could not be kept off the newly constructed surfaces for the desired length of time. To minimize rock turn-up, pilot trucks were used to lead the traffic back and forth across the newly constructed pavement at a low speed. This alleviated but did not eliminate the problem. Another problem was encountered in that it appeared that the bond did not occur as quick as expected between the emulsion and the Grade 4 stone. This also caused damage by traffic. The actual binder and aggregate quantities applied are shown in Table 27.

3. Performance

Immediately after construction, the pavement surface was in relatively good condition, except for the problems previously noted. One month later, there was virtually no change in the appearance of the surface.

Table 26. Laboratory and Field Data Used to Calculate Design Application Quantities for the Circleville Test Road.

Aggregate	ELT, mm	Voids in Layer,%
Grade 3	8.37	52.8
Grade 4	6.99	56.8

Surface Texture = 0.60 mm

Corrected Ball Penetration Value = 1.95 mm

ADT = 2500 Equivalent light vehicles/day/lane

Los Angeles Abrasion Value = 18%

Table 27. Design and Actual Application Quantities for the Circleville Test Road.

Layer	Aggregate Spread Rate, sy/cy		Residual Binder Application Rate gsy	
	Design	Actual	Design	Actual
Grade 3	90	85	0.29	0.28
Grade 4	120	116	0.38	0.36

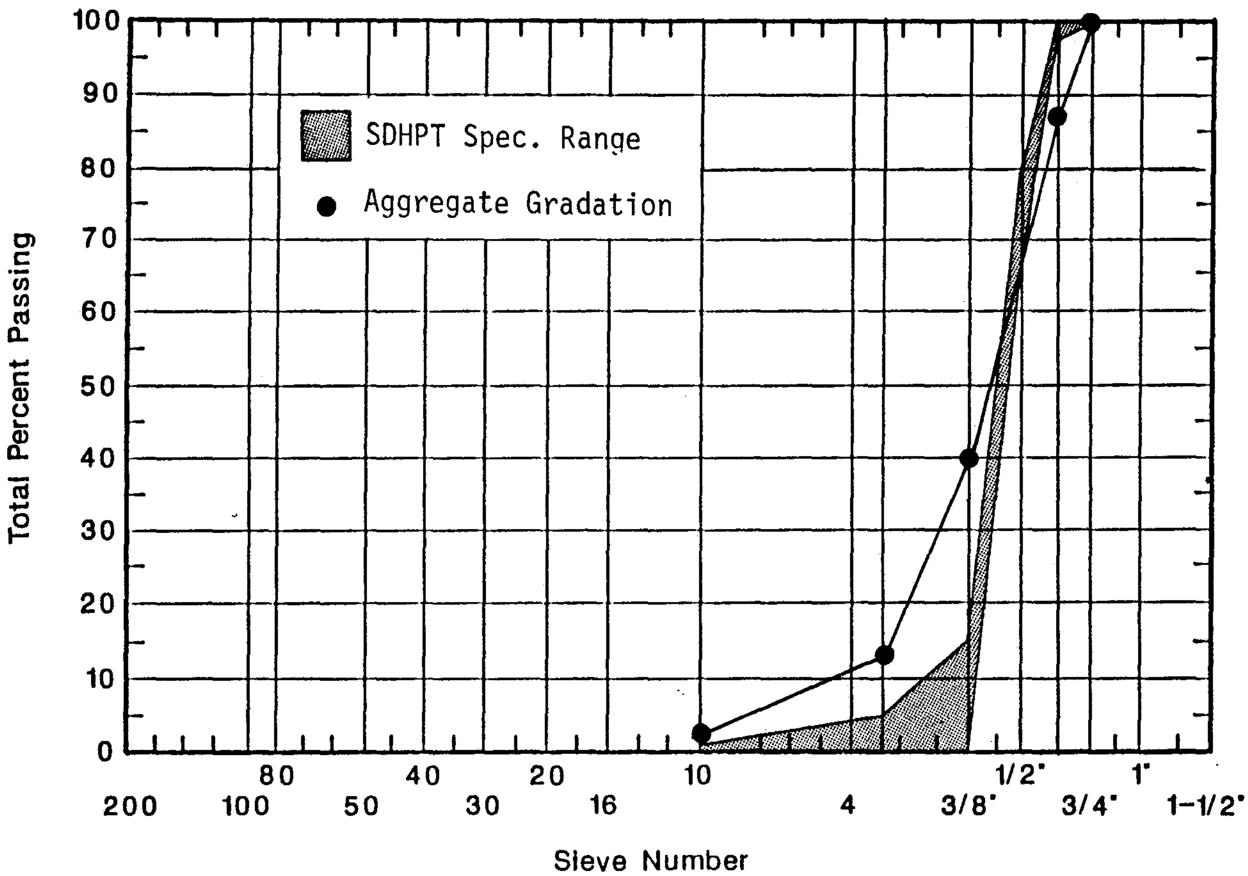


Figure 58. Aggregate Gradation for Grade 3, Crushed Limestone for Circleville Test Road.

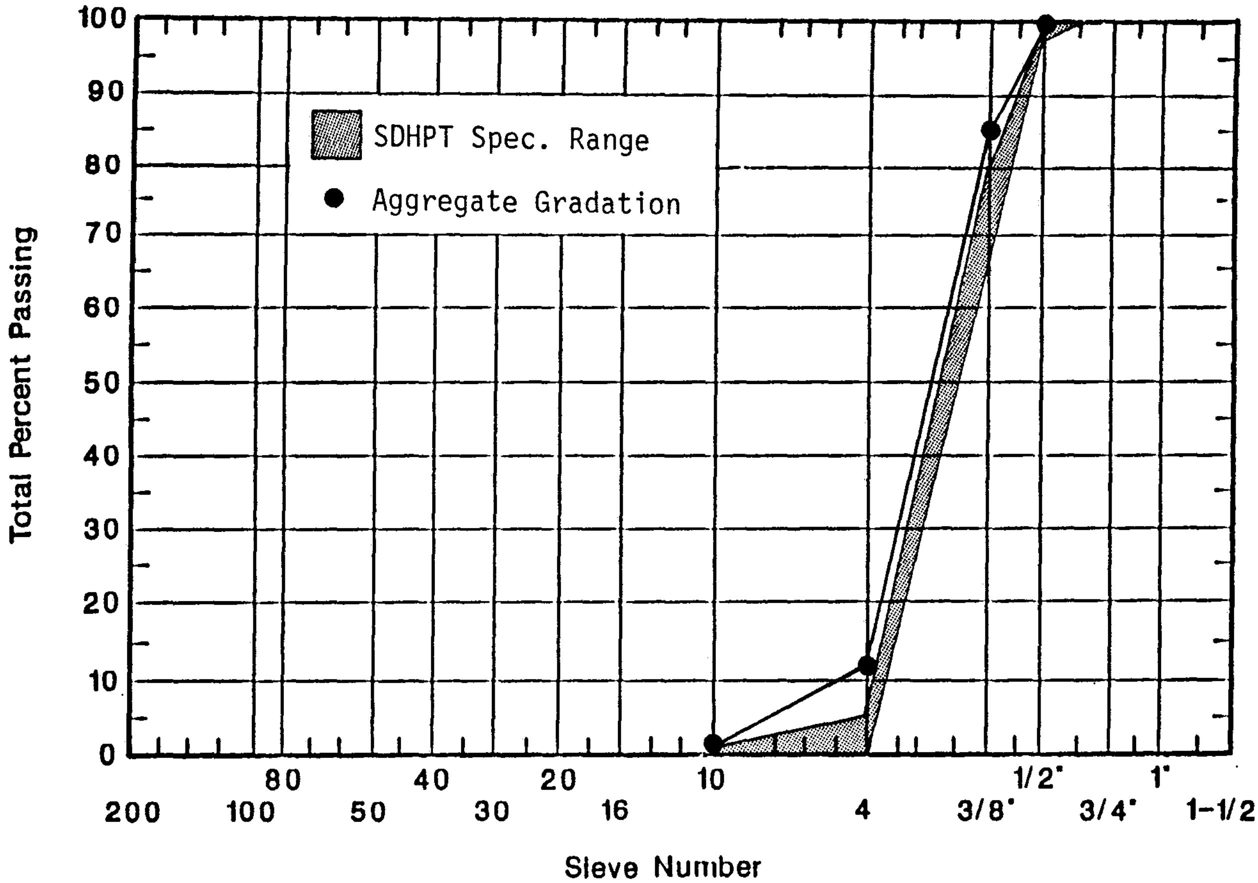


Figure 59. Aggregate Gradation for Grade 4 for Circleville Test Road.

CHAPTER IX

CONCLUSIONS

In order to establish a design method for multiple seal coats, a thorough evaluation of the literature was conducted and factors influencing the performance of both single and multiple seals were identified. Existing design procedures which took most of these factors into account were further evaluated, as well as the theories behind these procedures. From this review, it was concluded that the key to executing an effective design for multiple seal coats was in the ability to measure the available void space in multiple stone layers that could be filled with binder. A design method developed by the NITRR(4), including a simple test procedure for measuring the void content and effective thickness of a stone layer, was chosen for further evaluation in the laboratory and field.

In this study, crushed limestone that met the Texas specifications for grades 2,3,4 and 5 seal coat aggregate was used to evaluate the suitability of the Modified Tray Test for use in designing multiple seal coats. The Modified Tray Test can be used to measure the void content in a layer of stone and the effective thickness of that layer. The design procedure differs from any existing seal coat design method presently used in the United States in that it takes into account, from sound design principles, the factors which affect the change in the void volume in a single layer of stone in shoulder-to-shoulder contact in order to determine the rate of binder application.

Based on a statistical analysis of forty different samples (10 samples of 4 aggregate grades), the Modified Tray Test was found to be a test which could be repeated with little variability in results. It was also determined from the laboratory study that a single sample of stone as tested by means of the Modified Tray Test, gives a good indication of the overall void content and effective layer thickness for a particular type and grade of stone.

Since aggregate particles in a seal coat eventually lie on their flattest side, the average thickness of a seal coat is determined from the overall average smallest dimension of the aggregate particles. The

Average Least Dimension (ALD) using McLeod's apparatus was compared with the Effective Layer Thickness (ELT) using the Modified Tray Test, and the results of both were compared with the calipered measurements of individual stones. The results obtained with the Modified Tray Test are very close to those obtained using the calipers. The ALD obtained using McLeod's method were significantly higher. Therefore, it is concluded that the Modified Tray Test to measure the ELT of a sample gives a very good indication of the actual average least dimension for a particular aggregate.

The suitability of the Modified Tray Test for double seals was verified in TTI's laboratory by using the stone samples used in the initial evaluation of the Modified Tray Test. The Modified Tray Test was used to determine the true void content and effective layer thickness of double seals made up by different combinations of the above mentioned aggregate grades. Results obtained by the NITRR (4) were verified in this portion of the study. A good relationship exists between the effective layer thickness (ELT) of a double seal and the sum of the ELTs of the bottom and top stone layers.

It is possible to determine the aggregate spread rate very accurately by means of this method and a measuring cylinder. This process gives a very useful double check of the measured values of the effective layer thickness and void content used in calculating the binder application rate.

Using the previously mentioned aggregate, multiple seal coats were fabricated in the laboratory to evaluate the design procedure. The multiple seal coats were fabricated on boards with a surface area of one-half square yard. The asphalt was applied with a small laboratory distributor utilizing standard distributor nozzles. Cover stone was spread and brushed by hand; rolling was accomplished with a small pneumatic-tire roller. The multiple seal coats were evaluated for embedment depth, aggregate retention and surface texture. Based on results from the laboratory seal coats and from a field test section, the design procedure appeared to produce excessive binder application rates. At this point, some modifications were made to some of the design parameters which are reflected in Appendix E.

