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16. Abstract

Significant research findings have been made to assist in the placement of adequate open-graded asphalt friction courses (OGAFC) with full confidence on a routine basis.

Recommendations are made indicating where improvements can be made in raw materials specification requirements, mix design methods, and construction procedures which should promote better performance of OGAFC overlays. The method for measuring permeability of such pavement layers, developed in this study, should be applied in the field for monitoring construction and for measuring changes of OGAFC internal drainage capacity in service.

Use of OGAFC overlays should be restrictied to locations where the full benefits can be realized; guidelines given in this report can be used in the selection of such pavements.

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PERFORMANCE OF OPEN-GRADED FRICTION COURSES

by

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Research Report 234-1F

Research Study 2-9-78-234

Sponsored by

State Department of Highways and Public Transportation
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Texas Transportation Institute

Texas A&M University

College Station, Texas

PREFACE

The information presented in this report was developed in Research Study 2-9-78-234 titled "Performance of Open-Graded Friction Courses", a cooperative study with the Texas State Department of Highways and Public Transportation (SDHPT) and the Federal Highway Administration (FHWA).

The principal objective of this study was to find answers to various questions related to application, raw materials selection criteria, mix design approaches, layer thickness, construction practices, performance evaluation criteria, cost effectiveness, and repair procedures for open-graded asphalt friction courses (OGAFC), so that this technique for improving highway safety can be implemented with confidence on a routine basis.

Answers to most, but not all, of these questions were developed based on published reports, previous TTI studies and the field and laboratory investigations included in this study.

DISCLAIMER

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

ACKNOWLEDGEMENTS

The assistance and cooperation of a number of Texas SDHPT personnel in this study are gratefully acknowledged. In particular, thanks go to Mr. David Bass (District 2), Mr. Morgan Prince (District 11), and Mr. Warren Dudley (District 20), for providing information, road surface samples, assistance in making a pavement condition survey and photographs showing vehicle splash and spray in rainfall for the OGAFC evaluation pavements in this study. Also, thanks are due Mr. C. H. Hughes, Sr. of Division 9, who, in his capacity of SDHPT representative on this study, obtained related data from various division offices and made arrangements for division personnel to participate in a condition survey of these pavements. He also made all of the photographs shown in Appendix A of this report. Particular thanks go to Mr. J. L. Brown (Division-8), Mr. C. F. Jett (Division-6), Mr. I. E. Larrimore (Division-18), and Mr. J. P. Underwood (Division-10) who participated in the pavement condition survey summarized in Appendix A.

KEY WORDS

BITUMINOUS MIXTURES, ASPHALT, OPEN-GRADED, SURFACE COURSE, SKID RESISTANCE, AND PAVEMENT DRAINAGE.

SUMMARY

Although open-graded asphalt friction courses (OGAFC) have been applied successfully in Texas and other states for a number of years, as a means of improving wet weather highway safety, a number of problems remain to be solved before such overlays can be applied with full confidence on a routine basis. In this study solutions to such problems were sought by, 1) reviewing the experience with and making field evaluations of the performance of 22 different examples of OGAFC overlays in Texas, including 4 experimental sections conducted under TTI supervision, 2) conducting laboratory studies including examination of cores from the evaluation and experimental OGAFC sections and developing and applying methods for accurate determination of the internal drainage capacity of OGAFC layers, and 3) reviewing applicable published studies of OGAFC performance.

The findings of this study have indicated that materials selection criteria, mix design methods, and construction techniques used for the OGAFC surfaces evaluated in this study have resulted in acceptable pavement structural performance and durability. However, pavement rating scores and ride roughness measurements, used as indicators of such performance factors, were strongly influenced by the surface condition, structural section and roughness of the underlying pavement. In addition, the internal drainage capacity of the OGAFC mats considered in this study often was significantly lower than desired which indicates a need for increasing layer thickness and improving mix design and/or construction procedures.

Satisfactory OGAFC pavements can be produced in Texas using mixes made with AC-20 asphalt cement and grade 4 surface treatment aggregates. However, it may be desirable to use somewhat more restrictive specification requirements for these raw materials. In particular, better oxidation stability (as may be indicated by the thin film oven test or by other methods) is required for the AC-20 asphalt cement. Under high-speed heavy traffic conditions a minimum SN_{40} of 40 is suggested. Less demanding traffic may permit a lower value. The amount of aggregate passing a 3/8 inch sieve and retained on a No. 4 sieve should be no less than 60 percent, the proportion of flat and elongated aggregate particles allowed should be strictly limited, and consideration should be given to reducing the L. A. Abrasion loss limit on lightweight aggregates used in OGAFC mixes.

The current FHWA design procedure (reference 3) appears to be the best choice for estimating the proportion of asphalt cement in an OGAFC mix. Addition of up to 10 to 12 percent of fine aggregate (passing a No. 10 sieve) appears to be desirable but care should be taken to ensure that the VMA of the coarse aggregate will allow such additions without severely reducing the internal drainage capacity of the compacted OGAFC mat. Further study appears to be necessary to find a method for estimating the optimum content of fine aggregate in an OGAFC mix that takes into account such factors as fine aggregate particle shape and size distribution.

A method for accurately determining OGAFC layer permeability was developed in this study that will reliably predict the rainfall intensity which will cause incipient flooding of the pavement surface (see Appendices

B and C for details). This method can be applied for field measurements to monitor the internal drainage capacity of OGAFC overlays when they are constructed as well as to assess changes in this aspect of performance that may result from layer densification by traffic. Such permeability measurements appear to be more practical and meaningful as OGAFC drainage capacity indicators than air void determinations.

Separation or drainage of asphalt from OGAFC hot mixes during transport continues to be a problem. A possible solution is the addition of a suitable mineral filler (material passing a No. 200 sieve) to the OGAFC mix.

Guidelines for selecting pavements for OGAFC application and recommendations for further study are also given in this report.

IMPLEMENTATION STATEMENT

Information is included in this report that is intended to assist in the placement of adequate open-graded asphalt friction courses (OGAFC) with full confidence on a routine basis.

Recommendations are made indicating where improvements can be made in raw materials specification requirements, mix design methods, and construction procedures which should promote better performance of OGAFC overlays. The method for measuring permeability of such pavement layers, developed in this study, should be applied in the field for monitoring construction and for measuring changes of OGAFC internal drainage capacity in service.

Use of OGAFC overlays should be restricted to locations where the full benefits can be realized; guidelines given in this report can be used in the selection of such pavements.

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INTRODUCTION

Application of highway surface courses, constructed with bituminous mixes designed, mixed, spread and compacted so that rainfall tends to flow through the layer to the roadway shoulder rather than over the surface, has expanded significantly over the past ten years. Forty-nine states have constructed such surface courses [1], as well as many other countries of the world (including Australia, Denmark, Great Britain, Japan, the Netherlands and South Africa). In addition they are being evaluated as friction courses for airfields [2].

Among the names that have been used to designate such surface courses are, "plant-mix seal", "porous friction course", "porous asphalt", "drainage asphalt", "popcorn mix", and "open-graded friction course". In this report we will use the term "Open-Graded Asphalt Friction Course" (shortened to OGAFC for brievity) that has been proposed by the Federal Highway Administration [3] to describe such pavement layers constructed primarily for the improvement of surface friction.

The increasing acceptance and application of OGAFC has largely been the result of recognition of the following principal benefits associated with their use on highway pavements.

1. Improved skid resistance and reduction of dynamic hydroplaning in wet weather,
2. Reduction of splash and spray in wet weather,
3. Improved night visibility during rainfall (as a result of reduced headlight glare),

4. Production of a smooth riding surface having a uniform appearance and a lower highway noise level (demonstrated in field tests [4]) and
5. Improved visibility and durability of painted traffic markings.

Other benefits are also claimed sometimes but those listed are the most important. Interestingly, in Japan, porous pavement layers are utilized to also assist in replenishing ground water, lowering sub-surface soil temperature, and supplying water and oxygen to tree roots [5].

A comprehensive discussion of the development and current status and application of OGAFC is given in an NCHRP synthesis of highway practice [1] and need not be repeated in this report. In 1973, Gallaway [6] included OGAFC among twelve different ways of producing pavement surfaces having high wet skid resistance. There has been a growing realization that the use of open-graded surface courses offers one of the best ways of improving driving safety on wet pavements, but questions about design, construction techniques and performance have tended to inhibit widespread application of this technique. However, use of OGAFC has been promoted actively by the Federal Highway Administration which has published a design method [3], studied performance [7], and supported a demonstration project [8]. In addition, The Asphalt Institute [9] has disseminated information concerning design and construction of such surface courses.

At present, over twenty-five states are using OGAFC's on a regular basis and others are experimenting actively with this method of constructing safe pavement surfaces. Those states making extensive use of OGAFC's have generally expressed satisfaction with performance on properly designed and constructed projects. In particular, OGAFC's have been constructed extensively in Georgia, North Carolina, Louisiana, Colorado, Wyoming, Utah, Arizona and California.

Texas has experimented with OGAFC's for a number of years in several districts, as indicated by several SDHPT reports [10], [11], [12], [13] and their construction is now operational in a number of districts. The Texas Transportation Institute has made studies of the concept [14], [15] and has published guidelines for design, testing and construction [16]. However, as pointed out by Copas [1], there remains a need to understand more completely the role of OGAFC with respect to the total objective of providing the safest and most economical highway transportation possible. The study covered by this report is a continuation and extension of previous research conducted by the Texas Transportation Institute to help meet this need and to allow full and confident implementation of this technique for construction of safe roadway surfaces.

FACTORS INFLUENCING OGAFC PERFORMANCE

In many engineering projects, performance and cost trade-offs are involved. The necessity of making such trade-offs is encountered in the design and construction of open-graded asphalt friction courses; these are illustrated in a general way by the trends indicated in Figure 1. Note that as the mix design and compaction is varied to increase porosity, the permeability of the layer is increased which results in an improvement in wet weather driving safety. Concurrently, the resistance of the layer to deformation and disintegration tends to decrease and access of water and air into the mixture may promote asphalt stripping and hardening. The tendency of an OGAFC layer to densify under traffic must also be taken into account.

Thus, in designing and constructing an OGAFC, a principal goal is to achieve an optimum balance between internal drainage capacity on one hand and the structural integrity and durability of the layer on the other. A number of what might be called "input variables" will affect this balance. These input variables include characteristics of the existing pavement (type and design, cross slope, present surface condition), properties of materials used in the OGAFC mix design and OGAFC construction procedures. How these input variables will influence OGAFC drainage capacity is indicated by Table 1. How they will affect OGAFC structural behavior and durability is indicated by Table 2. In these tables the input variables are ranked in the order of their estimated influence on OGAFC behavior. This estimate was based on theoretical considerations, on discussions in Reference 1 and on observation of the performance of OGAFC evaluation sections considered in this study. While mix design has a strong influence

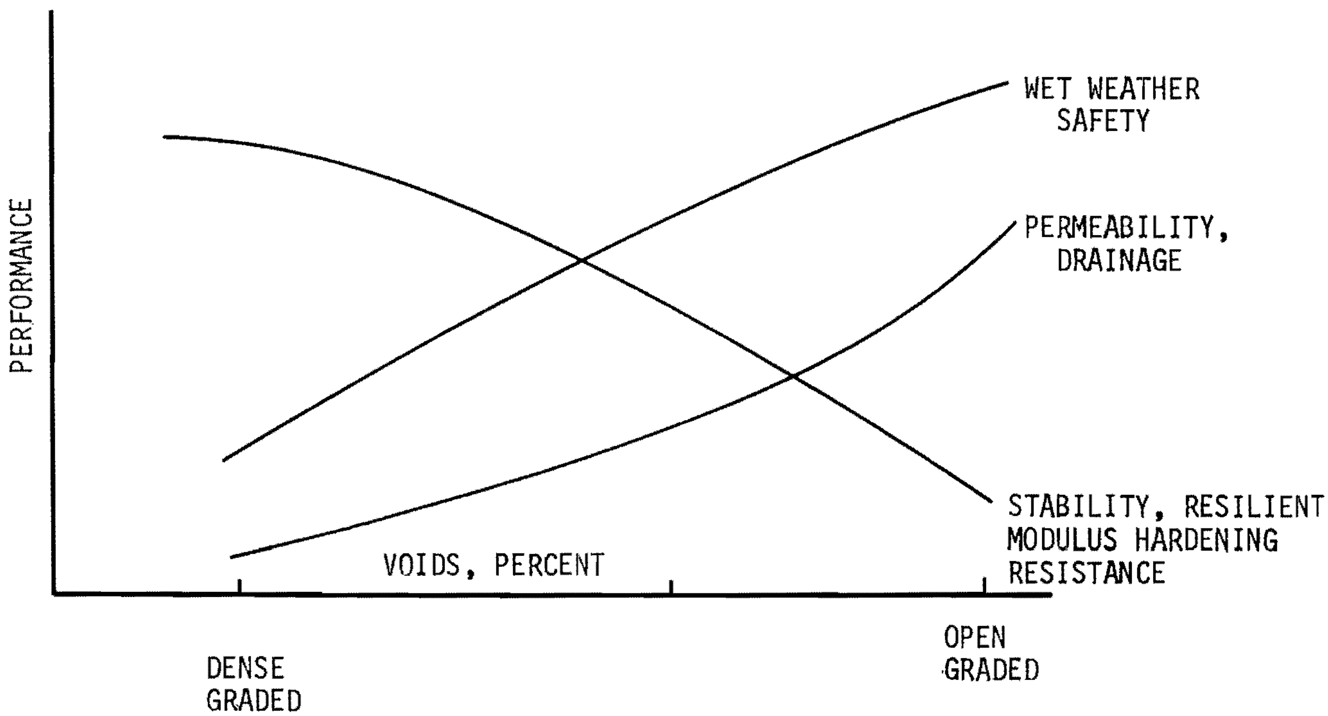

Figure 1. Performance of Compacted Bituminous Mixtures as Influenced by Their Porosity

Table 1. Input Variables Influencing Internal Drainage Capacity of Open-Graded Asphalt Friction Courses.

Importance Rank	Input Variable	Factors of Variable	Drainage Influenced by
1	Pavement Cross-Slope	Pavement Geometric Design	Hydraulic Gradient
2	Aggregate Geometric Characteristics	Top Size, Gradation, Particle Shape and Surface Texture	VMA (Voids in Mineral Aggregate); Compacted Layer Permeability
3	OGAFC Mix Design	Proportions of Asphalt and Aggregate	Void Content of Compacted Mix; Compacted Layer Permeability
4	Condition of Pavement Surface before Application of OGAFC	Flushing-Bleeding on Pavement Surface	Decrease in Void Content of Compacted Mix by Filling with Excess Asphalt
5	Construction Procedures	Mixing, Placing and Rolling Techniques	Void Content of Compacted Mix

Table 2. Input Variables Influencing Structural Behavior and Durability of Open-Graded Asphalt Friction Courses.

Importance Rank	Input Variable	Factors of Variable	Failure or Performance Mode Most Influenced
1	Type and Design of Underlying Pavement	Flexible Pavement - Characteristics and Thicknesses of Subgrade, Base, and Surface Courses PCC Pavement - Subgrade and Base Characteristics; PCC Slab Thickness and Characteristics	Rutting, Corrugations, Cracking Cracking (Especially Reflection Cracks at Joints)
2	Condition of Pavement Surface before Application of OGAFC	Roughness, Porosity, Cracking, Flushing, Stripping	Rutting, Raveling, Flushing, Corrugations, Stripping
3	Treatment of Pavement Surface before Application of OGAFC	Overlay Type and Thickness, Use of Reinforcing Fabric; Prime, Tack or Seal Asphalt Coating	Raveling, Flushing, Cracking
4	Construction Procedures	Mixing and Placing Temperatures; Mixing, Placing and Rolling Techniques	Pavement Roughness, Raveling, Rutting, Corrugations
5	OGAFC Mix Design	Proportions of Asphalt and Aggregate	Raveling, Flushing, Rutting, Corrugations
6	Asphalt Properties	Viscosity; Viscosity-Temperature Slope; Weather Resistance	Raveling, Flushing, Rutting, Corrugations

Table 2. (cont'd)

Importance Rank	Input Variable	Factors of Variable	Failure or Performance Mode Most Influenced
7	Aggregate Type	Petrology; Microtexture; Strength and Durability; Surface Chemistry	Polish and Wear (Skid Resistance), Raveling, Flushing
8	Aggregate Geometric Characteristics	Top Size; Gradation; Particle Shape and Surface Texture	Pavement Roughness, Raveling, Flushing

on OGAFC, note that some of the other input variables may have a greater effect on results. For example, even though an OGAFC layer has been designed and constructed so that it has a high permeability, drainage capacity will not be high unless the pavement has an adequate cross-slope.

The failures of OGAFC surfaces indicated in Table 2 will mostly be the result of service exposure (as measured by time, temperature cycles, ambient moisture, traffic volume, weight and speed, and total traffic). Also, the drainage capacity considered in Table 1 will change with service exposure as a result of densification of the OGAFC layer. Accordingly, the effect of the input variables listed in Tables 1 and 2 on the resistance to change may be as significant as their influence on performance of the surface as constructed. Or, stated another way, an optimum combination of these variables should result in maximizing the performance over the expected life of an OGAFC surface.

The following discussion considers the principal effects of OGAFC drainage capability on driving safety in wet weather and, in some depth, the effects of the more important input variables on OGAFC performance.

Adequate OGAFC drainage capacity is required to reduce the thickness of the water layer on the riding surface to a negligible value until a limiting or flooding rainfall intensity is reached. The two principal benefits of minimizing the thickness of the surface water layer are, a) reduction in splash and spray and b) reduction in the possibility of the vehicle encountering dynamic hydroplaning.

Previous TTI research, reported by Ivey, et al. [18], showed the direct effect of rainfall impingement on the motor vehicle windshield or visibility. This work indicated a loss in visibility of only about 25 to 30 percent at 55 mph in a rainfall of 1 in/h. However, such a rainfall intensity will produce water depths (even on many OGAFC pavements) that will result in the tires producing splash and spray at high vehicle speeds which can be expected to have a much more pronounced effect on visibility. Accordingly, the significant measure of this aspect of OGAFC performance is the rainfall intensity that can be handled before the surface begins to flood.

When a tire is completely separated from the road surface by a layer of water so that the only force opposing any vehicle motion is that resulting from hydrodynamic drag of the water layer, a state of "hydrodynamic hydroplaning" is encountered. The opposing force is relatively small and is not sufficient to permit safe control and stopping of the vehicle. When operating conditions are such that the water layer is quite thin, a state of "viscous hydroplaning" may exist, where the opposing force is the result of viscous drag, hysteresis losses in the tire, and partial direct contact between the pavement microasperities and the tire tread. This force, while lower than that resulting from dry surface friction, is significantly larger than that observed during dynamic hydroplaning, and can be sufficient to allow normal vehicle maneuvers safely. ASTM Method E 274, using a locked-wheel skid trailer with internal watering, probably produces a state of viscous hydroplaning and the friction or skid number (100 x tractive force/dynamic vertical load) resulting from application of this procedure is a reasonable measure of frictional forces attainable in this condition.

In general, water layer thicknesses resulting from rainfall on a well drained OGAFC should be quite small and dynamic hydroplaning will be avoided at any reasonable vehicle speed. Thus, on such wet pavements, tire pavement frictional forces indicated by ASTM 274 skid numbers can be achieved. On less well drained surfaces, rainfall can be expected to produce significant water depths and dynamic hydroplaning may be encountered. The changes in observed skid numbers resulting from such differences in pavement surface drainage are indicated by data presented by Gallaway, et al. [17]. An example of these data, illustrating this point, is shown in Figure 2. The resulting effect of these differences can be illustrated by using the reported skid numbers to estimate vehicle locked wheel distances, as follows:

Pavement	Tire	Pavement Condition	Vehicle Speed MPH	Estimated Level Road Braking Distance, ft.
Dense-Graded	ASTM E 501 11/32-in. Tread 24 PSI	Dry	55	126
OGAFC	"	Dry	55	126
Dense-Graded	"	Wet; 3/32-inch water depth	55	720
OGAFC	"	Wet, but not flooded	55	194

From the foregoing discussion, it is evident that the most significant measure of OGAFC drainage capacity is a limiting rainfall intensity. That is, the maximum rainfall intensity that can be handled by the OGAFC layer before flooding begins. This aspect of OGAFC performance can be assessed by measurements of layer permeability and porosity. For example, in a study of porous friction courses for airfield pavements, White [2], [19] employed a permeability apparatus to obtain relative ratings of internal drainage capacity. However, he made no attempt to estimate flooding rainfall intensity from the data collected. Smith [7] attempted to estimate a

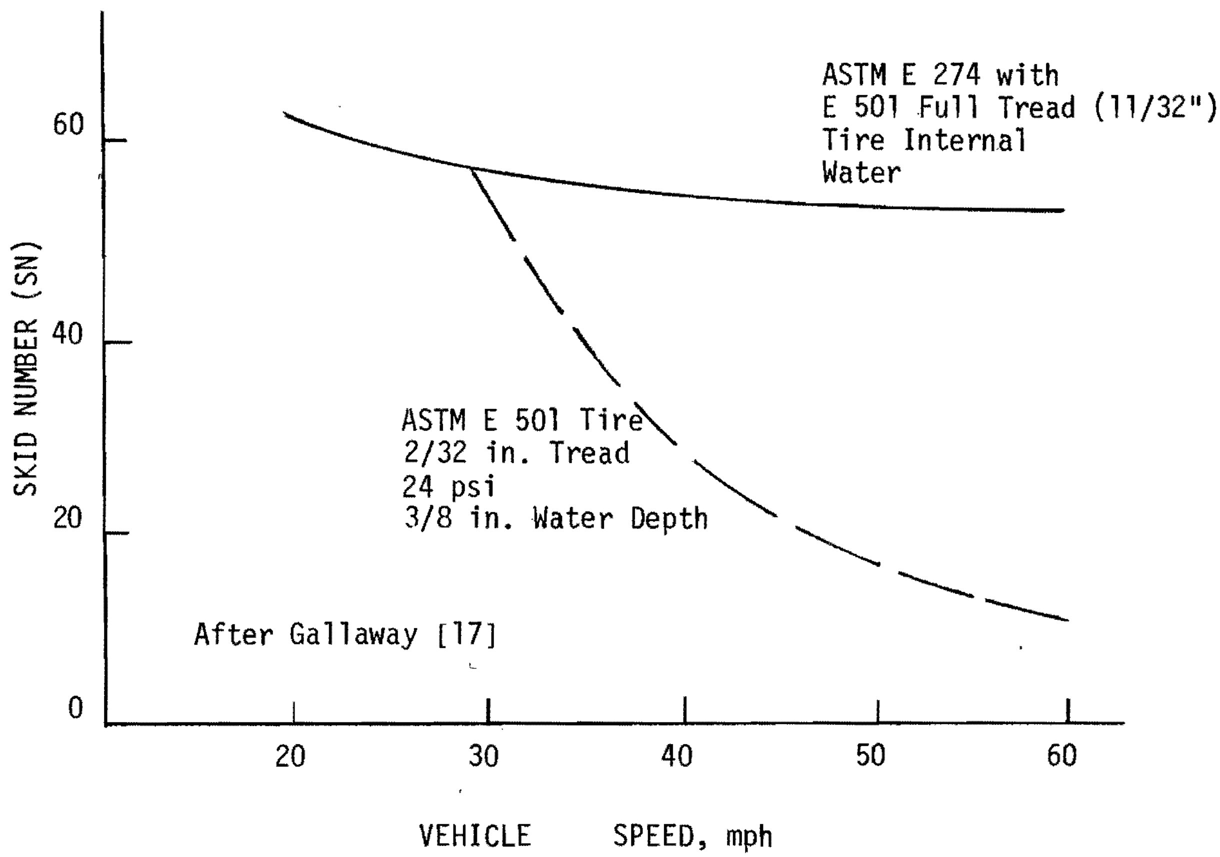

Figure 2. Water Film Thickness Influences Tire-Pavement Friction for an OGAFC

limiting rainfall intensity on the basis of the Chezy-Manning equation, the Rational runoff equation, average OGAFC aggregate particle size, and void content. However, the resulting predictions of limiting rainfall intensity appear to be too high by a factor between 5 and 10. Although Smith has taken a logical approach, it is believed that the indicated error in his predictions is the result of certain simplifying assumptions that were made. A similar approach has been taken in the present study, but such assumptions have been avoided. Instead, direct drainage measurements have been employed. In addition, since direct OGAFC permeability measurements are feasible in the field, a correlation between direct drainage measurements and permeability has been included in this study (see Appendices B and C which are discussed more completely in later sections of this report).

The influence of a number of input variables on OGAFC performance factors was indicated in a general way in Tables 1 and 2. However, a systematic approach to finding an optimum combination of these variables demands a more complete understanding of their effects. The aim of the following discussion is to provide a basis for such understanding of the influence of pavement cross-slope, aggregate characteristics, asphalt properties, mix designs, condition and treatment of the supporting surface and construction procedures on OGAFC performance.

Prediction of the effect of pavement cross-slope on OGAFC drainage capacity can be based on the Chezy-Manning equation (see Appendix C). For a given section this reduces to,

$$Q_F = K \quad S^{1/2}$$

where Q_F = water runoff rate just causing flooding

K = constant depending on porosity and other flow resistance factors of the OGAFC layer

S = pavement cross-slope

By applying the rational runoff equation, the flooding rainfall intensity can be related to cross-slope, as follows:

$$I_F = K^1 \quad \frac{S^{1/2}}{L}$$

where I_F = limiting (flooding) rainfall intensity

K^1 = constant depending on K and other flow path characteristics

L = lane width drained

Acceptable drainage performance can be achieved with OGAFC layers having cross-slopes in the range usually recommended for highways (1 to 2 percent) but it is clear that pavements with low (approaching zero) cross-slopes will accept very little rainfall without flooding even when they are constructed to have high permeabilities. In such cases, the cross-slope of the underlying pavement should be corrected <u>before</u> an OGAFC is applied.

Aggregate characteristics that will influence OGAFC drainage capacity, structural behavior and durability include: particle size and particle size distribution (gradation), particle shape, surface texture, polish resistance, and wear and abrasion resistance.

The coarse aggregate (material retained on a No. 8 or No. 10 sieve) usually makes up over 80 weight percent of an OGAFC mix. Pavement surface macrotexture and internal drainage capacity depend on the gradation of such open-graded coarse aggregates. Skid resistance will depend on the original particle surface microtexture and polish resistance of these aggregates.

While addition of fine aggregate (material passing a No. 8 or No. 10 sieve) may reduce the porosity of an OGAFC surface, some proportion of fine material may be required (depending on the angularity of the coarse aggregate) to provide a chocking action to stabilize the mix against distortion and displacement under traffic. Also, it has been found that addition of fine aggregate broadens the range of the laydown temperature.

While some states have specifications that limit the amount of material passing a No. 200 sieve to low values, there is evidence that 2 percent or more of natural fines or added mineral filler (including additions of hydrated lime, limestone, or portland cement) has several beneficial effects, including increasing the binder viscosity and thus reducing asphalt drain-down during transport, and decreasing the tendency of the pavement surface to ravel.

A more complete discussion of OGAFC aggregate selection, including consideration of gradation and other specification requirements, can be found in Chapter 3 of Reference 1.

The stiffness of an OGAFC mix depends largely upon the asphalt viscosity at the time and temperature of interest. At the time the pavement surface is constructed, the mix should be soft enough to be readily placed and compacted, but the asphalt must not be so fluid that it drains down excessively during transport. In service, the OGAFC layer should be stiff enough in the summer to resist distortion and densification by traffic, but should not become hard and brittle in winter so that cracking and raveling take place. The viscosity-temperature relation of the asphalt in the surface layer is the key to this problem. However, the binder exposed to the atmosphere tends to harden (increase in viscosity), depending on the degree of exposure and chemical resistance of the asphalt. Use of softer grades of asphalt cement (e.g., AC-10) may improve durability because it will take longer for the viscosity to become so high that the mix is too stiff. On the other hand use of harder grades provides thicker binder films that are more resistant to hardening, especially when a stable (as indicated by laboratory procedures such as the thin film oven test) asphalt is used. In most states AC-20 viscosity grade asphalt cements are selected for OGAFC mixes, with AC-40 as an alternate choice where summer temperatures are extreme and winter temperatures are mild. However, generally applicable guidelines for OGAFC asphalt selection will require more specific information.

OGAFC mixture design comprises determination of suitable proportions of asphalt cement and of fine aggregate (material passing a No. 8 or No. 10 sieve). Determination of amounts of mineral fillers, and anti-strip and adhesive agents may also become part of the mix design or some additives may be introduced as constituents of the asphalt cement.

Among the input variables listed in Tables 1 and 2, OGAFC mix design probably has received the most attention. Early attempts to use methods developed for design of dense-graded asphalt concrete mixtures were not very successful because stability and flow values determined were insensitive to variations in asphalt content. That this could be a problem is evidenced by ~~data from direct shear tests on O~~GAFC mixes reported by White [19]: appreciable variations in direct shear load values resulted from changes in asphalt penetration grade, but variations in asphalt content from 6 to 12 percent resulted in no significant differences in shear test results. As a result, most designs were then based solely on judgement and past experience. In fact Copas [1] reports that 12 states depend on experience and visual examination of trial mixtures to set OGAFC asphalt contents.

The FHWA procedure [3] is a better engineering approach to OGAFC mix design and now has been adopted in some form by twenty-two states. A comprehensive discussion of the engineering design of such mixes can be found in Chapter 3 of Copas' paper [1].

This design method is guided mostly by consideration of the following criteria:

1. Sufficient binder should be present to hold the aggregate particles tightly so that raveling is minimized.
2. The void content of the mix should be high enough to ensure adequate drainage capacity of the compacted OGAFC.
3. The mix should be stable under traffic loading.
4. Mix workability should be adequate for satisfactory placing and rolling.
5. Excessive asphalt drainage off of the aggregate should not occur during construction. Smith [3] emphasizes that this problem should be controlled by proper adjustment of mixing and placing temperatures rather than by variations in asphalt content. However, some control can be achieved by the addition of mineral fillers.
6. The mix should be resistant to the effects of water exposure.

Figure 3 illustrates how these criteria are influenced by materials properties and by mix design factors.

The asphalt requirement is controlled by the surface capacity of the aggregate which includes absorption, superficial area and surface roughness. In practice, it appears that asphalt absorption usually can be

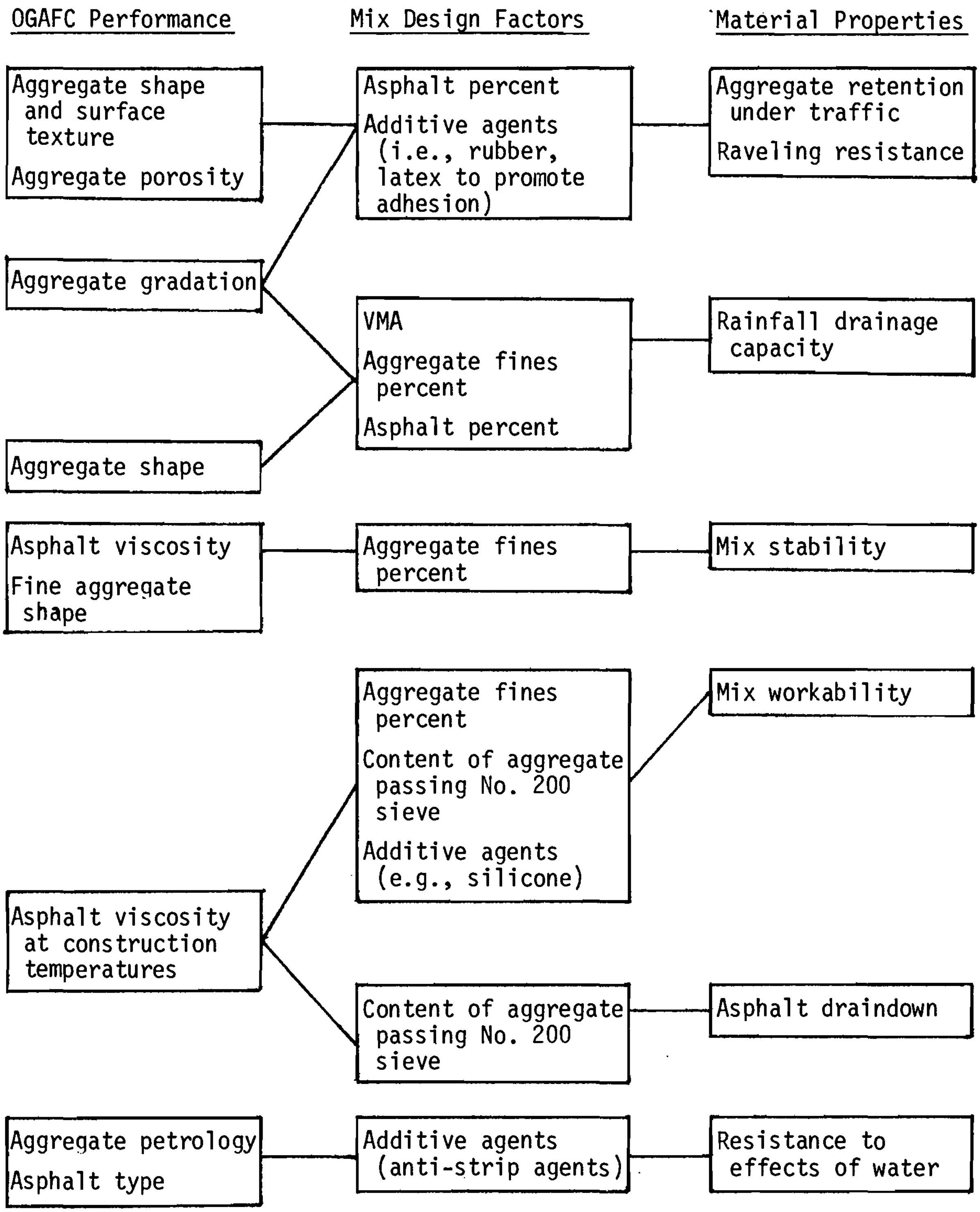

Figure 3. Influence of Material Properties and Mix Design on OGAFC Performance

neglected. For example, Gallaway and Epps [16] reported data on asphalt absorption by lightweight aggregates. Even though completely dry aggregates were tested, asphalt absorption was relatively small (less than 3 percent) and did not appear to be related to water absorption capacities which were as high as 27 percent. When such aggregates contain some moisture, as they usually do in the field, even less absorption of asphalt will take place.

The surface capacity of the OGAFC aggregate retained on a No. 4 (4.75 mm) sieve is measured, in the FHWA and related procedures, by employing a modified oil equivalent test developed in California [20]. This test and its use in OGAFC mix design are presented in detail in papers by Smith [3], Gallaway and Epps [16], and Copas [1]. The K_c value obtained as a result of this test is used to estimate asphalt content by the following equation:

$$A = [2.0\ K_c + 4.0]\frac{2.54}{G}$$

where

A = corrected asphalt weight percent (aggregates basis)

G = apparent specific gravity of aggregate retained on the No. 4 sieve

Slight variations of this equation are in use. Some states change the coefficient on the K_c term from 2.0 to 1.5, and some use constants of 3.5 or 4.5 instead of 4.0. Some states, notably Colorado, Kansas, Pennsylvania, and Wyoming, use the asphalt content obtained by this equation plus an adjustment factor based on laboratory observation of trial mixes.

The capacity of an OGAFC to drain off rainfall depends largely on the void content of the compacted layer. The FHWA design procedure begins with a vibratory unit weight determination on the coarse aggregate fraction, from which the available void volume (VMA) can be estimated. The void volume, V_d, remaining to provide water flow channels can then be calculated from:

$$V_d = VMA - V_b - V_{fa}$$

where,

V_b = volume percent of asphalt

V_{fa} = volume percent of fine aggregate

The FHWA procedure assumes a minimum permissible V_d of 15 percent for an OGAFC mix. However, there appears to be some question as to whether this minimum void content is adequate. For example, Kandhal, et al [21], recommend a minimum V_d of 25 percent to allow for densification by traffic and void clogging by debris. Probably more to the point, White [19] recommends validation of OGAFC drainage capacity by use of a permeability test.

Brief discussions of the condition and treatment of the pavement surface upon which an OGAFC is to be placed are given by Copas [1] and Gallaway and Epps [16]. From these and other sources it appears that:

1. An OGAFC should be placed only on structurally sound pavements and should not be relied upon to correct pavement distress,
2. Usually, an OGAFC should not be placed directly on portland cement concrete surfaces,
3. Bleeding or flushing of flexible support pavement surfaces should be corrected before an OGAFC is placed,
4. An OGAFC cannot be relied upon to seal the underlying surface. Additional asphalt added to a mix for the purpose of such sealing will tend to drain off during transport of the mix and will not be available for sealing and

5. A uniformly spread tack coat is necessary to assist bonding of an OGAFC to the substrate. An adequate quantity of tack should be applied. Tack should not be assumed to serve as a seal for the old surface.

Hot mix construction techniques for OGAFC layers are discussed at some length by Copas [1] and by Gallaway and Epps [16]. One point on which there is considerable disagreement is the proper mixing and placing temperatures for OGAFC mixes. The FHWA recommends the target mixing temperature be that at which the asphalt cement used has a viscosity of 7 to 9 cm^2/sec (700 to 900 centistokes). However, Kandhal, et al. [21] believe that the optimum range for asphalt viscosity at the mixing temperature is 14 to 17 cm^2/sec (1400 to 1700 centistokes). Use of an asphalt drainage test is sometimes used in the estimation of optimum mixing temperatures. Use of such a test is discussed by Smith [3], Gallaway and Epps [16], and White [19]. However, reliability of this test is uncertain because the procedure has not been standardized and interpretation of the results is quite subjective. Actual mixing temperatures used in the various states applying OGAFC surfaces vary from 200°F to 280°F (see Chapter 6 of reference 1). Of 34 ranges reported, 27 have midpoints falling between 220°F and 260°F. In Texas, the target value for OGAFC mixing temperature is on the low side: about 200°F. At this temperature the viscosity of the AC-20 asphalt cements used is about 50 cm^2/sec (5000 centistokes). Historically, Texas has not used fine aggregate in their mix design; hence, asphalt drain-down would be a problem at, say, 240°F. Construction temperatures in the 240°F range will be found quite acceptable when fines are used (about 3 percent minus No. 200 in a total of about 10 percent fines).

STUDY OBJECTIVES AND APPROACH

Although, as indicated in the foregoing discussion, open-graded friction courses have been applied and used with some success for a number of years and the relation among the input variables and pavement performance is generally understood, a number of problems remain to be solved before this method for improving highway safety can be implemented with confidence on a routine basis. The principal objective of this study was to seek solutions to the most pressing of these problems. In particular, this involves finding answers to the following questions:

1. Where and when are OGAFC surfaces applied most effectively?
2. Are current criteria for selection and acceptance of OGAFC mix raw materials adequate? What revisions and additions to specification requirements should be made?
3. What are the optimum proportions of asphalt, fine aggregate, and other constituents of OGAFC hot mixes? How much variation in these proportions is permissible in practice?
4. How does OGAFC layer thickness influence its performance and durability?
5. How can currently used OGAFC construction practices be improved and standardized to
    a) promote the confidence of those responsible for their construction?
    b) achieve an optimum balance among performance, durability and cost?
6. What are the most significant criteria for assessing OGAFC performance and durability? How can these best be measured in the field?

7. How does the cost effectiveness of an OGAFC compare with other methods of improving wet weather highway safety considering construction, maintenance, and user costs?
8. How can OGAFC surfaces be maintained and repaired most effectively?

The research approach taken in this study to find answers to these questions is outlined in Table 3. Evaluation of experience in several of the SDHPT Districts is emphasized in this program. A number of OGAFC highway pavements, listed and described in Table 4, were selected for this part of the study. Note that a variety of types, traffic volumes, aggregates, mix designs, and times in service have been included. Data from these evaluation pavements were augmented by information in experimental OGAFC pavements in District 17, described in Table 5.

In his review of OGAFC practices in the United States, Copas [1] has clearly pointed out some problems that require further research. These research needs are compared with the approach taken in the current study in Table 6. In addition some of the details concerning the approach taken in the current study are given in this table which augments the outline presented in Table 3.

Table 3. Outline of Study Approach

I. EXPERIENCE ON TEXAS HIGHWAYS

A. Design and construction methods

B. Performance: Drainage, Skid Resistance

C. Performance: Durability or Serviceability

D. Costs/Benefits; Construction, Maintenance Costs

vs.

Wet Weather Accident Reduction

II. EXPERIMENTAL OGAFC PAVEMENT (SH 21)

A. Data from DOT-FH-11-8269, Phase II

III. OTHER INPUT INFORMATION

A. FHWA studies and recommendations

B. Experience in other states

C. U. S. Engineer W.E.S. (Airfield Application)

IV. LAB STUDIES

A. Drainage performance measurement

B. Mix design methods

C. Effect of mineral filler content

Table 4. Texas OGAFC Evaluation Pavements

Site Location			OGAFC Mix				Traffic		Pavement		
			Aggregate			Asphalt	ADT				
Distr.	Hwy.	City	Name	dav in	%Pass No. 10	Percent	Veh/Lane	% Trucks	Structural No.	OGAFC Constr. Date	OGAFC Thickness in.
2	I 820	Ft.Worth	Rhyolite	0.3	0.1	6.7-7.7	14,750	9.0	4.8	8/73	0.8
2	I 30	Ft.Worth	Eastland LW	0.34	0.4	10-10.5	20,700	11.6	7.7	8/73	0.7
2	US 81	Decatur	Streetman LW	0.32	1.7	11.7	2,325	19.0	7.8(N), 4.8(S)	9/77	0.7, 0.6
2	SH101	Bridge-port	Eastland LW	0.33	1.7	10.3	2,440	26.3	7.0	5/76	0.68
2	SH114	Boyd	Eastland LW	0.33	1.7	9.9	2,300	30.5	6.3	6/76	0.5, 0.4
11	US 59	Diboll	Eastland LW	0.27	6.0	10.5-11.5	2,950	21.5	10.8	3/73	0.6
11	US 59	Diboll	Superock LW	0.30	5.5	12.5	2,950	21.5	10.8	3/73	0.9
11	US 59	Redlands	Cr.Slag	0.16	12.1	8.0	4,100	19.1	10.8	3/73	0.55
11	US 59	Redlands	Rock Asphalt	0.27	3.8	7.5	4,100	19.1	10.8	3/73	0.55
11	US 59	Redlands	Dallas LW	0.21	2.7	13.0	3,280	19.1	9.3	11/71	
11	US 59	Redlands	Knippa Trap Rock	0.22	1.4	6-6.8	4,100	19.1	9.3	11/71	0.5

Table 4. (cont'd)

Site Location			OGAFC Mix				Traffic		Pavement		
			Aggregate			Asphalt	ADT		Structural No.	OGAFC Constr. Date	OGAFC Thickness in.
Distr.	Hwy.	City	Name	d_{av} in	%Pass No. 10	Percent	Veh/Lane	% Trucks			
11	US 59	Redlands	Hable Sandstone	0.27	0.8	6-6.5	4,100	19.1	9.3	11/71	0.5, 0.7
11	US 59	Nacogdoches	Rhyolite	0.30	2.8	7.0	3,250	21.0	8.6	9/77	0.6
20	I 10	Beaumont	Clodine LW	0.28	2.8	10.5	5,280	25.0	9.6	9/75	0.6
20	I 10	Beaumont	Superock +Sand	0.26	11.2	13.0	12,800	11.5	7.3	9/76	1.0, 0.85
20	SH 87	Orange	Knippa Trap Rock	0.27	2.3	6.0	1,800	8.5	4.7	7/74	0.6
20	SH 87	Orange	Superock LW	0.26	1.5	12.5	2,200	7.6	4.3	5/75	0.9
20	US 96	Lumberton	Superock LW	0.26	1.3	12.9	3,250	10.7	5.6	9/75	0.75

Table 5. Experimental OGAFC Pavements in District 17

Site Location			OGAFC Mix			Traffic	Pavement	
Highway	City	Test Section Number	Aggregate Name	% Passing No. 10 Sieve	Asphalt Percent	Total Traffic 10^6 veh/lane	Date OGAFC Constr.	OGAFC Thickness in.
SH 21	Bryan	1	Superock & Crushed Fines	0	13.9	1.6	10/75	1.0
SH 21	Bryan	2	"	8	13.9	1.6	10/75	1.03
SH 21	Bryan	3	"	15	13.9	1.6	10/75	0.94
SH 21	Bryan	4	"	22	13.9	1.6	10/75	0.91

Table 6. Comparison of Research Needs Indicated in Chap. 7, NCHRP Synthesis 49 and TTI OGAFC Study (2234)

PROBLEM - RESEARCH NEED	STUDY 2234 APPROACH
Estimation of Critical Rainfall Intensity for Given OGAFC Layer	1. Primary measurement: Permeability K, using modified W.E.S. permeameter. 2. Correlate K with results of lab drainage test and estimate I_F. 3. Make secondary correlation; K vs. % voids.
Optimum aggregate top size and gradation	1. Using D_{av} and % "one-size" to characterize gradation: A) Study influence on performance in Texas OGAFC evaluation sections. B) Compare current specs. for OGAFC aggregates: FHWA, Texas, other states.
Optimum Percent fine (passing No.8 or No. 10 sieve) aggregate	1. Evaluation on SH 21 test pavement. 2. Experience on Texas OGAFC pavements. 3. Lab evaluation using fines with various roundness characteristics determine: A) Effect on voids & permeability, as compacted. B) Effect on compacted mix mechanical behavior: stability, compr. str., resil. modulus, etc.

Table 6. (cont'd)

PROBLEM - RESEARCH NEED	STUDY 2234 APPROACH
Role of mineral filler (passing No. 200 sieve), optimum percent	1. Measure viscosity of asphalt, -200 mixtures (2% to 10%) at 2 temperatures. Use various fillers (crusher fines, cement, carbon black, etc.) 2. On selected mixtures, compare asph. drain-down at several temperatures, using glass-dish drain-down tests.
Mixture closing vs. splash & spray	1. Refer to data on Gallaway FHWA Study, otherwise no specific studies planned.

RESULTS

OGAFC Materials, Design and Construction

Summary data covering details concerning materials, design, and construction of the Texas OGAFC evaluation pavements listed in Table 4 are presented in Tables 7, 8 and 9. Similar data for the experimental District 17 OGAFC pavements are presented in Table 10. The aggregate and asphalt data shown in these tables were obtained from daily construction reports covering the work. Temperature and weather data were also obtained from these reports. Location, pavement section, and construction dates were based on information appearing on road record sheets (TSDHPT Form RI-1) and log record of project construction and retirement sheets (TSDHPT Form RL-2, Rev.) covering each project.

As indicated in Tables 1 and 2, the gradation of the aggregate used in an OGAFC mix will have a significant effect on performance. A survey of state practices in this regard, reported by Copas [1], indicates that most state OGAFC aggregate specifications fall within the master range recommended by the FHWA; that is, 95 to 100 percent of the material should pass the 3/8 inch (9.5 mm) sieve, and 30 to 50 percent should pass the No. 4 (4.75 mm) sieve. A few states use larger stone for OGAFC mixes. Grade 4 surface treatment aggregates usually have been used in Texas for OGAFC mixes. This grade has nine particles larger than 3/8 inch (9.5 mm) recommended by the FHWA master range, but Grade 5 permits too much material passing the No. 4 (4.75 mm) sieve.

