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16. Abstract

Numerous factors, including aggregate characteristics, construction variables, traffic volume, and environment, are believed to be affecting the frictional performance of highway pavements. The objective of this phase of the study was to investigate the effects of these factors on the field frictional resistance of seal coat surfaces.

The investigation involved establishing seal coat test sections in different climatic regions in the State of Texas with various aggregate types and sources and under different traffic volumes. Samples of the aggregates used were examined in the laboratory to determine their physical properties, polish and wear characteristics, resistance to weathering, resistance to impact and abrasion, and petrographical and mineralogical qualities. Field tests which involve measuring friction and texture are being performed on the surface of test sections twice a year at random intervals. Annual and periodical climatological data are being collected for each test section. An in-depth statistical analysis will be performed on the data in order to formulate probabilistic models for predicting seal coat friction.

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Strategic Research Plan for Achieving Adequate Pavement Friction

Research Project 3-9-86-490

conducted for

**Texas State Department of Highways
and Public Transportation**

in cooperation with the

**U.S. Department of Transportation
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CENTER FOR TRANSPORTATION RESEARCH

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PREFACE

In the interest of highway safety, it is essential that pavements be designed and constructed with surface characteristics adequate for minimizing loss of surface friction in wet weather. In this research, the overall objective is to investigate and develop design criteria which provide adequate surface frictional resistance. The first phase of the research is concerned with improving the frictional resistance of existing pavements. Therefore, the frictional resistance of seal coat surfaces, the most widely used rehabilitation method on Texas rural highways, is being investigated.

Many individuals have contributed their time, suggestions, and efforts to this research study. We are particulary appreciative of the Advisory Committee, whose members are Caroline Herrera, D-9 Technical coordinator; James Brown, D-8; Brad Hubbard, D-10; Leo Mueller, D-8; Billy Neely, D-9; and John Nichols, FHWA.

District personnel throughout the state have been very helpful in locating test sections for the study. David Whitney and David Price of the Center for Transportation Research have contributed their efforts, and thanks are due to Joy Suvunphugdee for typing the report.

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Alvin H. Meyer

ABSTRACT

Numerous factors, including aggregate characteristics, construction variables, traffic volume, and environment, are believed to be affecting the frictional performance of highway pavements. The objective of this phase of the study was to investigate the effects of these factors on the field frictional resistance of seal coat surfaces.

The investigation involved establishing seal coat test sections in different climatic regions in the State of Texas with various aggregate types and sources and under different traffic volumes. Samples of the aggregates used were examined in the laboraotry to determine their physical properties, polish and wear characteristics, resistance to weathering, resistance to impact and abrasion, and petrographical and mineralogical qualities. Field tests which involve measuring friction and texture are being performed on the surface of test sections twice a year at random intervals. Annual and periodical climatological data are being collected for each test section. An in-depth statistical analysis will be performed on the data in order to formulate probabilistic models for predicting seal coat friction.

SUMMARY

The overall objective of the study is to investigate and develop design criteria which will provide and maintain adequate pavement friction. In this phase, the prediction of the frictional resistance of seal coat surfaces is being investigated through the establishment of test sections in different climatic regions, with different aggregate types and sources, and under various traffic volumes.

IMPLEMENTATION STATEMENT

Prediction models resulting from this study can be implemented throughout the state. The models will provide an engineering solution whereby the frictional life of a seal coat surface can be predicted during the planning stage of a rehabilitation project. The models will also provide a method at the design stage for determining the characteristics of the aggregate required to maintain a given level of frictional resistance.

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CHAPTER 1. INTRODUCTION

BACKGROUND

The skid resistance of highway pavements, particularly when wet, is a serious problem of increasing concern to highway engineers and researchers. As traffic speeds and average daily traffic (ADT) continue to rise, the chances of skidding accidents as well as their consequences are growing at an alarming rate with each passing year (12, 14).

Unfortunately, nearly all pavement surfaces that are economically feasible to construct lose their initial frictional resistance with exposure to traffic. In addition, while the frictional resistance of dry pavements is generally good and nearly independent of speed, wet pavements often have poor frictional resistance even at low speeds. To make matters worse, frictional resistance can be substantially lowered at high speeds, where it is critical. Improvements and advancements in areas such as design and development of frictional resistant pavement surfaces and vehicle and tire performance would contribute much to safer highways. However, a successful solution will require a comprehensive effort which focuses on a wide range of variables and brings to bear the expertise of many researchers.

As a consequence, highway engineers are faced with the continuing problem of constructing pavements with higher and longer lasting frictional resistance. To deal with the problem rationally and objectively, the engineer and researcher need to understand as thoroughly as possible the multitude of complex and interrelated factors that make for good, long lasting skid resistance.

Many variables have been identified as important in wet weather accidents. These include pavement surface friction, pavement microtexture and macrotexture, construction variables, drainage properties of the surface, traffic volume, environment, highway geometrics, vehicle speed and load, tire tread depth and inflation pressure, driver experience, and rainfall intensity.