The following modifications were incorporated into the design procedure:

1) The required surface texture of the seal coat was increased from 0.64 mm to 1.0 mm, and

2) The minimum voids that have to be filled with binder in order to prevent initial stone loss was decreased from 65% to 55%.

An innovative test procedure to measure the embedment of the stone into the underlying road surface due to construction rolling and traffic was introduced. Embedment has been found to be an important factor in the void reduction process and thus, has a great effect on the binder quantity to be applied. With the Ball Penetration Test (3), the embedment of the stone particles into the existing road surface to be treated can actually be measured and taken into account in the design process.

Four multiple seal coat test roads were investigated under this study for evaluation of a design and construction procedure. Initial field test sections confirmed results from the laboratory fabrication of seal coats that the design binder quantities were too high. The last two test roads, Paige and Circleville, incorporated the above mentioned changes and appear to be performing successfully to date.

A workable design procedure for double seal coats is presented in this report. It is recommended that the procedure be reevaluated once it has been used in the field for a number of years.

It is recommended that further research be performed on the Ball Penetration Test to verify the relationship presented here between the Ball Test value, traffic and embedment.

REFERENCES

1. Hanson, F.M., "Bituminous Surface Treatments on Rural Highways," Proceedings, New Zealand Society of Civil Engineers, Vol. 21, 1934-1935.

2. Marais, C.P., "A Fresh Outlook on the Design of Single Surface Treatments," Proceedings of the First Conference on Asphalt Pavements for Southern Africa, Durban, 1969.

3. Marais, C.P., "Advances in the Design and Application of Bituminous Materials in Road Construction," Ph.D. Thesis, University of Natal, South Africa, 1979.

4. Marais, C.P., "A Rational Design of the Single Surface Technique for Road Maintenance," The Civil Engineer in South Africa, 1981.

5. Semmelink, C.J., "Findings of Research on the Rational Design of Single and Double Seals," National Institute for Transport and Road Research, Council for Scientific and Industrial Research, RP/1, Pretoria, South Africa, January, 1985.

6. Semmelink, C.J., "A Laboratory Study of the Aggregate Spread Rates of Seals," National Institute for Transport and Road Research, Council for Scientific and Industrial Research, RP/19, Pretoria, South Africa, February, 1986.

7. Epps, J.A., Gallaway, B.M. and Hughes, C.H., "Field Manual on Design and Construction of Seal Coats," Texas Transportation Institute, Research Report 214-25, July, 1981.

8. Hveem, F.N., Lovering, W.R. and Sherman, G.B., "The Design of Seal Coats and Surface Treatments," California Highways and Public Works, Vol. 28, 1949.

9. Kearby, J.P., "Tests and Theories on Penetration Surfaces," Proceedings of the Highway Research Board, Vol. 32, 1953.

10. McLeod, N.W., "A General Method of Design for Seal Coats and Surface Treatments," Proceedings of the Association of Asphalt Paving Technologists, Vol. 38, 1969.

11. Benson, F.J. and Gallaway, B.M., "Retention of Cover Stone by Asphalt Surface Treatments," Bulletin 133, Texas Engineering Experiment Station, Texas A&M University, September 1953.

12. Herrin, M., Marek, C.R. and Majidzadeh, K. "State of the Art: Surface Treatments Summary of Existing Literature," Highway Research Record, Special Report No. 96, 1968.

13. McLeod, N.W., "Basic Principles for the Design and Construction of Seal Coats and Surface Treatments with Cutback Asphalts and Asphalt Cements," Proceedings of the Association of Asphalt Paving Tech nologists, Supplement to Volume 29, 1980.

14. National Institute for Transport and Road Research of the Council for Scientific and Industrial Research, Surfacing Seals for Rural and Urban Roads and Compendium of Design Methods for Surfacing Seals Used in the Republic of South Africa, Draft TRH3, Pretoria, South Africa, July 1986.

15. American Society for Testing and Materials, Annual Book of ASTM Standards, ASTM Designation C535-81, Vol. 4.03, 1988.

16. American Society for Testing and Materials, Annual Book of ASTM Standards, ASTM Designation C88-83, Vol. 4.03, 1988.

17. Saner, J.L. and Herrin, M. "Voids in One-Size Surface Treatment Aggregates," Highway Research Record No. 104, 1965.

18. Potter, J.L. and Church, M. "The Design of Sprayed Single Seals," Proceedings of the Eighth Australian Road Research Board Conference, Vol. 8, August, 1976.

19. Sabey, B.E. "Road Surface Texture and Change in Skidding Resistance with Speed," Road Research Laboratory, Report 20, United Kingdom, 1966.

20. "Skid Resistance of Highway Pavements," A Symposium Presented at the Seventy-Fifth Annual Meeting of the American Society for Testing and Materials, STP 530, Los Angeles, June 1976.

21. Gallaway, B.M., Epps, J.A. and Tomita, H., "Effects of Pavement Surface Characteristics and Textures on Skid Resistance," Texas Transportation Institute, Research Report 138-4, 1971.

22. Gallaway, B.M., et al., "The Relative Effects of Several Factors Affecting Rainwater Depth on Pavement Surfaces," Highway Research Record No. 395, 1972.

23. Rose, J.G., et al, "Macro-Texture Measurements and Related Skid Resistance at Speeds from 20 to 60 mph," Highway Research Record No. 341, 1970.

24. National Cooperative Highway Research Program, Skid Resistance, Synthesis of Highway Practice No. 14, 1972.

25. Mackintosh, C.S., "Rates of Spread and Spray in Bituminous Surface Dressings on Roads," The Civil Engineer in South Africa, Vol. 3, 1961.

26. Meijer, M., "Report on the Laying and First Inspection of the First Full-Scale Experiment on the Bituminous Road Surfacing Methods for New Construction, Laid on National Route T3/8, Platrand, Transvaal, Feb/March 1960," National Institute for Transport and Road Research, Report RB/5/60, Pretoria, South Africa.

27. Walker, R.N., "Report on the Laying and First Inspection of the Second Full-Scale Road Experiment on the Bituminous Road Surfacing Methods for New Construction, Laid on National Route 11/2, Malmesbury, Cape, Feb, 1961," National Institute for Transport and Road Research, Report RB/2/61, Pretoria, South Africa.

28. Walker, R.N. and Marais, C.P., "Surface Treatment Experiment on Adhesion when Wet Conditions Follow Laying," Proceedings of the Second Conference of the Australian Road Research Board, Vol. II, 1964.

29. Marais, C.P., "Report on the Laying and First Inspection of the Third Full-Scale Road Experiment on Bituminous Road Surfacing Methods for New Construction, Laid on P23/1, Kroonstad, OFS, Feb/March 1964," National Institute for Transport and Road Research, Report RB/2/64, Pretoria, South Africa.

30. Walker, R.N., "An Investigation of the Effect of Grading and Particle Shape on the Average Least Dimension of Reef Quartzite Aggregates and the Relationship between ALD and Rate of Spread of Aggregates in Surface Treatment Work," National Institute for Transport and Road Research, Internal Report RB/16/62, October, 1962.

31. <u>Special Methods for Testing Roads</u>, National Institute for Transport and Road Research, Council for Scientific and Industrial Research, Technical Methods for Highways, Draft TMH6, Pretoria, South Africa, 1984.

32. South African Bureau of Standards, "FACT Value (10% Fine Aggregate Crushing Value) of Coarse Aggregates," SABS Standard Method 842, Pretoria, South Africa.

33. Semmelink, C.J., "A Rational Design Approach for Single and Double Surfacing Seals Based on the Modified Tray Test," Transportation Record Record No. 1106, Vol. II, 1987.

34. Gallaway, B.M., Ivey, D.L., Hayes, G., Ledbetter, W.B., Olson, R.M., Woods, D.L., and Schiller, Jr., R.F.," Pavement and Geometric Design Criteria for Minimizing Hydroplaning," Federal Highway Administration, Report No. FHWA-RD-79-31, December, 1979.

35. American Association of State Highway and Transportation Officials, <u>Part II Methods of Sampling and Testing</u>, AASHTO Designation T248, Fourteenth Edition, 1986.

APPENDIX A

A METHOD FOR DETERMINING THE AVERAGE LEAST DIMENSION OF COVER AGGREGATES FOR BITUMINOUS SURFACE AND SEAL COATS

(Extracted from Reference 10)

APPENDIX A

METHOD FOR DETERMINING THE AVERAGE LEAST DIMENSION OF COVER AGGREGATES FOR BITUMINOUS SURFACE TREATMENTS AND SEAL COATS

This method describes a simplified procedure which is to be followed to determine the Average Least Dimension of a cover aggregate intended for use in a bituminous surface treatment or seal coat.

METHOD:

(a) The Sieve Analysis shall be carried out by the method described in Part 1.

(b) The Flakiness Index shall be determined by the method described in Part 2.

(c) The Average Least Dimension shall be determined from Figure C.

PART 1

SIEVE ANALYSIS

SAMPLE SIZE:

TABLE A

Weight of Sample for Sieve Analysis (U.S. Standard Sieves square openings).

Nominal Size	Minimum Weight of Sample for Sieving
Inches	Grams
3/4	5,000
5/8	4,000
1/2	2,500
3/8	1,000
1/4	750

METHOD:

The surface-dry sample shall be weighed and the following distribution of particle sizes obtained by means of sieves with square openings, employing the procedure laid down in A.S.T.M. C 136.

Passing	Retained
1 inch	3/4 inch
3/4 inch	1/2 inch
1/2 inch	3/8 inch
3/8 inch	1/4 inch
1/4 inch	No.4

WEIGHING:

On completion of sieving, the material retained on each sieve shall be weighed on a balance sensitive to 0.1% of weight of the test sample. This is recorded on the work sheet and the weight passing each sieve is expressed as a percentage of the total weight of the sample.

REPORT:

Results are reported to the nearest one per cent, and the grading curve is plotted as illustrated in Figure A.

MEDIAN SIZE:

The Median Size is that theoretical sieve size opening in inches through which 50% of the material will pass.

The Median Size may be read from the scale at the bottom of Figure A.

PART 2

FLAKINESS INDEX*

SAMPLE:

The material employed in this test shall consist of all aggregate used in the sieve analysis that falls within the size ranges specified below.

AGGREGATES

TABLE B

SIEVE SIZES TO BE SELECTED FOR FLAKINESS INDEX

Stone Size Number	Nominal Range of Sizes U.S. Standard Sieves Square Openings		All Material Larger Than
	Passing	Retained	
E	3/4 inch	1/2 inch	1/2 inch
F	5/8 "	3/8 "	3/8 "
G	1/2 "	3/8 "	3/8 "
H	3/8 "	1/4 "	1/4 "

METHOD:

Each fraction of material, as shown in the previous paragraph, shall be tested particle by particle for its ability to pass through an appropriate slotted sieve* (or a gauge made by filing an elongated slot of the required width in a sheet of metal 1/16" thick). The size of slots required for each fraction is given in Table C and illustrated in Figure B.

TABLE C

Size of Material		Slot Width Inch	Approximate Width of Slotted Sieves Issued Inch
Passing	Retained		
1"	3/4"	0.525	0.532
3/4"	1/2"	0.375	0.384
1/2"	3/8"	0.263	0.258
3/8"	1/4"	0.184	0.184
1/4"	No.4	0.131	0.123

* See British Standards Institution 812.

WEIGHING:

The total amount passing the appropriate slotted sieve openings shall be weighed to an accuracy of at least 0.1 per cent of the weight of the test sample.

FLAKINESS INDEX:

The Flakiness Index is the total weight of the material passing the appropriate slotted sieve openings expressed as a percentage of the combined weight of the fractions tested on the slotted sieves.