While a common practice in reporting aggregate particle size distribution is to use a grading chart (log sieve opening vs. cumulative

Table 7. Summary of Materials, Design, and Construction of OGAFC Evaluation Pavements in District 2

AGGREGATE	RHYOLITE				EASTLAND LW			
d, ave, in.	0.30				0.36	0.32	0.29	0.38
%, 1-size	70				51	62	75	47
%, - No. 10	0.1				0.3	1.0	0.2	0.1
Asphalt	Kerr-McGee				Kerr-McGee			
Grade	AC-20				AC-20			
Source	Wynnewood, Okla.				Wynnewood, Okla.			
Content %	7.7	7.2	6.7	6.7	10.5	10.0	10.5	10.0
CONSTRUCTION								
Mix Temp, °F	210 (Plant)	195	210	210	185	185	190	185
Air Temp, °F	74-97	74-96	72-91	72-84	76-96	76-96	78-96	77-96
Weather	Fair	Fair	Fair	Partly Cloudy	Fair	Fair	Fair	Fair
PAVEMENT SECTION AND CONSTR. DATES	OGAFC 0.81 in 8/73 HMAC 0.7 in 6/73 HMAC 0.5 in 7/71 HMAC 2.1 in 7/58 Base-Lean PCC 9 in 7/58				OGAFC 0.7 in 8/73 HMAC 0.7 in 6/73 HMAC 0.5 in 7/71 PCC 7 in 8/51 Base			
No. Lanes	4 (Divided)				4 (Divided)			
Lane Width, ft.	13				12			
ADT/Lane	14,750				20,700			
Lane	L	M	R	S	L	M	R	S
Milepost	8.1; 9.4; 11.4				430.8; 433.6			
Control No.	8-12				1068 - 1			
Highway	I - 820				I - 30			
County	220				220			

Table 7. (cont'd)

AGGREGATE	TXI - STREETMAN LW		EASTLAND LW	EASTLAND LW		
d, ave., in.	0.32		0.33	0.33		
%, 1-size	58		54	55		
%, - No. 10	1.7		1.7	1.7		
Asphalt	Vickers Petrol. Co.		Bell Oil & Gas	Bell Oil & Gas Co.		
Grade	AC-20		AC-20	AC-20		
Source	Ardmore, Okla.		Ardmore, Okla.	Ardmore, Okla.		
Content, %	11.7		10.3	9.9		
CONSTRUCTION Mix Temp. °F	180 - 215 (Plant)		185 - 195	185 - 195		
Air Temp. °F	79 - 98		64 - 79	59 - 95		
Weather	Clear-Ptly Cldy Some Rain		Clear-Ptly Cldy Some Rain	Clear-Ptly Cldy		
PAVEMENT SECTION AND CONSTR. DATES	OGAFC 0.7 in 9/77 HMAC 1.5 in 11/68 HMAC 2.2 in 8/55 PCC 9-6-9 in 3/36 Base	OGAFC 0.6 in 9/77 Seal Coat 6/74 HMAC 1.5 in 11/68 HMAC 2 in 8/58 FLEX BASE 9 in 8/58	OGAFC 0.6 in 5/76 HMAC 1.1 in 11/73 FLEX BASE 4.5 in 11/73 HMAC 1.2 in 8/69 HMAC 1.8 in 8/62 Dbl. Bit 0.7 in 8/61 FLEX BASE 10 in 8/61	OGAFC 0.4 in 6/76 Seal Coat 8/73 HMAC 1.1 in 7/69 Dbl. Bit 0.6 in 7/67 FLEX BASE 8 in 7/67 Seal Coat 4/52 Seal Coat 4/49 Dbl. Bit 0.5 in 7/43 FLEX BASE 8 in 7/43	OGAFC 0.5 in 6/76 Seal Coat 8/73 HMAC 1.6 in 5/67 Dbl. Bit 0.7 in 1/58 FLEX BASE 4 in 1/58 Seal Coat 4/52 Seal Coat 4/49 Dbl. Bit 0.5 in 6/42 FLEX BASE 8 in 7/43	OGAFC 0.5 in 6/76 Seal Coat 8/73 HMAC 1.2 in 6/67 Dbl. Bit 0.6 in 10/63 FLEX BASE 10 in 10/63 Seal Coat 4/52 Seal Coat 4/49 Dbl. Bit 0.5 in 6/42 FLEX BASE 6 in 6/42
No. Lanes	4, (Divided)		2, 2-Way	2, 2-Way	2, 2-Way	2, 2-Way
Lane Width, ft	10 10	12 12	13	13	13	13
ADT/Lane	2,325		2,440	2,100	2,100	2,500
Lane	L M	R S	R&L	R&L	R&L	R&L
MilePost	8.3; 11.5; 14.6		21.7; 14.3	22.2	27.2	38.6
Control No.	13-7		134-7	352-1	352-1	352-2
Highway	US 81		SH 101	SH 114	SH 114	SH 114
County	249		249	249	249	249

Table 8. Summary of Materials, Design, and Construction of OGAFC Evaluation Pavements in District 11

AGGREGATE	TXI-EASTLAND LW				SUPEROCK LW	CR. SLAG	ROCK ASPHALT	TXI-DALLAS LW
d, ave, in.	0.28	0.24	0.29	0.28	0.30	0.16	0.27	0.21
%, 1-size	65	63	73	65	60	45	76	59
%, - No. 10	4.0	6.3	6.3	6.5	5.5	12.1	3.8	2.7
Asphalt	TEXACO				TEXACO	TEXACO	TEXACO	TEXACO
Grade	AC-20				AC-20	AC-20	AC-20	AC-20
Source	Pt. Neches				Pt. Neches	Pt. Neches	Pt. Neches	Pt. Neches
Content, %	11.5	11.5	11.0	10.5	12.5 12.5	8.0	7.5	13.0
CONSTRUCTION								
Mix Temp °F	200	185	205	200	200	160	225	------
Air Temp °F	55-75	60-80	60-80	65-80	70-80	65-70	60-70	
Weather	Ptly Cldy Showers	Clear to Ptly Cldy	Clear to Ptly Cldy	Ptly Cldy	Ptly Cldy Rain	Clear	Clear	
PAVEMENT SECTION AND CONSTR. DATES	OGAFC 0.6 in 3/73 HMAC 1.5 in 5/67 PCC 10 in 10/62 Base				OGAFC 0.9 in 3/73 HMAC 1.5 in 5/67 PCC 10 in 10/62 Base	OGAFC 0.55 in 3/73 HMAC 1.5 in 5/67 PCC 10 in 11/63 Base	OGAFC 0.55 in 3/73 HMAC 1.5 in 5/67 PCC 10 in 11/63 Base	OGAFC ------ 11/71 HMAC 1.1 in 5/67 HMAC 1.6 in 11/63 PCC 8 in 10/49 Base
No. Lanes	2, of 4 Div.				2, of 4 Div.	2, of 4 Div.	2, of 4 Div.	2, of 4 Div.
Lane Width,ft	12				12	12	12	12
ADT/Lane	3540	2360	3540	2360	3540 2360	4920/3280	4920/3280	3280
Lane	R	S	R	S	R S	R&S	R&S	S
MilePost	20.5	22.0	22.0	20.5	22.4 22.4	3.45	3.57	4.27
Control No.	176-3				176-3	176-2	176-2	176-2
Highway	US 59				US 59	US 59	US 59	US 59
County	3				3	3	3	3

Table 8. (cont'd)

AGGREGATE	KNIPPA TRAPROCK				HABLE CRUSHED SANDSTONE				
d, ave, in.	0.22				0.27				
%, 1-size	65				69				
%, - No. 10	1.4				0.8				
Asphalt	TEXACO				TEXACO				
Grade	AC-20				AC-20				
Source	Pt. Neches				Pt. Neches				
Content, %	6.0	6.5	6.8	6.5	6.5	6.5	6.3	6.3	6.0
CONSTRUCTION Mix Temp, °F Air Temp, °F Weather	----	----	----	----	----	----	----	----	----
PAVEMENT SECTION AND CONSTR. DATES	OGAFC 0.5 in 11/71 HMAC 1.1 in 5/67 HMAC 1.6 in 11/63 PCC 8 in 10/49 Base				OGAFC 0.7 in 11/71	OGAFC 0.7 in 11/71	OGAFC 0.5 in 11/71 HMAC 1.1 in 5/67 HMAC 1.6 in 11/63 PCC 8 in 10/49 Base	OGAFC 0.5 in 11/71	OGAFC 0.5 in 11/71
No. Lanes	2, of 4 Div.				2, of 4 Div.				
Lane Width, ft	12				12				
ADT/Lane	4920	3280	4920	3280	4920	3280	4920	3280	4920
Lane	R	S	R	S	R	S	R	S	R
MilePost	3.85	3.85	4.21	4.21	4.86	4.86	5.09	5.09	5.22
Control No.	176-2				176-2				
Highway	US 59				US 59				
County	3				3				

Table 8. (cont'd)

AGGREGATE	RHYOLITE		
d, ave, in.	0.3		
%, 1-size	58		
%, - No. 10	2.8		
Asphalt			
Grade			
Source			
Content, %	7.0		
CONSTRUCTION			
Mix Temp °F	190-240°F		
Air Temp °F	70-95		
Weather	Clear to Ptly Cldy		
PAVEMENT SECTION AND CONSTR. DATES	OGAFC	0.6 in	9/77
	Seal Coat	------	8/71
	HMAC	1.2 in	6/65
	PCC	8 in	11/46
	Base		
No. Lanes	4 + Median		
Lane Width, ft	10		
ADT/Lane	3250		
Lane	ALL		
MilePost	23.6		
Control No.	176-1		
Highway	US 59		
County	174		

Table 9. Summary of Materials, Design, and Construction of OGAFC Evaluation Pavements in District 20

AGGREGATE	CLODINE LW	SUPEROCK LW + 10% SAND	KNIPPA TRAPROCK	SUPEROCK LW	SUPEROCK LW
d, ave, in.	0.28	0.26	0.27	0.26	0.26
%, 1-size	73	64	67	62	82
%, - No. 10	2.8	11.2	2.3	1.5	1.3
Asphalt	TEXACO	TEXACO	TEXACO	TEXACO	TEXACO
Grade	AC-20	AC-20	AC-20	AC-20	AC-20
Source	Pt. Neches	Pt. Neches	Pt. Neches	Pt. Neches	Pt. Neches
Content, %	10.5	13	6.0	12.5	12.9
CONSTRUCTION					
Mix Temp °F	185-205	200-220	180-210	180-185	200-250
Air Temp °F	73-96	70-94	68-98	64-85	60-95
Weather	Clear, No Rain	Clear to Ptly Cldy 3 Rainy Days	Partly Cloudy	Partly Cloudy	Clear to Ptly Cldy 3 Rainy Days
PAVEMENT SECTION AND CONSTR. DATES	OGAFC 0.63 in 9/75 HMAC 3.3 in 9/75 PCC 8 in 6/63 Base-Lime+Asph. 6/63	OGAFC 0.97 in 9/76 HMAC+Seal Coat 2.5 in 10/68 Seal Coat 9/59 HMAC 3 in 8/56 FLEX BASE 14 in 8/56	OGAFC 0.59 in 7/74 Seal Coat 12/69 HMAC 1.1 in 10/66 Seal Coat 9/58 HMAC 1.5 in 4/53 FLEX BASE 10 in 4/53	OGAFC 0.94 in 5/75 Seal Coat 10/70 HMAC 0.9 in 3/66 HMAC 0.3 in 9/58 HMAC 1.5 in 5/53 Sand Base (Cement Treat) 10 in 5/53 5/75	OGAFC 0.75 in 9/75 HMAC 0.8 in 9/75 HMAC 1.1 in 6/67 HMAC 1.1 in 8/58 HMAC 1.7 in 10/50 FLEX BASE 10 in 10/50
No. Lanes	4, of 2 Div.	4, of 2 Div.	2, 2-Way	2, 2-Way	2, 2-Way
Lane Width,ft	12	12	12	13	12
ADT/Lane	5280	12,800	1800	2200	3250
Lane	L	R	R	R	L
MilePost	847	861	1	3.5	23
Control No.	739-2	28-9	305-6 & 305-7	305-7	65-5
Highway	I-10	I-10	SH 87	SH 87	US 96
County	124	181	176 & 181	181	101

Table 10. Summary of Materials, Design, and Construction of Experimental OGAFC Pavements in District 17

AGGREGATE	SUPEROCK	SUPEROCK + 8% FINES	SUPEROCK + 15% FINES	SUPEROCK + 22% FINES
d, ave, in.	0.27	0.25	0.23	0.21
%, 1-size	55	50	45	41
%, No. 10	18.3	25.9	33.3	39.2
Asphalt				
Grade	AC-20	AC-20	AC-20	AC-20
Source				
Content, %	13.9	13.9	13.9	13.9
CONSTRUCTION Mix Temp, °F Air Temp, °F Weather	-------	-------	-------	-------
PAVEMENT SECTION AND CONSTR. DATES	← OGAFC 1.0 in. 10/75 HMAC 1.5 in. 7/67 HMAC 0.5 in. 10/62 HMAC 2.2 in. 7/57 FLEX BASE 12 in. 7/57 →			
No. Lanes		2, of 4 Div.		
Lane Width, ft.		12		
ADT/Lane	2100/1400			
Lane	R&S	R&S	R&S	R&S
MilePost	5.5	5.6	5.7	5.8
Control No.	116-4	116-4	116-4	116-4
Highway	SH 21	SH 21	SH 21	SH 21
County	21	21	21	21
Test Section	1	2	3	4

percent passing), a more concise approach was desired for this report. Accordingly, three parameters were chosen: an average particle size (d_{av}), percent of "one-size" material in the aggregate, and percent of fine aggregate. The average particle size, d_{av}, reported was the interpolated 50 percent passing point on a grading chart. The d_{av} values reported were estimated using numerical (semi-logarithmic) rather than graphical interpolation of the sieve analysis data. The percent "one-size" was considered to be the difference between the percent of material passing a 3/8 inch sieve and that passing a No. 4 (4.75 mm) sieve. While the aggregate particles in this range are not strictly of uniform size, the "one-size" data reported was considered to be a sufficient indication of how open-graded the aggregate was and thus should be related to such performance factors as layer permeability, resistance to raveling, and resistance to asphalt hardening. These data were supplemented by an estimation of the proportions of particles smaller than, and larger than the range used to estimate percent "one-size". For this report, the fine aggregate content was considered to be the percent of material passing the No. 10 (2.00 mm) sieve. This parameter was expected to be related to indication of OGAFC layer stability on one hand and layer permeability on the other.

These gradation parameters for the aggregates used in Texas OGAFC evaluation pavements are presented graphically in Figures 4, 5, 6 and 7. Gradation parameters for aggregates used for the experimental OGAFC pavements are presented in Figure 8. In each of these figures the aggregate is identified by name, highway route number, nearest town, and highway control number.

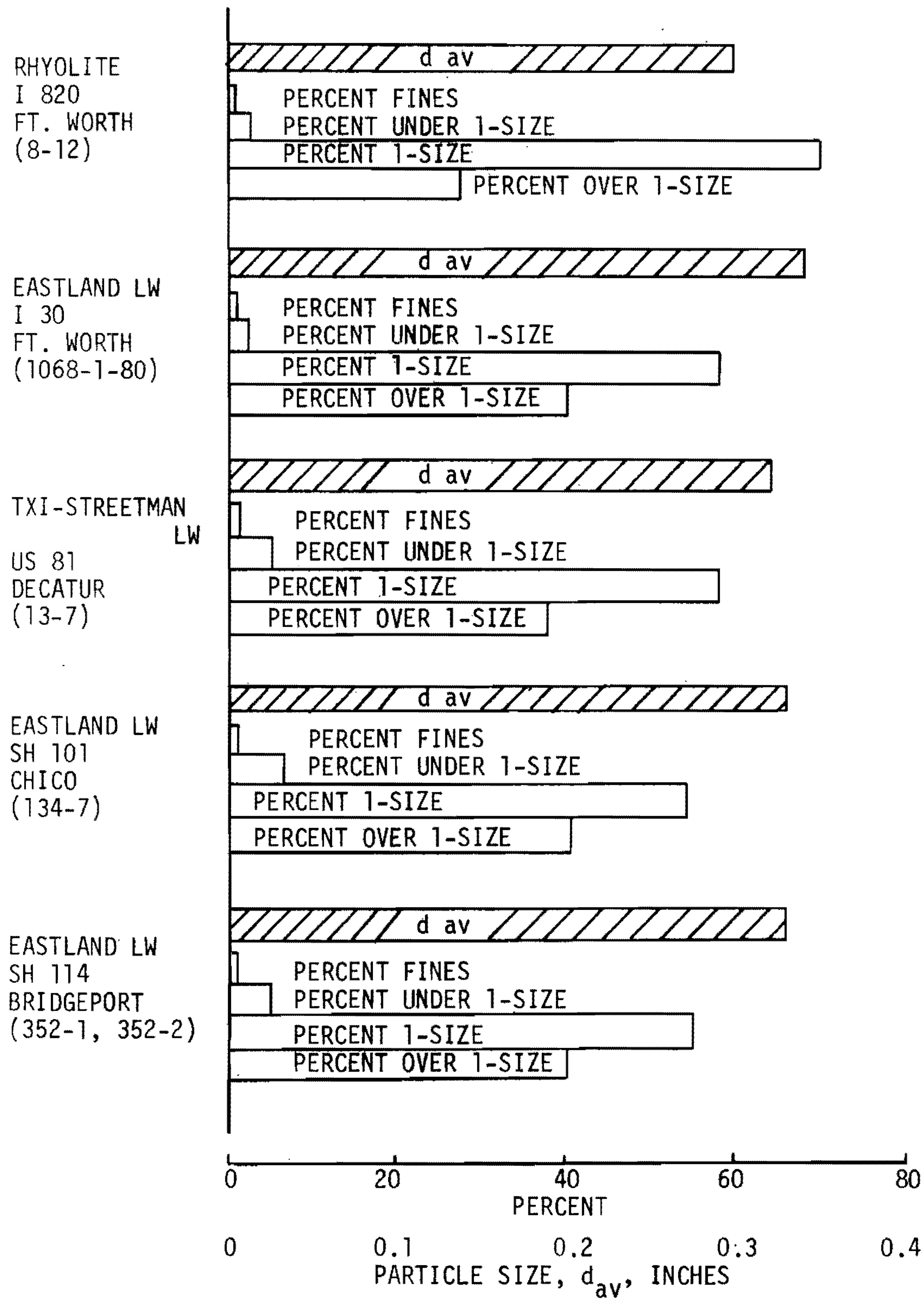

Figure 4. Gradation of Aggregates Used in Texas OGAFC Evaluation Pavements - District 2.

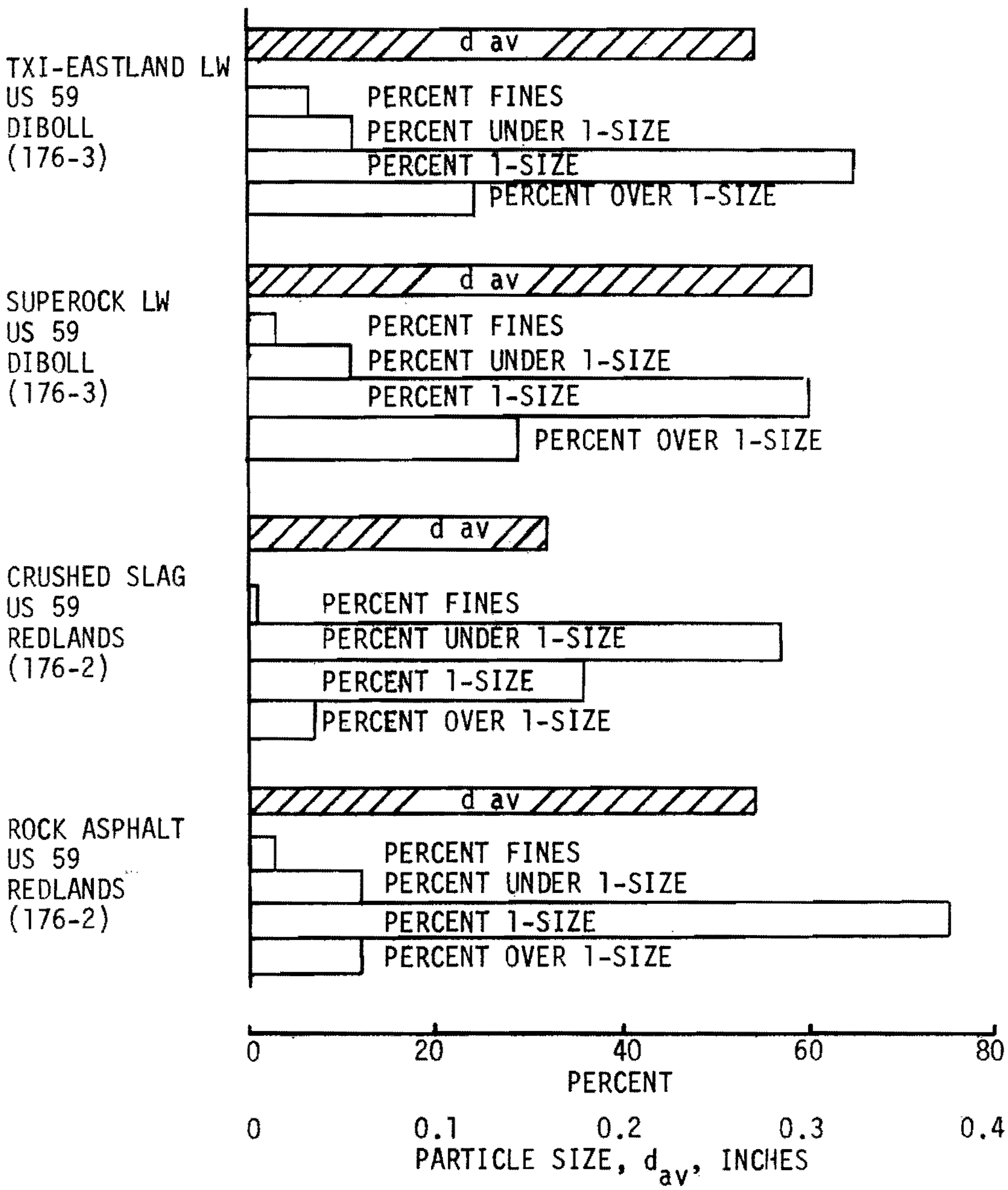

Figure 5. Gradation of Aggregates Used in Texas OGAFC Evaluation Pavements - District 11

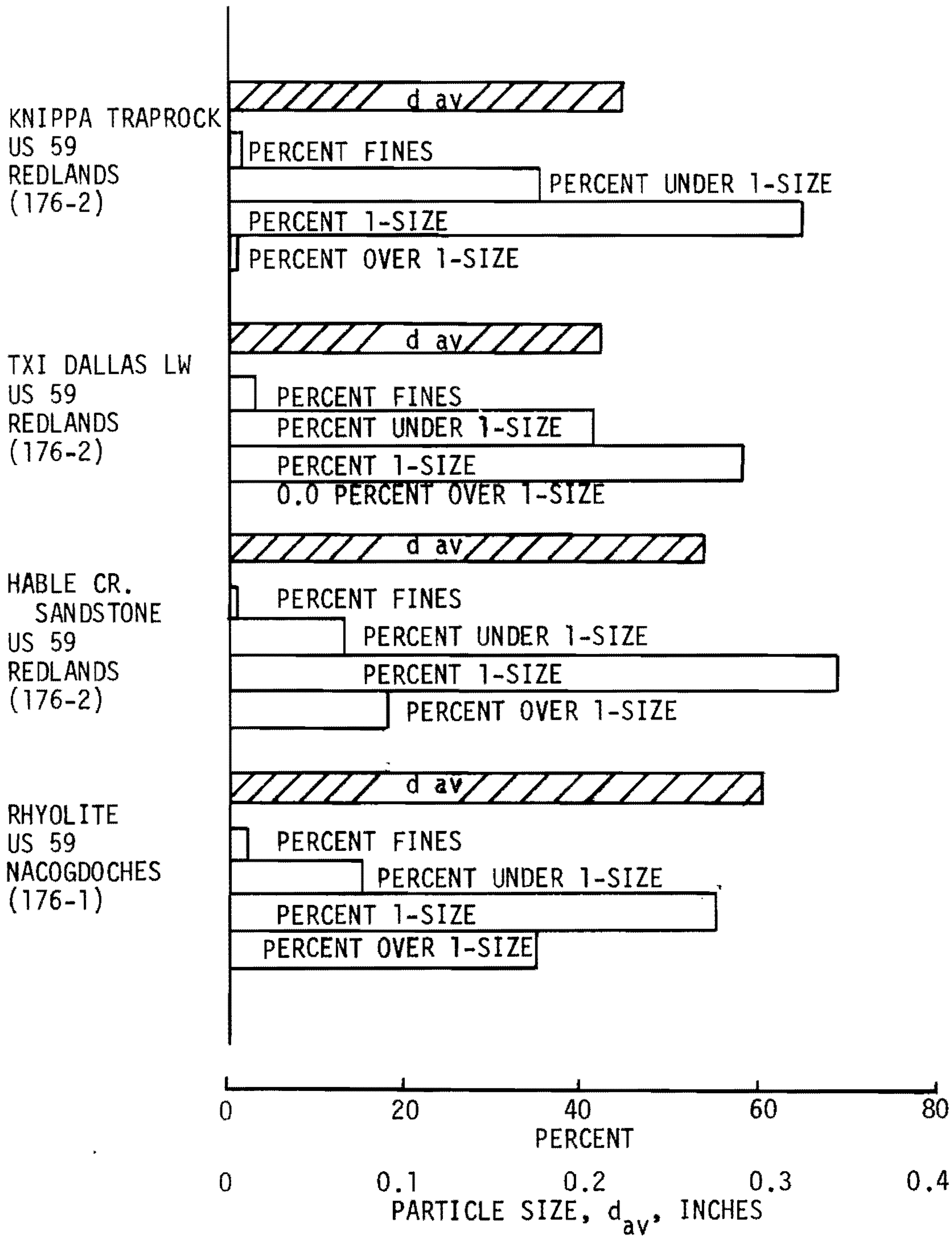

Figure 6. Gradation of Aggregates Used in Texas OGAFC Evaluation Pavements - District 11

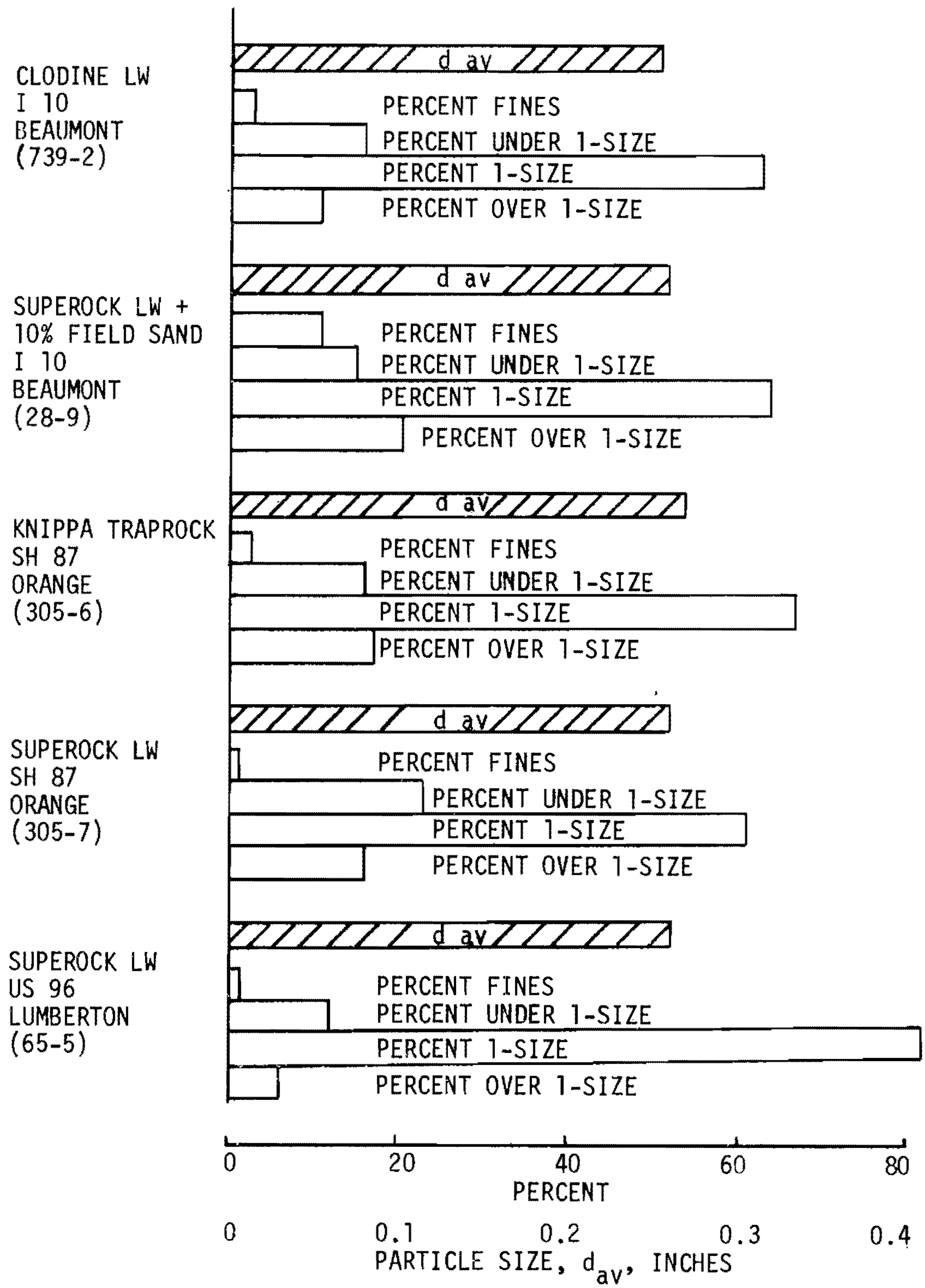

Figure 7. Gradation of Aggregates Used in Texas OGAFC Evaluation Pavements - District 20

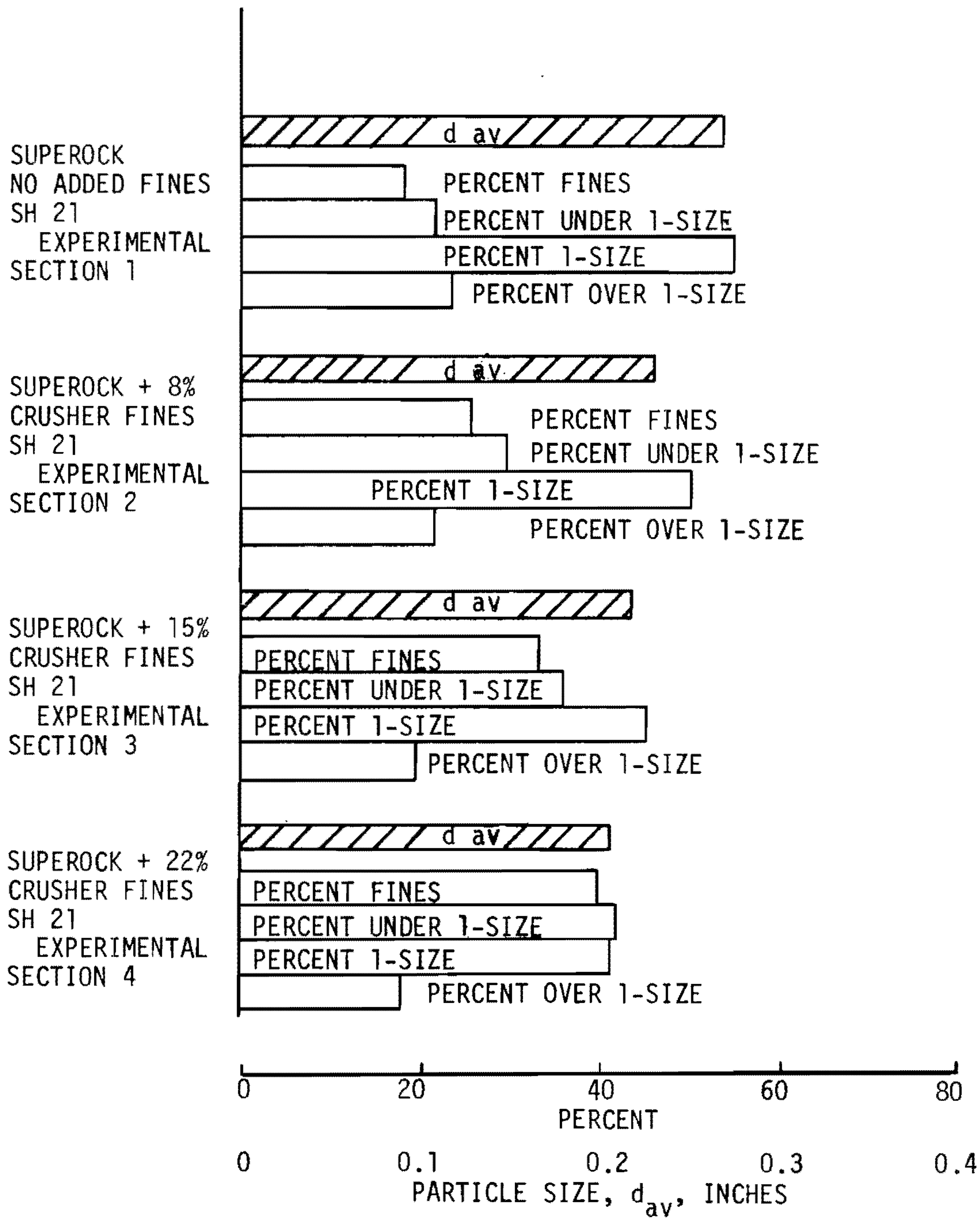

Figure 8. Gradation of Aggregates Used in Experimental OGAFC Sections - District 17

All of the aggregates used in the OGAFC evaluation pavements, except the crushed slag, were Grade 4. Average particle size, d_{av}, of these Grade 4 aggregates varied within a narrow range: from 0.25 inches (6 mm) to 0.33 inches (8 mm). The content of "one-size" material (as defined in this report) ranged from 55 to 81 percent, and was 60 percent or more for 13 out of 17 of these aggregates. For comparison, aggregates meeting Texas Grade 4 gradation requirements can have percentages of "one-size" particles from 50 to 80. Also, aggregates within the master gradation range recommended by FHWA for OGAFC aggregates can have percentages of "one-size" particles from 45 to 75. The content of fine material (passing the No. 10 sieve) in all but two of the aggregates used in the OGAFC evaluation pavements was 3 percent or less. In one case, where 10 percent of field sand was added to a lightweight aggregate, the amount of fines was 6 percent. The content of fine material was a major variable in the experimental OGAFC pavements constructed on SH 21 in District 17. In the mixes used for these pavements, crusher fines were added in amounts equivalent to 5, 10 and 15 percent of the aggregate. The percentage of material passing the No. 200 (7.5 μm) sieve was not always reported for aggregates used in the OGAFC evaluation pavements. Where this value was reported, it was usually less than 2 percent.

Lightweight aggregates (including crushed slag) used in twelve of the OGAFC evaluation pavements came from 5 different sources. Four kinds of natural aggregates were used in six of the evaluation pavements. Available laboratory test data (other than gradation), on these aggregates are summarized in Tables 11, 12 and 13.

Laboratory test data on the asphalt cements used to make OGAFC mixes for the Texas Evaluation pavements are summarized in Table 14. All of

Table 11. Laboratory Test Data on Aggregates Used in Texas OGAFC Evaluation Pavements in District 2

TEST \ AGGREGATE HIGHWAY LOCATION CONTROL	RHYOLITE I-820 Ft.Worth 8-12	EASTLAND LW I-30 Ft. Worth 1068-1-80	STREETMAN LW US 81 Decatur 13-7	EASTLAND LW SH 101 Chico 134-7	EASTLAND LW SH 114 Bridgeport 352-1; 352-2
L. A. Abrasion percent wt. loss	---------	21		---------------	-----------
Dry, loose unit wt. lbs./cu.ft.	85.6	54.7		54.8	54.8
Sp. Gr., bulk	2.555	------------		1.612	1.612
Absorption, %	1.3	------------		1.0	1.0
Polish Value (Texture)	------	40		---------------	-----------

Table 12. Laboratory Test Data on Aggregates Used in Texas OGAFC Evaluation Pavements in District 11

TEST \ AGGREGATE / HIGHWAY / LOCATION / CONTROL	EASTLAND LW US 59 Diboll 176-3	CR. SLAG US 59 Redlands 176-2	ROCK ASPH. US 59 Redlands 176-2	TRAPROCK US 59 Redlands 176-2	DALLAS LW US 59 Redlands 176-2	CR. SANDSTONE US 59 Redlands 176-2	RHYOLITE US 59 Nacogdoches 176-1
L. A. Abrasion percent wt. loss	17.3	---	33.3	10.0	20.6	29.2	2.3
Dry, loose unit st. lbs/cu. ft.	41.1	78.1	78.2	98.4	40.1	89.1	92.0
Sp. gr., bulk	1.178	2.709	2.203	3.054	1.175	2.632	2,560
Absorption, %	4.6	1.2	3.7	0.8	20.6	0.6	1.4
Polish Value (Texture)	---	---	---	34	43	---	37

Table 13. Laboratory Test Data on Aggregates Used in Texas OGAFC Evaluation Pavements in District 20

TEST \ AGGREGATE / HIGHWAY / LOCATION / CONTROL	CLODINE LW I 10 Beaumont 739-2	SUPEROCK LW I 10 Beaumont 28-9	TRAPROCK SH 87 Orange 305-6	SUPEROCK LW US 96 Lumberton 65-5
L. A. Abrasion, percent wt. loss	23	----	11	20
Dry, loose unit wt., lbs./cu. ft.	43.0	41.8	----	39.8
Sp. gr., bulk	----	1.196	----	-----
Absorption, %	----	----	----	-----
Polish Value (Texture)	48	----	34	45

Table 14. Laboratory Test Data on Asphalt Cements Used in Texas OGAFC Evaluation Pavements

Dist.	Highway	Control No.	Supplier	Vis. 140°F Stokes	Vis. 275°F Stokes	Penetration 77°F	Sp. Gr. 60°F	TFOT RESIDUE Vis. 140°F Stokes	TFOT RESIDUE Ductility 77°F cm.	Remarks
2	I 820	8-12	Kerr-McGee	2018	4.7	71	1.060	4630	141+	0.3% Anti-strip agent
2	I 30	1068-1	Kerr-McGee	2018	4.7	71	1.060	4630	141+	"
2	US 81	13-7	Vickers	1915	4.4	75	1.060	5270	141	
2	SH 101	134-7	Bell Oil & Gas	1920	4.8	76	1.060	4130	141+	
2	SH 114	352-1	Bell Oil & Gas	1920	4.8	76	1.060	4130	141+	
11	US 59	176-3	TEXACO	1880	3.8	74	1.010	4360	141+	
11	US 59	176-2	TEXACO	2400	4.3	75	1.012	----	----	1971 Constr.
11	US 59	176-2	TEXACO	2400	4.3	75	1.010	----	----	1971 Constr.
20	I 10	739-2	TEXACO	1884	4.1	73	1.02	3940	141+	
20	I 10	28-9	TEXACO	1810	4.4	77	1.026	4070	141	
20	SH 87	305-7	TEXACO	1920	4.2	80	1.02	4220	141+	
20	US 96	65-5	TEXACO	1900	4.0	75	1.02	4140	141+	

these binders were AC-20 grade. The Schweyer [22] viscosity-temperature susceptibility parameters, M, for these materials varied over a narrow range (from -3.40 to -3.57) and were typical of most American midcontinent asphalt cements. Durability, as indicated by the thin film oven test, appears to be adequate in all cases; and does not appear to differ significantly among these asphalt cements.

Condition of OGAFC Evaluation Pavements

In this study, performance and serviceability of the Texas OGAFC evaluation pavements were based on observations indicating the condition and internal drainage capacity of the surface layers.

Field measurements of surface layer condition included: 1, visual pavement rating scores; 2, serviceability index values based on Mays meter ride roughness values; and 3, assessment of skid resistance based on SN_{40} results and pavement macrotexture measurements. These data for the OGAFC evaluation pavements are summarized in Tables 15, 16 and 17. Pavement rating scores given in these tables are discussed in detail in Appendix A, which also includes a photographic record taken when the visual ratings were made. These tables also show the aggregates used in the OGAFC mixes, ADT values, total traffic (since OGAFC construction date to date of rating), and the number of seasonal cycles (summer-winter-summer) that the surface was exposed to prior to the condition rating date. The serviceability index (S.I.) data presented were based on readings taken with the TTI Mays meter (see Epps, et al [23]). The skid numbers at 40 mph (SN_{40}) shown, obtained by ASTM method E274, were obtained from Skid Resistance Report 4 computer data sheets for the highway district in which the measurements were made. Pavement

Table 15. Summary of Surface Condition of OGAFC Evaluation Pavements in District 2

Pavement* Location	Aggregate	ADT Per Lane (1978)	Total Traffic 10^6 veh/lane	No. Seasons	Pavement Rating Score**				S.I. (Mays)	Skid Resistance		
					Date	No. Locations	Ave	Range	Test On: (3/31/78)	Date	SN_{40}	Texture Depth Inches
820/812/R&S/73	Rhyolite	14,750	18.3	5	3/30/78	6	62	56-68	3.7	8/76	42	-
820/812/L&M/73	Rhyolite	14,750	18.3	5	3/30/78	6	74	69-77	3.5	8/76	44	-
30/10681/R&S/73	Eastland LW	20,700	34.0	5	3/30/78	4	78	76-80	-			0.068
30/10681/L&M/73	Eastland LW	20,700	34.0	5	3/30/78	4	84	76-97	-			0.064
81/137/R/77	Streetman LW	2,790	0.4	1	3/31/78	3	100	-	4.1			0.086
81/137/S/77	Streetman LW	1,860	0.3	1	3/31/78	3	100	-	-			0.090
81/137/L/77	Streetman LW	2,790	0.4	1	3/31/78	3	100	-	3.9			0.091
81/137/M/77	Streetman LW	1,860	0.3	1	3/31/78	3	100	-	4.2			0.090
101/1347/R/76	Eastland LW	2,440	1.5	2	3/31/78	2	92	85-100	4.0	8/76	46	0.078
101/1347/L/76	Eastland LW	2,440	1.5	2	3/31/78	2	97	95-100	4.1	8/76	47	0.073
114/3521/R/76	Eastland LW	2,100	1.3	2	3/31/78	2	100	-	4.2	8/76	45	0.054
114/3521/L/76	Eastland LW	2,100	1.3	2	3/31/78	2	100	-	4.3			0.079
114/3522/R/76	Eastland LW	2,500	1.5	2	3/31/78	1	100	-	4.2	8/76	47	0.078
114/3522/L/76	Eastland LW	2,500	1.5	2	3/31/78	1	100	-	4.1			0.089

*Location Code: Highway No./Control No./Lane Designation/Year OGAFC Applied

**Also see photographic record in Figures A-1 through A-8 in Appendix A

Table 16. Summary of Surface Condition of OGAFC Evaluation Pavements in District 11

Pavement* Location	Aggregate	ADT Per Lane (1978)	Total Traffic 10^6 veh/Lane	No. Seasons	Pavement Rating Score**				S.I. (Mays) Test On: (3/17/78)	Skid Resistance		
					Date	No. Locations	Ave	Range		Date	SN_{40}	Texture Depth Inches
59/1763/R/73	Eastland LW	3,540	4.7	5	3/16/78	2	88	85-90	3.9	5/77	50	0.070
59/1763/S/73	Eastland LW	2,360	3.1	5	3/16/78	2	100	-	4.2	5/77	49	0.065
59/1763/R/73	Superock LW	3,540	4.7	5	3/16/78	1	92	-	4.0	5/77	61	0.046
59/1763/S/73	Superock LW	2,360	3.1	5	3/16/78	1	100	-	4.2	5/77	63	0.070
59/1762/R/73	Cr. Slag	4,920	7.6	5	3/17/78	1	85	-	3.2	5/77	43	0.044
59/1762/S/73	Cr. Slag	3,280	5.1	5	3/17/78	1	97	-	3.9	5/77	55	0.058
59/1762/R/73	Rock Asphalt	4,920	7.6	5	3/17/78	1	85	-	3.2	5/77	20	0.024
59/1762/S/73	Rock Asphalt	3,280	5.1	5	3/17/78	1	92	-	3.8	5/77	37	0.052
59/1762/R/71	Knippa Traprock	4,920	9.0	7	3/17/78	2	84	73-95	3.8	5/77	30	0.039
59/1762/S/71	Knippa Traprock	3,280	6.0	7	3/17/78	2	100	-	3.8	5/77	38	0.053
59/1762/S/71	Dallas LW	3,280	6.0	7	3/17/78	1	90	-	-	5/77	64	-
59/1762/R/71	Hable Sandstone	4,920	9.0	7	3/17/78	3	81	73-95	3.7	5/77	57	0.066
59/1762/S/71	Hable Sandstone	3,280	6.0	7	3/17/78	2	98	95-100	4.3	5/77	64	0.043
59/1761/R&S/77	Rhyolite	3,250	0.5	1	3/17/78	2	100	-	4.2			0.063
59/1761/L&M/77	Rhyolite	3,250	0.5	1	3/17/78	2	100	-	4.4			0.079

*Location Code: Highway No./Control No./Lane Designation/Year OGAFC Applied

**Also see photographic record in Figures A-9 through A-15 in Appendix A

Table 17. Summary of Surface Condition of OGAFC Evaluation Pavements in District 20

Pavement* Location	Aggregate	ADT Per Lane (1978)	Total Traffic 10^6 veh/ Lane	No. Sea-sons	Pavement Rating Score**				S.I.(Mays) Test On: (4/28/78)	Skid Resistance		
					Date	No. Loca-tions	Ave	Range		Date	SN_{40}	Texture Depth Inches
10/7392/L/75	Clodine LW	5,280	4.3	3	2/27/78	1	95	-	4.3			0.045
10/289/R/76	Superock LW + Sand	12,800	5.8	2	2/27/78	1	95	-	4.6			0.050
87/3056/R/74	Knippa Traprock	1,800	2.1	4	2/27/78	1	78	-	4.1	11/77	28	0.102
87/3057/R/75	Superock LW	2,200	2.5	3	2/27/78	1	90	-	4.2	6/77	54	0.097
96/655/L/75	Superock LW	3,250	2.7	3	2/27/78	1	90	-	3.4	5/77	56	0.052

*Location Code: Highway No./Control No./Lane Designation/Year OGAFC Applied

**Also see photographic record in Figures A-16 through A-20 in Appendix A

macrotextures were indicated by the silicone putty texture depth values given in these tables. These texture depths were not measured when the surfaces were inspected to obtain pavement rating scores, but were determined in the laboratory on cores taken later at the rating locations.