EXAMPLE

(a) SIEVE ANALYSIS

TABLE D

FULL GRADING

Total Weight of dry sample = 2,600 grams.

Sieve No. U.S. Standard Square Opening	Weight Retained Grams	Weight Passing Grams	Total Passing Per Cent
5/8"	-	2600	100
1/2"	104	2496	96
3/8"	1872	624	24
1/4"	442	182	7
No.4	78	104	4
No.8	65	39	1.5

The Material is stone size number G.

From the grading curve, Figure A, the Median Size is 0.41 inch.

(b) FLAKINESS INDEX

TABLE E

FLAKINESS INDEX

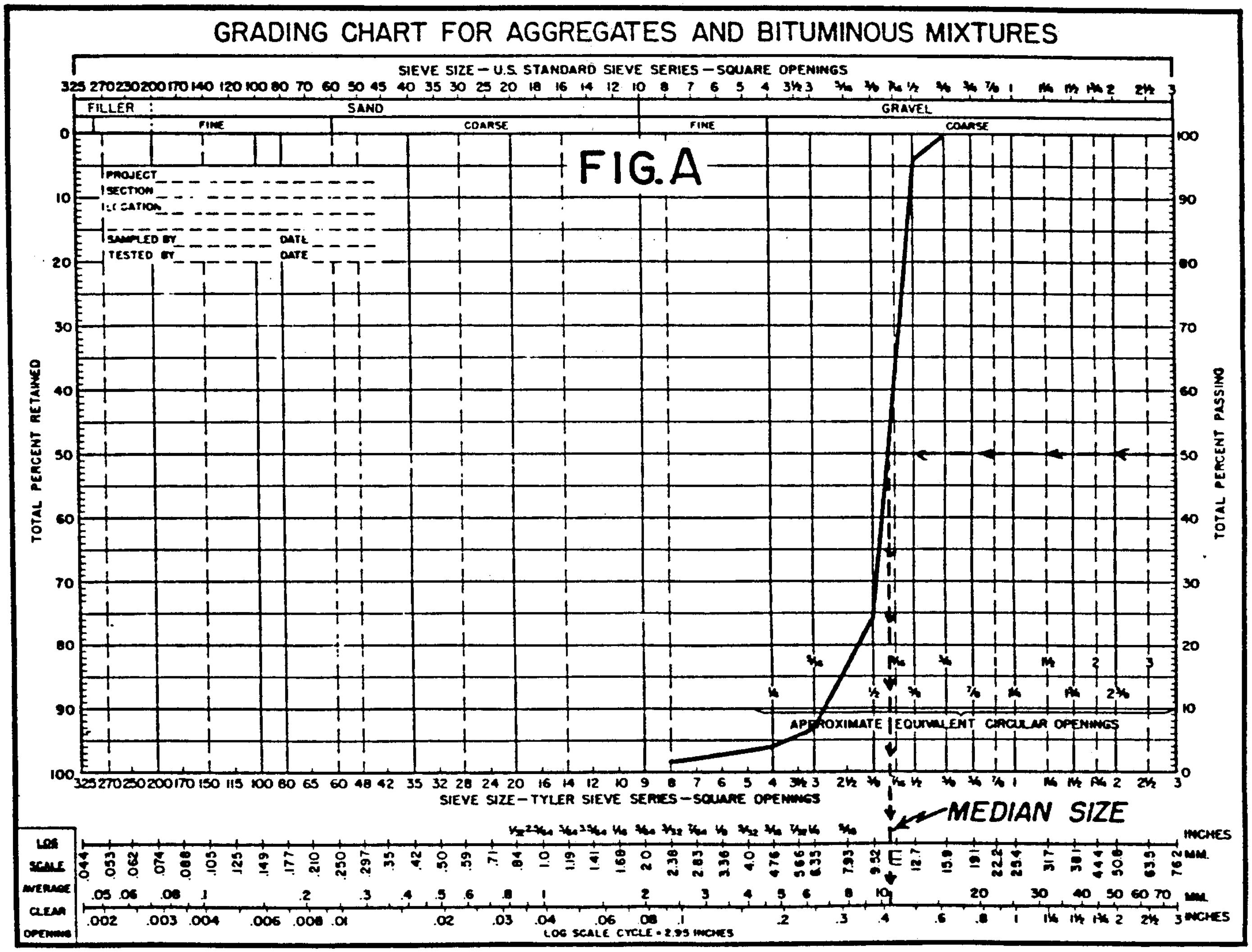
Sieve Size U.S. Standard Square Opening Inch	Width of Slotted Sieve Inch	Weight Retained Slotted Sieve Grams	Weight Passing Slotted Sieve Grams	Total Weight Grams	Flakiness Index Per Cent
3/4 - 1/2	0.375	78	26	104	
1/2 - 3/8	0.262	1421	451	1872	
Total		1499	477	1976	24.1

Note: Where there is any insignificant amount of material (not more than 5%) of any one size, it may be neglected in determination of Flakiness Index. Material 3/4" - 1/2" could be neglected in above Flakiness Index test and the result would not be appreciably changed.

(c) AVERAGE LEAST DIMENSION

On Figure C, proceed horizontally from the median size on the vertical axis to the diagonal line representing the flakiness index for the sample. From this point of intersection, proceed vertically to the horizontal axis and read off the Average Least Dimension.

For this particular aggregate sample, the median size is 0.41 inch, and the flakiness index is 24 per cent. The broken line on Figure C indicates that the Average Least Dimension (A.L.D.) of this sample is 0.29 inch (reading to the nearest 0.01 inch).


GRADING CHART FOR AGGREGATES AND BITUMINOUS MIXTURES
SIEVE SIZE — U.S. STANDARD SIEVE SERIES — SQUARE OPENINGS
FILLER
SAND
GRAVEL
FINE
COARSE
FIG. A
PROJECT
SECTION
LOCATION
SAMPLED BY
DATE
TESTED BY
TOTAL PERCENT RETAINED
TOTAL PERCENT PASSING
APPROXIMATE EQUIVALENT CIRCULAR OPENINGS
SIEVE SIZE — TYLER SIEVE SERIES — SQUARE OPENINGS
MEDIAN SIZE
LOG SCALE
AVERAGE CLEAR OPENING
INCHES
MM.
LOG SCALE CYCLE = 2.95 INCHES

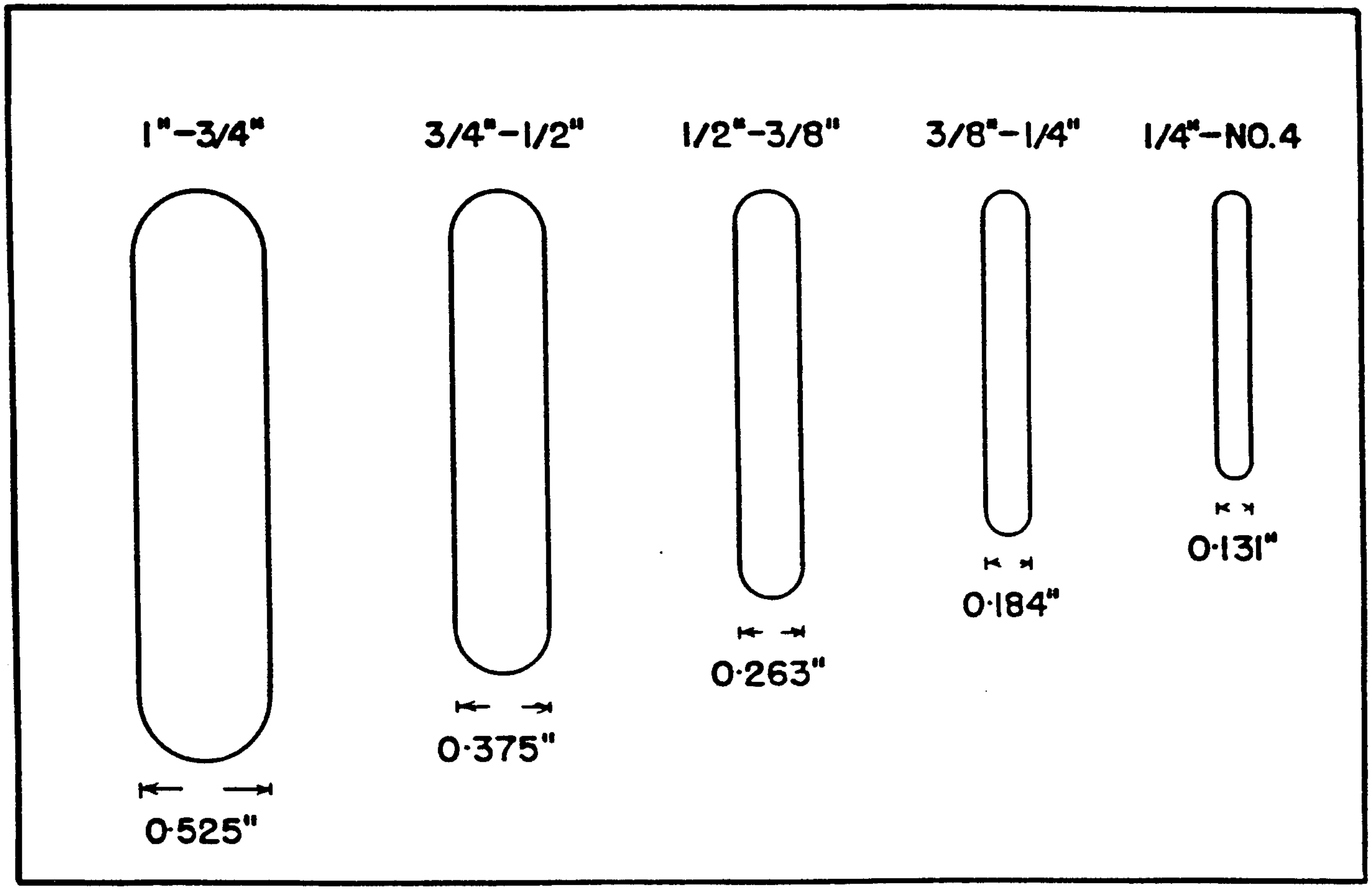


FIG. B SLOTTED SIEVE OPENINGS FOR TESTING AGGREGATES FOR ELONGATED FLAT PARTICLES.