Even though some of the evaluation pavements had been exposed to as many as seven seasonal cycles and total traffic applications had been as high as 34 million vehicles per lane, all of the surfaces appeared to be in serviceable condition. Pavement rating scores varied from 62 to 100 and S.I. values ranged from 3.2 to a very good 4.6. In fact, of the 30 S.I. values tabulated, 18 (60 percent) were 4.0 or greater. Surface microtexture depths ranged from 24 mils (0.024 in.) to 102 mils, but only 6 values were less than 50 mils. Only three SN_{40} values were below 35; these were observed in high traffic volume lanes where aggregates having a low polish resistance were used in the OGAFC mixes. Note that such low values of SN_{40} can be particularly undesirable if the internal drainage of the pavement surface layer is inadequate (refer to previous discussion of Figure 2).

It was not feasible to assess several aspects of the condition of the OGAFC evaluation pavements (including thickness of the surface layer, wear and crushing of aggregate particles, condition of the interface between the open-graded layer and its support surface, and the support surface itself) by means of field observations. However, it was possible to evaluate these factors by making a visual examination of pavement cores taken primarily for the purpose of making permeability measurements in the laboratory. The results of this inspection are summarized in Tables 18, 19 and 20. More detailed information can be found in Appendix A.

Determination of OGAFC layer thickness was one of the more significant

Table 18. Summary of Core Condition Ratings - OGAFC Evaluation Pavements in District 2

Pavement Location*	Aggregate	Condition of OGAFC Layer						Condition of Layer Interface		Condition of Support Layer
		No. Cores	Thick-ness in.	Raveling	Bleeding Flushing	Aggr Crushing	Aggr Surface Wear	Interlayer Adhesion	OGAFC Aggr Intrusion	Stripping Deterioration Disintegratio
820/812/R,S,L,M/73	Rhyolite	0**	-	-	-	-	-	-	-	-
30/10681/R&L/73	Eastland LW	4	0.77±0.21	None to Moderate	Slight to Moderate ***	Negligible	Slight	Adequate	Slight	Slight
30/10681/S&M/73	Eastland LW	4	0.80±0.13	None to Moderate	Moderate ***	Negligible	Slight	Excellent	Slight	Slight
81/137/R/77	Streetman LW	2	0.69±0.08	None	None	Moderate	Negligible	Excellent	None	Slight
81/137/S/77	Streetman LW	2	0.69	None	None	Negligible	Negligible	Excellent	Slight	Slight
81/137/L/77	Streetman LW	2	0.66±0.04	None	None	Negligible	Negligible	Excellent	Moderate	Slight
81/137/M/77	Streetman LW	2	0.72	None	None	Negligible	Negligible	Excellent	Moderate	Slight
101/1347/R/76	Eastland LW	2	0.68±0.02	None	None	Moderate	Moderate	Excellent	Moderate	Slight
101/1347/L/76	Eastland LW	2	0.68±0.06	None to Slight	None	Moderate	Slight	Excellent	Slight	Slight
114/3521/R/76	Eastland LW	2	0.43±0.06	None	Slight	Moderate	Slight	Excellent	None to Moderate	Slight
114/3521/L/76	Eastland LW	2	0.47±0.13	None	Slight	Moderate	Slight	Excellent	Slight to Moderate	Slight
114/3522/R/76	Eastland LW	2	0.46±0.10	None	None to Slight	Slight	Slight	Excellent	Slight to Moderate	Slight
114/3522/L/76	Eastland LW	2	0.48±0.05	None	None to Slight	Slight	Slight	Excellent	Slight to Moderate	Slight

*Location Code: Highway No./Control No./Lane Designation/Year OGAFC Applied
**High traffic volume on this highway made coring impractical
***OGAFC layer porous under a thin (~0.1 in) impermeable surface coating

Table 19. Summary of Core Condition Ratings - OGAFC Evaluation Pavements in District 11

Pavement Location*	Aggregate	Condition of OGAFC Layer						Condition of Layer Interface		Condition of Support Layer
		No. Cores	Thickness in.	Raveling	Bleeding Flushing	Aggr Crushing	Aggr Surface Wear	Interlayer Adhesion	OGAFC Aggr Intrusion	Stripping Deterioration Disintegration
59/1763/R/73	Eastland LW	4	0.66±0.14	None	Slight	Severe	Slight to Moderate	Adequate	Slight to Moderate	Moderate
59/1763/S/73	Eastland LW	4	0.55±0.12	None	None	Severe	Slight	Adequate	Moderate	Moderate
59/1763/R/73	Superock LW	2	0.72±0.23	None	None to Slight	Moderate	Slight to Moderate	Questionable	Moderate	Moderate
59/1763/S/73	Superock LW	2	0.96±0.21	None	None	Slight	Slight	Questionable	Slight	Moderate
59/1762/R/73	Cr. Slag	2	0.63±0.05	None	None	Negligible	Slight	Questionable	Slight	Slight
59/1762/S/73	Cr. Slag	2	0.53±0	None	None	Negligible	Slight	Questionable	Slight	Moderate
59/1762/R/73	Rock Asphalt	1	0.56	None	Moderate	Negligible	Moderate	Adequate	None	Slight
59/1762/S/73	Rock Asphalt	1	0.66	None	None	Negligible	Slight	Adequate	None	Moderate
59/1762/R/71	Knippa Traprock	2	0.43±0.02	None	Slight to Moderate	Negligible	Slight	Questionable	Slight	Moderate
59/1762/S/71	Knippa Traprock	2	0.55±0.06	Slight	None	Slight	Slight	Questionable	None	Moderate
59/1762/S/71	Dallas LW	0	-	-	-	-	-	-	-	-
59/1762/R/71	Hable Sandstone	4	0.62±0.23	None to Slight	Slight	Negligible	Moderate	Adequate	Slight	Moderate
59/1762/S/71	Hable Sandstone	0	-	-	-	-	-	-	-	-
59/1761/R&S/77	Rhyolite	2	0.70±0.20	None	None	Slight	Negligible	Excellent	Slight	Slight to Moderate
59/1761/L&M/77	Rhyolite	2	0.64±0.11	None	None to Slight	Slight	Negligible	Excellent	Slight	Slight

*Location Code: Highway No./Control No./Lane Designation/Year OGAFC Applied

Table 20. Summary of Core Condition Ratings - OGAFC Evaluation Pavements in District 20

Pavement Location*	Aggregate	Condition of OGAFC Layer							Condition of Layer Interface		Condition of Support Layer
		No. Cores	Thick-ness in.	Ravel-ing	Bleeding Flushing	Aggr Crushing	Aggr Surface Wear	Interlayer Adhesion	OGAFC Aggr Intrusion	Stripping Deterioration Disintegration
10/7392/L/75	Clodine LW	2	0.83±0.07	None	None	Slight	Slight	Adequate	Slight to Moderate	Slight
10/7392/M/75	Clodine LW	2	0.61±0.03	None	None	Slight	Slight	Adequate	Slight	Slight
10/289/R/76	Superock LW + Sand	2	0.85±0.13	None	Slight to Moderate	Slight	Slight	Adequate	Slight	Slight
10/289/S/76	Superock LW + Sand	2	1.19±0.18	None	Slight	Moderate	Severe to Moderate	Adequate	Slight	Slight
87/3056/L/74	Knippa Traprock	2	0.55±0.11	None	Slight	Negligible	Negligible	Adequate	-	Slight
87/3057/R/75	Superock LW	2	1.02±0.02	None	None	Negligible	Severe to Moderate	Adequate	Slight	Slight
87/655/L/75	Superock LW	2	0.66±0.09	None	Moderate	Negligible	Moderate	Adequate	Slight	Slight
87/655/M/75	Superock LW	2	1.10±0.30	None	None	Moderate	Moderate	Excellent	Slight	Slight

*Location Code: Highway No./Control No./Lane Designation/Year OGAFC Applied

results of the laboratory core examination. The overall range of these measurements was from 0.43 inches to 1.19 inches with 35 percent less than 5/8 (0.625) and 3/4 (0.75) inch, and 35 percent greater than 3/4 (0.75) inch.

Examination of the cores for raveling and bleeding of the surface layer gave information supplementing the visual surveys made in the field. The information presented in Tables 18, 19 and 20 reveals few problems with raveling or bleeding on the OGAFC evaluation pavements. The one instance where a moderate amount of raveling was observed (highway I 30 in District 2) was associated with high traffic volume and total traffic (34 million vehicle passages per lane). Some bleeding and flushing was also observed with this pavement. Since no such bleeding occurred on entrance and exit ramps paved with the same mixture, it appears that the bleeding observed on the traffic and passing lanes was due to the accumulated action of the traffic.

Lightweight aggregates were used to make the OGAFC mixes used for over one-half of the evaluation pavements considered in this study. While selection of this kind of aggregate is beneficial with respect to skid resistance, problems with aggregate crushing during construction and surface wear in service might be expected. The crushing recorded in Tables 18, 19 and 20 varied from negligible to slight with natural aggregates and crushed slag and from negligible to severe for fired clay lightweight aggregates. With one exception, surface wear observed on all OGAFC evaluation pavements was not greatly dependent on aggregate type and varied from negligible to moderate. The one case of severe wear noted was observed where traffic volume was relatively high, 12,800 vehicles per lane ADT. Behavior of natural and lightweight aggregates with respect to crushing and wear is compared and considered in greater detail in the following section of this report.

The condition of the interface between the OGAFC layer and its substrate can be expected to influence pavement performance. If interlayer adhesion is poor, the traffic may remove the surface layer. If the substrate is not adequately sealed, water may penetrate into and soften the pavement base courses. An asphalt film between the two layers will promote adhesion and help to seal the pavement, but an excess of asphalt will fill the voids in the OGAFC layer and may even bleed to the exposed surface. Thus, the cores were examined to assess the condition of this layer interface. No occurrence of excessive amounts of asphalt at the interface was found, so only an estimate of interlayer adhesion was reported in Tables 18, 19 and 20. In most instances this was judged to be excellent (i.e., clear evidence of a tightly bound asphalt film) or adequate (no visible film, but no evidence of interlayer separation). Where the interlayer adhesion was rated "questionable," usually there was evidence of layer separation or incipient separation. However, even when this was noted, field observations did not show significant removal of the OGAFC layer, although some potholing along reflection cracks was noted where the adhesion was rated "questionable," as illustrated by Figure 9. The possibility that this problem with OGAFC pavements might be aggravated by the application of deicing salts in cold climates (for example, see Fruggiero and Gardino [30]) should be considered.

Finally, an attempt was made to evaluate the condition of the asphalt concrete layer supporting the OGAFC by examining this layer of the core samples for evidence of stripping, deterioration, or incipient disintegration. Such problems could occur if this underlying course was in poor

Figure 9. Example of OGAFC Layer Removal Along Reflection Crack. Location: Highway US 59, Control No. 1763, M.P. 22.4, District 11

condition when the OGAFC was constructed or as a result of water migration from either above or below the pavement structure. Resulting loss of structural integrity of the supporting layer could have deleterious effects on pavement performance. Ratings of the condition of the OGAFC support layer, summarized in Tables 18, 19 and 20, appear to indicate no serious problems in this regard. In most cases only a slight amount of stripping or deterioration were noted.

Availability of cores from the OGAFC evaluation pavements also provided a means for estimating another factor related to pavement durability: hardening of the asphalt binder. If the asphalt cement becomes too hard in service, cracking and raveling of the surface layer may result. As pointed out in the section on Factors Influencing OGAFC Performance, this problem will be an important consideration in selecting asphalt cements for OGAFC mixes; it will influence establishment of viscosity grade and stability requirements. Since exposure to atmospheric oxygen leads to asphalt hardening, this problem tends to be intensified by the porosity of an OGAFC mat. Thus, the void content, as well as the asphalt content (ASTM D2172, Method B), viscosity at 140°F, and penetration at 77°F were determined on the OGAFC pavement cores. These data are summarized in Tables 21, 22 and 23.

The void contents shown were estimated using the following relation.

$$\text{Air Voids (\%)} = 100 - \left(\frac{w_a}{g_a} + \frac{w_b}{g_b}\right) \frac{w_c}{v_c}$$

where,

w_a = weight percent of aggregate in mix

w_b = weight percent of asphalt in mix

g_a = bulk specific gravity (SSD) of aggregate retained after extraction

Table 21. Asphalt Hardening in OGAFC Evaluation Pavements, District 2

Pavement/Core Location*	Exposure, t, Yrs	Asphalt Viscosity At 140°F, Poise		Penetration at 77°F	Hardening Index		Voids Percent	% Asphalt by Weight
		Original	Core Extract		$H.I._t$	$H.I._2$		
30/10681/433.6/LOWP	5	2060	84,300	11	41	18.2	31	7.06
LBWP			5,600	17	2.7	1.75	18	7.82
MOWP			26,300	24	12.8	6.1	16	10.68
ROWP			35,300	18	17.2	8.0	15	7.45
SOWP			43,700	18	21.2	9.7	23	8.46
81/137/14.6/LOWP	1	1970	16,900	27	8.6	11.2	29	9.60
LBWB			7,100	35	3.6	4.7	2	10.25
MOWB			25,900	25	13.1	17.0	45	7.46
ROWP			7,900	32	4.0	5.2	29	11.36
RBWP			16,100	32	8.2	10.2	30	11.03
SOWP			17,100	27	8.7	11.3	24	6.43
SBWP			43,700	25	22.1	28.8	41	6.33
101/1347/21.7/ROWP	2	1980	37,600	17	19.0	19.0	24	10.08
RBWP			16,100	21	8.2	8.2	13	12.55
LOWP			41,600	19	21.1	21.1	12	8.68
LBWP			37,900	18	19.2	19.2	22	8.65
114/3521/22.2/ROWP	2	1980	16,300	29	8.2	8.2	22	10.98
RBWP			15,800	28	8.0	8.0	16	12.86
LOWP			102,300	12	51.7	51.7	24	7.20
114/3522/35.4/ROWP	2	1980	31,600	21	16.0	16.0	22	6.75
RBWP			16,800	28	8.5	8.5	23	9.79

*Location Code: Highway No./Control No./Milepost/Lane and Wheel Path Designation

Table 22. Asphalt Hardening in OGAFC Evaluation Pavements, District 11

Pavement/Core Location*	Exposure, t, Yrs	Asphalt Viscosity At 140°F Poise		Penetration at 77°F	Hardening Index		Voids Percent	% Asphalt by Weight
		Original	Core Extract		H.I.$_t$	H.I.$_2$		
59/1763/20.5/ROWP	5	1850	160,900	8	87.1	38.1	31	9.58
SOWP			-	-	-	-	24	7.66
SBWP			-	-	-	-	39	7.43
/22.0/RBWP			151,300	9	82.0	35.9	28	9.67
/22.4/SOWP			52,500	7	28.4	12.8	38	9.82
SBWP			251,000**	4	136	59	41	9.42
59/1762/3.45/RBWP	5	2360	2,398,000'	1	1015	438	14	7.65
/SBWP			417,000**	2	177	77	21	13.79
/3.57/RBWP			88,200	10	37.3	16.6	9	12.83
/SBWP			51,200	4	21.7	9.9	20	10.61

*Location Code: Highway No./Control No./Milepost/Lane and Wheel Path Designation

**Estimated from penetration value

Table 23. Asphalt Hardening in OGAFC Evaluation Pavements, District 20

Pavement/Core Location*	Exposure, t, Yrs	Asphalt Viscosity At 140°F, Poise		Penetration at 77°F	Hardening Index		Voids Percent	% Asphalt by Weight
		Original	Core Extract		$H.I._t$	$H.I._2$		
10/7392/847/LOWP	3	1880	61,400	10	32.7	21.0	-	-
LBWP			44,700	17	23.8	15.4	39	11.38
10/289/861/SOWP	2	1800	33,400	15	18.5	18.5	20	7.83
SBWP			29,400	16	15.3	15.3	21	9.80
87/3056/1/LOWP	4	1900	20,300	15	10.7	5.8	22	5.62
LBWP			16,100	21	8.5	4.7	41	7.95
87/3057/4/ROWP	3	1900	43,800	14	23.0	14.9	40	10.00
RBWP			53,700	12	28.2	18.2	36	9.68
96/655/23.6/MOWP	3	1880	52,900	14	28.1	18.1	27	11.63
MBWP		1880	46,200	16	24.5	15.9	0	9.35

*Location Code: Highway No./Control No./Milepost/Lane and Wheel Path Designation

g_b = specific gravity of asphalt

w_c = weight of OGAFC core layer, gm

v_c = volume of OGAFC core layer, cm^3

$v_c = \pi \left(\frac{D}{2}\right)^2 \eta$

D = Core diameter, cm

η = OGAFC layer thickness, cm

Air void contents estimated on the basis of the above equation are subject to considerable error, but a number of practical difficulties precluded measurement of air void contents by other, usually more reliable, methods. Additionally, the values so determined are much higher than expected, in most cases. This probably is because the total volume, v_c, included both the internal voids and the volume of macrotexture depressions.

The penetrations of the extracted asphalt were in the range of 1 to 35, and viscosities ranged from 7000 to 2,398,500 poises, indicating considerable hardening of many of the OGAFC pavements. The hardening index (H.I.) values reported were ratios of aged to original asphalt cement viscosities. Two-year hardening index ($H.I._2$) values reported were estimated, as explained in Appendix D, and reported in order to have a comparable basis on which to rate the relative tendencies of the asphalt binder to harden in service. $H.I._2$ values obtained were distributed as follows:

under 10	32 percent
10 to 20	47 percent
over 20	21 percent

Traxler and Shelby [26] reported $H.I._2$ values up to 40 for dense-graded asphalt pavements. In this study, only 4 such values were over 40, including an extremely high index of 438. These data are considered further in this report under Analysis and Discussion of Results.

Drainage Capacity of OGAFC Pavements

Quantitative evaluation of the internal drainage capacity of the OGAFC pavements considered in this study was made by:

1. Measurement of OGAFC layer permeability,
2. Determination of layer void content,
3. Direct determination of the water runnoff rate causing incipient surface flooding.

All of these tests were made on 6-inch cores representing the pavements under study.

Permeability values were measured by means of an outflow permeameter similar to the one used by the U. S. Army Waterways Experiment Station and described by White [2] [19]. A detailed record of the permeability test data, as well as a description of the apparatus used, the test procedures employed, and the method of calculating permeability K-values from the test data are presented in Appendix B. These data, for cores taken from the OGAFC evaluation pavements, are summarized in Tables 24, 25 and 26. Permeability data for cores taken from experimental OGAFC pavements in District 17 are given in Table 27.

Examination of these data indicates that the drainage capacities of most (76 percent) of the OGAFC evaluation pavements had relatively low permeabilities (less than 0.05 cm/sec) while only a few (18 percent) had permeabilities greater than 0.1 cm/sec. The highest permeabilities were observed with OGAFC pavements on highway US 81 in District 2. By comparison, Lambe [31] indicates that soils having permeabilities over 0.1 cm/sec can be considered to have a high degree of permeability.

Tables 24, 25, 26 and 27 also give air void contents of the cores from which asphalt was extracted for viscosity determination, as previously

Table 24. Summary of Permeability and Void Measurements on OGAFC Pavements in District 2

Pavement Location*	Aggregate	ADT Per Lane (1978)	Total Traffic 10^6 Veh/Lane	No. Seasons	Permeability, cm/sec				Air Voids		
					Core Date	No. Cores Tested	K Avg. cm/sec	K Range cm/sec	No. Cores Tested	% Avg.	% Range
820/812/R,S,L,M/73	Rhyolite	14,750	18.3	5	-	0	-	-	0	-	-
30/10681/R&L/73	Eastland LW	20,700	34.0	5	8/78	4	0.021	0 to 0.085	3	21	15-31
30/10681/S&M/73	Eastland LW	20,700	34.0	5	8/78	4	0.006	0 to 0.022	2	20	16-23
81/137/R/77	Streetman LW	2,790	0.4	1	8/78	2	0.080	0.074 to 0.086	2	30	29-30
81/137/S/77	Streetman LW	1,860	0.3	1	8/78	2	0.271	0.244 to 0.298	2	32	24-41
81/137/L/77	Streetman LW	2,790	0.4	1	8/78	2	0.217	0.200 to 0.233	2	16	2-29
81/137/M/77	Streetman LW	1,860	0.3	1	8/78	2	0.418	0.268 to 0.569	1	45	-
101/1347/R/76	Eastland LW	2,440	1.5	2	8/78	2	0.002	0 to 0.004	2	18	13-24
101/1347/L/76	Eastland LW	2,440	1.5	2	8/78	2	0.013	0 to 0.026	2	17	12-22
114/3521/R/76	Eastland LW	2,100	1.3	2	8/78	2	0.000	-	2	19	16-22
114/3521/L/76	Eastland LW	2,100	1.3	2	8/78	2	0.000	-	1	24	-
114/3522/R/76	Eastland LW	2,500	1.5	2	8/76	2	0.000	-	2	22	22-23
114/3522/L/76	Eastland LW	2,500	1.5	2	8/76	2	0.000	-	0	-	-

*Location Code: Highway No./Control No./Lane Designation/Year OGAFC Applied

Table 25. Summary of Permeability and Void Measurements on OGAFC Pavements in District 11

Pavement Location*	Aggregate	ADT Per Lane (1978)	Total Traffic 10^6 Veh/Lane	No. Seasons	Permeability, cm/sec				Air Voids		
					Core Date	No. Cores Tested	K Avg. cm/sec	K Range cm/sec	No. Cores Tested	% Avg.	% Range
59/1763/R/76	Eastland LW	3,540	4.7	5	5/78	4	0.038	0 to 0.056	2	30	28-31
59/1763/S/73	Eastland LW	2,360	3.1	5	5/78	3	0.022	0 to 0.026	2	32	24-39
59/1763/R/73	Superock LW	3,540	4.7	5	5/78	2	0.029	0.022 to 0.036	0	-	-
59/1763/S/73	Superock LW	2,360	3.1	5	5/78	1	0.192	-	2	40	38-41
59/1762/R/73	Cr. Slag	4,920	7.6	5	5/78	2	0.020	0.015 to 0.025	1	14	-
59/1762/S/73	Cr. Slag	3,280	5.1	5	5/78	2	-	-	1	21	-
59/1762/R/73	Rock Asphalt	4,920	7.6	5	5/78	1	0.000	-	1	9	-
59/1762/S/73	Rock Asphalt	3,280	5.1	5	5/78	1	0.000	-	1	20	-
59/1762/R/71	Knippa Traprock	4,920	9.0	7	5/78	2	0.006	0 to 0.013	0	-	-
59/1762/S/71	Knippa Traprock	3,280	6.0	7	5/78	1	0.041	-	0	-	-
59/1762/R/71	Hable Sandstone	4,920	9.0	7	5/78	4	0.013	0 to 0.034	0	-	-
59/1762/L/71	Hable Sandstone	3,280	6.0	7	-	0	-	-	-	-	-
59/1761/R&L/71	Rhyolite	3,250	0.5	1	5/78	2	0.006	0 to 0.012	0	-	-
59/1761/S&M/71	Rhyolite	3,250	0.5	1	5/78	2	0.000	-	0	-	-

*Location Code: Highway No./Control No./Lane Designation/Year OGAFC Applied

Table 26. Summary of Permeability and Void Measurements on OGAFC Pavements in District 20

Pavement Location*	Aggregate	ADT Per Lane (1978)	Total Traffic 10^6 Veh/Lane	No. Seasons	Permeability, cm/sec				Air Voids		
					Core Date	No. Cores Tested	K Avg. cm/sec	K Range cm/sec	No. Cores Tested	% Avg.	% Range
10/7392/L/75	Clodine LW	5,280	4.3	3	9/78	2	0.153	0.150 to 0.156	1	39	-
10/7392/M/75	Clodine LW	3,520	2.9	3	9/78	2	0.191	0.167 to 0.215	0	-	-
10/289/R/76	Superock LW + Sand	12,800	5.8	2	9/78	2	0.108	0.107 to 0.109	0	-	-
10/289/S/76	Superock LW + Sand	12,800	5.8	2	9/78	2	0.095	0.045 to 0.117	2	20	20-21
87/3056/L/74	Knippa Traprock	1,800	2.1	4	9/78	2	0.011	0 to 0.022	2	32	22-41
87/3057/R/75	Superock LW	2,200	2.5	3	9/78	2	0.072	0.070 to 0.075	2	38	36-40
87/655/L/75	Superock LW	3,250	2.7	3	9/78	2	0.000	-	0	-	-
96/655/M/75	Superock LW	3,250	2.7	3	9/78	2	0.012	0.010 to 0.015	2	13	0-27

*Location Code: Highway No./Control No./Lane Designation/Year OGAFC Applied

Table 27. Permeability Measurements on Experimental OGAFC Pavements in District 17

Pavement Location*	Permeability K, cm/sec
21/1164/1/ROWP/75	0.08
21/1164/1/BWP/75	0.13
21/1164/2/ROWP/75	0.14**
21/1164/2/SOWP/75	0.26**
21/1164/3/ROWP/75	0.16**
21/1164/4/ROWP/75	0.05

*Pavement Location Code: Highway No./Control No./Section No./Lane and Wheel Path Designation/Year OGAFC applied

**Estimated from K_D measurements

Other Data:

Milepost	5.5 to 5.8
Date Cored	3/78
ADT/Lane	1750
Total Traffic, 10^6 veh/lane	1.6
No. Seasons	3

discussed.

In the direct test for drainage capacity, samples cut from some of the OGAFC pavement cores used for permeability determinations were monitored in an apparatus so that water flow rates causing incipient flooding of the sample surface can be measured at several different values of cross-slope. In Appendix C this test is described and it is shown that, by applying the Chezy-Manning equation, the following relation can be derived.

$$\frac{Q_F}{w_z} = Q_F{}^{/} = K_D \quad S^{1/2}$$

where,

Q_F = water flow rate causing incipient surface flooding, cm^3/sec,

S = sine θ ≈cross-slope,

w = width of test sample, cm,

z = thickness of OGAFC layer in sample, cm,

K_D = constant characterizing the drainage capacity of the OGAFC layer, cm/sec.

From K_D, an equivalent rainfall intensity that will begin to cause pavement surface flooding can also be estimated. In Appendix C it is shown that, for a 12 ft lane with an OGAFC layer 1-inch thick, having a 2 percent cross-slope:

$$I_F = 1.39K_D \quad \text{in/hr}$$

A summary of the K_D determinations and estimated I_F values for 20 of the OGAFC pavements is given in Table C-2.

One way to verify the drainage capacity of OGAFC pavements is to observe the tendency of the surfaces to flood and produce splash and spray behind moving vehicles in measured natural rainfall. A number of observations of this kind were made on several of the OGAFC evaluation pavements and on the OGAFC experimental sections (as part of the study reported in reference 17). These were recorded photographically and are presented as Figures 10 through 28. Although no vehicle speed measurements were made, it is estimated that they were between 50 and 60 mph in all cases. However, since trucks tend to produce much more splash and spray than automobiles, separate observations were made and recorded for each type of vehicle.

These observations, along with other data related to pavement drainage capacity are summarized in Table 29. Note that in this table, observations of splash and spray are recorded in terms of a numerical rating to provide some basis for relating such information with other numerical data measuring pavement drainage capacity. In several instances (Figures 14, 24 and 27) it was possible to make a direct comparison of splash and spray observed on OGAFC pavements with that produced by vehicles on nearby portland cement or dense-graded flexible pavements.

As might be expected since it was necessary to make these observations at rainfall intensities which ranged from 0.02 in/h to 0.25 in/h, a systematic comparison of pavement drainage performance was difficult. However, note that in some instances, the splash and spray behavior of the OGAFC evaluation pavements was marginal even in relatively light rainfall. On the other hand, two of the OGAFC pavements showed excellent drainage when the rainfall intensity was as high as 0.25 in. Other observations (not recorded photographically) indicate significant surface flooding, even on rather porous OGAFC pavements, when the rainfall intensity approaches 0.5 in.

Figure 10. Splash and Spray Behind Automobiles in 0.02 in/h Rainfall; Location: 820/812/L,M,R,S
11/8/77

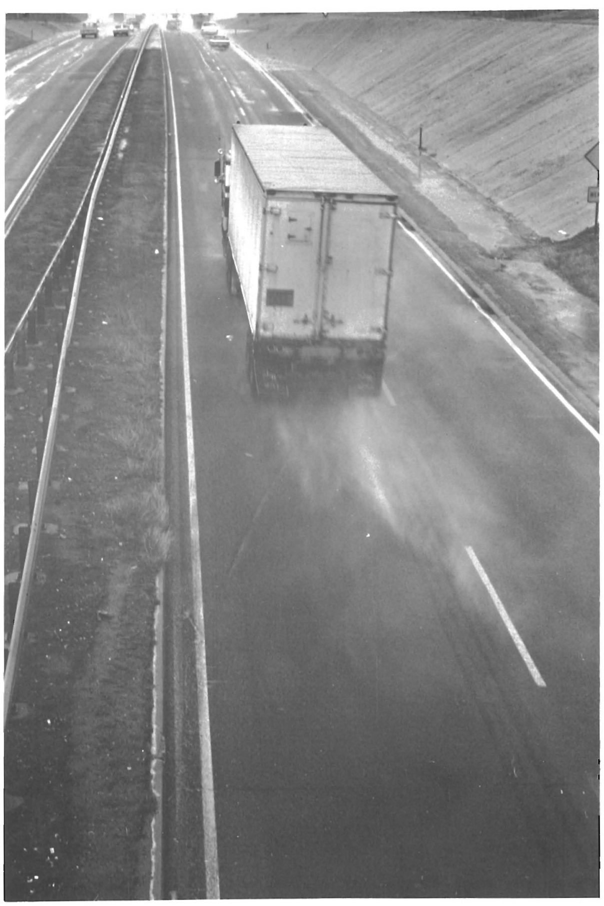

Figure 11. Splash and Spray Behind Truck in 0.02 in/h Rainfall; Location: 820/812/M
11/8/77

Figure 12. Splash and Spray Behind Automobiles in 0.04 in/h Rainfall
K_{avg} = 0.014; Location: 30/1681/R&S

Figure 13. Splash and Spray Behind Truck in 0.04 in/h Rainfall
K_{avg} = 0.014; Location: 30/1681/R&S

Figure 14. Splash and Spray Behind Automobiles in 0.04 in/h Rainfall K_{avg} = 0.014; Location: Portland Cement Concrete Pavement on I 30 Contiguous to Locations in Figures 12 and 13

Figure 15. Splash and Spray Behind Automobile in 0.25 in/h Rainfall
K_{avg} = 0.15; Location: 10/7392/L 2/9/78

Figure 16. Splash and Spray Behind Truck in 0.25 in/h Rainfall
K_{avg} = 0.15; Location: 10/7392/L 2/9/78

Figure 17. Splash and Spray Behind Automobile in 0.25 in/h Rainfall
K_{avg} = 0.11; Location: 10/289/R 2/9/78

Figure 18. Splash and Spray Behind Truck in 0.25 in/h Rainfall
K_{avg} = 0.11; Location: 10/289/R 2/9/78

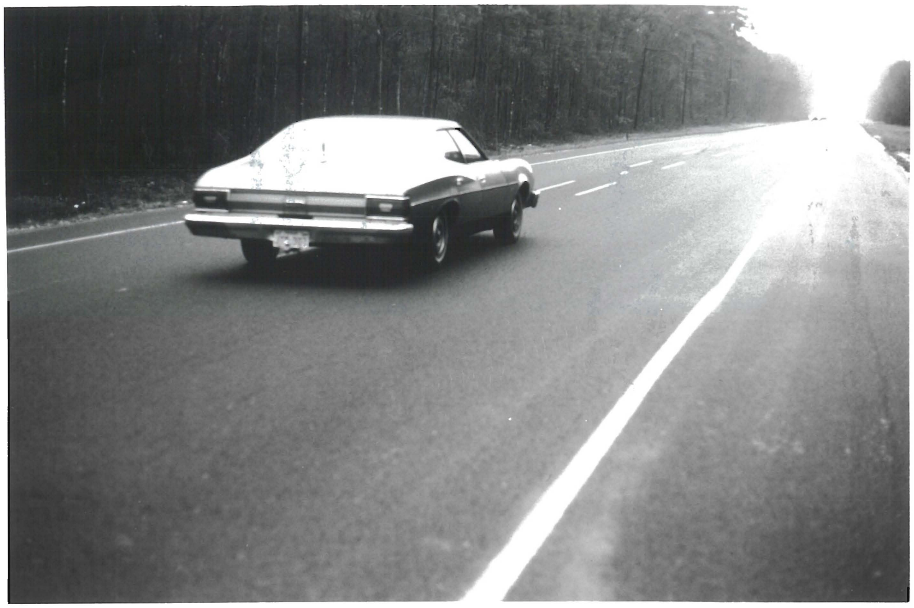

Figure 19. Splash and Spray Behind Automobile in 0.05 in/h Rainfall
K_{avg} = 0.07; Location: 87/3057/L&R 2/9/78

Figure 20. Splash and Spray Behind Truck in 0.05 in/h Rainfall
K_{avg} = 0.07; Location: 87/3057/L&R

Figure 21. Splash and Spray Behind Pickup in 0.05 in/h Rainfall
K_{avg} = 0.011; Location: 87/3056/R&L 2/9/78

Figure 22. Splash and Spray Behind Truck in 0.06 in/h Rainfall
K_{avg} = 0.011; Location: 87/3056/R&L 2/9/78

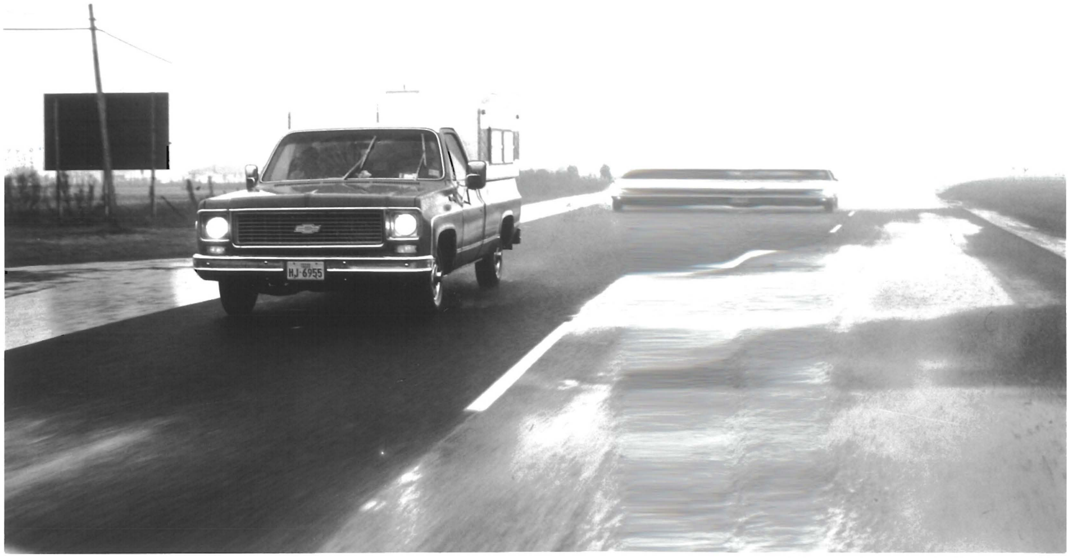

Figure 23. Splash and Spray Behind Automobiles in 0.25 in/h Rainfall K_{avg} = 0.11, Experimental OGAFC Section 1, SH 21, Control No. 1164, District 17

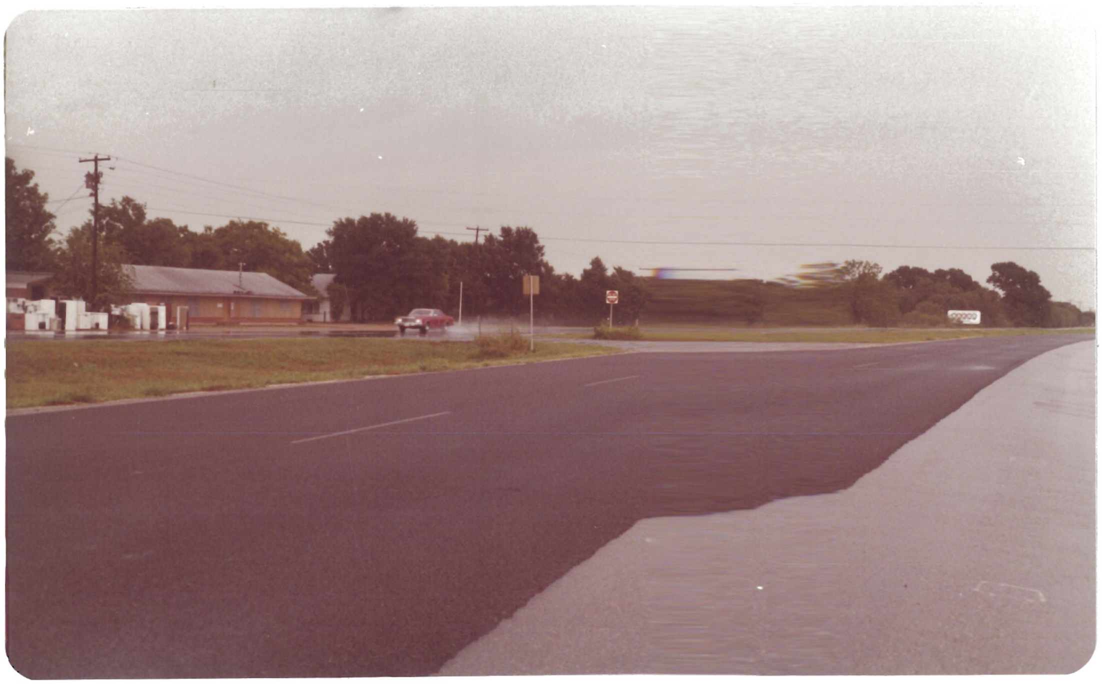

Figure 24. Pavement Surface in 0.02 in/h Rainfall K_{est} = 0.2, Experimental OGAFC Section 2, Control No. 1164, District 17. Spray Shown Behind Automobile on Dense-Graded Median.

Figure 27. Splash and Spray Behind Truck in 0.08 in/h Rainfall
K = 0.05, Experimental OGAFC Section 3 in Foreground,
Truck at End of Section 4

Figure 28. Splash and Spray Behind Automobile in 0.02 in/h Rainfall,
K = 0.05, Experimental OGAFC Section 4. Dense-Graded
Pavement in Foreground Shows Flooding Indicated by
Reflected Light.

Table 28. Splash and Spray Behind Automobiles and Trucks on Texas OGAFC Pavements in Natural Rainfall

Pavement Location		Aggregate	ADT Per Lane (1978)	Total Traffic 10^6 Veh/ Lane	Perme-ability K,cm/sec *	Predicted Flooding Rainfall Intensity in/h	Splash and Spray Observations		
District	Pavement						Automobiles †	Trucks †	Measured Rainfall Intensity in/h
2*	820/812/R&S/73	Rhyolite	14,750	18.3	-	-	8(Fig.10)	5(Fig.11)	0.02
2*	30/1681/R&S/73	Eastland LW	20,700	34.0	0.014	0.02	5(Fig.12)	3(Fig.13)	0.04
20*	10/7392/L/75	Clodine LW	3,520	2.9	0.15	0.21	10(Fig.15)	8(Fig.16)	0.25
20*	10/289/R/76	Superock + Sand	12,800	5.8	0.11	0.16	10(Fig.17)	8(Fig.18)	0.25
20*	87/3057/L&R/75	Superock LW	2,200	2.5	0.07	0.10	10(Fig.19)	10(Fig.20)	0.05
20*	87/3056/L&R/74	Knippa Traprock	1,800	2.1	0.01	0.02	10(Fig.21)	-	0.05
20*	87/3056/L&R/74	Knippa Traprock	1,800	2.1	0.01	0.02	-	5(Fig.22)	0.06
17**	21/1164/R/75/1	Streetman LW	1,750	1.6	0.11	0.16	10(Fig.23)	-	0.25
17**	21/1164/R/75/3	Streetman LW	1,750	1.6	-		10(Fig.26)	8(Fig.25)	0.08
17**	21/1164/R/75/4	Streetman LW	1,750	1.6	0.05	0.08	10(Fig.28)	-	0.02
17**	21/1164/R/75/4	Streetman LW	1,750	1.6	0.05	0.08	-	8(Fig.27)	0.08

*Location Code, OGAFC Evaluation Pavements: Highway No./Control No./Lane Designation/Year OGAFC Applied
**Location Code, OGAFC Experimental Pavements: Highway No./Control No./Lane Designation/Year OGAFC Applied/ Section No.
***See Appendix B and Tables 24, 26 and 27
****See Appendix C
†Ratings on scale of 1 to 10, as follows:

10 = No apparent spray
8 = Slight spray
5 = Moderate spray
3 = Objectionable spray
1 = Very objectionable spray

Other Results

Two segments of this study, on which little progress has been made to date, are an economic analysis of OGAFC overlays and an examination of methods for their repair.

It was intended to base the economic analysis on a cost-benefit study which would balance off construction and maintenance costs against benefits resulting from the potential reduction in wet weather accidents. Completion of this part of the study has been seriously impeded by the lack of reliable construction and maintenance data for the OGAFC evaluation pavements of this study. In particular, it proved to be impossible to separate out the maintenance costs attributable solely to the OGAFC pavement sections. It appears that to obtain information of this kind, it will be necessary to set up a data acquisition system at the time an OGAFC project is initiated.

Experiments with two methods of making OGAFC repairs were conducted on the SH 21 experimental sections. These repairs were made to replace holes in the pavement resulting when cores were taken from these sections.

A tack coat was applied to all core holes and a mixture containing cold mix, cement, and enough water to dampen was tamped in increments to within approximately 2 inches of the existing OGAFC surface. This mixture provided the impermeable substrate which is necessary to prevent water from penetrating into the base and subgrade. Before applying an OGAFC layer, a tack coat was applied to the surface of the compacted cold mix.

One method of making OGAFC repairs involved the use of a retained sample of hot mix used in the construction of one of the experimental OGAFC sections. The mix was heated to 200°F and tamped in 1 inch increments into the hole with a Marshall hammer. The other method involved the use of Superock lightweight aggregate and a cationic, rapid-set emulsion.* The aggregate was placed into a container of water in order to wet the surface of the particles.** The wet aggregate was then placed into the hole and rodded. The asphalt emulsion was then poured over the wet aggregate. Since traffic was released immediately after repair work was complete, the surfaces of the new OGAFC layers were dusted with Minus 200 material in an attempt to prevent aggregate pick up. These repairs were examined 11 months later and were found to be intact.

*It was determined in the laboratory that an anionic emulsion did not completely coat the aggregate nor did it provide an adequate bond between particles.

**It was determined in the laboratory that it was necessary to wet the aggregate in order for the emulsion to completely coat the aggregate particles.

ANALYSIS AND DISCUSSION OF RESULTS

Factors Considered

In the introductory sections of this report, the influence of a number of important input variables on the structural behavior, durability, rainfall drainage capacity, and skid resistance of OGAFC pavements was considered in a general way. In the following discussion, results of the present study are examined with the intention of delineating these effects more exactly and answering some of the questions posed in the statement of objectives and approach for this project. In particular, the effects of the following groups of OGAFC input variables are considered:

1. Characteristics and condition of the pavement supporting the friction course,
2. Raw material characteristics,
3. Mix design and layer thickness and
4. Construction practices.

The effects of each of these classes of input variables on performance of OGAFC evaluation and experimental pavements are considered in this analysis. Performance is estimated in terms of:

1. Structural behavior and durability indicated by field surveys and laboratory examination of representative cores,
2. Capacity to drain rainfall without surface flooding; predicted from core permeability and direct drainage tests and supplemented by observations of splash and spray in natural rainfall and
3. Skid resistance as indicated by SN_{40} data and surface macrotexture measurements.

Characteristics and Condition of Supporting Pavement

Even after as many as seven seasons of exposure and total traffic applications as high as 34 million vehicles per lane, the results of the field survey (summarized in Tables 15, 16 and 17) generally showed that all of the OGAFC evaluation pavements were quite serviceable when these observations were made. The pavements that had seen more service tended to have lower pavement rating scores, but it was apparent that some were resisting the effects of age and traffic better than others and that such differences might be more strongly influenced by the behavior of the underlying pavement structure than any other factor. To confirm general observations of this kind, the structural characteristics of the underlying pavements (based on pavement cross-sections shown in Tables 7, 8 and 9) were determined by estimating AASHO Structural Numbers, as outlined in Appendix E. These numbers fell within a range of 4.3 and 10.8, and for the purpose of this analysis were divided into two groups: 4 to 6, and over 6.

The greater resistance to deterioration of OGAFC layers supported by pavement structures having structural numbers over 6 is clearly indicated by the plots of pavement rating score vs. total traffic application given in Figure 29. Some dispersion of the data is evident, no doubt resulting from the effects of the many other input variables, but the predominant influence appears to be that resulting from the structural characteristics of the supporting pavement.

In contrast, similar effects were not observed with respect to roughness of the OGAFC surfaces as measured by the Mays meter. The serviceability index calculated for all of these surfaces was quite acceptable (a minimum value of 3.4 and 72 percent with values of 4.0

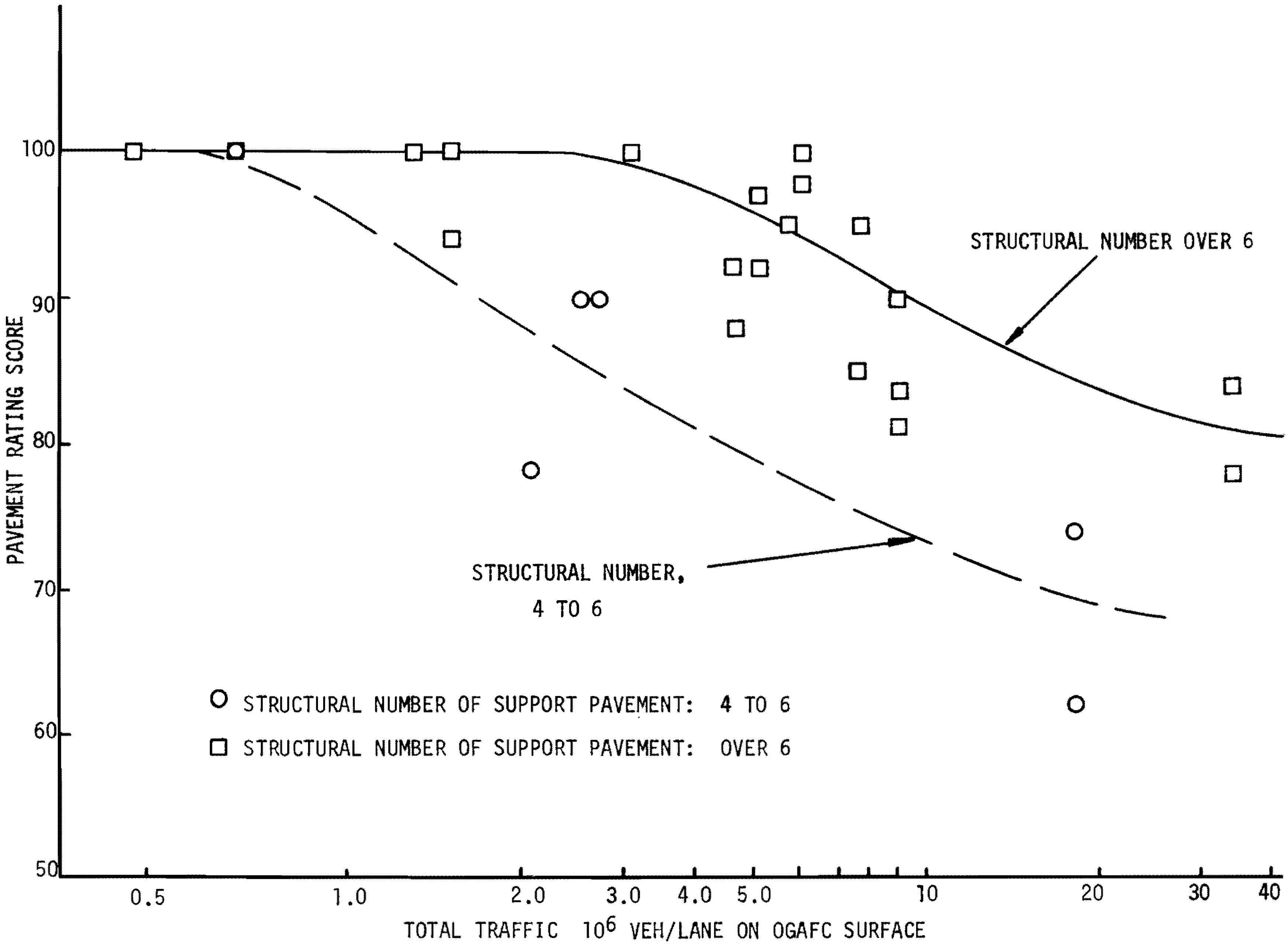

Figure 29. Influence of Support Pavement Structural Number on Deterioration of OGAFC Evaluation Pavement Condition Resulting from Traffic Application

or more), and the data plot in Figure 30 shows no trends with either the total traffic applications or the structural number of the supporting pavement. The riding quality of thin OGAFC mats probably is much more responsive to the roughness of the surface over which such overlays are applied than to any other factor. For example, the paired data given in Table 30 show that the OGAFC pavements in traffic lanes were always rougher than pavements in passing lanes, as might be expected, regardless of how long the OGAFC surface had been in service. This evidence clearly supports the desireability of applying a level-up course on a rough pavement before placing an OGAFC overlay.