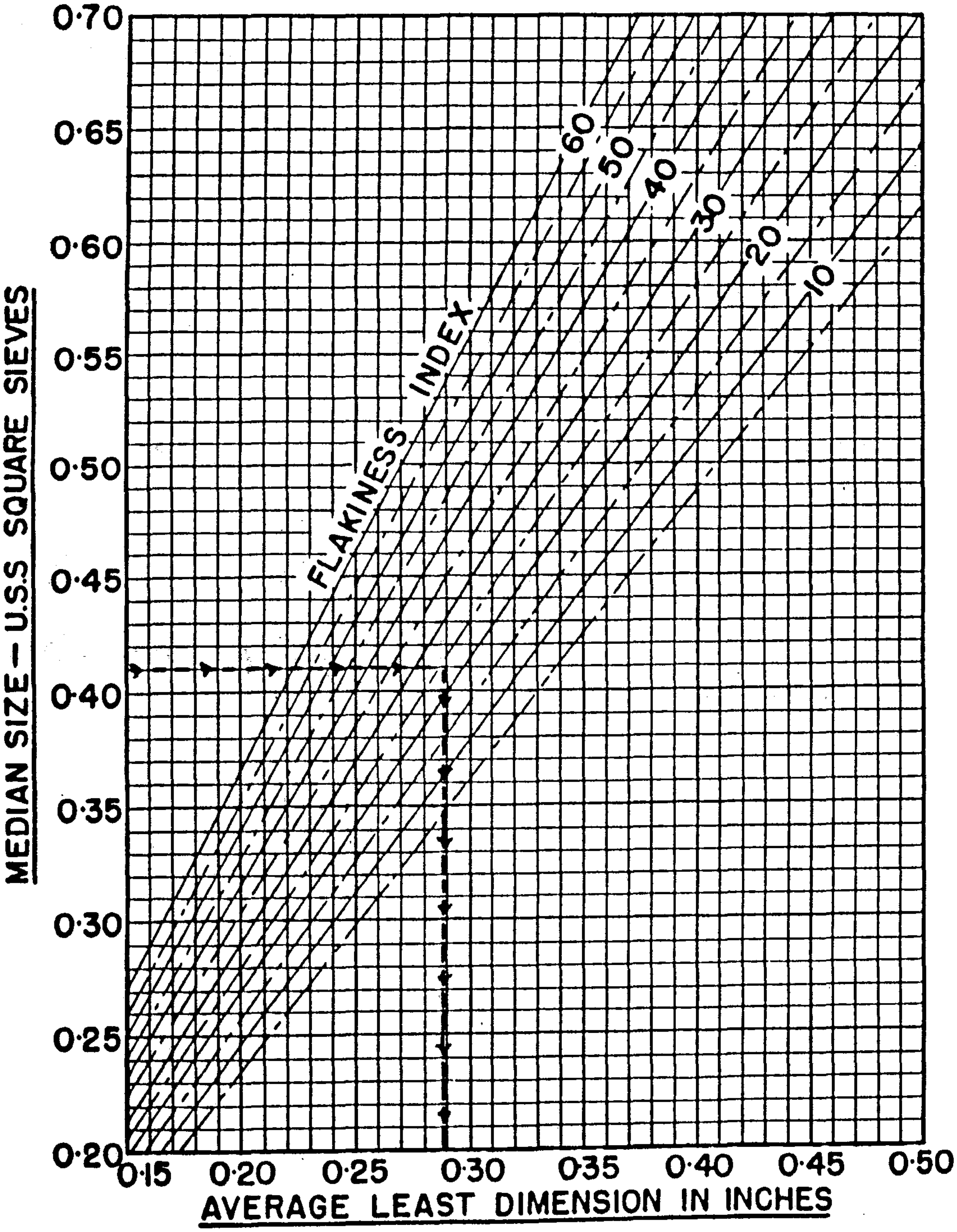


FIG.C DETERMINATION OF AVERAGE LEAST DIMENSION OF COVER AGGREGATE.

APPENDIX B (14)

THE MODIFIED TRAY TEST PROCEDURE

THE DETERMINATION OF THE EFFECTIVE LAYER THICKNESS, SPREAD RATE AND VOID CONTENT OF A LAYER OF SEAL AGGREGATE

1 SCOPE

The effective layer thickness, the spread rate and the void content of the layer of aggregate are determined by means of the modified tray test and a measuring cylinder. The modified tray test measures the volume displaced by the aggregate plus voids in the tray. The relative density of the aggregate is required to determine the void content in the layer (see TMH1 - method B14). (36)

Definitions

The effective layer thickness is the average thickness of the layer of aggregate and is determined by dividing the volume displaced by the aggregate plus void space in between, by the area of the tray.

The void content of the layer is the void space in the layer expressed as a percentage of the effective layer thickness.

The bulk void content is the void space in the aggregate in bulk expressed as a percentage of the bulk volume.

2 APPARATUS

2.1 The modified tray test apparatus. This consists of a circular tray with an area of 0.05 m^2 (internal diameter 252 mm) with a wall height of 50 mm. A shoulder piece which fits snugly on top of the tray and has the same internal diameter as the tray and is fitted with a loose-fitting cloth membrane large enough to fit tightly against the sides of the circular tray. The purpose of the membrane is to prevent the "density sand" from flowing into the voids between the stones (see Figure A1).

2.2 A balance to weigh up to 10 kg, accurate to 1 g

2.3 A 5ℓ beaker with density sand

2.4 A straight edge for scraping off the sand

2.5 A paint brush

2.6 A large tray to collect excess sand

2.7 A plastic measuring cylinder with a capacity of 2ℓ

3 METHOD

3.1 Determination of the bulk density of the sand (to be done at 6-month intervals)

(a) Determine the average diameter (d) of the tray (without the shoulder piece) by taking at least 10 readings with a vernier gauge

(b) Determine the average depth (h) of the tray by taking 10 readings along the perimeter of the tray with a vernier gauge

(c) With the average diameter and average depth determine the theoretical volume of the tray ($V = (\pi d^2/4)x(h)$).

(d) Determine the mass of the empty tray

(e) Fill the tray with density sand in a smooth pouring motion until it is overfilled

(f) Scrape off the excess sand in one smooth flowing movement by means of the straight edge

(g) Determine the mass of the tray plus density sand

(h) Repeat steps (e) to (g) at least 10 times

(i) Determine the average mass of the sand necessary to fill the tray

(j) The bulk density of the sand (BDS) is the average mass (in g) divided by the theoretical volume of the tray (V) (in ml).

3.2 Determination of the internal volume of the tray plus shoulder (to be done at 6 month intervals)

(a) Determine the mass of the tray plus shoulder (M3)

(b) Smooth out the cloth membrane against the bottom and sides of the tray. Make certain that the membrane is not pinched between the shoulder and the tray.

(c) Fill the tray and shoulder with "density sand" in one smooth pouring motion, making sure that the space is over-filled. Scrape off the excess sand in a smooth flowing movement by means of a straight edge. Brush off any sand left on the shoulder edge.

(d) Determine the mass of the tray plus shoulder plus density sand (M4)

(e) The volume of the tray plus shoulder is equal to the mass of sand required to fill the tray plus shoulder divided by the bulk density of the sand. Because the volume of the tray plus shoulder is constant, M3 and M4 do not have to be determined for each sample tested. The values for M3 and M4 could be taken to be the average number of repeated readings (e.g. 10).

3.3 Determination of the effective layer thickness (ELT) and the void content

(a) Pack the stone in the tray in a single layer with their least dimension in a vertical direction. The stone should be packed shoulder to shoulder.

(b) Place the shoulder on top of the tray with stone ensuring that the cloth membrane is not pinched between the shoulder and tray and smooth out the membrane without disturbing the stone.

(c) Determine the mass of the tray plus shoulder plus stone (M1)

(d) Fill the space above the stone with "density sand" in one smooth pour. The tray should once again be over-filled and the excess sand scraped off with a straight edge. Brush off any sand left on the shoulder edge.

(e) Determine the mass of the tray plus shoulder plus stone plus sand (M2)

(f) Lift off the shoulder with the sand and repeat steps (d) and (e) at least 3 times. The stone should not be repacked (repacking unnecessary).

(g) Determine the relative density of the stone in the normal manner (see TMH1 - Method B14, page 150).

3.4 Determination of the spread rate and bulk void content

(a) Take the aggregate sample used with the tray test and pour it into the plastic measuring cylinder

(b) Read off the average volume occupied by the sample in ml

(c) Repeat steps (a) and (b) at least 5 times.

4 CALCULATIONS

(a) Void space occupied by stone plus voids in layer

$$V1 = ((M4-M3) - (M2-M1))/BDS$$

where

BDS = bulk density of the sand (g/ml)

V1 = space occupied by stone plus voids in layer (ml)

M4 = mass of tray plus shoulder plus sand (without stone)(g)

M3 = mass of tray plus shoulder (without stone((g)

M2 = mass of tray plus shoulder, plus stone plus sand (g)

M1 = mass of tray plus shoulder plus stone (g)

(b) Effective layer thickness (mm)

$$ELT = (V1x10)/A1$$

A1 = area of tray (cm^2)

(c) Void content = (V1-V stone)/(V1 x 100)

= (V1 - (M stone/RD stone))/V1 x 100

= (V1 - (M1-M3)/RD stone))/V1 x 100

where

void content = void space in layer (%)

Vstone = space occupied by stone (ml)

V1 - void space occupied by stone plus voids in layer (ml)

RD stone - relative density of stone

Mstone - mass of stone (g)

M1 - mass of tray plus shoulder plus stone (g)

M3 - mass of tray plus shoulder (g)

(d) Use the average result of the three sets of answers. The repetitions are done to ensure that no serious mistakes arose in the performance of the measurements.

(e) Determine the average bulk volume of the aggregate sample from the 5 readings.

(f) The spread rate = $\dfrac{\text{bulk volume of sample (in } \ell)}{\text{area of tray } (m^2)}$

$$= V2/A1 \times 10^{-3} \ (m^3/m^2)$$

where

V2 - bulk volume of the sample (ℓ)

Note: In Texas, spread rate is normally expressed in units of yd^2/yd^3. To obtain the spread rate in these units, use the following equation:

$$\text{Spread Rate} = \frac{\text{Area of tray } (yd^2)}{\text{bulk volume of sample } (\ell) \times (1.309 \times 10^{-3} \ yd^3/\ell)}$$

$$= \frac{A1 \ (yd^2)}{V2 \times (1.309 \times 10^{-3})} \quad yd^2/yd^3$$

(g) The bulk void content = (V2-V-stone)/V2 x 100)

= (V2-Mstone/RDstone)/V2x100

where

Vstone = space occupied by stone (ml)

Mstone = mass of stone (g)

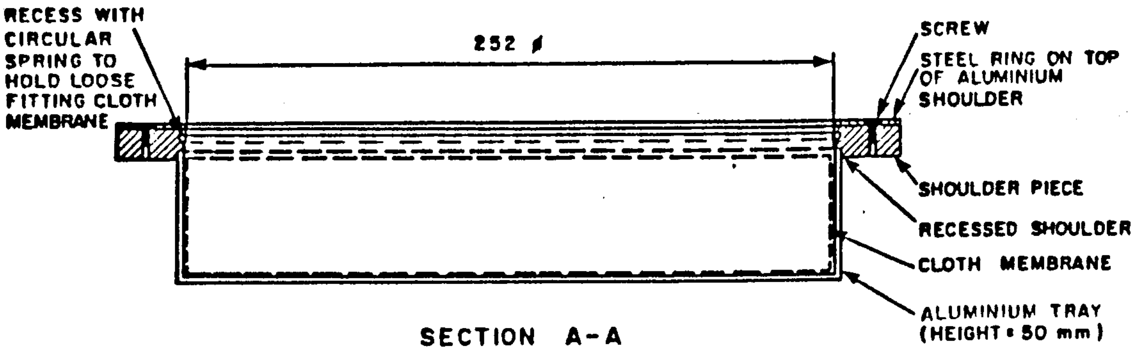
RDstone = relative density of stone

V2 = bulk volume of sample (ml)

(h) Theoretical spread rate = ELT-(100-void content in layer)/ (100-bulk void content x $10^{-3}(m^3/m^2)$

(i) Check the theoretical spread rate (h) with the practical determined spread rate (f). If no mistakes were made the values should approximately be the same.

(j) If they are the same, increase this spread rate value by 6% for variations in practice in the case of single seals and the second layer of a double seal. The spread rate of the first layer of a double seal should not be increased.



SECTION A-A

STRAIGHT EDGE CONSIST OF ALUMINIUM PLATE (4 mm THICK OF 500 x 100 (APROX)

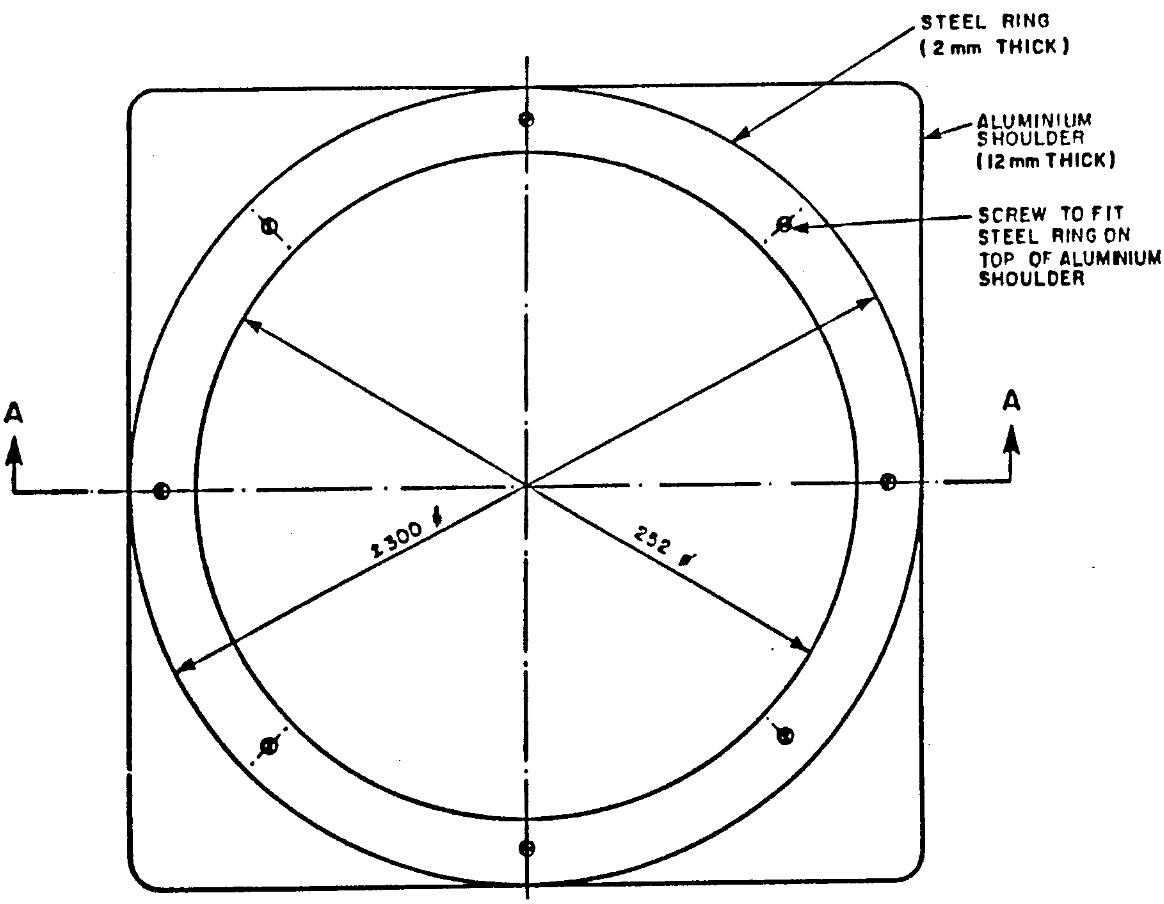


FIGURE A1

TMH1 - METHOD B14

THE DETERMINATION OF THE DRY BULK DENSITY,

APPARENT RELATIVE DENSITY AND WATER ABSORPTION OF AGGREGATE RETAINED ON A 4,75 MM (No. 4) SIEVE

1. SCOPE

The dry bulk density and apparent relative density of the + 4.75 mm (No. 4) material, as defined below, are calculated from the loss in mass of the saturated surface-dry aggregate when it is submerged in water.

The water absorption is determined by calculating the mass of water absorbed after the 24-hour immersion in water of the oven-dried material.

Definitions

Relative density is the ratio of the mass in air of a given volume of a material at a stated temperature to the mass in air of an equal volume of distilled water at the same temperature.

Bulk relative density is the ratio of the mass in air of a given volume of material (including the permeable and impermeable voids normal to the material) at a stated temperature to the mass in air of an equal volume of distilled water at the same temperature.

Apparent relative density is the ratio of the mass in air of a given volume of material (excluding the permeable voids but including the impermeable voids normal to the material) at a stated temperature to the mass in air of an equal volume of distilled water at the same temperature.

2. APPARATUS

2.1 A balance with a capacity of 5 kg, accurate to 0.5 g.

2.2 A wire basket, approximately 200 mm in diameter and 200 mm high, manufactured from a 3,35 mm (No. 6) screen.

2.3 A suitable container with water for immersing the wire basket and a suitable arrangement for suspending the wire basket from the center of the balance pan.

2.4 A thermometer measuring 0-100°C.

2.5 A drying oven, thermostatically controlled and capable of maintaining a temperature of 105 to 110°C.

3. METHOD

Quarter out approximately 3 kg of the material retained on the 4,75 mm (No. 4) sieve. Wash the sample thoroughly to remove dust from the surfaces of the particles and soak for 24 hours in water. Remove the material from the water, drain off the free water for a few seconds and transfer it to a large absorbent cloth. In order to obtain the so-called saturated surface-dry condition, the sample is rolled in the cloth until all visible water has been absorbed, but the surfaces of the particles should still appear damp.

Large-aggregate particles may be wiped individually. As soon as the surface-dry condition is reached, weigh the sample, accurate to 0,5 g, and transfer it to a wire basket that has previously been weighed in water. Weigh the basket with sample in water at 25 ± 1°C taking care that no air is entrapped (see 5.1).

Remove the sample from the wire basket, allow the free water to drain off and then dry it to a constant mass in an oven at a temperature of 105 to 110°C.

Weigh the oven-dried sample.

This test must be done in duplicate.

4. CALCULATIONS

4.1 Calculate the dry bulk density and apparent relative density to the nearest 0,001 from the following forumula:

$$\text{Dry bulk density (25/25°C)} = \frac{A}{B - C}$$

$$\text{Apparent relative density (25/25°C)} = \frac{A}{A - C}$$

where:

A = mass of oven-dry sample in air

B = mass of saturated surface-dry sample in air

C = mass of saturated sample in water at 25°C

Duplicate results should agree within + 0,005 or be repeated.

4.2 Calculate the percentage of water absorbed to the nearest 0,1 from the formula:

Water absorption m/m

$$\frac{(B-A)}{A} \times 100$$

Report relative density to the nearest 0,0001 and water absorption to the nearest 0,1.

5. **NOTES**

5.1 The standard temperature is taken as 25°C. If the test is done at any other temperature, this should be stated or the RD should be adjusted for a temperature of 25°C.

5.2 The relative density of material retained on the 4,75 mm sieve (No. 4) can also be determined by using a pycnometer (see Method B15). The volume of the pycynometer should then be between 1,000 and 3,000 mℓ.

5.3 Samples containing material passing and retained on the 4,75 mm (No. 4) sieve must be divided by means of this sieve and the appropriate test method used on the separate samples. The relative density of the total material must then be calculated as follows:

Relative density of the total

$$\text{material} = \frac{100}{\frac{P1}{G1} + \frac{P2}{G2}}$$

where

P1 = percentage of material passing the 4,75 mm sieve (No. 4)

P2 = percentage of material retained on the 4,75 mm sieve (No. 4)

G1 = relative density of the material passing the 4,75 mm sieve (No. 4)

G2 = relative density of the material retained on the 4,75 mm (No. 4) sieve

5.4 When only the apparent relative density is required, the determination of the saturated surface-dry mass of the sample in air is not required.

References

ASTM Designation C127-73

D854-58 AASHTO Designation T85-70

SABS Method 843 and 844.

APPENDIX C

LABORATORY DATA FROM MODIFIED TRAY TEST EXPERIMENT DESCRIBED IN CHAPTER VI

Stone Combination	Measured Properties of Bottom Layer ELT_b	Measured Properties of Bottom Layer $Voids_b$	Measured Properties of Top Layer ELT_t	Measured Properties of Top Layer $Voids_t$	Measured Properties of Double Layer ELT_d	Measured Properties of Double Layer $Voids_d$	Calculated Voids in Double Layer $Voids_c$*	Calculated Voids in Double Layer $Voids_c$**
Grade 2 on 2	9.83	44.26	9.77	42.69	20.10	40.09	(44.59)	40.77
	9.37	44.79	9.57	46.63	18.64	42.08	45.00	42.70
	9.93	44.13	9.46	44.11	18.96	42.21	43.14	(41.32)
Grade 3 on 2	9.52	45.13	7.43	44.90	15.21	40.09	40.41	41.50
	9.85	45.49	7.66	47.17	15.63	41.51	41.26	43.66
	9.28	43.86	7.36	46.50	15.37	39.98	41.59	41.40
Grade 4 on 2	9.34	45.61	6.53	47.23	13.39	39.40	39.04	42.28
	9.69	44.60	6.47	47.13	14.52	40.01	40.98	41.77
	9.84	45.15	6.19	50.06	13.10	37.51	38.44	(43.03)
Grade 3 on 3	7.15	47.59	7.43	48.33	14.10	45.25	46.39	43.30
	7.23	46.52	7.22	46.29	13.62	40.33	(43.74)	41.81
	7.51	46.27	7.31	45.13	14.48	43.81	44.66	(41.33)
Grade 4 on 3	7.69	44.25	5.98	44.79	12.24	38.91	39.83	39.73
	7.13	46.02	6.51	49.19	11.79	41.06	41.09	42.45
	7.22	47.50	6.37	46.12	12.03	40.32	41.47	41.82
Grade 4 on 4	6.44	46.88	6.39	48.08	12.02	40.34	(44.48)	41.96
	6.25	48.03	6.72	47.78	10.53	40.31	38.89	42.40
	6.59	47.91	6.28	47.13	11.12	40.16	41.07	42.03
Grade 5 on 2	9.13	44.78	3.67	56.24	10.79	40.80	40.52	42.43
	9.72	46.32	3.82	52.39	11.18	40.82	39.66	42.82
	9.46	45.11	4.25	53.84	10.90	37.04	38.01	(42.72)
Grade 5 on 3	7.43	46.66	3.69	54.36	9.08	39.67	40.19	42.31
	7.23	48.02	3.75	57.22	9.46	42.90	44.08	43.85
	7.25	45.21	3.62	55.01	8.90	39.05	39.69	41.47
Grade 5 on 4	6.36	46.29	4.26	54.26	8.39	40.60	39.10	42.12
	6.22	46.89	3.77	55.61	8.42	41.93	42.29	42.09
	6.46	45.34	3.84	53.98	9.12	41.06	43.00	41.02
Grade 5 on 5	3.40	58.10	4.01	56.11	6.24	42.01	(48.02)	(43.86)
	3.78	57.21	3.39	57.29	6.80	47.76	(54.30)	(43.51)
	3.51	56.96	4.72	57.46	7.24	43.31	(50.36)	45.56

*$Voids_c$ Using Measured ELT_d
**$Voids_c$ Using Calculated ELT_d
Note: Values in Parentheses Discarded in Determining Equation and R^2.

APPENDIX D

THE BALL PENETRATION TEST FOR SURFACE TREATMENT DESIGN

(Extracted from Reference 31)

METHOD ST4

THE BALL PENETRATION TEST FOR SURFACE TREATMENT DESIGN

1 SCOPE

This method describes a test for measuring the penetration resistance of a road surface using a steel ball with a diameter of 19,0 mm. The result may be used when designing a surface treatment for a road.

2 APPARATUS

(See also Figure ST4/I.)

2.1 A circular (127 mm) tripod stand and cross-bar.

2.2 A steel ball with a diameter of 19,0 mm.

2.3 A depth gauge graduated in mm.

2.4 A surface thermometer graduated in degrees Celsius (25 to 55 °C).

2.5 A standard Marshall compaction hammer complying with TMH1, Appendix to Method C2.

3 METHOD

Subdivide the road into a number of representative sites.