The only direct observation made in the course of this study which related to the effect of the condition of the supporting pavement on OGAFC drainage was one instance where a friction course was applied over an old flexible pavement without first sealing the badly weakened surface. This occurred on a section of SH 103 east of Lufkin, Texas. Serious alligator cracking, rutting, and surface roughness, illustrated in Figure 31, developed on this pavement soon after the OGAFC layer was applied as a result of increased water drainage into the base courses and subgrade.

Of course, the cross-slope can be expected to have a major influence on OGAFC drainage; this is clearly demonstrated by the data presented in Appendix C.

However, it was not practical to obtain field confirmation in this study by making cross-slope measurements of the OGAFC evaluation pavements.

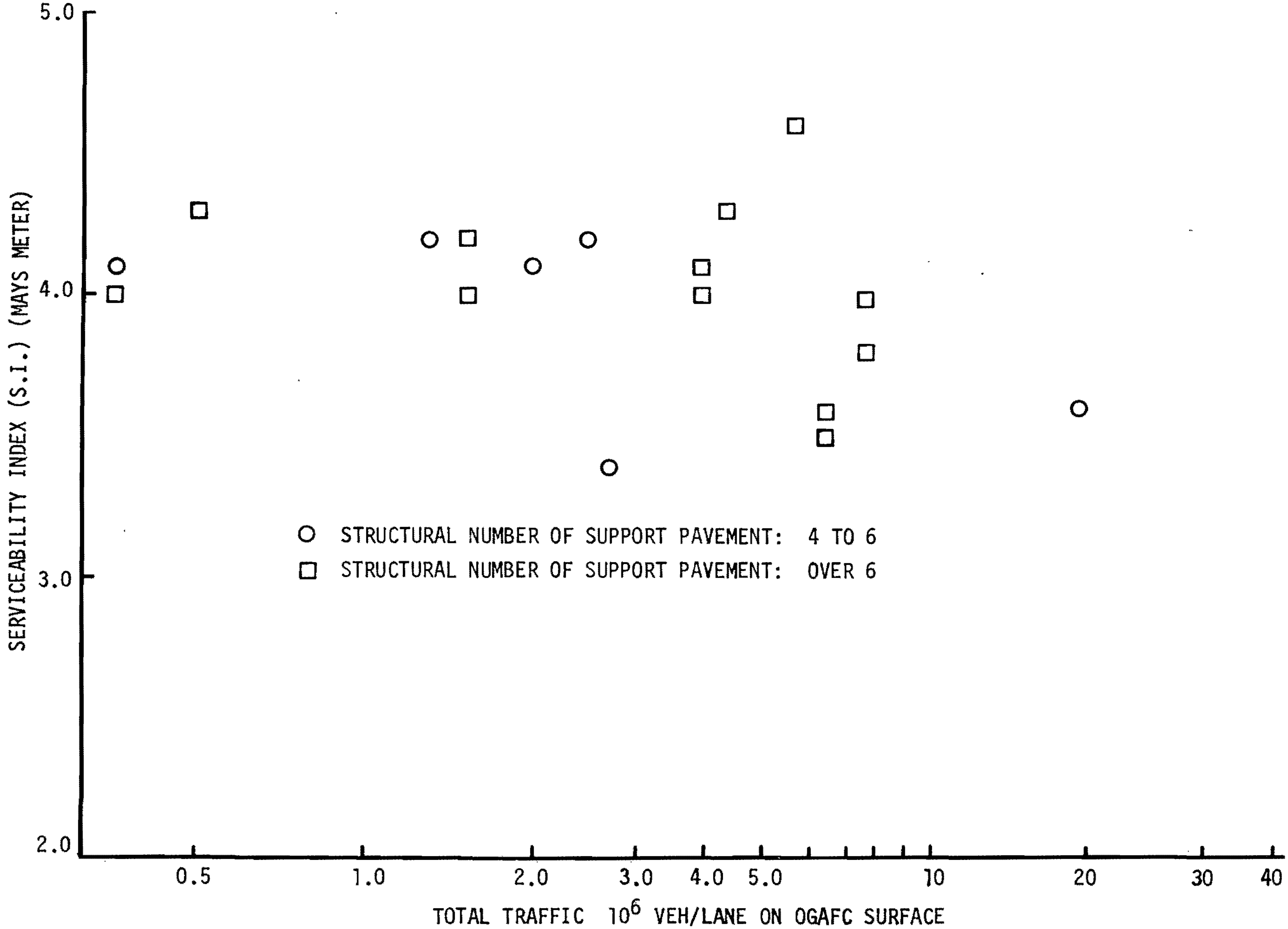

Figure 30. Riding Quality of OGAFC Pavements After Various Amounts of Traffic Application

Table 29. Effect of Traffic on Riding Quality of OGAFC Evaluation Pavements - Paired Data

Pavement Location*	Lane	Total Traffic on OGAFC Surface 10^6 Veh/Lane**	Serviceability Index (Mays Meter)
81/137/11.5	L - Traffic	0.4	3.9
	M - Passing	0.3	4.2
59/1763/22	R - Traffic	4.7	3.9
	S - Passing	3.1	4.2
59/1763/22.4	R - Traffic	4.7	4.0
	S - Passing	3.1	4.2
59/1762/3.45	R - Traffic	7.6	3.2
	S - Passing	5.1	3.9
59/1762/3.57	R - Traffic	7.6	3.2
	S - Passing	5.1	3.8
59/1762/4.21	R - Traffic	9.0	3.8
	S - Passing	6.0	3.8
59/1762/5.09	R - Traffic	9.0	3.7
	S - Passing	6.0	4.3

*Location Code: Highway No./Control No./Milepost

**Based on assumption of 60 percent of traffic in traffic lane and 40 percent in passing lane

Figure 31. OGAFC on SH 103 East of Lufkin, Texas 3/30/78

Raw Materials Characteristics

OGAFC mix raw materials characteristics considered in the following discussion include aggregate type and gradation, asphalt cement grade, viscosity-temperature slope, and hardening (oxidation) resistance.

Lightweight aggregates are often chosen for friction course mixes because they tend to have a renewable surface microtexture which can promote retention of skid resistance. Such aggregates were used in 2/3 of the OGAFC evaluation pavements considered in this study. However, two potential problems could limit selection of lightweight aggregates: high surface wear under traffic and particle crushing during construction.

Descriptions of aggregate wear on OGAFC evaluation pavements, given in Tables 18, 19, and 20 were converted into numerical "merit ratings" and these values plotted against total traffic in Figure 32. Generally, the lightweight fired clay aggregates do appear to wear somewhat faster than natural aggregates, but performance in this respect appears to be acceptable. The wear found with crushed slag is comparable to that observed with natural aggregates. Some of the lightweight aggregates showed indicated wear rates higher than others; the current L.A. Abrasion loss limits in Texas specifications covering such aggregates probably should be retained or even lowered somewhat.

Descriptions of aggregate crushing, based on laboratory examination of OGAFC evaluation pavement scores reported in Tables 18, 19, and 20, were also converted into ratings based on the relative degree of aggregate particle crushing noted. The distributions of these ratings

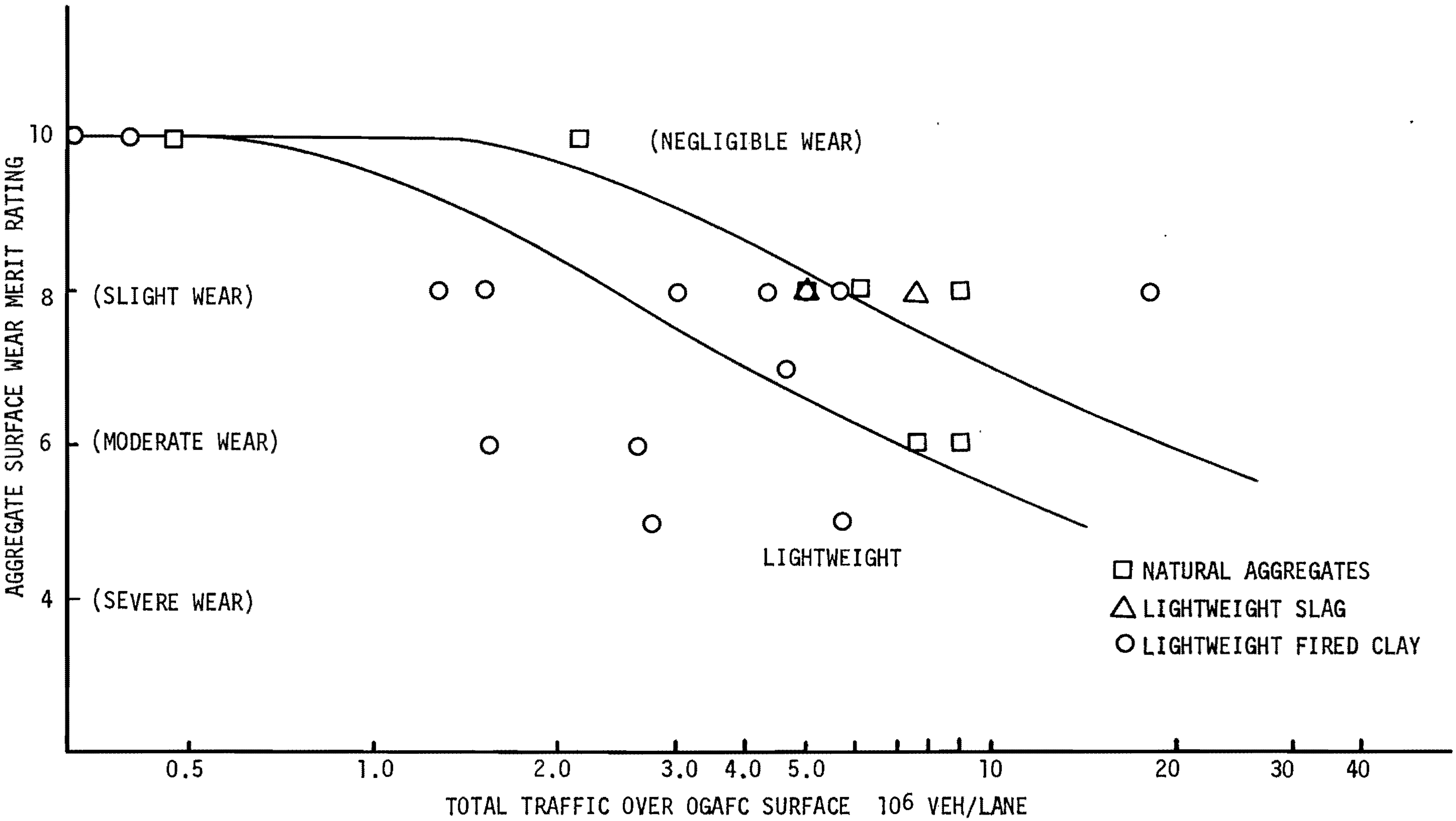

Figure 32. Trend of OGAFC Surface Wear With Applied Traffic With Various Kinds of Aggregate

for each kind of aggregate are shown in Figure 33. As expected, the fired clay lightweight aggregates appear to be more easily crushed than natural aggregates or slag. However, it also is evident that such aggregates can be used without encountering objectionable particle crushing if some care is taken when an OGAFC mix is made and placed. In any event, even in the few instances where more than a moderate degree of particle crushing occured, no specific service problems were evident.

In a previous discussion of the significance of Figure 2, it was pointed out that when the surface is not flooded, the relative wet skid resistance of an OGAFC pavement will be indicated by SN_{40} (ASTM E274) values. These numbers, in turn, are controlled by the pavement surface microtexture which, for OGAFC pavements, depends mostly on the aggregate particle surface texture. The information obtained in this study clearly supports this view. For example, Table 31 summarizes the SN_{40} values found on the OGAFC evaluation pavements and compares these numbers with representative polish values (Texas Method, Tex-438-A) of the aggregates used in the construction of these friction courses. The resulting relation between OGAFC pavement skid resistance and aggregate polish value is shown in Figure 34. As expected, somewhat lower skid numbers are measured on traffic lanes than on adjacent passing lanes as a result of a slightly different balance between aggregate weathering and tire polishing in the two situations. The benefits of using aggregates with relatively high polish values, such as the lightweight aggregates often

CRUSHING RATINGS: 1 = NEGLIGIBLE, 2 = SLIGHT, 3 = MODERATE, 4 = SEVERE

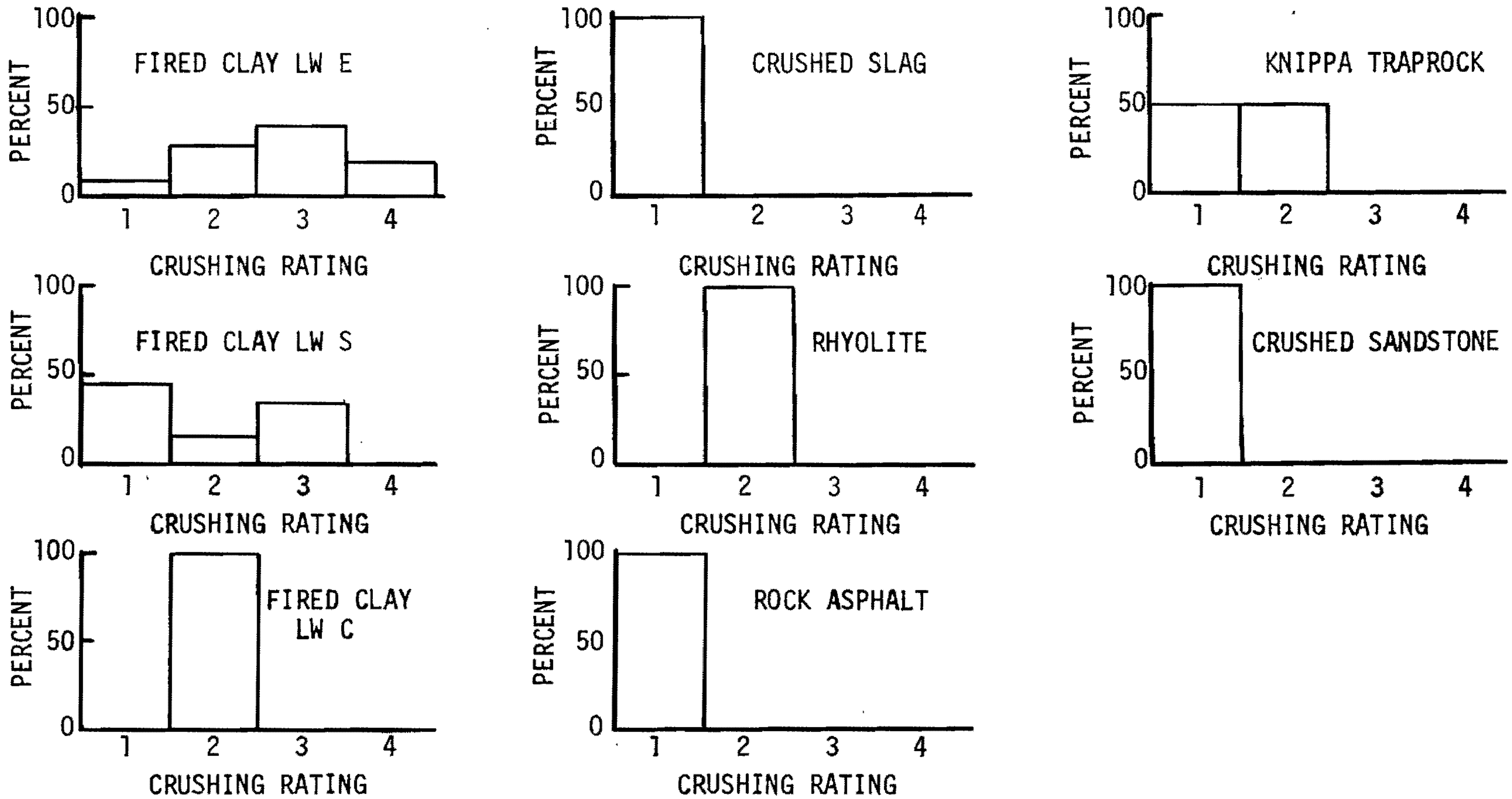

Figure 33. Distribution of Aggregate Crushing Observed in OGAFC Evaluation Pavement Cores

favored in Texas for making OGAFC mixes, is clearly demonstrated by these results. These data also suggest that aggregates with polish values lower than 40 may not be a good choice for OGAFC mixes. Or, to put it another way, construction of OGAFC mixes (or "plant mix seals") is not an acceptable way of avoiding the skid resistance problems inherent in the use of polishing aggregates.

As indicated in Table 2 (previously discussed), aggregate gradation is one of the input variables which could influence structural behavior and durability of OGAFC pavements. However, it has already been shown that such performance factors for the OGAFC evaluation pavements considered in this study were sensitive mainly to the structure and condition of the underlying pavement, and no influence of the aggregate used in the mixes could be discerned.

It was possible to estimate the effect of aggregate gradation, as indicated by the percent of fine material (passing a No. 10 sieve) used in the mix, on the drainage capacity of experimental sections of OGAFC on SH 21. This effect is indicated by the plot of permeability vs. percent fines in Figure 35. Since added fines will tend to fill voids between the "one-size" aggregate particles, the initial increase in permeability shown in the plot, to a maximum value, was unexpected. However, the influence of the initial addition of fine material on mix workability and compactability may be stronger than the void-filling tendency, and this could result in the trend shown. This suggests that addition of fine material to an OGAFC mix, up to 10 or 12 percent, may be beneficial in many respects. However, the size distribution and shape of such material may strongly influence the balance implied by the Figure 35 plot, and effects of these parameters

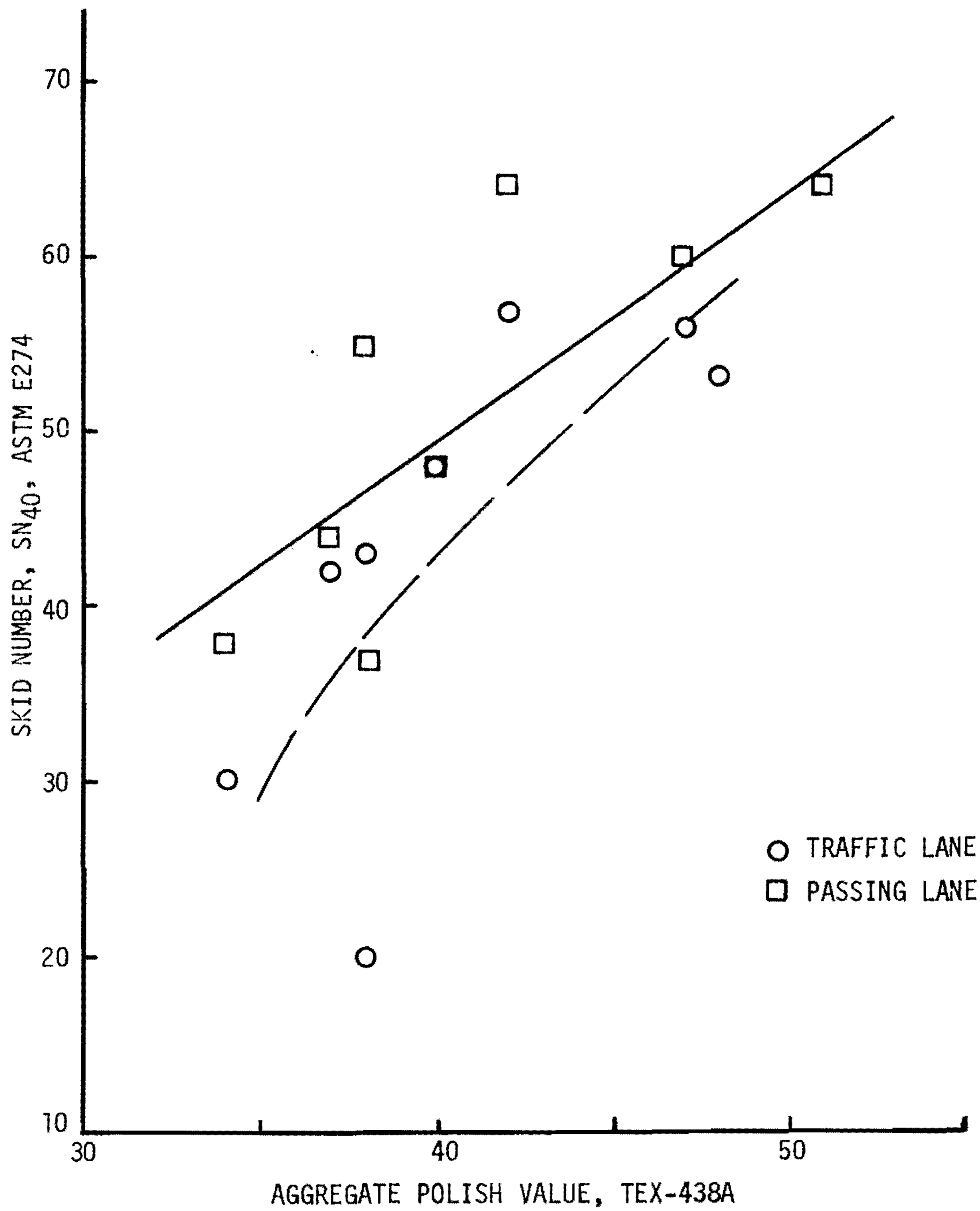

Figure 34. Relation Between OGAFC Pavement Skid Resistance and Aggregate Polish Value

favored in Texas for making OGAFC mixes, is clearly demonstrated by these results. These data also suggest that aggregates with polish values lower than 40 may not be a good choice for OGAFC mixes. Or, to put it another way, construction of OGAFC mixes (or "plant mix seals") is not an acceptable way of avoiding the skid resistance problems inherent in the use of polishing aggregates.

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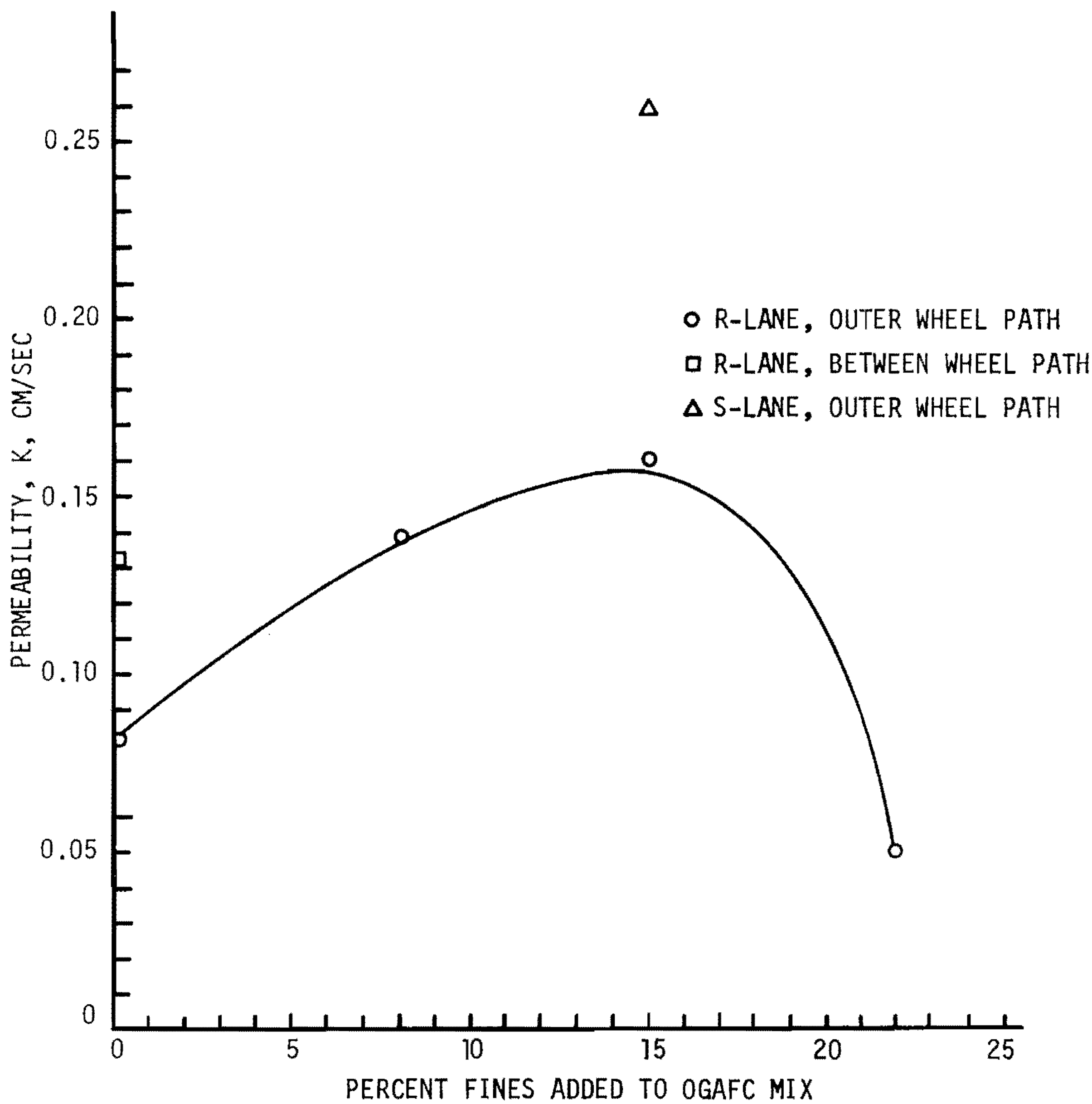


Figure 35. Effect of Mix Fine Aggregate Content on Permeability of Experimental OGAFC Pavements

require further investigation.

The trend of drainage capacity with percent of fine material in the aggregate could not be confirmed with the permeability data obtained on cores from the OGAFC pavements considered in this study. Other variables, particularly construction practices, appeared to have a much greater influence on the drainage capacity of these pavements.

While removal of rainfall without surface flooding is the most important reason for applying OGAFCs, there is another potential benefit: relatively high surface macrotexture resulting from projection of the aggregate particles out of the mix matrix. A logical expectation is that surface macrotexture would be strongly influenced by the particle size of the aggregate used to make the OGAFC mix. This expectation is confirmed by Figure 36, which is a plot of putty texture depth vs. average particle size of the aggregates used to produce the OGAFC evaluation pavement mixes. The correlation is only fair ($r = 0.75$), and other factors have also influenced the macrotexture of these pavement surfaces. For example, the potential macrotexture possible with a given size aggregate may be somewhat diminished by the tendency of the traffic to push and orient the particles. This effect is clearly indicated by the paired data given in Table 32, and probably is accentuated where the aggregate contains a significant proportion of elongated or flat particles. However, the predominant influence of aggregate particle size is evident. This is a very important consideration because even after the drainage capacity of an OGAFC pavement has diminished as a result of densification under traffic, or pore plugging, or other reasons, the surface will still offer

Table 31. Effect of Traffic on Surface Macrotexture of OGAFC Evaluation Pavements - Paired Data

Pavement Location*	Lane	Total Traffic on OGAFC Surface 10^6 Veh/Lane**	Putty Texture Depth Mils
81/137/11.5	R - Traffic	0.4	86
	S - Passing	0.3	90
81/137/11.5	L - Traffic	0.4	91
	M - Passing	0.3	91
59/1763/22	R - Traffic	4.7	70
	S - Passing	3.1	65
59/1763/22.4	R - Traffic	4.7	46
	S - Passing	3.1	70
59/1762/3.45	R - Traffic	7.6	44
	S - Passing	5.1	58
59/1762/3.57	R - Traffic	7.6	24
	S - Passing	5.1	52
59/1762/3.85	R - Traffic	9.0	39
	S - Passing	6.0	53
59/1762/5.09	R - Traffic	9.0	43
	S - Passing	6.0	63

*Location Code: Highway No./Control No./Milepost

**Based on assumption of 60 percent of traffic in traffic lane and 40 percent in passing lane

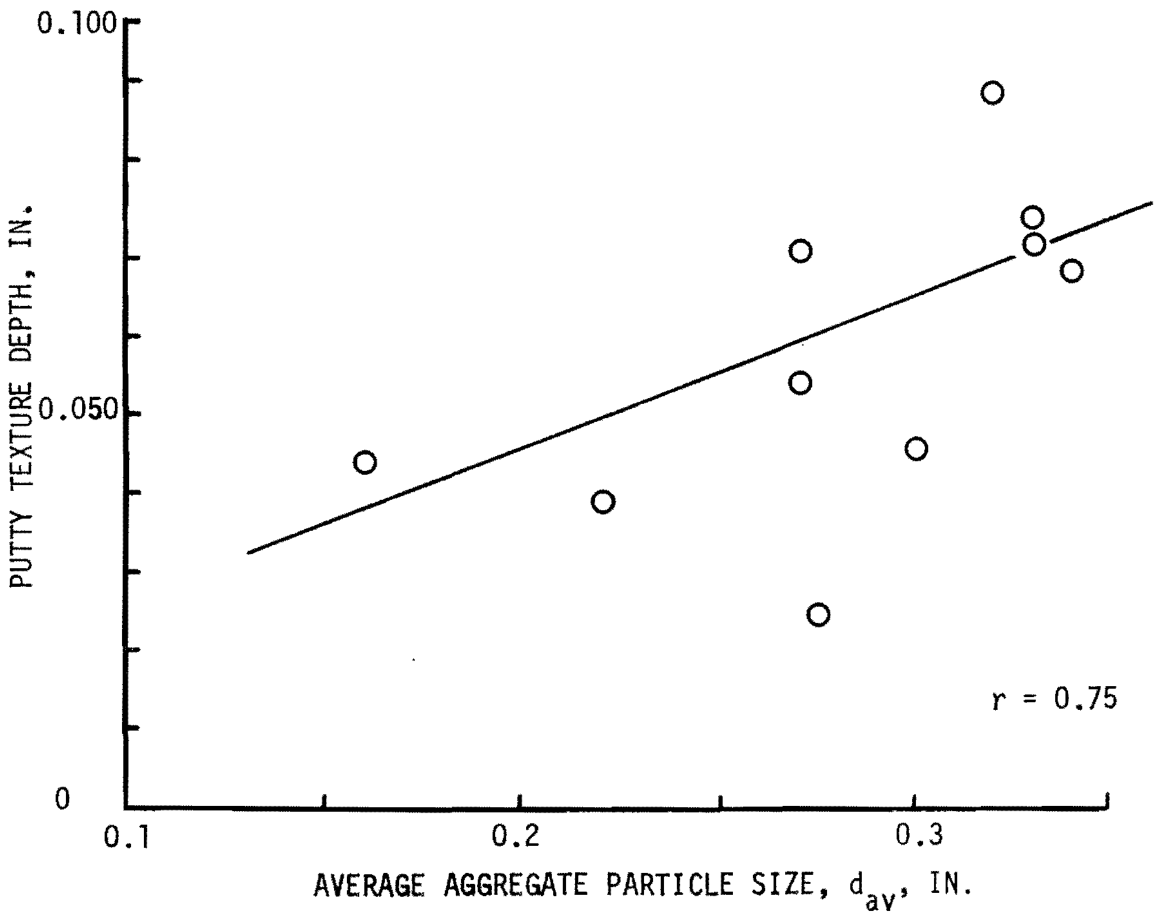


Figure 36. Influence of Aggregate Particle Size on Surface Macrotexture of OGAFC Pavements

some high-speed skid resistance if a high polish value aggregate has been used. This favors the selection of larger sized aggregates for OGAFC mixes; note that such aggregates can be used in open-graded mixes without encountering excessive vehicle noise levels (see reference [4]).

All of the mixes used to construct the OGAFC pavements considered in this study were made with AC-20 viscosity grade asphalt cement. Also, variations in viscosity-temperature slope among these asphalts were relatively small. Accordingly, none of the results of this study could be related directly to these aspects of binder selection. However, in a prior discussion, it was pointed out that the tendency for an asphalt to harden in service would have an important influence on selection of the appropriate viscosity grade as well as the rigor of any viscosity-temperature and oxidation stability specification requirements.

In this study, the tendency of the asphalt binder to harden was indicated by estimating a 2-year Hardening Index ($H.I._2$) from the viscosity of asphalts extracted from selected cores of OGAFC evaluation pavements (Tables 21, 22 and 23). Both the oxidation stability of the asphalt used and the air void content will affect these results. However, results of the thin film oven test (TFOT) (Table 14) indicate little variation in oxidation stability among the asphalts used and so the major consideration was air exposure as indicated by void content. A plot of $H.I._2$ values against air-void content is given in Figure 37. Although there appears to be a general tendency for the hardening index to increase as the air void increases, as might be

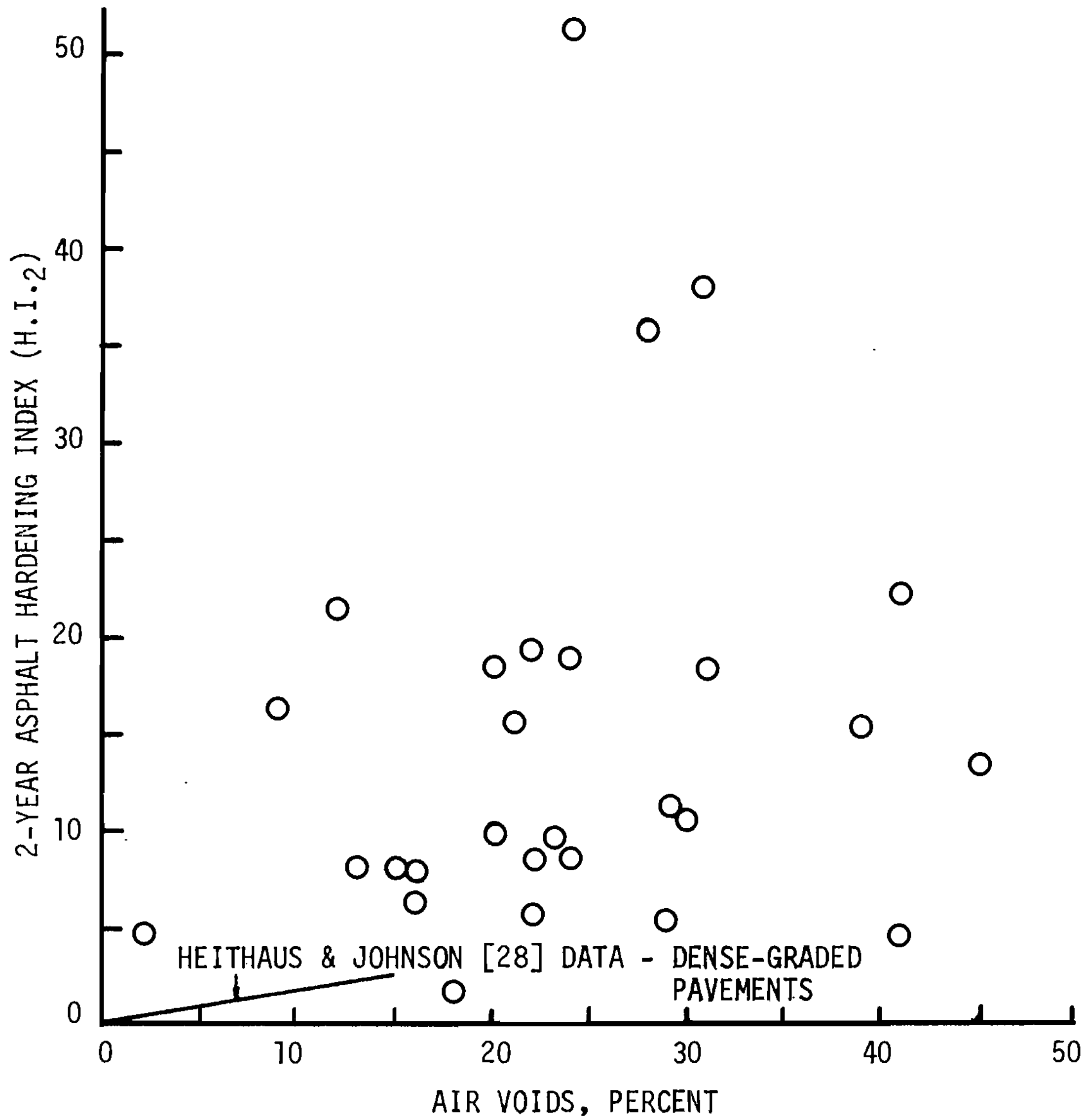


Figure 37. Plot of Asphalt Hardening Index Against OGAFC Air Void Content

expected; no trend line is shown on this plot because distortions resulting from the number of extreme values shown prevented making a reasonable regression analysis. However, note that nearly all of the $H.I._2$ values for the OGAFC pavements represented on this plot were well above the trend line developed from Heithaus and Johnson [28] data for dense-graded asphalt pavements. Also, as previously noted, the values are in about the same range as those reported by Traxler and Shelby [28] for dense-graded asphalt pavements. Thus, it appears that the contents with respect to asphalt hardening are at least as severe with OGAFC mats as with dense-graded overlays. Since a well designed and constructed OGAFC will have a relatively high air void content, this implies the need to select asphalt cements with superior oxidation resistance for OGAFC mixes.

OGAFC Mix Design and Layer Thickness

Of the various aspects of OGAFC design indicated in Figure 3 (considered in previous discussion), the relative proportions of asphalt and aggregate are most important. Several methods are used to estimate design asphalt contents for the OGAFC pavements considered in this study. These are outlined and compared with the FHWA recommended procedure in Table 33.

Since acceptable structural behavior and durability have been noted for all of the OGAFC pavements considered in this study, there appears to be little choice, in this respect, among the different design procedures used. In particular, no serious problems with surface bleeding or raveling were evident on these pavements.

Table 32. Comparison of Design Procedures for Estimating OGAFC Asphalt Content

Procedure	Aggregate Surface Capacity or Trial Asphalt Content		Design Asphalt Content	Correction for Asphalt Absorption?
	Measurements	Calculations		
A - FHWA [1][3][16] Used for SH 21 experimental sections and District 20 evaluation pavements.	Net retention (wt. %) of SAE 10 oil at 140F by coarse dry aggregate; corrected for oil absorption in aggregate pores and aggregate specific gravity	$K_C = 0.496O^{0.904}$ Use chart [1][3][16] O = corrected wt. % oil retention	$(2.0K_C + 4.0)\frac{2.65}{G_{CA}}$ G_{CA} = coarse aggregate Sp. Gr. (SSD)	Yes (Not used in Texas)
B - Used for District 2 evaluation pavements	None	Assume asphalt requirement = 16.5% by volume Trial asphalt content, $A = \frac{0.165 \times G_b}{0.165G_b + 0.835G_a} \times 100$ wt. percent G_b = Asphalt cement Sp. Gr. G_a = Aggregate Sp. Gr.	Lab mix 7 samples at trial asphalt content, A, and in 0.5% increments above and below A, hot (275F asphalt, 250F aggregate) and subjectively rate ease of mixing and aggregate coating. Select asphalt content, B, giving best results. --- Place 7 lab mixes on glass plate and observe draindown at 140F for 15, 45, 60 min. Select asphalt content, C, giving 60-70% plate bottom coverage in 60 min. --- Base design asphalt content on inspection of A, B and C	Inherent in experimental design procedure
C - Used for District 11 evaluation pavements	None	None	Asphalt content based on past experience	Past experience

On the other hand, the choice of design procedure may be of greater significance in producing adequate OGAFC internal drainage capacity. This is indicated by the analysis and summary of core permeability measurements presented in Table 34. The significance of such permeability measurements in terms of OGAFC drainage capacity has been indicated by the relation among permeability (K), direct drainage test values (K_D), and predicted flooding rainfall intensity (I_f) shown in Appendix C and Tables 28 and 29. From these data the categories of core permeabilities reported in Table 34 can be interpreted in terms of equivalent flooding rainfall intensity as follows:

Permeability K, cm/sec	Equivalent Flooding Rainfall Intensity, I_f, in/h (2% cross-slope)
Less than 0.05	Less than 0.07
0.05 to 0.1	0.07 to 0.14
0.10 to 0.20	0.14 to 0.28
over 0.20	over 0.28

Thus, the data in Table 34 indicate that many of the OGAFC evaluation pavements had low internal drainage capacity, in some cases even before these surfaces had been subjected to much traffic. Application of design procedure A (i.e., the FHWA procedure) appears to have resulted in the highest probability of producing an acceptable OGAFC drainage capacity. The one exception is the pavement where application of design procedure B resulted in attainment of the highest of the measured permeabilities. Of course, OGAFC permeability is also strongly dependent on construction techniques, (to be considered in

Table 33. Distribution of OGAFC Permeability Related to Design Procedure and Total Traffic

Design Procedure	Total Traffic 10^6 Veh/Lane	Number of OGAFC Pavement Cores Having Permeability (K, cm/sec) of			
		Less Than 0.05 (V.Low)	0.05 to 0.10 (Low)	0.10 to 0.2 (Medium)	Over 0.2 (High)
A (Experimental OGAFC Pavements and Dist. 20 Evaluation Pavements)	Less than 2	0	1*	3	0
	2 to 5	2	1	1	0
	5 to 10	0	0	1**	0
	over 10	0	0	0	0
	All	2	2	4	0
B (Dist. 2 OGAFC Evaluation Pavements)	Less than 2	3	0	0	1
	2 to 5	0	0	0	0
	5 to 10	0	0	0	0
	over 10	1	0	0	0
	All	4	0	0	1
C (Dist. 11 OGAFC Evaluation Pavements)	Less than 2	1	0	0	0
	2 to 5	2	0	0	0
	5 to 10	4	0	0	0
	over 10	0	0	0	0
	All	7	0	0	0

*Large proportion (22 percent) of fines added to mix used for this pavement

**10 percent field sand added to mix used for this pavement the following discussion) and the exception noted appears to have been the result of an optimum combination of design and construction.

Adjustment of the aggregate gradation by addition of fine material (passing the No. 8 or No. 10 sieve) may also be considered to be part of the mix design. For example, if this part of the FHWA design procedure is followed, the mix design will require significant additions of fine aggregate. Data on the effect of addition of fines on OGAFC permeability was considered in the foregoing discussion of aggregate gradation. One case of very low permeability resulting from very large additions of fine material is indicated in Table 34. On the other hand, this table also includes data on another OGAFC pavement made with addition of 10 percent field sand that had acceptable permeability even though Table 20 indicates slight to moderate surface bleeding.

An OGAFC mix design might also require the addition of mineral filler or agents that promote adhesion, stripping resistance, or mix workability (see Figure 3). However, no information concerning the effects of such additions could be obtained within the scope of this study, but such modifications should be considered seriously where special problems might dictate their use.

The thickness of OGAFC layers can exert a powerful influence on the internal drainage capacity of overlays of this kind. It is clear that, if an OGAFC has a thickness equivalent only to that obtained with a double aggregate seal coat, there will be little chance of forming internal passages for water drainage. Thus, a layer thickness equivalent to packing the aggregate particles at least 3 layers deep is desireable. This requirement is expressed by the Asphalt Institute recommendation [9] of a minimum OGAFC layer thickness two times the maximum aggregate size; that is, a layer thickness of 3/4 inch high for the Grade 4 aggregates used for the evaluation pavements of this study. Copas [1] reported that in 37 out of 47 states, a target thickness of either 5/8 inch or 3/4 inch was required, and that results obtained with mats 1/2 inch thick, or less, were not always satisfactory. Such criteria for OGAFC thickness can be compared with the actual thickness measured on evaluation pavements (recorded in Tables 18, 19, and 20) as follows.

District	Number of OGAFC Evaluation Pavements Having Thickness of:		
	Less than 5/8 in.	5/8 in. to 3/4 in.	over 3/4 in.
2	2	2	1
11	3	3	1
20	1	0	4
All	6	5	6

Note that 35 percent of the OGAFC evaluation pavements were less than 5/8 inch thick. This could be another contributing factor in the generally low drainage capacities found for the OGAFC evaluation pavements as indicated by the permeability measurements discussed above. For this reason, placement of too-thin OGAFC overlays is believed to be false economy. The sacrifice in overall performance resulting from placing OGAFC layers that are too thin is indicated by the predictions given in Table 35. In addition, Gallaway and Epps [16] have pointed out that placement of thicker OGAFC mats

Table 34. How OGAFC Pavement Drainage, Spray and Skid Resistance May Be Influenced by Layer Thickness

Point in OGAFC Life Cycle	Potential Performance With Layer Thickness 3/4 to 1 in.	Potential Performance With Layer Thickness ~ 1/2 in.
As constructed	High permeability. Good drainage. Little spray, low probability of dynamic hydroplaning if $I < 0.5$ in/h. Good macrotexture; high speed SN depends on aggregate used.	Low permeability. Fair drainage. Little spray, low probability of dynamic hydroplaning if $I < 0.05$ in/h. Good macrotexture; high speed SN depends on aggregate used.
At life-cycle mid-point (total traffic 15-20 x 10^6 vehicles per lane)	Medium permeability. Fair drainage. Little spray, low probability of dynamic hydroplaning if $I = 0.1$ to 0.2 in/h. Good macrotexture; high speed SN depends on aggregate used.	Impermeable. No drainage. Spray and dynamic hydroplaning resistance depend on drainage thru surface macrotexture. Original macrotexture preserved so that high speed SN depends on aggregate used.
At life-cycle end-point (total traffic 30-40 x 10^6 vehicles per lane)	Low permeability. Low to fair drainage. Little spray, low probability of dynamic hydroplaning if $I < 0.05$ in/h. Good macrotexture; high speed SN depends on aggregate used.	Impermeable. No drainage. Spray and dynamic hydroplaning resistance equal to chip seal surface with same macrotexture. Macrotexture and high speed SN depend on aggregate used.

promotes easier compaction, improved riding quality, and lower bleed-through potential over "fat spots" on the supporting surface. Another potential benefit of placing thicker layers would be an improvement in the contractor's confidence in successful completion of an OGAFC job which could result in lower unit bid prices.