Toss the steel ball onto the road at each site in a random manner.

Place the circular tripod stand over the ball at the point where it comes to rest so that the ball is in the centre of the circular frame.

Place the cross-bar in the slots provided on the stand so that the forward edge of the bar is vertically above the centre of the ball.

Take an initial reading by means of a depth gauge from the top of the cross-bar to the top of the ball and remove the bar without disturbing the tripod stand.

Give the ball one blow with the Marshall hammer and replace the cross-bar in the same position as before. Take a second reading as above. The depth of penetration is the difference between the two readings. Repeat the procedure at least 10 times at each site and report the mean depth of penetration of the steel ball.

Take the temperature of the road surface at each site for each set of penetration readings.

4 CALCULATIONS

Correct the penetration reading by means of the following formula:

$$\text{Pen } T_0 = \text{Pen } T_1 - K(T_1 - T_0)$$

where

Pen T_0 = penetration depth at suggested road surface temperature (mm)

Pen T_1 = penetration depth at measured road surface temperature (mm)

T_1 = temperature of road at time of ball test (°C)

T_o = temperature of road suggested for particular location (°C)

K = temperature-susceptibility of penetration (mm/°C).

K-factors recommended:

0,04 mm/°C	–	Single and multiple seals (not fatty)
0,05 mm/°C	–	Slurry seals (not fatty)
0,07 mm/°C	–	Cape seals (not fatty)
0,08 mm/°C	–	Fatty roads and premix surfacings.

It should be noted that the relationship is valid for all road surfaces and temperatures (T_1) lying between 25 and 55 °C.

REFERENCE

MARAIS, C P. *Advances in the design and application of bituminous materials in road construction.* PhD (Eng) thesis, University of Natal, Durban, South Africa, 1979.

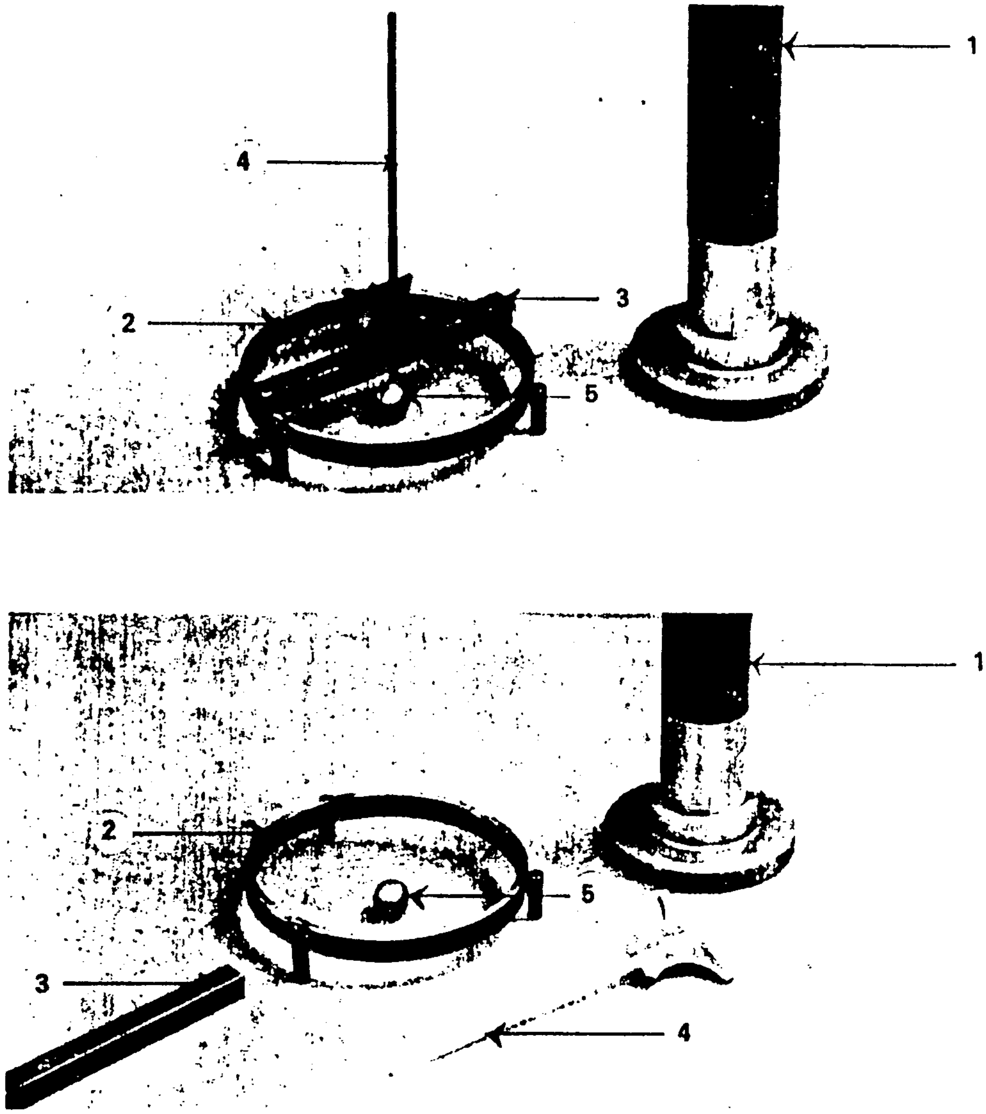


FIGURE ST4/1: TWO VIEWS OF THE APPARATUS FOR THE BALL PENETRATION TEST

APPENDIX E

NUMERICAL EXAMPLE FOR THE DESIGN OF DOUBLE SEALS

Example - Design of Double Seals

The ELT of the double seal (ELT_d) can be determined by using the following equation:

$$ELT_d = 0.86(\Sigma ELT)+0.19$$

where $\Sigma ELT = ELT_1 + ELT_2$
$ELT_1 = ELT$ (bottom layer)
$ELT_2 = ELT$ (top layer)

Calculate the factor F by means of the following equation:

$$F = \frac{(ELT_1(0.95V_{L1} + 5) + ELT_2(V_{L2})}{(\Sigma ELT)} \quad \frac{(ELT_d)}{(\Sigma ELT)}$$

where V_{L1} = true void content of the bottom layer as a percentage
V_{L2} = true void content of the top layer as a percentage

The true void content of the double seal can now be determined by using the following equation:

Percentage voids in double seal (V_d) = 1.006(F)-0.87

The aggregate spread rate = $(f)ELT(100 - V_L)/(100 - V_b) \times 10^2$ (m^3/m^2)

where V_L = void content in the aggregate layer (%)
V_b = bulk void content of the aggregate (%)
f = increase factor for variations in workmanship, etc.
= 1.00 for bottom layer of aggregate
= 1.06 for top layer of aggregate

EXAMPLE

Data obtained from tests:

Traffic (ADT/lane) = 7100 elv
Texture depth of present surface = 0.55 mm
(as determined with sand patch test)
Corrected ball penetration value = 1.05 mm
ELT_1 = 8.25 mm; V_{L1} = 58.91% (determined from Modified Tray Test)
ELT_2 = 7.38 mm; V_{L2} = 51.62% (determined from Modified Tray Test)
10% FACT value of aggregate = 200 kN

(a) $\Sigma ELT = ELT_1 + ELT_2$
$= 8.25 + 7.38$
$= 15.63$

$ELT_d = 0.86(\Sigma ELT) + 0.19$
$= 0.86(15.63) + 0.19$
$= 13.63$

(b) $F = \frac{(ELT_1(0.95V_{L1} + 5) + ELT_2(V_{L2}))}{(\Sigma ELT)} \frac{(ELT_d)}{(\Sigma ELT)}$

$= \frac{[8.25(0.95(58.91) + 5) + 7.38(51.62)]}{15.63} \frac{(13.63)}{15.63}$

$= \frac{(502.96 + 380.96)}{15.63} \frac{(13.63)}{15.63}$

$= 49.32$

$V_d = 1.006(F) - 0.87$
$= 1.006(49.32) - 0.87$
$= 48.75$

(c) Embedment of aggregate (From Table 5.4) = 0.757 mm

Embedment as a fraction of the ELT_d = 0.757/13.63
= 0.055

(d) Wear of aggregate (From Table 5.5) = 0.902 mm

Wear as a fraction of ELT_d = 0.902/13.63
= 0.066

(e) Fractional void loss due to embedment (Table 5.6) = 0.126

(f) Fractional void loss due to wear (Table 5.6) = 0.148

(g) Fractional voids required for skid resistance = 1.00/(0.4874 x 13.63)
= 0.151

(h) Total void loss = 0.126 + 0.148 + 0.151
= 0.425

(i) Available void fraction (if greater than 0.55 use 0.55) = 1 - 0.425
= 0.575 (use 0.55)

(j) Rolling embedment = 0.90 x 0.757
= 0.68 mm

Rolling embedment as a fraction of ELT_d = 0.68/13.63
= 0.050

(k) Void loss due to rolling embedment (Table 5.6) = 0.115

(l)* Minimum voids to be filled to prevent inital stone loss = 0.55 - 0.115
= 0.435

(m) The available void fraction is larger than the minimum required void fraction, therefore the seal will have a normal life.

Nominal quantity of cold binder (max.) = (0.55)(0.4875)(13.63)
= 3.63 l/m^2

Nominal quantity of cold binder (min.) = (0.435)(0.4875)(13.63)
= 2.89 l/m^2

(n) Additional binder required due to surface texture (Table 5.7) = 0.18 l/m^2

(o) Total quantity of cold binder required = 3.07 l/m^2

Note: To convert l/m^2 into gal/yd^2 simply divide by 4.527.

$$\frac{3.07\ l/m^2}{4.527} = 0.68\ gal/yd^2$$

(p) The total quantity of cold binder does not have to be divided 50/50 between the two layers. A 60/40 ratio has also been used with success.

---

* In the case of a double seal, it is recommended that 55 percent of the voids be filled with binder to ensure that the top layer of aggregate is not lost due to whip-off.