Construction Practices

The OGAFC evaluation pavements in this study were constructed from one to seven years before this study was undertaken. Consequently, there was no opportunity for direct observation of the procedures used to construct these pavement surfaces. However, some observations have been reported by Gallaway and Epps [16] and a limited amount of data were available from the daily construction reports. In addition, some of the consequences of the construction practices followed could be inferred from observations made in the course of this study. In particular, the effects of surface preparation, weather, mix temperature, and transport, laydown, and rolling procedures are considered in the following discussion.

Potential problems related to preparation of the underlying surface include inadequate bonding to the OGAFC mat, lack of surface seal, bleeding of excess support surface asphalt into the OGAFC, and propagation of portland cement concrete joint cracks through the OGAFC layer. While generally adequate bonding of the OGAFC mats considered in this study was indicated by the visual examination of pavement cores, the possiblity of problems above portland cement concrete slab joints, illustrated by Figure 9, should be considered.

In addition, even with dense-graded overlays interposed between portland cement concrete support surfaces and the OGAFC mat, there was a serious reflection crack problem that was quite evident when Mays meter readings were taken on this kind of OGAFC evaluation pavement. Both the bonding and reflection crack problems probably could be alleviated by the use of available reinforcing fabrics over portland cement concrete slab joints before the first overlay is applied.

A condition of mild asphalt bleeding on the OGAFC support surface appears to pose no serious problem; in one pavement example of this study, a small amount of asphalt cement from an underlying chip seal surface appeared mostly to assist the interlayerband, and did not proceed into the OGAFC layer. On the other hand, instances are known where excess support surface asphalt have completely inundated the OGAFC mat.

The use of the term "plant mix seal" for OGAFC construction is very misleading. Open-graded plant mixes will not seal an old flexible pavement surface and the disasterous results previously noted (see discussion of Figure 31, above) can be expected.

OGAFC overlays should not be constructed during cold, wet weather, or when ambient temperatures are too low. Usually, there is little disagreement with such a rule, and it appears to have been followed in the construction of the OGAFC evaluation pavements of this study, as indicated by the weather data summarized in Tables 7, 8, 9, and 10. This precaution probably was an important contributing factor to the generally excellent durability observed with these pavements.

Mixing and placing temperatures usually were maintained between 100°F and 250°F being reported (Tables 7, 8, 9 and 10). These temperatures were significantly lower than those used in other states (mostly between 220°F and 250°F) and reflect a higher asphalt viscosity (about 50 cm^2/sec or 5000 centistokes) than the 7 to 9 cm^2/sec suggested by FHWA. No doubt, the lower mixing and placing temperatures usually employed in Texas aid in reducing asphalt drain-off during transport of the hot mix, but probably also result in relatively poor mix workability. It is believed that improved workability would result if this temperature was increased to 230°F to 240°F and, also if about 10 percent of a suitable fine aggregate (material passing a No. 10 sieve) were used in the mix. Under these conditions, asphalt drain-off could be controlled by the addition of from 3 to 5 percent of a suitable mineral filler (material passing a No. 200 sieve). Experiments to find the effects of several such fillers were a part of this study not yet completed when this report was drafted.

While results of direct observation of laydown and rolling practices used for the OGAFC pavements considered in this study were not available to the writer, some pertinent points can be made.

First, while satisfactory pavement structural performance and durability were achieved with the procedures actually used, the drainage capacities, indicated by core permeability measurements, were often not adequate for an OGAFC layer (see Table 34). Although mix design had an important influence on OGAFC drainage capacity, it is clear that placing and rolling techniques also contributed to these results. Improvements in these techniques should be developed in the field. It is suggested that use of the permeameter described in Appendix B would be quite helpful in achieving a goal of improved OGAFC drainage capacity. This rather simple piece of apparatus can be adapted easily for use in the field (see reference [9]), and should be used to make permeability measurements on the surface soon after the OGAFC mat has cooled, so that necessary adjustments in placing and compaction techniques can be made (and also mix design revisions) during the course of a construction project.

A second problem appears to have been encountered in transporting and placing the OGAFC mixes. In Figure 38, the amount of asphalt added to OGAFC mixes (construction report data summarized in Tables 7, 8 and 9) was compared with the asphalt percent determined by extraction on cores taken from corresponding OGAFC pavement layers (Tables 21, 22 and 23). The problem is indicated by the following:

1. The amount of asphalt found in the cores was frequently significantly different (usually less) than the amount added when the mix was made, and

2. In a given pavement, there was a considerable variation among samples in the amount of asphalt found. These variations were as much as 10 times the expected reproducibility of the test results.

One of the most likely explanations of these results is excessive asphalt drain-off during mix transport, even though the temperature was relatively low (185°F - 210°F). As previously discussed, this problem may be reduced by the addition of suitable mineral fillers to the mix.

Finally, it appears that rolling equipment and procedures should

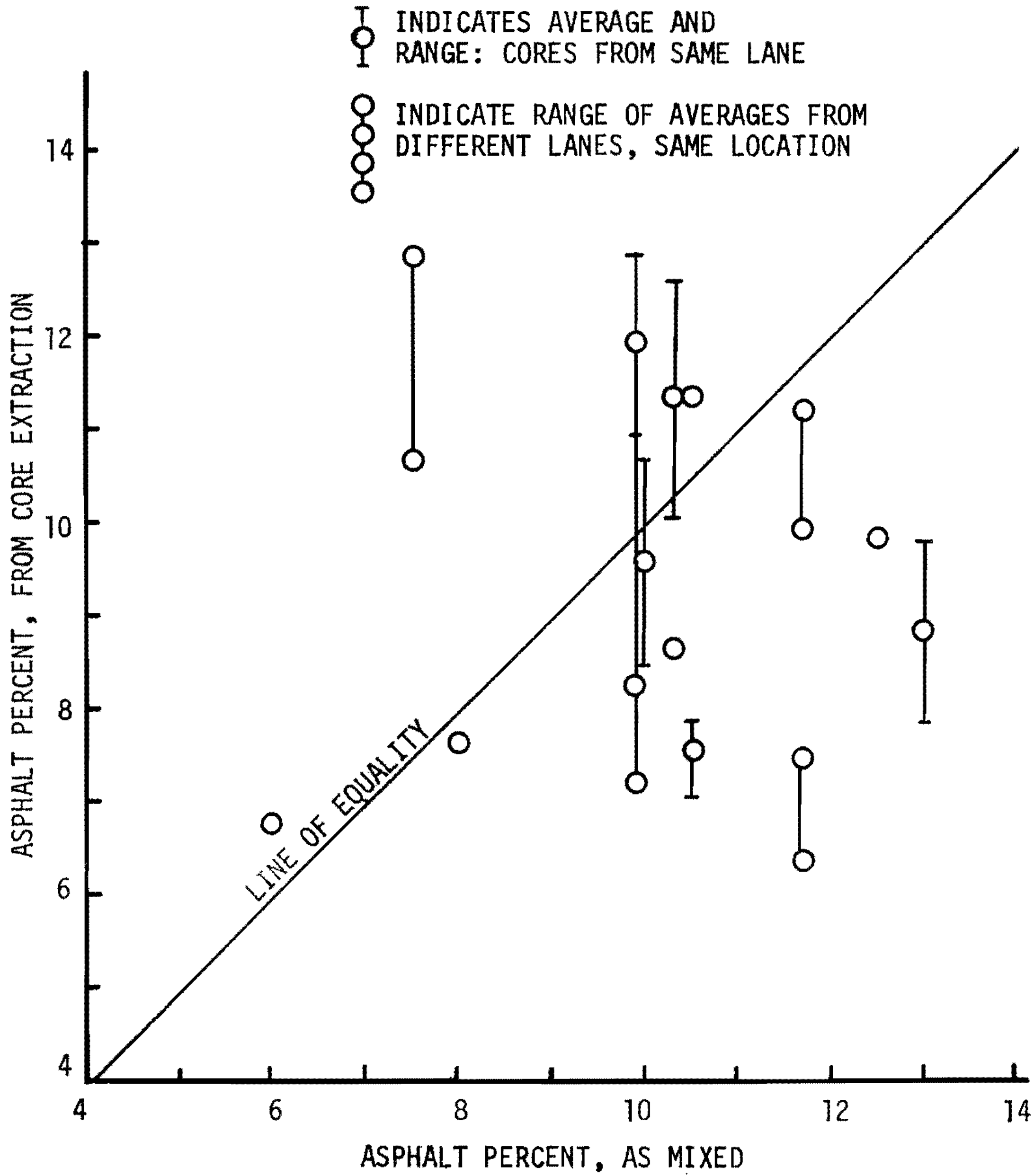


Figure 38. Comparison of OGAFC Mix Asphalt Content with Asphalt Percent Determined on Evaluation Pavement Cores

be reviewed to determine how to control the crushing occasionally observed with light weight aggregates. One potential benefit would be improved OGAFC layer porosity and drainage capacity.

CONCLUSIONS AND RECOMMENDATIONS

The following tentative conclusions and recommendations have been based on published reports, previous TTI studies, and the results of this study to date.

1. The generally excellent structural performance and durability observed on OGAFC evaluation pavements located in Texas SDHPT districts 2, 11 and 20 indicate that in these respects the materials selection criteria, mix design methods, and construction techniques used were satisfactory. However, it appears that mix design procedures and construction techniques may require some improvement in order to achieve the desired internal drainage capacity with assurance.

2. The tendency of the pavement rating score (PRS) to decrease as total traffic applied increases, for a properly designed and constructed OGAFC, depends strongly on the structural capacity of the underlying pavement. A life expectancy for a properly applied OGAFC mat appears to be at least 35 million vehicles per lane or about 7 years. An important factor that will tend to limit this life expectancy is the tendency of the asphalt binder to harden.

3. The riding quality of a properly constructed OGAFC surface will be retained indefinitely and will depend primarily on the roughness of the pavement on which it is placed. A level-up course should be applied before placing an OGAFC mat on a rough pavement. The underlying pavement should have a minimum serviceability index (as indicated by the Mays meter or other instruments) of about 4.0.

4. An OGAFC hot mix cannot be depended upon to seal a weathered, porous underlying pavement; adequate prior surface sealing is required in such instances. Tack coats, as normally applied, will not provide such sealing and attempts to use thick tack coats may cause construction related problems.

5. Use of Texas grade 4 surface treatment aggregates appears to be a good choice for OGAFC mixes. However, to ensure adequate pavement skid resistance such aggregates, particularly those that undergo distinct seasonal changes, should have a minimum polish value (Tex-438A) of about 40 and/or have demonstrated a capability of maintaining a minimum SN_{40} of about 40 under heavy traffic volumes. At least 60 percent of the particles in an OGAFC aggregate should be "one-size" (percent of material passing a 3/8 inch sieve and retained on a No. 4 sieve). An upper limit on the content of flat and elongated particles should be required in order to reduce the tendency of an OGAFC mat to close up and to lose surface macrotexture in service; a minimum flakiness index of 10 is suggested. The L. A. abrasion limit for lightweight aggregates used in OGAFC mixes should be retained at 35 percent, or even reduced to lessen the tendency of such aggregates to crush on handling.

6. AC-20 grade asphalt cement appears to be adequate for most OGAFC applications in Texas. However, improvements in oxidation resistance (as measured by a thin film oven test (ASTM D1754 or D2872) or other test methods) are desireable to reduce the tendency of the binder to harden in service and thus limit OGAFC life expectancy.

7. The current FHWA design procedure (reference 3) appears to be the best choice for estimation of the proportion of asphalt cement to

be used in an OGAFC mix. Other methods that may indicate asphalt coating and mix workability can be considered as useful adjuncts to the FHWA procedure.

8. Addition of up to 10 to 12 percent of fine material (passing a No. 10 sieve) should improve OGAFC mix workability and stability and will usually result in adequate mat porosity and drainage, provided the VMA value for the coarse aggregate used is adequate. However, this void capacity should be determined by an appropriate method (such as the one recommended by the FHWA [3]) and not be based on guess-work. Further studies should be made to determine the validity of the FHWA recommended method for estimating the proportion of added fine material, particularly as to how this percentage is influenced by the particle shape and size distribution of this material.

9. Details of OGAFC placement and compaction procedures currently used in Texas appear to require some revision in order to ensure placement of mats having adequate and uniform internal drainage capacity. These revisions should be developed in the field and monitored by surface permeability measurements made during construction, using the apparatus described in Appendix B.

10. Use of asphalt emulsions or other spray coatings to soften age hardened asphalt in an attempt to extend the life of OGAFC pavements will usually reduce the drainage capacity of the mat to zero. A better approach for achieving long OGAFC pavement life would be to make the original mixes with asphalt cements having superior oxidation resistance.

11. Determination and interpretation of the air void content of

OGAFC layers will probably always be a difficult and uncertain task. Permeability measurements, as discussed in this report, appear to be a much more practical and reliable way of evaluating the internal drainage capacity of such pavement surfaces.

12. OGAFC mixes containing lightweight aggregates can be placed with little or no aggregate crushing, if the mat is not too thin and if appropriate precautions are taken when the mat is compacted.

13. Separation or drainage of asphalt from OGAFC hot mixes during transport continues to be a serious problem, indicated by observations of significant differences between as constructed and design asphalt contents. Further work in this study should emphasize the investigation of addition of mineral fillers of various types as a method of controlling this problem.

14. The following guidelines should be considered when application of an OGAFC is being planned:

a) This kind of overlay should be used only when significant driver benefits can be realized as a result of improved skid and splash resistance. It is not a satisfactory method for sealing weathered surfaces or correction of surface roughness.

b) OGAFC mats should be placed only on structurally sound pavements having few cracks. Portland cement concrete slab joints can be covered with a reinforcing fabric and a dense-graded overlay before construction of an OGAFC mat to reduce reflection cracks.

c) In planning construction of an OGAFC, mat thicknesses of less than 3/4 inch should not be considered (assuming use of grade 4 aggregates in the mix).

d) Construction of an OGAFC may be a better choice than a chip seal for improving skid resistance on horizontal highway curves or where early exposure to traffic is required.

e) In planning construction of an OGAFC, considerable attention should be given to availability of adequate mixing, placing, and compaction equipment and to adequate field inspection. Such inspection should include permeability measurements to ensure adequate internal drainage capacity.

15. Further studies of the performance of OGAFC performance are recommended which should include:

Installation of a systematic record keeping plan in concerned SDHPT district offices on new OGAFC construction projects to acquire information including specific locations, materials test data, mix design data, and construction records (including permeability test data) followed up by periodic observation of the performance of such pavements including permeability measurements, SN_{40} data, pavement condition ratings (PRS), and Mays meter readings. Such data might be sent to TTI for analysis and interpretation.

REFERENCES

1. Copas, T. L., and Pennock, H. A., "Open Graded Friction Courses for Highways" NCHRP Synthesis of Highway Practice 49, Transportation Research Board, 1978.

2. White, T. D., "Construction and Evaluation of Airfield PFC in the United States", Proceedings, International Symposium on Porous Asphalt, Amsterdam, June 1976, Studie Centrum Wegenbouw, Record 2, pp 136-160, 1977.

3. Smith, R. W., Rice, J. M., and Spelman, S. R., "Design of Open-Graded Asphalt Friction Courses" Report No. FHWA-RD-74-2 and Supplement No. 1, Federal Highway Administration, Washington, D.C., January 1974 and July 1975.

4. Williams, W. L., Kay, R. A., and Stephens, J. K., "Noise Produced by Open-Graded Asphaltic Friction Courses", Public Roads, Vol. 39, No. 1, pp 16-20, June 1975.

5. Nakajiama, A., "Some Problems on Porous Asphalt in Japan", Proceedings, International Symposium on Porous Asphalt, pp 213-215, Studie Centrum Wegenbouw, the Netherlands, June 1976.

6. Gallaway, B. M., "A Review of Current Methods and Mechanisms for Producing Skid Resistant Pavements", Proceedings Association of Asphalt Paving Technologists, Vol. 42, pp 401-422, 1973.

7. Smith, R. W., "Examination of Factors Related to the Development and Performance of Open-Graded Asphalt Friction Courses", Proceedings, International Symposium on Porous Asphalt, Amsterdam, June 1976, Studie Centrum Wegenbouw, Record 2, pp 91-135, 1977.

8. Pelletier, R. F., "Demonstration Project No. 10, Improved Skid Resistant Pavements", Report No. FHWA-DP-10, Federal Highway Administration, February 1976.

9. ____________________, "Open-Graded Asphalt Friction Courses" Construction Leaflet No. 10, The Asphalt Institute, November 1974.

10. Bass, D. A., Norwood, J. W., and French, J. F., "Plant Mix Seal Coat or Open Grade Hot Mix", Report No. 602-1, Texas State Department of Highways and Public Transportation, July 1975.

11. Harrington, W. P., "Plant Mix Seal in District 7", Report No. 602-2, Texas State Department of Highways and Public Transportation, August 1976.

12. Little, C. H., "Open Graded Asphalt Friction Course", Report No. 602-3, Texas State Department of Highways and Public Transportation, December 1976.

13. Dudley, W. N., "Traveling Plant Open Graded Surface Course", Report No. SS 15.10, Texas Highway Department, December 1974.

14. Gallaway, B. M., and Epps, J. A., "Porous Pavements - Laboratory and Field Observations", Proceedings, International Symposium on Porous Asphalt, pp 48-89, June 1976.

15. Gallaway, B. M., "Tire-Pavement Interactions on Open Graded Friction Courses in Simulated and Natural Rainfall", Chapter IX of Report for DOT-FH-11-8269, Phase II pp 279-440, 1978.

16. Gallaway, B. M. and Epps, J. A., "Mixture Design Concepts, Laboratory Tests and Construction Guides for Open-Graded Bituminous Overlays", Research Report 36-1F, Texas Transportation Institute, Texas A&M University, October 1974.

17. Gallaway, B. M., Ivey, D. L., Hayes, G., Ledbetter, B. M., Olsen, R. M., Woods, D. L., and Schiller, R. F. Jr., "Pavement and Geometric Design Criteria for Minimizing Hydroplaning" Final Report, Phase II, Contract DOT-FH-11-8269, Texas Transportation Institute, Texas A&M University, January 1979.

18. Ivey, D. L., Lehtipuw and Button, J. W., "Rainfall and Visibility - The View from Behind the Wheel", Research Report 135-3, Texas Transportation Institute, Texas A&M University, February 1975, 51 pp.

19. White, T. D., "Porous Friction Surface Course", Misc. Paper S-75-12, U. S. Army Waterways Experiment Station, February 1975, 117 pp.

20. ____________________, "Method of Test for Centifuge Kerosene Equivalent Including K-Factor" Test Method No. Calif. 303-F, California Division of Highways (October 7, 1974).

21. Kandhal, P. S., Brunner, R. J., and Nichols, T. H., "Design, Construction and Performance of Asphalt Friction Courses", Transportation Research Record 659, Transportation Research Board, pp 18-23, 1977.

22. Schweyer, H. E., Moore, J. P., and Ting, J. K., "Rheology of Asphalt Cements at 60°C (140°F)", Special Technical Publication 532, ASTM, pp 3-15, 1973.

23. Epps, J. A., Shaw, C. W., Harvey, G. G., Mahoney, J. P., and Scott, W. W., Jr., "Operational Characteristics of Mays Ride Meter", Research Report 151-3, Texas Transportation Institute, Texas A&M University, September, 1976.

24. Epps, J. A., Meyer, A. H., Larrimore, I. E., Jr., and Jones, H. L., "Roadway Maintenance Evaluation Users Manual", Research Report 151-2, Texas Transportation Institute, Texas A&M University, September, 1974.

25. Epps, J. A., Larrimore, I. E., Jr., Meyer, A. H., Cox, S. G., Jr., Evans, J. R., Jones, H. L., Mahoney, J. P., Wootan, C. V., and Lytton, R. C., "The Development of Maintenance Management Tools for Use by the Texas Department of Highways and Public Transportation", Research Report 151-4F, Texas Transportation Institute, Texas A&M University, September 1976.

26. Traxler, R. N. and Shelby, M. D., "Reduction of Asphalt Hardening in Surface Courses of Bituminous Pavements", Proceedings, Association of Asphalt Paving Technologists, Vol. 42, pp 126-159, 1973.

27. Coons, R. F., and Wright, P. H., "An Investigation of the Hardening of Asphalt Recovered from Pavements at Various Ages", Proceedings, Association of Asphalt Paving Technologists, Vol. 37, pp 510-528, 1968.

28. Heithous, J. J., and Johnson, R. W., "A Microviscometer Study of Road Asphalt Hardening in the Field and in the Laboratory", Proceedings Association of Asphalt Paving Technologists, Vol. 27, pp 17-34, 1958.

29. Corbett, L. W., and Schweyer, H. W., "Viscosity Characterization of Asphalt Cements", ASTM Special Technical Publication 532, pp 40-51, 1972.

30. Fruggiero, R. L., and Giardino, N. A., "Pavement Failure Investigation, Route I-95 (Route 2 to Route 3)", Research Report, Rhode Island Department of Transportation, Materials Section, June 1978.

31. Lambe, T. W., "Soil Testing", John Wiley and Sons, Inc., p. 60, 1951.

32. ____________________, "AASHO Interim Guide for Design of Pavement Structures - 1972", American Association of State Highway and Transportation Officials, Washington, D. C., 1972.

33. Van Til, C. J., et al., "Evaluation of Interim AASHO Guides for Design of Pavement Structures", NCHRP Report 128, Transportation Research Board, 1972.

34. Edris, E. V., Jr., Epps, J. A., and Lytton, R. L., "Layer Equivalents for Base Courses in City of Houston - Harris County", Special Report, Texas Transportation Institute, August 1974.

35. Gallaway, B. M., Ivey, D. L., Ross, J. E., Jr., Ledbetter, W. B., Woods, D. L., and Schiller, R. E., Jr., "Tentative Pavement and Geometric Design Criteria for Minimizing Hydroplaning", Final Report, Phase I, Contract DOT-FH-11-8269, Texas Transportation Institute, Texas A&M University, February 1975.

36. McLaughlin, J. F. and Goetz, W. H., "Permeability, Void Content, and Durability of Bituminous Concrete", Proceedings, Highway Research Board, Vol. 34, pp 274-286, 1955.

37. Moore, D. F., "Prediction of Skid-Resistance Gradient and Drainage Characteristics for Pavements", Highway Research Record, No. 131, Design, Performance and Surface Properties of Pavements, pp 181-203, 1966.

38. Hutchinson, J. W., Kao, T. H., and Pendley, L. C., "Pavement Dynamic Permeability Testing", Highway Skid Resistance, ASTM, STP 456, pp 159-176, 1968.

39. Scheidegger, A. E., The Physics of Flow Through Porous Media, 3rd ed., University of Toronto Press, 1974.

40. Kilpatrick, M. J. and McQuate, R. G., Bituminous Pavement Construction, Research and Development Report, U.S. Department of Transportation, June 1967.

41. Scrivner, F. H. and Moore, W. M., "Evaluation of the Stiffness of Individual Layers in a Specially Designed Pavement Facility from Surface Deflections", Research Report 32-8, Texas Transportation Institute, Texas A&M University, June 1966.

APPENDIX A

DETERMINATION OF PAVEMENT RATING SCORES FOR TEXAS OGAFC EVALUATION PAVEMENTS

APPENDIX A

DETERMINATION OF PAVEMENT RATING SCORES FOR TEXAS OGAFC EVALUATION PAVEMENTS

Introduction

One of the most important indications of the performance of open-graded friction courses is their durability compared to that observed for surface courses constructed using conventional dense-graded asphalt concrete mixes. Such indications of durability can be obtained by determining the changes in quantitative indices of pavement serviceability with total traffic and/or time. One index of this kind, chosen for this study, was the Pavement Rating Score based on a pavement condition survey method developed as part of a Maintenance Rating System for use on Texas highways (Epps, et al. [24] [25]). Although there are problems in applying this method, it is not difficult to use, and data for making performance comparisons are available (Epps, et al. [25]).

Approach

In general, the rating method used in this study depended on making visual estimations of the degree of severity and extent of the following forms of pavement distress:

1. Rutting
2. Raveling
3. Flushing
4. Corrugations

5. Alligator Cracking
6. Longitudinal Cracking
7. Transverse Cracking
8. Patching

In addition, supplementary observations were made and recorded. A numerical pavement rating score was calculated from these estimates by subtracting "deduct values" associated with the various forms of distress from 100. Thus a score of 100 indicated a pavement with no observable distress. Deduct values used are summarized in Table A-1.

In this study, no deduct points were made for ride roughness indicated by Mays meter readings; these were used to estimate a serviceability index reported separately. Where OGAFC surfaces had been placed over portland cement concrete pavements, it was observed that invariably transverse reflection cracks appeared over the joints in the concrete slab. Since the OGAFC layers were quite thin, it was felt that in such instances, reduction in the pavement rating scores for transverse cracking would result in a rating which would not accurately evaluate the service performance of such surface layers. Accordingly, in this study, deduct points for transverse cracking were not made when pavement rating scores were calculated for OGAFC evaluation pavements laid over portland cement concrete slabs.

Visual pavement ratings were made by a team of engineers from SDHPT Divisions D-6, D-8, D-9, D-10, and D-18 together with a Texas Transportation Institute representative and personnel of the highway district which the evaluation pavement was located. This team was organized with the expectation that the varied backgrounds among the members would tend to reduce

Table A-1. Deduct Table Flexible Pavement Evaluation

Negative Values to be Assigned to the Various Degrees of Pavement Failures

Type of Distress	Degrees of Distress	Extent or Amount of Distress (1)	(2)	(3)
Rutting	Slight	0	2	5
	Moderate	5	7	10
	Severe	10	12	15
Raveling	Slight	5	8	10
	Moderate	10	12	15
	Severe	15	18	20
Flushing	Slight	5	8	10
	Moderate	10	12	15
	Severe	15	18	20
Corrugations	Slight	5	8	10
	Moderate	10	12	15
	Severe	15	18	20
Alligator Cracking	Slight	5	10	15
	Moderate	10	15	20
	Severe	15	20	25
Patching	Good	0	2	5
	Fair	5	7	10
	Poor	7	15	20

Deduct Points for Cracking

Longitudinal Cracking

	Sealed (1)	(2)	(3)	Partially Sealed (1)	(2)	(3)	Not Sealed (1)	(2)	(3)
Slight	2	5	8	3	7	12	5	10	15
Moderate	5	8	10	7	12	15	10	15	20
Severe	8	10	15	12	15	20	15	20	25
Transverse Cracking									
Slight	2	5	8	3	7	10	3	7	12
Moderate	5	8	10	7	10	15	7	12	15
Severe	8	10	15	10	15	20	12	15	20

the human factor effects present in making such subjective ratings and so as to be in a position to make comparable future ratings of OGAFC pavements. The rating schedule and team make-up for this study is shown in Table A-2.

The OGAFC evaluation pavements varied in length from a few hundred feet to 11 miles. In addition, variations in rating scores from lane-to-lane on multilane highways could be expected. Thus to obtain representative pavement ratings it was desirable to make visual observations at several locations on each of the OGAFC evaluation pavements. The number of rating locations for each of these pavements is indicated in Table A-2; each lane at a given milepost was considered to be a separate location in making this count. Every effort was made to select a location where the road surface condition could be considered to be representative of that roadway section. Since the trend of pavement rating score with total traffic and/or time is desired, future pavement condition surveys on these evaluation pavements should be made at the same locations (i.e., the same lane and milepost).

Mays meter readings (taken by J. P. Underwood and S. C. Britton in Districts 2 and 11 and by J. P. Mahoney and S. C. Britton in District 20) on the OGAFC evaluation pavements were made so that these measurements would represent the pavement roughness at the locations listed in Table A-2.

To supplement the results of the field survey, the condition of the evaluation pavements was also assessed by examination of cores taken at selected locations primarily for the purpose of making laboratory permeability measurements. OGAFC layer thickness was determined by direct measurements made on the cores. Subjective visual ratings were made and

Table A-2. Schedule of Condition Ratings for Texas OGAFC Evaluation Pavements

Site Location			Date Rated	Number of Rating Locations	Visual Ratings Made By
Distr.	Hwy	Control No.			
2	I 820	812	3/30/78	12	R. Rawle, D. A. Bass, C. F. Jett, J. L. Brown, C. H. Hughes, J. P. Underwood, I. E. Larrimore, S. C. Britton
2	I 30	10681	3/30/78	8	" "
2	US 81	137	3/31/78	12	" "
2	SH 101	1347	3/31/78	4	" "
2	SH 114	3521 3522	3/31/78	6	" "
11	US 59	1763	3/16/78	8*	Johnson, S. M. Prince, C. F. Jett, J. L. Brown, C. H. Hughes, J. P. Underwood, I. E. Larrimore, S. C. Britton
11	US 59	1762	3/17/78	14**	" "
11	US 59	1761	3/17/78	4	" "
20	I 10	7392	2/27/78	1	Butcher, W. N. Dudley, J. L. Brown, C. H. Hughes, J. P. Underwood
20	I 10	289	2/27/78	1	" "
20	SH 87	3056	2/27/78	1	" "
20	SH 87	3057	2/27/78	1	" "
20	US 96	655	2/27/78	1	" "

*Ratings on 2 sections made with different aggregates

**Ratings on 5 short sections made with different aggregates recorded to assess the condition of the OGAFC layers with respect to raveling and bleeding as follows: none, slight, moderate, and severe. The remaining factors describing the condition of OGAFC layers were rated on a numerical scale as outlined in Table A-8.

Results and Photographic Record

An example of the data sheets resulting from the visual survey of the OGAFC evaluation pavements, by the rating team, is presented as Table A-3. Calculations of pavement rating scores corresponding to these data are indicated by Table A-4. All of the resulting pavement rating scores are tabulated in Tables A-5, A-6 and A-7, and also presented in the main body of this report. Photographs were taken, at representative locations which provide a visual record of the condition of each of these evaluation pavements. This record is presented as Figures A-1 through A-20. In these figures each location is identified by a code which can be translated as follows: Highway No./ Control No./ Milepost/ Lane Designation (for lanes appearing in each general view).

The supplementary visual condition ratings made on cores taken from the OGAFC evaluation pavements are presented in Tables A-9, A-10, A-11 and A-12. When these data were summarized for tables in the main body of this report, numerical ratings were converted to the equivalent subjective ratings listed in Table A-8.

Table A-3. Example of Data Sheet Taken for Visual Condition Ratings of Texas OGAFC Evaluation Pavements

Rating Location							Pavement Distress Mode																									Remarks			
District No.	Rating Sect.	County No.	Highway No.	Control No.	Milepost	Lane	Rutting			Raveling			Flushing			Corrugations			Alligator Cracking			Longitudinal Cracking			Transverse Cracking			Sealing	Patching			Slight closing in wheel path	Reflection Cracking	Longitudinal Cracks Between Lanes	Other Remarks
							Slight	Moderate	Severe	Slight	Moderate	Severe	Slight	Moderate	Severe	Slight	Moderate	Severe	Slight	Moderate	Severe	Slight	Moderate	Severe	Slight	Moderate	Severe	Crack	Good	Fair	Poor				
0 2	0 1	2 2 0	I820	812	11.4	L	2				3			‡2		0			0				* 2			**1		3		0		✓	**	*	‡Apparent flushing may be due to sealer applicator
0 2	0 1	2 2 0	I820	812	11.4	M	1			1			1			0			0				* 2			**1		3		0		✓	**	*	
0 2	0 2	2 2 0	I820	812	9.4	L	1				2			2		0			0				* 2			**1		3		0		✓	**	*	
0 2	0 2	2 2 0	I820	812	9.4	M	1			1			1			0			0				* 2			**1		3		0		✓	**	*	
0 2	0 3	2 2 0	I820	812	8.1	L	1				3			2		0			0				* 2			**1		3		0		✓	**	*	*Cracking in center of lane
0 2	0 3	2 2 0	I820	812	8.1	M	1			1			1			0			0				* 2			**1		3		0		✓	**	*	
0 2	0 4	2 2 0	I820	812	8.1	R	1				2		1			0			0				* 2			**1		3		0		No	**	*	*Cracking in center of lane
0 2	0 4	2 2 0	I820	812	8.1	S	1			1			1			0			0				* 2			**1		3		0		No	**	*	
0 2	0 5	2 2 0	I820	812	9.4	R	1			1				3		0			0				* 2			**1		3		0		✓	**	*	*Cracking in center of lane
0 2	0 5	2 2 0	I820	812	9.4	S	1			1			1-			0			0				* 2			**1		3		0		No	**	*	
0 2	0 6	2 2 0	I820	812	11.4	R	1				2			2		0			0				* 2			**1		3		0		✓	**	*	Bad pot-hole raveling around cracks
0 2	0 6	2 2 0	I820	812	11.4	S	1			1			2			0			0				* 2			**1		3		0		✓	**	*	

Notes a) Frequently most raveling was observed outside of normal wheel paths
b) Ratings for severity and extent of distress in accordance with reference 24

Table A-4. Example of Calculations of Pavement Rating Scores From Visual Ratings Given in Table A-3

Rating Location				Deduct Points (Associated with Visual Ratings in Table A-3)							
Hwy	Control No.	Mile-Post	Lane	Rutting	Raveling	Flushing	Corrugations	Longitudinal Cracks	Transverse Cracks	Patching	Pavement Rating Score
I820	812	11.4	L	2	15	12	0	15	0	0	56
		11.4	M	0	5	5	0	15	0	0	75
		11.4	R	0	12	12	0	15	0	0	61
		11.4	S	0	8	8	0	15	0	0	69
I820	812	9.4	L	0	12	12	0	15	0	0	61
		9.4	M	0	5	5	0	15	0	0	75
		9.4	R	0	5	15	0	15	0	0	65
		9.4	S	0	5	3	0	15	0	0	77
I820	812	8.1	L	0	12	12	0	15	0	0	61
		8.1	M	0	5	5	0	15	0	0	75
		8.1	R	0	12	5	0	15	0	0	68
		8.1	S	0	5	5	0	15	0	0	75

Table A-5. Summary of Results: Survey of Condition of OGAFC Pavements in District 2

Rating Location				Pavement Rating Score	Photographic Record in Fig. No.
Highway	Control No.	Milepost	Lane		
I 820	812	11.4	R	61	--
			S	69	--
			L	56	A-1
			M	75	A-1
I 820	812	9.4	R	65	A-2
			S	77	A-2
			L	61	A-2
			M	75	A-2
I 820	812	8.1	R	68	A-3
			S	75	A-3
			L	61	A-3
			M	75	A-3
I 30	10681	430.8	R	76	A-4
			S	80	A-4
			L	76	A-4
			M	76	A-4
I 30	10681	433.6	R	80	--
			S	84	--
			L	78	--
			M	97	--
US 81	137	14.6	R	100	A-5
			S	100	A-5
			L	100	A-6
			M	100	A-6
US 81	137	11.5	R	100	--
			S	100	--
			L	100	--
			M	100	--

Table A-5 (cont'd)

Rating Location				Pavement Rating Score	Photographic Record in Fig. No.
Highway	Control	Milepost	Lane		
US 81	137	8.3	R	100	--
			S	100	--
			L	100	--
			M	100	--
SH 101	1347	14.3	R	100	A-7
			L	100	A-7
SH 101	1347	21.7	R	85	--
			L	95	--
SH 114	3521	22.2	R	100	--
			L	100	--
SH 114	3521	27.2	R	100	A-8
			L	100	A-8
SH 144	3522	35.4	R	100	--
			L	100	--

Table A-6. Summary of Results: Survey of Condition of OGAFC Pavements in District 11

Rating Location				Pavement Rating Score	Photographic Record in Fig. No.
Highway	Control	Milepost	Lane		
US 59	1763	20.5	R	85	--
			S	100	--
US 59	1763	22	R	90	A-9
			S	100	A-9
US 59	1763	22.4	R	92	--
			S	100	--
US 59	1762	3.45	R	85	A-10
			S	97	A-10
US 59	1762	3.57	R	85	A-11
			S	92	A-11
US 59	1762	3.85	R	73	A-12
			S	100	A-12
US 59	1762	4.21	R	95	--
			S	100	--
US 59	1762	4.27	S	90	A-13
US 59	1762	4.86	R	75	--
			S	95	--
US 59	1762	5.09	R	95	A-14
			S	100	A-14
US 59	1762	5.22	R	73	--
US 59	1761	23.6	R	100	A-15
			S	100	A-15
			L	100	A-15
			M	100	A-15

Table A-7. Summary of Results: Survey of Condition of OGAFC Pavements in District 20

Rating Location				Pavement Rating Score	Photographic Record in Fig. No.
Highway	Control	Milepost	Lane		
I 10	7392	847	L	95	A-16
I 10	289	861	R	95	A-17
SH 87	3056	1	R	78	A-18
SH 87	3057	3.5	R	90	A-19
US 96	655	23	L	90	A-20

Table A-8. Visual Rating System Used in Examination of OGAFC Pavement Evaluation Cores

Condition Evaluated	Description	Numerical Rating	Equivalent Objective Rating
Aggregate Wear	No observable wear at exposed surfaces of aggregate particles	10	Negligible
	Some surface wear, but very small change in particle size (< 5 percent).	8	Slight
	Surface wear equivalent to 5 to 10 percent of particle diameter.	6,7	Moderate
	Considerable surface wear; equivalent to 20 to 25 percent.	5	Severe
	Surface wear equivalent to more than 25 percent of particle diameter.	3	Very Severe
Interlayer Adhesion	Asphalt film between layers clearly evident; excellent adhesion.	10	Excellent
	Very thin asphalt film between layers; excellent adhesion.	8	Excellent
	No asphalt film between layers; no evidence of adhesive failure.	5	Adequate
	No asphalt film between layers; incipient adhesive failure.	4	Questionable
Penetration of OGAFC Aggregate	Reported in terms of intrusion of aggregate into substrate, percent of average aggregate particle size.	0 to 5% 5 to 10% 15 to 20% Over 20%	None Slight Moderate Severe
Deterioration of Underlying Course	No deterioration; looks like newly laid asphalt concrete.	10	None
	All particles asphalt coated; some evidence of weathering.	7,8	Slight
	Some evidence of asphalt stripping; significant weathering.	5,6	Moderate
	Significant amount of asphalt stripping; incipient disintegration.	4 or less	Severe

Table A-9. Visual Condition Ratings on OGAFC Cores, District 2

Core Identification*	Aggregate	Underlying Course	Layer Interface		OGAFC Layer			
		Deterioration	Adhesion	Penetration of OGAFC Aggr, %	Raveling	Bleeding/ Flushing	Aggregate Wear	Thickness in.
30/1681/433.6/LOWP	Eastland LW	8	8	5	Moderate	Slight	8	0.78
30/1681/433.6/LBWP	"	8	6	0	None	Moderate	8	1.00
30/1681/433.6/MOWP	"	8	8	0	None	Moderate	8	0.66
30/1681/433.6/MBWP	"	8	8	5	None	Moderate	8	0.75
30/1681/433.6/ROWP	"	8	6	5	Moderate	Slight	8	0.50
30/1681/433.6/RBWP	"	6	7	5	None	Moderate	8	0.81
30/1681/433.6/SOWP	"	8	9	5	Slight	Moderate	8	0.81
30/1681/433.6/SBWP	"	8	8	10	Slight	Moderate	8	0.97
81/137/14.6/LOWP	TX1-Streetman LW	8	10**	15	None	None	10	0.63
81/137/14.6/LBWP	"	8	10**	15	None	None	10	0.69
81/137/14.6/MOWP	"	8	10**	15	None	None	10	0.72
81/137/14.6/MBWP	"	8	10**	15	None	None	10	0.72
81/137/14.6/ROWP	"	8	8	0	None	None	10	0.63
81/137/14.6/RBWP	"	8	8	0	None	None	10	0.75
81/137/14.6/SOWP	"	8	10**	5	None	None	10	0.69
81/137/14.6/SBWP	"	8	10**	5	None	None	10	0.69

*Location Code: Highway No./Control No./Milepost/Lane and Wheel path designation
**Source of asphalt appeared to be seal coat surface of underlying course

Table A-9. (cont'd)

Core Identification*	Aggregate	Underlying Course	Layer Interface			OGAFC Layer		
		Deterioration	Adhesion	Penetration of OGAFC Aggr, %	Raveling	Bleeding/ Flushing	Aggregate Wear	Thickness in.
101/1347/21.7/ROWP	Eastland LW	8	10**	10	None	None	7	0.66
101/1347/21.7/RBWP	"	8	10**	15	None	None	7	0.69
101/1347/21.7/LOWP	"	8	10**	10	None	None	8	0.72
101/1347/21.7/LBWP	"	8	10**	10	Slight	None	8	0.63
114/3521/22.2/ROWP	Eastland LW	8	10	15***	None	Slight	8	0.47
114/3521/22.2/RBWP	"	8	10	0***	None	Slight	8	0.38
114/3521/22.2/LOWP	"	8	10	10***	None	None	8	0.56
114/3521/22.2/LBWP	"	8	10	5***	None	Slight	8	0.38
114/3522/35.4/ROWP	"	8	8	10	None	None	8	0.53
114/3522/35.4/RBWP	"	8	8	5	None	Slight	8	0.38
114/3522/35.4/LOWP	"	8	8	5	None	None	8	0.47
114/3522/35.4/LBWP	"	8	8	10	None	Slight	8	0.50

*Location Code: Highway No./Control No./Milepost/Lane and Wheel path designation

**Source of asphalt appeared to be seal coat on surface of underlying course

***Aggregate crushing noted

Table A-10. Visual Condition Ratings on OGAFC Cores, District 11

Core Identification*	Aggregate	Underlying Course	Layer Interface			OGAFC Layer		
		Deterioration	Adhesion	Penetration of OGAFC Aggr., %	Raveling	Bleeding/ Flushing	Aggregate Wear	Thickness in.
59/1763/20.5/ROWP	Eastland LW	5	5	20	None	Slight	6	0.50
59/1763/20.5/RBWP	"	5	5	10**	None	Slight	6	0.63
59/1763/20.5/SOWP	"	6	5	10**	None	None	8	0.38
59/1763/20.5/SBWP	"	6	5	20**	None	None	8	0.63
59/1763/22/ROWP	"	7	5	20	None	None	8	0.66
59/1763/22/RBWP	"	6	5	10	None	None	8	0.84
59/1763/22/SOWP	"	5	5	25**	None	None	6	0.63
59/1763/22/SBWP	"	5	5	25**	None	None	8	0.56
59/1763/22.4/ROWP	Superock LW	6	5	10	None	Slight	6	0.56
59/1763/22.4/RBWP	"	5	4	20	None	None	8	0.88
59/1763/22.4/SOWP	"	5	4	10	None	None	8	0.97
59/1763/22.4/SBWP	"	5	4	5	None	None	8	0.94
59/1762/3.45/ROWP	Crushed Slag	6	5	10	None	None	8	0.59
59/1762/3.45/RBWP	"	7	5	0	None	None	8	0.66
59/1762/3.45/SOWP	"	5	4	5	None	None	8	0.53
59/1762/3.45/SBWP	"	5	4	5	None	None	8	0.53

*Location Code: Highway No./Control No./Milepost/Lane and wheel path designation

**Aggregate crushing noted

Table A-10. (cont'd)

Core Identification*	Aggregate	Underlying Course Deterioration	Adhesion	Penetration of OGAFC Aggr., %	Raveling	Bleeding/ Flushing	Aggregate Wear	Thickness in.
59/1762/3.57/RBWP	Rock Asphalt	7	5	0	None	Moderate	6	0.56
59/1762/3.57/SBWP	"	5	5	5	None	None	8	0.66
59/1762/3.85/ROWP	Knippa Trap Rock	5	4	5	None	Moderate	8	0.44
59/1762/3.85/SOWP	"	5	4	0***	Slight	None	8	0.59
59/1762/4.21/ROWP	"	5	5	5	None	Slight	8	0.41
59/1762/4.21/SOWP	"	5	4	0***	Slight	None	8	0.50
59/1762/4.86/ROWP	Hable Cr. Stone	6	5	25	Slight	None	10	0.81
59/1762/4.86/RBWP	"	6	5	10	None	Moderate	7	0.81
59/1762/5.08/ROWP	"	5	5	10	None	Slight	7	0.34
59/1762/5.32/ROWP	"	5	5	10	None	Slight	7	0.50
59/1761/23.6/LBWP	Rhyolite	7	10**	10	None	None	10	0.72
59/1761/23.6/MBWP	"	7	10**	5***	None	Slight	10	0.56
59/1761/23.6/RBWP	"	8	10**	5***	None	None	10	0.84
59/1761/23.6/SBWP	"	5	10**	10***	None	Slight	10	0.56
59/1761/23.6/XBWP	"	1						-----

*Location Code: Highway No./Control No./Milepost/Lane and wheel path designation

**Source of asphalt appeared to be seal coat on surface of underlying course

***Aggregate crushing noted

Table A-11. Visual Condition Ratings on OGAFC Cores, District 17

Core Identification*	Aggregate	Underlying Course	Layer Interface			OGAFC Layer		
		Deterioration	Adhesion	Penetration of OGAFC Aggr., %	Raveling	Bleeding/ Flushing	Aggregate Wear	Thickness in.
21/1164/5.5/ROWP	Superock LW	8	5	20	None	None	8	0.50
21/1164/5.5/RBWP	"	8	5	20	None	None	10	0.88
21/1164/5.5/SOWP	"	8	5	0	None	None	8	1.25
21/1164/5.6/ROWP	"	8	5	20	None	None	8	0.97
21/1164/5.6/SOWP	"	5	5	10	None	None	10	1.06
21/1164/5.7/ROWP	"	8	7	20	Slight	None	8	0.94
21/1164/5.8/ROWP	"	5	5	20	Slight	None	8	0.91

*Location Code: Highway No./Control No./Milepost/Lane and wheel path designation

Table A-12. Visual Condition Ratings on OGAFC Cores, District 20

10/7392/847/LOWP	Aggregate	Underlying Course	Layer Interface			OGAFC Layer			
		Deterioration	Adhesion	Penetration of OGAFC Aggr.,%	Raveling	Bleeding/ Flushing	Compaction	Aggregate Wear	Thickn in
10/7392/847/LOWP	Clodine LW	8	5	20	None	None	10	8	0.88
10/7392/847/LBWP	"	8	5	10	None	None	10	8	0.78
10/7392/847/MOWP	"	7	5	5	None	None	10	8	0.63
10/7392/847/MBWP	"	7	5	5	None	None	10	8	0.59
10/289/860/ROWP	Superock LW	8	5	10	None	Moderate	8	8	0.94
10/289/860/RBWP	"	8	5	10	None	Slight	8	8	0.75
10/289/860/SOWP	"	8	5	10	None	Slight	8	5	1.06
10/289/860/SBWP	"	8	5	5	None	None	8	7	1.31
87/3056/1/LOWP	Knippa Trap Rock	8	5	--	None	Slight	6	10	0.63
87/3056/1/LBWP	"	8	5	--	None	Slight	3	10	0.47
87/3057/4/ROWP	Superock LW	8	5	10	None	None	8	5	1.03
87/3057/4/RBWP	"	8	5	10	None	None	8	6	1.00
96/655/23.6/LOWP	"	8	5	10	None	Moderate	6	6	0.59
96/655/23.6/LBWP	"	8	8	10	None	Moderate	6	6	0.72
96/655/23.6/MOWP	"	8	8	10	None	None	8	8	1.31
96/655/23.6/MBWP	"	8	8	10	None	None	6	7	0.88

*Location Code: Highway No./Control No./Milepost/Lane and wheel path designation

General View

Pavement Surface

Figure A-1. Photographic Record of OGAFC Pavement
Location: 820/812/11.4/L&M 3/30/78

General View

Pavement Surface

Figure A-2. Photographic Record of OGAFC Pavement
Location: 820/812/9.4/R,S,L&M 3/30/78

General View

Pavement Surface

Figure A-3. Photographic Record of OGAFC Pavement
Location: 820/812/8.1/R,S,L&M 3/30-78

General View

Pavement Surface

Figure A-4. Photographic Record of OGAFC Pavement
Location: 30/10681/430.8/R,S,L&M 3/30/78

General View

Pavement Surface

Figure A-5. Photographic Record of OGAFC Pavement
Location: 81/137/14.6/R&S 3/31/78

General View

Pavement Surface

Figure A-6. Photographic Record of OGAFC Pavement
Location: 81/137/14.6/L&M 3/31/78

General View

Pavement Surface

Figure A-7. Photographic Record of OGAFC Pavement
Location: 101/1347/14.3/R&L 3/31/78

General View

Pavement Surface

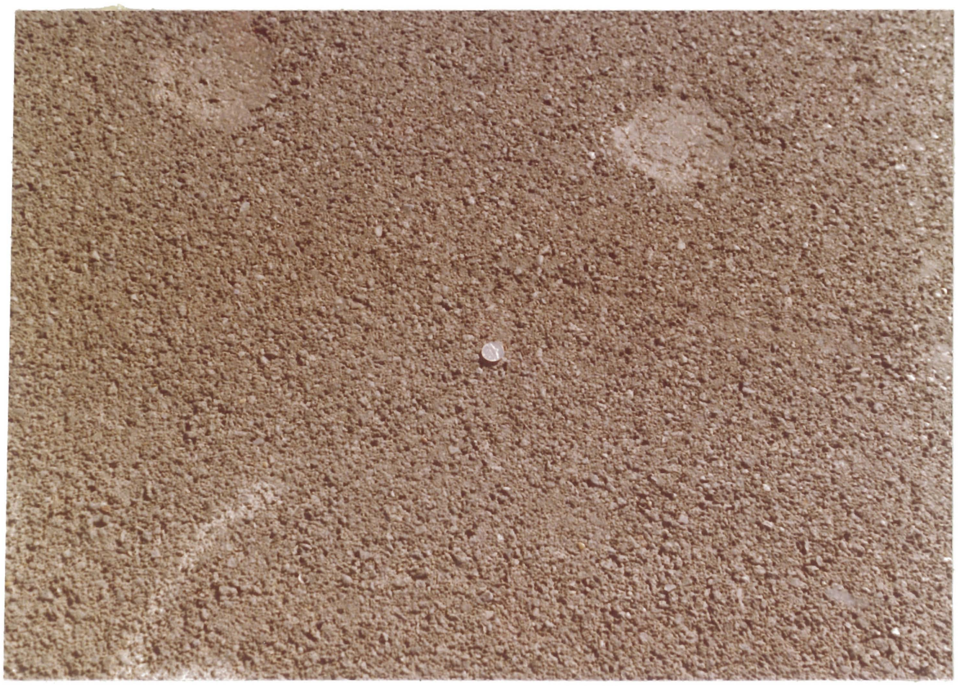
Figure A-8. Photographic Record of OGAFC Pavement
Location: 114/3521/27.2/R&L 3/31/78

General View

Pavement Surface

Figure A-9. Photographic Record of OGAFC Pavement
Location: 59/1763/22/R&S 3/16/78

General View



Pavement Surface

Figure A-10. Photographic Record of OGAFC Pavement
Location: 59/1762/3.45/R&S 3/17/78

General View

Pavement Surface

Figure A-11. Photographic Record of OGAFC Pavement
Location: 59/1762/3.57/R&S 3/17/78

General View

Pavement Surface

Figure A-12. Photographic Record of OGAFC Pavement
Location: 59/1762/3.85/R&S 3/17/78

General View

Pavement Surface

Figure A-13. Photographic Record of OGAFC Pavement
Location: 59/1762/4.27/S 3/17/78

General View

Pavement Surface

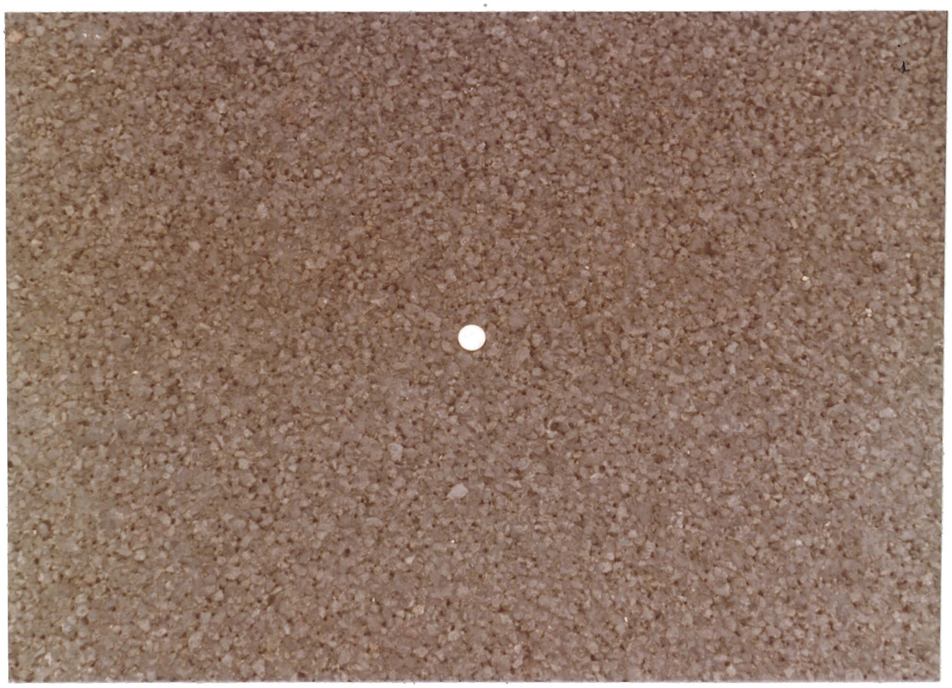
Figure A-14. Photographic Record of OGAFC Pavement
Location: 59/1762/5.09/R&S 3/17/78

General View

Pavement Surface

Figure A-15. Photographic Record of OGAFC Pavement
Location: 59/1761/23.6/R,S,L&M 3/17/78

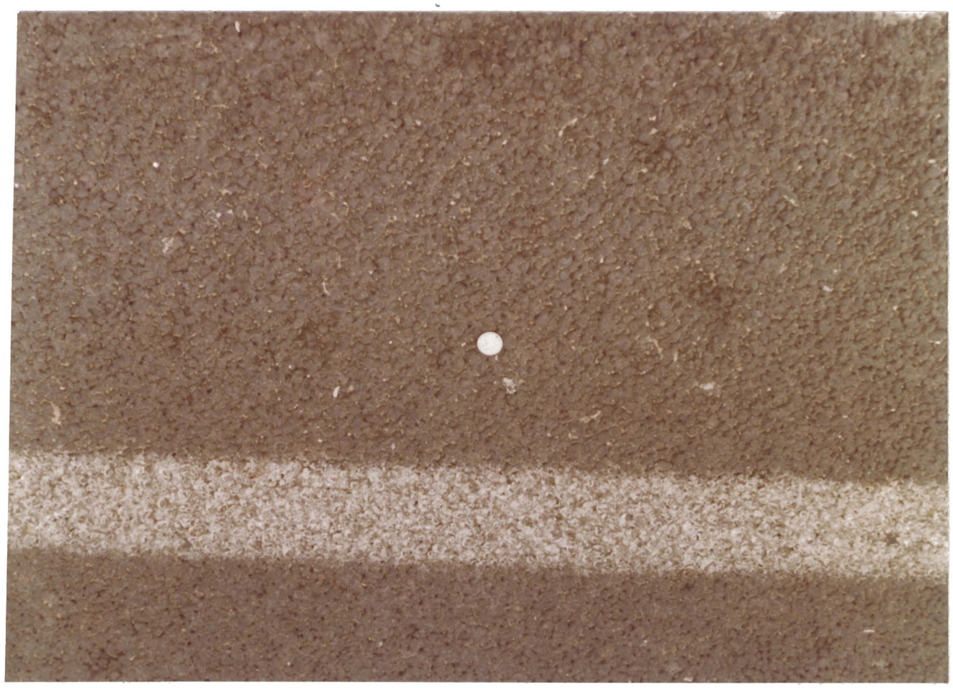
General View



Pavement Surface

Figure A-16. Photographic Record of OGAFC Pavement
Location: 10/7392/847/L 2/27/78

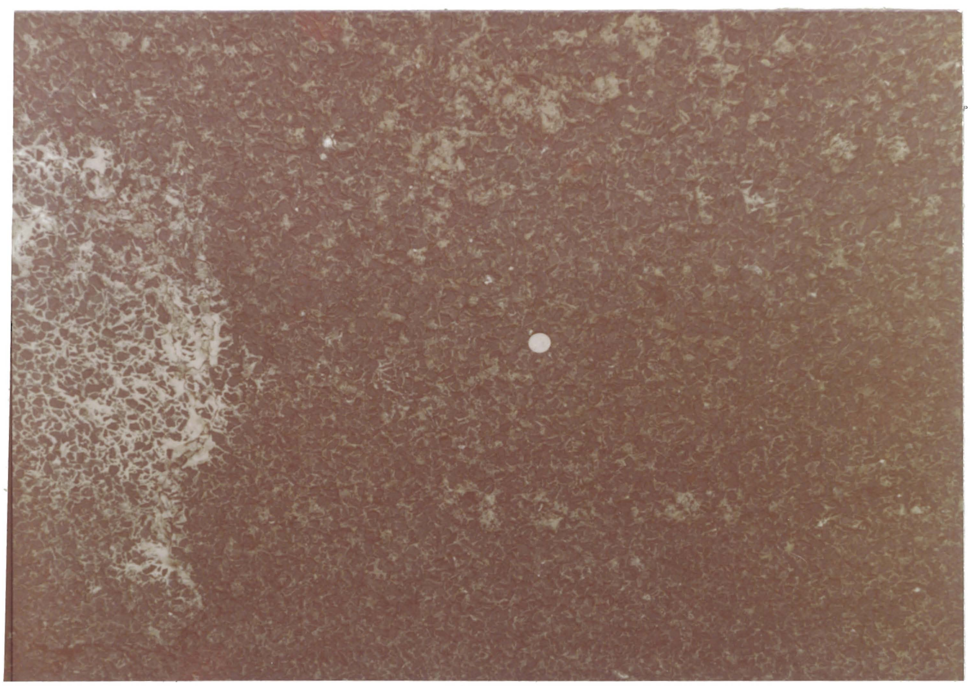
General View



Pavement Surface

Figure A-17. Photographic Record of OGAFC Pavement
Location: 10/289/861/R 2/27/78

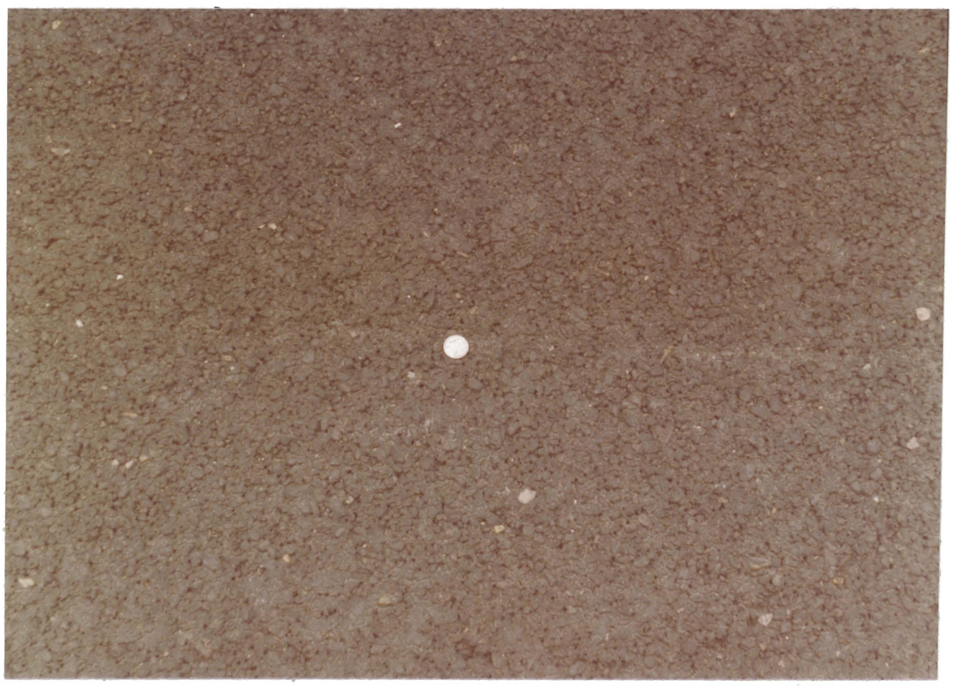
General View



Pavement Surface

Figure A-18. Photographic Record of OGAFC Pavement
Location: 87/3056/1/R 2/27/78

General View



Pavement Surface

Figure A-19. Photographic Record of OGAFC Pavement
Location: 87/3057/3.5/R 2/27/78

General View

Pavement Surface

Figure A-20. Photographic Record of OGAFC Pavement
Location: 96/655/23/L 2/27/78

APPENDIX B

OGAFC PERMEABILITY TEST METHOD, CALCULATIONS AND CORE DATA

APPENDIX B

OGAFC PERMEABILITY TEST METHOD,
CALCULATIONS AND CORE DATA

Introduction

During periods of rainfall, a film of water tends to develop on the surface of conventional dense-graded asphaltic concrete pavements. This film of water is what causes hydroplaning, the loss of contact between the tire and pavement surface, to occur. Earlier studies have indicated that the application of OGAFC's, constructed of open-graded, high-void bituminous mixtures, can minimize the potential for developing a hydroplaning condition and thereby improve skid resistance [35].

During the course of this study a method was developed by which to evaluate the permeability of OGAFC pavements. The following discussion describes the reasoning and methods employed in obtaining permeability, K, values (cm/sec) for OGAFC cores.

Background - Permeability Measurements

A survey of existing methods of determining permeability was conducted in an attempt to arrive at a method which might be applicable to this study. The various methods considered are briefly discussed below. The method which was finally chosen will be discussed in the following sections.

Among the earliest types of permeability tests were those conducted on soils. Darcy studied the flow of water through soils, and by experiments he arrived at the relation "$q = kiA$," which today is known as Darcy's Law.

Darcy's Law states that the flow rate of water, q, is proportional to the cross-sectional area, A, and to the hydraulic gradient, i. The constant of proportionality, k, has been called the "coefficient of permeability," or simply "permeability." It was based upon this law that Lambe [31] developed methods for obtaining permeability values from both variable head and constant head permeability tests on soils. As will be shown later, the permeability equations proposed by Lambe were adopted for use in this study of OGAFC surface courses.

One of the first decisions to be made in designing a permeability apparatus is which type of fluid (liquid or gas) to use for making permeability measurements. McLaughlin and Goetz [36] developed a method in which a gas permeameter was used to determine the permeability of dense-graded bituminous concrete.

The decision to use a gas permeameter, as opposed to the conventional water permeameter, was made because the use of a gas (in this case air) would not require excessive pressures in order to obtain measurable flows. It was the consensus at the time of their study that the permeabilities would be extremely low and therefore it would be difficult to force a measurable quantity of water through the samples.

However, after performing several tests they found that extremely high pressures were not necessary and therefore a water permeameter could be used.

The U. S. Army Waterways Experiment Station developed a method for determining the permeability values of OGAFC pavements (described by White [2, 19]). The basic design of the permeability apparatus was similar to that of an outflow meter (see Moore [37]). In short, the difference is that the outflow meter was designed to provide a means by which to measure the surface drainage capacities of dense-graded pavements; whereas, the permeability apparatus developed by the U. S. Army Waterways Experiment Station was designed to provide a means by which to measure the internal drainage capacities of open-graded pavements.

The permeability apparatus developed by the U. S. Army Waterways Experiment Station was designed to run both falling head and constant head permeability tests. The apparatus consisted of a plastic standpipe with a 5.08 cm (2 in.) inside diameter and a 10.16 cm (4 in.) diameter baseplate with a foam rubber gasket on the bottom of the baseplate that contacted the pavement surface. Tests were conducted on both 10.16 cm (4 in.) and 15.24 cm (6 in.) diameter samples, however it was pointed out that the results obtained with 15.24 cm (6 in.) diameter specimens compared better with the results obtained in the field. The U. S. Army Waterways Experiment Station reported falling head permeability as the "time to fall" for a given head condition, and the constant head permeability was reported as "flow rate." They did not make any attempt to convert these values to conventional permeability units (cm/sec). Their permeability apparatus was portable and could be adapted to field testing.

Type of Fluid Used

For the purpose of this study, the decision was made to use water as the fluid medium on which to base the internal drainage capacity. This decision was made based on the following criteria:

1. As stated earlier, McLaughlin and Goetz [36] found that extremely high pressures were not necessary and therefore

a water permeameter could be used.

2. Even though air to water permeability conversions and correlations have been suggested by some researchers [38], there are several who claim to have found no correlation between liquid (water) and gas (air) permeabilities of porous media [39].
3. The purpose of this study was to determine the internal drainage capacity of OGAFC pavements with respect to rainfall (water).
4. The use of water would be more convenient because of simpler instrumentation, and it could be more easily adapted to field permeability tests.
5. Study results by Kilpatrick and McQuate [40] indicated that air flow was primarily a surface phenomenon; and pavements with equal densities but different surface textures had different air flow values.

Permeability Test Apparatus

The permeability apparatus developed for this study (see Figure B-1) was similar to the one used by the U. S. Army Waterways Experiment Station. The permeameter assembly basically consisted of a plastic standpipe with a 6.98 cm (2.75 in.) inside diameter and a 17.78 cm (7 in.) diameter metal standpipe base (see Figure B-2).

For testing purposes, a support assembly was constructed to hold the specimen and support the permeameter assembly. A "silicone-sponge rubber" gasket, unlike the gasket used by the Waterways Experiment Station, was developed and used as a seal between the standpipe base and the pavement surface (see discussion in next section). Compression

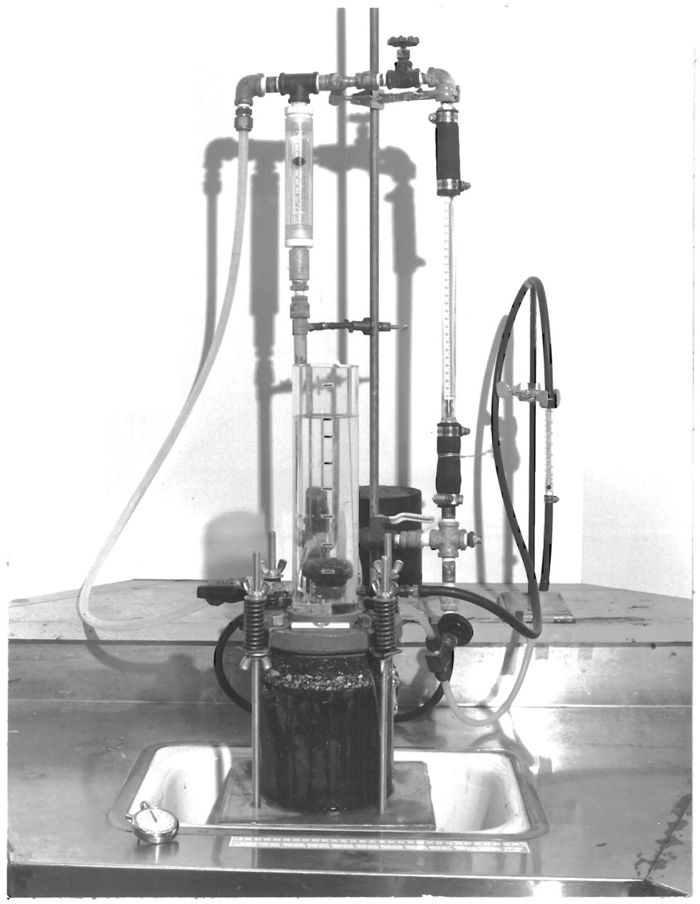


Figure B-1. Permeability Test Apparatus

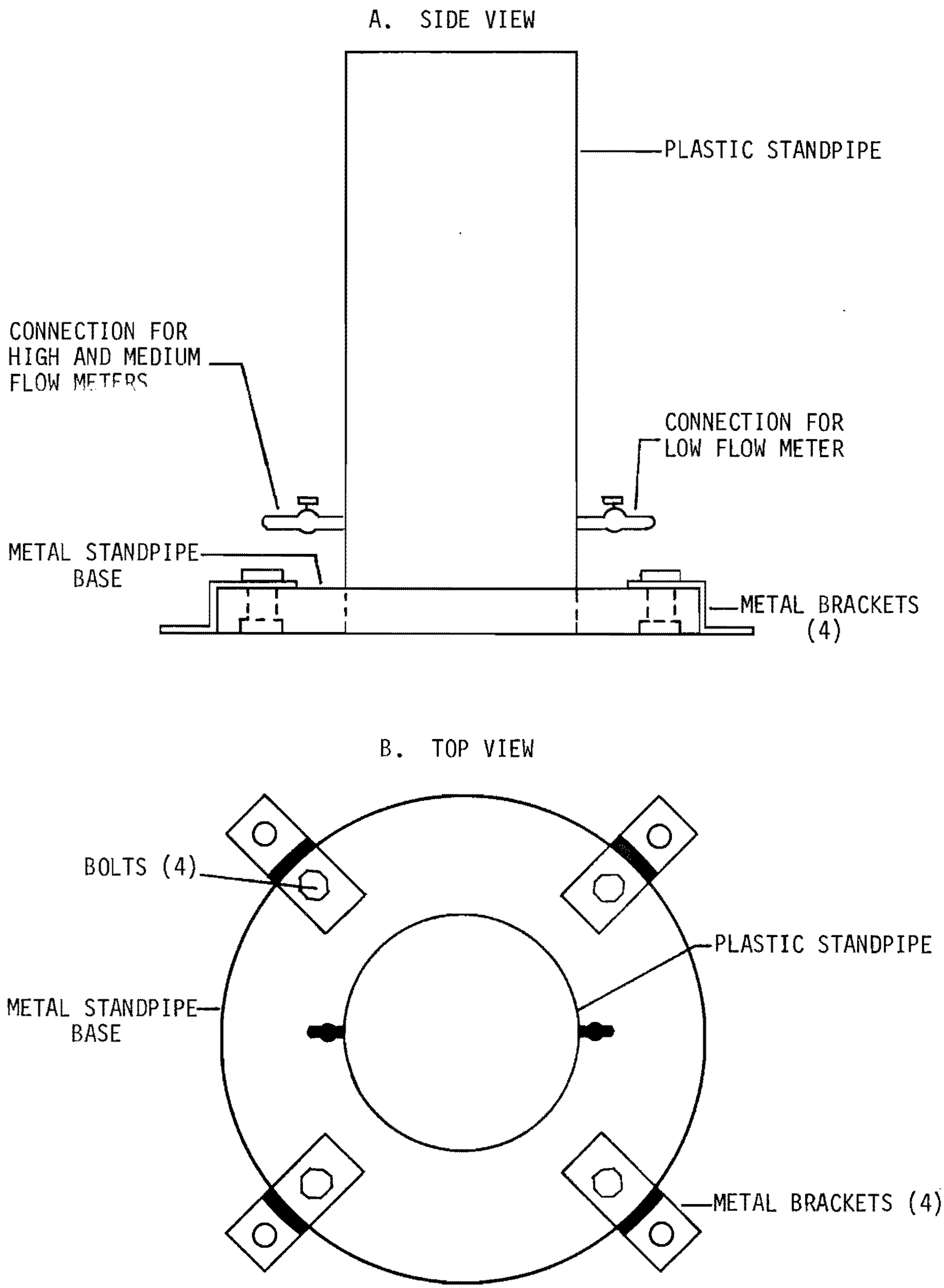


Figure B-2. Schematic of Permeameter Assembly springs were used to apply a load to the permeameter assembly in order to create a better seal between surfaces and eliminate surface flow. A schematic of the permeability test set-up procedure is shown in Figure B-3.

"Silicone-Sponge Rubber" Gasket

The intention was to use a gasket which would prohibit all surface flow, and this required the use of a material which could conform to the macrotexture of the pavement surface. Some of the different types of materials experimented with were "bowl wax," "permagum," and sponge rubber. The bowl wax and permagum gaskets did seal off the surface, but they also tended to flow into and seal portions of the internal drainage system. The sponge rubber gasket appeared to conform well to the surface of the specimen, however leaks developed between the gasket and the standpipe base. It should also be noted that poor repeatability was evidenced for these three types of gaskets.

The gasket finally developed for use in this study was a combination of two materials: (1) a 0.64 cm (0.25 in.) layer of silicone rubber (General Electric RTV 11)* and (2) a 0.64 cm (0.25 in.) layer of silicone sponge rubber (Connecticut Hard Rubber Co.)*. The silicone sponge rubber layer was placed in contact with the surface of the specimen because it was capable of conforming to the macrotexture. The silicone rubber layer was comparatively stiff, yet flexible enough to provide a good seal between it and the metal standpipe base.

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*Note: The names of suppliers are given for information purposes only.

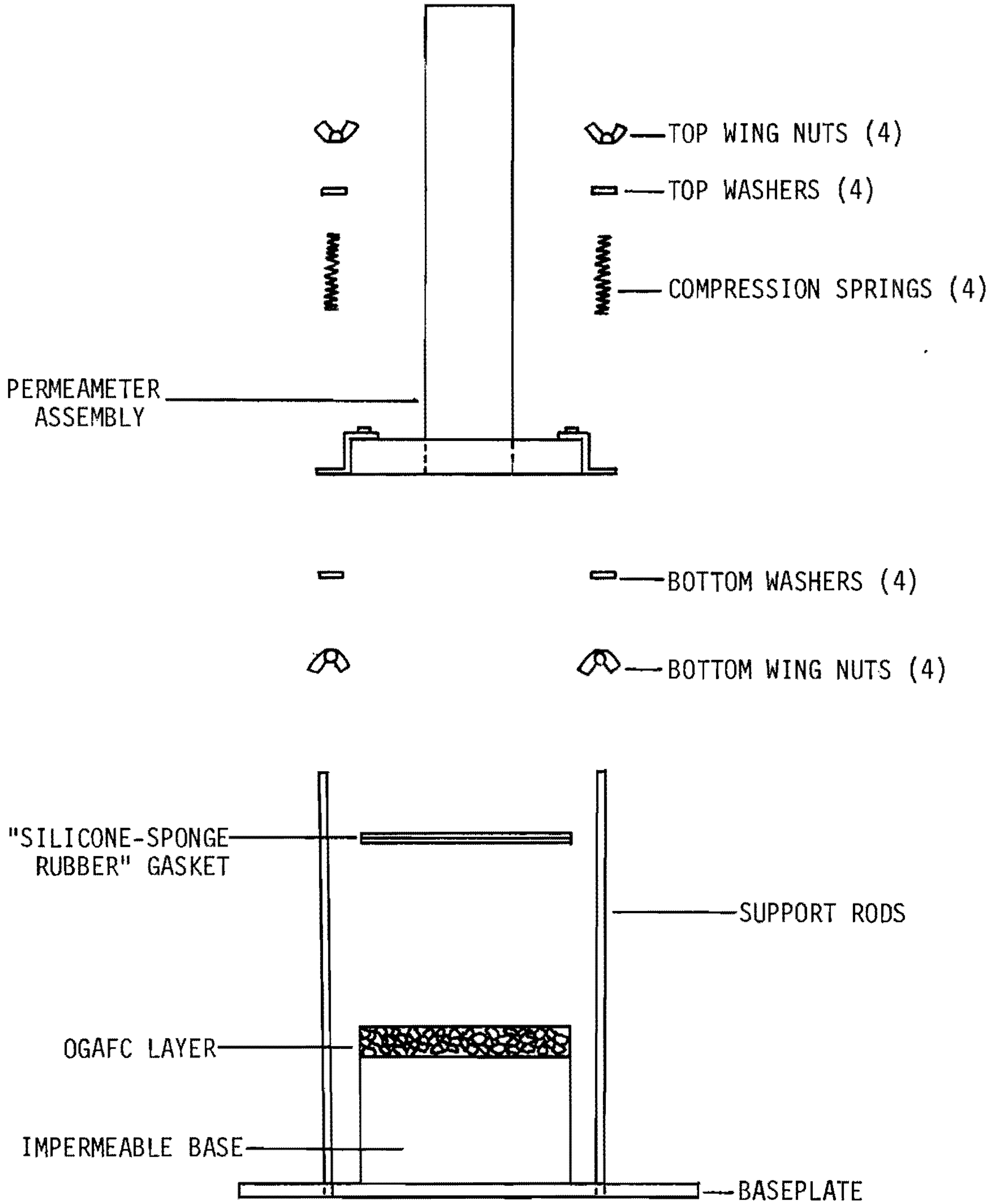


Figure B-3. Schematic of Permeability Test Set-Up Procedure

A mold was constructed according to the dimensions of the desired gasket [15.24 cm (6 in.) outside diameter and a 6.98 cm (2.75 in.) inside diameter]. The silicone rubber was poured into the mold to a depth of 0.64 cm (0.25 in.). Next, the silicone sponge rubber, cut to the dimensions shown above, was placed on top of the silicone rubber layer. The curing process causes an adhesion between the two surfaces. Note that it may be necessary to allow the silicone rubber to cure for a while before applying the silicone sponge rubber. The set-up for the gasket preparation process is shown in Figure B-4.

Specimen Preparation

All permeability tests for this study were performed on 15.24 cm (6 in.) cores obtained from the evaluation pavements. For the purpose of this test, it was necessary that the substrate upon which the OGAFC layer rests be impermeable. In most cases the cores included the OGAFC surface layer along with an impermeable substrate. However, there were a few instances in which a sufficiently impermeable substrate did not exist. For these specimens an impermeable plaster base was molded to the bottom of the OGAFC layer before testing (see Figure B-5).

Permeability Test Procedures

The permeability apparatus developed for this study could be used to run both constant and variable head tests. The recommended test procedures for both the constant and variable head tests are described in Tables B-1 and B-2. For tests performed in the laboratory, there is no advantage to using one test as opposed to the other, however for field application the variable head test would appear to be the more practical choice. For field testing the constant head test would require a

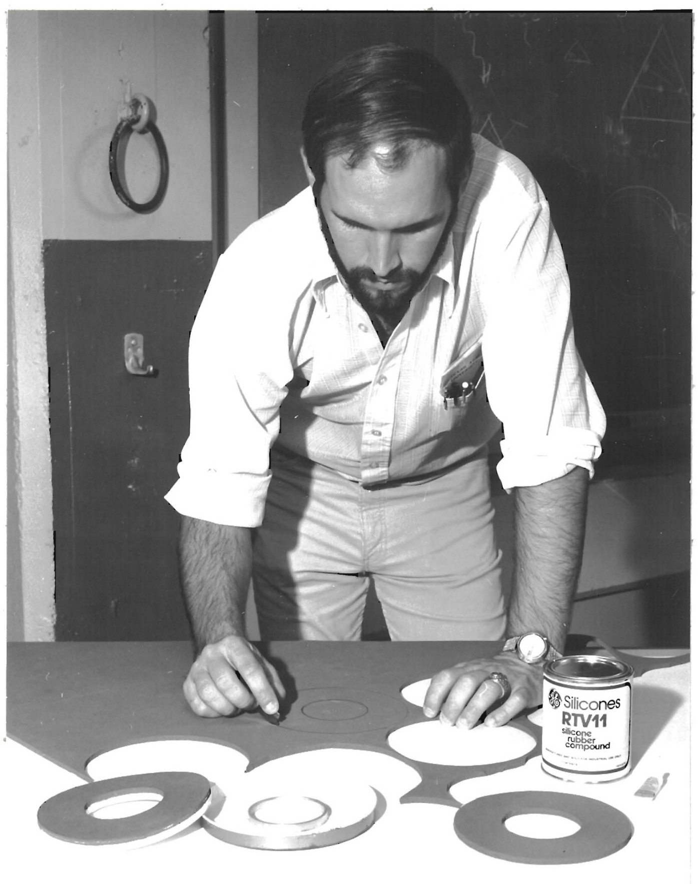


Figure B-4. Preparation of "Silicone-Sponge Rubber" Gasket

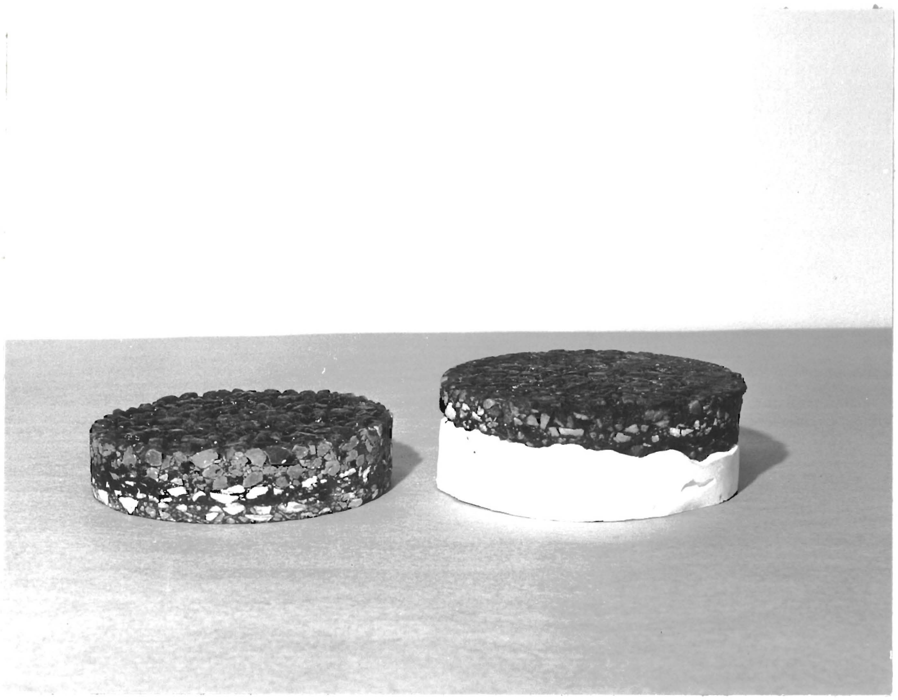


Figure B-5. Specimens Showing Impermeable Base

Table B-1. Test Procedures for Laboratory Permeability Measurements Variable Head Test

Procedure	Remarks
1. Record specimen number, give a brief description of OGAFC layer (i.e. surface irregularities, damaged surface, macrotexture, density, etc.), and determine the average thickness of the OGAFC layer.	This information will serve as a quick reference and may provide possible reasons for errors in the event the results appear questionable.
2. Place a 15.24 cm (6 in.) diameter core on the base plate of the support assembly (Figure B-3).	
3. Place "silicone-sponge rubber" gasket on surface of OGAFC layer making certain it is centered on surface (Figure B-6).	Several gaskets should be on hand and used on a rotation basis due to the temporary deformation of the sponge rubber.
4. Lower the permeameter assembly onto the specimen making certain it is aligned with the gasket (Figure B-7).	
5. Slide the 4 compression springs and washers onto the support rods. (Figure B-8).	These springs should be precalibrated to determine their compressed length under a 445 N (100 lbs.).
6. Apply a 445 N (100 lbs.) at each spring by tightening the upper wing nuts until the spring is compressed to the pre-determined length. (Figure B-9).	Loads in excess of this may cause damage to samples.
7. Screw the lower wing nuts up until they just come into contact with the metal brackets.	
8. Make certain the apparatus is level.	Set level on surface of metal standpipe base and adjust the complete apparatus until level.
9. Open valve and allow water to flow into standpipe and through specimen for approximately 2-3 minutes before beginning test.	This was done in order to wet exposed surfaces and flow paths. Also check to make sure there is a good surface seal.
10. Locate and measure the heads h_o and h_1.	The values used for this study were h_o = 25.40 cm and h_1 = 8.65 cm.

Table B-1. (cont'd)

Procedure	Remarks
11. Fill the permeameter tube with water to an elevation slightly above h_o.	
12. Close main valve; start the stopwatch when the water level is at h_o and record the elapsed time when water level reaches h_1. Make three determinations and compute the average (Figure B-10).	If the elapsed time is greater than 10 minutes, then two determinations will be sufficient.
13. Measure temperature of the water and record.	For this study, the temperature of the water was maintained at approximately 25°C (fluctuations were insignificant as far as changes in viscosity were concerned.)

Table B-2. Test Procedures for Laboratory Permeability Measurements Constant Head Test

Procedure	Remarks
1. Follow steps 1-9 listed in variable head test procedure.	For this study, the constant head and variable head tests for a particular specimen were run back to back. This required only one set-up and therefore cut down on the amount of time required to perform the tests.
2. Locate and measure the different heads (h_i).	In some instances the flow required to obtain a particular constant head was too high for the system ($Q \geq 4{,}500$ ml/min).
3. Open valve and adjust the flow until equilibrium conditions are obtained.	For performing this test it is necessary to have a constant water line pressure.
4. Determine flow rate, Q, (ml/min) from flow meter and record (Figure B-11).	Three different flow meters were used in this study: (1) low flow meter - 0 to 250 ml/min, (2) medium flow meter - 200 to 2,000 ml/min, and (3) high flow meter - 2,000 to 6,000 ml/min. The system was constructed whereby the water could be directed through the appropriate flow meter.
5. Repeat steps 3 and 4 for each different head.	

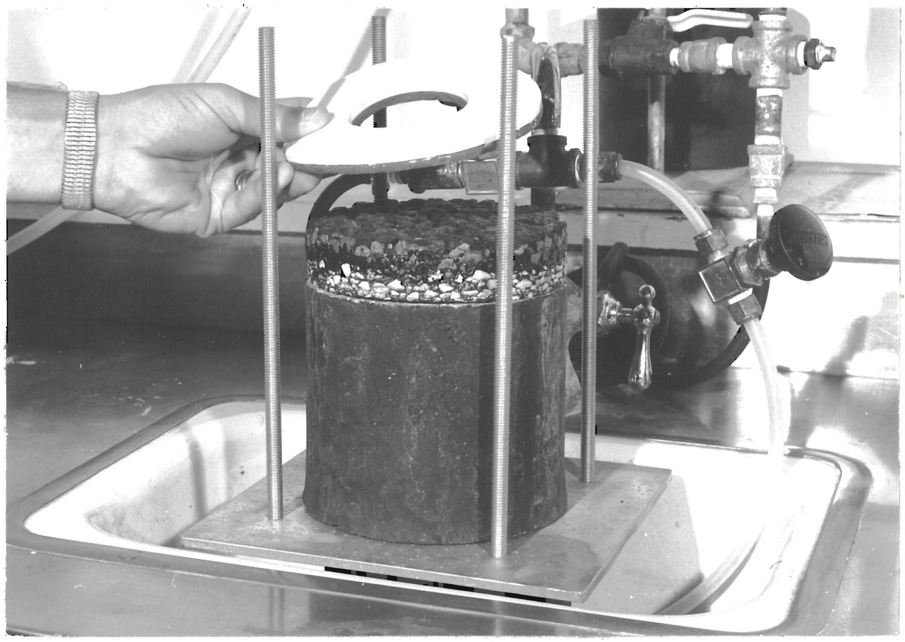


Figure B-6. Specimen Positioned on Baseplate and "Silicone-Sponge Rubber" Gasket Being Applied

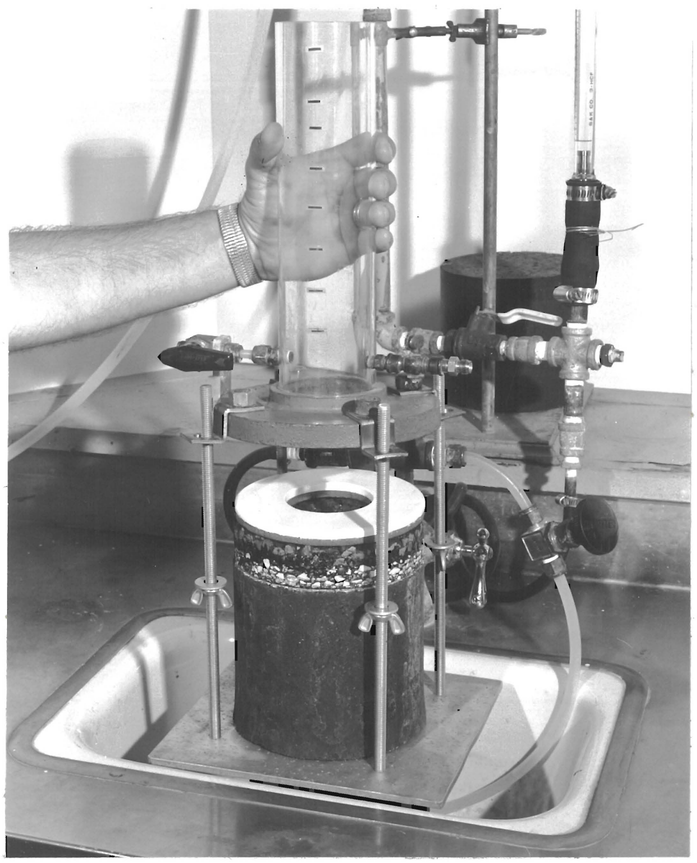


Figure B-7. Gasket in Place and Permeameter Assembly Being Lowered Into Position

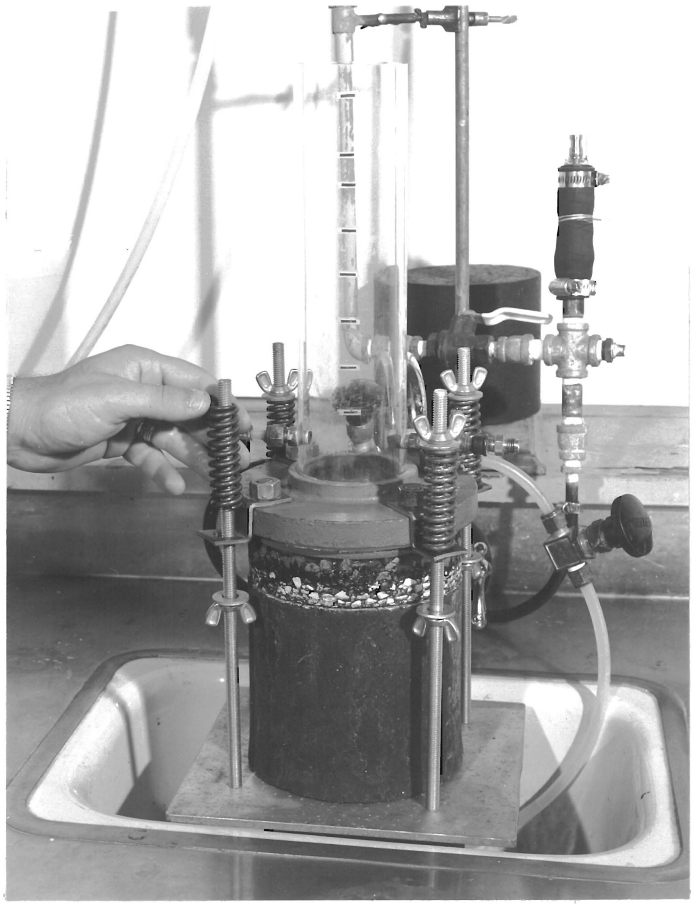


Figure B-8. Compression Springs Being Positioned on Support Rods

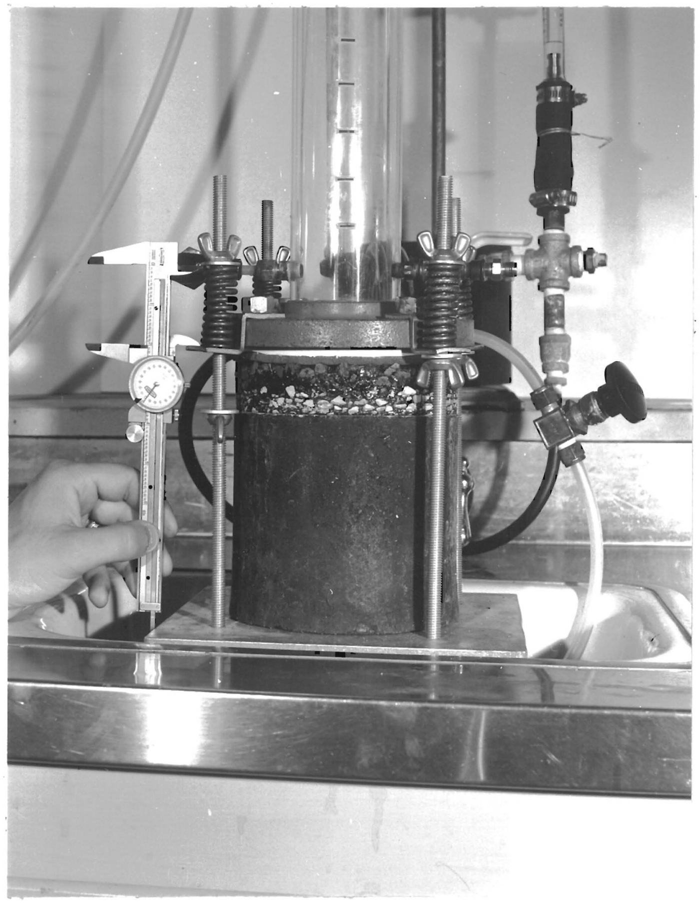


Figure B-9. Compression Springs in Place and Load Being Applied

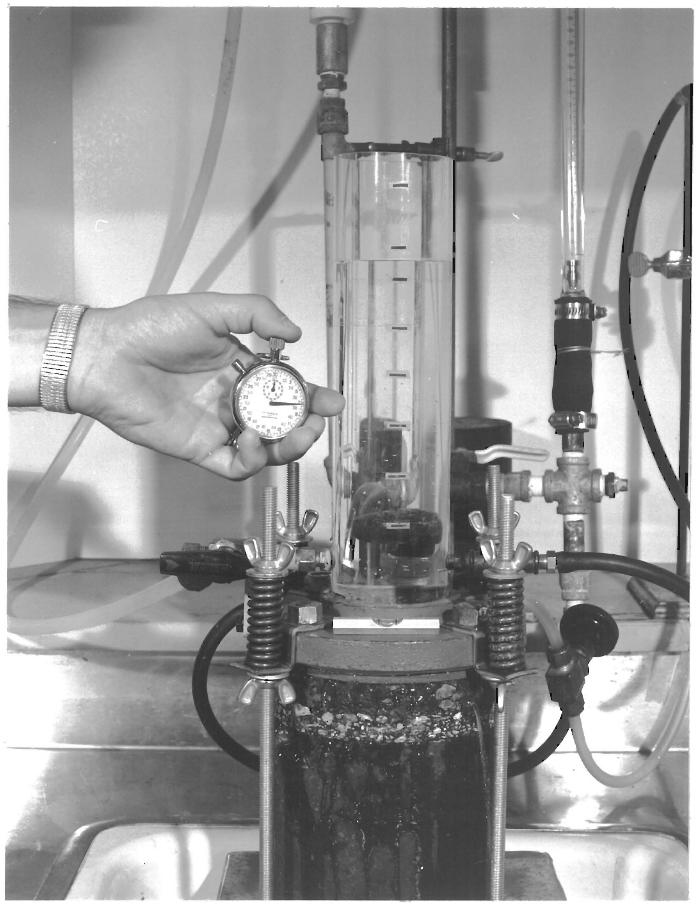


Figure B-10. Variable Head Permeability Test in Progress

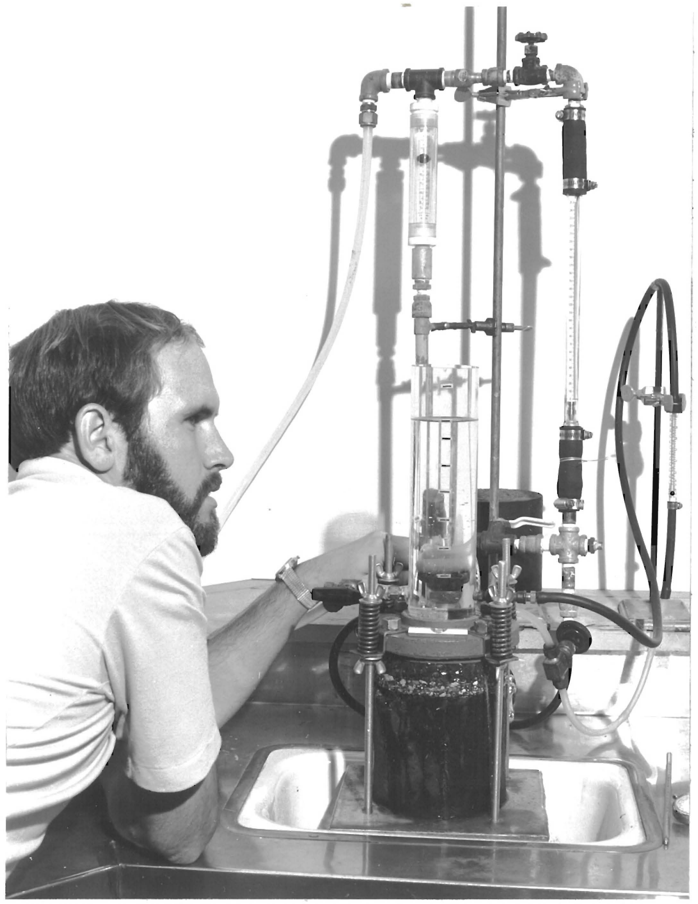


Figure B-11. Constant Head Permeability Test in Progress calibrated, variable flow pump. Since this was a laboratory study, both tests were performed (in most cases*) and the results compared. A sample data sheet containing permeability test measurements is shown in Figure B-12.