TABLE 5.4 EMBEDMENT DUE TO TRAFFIC AS DETERMINED BY THE BALL PENETRATION TEST(MM)

CORRECTED BALL-PEN (MM)	AVERAGE DAILY TRAFFIC(EQUIVALENT LIGHT VEHICLES/LANE/DAY) 125	250	500	750	1 000	2 000	3 000	4 000	5 000	10 000	20 000	40 000
0,75	0,006	0,012	0,024	0,036	0,048	0,095	0,244	0,349	0,431	0,684	0,938	1,192
1,00	0,016	0,031	0,063	0,094	0,126	0,252	0,421	0,542	0,635	0,925	1,215	1,505
1,25	0,023	0,047	0,093	0,140	0,187	0,373	0,559	0,691	0,793	1,111	1,429	1,747
1,50	0,030	0,059	0,118	0,177	0,236	0,472	0,672	0,813	0,923	1,264	1,605	1,946
1,75	0,035	0,070	0,139	0,209	0,278	0,556	0,767	0,916	1,032	1,393	1,753	2,113
2,00	0,039	0,079	0,157	0,236	0,314	0,629	0,849	1,006	1,127	1,504	1,881	2,259
2,25	0,043	0,087	0,173	0,260	0,346	0,693	0,922	1,085	1,211	1,603	1,995	2,387
2,50	0,047	0,094	0,187	0,281	0,375	0,750	0,987	1,155	1,286	1,691	2,096	2,501
2,75	0,050	0,100	0,200	0,301	0,401	0,802	1,046	1,219	1,353	1,771	2,188	2,605
3,00	0,053	0,106	0,212	0,318	0,425	0,849	1,100	1,277	1,415	1,843	2,271	2,700
3,25	0,056	0,112	0,223	0,335	0,446	0,893	1,149	1,331	1,472	1,910	2,348	2,787
3,50	0,058	0,117	0,233	0,350	0,466	0,933	1,195	1,380	1,525	1,972	2,420	2,867
3,75	0,061	0,121	0,243	0,364	0,485	0,970	1,237	1,427	1,574	2,030	2,486	2,942
4,00	0,063	0,126	0,251	0,377	0,503	1,005	1,277	1,470	1,619	2,084	2,548	3,013
4,25	0,065	0,130	0,260	0,389	0,519	1,038	1,315	1,510	1,662	2,134	2,607	3,079
4,50	0,067	0,134	0,267	0,401	0,535	1,069	1,350	1,549	1,703	2,182	2,661	3,141
4,75	0,069	0,137	0,275	0,412	0,549	1,099	1,383	1,585	1,741	2,227	2,714	3,200
5,00	0,070	0,141	0,282	0,423	0,563	1,127	1,415	1,619	1,778	2,270	2,763	3,255
5,25	0,072	0,144	0,288	0,432	0,577	1,153	1,445	1,652	1,812	2,311	2,810	3,308
5,50	0,074	0,147	0,295	0,442	0,589	1,179	1,474	1,683	1,846	2,350	2,855	3,359
5,75	0,075	0,150	0,301	0,451	0,601	1,203	1,501	1,713	1,877	2,387	2,897	3,407
6,00	0,077	0,153	0,306	0,460	0,613	1,226	1,527	1,741	1,907	2,423	2,938	3,454
6,25	0,078	0,156	0,312	0,469	0,624	1,248	1,553	1,769	1,936	2,457	2,977	3,498
6,50	0,079	0,159	0,317	0,476	0,635	1,269	1,577	1,795	1,964	2,490	3,015	3,541
6,75	0,081	0,161	0,322	0,484	0,645	1,290	1,600	1,820	1,991	2,521	3,051	3,582
7,00	0,082	0,164	0,327	0,491	0,655	1,310	1,623	1,845	2,017	2,552	3,086	3,621
7,25	0,083	0,166	0,332	0,498	0,664	1,329	1,644	1,868	2,042	2,581	3,120	3,660
7,50	0,084	0,168	0,337	0,505	0,674	1,347	1,665	1,891	2,066	2,609	3,153	3,696
7,75	0,085	0,171	0,341	0,512	0,683	1,365	1,685	1,913	2,089	2,637	3,184	3,732
8,00	0,086	0,173	0,346	0,518	0,691	1,332	1,705	1,934	2,112	2,663	3,215	3,767

Surfacing seals for roads
Draft TRH3, Pretoria, South Africa 1986

TABLE 5.5 ESTIMATED WEAR UNDER CONSTRUCTION ROLLING AND TRAFFIC(10 YEAR LIFE)(MM)

	AVERAGE DAILY TRAFFIC(EQUIVALENT LIGHT VEHICLES/LANE/DAY)											
10%FACT	125	250	500	750	1 000	2 000	3 000	4 000	5 000	10 000	20 000	40 000
150	0,461	0,495	0,559	0,618	0,671	0,832	0,909	0,935	0,961	0,961	0,961	0,961
160	0,448	0,482	0,547	0,605	0,659	0,820	0,897	0,923	0,949	0,949	0,949	0,949
170	0,436	0,470	0,534	0,593	0,647	0,808	0,885	0,911	0,937	0,937	0,937	0,937
180	0,424	0,458	0,523	0,581	0,635	0,796	0,873	0,899	0,925	0,925	0,925	0,925
190	0,413	0,447	0,511	0,570	0,623	0,785	0,861	0,887	0,913	0,913	0,913	0,913
200	0,401	0,435	0,499	0,558	0,612	0,773	0,850	0,876	0,902	0.902	0,902	0,902
210	0,390	0,424	0,488	0,547	0,600	0,762	0,838	0,864	0,890	0,890	0,890	0,890
220	0,378	0,412	0,477	0,535	0,589	0,750	0,827	0,853	0,879	0,879	0,879	0,879
230	0,367	0,401	0,465	0,524	0,578	0,739	0,816	0,842	0,868	0,868	0,868	0,866
240	0,356	0,390	0,454	0,513	0,567	0,728	0,805	0,831	0,857	0,857	0,857	0,857
250	0,345	0,379	0,444	0,502	0,556	0,717	0,794	0,820	0,846	0,846	0,846	0,846
260	0,335	0,369	0,433	0,492	0,545	0,707	0,783	0,809	0,835	0,835	0,835	0,835
270	0,324	0,358	0,422	0,481	0,535	0,696	0,773	0,799	0,825	0,825	0,825	0,825
280	0,314	0,348	0,412	0,471	0,524	0,686	0,762	0,788	0,814	0,814	0,814	0,814
290	0,304	0,338	0,402	0,461	0,514	0,675	0,752	0,778	0,804	0,804	0,804	0,804
300	0,293	0,328	0,392	0,451	0,504	0,665	0,742	0,768	0,794	0,794	0,794	0,794
310	0,284	0,318	0,382	0,441	0,494	0,655	0,732	0,758	0,784	0,784	0,784	0,784
320	0,274	0,308	0,372	0,431	0,484	0,646	0,722	0,748	0,774	0,774	0,774	0,774
330	0,264	0,298	0,362	0,421	0,475	0,636	0,713	0,739	0,765	0,765	0,765	0,765
340	0,255	0,289	0,353	0,412	0,465	0,627	0,703	0,729	0,755	0,755	0,755	0,755
350	0,245	0,279	0,344	0,402	0,456	0,617	0,694	0,720	0,746	0,746	0,746	0,746

Surfacing seals for roads
Draft TRH3, Pretoria, South Africa 1986

TABLE 5.6 FRACTIONAL VOID LOSS DUE TO EMBEDMENT OR WEAR

FRACTIONAL EMBEDMENT OR WEAR	EMBEDMENT OR WEAR AS FRACTION OF ELT									
	0,000	0,001	0,002	0,003	0,004	0,005	0,006	0,007	0,008	0,009
0,00	0,000	0,003	0,005	0,008	0,010	0,013	0,015	0,017	0,020	0,022
0,01	0,025	0,027	0,030	0,032	0,035	0,037	0,039	0,042	0,044	0,046
0,02	0,049	0,051	0,053	0,056	0,058	0,060	0,063	0,065	0,067	0,070
0,03	0,072	0,074	0,076	0,079	0,081	0,083	0,085	0,087	0,090	0,092
0,04	0,094	0,096	0,098	0,100	0,103	0,105	0,107	0,109	0,111	0,113
0,05	0,115	0,117	0,119	0,122	0,124	0,126	0,128	0,130	0,132	0,134
0,06	0,136	0,138	0,140	0,142	0,144	0,146	0,148	0,150	0,152	0,154
0,07	0,156	0,157	0,159	0,161	0,163	0,165	0,167	0,169	0,171	0,173
0,08	0,174	0,176	0,178	0,180	0,182	0,184	0,185	0,187	0,189	0,191
0,09	0,193	0,194	0,196	0,198	0,200	0,201	0,203	0,205	0,207	0,208
0,10	0,210	0,212	0,213	0,215	0,217	0,218	0,220	0,222	0,223	0,225
0,11	0,227	0,228	0,230	0,232	0,233	0,235	0,236	0,238	0,239	0,241
0,12	0,243	0,244	0,245	0,247	0,249	0,250	0,252	0,253	0,255	0,256
0,13	0,258	0,259	0,261	0,262	0,264	0,265	0,267	0,268	0,270	0,271
0,14	0,272	0,274	0,275	0,277	0,278	0,279	0,281	0,282	0,284	0,285
0,15	0,286	0,288	0,289	0,290	0,292	0,293	0,294	0,296	0,297	0,298
0,16	0,300	0,301	0,302	0,303	0,305	0,306	0,307	0,308	0,310	0,311
0,17	0,312	0,313	0,315	0,316	0,317	0,318	0,320	0,321	0,322	0,323
0,18	0,324	0,325	0,327	0,328	0,329	0,330	0,331	0,332	0,333	0,335
0,19	0,336	0,337	0,338	0,339	0,340	0,341	0,342	0,343	0,344	0,346
0,20	0,347	0,348	0,349	0,350	0,351	0,352	0,353	0,354	0,355	0,356
0,21	0,357	0,358	0,359	0,360	0,361	0,362	0,363	0,364	0,365	0,366
0,22	0,367	0,368	0,369	0,370	0,370	0,371	0,372	0,373	0,374	0,375
0,23	0,376	0,377	0,378	0,379	0,380	0,380	0,381	0,382	0,383	0,384
0,24	0,385	0,386	0,386	0,387	0,388	0,389	0,390	0,391	0,391	0,392
0,25	0,393	0,394	0,395	0,395	0,396	0,397	0,398	0,399	0,399	0,400
0,26	0,401	0,402	0,402	0,403	0,404	0,405	0,405	0,406	0,407	0,408
0,27	0,408	0,409	0,410	0,410	0,411	0,412	0,413	0,413	0,414	0,415
0,28	0,415	0,416	0,417	0,417	0,418	0,419	0,419	0,420	0,421	0,421
0,29	0,422	0,423	0,423	0,424	0,424	0,425	0,426	0,426	0,427	0,428
0,30	0,428	0,429	0,429	0,430	0,431	0,431	0,432	0,432	0,433	0,433
0,31	0,434	0,435	0,435	0,436	0,436	0,437	0,437	0,438	0,438	0,439
0,32	0,439	0,440	0,441	0,441	0,442	0,442	0,443	0,443	0,444	0,444
0,33	0,445	0,445	0,446	0,446	0,447	0,447	0,448	0,448	0,449	0,449
0,34	0,449	0,450	0,450	0,451	0,451	0,452	0,452	0,453	0,453	0,454
0,35	0,454	0,454	0,455	0,455	0,456	0,456	0,457	0,457	0,457	0,458
0,36	0,458	0,459	0,459	0,460	0,460	0,460	0,461	0,461	0,462	0,462
0,37	0,462	0,463	0,463	0,463	0,464	0,464	0,465	0,465	0,465	0,466
0,38	0,466	0,466	0,467	0,467	0,468	0,468	0,468	0,469	0,469	0,469
0,39	0,470	0,470	0,470	0,471	0,471	0,471	0,472	0,472	0,472	0,473
0,40	0,473	0,473	0,474	0,474	0,474	0,475	0,475	0,475	0,476	0,476
0,41	0,476	0,476	0,477	0,477	0,477	0,478	0,478	0,478	0,479	0,479
0,42	0,479	0,479	0,480	0,480	0,480	0,481	0,481	0,481	0,481	0,482
0,43	0,482	0,482	0,483	0,483	0,483	0,483	0,484	0,484	0,484	0,485
0,44	0,485	0,485	0,485	0,486	0,486	0,486	0,486	0,487	0,487	0,487
0,45	0,487	0,488	0,488	0,488	0,488	0,489	0,489	0,489	0,489	0,490
0,46	0,490	0,490	0,490	0,491	0,491	0,491	0,491	0,492	0,492	0,492
0,47	0,492	0,493	0,493	0,493	0,493	0,494	0,494	0,494	0,494	0,495
0,48	0,495	0,495	0,495	0,495	0,496	0,496	0,496	0,496	0,497	0,497
0,49	0,497	0,497	0,498	0,498	0,498	0,498	0,499	0,499	0,499	0,499
0,50	0,499	0,500	0,500	0,500	0,500	0,501	0,501	0,501	0,501	0,502

Surfacing seals for roads
Draft TRH3, Pretoria, South Africa 1986

TABLE 5.7 ADDITIONAL COLD BINDER REQUIRED FOR SURFACE TEXTURE(L/SQ.M)