Formulas for Calculating Permeability

The permeability measurements determined from the variable and constant head tests were recorded as "time to fall" and "flow rate," respectively. From these values the coefficients of permeability k (cm/sec) were computed from equations presented by Lambe [31].

Variable Head Test: $k_v = 2.3 \frac{aL}{A(t)} \log_{10} \frac{h_o}{h_1}$ Equation B-1

in which:

a = cross-sectional area of standpipe, cm^2

L = length of flow path, cm

A = area perpendicular to the flow path, cm^2

t = time for water level to fall from h_o to h_1, sec

h_o, h_1 = the heads between which the permeability is determined, cm

Constant Head Test: $k_c = \frac{QL}{hA}$ Equation B-2 in which:

Q = flow rate, ml/sec cm^3/sec

L = length of low path, cm

A = area perpendicular to the flow path, cm^2

h = total head lost, cm

*Constant head tests were not performed when the variable head test results showed the specimen to be impermeable.

PERMEABILITY TEST

Date: 2/23/79 Operator: RT

Core Identification: 59/1763/22.4/SOWP/73

Visual Rating: Good macrotexture, appears very porous

Thickness: 1.43 cm Water Temperature: 25°C

Falling Head Test		Constant Head Test		
Time to Fall (sec)	k_v, cm/sec (calculated)	Head -- cm	Flowrate (ml/min)	k_c, cm/sec (calculated)
t_1 = 10.7		h_1 -- 8.65	2600	0.247
t_2 = 10.5		h_2 -- 11.67	3025	0.213
t_3 = 10.5		h_3 -- 14.68	3300	0.185
		h_4 -- 17.78	3850	0.178
t_{AVG} = 10.6	0.191	h_5 -- 20.56	4225	0.169
		h_6 -- 23.50	4525	0.158
		h_7 -- 25.40	4525	-----
		h_8 -- 29.13	4525	-----

Figure B-12. Typical Data Sheet With Data from Permeability Test

In order to apply these equations, several assumptions had to be made in regard to the flow path. First, it was assumed that the water initially flowed vertically downward and then, radially out of the sample. It was also assumed that a single flow path through the specimen has both a vertical and a horizontal component. These flow path assumptions are shown in Figure B-13. Since the ratio of length of flow path to perpendicular area of flow path (L/A) exists in both equations, a formula was derived by which to calculate this ratio based on the thickness of the OGAFC layer.

The average length of the flow path was determined based on the following equation:

$$L_{AVG} = L_V + L_H \qquad \text{Equation B-3}$$

where:

L_{AVG} = average length of the flow path

L_V = average length of the vertical component

L_H = average length of the horizontal component

L_V was assumed to be equal to half the thickness (z) of the OGAFC layer ($L_V = z/2$) and L_H was assumed to be equal to the radius ($r_2 = 7.62$ cm) of the specimen minus half the radius ($r_1 = 3.49$ cm) of the standpipe ($L_H = r_2 - r_1/2$). By setting $r_1/2 = r_o$ and substituting these values into Equation B-3, it gives the following expression:

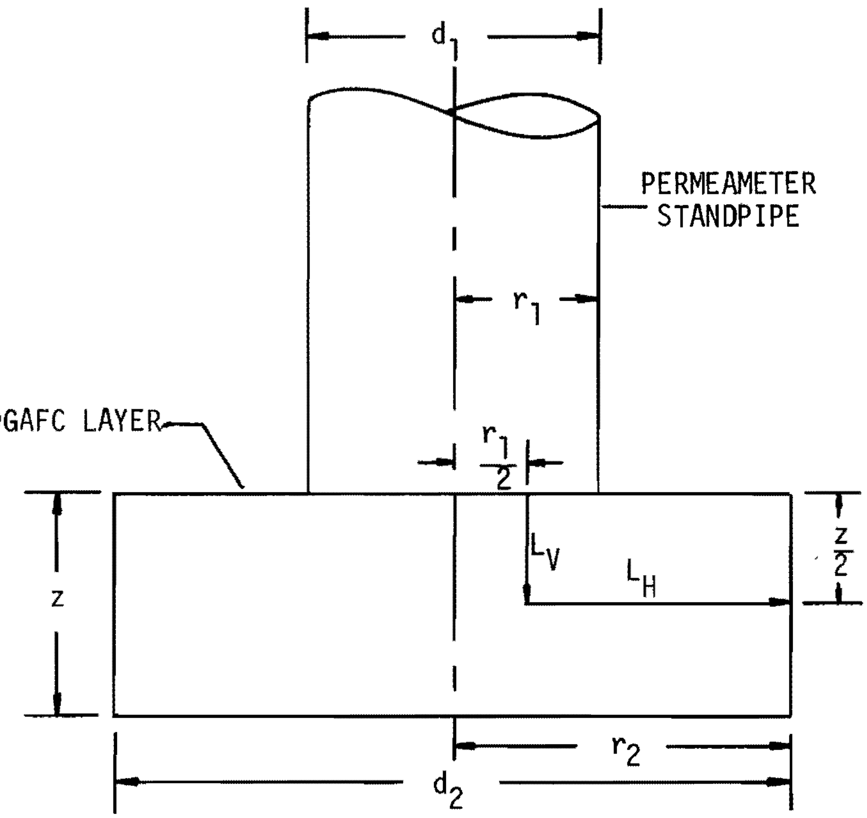
$$L_{AVG} = z/2 + (r_2 - r_o) \qquad \text{Equation B-4}$$

The flow area (A_V) perpendicular to L_V is equal to the area of the standpipe.

$$A_V = \pi r_1^2 = \pi(3.49 \text{ cm})^2$$

$$A_V = 38.3 \text{ cm}^2 \text{ or } (5.94 \text{ in.}^2)$$

A. SIDE VIEW



B. TOP VIEW

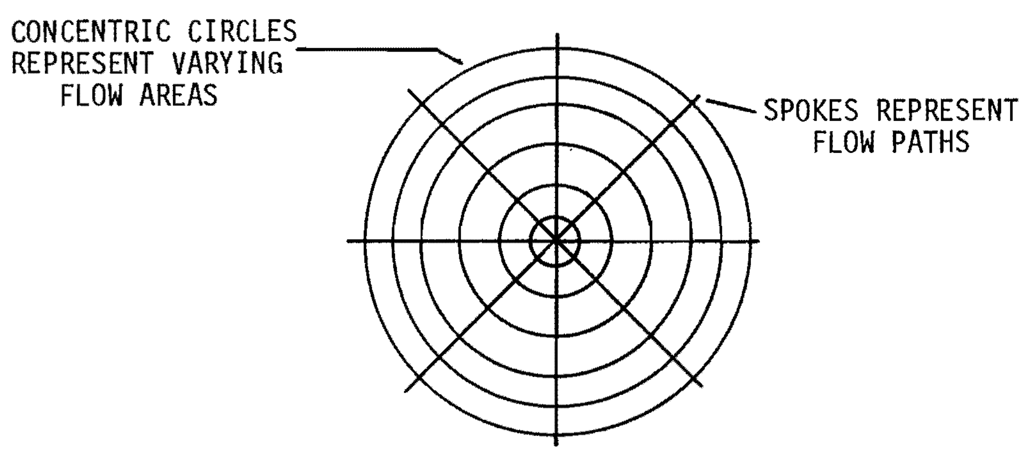


Figure B-13. Schematics Showing Flow Assumptions

The flow area (A_H) perpendicular to the horizontal flow path varies as the distance (r_i) varies from $r_1/2$ to r_2.

The general equation for determining A_H is:

$$A_{H_{r_i}} = 2\pi r_i z \qquad \text{Equation B-5}$$

Figure B-14 shows how the flow area varies with the length of the flow path and Figure B-15 shows how the ratio L/A varies with the length of the flow path for a 2.54 cm (1.00 in.) thick OGAFC layer.

Since the ratio L/A increases as the length of the flow path increases it was necessary to determine an average value for L/A to be used in calculating permeability. In order to do this it was necessary to determine the area under the curve in Figure B-15. The equations given below are in general form and can be used for any thickness.

$$\text{Area 1} = 1/2(z/2)\left(\frac{z/2}{\pi r_1^2}\right)$$

$$\text{Area 1} = 1/8\pi \; (z/r_1)^2 \qquad \text{Equation B-6}$$

$$\text{Area 2} = \int_{L = z/2}^{L = z/2 + (r_2 - r_o)} L/A \; dL \qquad \text{Equation B-7}$$

Equation B-4 can be written in the general form:

$$L = z/2 + (r_i - r_o)$$

and by rearranging terms:

$$r_i = L + r_o - z/2$$

Substituting this into Equation B-5 gives:

$$A_{H_{r_i}} = 2\pi(L + r_o - z/2)z$$

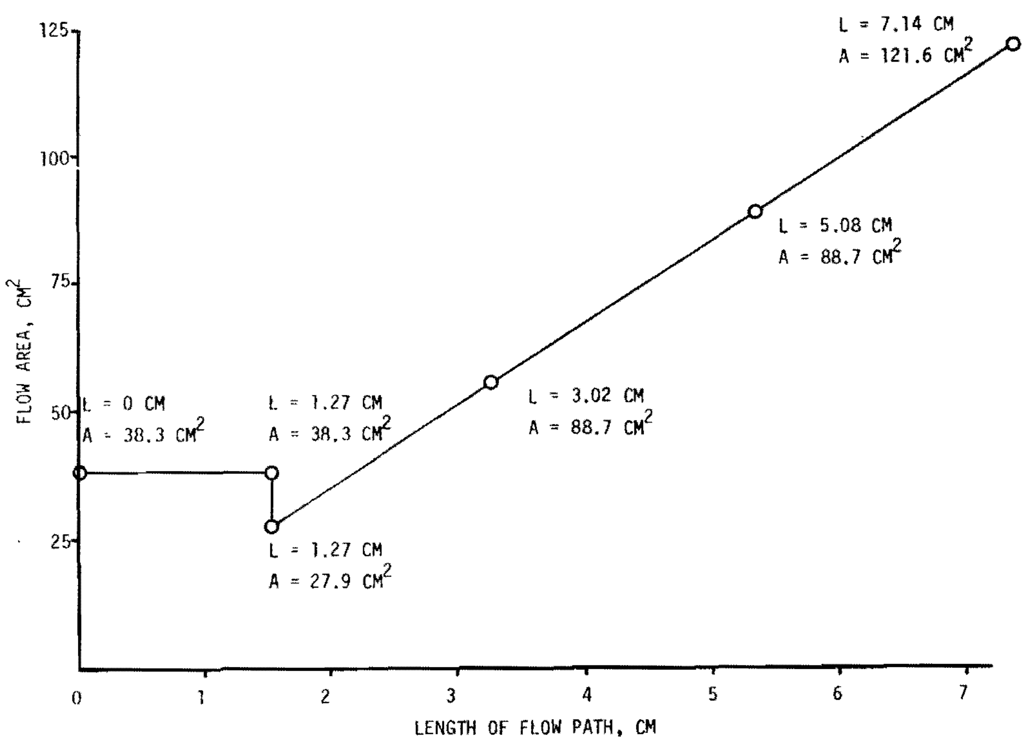


Figure B-14. Flow Area vs. Length of Flow Path for 15.24 cm (6 in.) Diameter, 2.54 cm (1 in.) Thick Specimen

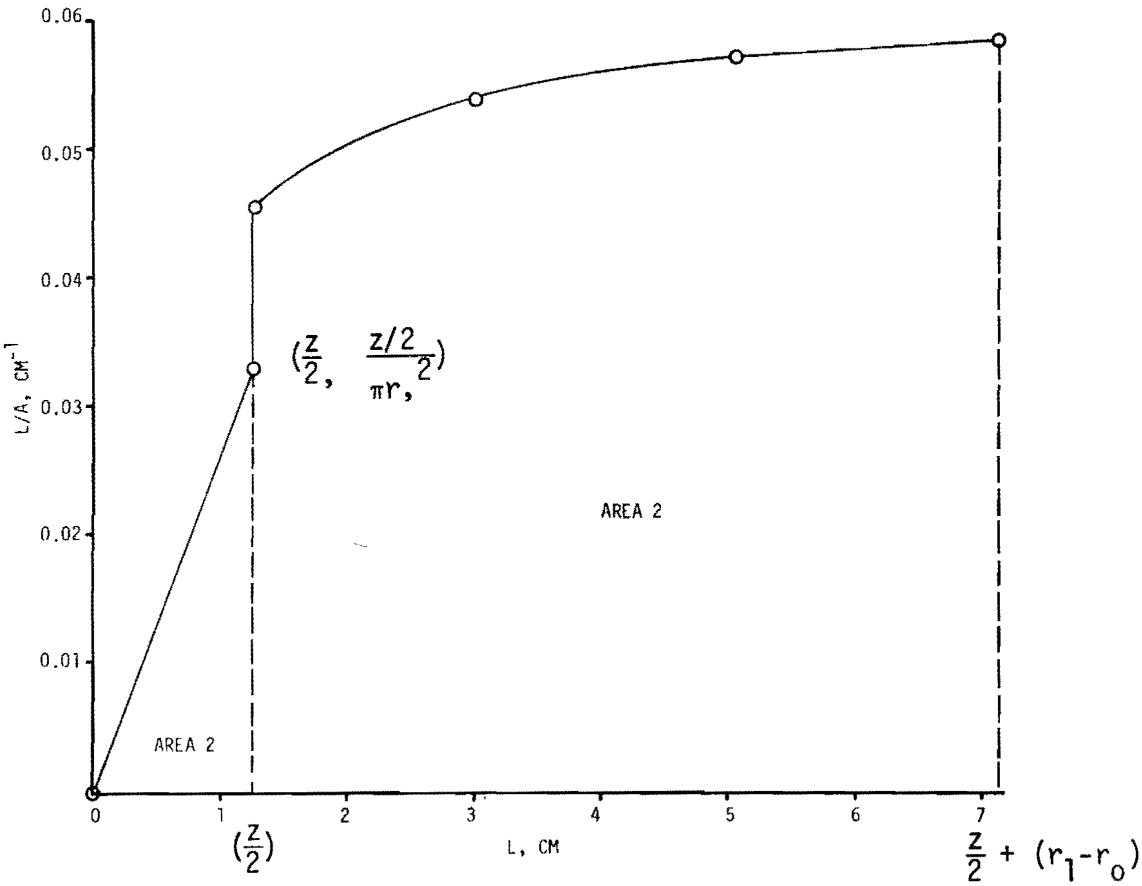


Figure B-15. L/A vs. L a 15.24 cm (6 in.), 2.54 cm (1 in.) Thick OGAFC Specimen

Therefore, Equation B-7 reduces to:

$$\text{Area 2} = 1/2\pi z \int_{L = z/2}^{L = z/2 + (r_2 - r_o)} \frac{L}{L + r_o - z/2}\, dL$$

which is of the form:

$\int \frac{X}{(ax + b)}\, dx$, where $a = 1$, $b = r_o - t/2$, and $x = L$.

Integrating this expression gives the following result:

$$\text{Area 2} = 1/2\pi z \left[L - (r_o - z/2)\ln(L + r_o - z/2)\right]_{L = z/2}^{L = z/2 + r_2 - r_o}$$

$$\text{Area 2} = 1/2\ z\left[(r_2 - r_o) + (r_o - z/2)\ln r_o/r_2\right] \qquad \text{Equation B-8}$$

Equations B-6 and B-8 can then be used to compute an average value for L/A:

$$(L/A)_{AVG} = \frac{\text{Area 1} + \text{Area 2}}{L_V + L_H}$$

$$= \frac{1/8\pi(z/r_1)^2 + 1/2\pi z[(r_2 - r_o) + (r_o - z/2)\ln r_o/r_2]}{z/2 + (r_2 - r_o)}$$

Substituting $r_1 = 3.49$ cm, $r_o = 1.75$ cm, and $r_2 = 7.62$ cm, this equation reduces to the following:

$$(L/A)_{AVG} = \frac{0.00326z^2 + 0.525/z + 0.117}{(z/2 + 5.87)}\ \text{cm}^{-1}$$

This was the equation used for computing the L/A term in both the constant and variable head permeability formulas.

Analysis of Results

The permeability coefficients calculated from the variable head and constant head test results are presented in Tables B-3, B-4, B-5 and B-6. A constant head permeability coefficient (k_c) was computed at several

Table B-3. Permeability Measurements on OGAFC Cores from District 2

Core Identification	Aggregate	OGAFC Layer Thickness	Variable Head	Permeability ($k = {}^{cm}/sec$) Constant Head, at h = (cm)									
				8.65	11.67	14.68	17.78	20.56	23.50	25.40	29.13	$K_{c_{AVG}}$	15.0
30/10681/433.6/LOWP/73	Eastland	1.90	0.085	-	-	-	-	-	-	-	-	-	0.094
30/10681/433.6/LBWP/73	Eastland	2.55	0.000	-	-	-	-	-	-	-	-	-	-
30/10681/433.6/MOWP/73	Eastland	1.67	0.000	-	-	-	-	-	-	-	-	-	-
30/10681/433.6/MBWP/73	Eastland	1.90	0.000	-	-	-	-	-	-	-	-	-	-
30/10681/433.6/ROWP/73	Eastland	1.27	0.000	-	-	-	-	-	-	-	-	-	-
30/10681/433.6/RBWP/73	Eastland	2.06	0.000	-	-	-	-	-	-	-	-	-	-
30/10681/433.6/SOWP/73	Eastland	2.06	0.022	0.030	0.024	0.027	0.023	0.023	0.023	0.022	0.019	0.024	0.024*
30/10681/433.6/SBWP/73	Eastland	2.46	0.000	-	-	-	-	-	-	-	-	-	-
81/137/14.6/LOWP/76	TXI Streetman	1.60	0.200	0.244	0.212	0.196	0.181	0.173	0.165	0.159	0.150	0.185	0.193*
81/137/14.6/LBWP/76	TXI Streetman	1.75	0.233	-	-	-	-	-	-	-	-	-	0.237
81/137/14.6/MOWP/76	TXI Streetman	1.83	0.268	-	-	-	-	-	-	-	-	-	0.263
81/137/14.6/MBWP/76	TXI Streetman	1.90	0.569	-	-	-	-	-	-	-	-	-	-
81/137/14.6/ROWP/76	TXI Streetman	1.67	0.086	-	-	-	-	-	-	-	-	-	0.086
81/137/14.6/RBWP/76	TXI Streetman	1.90	0.074	0.094	0.081	0.076	0.067	0.063	0.063	0.060	0.056	0.070	0.072*
81/137/14.6/SOWP/76	TXI Streetman	1.75	0.298	0.325	0.312	0.288	0.274	0.254	0.247	0.237	0.223	0.270	0.288*
81/137/14.6/SBWP/76	TXI Streetman	1.75	0.244	-	-	-	-	-	-	-	-	-	0.232

Note: Core Identification: Highway No./Control No./Mile Post/Lane and Wheel Path Designation/Year Constructed

* Constant Head Permeability at h = 15 cm obtained from plot of K_c vs. h

Table B-3. (cont'd)

Core Identification	Aggregate	OGAFC Layer Thick-ness	Variable Head	Permeability (k = cm/sec)									
				Constant Head, at h = (cm)									
				8.65	11.67	14.68	17.78	20.56	23.50	25.40	29.13	$K_{c_{AVG}}$	15.0
101/1347/21.7/ROWP/76	Eastland	1.60	0.004	-	-	-	-	-	-	-	-	-	0.005
101/1347/21.7/RBWP/76	Eastland	1.75	0.000	-	-	-	-	-	-	-	-	-	-
101/1347/21.7/LOWP/76	Eastland	1.90	0.026	-	-	-	-	-	-	-	-	-	0.026
101/1347/21.7/LBWP/76	Eastland	1.60	0.000	-	-	-	-	-	-	-	-	-	-
114/3521/22.2/ROWP/76	Eastland	1.20	0.000	-	-	-	-	-	-	-	-	-	-
114/3521/22.2/RBWP/76	Eastland	0.95	0.000	-	-	-	-	-	-	-	-	-	-
114/3521/22.2/LOWP/76	Eastland	1.43	0.000	-	-	-	-	-	-	-	-	-	-
114/3521/22.2/LBWP/76	Eastland	0.95	0.000	-	-	-	-	-	-	-	-	-	-
114/3522/35.4/ROWP/76	Eastland	1.35	0.000	-	-	-	-	-	-	-	-	-	-
114/3522/35.4/RBWP/76	Eastland	0.95	0.000	-	-	-	-	-	-	-	-	-	-
114/3522/35.4/LOWP/76	Eastland	1.20	0.000	-	-	-	-	-	-	-	-	-	-
114/3522/35.4/LBWP/76	Eastland	1.27	0.000	-	-	-	-	-	-	-	-	-	-

Note: Core Identification: Highway No./Control No./Mile Post/Lane and Wheel Path Designation/Year Constructed

Table B-4. Permeability Measurements on OGAFC Cores From District 11

Core Identification	Aggregate	OGAFC Layer Thickness	Variable Head	Permeability (k = cm/sec) Constant Head, at h = (cm)									
				8.65	11.67	14.68	17.78	20.56	23.50	25.40	29.13	$K_{c_{AVG}}$	15.0
59/1763/20.5/ROWP/73	Eastland	1.67	0.049	0.060	0.052	0.050	0.046	0.043	0.042	0.042	0.039	0.046	0.049*
59/1763/20.5/RBWP/73	Eastland	1.60	0.000	-	-	-	-	-	-	-	-	-	-
59/1763/20.5/SOWP/73	Eastland	0.95	0.027	-	-	-	-	-	-	-	-	-	0.029
59/1763/20.5/SBWP/73+	Eastland	1.60	0.025	0.036	0.029	0.029	0.026	0.024	0.022	0.021	0.020	0.026	0.028*
59/1763/22.0/ROWP/73	Eastland	1.67	0.056	-	-	-	-	-	-	-	-	-	0.057
59/1763/22.0/RBWP/73	Eastland	2.15	0.046	-	-	-	-	-	-	-	-	-	0.048
59/1763/22.0/SOWP/73+	Eastland	1.60	-	-	-	-	-	-	-	-	-	-	-
59/1763/22.0/SBWP/73	Eastland	1.43	0.026	0.039	0.030	0.025	0.023	0.021	0.021	0.020	0.019	0.025	0.025*
59/1763/22.4/ROWP/73	Superock	1.43	0.022	-	-	-	-	-	-	-	-	-	0.027
59/1763/22.4/RBWP/73	Superock	2.23	0.036	0.043	0.038	0.037	0.032	0.031	0.030	0.029	0.028	0.034	0.035*
59/1763/22.4/SOWP/73	Superock	2.47	0.191	0.247	0.213	0.185	0.178	0.169	0.158	-	-	0.192	0.192*
59/1763/22.4/SBWP/73+	Superock	2.37	-	-	-	-	-	-	-	-	-	-	-
59/1762/3.45/ROWP/73	Crushed Slag	1.50	0.025	0.030	0.031	0.028	0.025	0.024	0.022	0.021	0.021	0.025	0.027*
59/1762/3.45/RBWP/73	Crushed Slag	1.67	0.015	0.023	0.019	0.019	0.017	0.015	0.014	0.013	0.012	0.016	0.018*
59/1762/3.45/SOWP/73+	Crushed Slag	1.35	-	-	-	-	-	-	-	-	-	-	-
59/1762/3.45/SBWP/73+	Crushed Slag	1.35	-	-	-	-	-	-	-	-	-	-	-
59/1762/3.57/RBWP/73	Rock Asphalt	1.43	0.000	-	-	-	-	-	-	-	-	-	-
59/1762/3.57/SBWP/73	Rock Asphalt	1.67	0.000	-	-	-	-	-	-	-	-	-	-

Note: Core Identification: Highway No./Control No./ Mile Post/Lane and Wheel Path Designation/Year Constructed
* Constant Head Permeability at h = 15 cm obtained from plot of K_c vs. h
\+ Specimen damaged

Table B-4. (cont'd)

Core Identification	Aggregate	OGAFC Layer Thickness	Variable Head	Permeability (k = cm/sec) Constant Head, at h = (cm)									
				8.65	11.67	14.68	17.78	20.56	23.50	25.40	29.13	$K_{c_{AVG}}$	15.0
59/1762/3.85/ROWP/71	Knippa Traprock	1.10	0.013	-	-	-	-	-	-	-	-	-	0.014
59/1762/3.85/SOWP/71+	Knippa Traprock	1.50	-	-	-	-	-	-	-	-	-	-	-
59/1762/4.21/ROWP/71	Knippa Traprock	1.03	0.000	-	-	-	-	-	-	-	-	-	-
59/1762/4.21/SOWP/71	Knippa Traprock	1.27	0.041	0.040	0.041	0.039	0.035	0.035	0.033	0.035	0.032	0.036	0.038*
59/1762/4.27/SOWP/71+	TXI-Dallas	-	-	-	-	-	-	-	-	-	-	-	-
59/1762/4.86/ROWP/71	Hable Crushed Stone	2.05	0.034	-	-	-	-	-	-	-	-	-	0.036
59/1762/4.86/RBWP/71	Hable Crushed Stone	2.05	0.000	-	-	-	-	-	-	-	-	-	-
59/1762/5.09/ROWP/71	Hable Crushed Stone	0.87	0.000	-	-	-	-	-	-	-	-	-	-
59/1762/5.32/ROWP/71	Hable Crushed Stone	1.27	0.018	-	-	-	-	-	-	-	-	-	0.018
59/1761/23.6/LBWP/77	Rhyolite	1.83	0.000	-	-	-	-	-	-	-	-	-	-
59/1761/23.6/MBWP/77	Rhyolite	1.43	0.000	-	-	-	-	-	-	-	-	-	-
59/1761/23.6/RBWP/77	Rhyolite	2.15	0.012	0.016	0.016	0.014	0.013	0.012	0.012	0.011	0.010	0.013	0.014*
59/1761/23.6/SBWP/77	Rhyolite	1.43	0.000	-	-	-	-	-	-	-	-	-	-
59/1761/23.6/SBWP/77+	Rhyolite	-	-	-	-	-	-	-	-	-	-	-	-

Note: Core Identification: Highway No./Control No./Mile Post/Lane and Wheel Path Designation/Year Constructed
* Constant Head Permeability at h = 15 cm obtained from plot of K_c vs. h
\+ Specimen damaged

Table B-5. Permeability Measurements on OGAFC Cores from District 17

Core Identification	Aggregate	OGAFC Layer Thick-ness	Variable Head	Permeability (k = cm/sec) Constant Head, at h = (cm)									
				8.65	11.67	14.68	17.78	20.56	23.50	25.40	29.13	$K_{c_{AVG}}$	15.0
21/1164/1/ROWP/76	Superock	1.27	0.082	-	-	-	-	-	-	-	-	-	0.082
21/1164/1/RBWP/76	plus	2.23	0.132	-	-	-	-	-	-	-	-	-	0.132
21/1164/1/SOWP/76+	0% Fines	-		-	-	-	-	-	-	-	-	-	-
21/1164/2/ROWP/76	Superock	2.45		-	-	-	-	-	-	-	-	-	-
21/1164/2/SOWP/76	plus	2.70		-	-	-	-	-	-	-	-	-	-
	8% Fines												
21/1164/3/ROWP/76	Superock	2.37		-	-	-	-	-	-	-	-	-	-
	plus												
	15% Fines												
21/1164/4/ROWP/76	Superock	2.30	0.046	-	-	-	-	-	-	-	-	-	0.044
	plus												
	22% Fines												

Note: Core Identification: Highway No./Control No./Section No./Lane and Wheel Path Designation/Year Constructed
\+ Specimen Damaged

Table B-6. Permeability Measurements on OGAFC Cores from District 20

Core Identification	Aggregate	OGAFC Layer Thick-ness	Variable Head	Permeability (k = cm/sec) Constant Head, at h = (cm)									
				8.65	11.67	14.68	17.78	20.56	23.50	25.40	29.13	$K_{c_{AVG}}$	15.0
10/7392/847/LOWP/75	Clodine	2.23	0.150	0.181	0.161	0.147	0.133	0.126	0.122	0.116	0.107	0.137	0.144*
10/7392/847/LBWP/75	Clodine	1.97	0.156	0.189	0.169	0.154	0.142	0.137	0.126	0.122	0.115	0.144	0.152*
10/7392/847/MOWP/75	Clodine	1.60	0.215	0.247	0.241	0.217	0.197	0.186	0.174	0.170	0.157	0.198	0.212*
10/7392/847/MBWP/75	Clodine	1.50	0.115	0.161	0.137	0.125	0.118	0.106	0.099	0.097	0.092	0.117	0.120*
10/289/861/ROWP/76	Superock & 10% Fld. Sand	2.37	0.107	0.126	0.118	0.107	0.096	0.095	0.090	0.088	0.087	0.101	-
10/289/861/RBWP/76	Superock & 10% Fld. Sand	1.90	0.109	0.132	0.119	0.106	0.103	0.094	0.091	0.089	0.081	0.102	0.106*
10/289/861/SOWP/76	Superock & 10% Fld. Sand	2.70	0.045	0.050	0.053	0.045	0.040	0.037	0.036	0.035	0.035	0.041	0.044*
10/289/861/SBWP/76	Superock & 10% Fld. Sand	3.35	0.117	0.155	0.141	0.120	0.108	0.103	0.097	0.093	0.088	0.113	0.116*
87/3056/1/LOWP/74+	Knippa Traprock	1.60	0.022	0.036	0.029	0.027	0.024	0.022	0.020	0.021	0.020	0.025	-
87/3056/1/LBWP/74	Knippa Traprock	1.20	0.000	-	-	-	-	-	-	-	-	-	-
87/3057/4/ROWP/75	Superock	2.63	0.070	0.073	0.071	0.066	0.067	0.061	0.059	0.056	0.054	0.063	0.061*
87/3057/4/RBWP/75	Superock	2.55	0.075	0.079	0.077	0.078	0.072	0.063	0.062	0.059	0.059	0.068	0.074*
96/655/23.6/LOWP/75	Superock	1.50	0.000	-	-	-	-	-	-	-	-	-	-
96/655/23.6/LBWP/75	Superock	1.83	0.000	-	-	-	-	-	-	-	-	-	-
96/655/23.6/MOWP/75	Superock	3.35	0.015	-	-	-	-	-	-	-	-	-	0.015
96/655/23.6/MBWP/75	Superock	2.23	0.010	-	-	-	-	-	-	-	-	-	0.011

Note: Core Identification: Highway No./Control No./Mile Post/Lane and Wheel Path Designation/Year Constructed

* Constant Head Permeability at h = 15 cm obtained from plot of K_c vs. h

\+ Specimen damaged

different heads for each of twenty-four specimens which were selected based on earlier test results. A semi-log plot of k_c vs. h was made for each specimen (see typical plot in Figure B-16). This plot also shows an equivalent head (h_{eq}) where k_c is equal to k_v.

Theoretically k_c should be equal to k_v for each specimen. An average k_c value was computed for each of the twenty-four specimens and a plot was made of the average k_c vs. k_v (see Figure B-17). Considering the various assumptions which were made in arriving at these values, the results are considered to be very favorable. It should be noted that the high flow meter was calibrated in increments of approximately 25 ml/min and this could account for the greater discrepancies between the larger values of k_c and k_v.

An attempt was also made to determine an equivalent head (h_{eq}) where k_c would equal k_v. An h_{eq} value was obtained from each of the twenty-four semi-log plots of k_c vs. h described above. The average h_{eq} was found to be 15.6 cm (6.14 in.). It was noted that this value was very close to the logarithmic average of the heads (h_o = 25.4 cm and h_1 = 8.65 cm) used in the variable head test.

$$\log \text{average } (25.4/8.65) = 14.8 \text{ cm} \approx 15 \text{ cm}$$

For the remaining specimens (excluding those which were impermeable) a variable head test was performed as usual and a constant head test was performed at a single h value of 15 cm (5.9 in.). A k_c value at h = 15 cm was also obtained from the semi-log plots of k_c vs. h. The results are plotted in Figure B-18

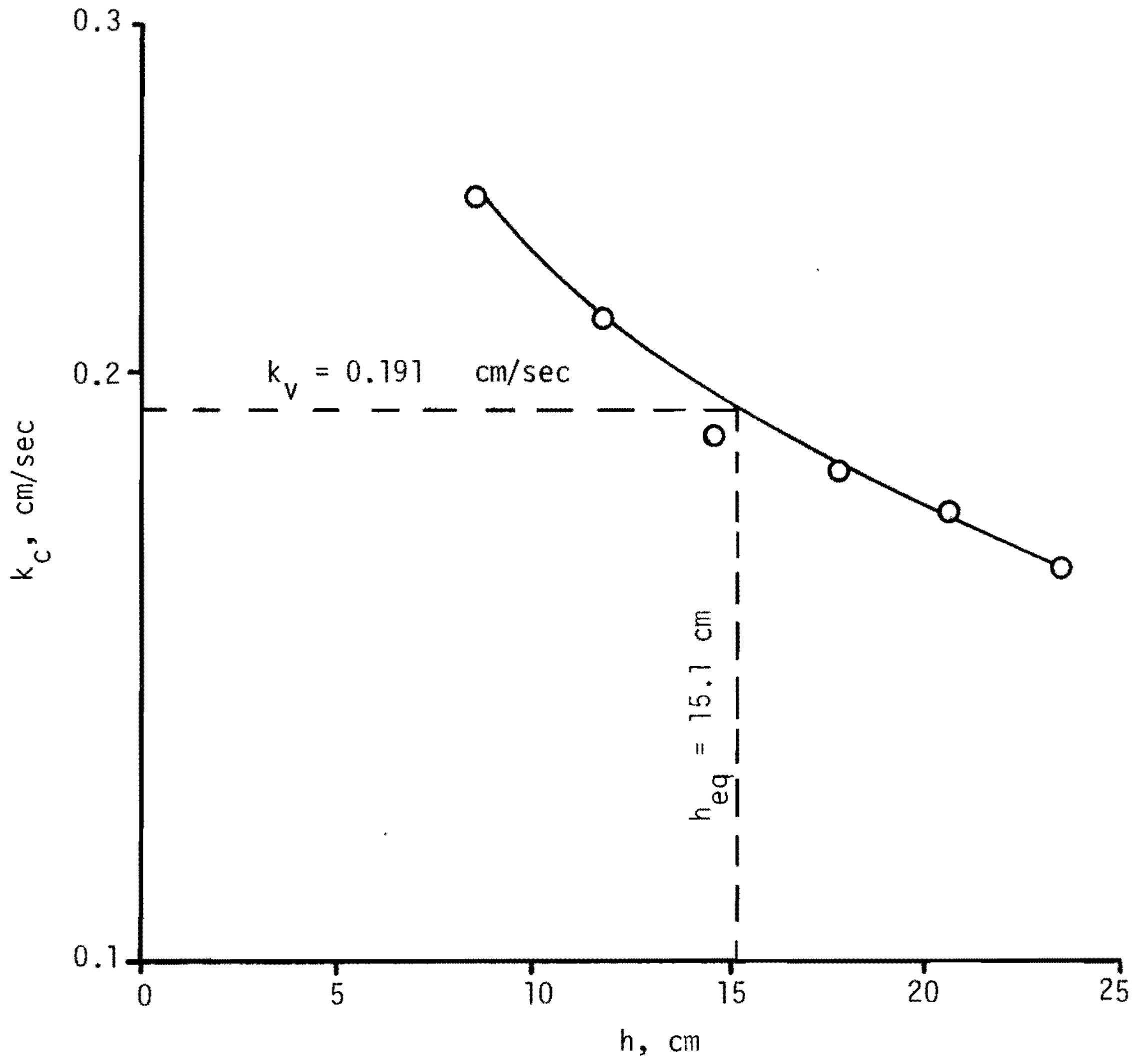


Figure B-16. Typical Semi-log Plot of k_c vs. h

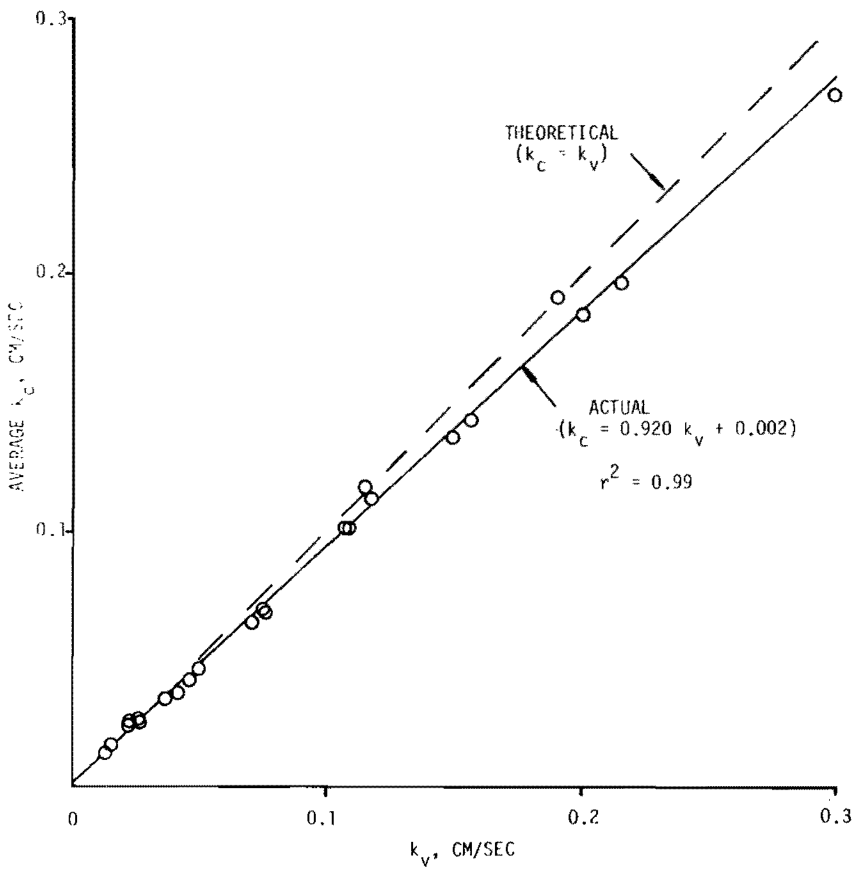


Figure B-17. Average k_c vs. k_v

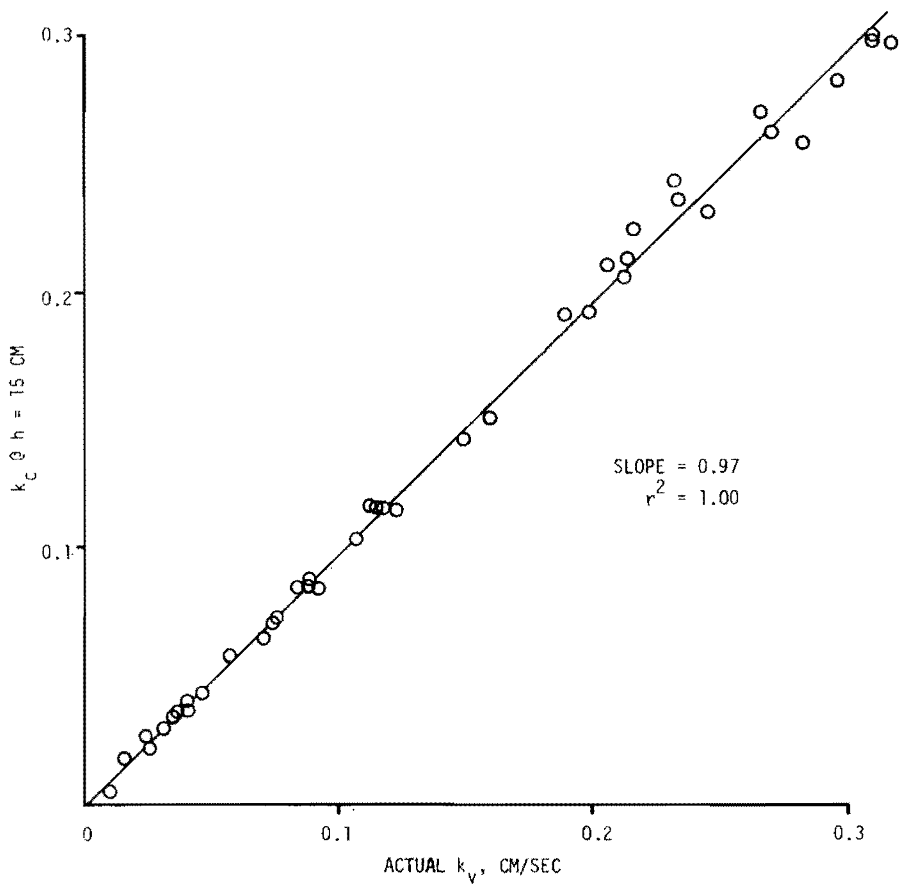


Figure B-18. K_c @ h = 15 cm vs. k_v

APPENDIX C

OGAFC DRAINAGE CHARACTERISTICS; TEST METHOD, CALCULATIONS, TEST DATA, AND CORRELATION WITH PERMEABILITY

APPENDIX C

OGAFC DRAINAGE CHARACTERISTICS; TEST METHOD, CALCULATIONS, TEST DATA, AND CORRELATION WITH PERMEABILITY

Introduction

Several theoretical approaches have been proposed for estimating the internal drainage capacity of OGAFC pavements. During the course of this study, a method was developed by which to determine a drainage coefficient, k_D (cm/sec), similar to the permeability coefficient discussed in Appendix B. This method was based upon actual drainage tests performed in the laboratory. From k_D, an equivalent rainfall intensity that will begin to cause pavement surface flooding was estimated. The following discussion describes how this was done.

Background Material

One method proposed for estimating the drainage capacity of OGAFC layers was developed by Gallaway, et al [35]. This method was based on Darcy's Law:

$$Q = kiA$$

where Q = quantity of water flow, cm^3/sec

k = coefficient of permeability, cm/sec

i = hydraulic gradient or head loss per unit length of flow (h/L)

A = cross-sectional area of flow, cm^2

By applying this technique to an "average" OGAFC pavement with an 11 m (36 ft.) drainage width, they estimated that a rainfall intensity of 2.5 mm/h (0.1 in/h) will cause incipient surface flooding to occur.

Another theoretical approach for estimating the water drainage capacity of OGAFC pavements was proposed by Smith [7]. This method was based on the Chezy-Manning equation for channel flow.

$$Q = 1/n \; AR^{2/3} \; S^{1/2} \qquad \text{(SI Units)}$$

where Q = flow rate, cm^3/sec

n = roughness coefficient

A = cross-sectional area of flow, cm^2

R = hydraulic radius or ratio of cross-sectional area to the wetter perimeter (A/P), cm

S = pavement cross-slope

Several assumptions were made in regard to this equation. First, the roughness coefficient was assumed to be the same as that for firm gravel, n = 0.02. Secondly, the cross-sectional area of flow was computed based upon a method for estimating accessible air void contents. Third, the hydraulic radius was calculated based upon a typical flow channel through a dense-packed layer of spherical, uniformly-graded aggregate of diameter d. After computing Q, the Rational Method was used to relate this drain-flow rate to the rainfall intensity required to produce that quantity of flow. The formula used in the Rational Method is:

$$A = CIa$$

where Q = peak runoff rate, cm^3/sec

C = runoff coefficient dependent on the characteristics of the drainage area

I = average rainfall intensity, cm/s

a = drainage area, cm^2

By applying this technique to an OGAFC pavement with a 2.54 cm (1 in.) thickness, an 11 m (36 ft.) width, a cross-slope of 1 in 48, and a void content of 20 percent (14.79 percent accessible void content); Smith estimated that a rainfall intensity value of 25.65 mm/h (1.01 in/h) will cause incipient surface flooding.