TEXTURE DEPTH(MM)	AVERAGE DAILY TRAFFIC(EQUIVALENT LIGHT VEHICLES/LANE/DAY) 125	250	500	750	1 000	2 000	3 000	4 000	5 000	10 000 OR MORE
0,10	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,08
0,11	0,09	0,09	0,09	0,09	0,09	0,09	0,09	0,09	0,09	0,09
0,12	0,10	0,10	0,10	0,10	0,10	0,10	0,10	0,10	0,10	0,10
0,13	0,10	0,10	0,10	0,10	0,10	0,10	0,10	0,10	0,10	0,10
0,14	0,11	0,11	0,11	0,11	0,11	0,11	0,11	0,11	0,11	0,11
0,15	0,12	0,12	0,12	0,12	0,12	0,12	0,12	0,12	0,12	0,11
0,16	0,13	0,13	0,13	0,13	0,13	0,13	0,13	0,13	0,13	0,11
0,17	0,14	0,14	0,14	0,14	0,14	0,14	0,14	0,14	0,14	0,11
0,18	0,14	0,14	0,14	0,14	0,14	0,14	0,14	0,14	0,14	0,11
0,19	0,15	0,15	0,15	0,15	0,15	0,15	0,15	0,15	0,15	0,11
0,20	0,16	0,16	0,16	0,16	0,16	0,16	0,16	0,16	0,16	0,11
0,21	0,17	0,17	0,17	0,17	0,17	0,17	0,17	0,17	0,16	0,11
0,22	0,17	0,17	0,17	0,17	0,17	0,17	0,17	0,17	0,17	0,11
0,23	0,18	0,18	0,18	0,18	0,18	0,18	0,18	0,18	0,17	0,11
0,24	0,19	0,19	0,19	0,19	0,19	0,19	0,19	0,18	0,17	0,11
0,25	0,20	0,20	0,20	0,20	0,20	0,20	0,20	0,18	0,17	0,11
0,26	0,21	0,21	0,21	0,21	0,21	0,21	0,21	0,19	0,17	0,11
0,27	0,21	0,21	0,21	0,21	0,21	0,21	0,21	0,19	0,17	0,11
0,28	0,22	0,22	0,22	0,22	0,22	0,22	0,21	0,19	0,17	0,11
0,29	0,23	0,23	0,23	0,23	0,23	0,23	0,21	0,19	0,17	0,11
0,30	0,24	0,24	0,24	0,24	0,24	0,24	0,21	0,19	0,17	0,11
0,31	0,25	0,25	0,25	0,25	0,25	0,24	0,21	0,19	0,17	0,12
0,32	0,25	0,25	0,25	0,25	0,25	0,24	0,21	0,19	0,17	0,12
0,33	0,26	0,26	0,26	0,26	0,26	0,24	0,21	0,19	0,17	0,12
0,34	0,27	0,27	0,27	0,27	0,27	0,24	0,21	0,19	0,17	0,12
0,35	0,28	0,28	0,28	0,28	0,28	0,24	0,21	0,19	0,17	0,12
0,36	0,29	0,29	0,29	0,29	0,29	0,24	0,21	0,19	0,17	0,12
0,37	0,29	0,29	0,29	0,29	0,29	0,25	0,21	0,19	0,17	0,12
0,38	0,30	0,30	0,30	0,30	0,30	0,25	0,21	0,19	0,17	0,12
0,39	0,31	0,31	0,31	0,31	0,30	0,25	0,21	0,19	0,17	0,12
0,40	0,32	0,32	0,32	0,32	0,30	0,25	0,21	0,19	0,17	0,12
0,41	0,32	0,32	0,32	0,32	0,30	0,25	0,22	0,19	0,17	0,12
0,42	0,33	0,33	0,33	0,32	0,30	0,25	0,22	0,19	0,18	0,12
0,43	0,34	0,34	0,34	0,33	0,30	0,25	0,22	0,19	0,18	0,12
0,44	0,35	0,35	0,35	0,33	0,30	0,25	0,22	0,19	0,18	0,12
0,45	0,36	0,36	0,36	0,33	0,30	0,25	0,22	0,19	0,18	0,12
0,46	0,36	0,36	0,36	0,33	0,30	0,25	0,22	0,20	0,18	0,12
0,47	0,37	0,37	0,36	0,33	0,30	0,25	0,22	0,20	0,18	0,12
0,48	0,38	0,38	0,36	0,33	0,31	0,25	0,22	0,20	0,18	0,12
0,49	0,39	0,39	0,36	0,33	0,31	0,25	0,22	0,20	0,18	0,12
0,50	0,40	0,40	0,36	0,33	0,31	0,25	0,22	0,20	0,18	0,12
0,51	0,40	0,40	0,36	0,33	0,31	0,25	0,22	0,20	0,18	0,13
0,52	0,41	0,41	0,36	0,33	0,31	0,25	0,22	0,20	0,18	0,13
0,53	0,42	0,42	0,36	0,33	0,31	0,25	0,22	0,20	0,18	0,13
0,54	0,43	0,42	0,36	0,33	0,31	0,25	0,22	0,20	0,18	0,13
0,55	0,44	0,42	0,36	0,33	0,31	0,25	0,22	0,20	0,18	0,13
0,56	0,44	0,42	0,36	0,33	0,31	0,25	0,22	0,20	0,18	0,13
0,57	0,45	0,42	0,36	0,33	0,31	0,26	0,22	0,20	0,18	0,13
0,58	0,46	0,42	0,36	0,33	0,31	0,26	0,22	0,20	0,18	0,13
0,59	0,47	0,42	0,37	0,33	0,31	0,26	0,22	0,20	0,18	0,13
0,60	0,47	0,42	0,37	0,33	0,31	0,26	0,22	0,20	0,18	0,13

Surfacing seals for roads
Draft TRH3, Pretoria, South Africa 1986

FRACTIONAL VOID LOSS DUE TO EMBEDMENT OR WEAR

FRACTIONAL EMBEDMENT OR WEAR	EMBEDMENT OR WEAR AS FRACTION OF ELT 0,000	0,001	0,002	0,003	0,004	0,005	0,006	0,007	0,008	0,009
0,50	0,499	0,500	0,500	0,500	0,500	0,501	0,501	0,501	0,501	0,502
0,51	0,502	0,502	0,502	0,503	0,503	0,503	0,503	0,504	0,504	0,504
0,52	0,504	0,504	0,505	0,505	0,505	0,505	0,506	0,506	0,506	0,506
0,53	0,507	0,507	0,507	0,507	0,508	0,508	0,508	0,508	0,509	0,509
0,54	0,509	0,509	0,510	0,510	0,510	0,510	0,511	0,511	0,511	0,511
0,55	0,512	0,512	0,512	0,512	0,513	0,513	0,513	0,513	0,514	0,514
0,56	0,514	0,514	0,515	0,515	0,515	0,516	0,516	0,516	0,516	0,517
0,57	0,517	0,517	0,518	0,518	0,518	0,518	0,519	0,519	0,519	0,520
0,58	0,520	0,520	0,520	0,521	0,521	0,521	0,522	0,522	0,522	0,523
0,59	0,523	0,523	0,523	0,524	0,524	0,524	0,525	0,525	0,525	0,526
0,60	0,526	0,526	0,527	0,527	0,527	0,528	0,528	0,528	0,529	0,529
0,61	0,529	0,530	0,530	0,530	0,531	0,531	0,531	0,532	0,532	0,533
0,62	0,533	0,533	0,534	0,534	0,534	0,535	0,535	0,536	0,536	0,536
0,63	0,537	0,537	0,537	0,538	0,538	0,539	0,539	0,539	0,540	0,540
0,64	0,541	0,541	0,542	0,542	0,542	0,543	0,543	0,544	0,544	0,545
0,65	0,545	0,545	0,546	0,546	0,547	0,547	0,548	0,548	0,549	0,549
0,66	0,550	0,550	0,550	0,551	0,551	0,552	0,552	0,553	0,553	0,554
0,67	0,554	0,555	0,555	0,556	0,556	0,557	0,557	0,558	0,558	0,559
0,68	0,560	0,560	0,561	0,561	0,562	0,562	0,563	0,563	0,564	0,564
0,69	0,565	0,566	0,566	0,567	0,567	0,568	0,568	0,569	0,570	0,570
0,70	0,571	0,571	0,572	0,573	0,573	0,574	0,575	0,575	0,576	0,576
0,71	0,577	0,578	0,578	0,579	0,580	0,580	0,581	0,582	0,582	0,583
0,72	0,584	0,584	0,585	0,586	0,586	0,587	0,588	0,589	0,589	0,590
0,73	0,591	0,591	0,592	0,593	0,594	0,594	0,595	0,596	0,597	0,597
0,74	0,598	0,599	0,600	0,600	0,601	0,602	0,603	0,604	0,604	0,605
0,75	0,606	0,607	0,608	0,608	0,609	0,610	0,611	0,612	0,613	0,613
0,76	0,614	0,615	0,616	0,617	0,618	0,619	0,619	0,620	0,621	0,622
0,77	0,623	0,624	0,625	0,626	0,627	0,628	0,629	0,629	0,630	0,631
0,78	0,632	0,633	0,634	0,635	0,636	0,637	0,638	0,639	0,640	0,641
0,79	0,642	0,643	0,644	0,645	0,646	0,647	0,648	0,649	0,650	0,651
0,80	0,652	0,653	0,655	0,656	0,657	0,658	0,659	0,660	0,661	0,662
0,81	0,663	0,664	0,666	0,667	0,668	0,669	0,670	0,671	0,672	0,674
0,82	0,675	0,676	0,677	0,678	0,679	0,681	0,682	0,683	0,684	0,686
0,83	0,687	0,688	0,689	0,691	0,692	0,693	0,694	0,696	0,697	0,698
0,84	0,699	0,701	0,702	0,703	0,705	0,706	0,707	0,709	0,710	0,711
0,85	0,713	0,714	0,715	0,717	0,718	0,720	0,721	0,722	0,724	0,725
0,86	0,727	0,728	0,729	0,731	0,732	0,734	0,735	0,737	0,738	0,740
0,87	0,741	0,743	0,744	0,746	0,747	0,749	0,750	0,752	0,753	0,755
0,88	0,756	0,758	0,760	0,761	0,763	0,764	0,766	0,767	0,769	0,771
0,89	0,772	0,774	0,776	0,777	0,779	0,781	0,782	0,784	0,786	0,787
0,90	0,789	0,791	0,792	0,794	0,796	0,798	0,799	0,801	0,803	0,805
0,91	0,806	0,808	0,810	0,812	0,814	0,815	0,817	0,819	0,821	0,823
0,92	0,825	0,826	0,828	0,830	0,832	0,834	0,836	0,838	0,840	0,842
0,93	0,843	0,845	0,847	0,849	0,851	0,853	0,855	0,857	0,859	0,861
0,94	0,863	0,865	0,867	0,869	0,871	0,873	0,875	0,877	0,880	0,882
0,95	0,884	0,886	0,888	0,890	0,892	0,894	0,896	0,899	0,901	0,903
0,96	0,905	0,907	0,909	0,912	0,914	0,916	0,918	0,920	0,923	0,925
0,97	0,927	0,929	0,932	0,934	0,936	0,939	0,941	0,943	0,946	0,948
0,98	0,950	0,953	0,955	0,957	0,960	0,962	0,964	0,967	0,969	0,972
0,99	0,974	0,977	0,979	0,982	0,984	0,986	0,989	0,991	0,994	0,996
1,00	0,999	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000

Surfacing seals for roads
Draft TRH3, Pretoria, South Africa 1986