Drainage Test Apparatus

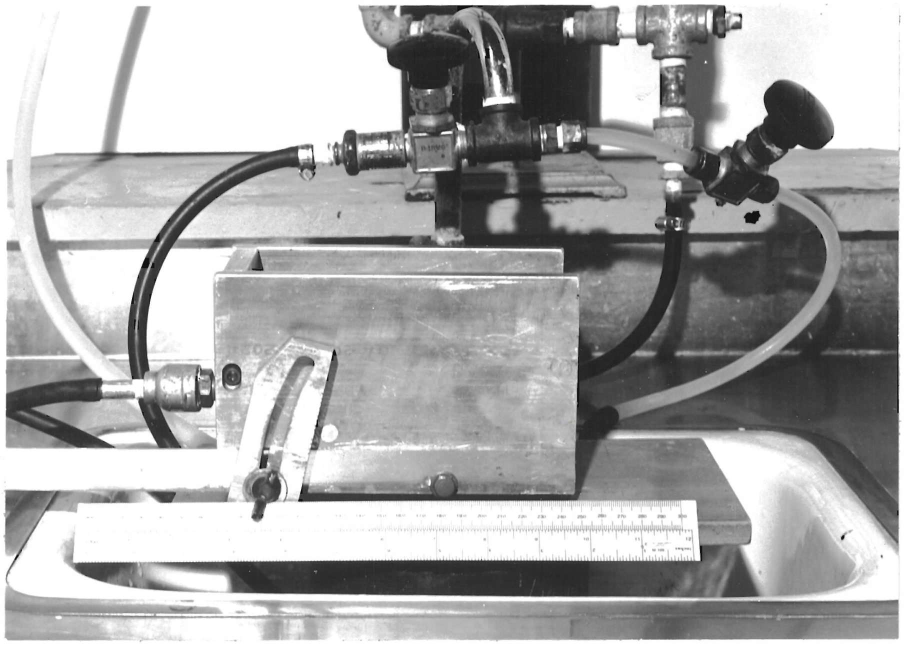
The drainage test apparatus developed for use in this study is shown in Figure C-1. It basically consisted of a rectangular box, with the top and one end open, mounted onto a metal base by a hinge (see schematic in Figure C-2). A hinge connection was used in order to provide a means by which to vary the cross-slope. A pointer attached to the metal box and a ruler, mounted to a metal platform, were used for setting the desired cross-slopes. A metal stop was inserted toward the back of the box in order to prevent the specimen from interfering with flow into the box.

The quantity of flow through the specimen was determined by using a flow meter. This meter measured flows in the range of 0 ml/min to 250 ml/min.

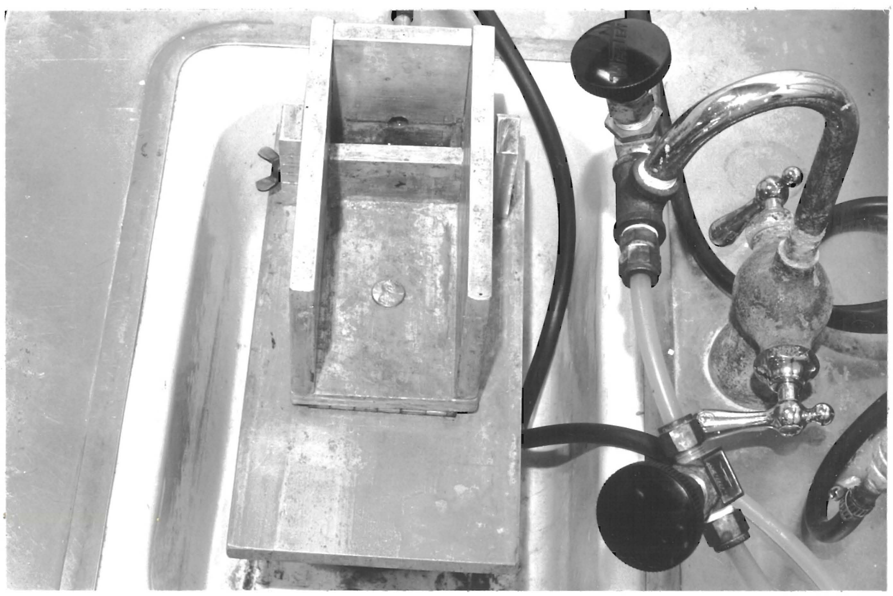
Specimen Preparation

The direct drainage tests for this study were performed on specimens cut from the 15.24 cm (6.00 in.) cores used for the permeability tests (see Figure C-3). These specimens were cut to fit the dimensions of the rectangular box as near as possible. As was the case for the permeability test, it was necessary for the OGAFC layer to be on an impermeable substrate.

An impermeable membrane was applied around the sides and bottom of the specimen in order to force all water to flow through the length of

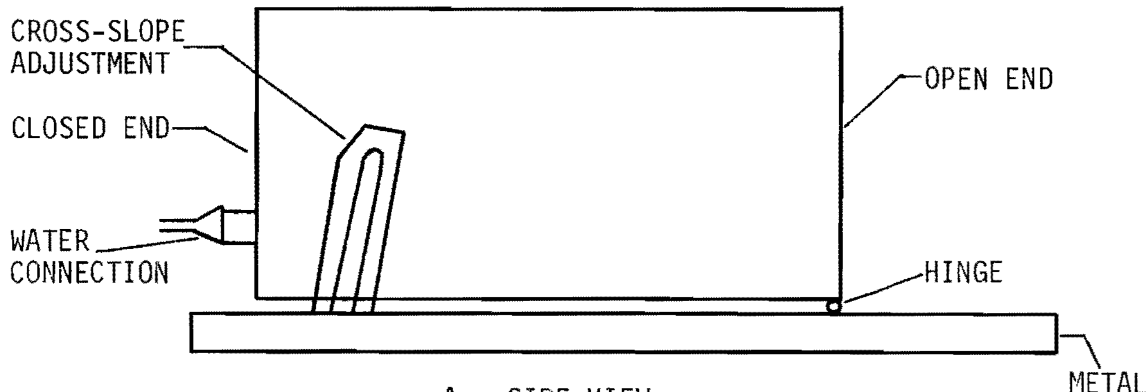


A. Side View

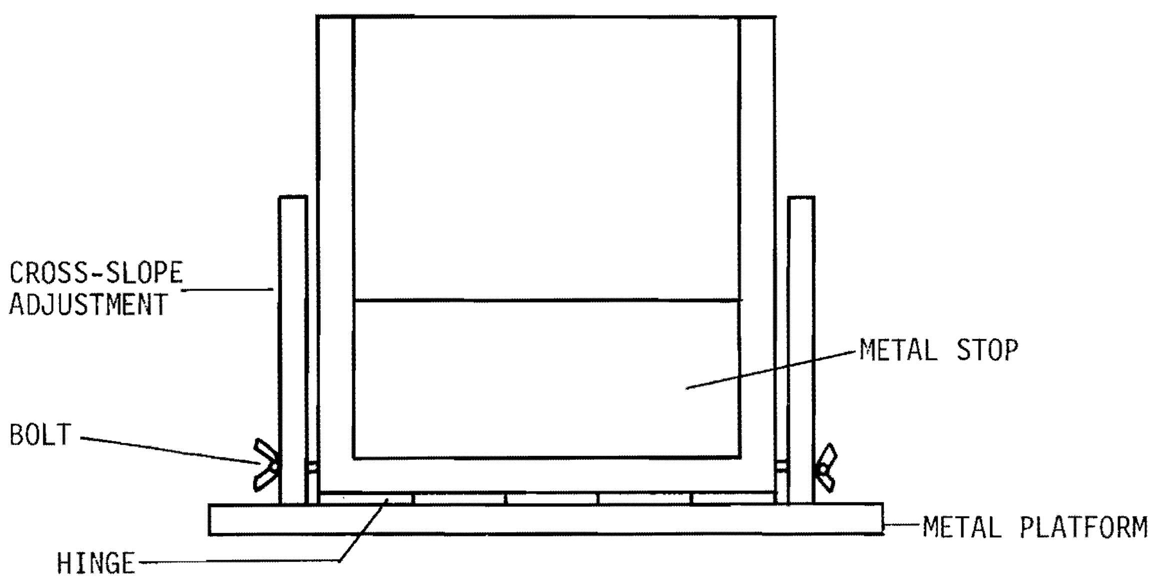


B. Open End View

Figure C-1. Drainage Test Apparatus



A. SIDE VIEW



B. OPEN END VIEW

Figure C-2. Schematic of Drainage Test Apparatus

Figure C-3. Drainage Test Specimen Being Cut from Permeability Test Specimen the specimen. This impermeable membrane consisted of a thin sheet of plastic wrap which was cut large enough to allow for approximately 0.64 cm (0.25 in.) of overlap at the top edges and one end of the specimen (see Figure C-4). Rubber cement was used to bond the membrane to the specimen. The overlap portion of membrane was used when the cracks between the specimen and the drainage box were sealed with permagum.

Drainage Test Procedure

The recommended test procedures for the direct drainage test are described in Table C-1. This test cannot be performed in the field, however a correlation can be made between this test and the permeability test which can be adapted for field testing. A sample data sheet containing actual test data is shown in Figure C-5.

Formulas for Calculating the Drainage Coefficient and Rainfall Intensity

The data obtained from the direct drainage tests were used to compute a drainage coefficient (k_D) for the OGAFC layers. The method developed for estimating k_D was based on the Chezy-Manning Equation for channel flow. The Chezy-Manning Equation is:

$$Q = 1/n\ AR^{2/3}\ S^{1/2} \quad \text{(SI Units)} \qquad \text{Equation C-2}$$

where Q = flow rate, cm^3/sec

n = Manning roughness coefficient

A = cross-sectional area of flow, cm^2

R = hydraulic radius = A/P, cm

P = wetted perimeter, cm

S = slope of the channel, cm/cm

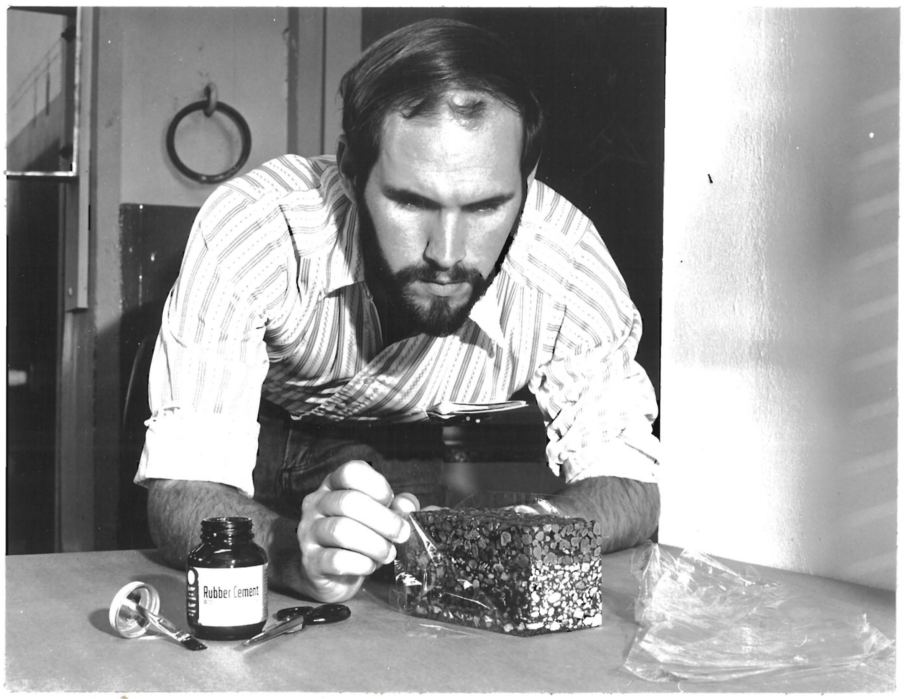


Figure C-4. Impermeable Membrane Being Applied to Drainage Test Specimen

Table C-1. Test Procedures for Drainage Test

Procedure	Remarks
1. Record specimen number and determine the average width and thickness of the OGAFC layer.	
2. Place the prepared specimen into the drainage box.	For preparing the specimen, follow the instructions given earlier in this report.
3. Fold the overlap portion of the membrane down onto the specimen and then press a strip of permagum between the membrane and the drainage box (see Figure C-6).	The permagum acts to seal the cracks around the edges of the specimen, thereby forcing water to flow in one end of the specimen and out the other.
4. After all cracks are sealed off, fold the overlap portion back over the top of the permagum (see Figure C-7).	Doing this keeps the permagum from filling the voids and obstructing flow.
5. Level the surface of the specimen as near as possible by placing a small level on the surface and adjusting the drainage box.	This is a somewhat subjective process due to the irregular surface texture of the OGAFC's.
6. Record the starting point or zero point reading from the ruler.	The pointer should be parallel to the OGAFC surface.
7. Set the value of cross-slope desired.	Several different values were used for the purpose of this study.
8. Open the main valve and allow water to flow through the specimen for 2-3 minutes.	This is done to saturate the specimen and also to check for leaks.
9. Adjust the flow rate until the water at the surface rises to a level of about one-half the diameter of the surface aggregate (Figure C-8).	This was a very subjective process, however checks showed good repeatability.
10. Determine the flow from the flow meter and record it.	
11. Go back to step 8 and repeat test for another cross-slope.	

DIRECT DRAINAGE TEST

Date: 4/30/79 Operator: RT

Specimen Identification: 21/1164/1/RBWP/76

Width: 7.38 cm Thickness: 2.23 cm

Distance to Slope Indicator (ℓ): 61.0 cm

Initial Reading (e_o) @ S = 0: 1.9 cm

Desired Cross-Slope cm/cm	Actual Reading (e_f) cm	Δe (e_f - e_o) cm	S ($\Delta e/\ell$) cm/cm	Q_F ml/min	Q_F cm^3/sec	$S^{1/2}$
0.250	17.2	15.3	0.251	35	0.58	0.493
0.208	14.6	12.7	0.208	30	0.50	0.451
0.167	12.1	10.2	0.167	27	0.45	0.406
0.125	9.5	7.6	0.125	23	0.38	0.352
0.062	5.7	3.8	0.062	18	0.30	0.249
0.042	4.4	2.5	0.041	15	0.25	0.202
0.021	3.2	1.3	0.021	10	0.17	0.146
Checks						
0.125	9.5	7.6	0.125	23	0.38	0.352
0.208	14.6	12.7	0.208	33	0.55	0.451

Figure C-5. Typical Data Sheet with Data from Drainage Test

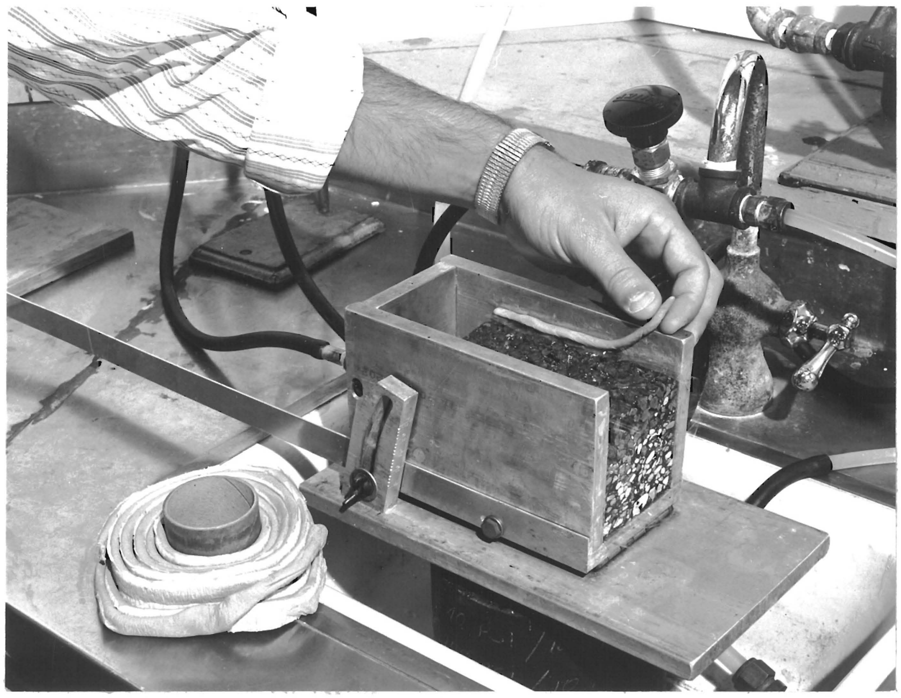
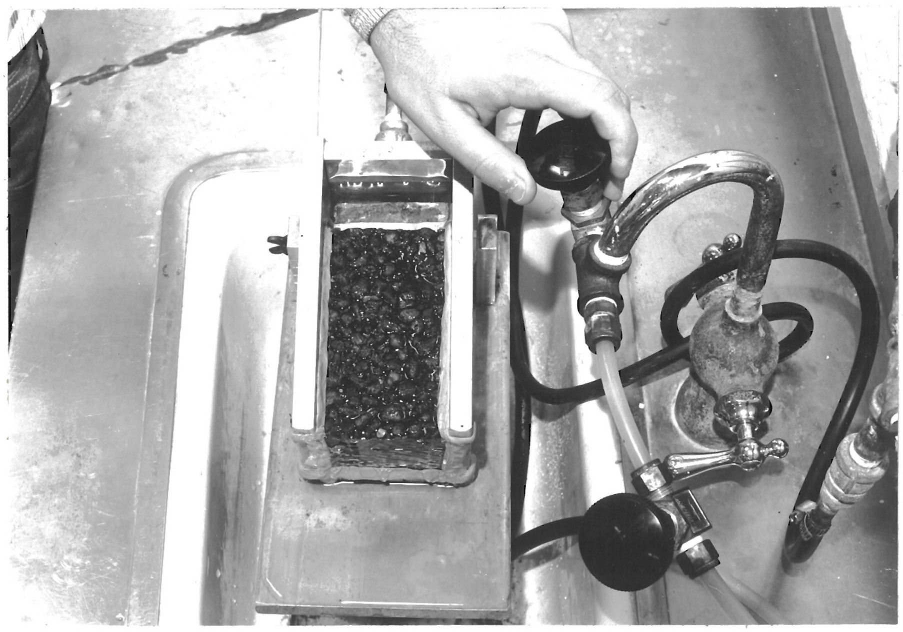


Figure C-6. Permagum Being Applied to Top Edges of Specimen

Figure C-7. Overlap Portion of Impermeable Membrane Being Folded Back Over Top of Permagum

A. Overall View



B. Close-up

Figure C-8. Drainage Test in Progress (Water Level at One-Half the Diameter of the Surface Aggregate)

Since n depends on the physical characteristics of the channel, it would be very difficult to establish a reliable roughness coefficient value for this particular case. Therefore, the ratio 1/n was assumed to be equal to a constant C and Equation C-2 becomes:

$$Q = C\ AR^{2/3}\ S^{1/2} \qquad \text{Equation C-3}$$

The value of A is related to the number of pore channels (y) in the total cross-sectional area (width times thickness) of the OGAFC layer. If the aggregate particles were single-sized and spherical in shape, then the cross-sectional area of a typical pore channel could easily be determined. However, this was not the case and therefore it was necessary to use a more general approach.

The cross-sectional area of one pore channel was assumed to be equal to a constant (c_1) times the average dimension of a typical pore channel squared ($d_{AVG}{}^2$). If y equals the number of pore channels, then

$$A = y\ c_1\ d_{AVG}{}^2 \qquad \text{Equation C-4}$$

As stated earlier, the hydraulic radius is equal to the cross-sectional area of the flow channel divided by the wetted perimeter. For this particular case, the wetted perimeter was assumed to be equal to a constant times the number of pore channels times the average dimension of one pore channel, or:

$$P = c_2\ y\ d_{AVG}$$

The equation for the hydraulic radius then becomes:

$$R = c_1/c_2\ d_{AVG} \qquad \text{Equation C-5}$$

The value of A is only a fraction of the total cross-sectional area of the OGAFC layer. Since the total cross-sectional area is equal to the width (w) times the thickness (z) of the OGAFC layer, this fraction (α) can be expressed as:

$$\alpha = A/wz$$

and by rearranging terms:

$$A = \alpha wz \qquad \text{Equation C-6}$$

By substituting the values for R and A obtained from Equations C-5 and C-6, respectively; Equation C-3 becomes:

$$Q = C\,\alpha wz\,(c_1/c_2\,d_{AVG})^{2/3}\,S^{1/2}$$

Now let $\quad Q' = Q/wz \qquad$ Equation C-7

or $\quad Q' = C\alpha\,(c_1/c_2\,d_{AVG})^{2/3}\,S^{1/2}$ cm/sec $\quad$ Equation C-8

Note that for a given OGAFC layer:

1. C is a constant which depends on the physical characteristics of the channel.
2. d_{AVG}, c_1, c_2, and α are constants which depend on particle parameters (size, shape, roughness, etc.) and the packing of the particles.

Therefore, the term $C\,\alpha\,(c_1/c_2\,d_{AVG})^{2/3}$ in Equation C-8 will be equal to a constant for any given OGAFC layer.

$$K = C\,\alpha\,(c_1 c_2\,d_{AVG})^{2/3}$$

If incipient flooding occurs, then Q' becomes Q'_F and K becomes K_D. Therefore:

$$Q'_F = K_D\,S^{1/2} \qquad \text{Equation C-9}$$

where K_D = drainage coefficient, cm/sec

The flowrate (Q_F) at which incipient flooding occurs for various values of cross-slope can be determined from the direct drainage test. A general equation for Q_F can then be established from a plot of

Q_F vs. $S^{1/2}$: (see Figure C-9)

$$Q_F = m\, S^{1/2} \qquad \text{Equation C-10}$$

where m = slope of the regression line for the plot of Q_F vs. $S^{1/2}$

From Equations C-7, C-9 and C-10:

$$K_D = m/wz \quad \text{cm/sec}$$

Therefore the drainage coefficient for the drainage test data plotted in Figure C-10 is equal to:

$$K_D = 1.12\ \text{cm}^3/\text{sec}\big/(7.38\ \text{cm})(2.23\ \text{cm})$$

$$K_D = 0.068\ \text{cm/sec}$$

The method used to relate the drainage flow rate to the rainfall intensity required to produce that quantity of flow was the Rational Method. The formula for this method is:

$$Q = CIa \qquad \text{Equation C-11}$$

where Q = peak runoff rate, mm^3/hr

C = runoff coefficient which depends on the characteristics of the drainage area (for very small watershed areas, water outflow very quickly becomes equal to water inflow during a rainstorm so that C can be assumed to equal unity) [7]

I = average rainfall intensity, mm/hr

a = drainage area, mm^2

If rainfall intensity is given in in/hr, A in ft^2, and Q in cfs, then since C equals unity:

$$Q = I\, a/43{,}200 \qquad \text{Equation C-12}$$

Rearranging the terms in Equation B-6 gives:

$$Q = wzQ' \qquad \text{Equation C-13}$$

and equating Q from Equations C-11 and C-13 gives:

$$I\, a = w\, z\, k_D\, S^{1/2}$$

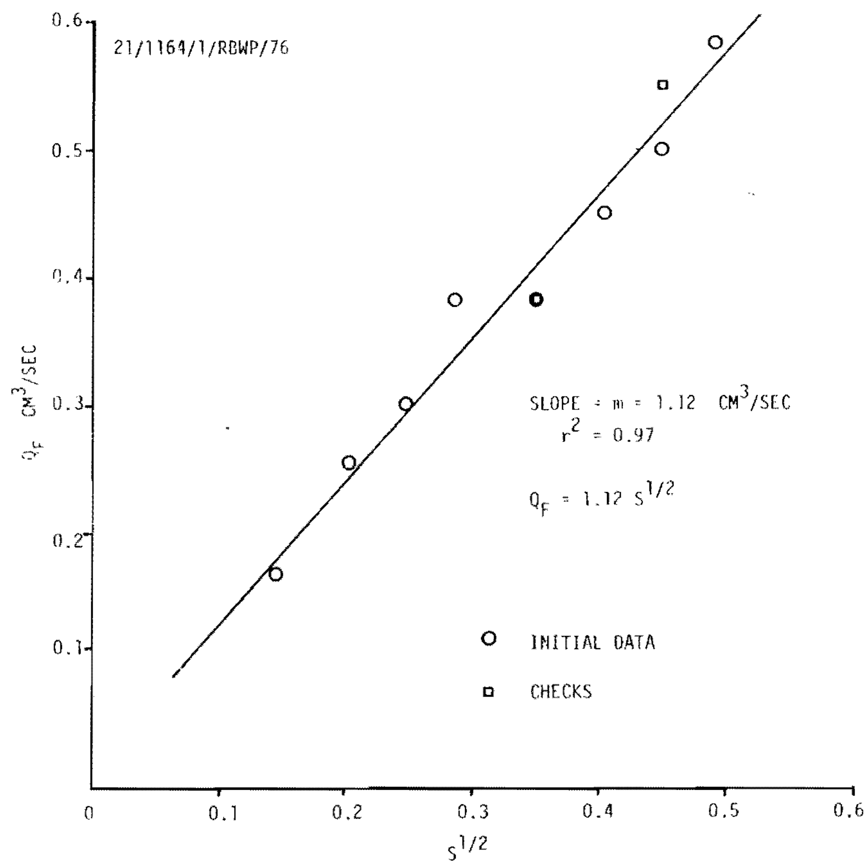


Figure C-9. Q_F vs. $S^{1/2}$ Representing Drainage Test Data from Figure C-5 since C equals unity. For the case of incipient flooding and since $a = wL$ this equation becomes:

$$I_F = z\ k_D\ S^{1/2}/L \quad \text{mm/hr} \quad (\div 25.4,\ \text{in/hr}) \quad \text{Equation C-14}$$

where I_F = average rainfall intensity where incipient flooding occurs, mm/hr

z = thickness of drainage test specimen, mm

k_D = drainage coefficient determined by direct drainage test, cm/sec x 36,000 = mm/hr

S = slope of the channel, mm/mm

L = flow length or lane width, mm

Therefore, for a 3.7 m (12 ft.) lane with an OGAFC layer thickness of 2.54 cm (1 in.) and a 2 percent cross-slope, Equation C-14 reduces to the following:

$$I_F = 35.4\ k_D \quad \text{mm/hr}$$

or $$I_F = 1.39\ k_D \quad \text{in/hr}$$

Drainage Test Results

The direct drainage test was performed on only twenty OGAFC specimens. These twenty specimens were chosen because they were representative of the range of k_p values obtained in this study. The results of these tests are given in Table C-2. The equivalent rainfall intensity (I_F) was estimated for a 3.66 m (12 ft.) lane width and a 2 percent cross-slope and a 2.54 cm (1 in.) thick OGAFC layer.

Comparison of Permeability Test Results and Drainage Test Results

For the purpose of this comparison a plot of k_D vs. k_v was made (see Figure C-10). Two types of regressions were performed on this data.

Table C-2. Results of Direct Drainage Tests

District	Core Location	Aggregate	OGAFC Layer Thickness mm	Drainage Coefficient cm/sec	Equivalent Flooding Rainfall Intensity mm/hr**
* 2	30/10681/433.6/LOWP/73	Eastland	19.0	0.080	2.79
2	81/137/14.6/LOWP/76	Streetman	16.0	0.289	10.41
2	81/137/14.6/MOWP/76	Streetman	18.3	0.389	13.97
2	81/137/14.6/MBWP/76	Streetman	19.0	0.450	16.26
2	81/137/14.6/RBWP/76	Streetman	19.0	0.122	4.32
2	81/137/14.6/SOWP/76	Streetman	17.5	0.368	13.21
2	81/137/14.6/SBWP/76	Streetman	17.5	0.176	6.60
2	101/1347/21.7/ROWP/76	Eastland	16.0	0.068	2.54
2	101/1347/21.7/LOWP/76	Eastland	19.0	0.098	3.56
*11	59/1763/22.0/SBWP/73	Eastland	14.3	0.126	4.57
11	59/1762/4.21/SOWP/71	Knippa Traprock	12.7	0.176	6.60
11	59/1761/23.6/RBWP/77	Rhyolite	21.5	0.071	2.54
+17	21/1164/1/ROWP/76	Superock	12.7	0.167	6.10
17	21/1164/1/RBWP/76	Superock	22.3	0.068	2.54
17	21/1164/2/ROWP/76	Superock	24.5	0.171	6.10
17	21/1164/2/SOWP/76	Superock	27.0	0.286	10.41
17	21/1164/3/ROWP/76	Superock	23.7	0.194	6.86
17	21/1164/4/ROWP/76	Superock	23.0	0.094	3.30
*20	10/7392/847/MOWP/75	Clodine LW	16.0	0.178	6.60
20	10/289/861/RBWP/76	Superock	19.0	0.123	4.32

*Core Identification: Highway No./Control No./Mile Post/Lane and Wheel Path Designation/Year Constructed
+Core Identification: Highway No./Control No./Section No./Lane and Wheel Path Designation/Year Constructed
**I_F is Estimated Rainfall Intensity causing flooding of 12 ft. lane, 1 in. thick OGAFC, 2 percent cross-slope

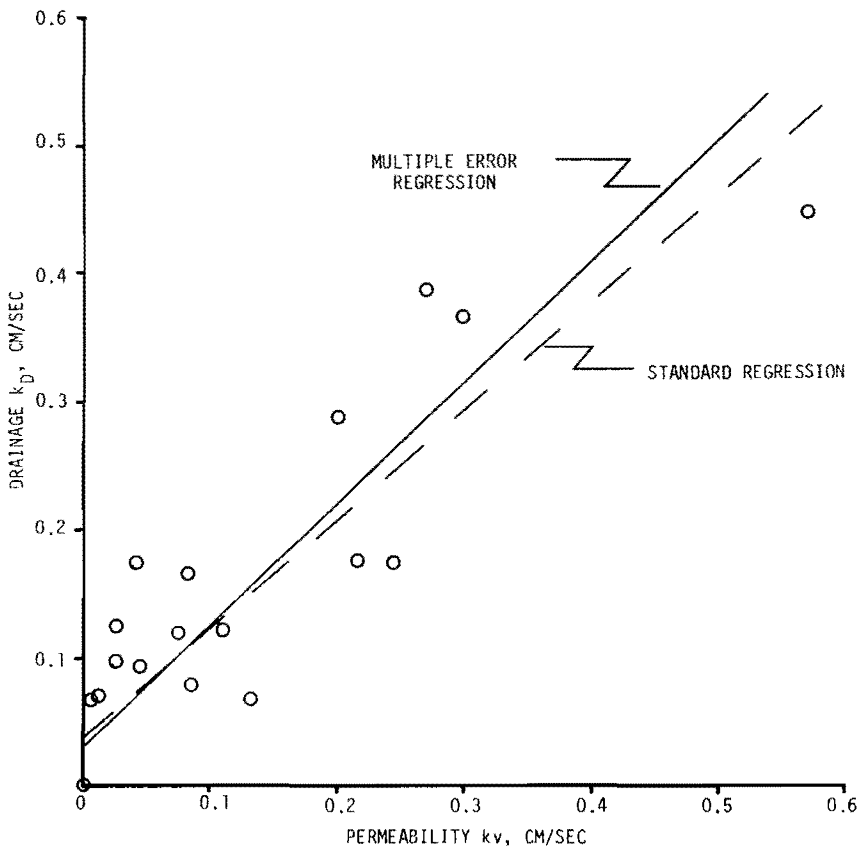


Figure C-10. Relation Between Drainage Coefficient and Permeability Coefficient

First, a standard linear regression was performed on the data. However, this type of regression assumes that the values of all but one of the variables is known precisely. For the case of k_D and k_v, there are errors of measurement in both variables and therefore this linear regression method gives a biased estimate of the regression coefficients.

For this reason a second regression was performed on the data. This multiple error regression accounts for errors in all variables [41]. By assuming that the "quality" of the two variables (k_D and k_v) is the same, the following equation was obtained:

$$k_D = 0.948\ k_p + 0.031$$

This line appears to fit the data better than the conventional linear regression line.

It should be noted that the "quality" of each of the two variables was assumed to be the same because there was not sufficient data to accurately predict "quality" values. It is quite possible that the "quality" of these two variables is not the same. Future tests to determine the repeatability of results would provide a better means for determining these "quality" values and thereby allow for a more reliable comparison between the drainage coefficient and permeability coefficient.

APPENDIX D

ESTIMATION OF 2 - YEAR ASPHALT HARDENING INDEX

APPENDIX D

ESTIMATION OF 2 - YEAR ASPHALT HARDENING INDEX

Introduction

The tendency of an asphalt binder to harden with time, as a result of oxidation and polymerization reactions promoted by exposure of a flexible pavement layer to actinic light and air, can be evaluated by determining the viscosity of the asphalt cement extracted from pavement cores. The ratio of this viscosity to the original viscosity of the asphalt cement has been called a "Hardening Index", or H.I., by Traxler and Shelby[26]. This value after 2 years field exposure was used to compare asphalt hardening resistance in pavements.

However, the asphalt in the cores taken from OGAFC evaluation pavements in the present study had been exposed from one to seven years. Thus it was necessary to find some method for estimating the 2-year Hardening Index ($H.I._2$) from the Hardening Index determined, or $H.I._t$. The following discussion indicates how this can be done.

Basis for Estimation of $H.I._2$

Coons and Wright [27] have shown a linear relation between the relative viscosity (i.e. the Hardening Index) of asphalt cement recovered from pavements and the logarithm of the age (or exposure time). In addition, Heithaus and Johnson [28] have presented data indicating how asphalt concretes with void contents varying from 2 percent to 14 percent harden with time of exposure in Midwestern (Wood River, Illinois) pavements. However, since they used penetration to measure asphalt cement consistency, application of their data in terms of Hardening Index values required conversion of penetration values to viscosity.

This conversion was made, for the purposes of this study, by employing data presented by Corbet and Schweyer [29] who proposed the following relation.

$$\log (P/P_1) = M \log (V/V_1)$$

where

P = penetration (77°F), 10^{-5}m

V = viscosity (140°F), poise

Measurements made on asphalt cements from 84 different worldwide sources resulted in values of M with an average of 0.68 (standard deviation, 0.076). Thus,

$$P = P_1 \ (V_1)^{0.68} \ (\frac{1}{V})^{0.68}$$

Data from these samples also indicated that when P = 90, viscosity at 140°F would average 1519 poise (standard deviatoin, 581 poise). Thus,

$$P = 90(1519)^{0.68} \ (\frac{1}{V})^{0.68}$$

from which,

$$V = (\frac{13,000}{P})^{1.47}$$

Using this conversion, Hardening Index (H.I.) values were calculated from the Heithaus and Johnson data, and are presented in Table D-1 and plotted in Figure D-1. This plot indicates that the relation between the increase in Hardening Index (ΔH.I. = H.I. - 1) and time can be expressed as follows.

$$\Delta H.I. = M \log t$$

The Hardening Index increase at 2-years is then,

$$\Delta H.I._2 = M \log 2$$

and, since

$$\Delta H.I._t = M \log t$$

Table D-1. Increase in Asphalt Hardening Index with Age in Midwestern Pavements

Voids, Percent	Exposure Time, t Years	log t	Penetration (77°F)*	Estimated Viscosity @ 140°F Poise	Hardening Index (H.I.)***	H.I. Increase
2	0	-----	73	2034	1.00	0.00
	2	0.301	67	2307	1.13	0.13
	4	0.602	60	2714	1.33	0.33
	5	0.699	59	2782	1.37	0.37
	8	0.903	53	3257	1.60	0.60
	10	1.000	49	3655	1.80	0.80
3	0	-----	73	2034	1.00	0.00
	2	0.301	63	2526	1.24	0.24
	4	0.602	56	3003	1.48	0.48
	5	0.699	53	3257	1.60	0.60
	8	0.903	47	3886	1.91	0.91
	10	1.000	45	4143	2.04	1.04
7	0	-----	65	2413	1.00	0.00
	2	0.301	50	3548	1.47	0.47
	4	0.602	41	4750	1.97	0.97
	5	0.699	39	5112	2.12	1.12
	8	0.903	34	6255	2.59	1.59
	10	1.000	32	6838	2.83	1.83
14	0	-----	65	2413	1.00	0.00
	2	0.301	35	5994	2.48	1.48
	4	0.602	24	10437	4.33	3.33
	5	0.699	22	11861	4.92	3.92
	10	1.000	20	13645	5.66	4.66

*Taken from curves presented by Heithaus and Johnson [28]

**Estimated using the relation: $V = \left(\frac{13,000}{P}\right)^{1.47}$

***H.I. = $\frac{V_t}{V_o}$

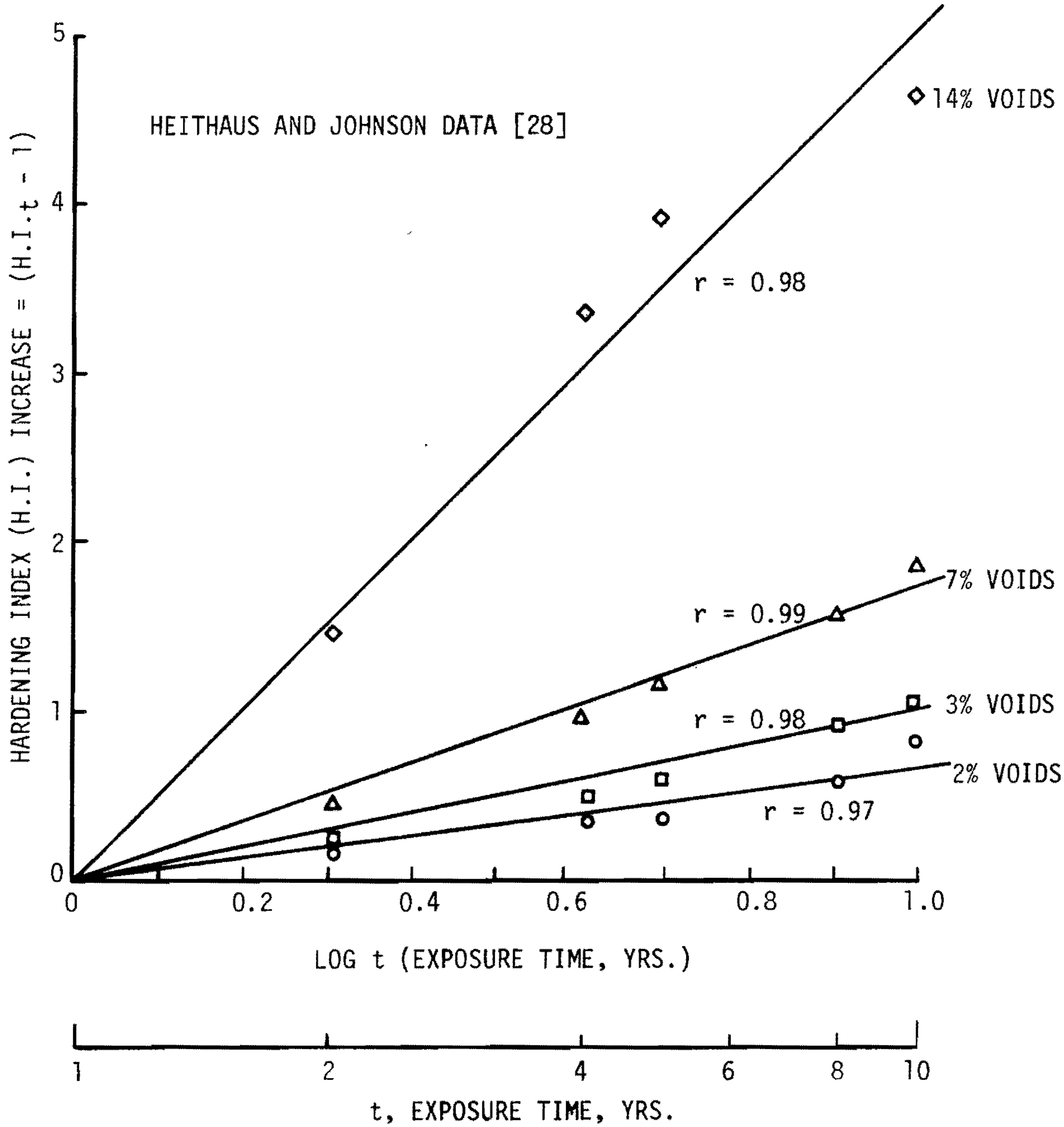


Figure D-1. Increase in Asphalt Hardening Index with Age in Midwestern Pavements then,

$$\frac{\Delta H.I._2}{\Delta H.I._t} = \frac{\log 2}{\log t}$$

and,

$$\Delta H.I._2 = 0.301 \frac{\Delta H.I._t}{\log t}$$

or,

$$H.I._2 = 0.301 \frac{(H.I._t - 1)}{\log t} + 1$$

This relation was used to estimate the two year Hardening Index values presented in the body of this report. The usefulness of this relation is demonstrated by the following comparison of estimated and observed $H.I._2$ values from the Heithaus and Johnson data.

Voids	Exposure time, t Years	$H.I._t$	$H.I._2$ Estimated	$H.I._2$ Observed
2	10	1.80	1.24	1.13
3	10	2.04	1.31	1.24
7	10	2.83	1.55	1.47
14	10	5.66	2.50	2.48

Effect of Void Content on Asphalt Hardening

These data also provide a basis for comparing the relative severity of atmospheric exposure, with respect to asphalt hardening, between asphalt concrete lifts made with dense-graded aggregates and those made with open-graded aggregates. It is well known that increase in the void content of compacted asphalt concrete will increase the tendency of the binder to harden. The relative asphalt hardening tendency in OGAFC pavements and those made with dense-graded aggregate can be assessed by comparing plots of $H.I._2$ vs.

percent voids for the two types of compacted mixes. Such a plot for dense-graded mixes can be made using the Heithaus and Johnson data; this plot is presented as Figure D-2. This plot can be compared with a similar plot of data obtained from OGAFC pavement cores taken in this study.

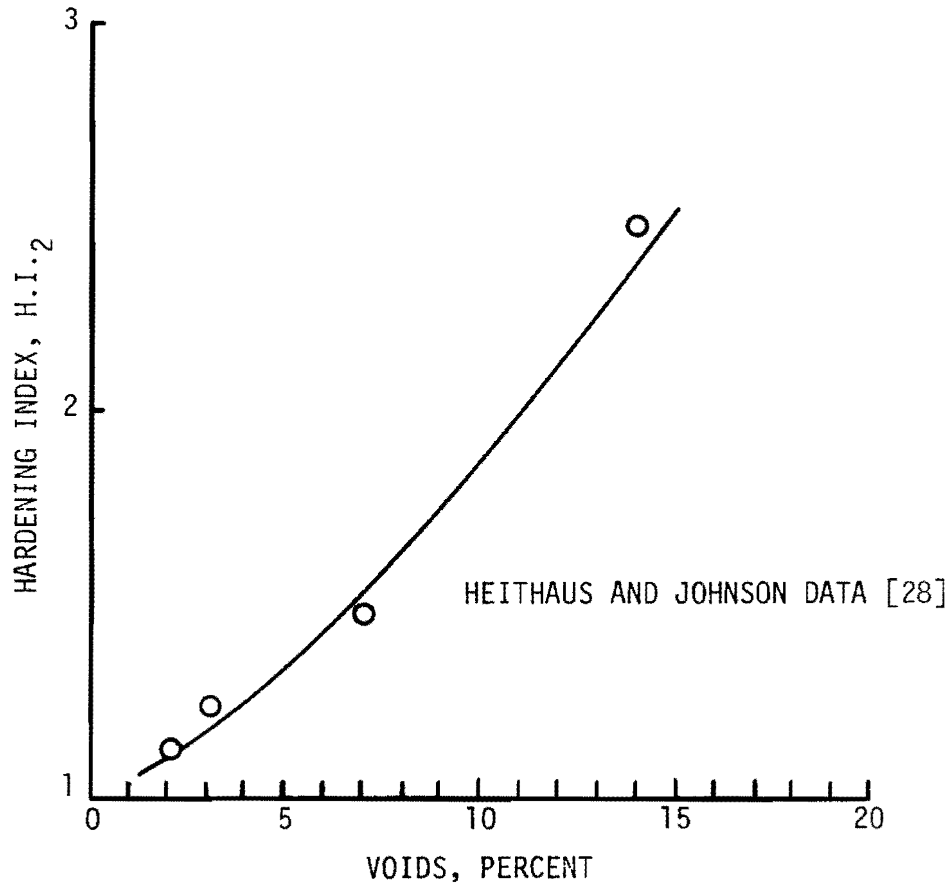


Figure D-2. Effect of Void Content on Asphalt Hardening in Dense-Graded Pavements

APPENDIX E

ESTIMATION OF STRUCTURAL NUMBERS OF OGAFC PAVEMENTS

APPENDIX E

ESTIMATION OF STRUCTURAL NUMBERS OF OGAFC PAVEMENTS

Introduction

One of the results of the AASHO road test was the publication of an empirical flexible pavement design procedure [32] that includes estimation of a Structural Number (SN) as an index of the resistance of the pavement to deterioration caused by passage of automotive traffic. This number is based on the layer thicknesses and coefficients that depend on the material being used. Such information was available for the OGAFC evaluation pavements of this study (Tables 7, 8, and 9) and thus estimation of AASHO Structural Numbers was the most practical way of assesing the relative structural resistance of these pavements.

SN Estimation Procedure

Analytically the Structural Number is given by,

$$SN = A_1D_1 + A_2D_2 + A_3D_3 + \dots$$

where,

A_i = coefficients depending on the structural characteristics of a given layer material

D_i = layer thickness (inches)

Layer coefficients are most reliably estimated from appropriate materials test data, such as Marshall stability, Cohesiometer values, and CBR, as indicated by Van Till, et al. [33]. However, since specific test data were not available for the layer materials used in the OGAFC evaluation pavements, arbitrary layer coefficients were assigned based on those recommended by AASHO supplemented by information presented in a report by Edris, Epps, and Lytton [34]. These coefficients are listed in Table E-1.

Results

Application of this SN estimation procedure is illustrated by the following example.

OGAFC Pavement: US 81, Control No. 8-12, R&S Lanes,

(data from Table 7)

Layer	D, in.	a
OGAFC	0.6	0.2
Chip Seal	0.3	0.1
HMAC	3.5	0.44
Black Base	9	0.34

$$SN = 0.2 \times 0.6 + 0.1 \times 0.3 + 0.44 \times 3.5 + 0.34 \times 9 = 4.8$$

SN values for the OGAFC pavements, estimated in this way, are given in Table E-2.

Table E-1. ASSIGNED LAYER COEFFICIENTS

Layer Material	Layer Coefficient, a
OGAFC	0.2
Single chip seal coat	0.1 (assume D=0.3 in.)
Double chip seal coat	0.2 (assume D=0.5 in.)
Hot-Mixed Asphaltic Concrete	0.44
Portland Cement Concrete	1.0
Concrete Stabilized Base (Lean PCC)	0.36
Black Base	0.34

Table E-2. AASHO STRUCTURAL NUMBERS FOR OGAFC EVALUATION PAVEMENTS

Pavement Location	Structural Number
820/812/R,S,L,M	4.8
30/10681/R,S,L,M	7.7
81/137/R&S	4.8
81/137/L&M	7.8
101/1347/R&L	7.0
114/3521/R&L	6.3
114/3522/R&L	6.4
59/1763/R&S	10.8
59/1762/R&S(M.P.3.45)	10.8
59/1762/R&S(M.P.3.57)	10.8
59/1762/R&S(M.P.4.21)	9.3
59/1762/R(M.P.4.27)	9.3
59/1762/R&S(M.P.5.09)	9.3
59/1761/R,S,L,M	8.6
10/7392/L	9.6
10/289/R	7.3
87/3056/R	4.7
87/3057/R	4.3
96/655/L	5.6