Pavement surface friction, as affected significantly by the frictional resistance of the coarse aggregate, has long been recognized as being the primary factor in the cause of skidding (53, 71, 75). The use of polish resistant coarse aggregates or aggregates which have proven to have good frictional performance has always been considered a remedial alternative. The Materials and Tests Division (D-9) of the Texas State Department of Highways and Public Transportation (SDHPT) employs the polish value (PV) test (115) in which an aggregate is subjected to accelerated polishing for evaluating the polish susceptibility of coarse aggregates incorporated in pavement work. The skid resistance test (8) is used by D-9 to measure the frictional resistance of pavement surfaces expressed as skid number, referred to in this report as friction number (FN). Minimum laboratory PVs of coarse aggregates have been established and in use in Texas for years for the purpose of providing acceptable pavement friction. Normally, high traffic volume roads require aggregates with high resistance to polish and wear while low traffic volume roads may operate with lower polish-resistant aggregates. The current PV requirements based on ADT are as follows:

ADT	P V
Where specified in the plans	35
Greater than 5000	32
5000 to 2000	30
2000 to 750	28
Less than 750	No requirements

OBJECTIVES OF THE STUDY

The overall objective of this study is to investigate and develop design criteria which will provide and maintain adequate pavement friction. Specifically, these objectives are to

(1) develop a comprehensive, long-range strategic research plan which addresses all aspects of pavement friction and
(2) investigate the relationship between laboratory frictional properties of coarse aggregates (i. e., PV) and frictional performances of roads built with these aggregates (FN).

While the second objective is included in the scope of achieving adequate pavement friction in the first objective, there is an immediate need to define, if possible, the relationship between PV and FN. Implicitly stated in the second objective is to investigate what predicts the friction number; the PV test by itself or a combination of laboratory tests, performed on the coarse aggregate, may predict the FN with a certain confidence. Investigation of the effects of traffic, environment, and other factors on any possible relationships is also included in the scope of the second objective.

THE FIRST PHASE OF THE STUDY

In general, providing skid resistant surfaces for highway pavements involves developing skid resistance design guidelines and incorporating these guidelines into the design of new pavements or into the process of maintaining and rehabilitating existing pavements. These research efforts should be directed more towards improving the frictional resistance of existing pavements since a huge highway network already exists in Texas.

Many pavement rehabilitation methods (1, 41, 50, 55, 79, 81), including seal coat and hot mix asphalt concrete (HMAC) overlays, have been used in Texas for the purpose of improving the frictional resistance and other surface characteristics of the highways. In this phase of the study, the frictional resistance of seal coat overlays is being investigated; that of HMAC will be investigated in a later phase.

A seal coat overlay is a rehabilitation method for pavements of all classes, from low-volume roads to interstate highways, used mostly on rural highways. This rehabilitation method is an application of asphalt and aggregate to a roadway surface, generally less than one inch thick, which improves the frictional resistance and other surface characteristics of the roadway.

SCOPE OF THE FIRST PHASE

The investigation included gathering and assimilating the pertinent literature available on the subject, surveying nine selected districts in Texas, establishing seal coat test sections with various coarse aggregate types and traffic volumes, performing laboratory tests on the obtained samples and field tests on the established test sections, and designing the layout of the analysis to be performed on the data. The report overviews the progress of the investigation as of Fall 1987 and includes the following sections:

Chapter 2 summarizes the literature review. Chapter 3 summarizes the findings of the survey of Texas districts. Chapter 4 summarizes the research methodology and test sections. Chapter 5 discusses the collection of data. Chapter 6 describes the layout of the intended analysis. Chapter 7 gives a summary, conclusions, and recommendations.

CHAPTER 2. LITERATURE REVIEW ON THE FRICTIONAL RESISTANCE OF SEAL COAT PAVEMENT SURFACES

PURPOSE AND USES OF SEAL COATS

A seal coat is an economical method for pavement rehabilitation which involves the application of asphalt and aggregate to an existing bituminous surface. The asphalt binder is sprayed uniformly across and along the road surface at a designed rate. The cover aggregate is then spread uniformly on top of the asphalt at a specified rate. The additional pavement thickness supplied by a seal coat is generally less than one inch, providing little increase in the load carrying capacity of a pavement section (133). However, successfully placed seal coats applied to pavements showing signs of non-traffic-load-associated cracking have proven to somewhat improve the load carrying capacity by satisfactorily bridging the cracks and consequently altering the water content of the materials composing the pavement structure (122).

The main reason for using seal coats is to improve the frictional resistance of highway bituminous pavements, with the improvement being largely dependent on the frictional properties of the aggregate used and the quality of construction. Other purposes for which seal coats may be used (122, 131, 133) are to

(1) enrich a raveled surface,
(2) increase pavement visibility at night,
(3) reduce tire noise,
(4) improve demarcation of traffic lanes, and
(5) attain a uniform appearing surface.

PARAMETERS OF FRICTIONAL RESISTANCE: MICROTEXTURE AND MACROTEXTURE

The magnitude of frictional resistance developed between the tire and the pavement surface is generally controlled by the characteristics of the pavement surface. It can be explained by the behavior of the rubber as it rolls over the pavement surface. There are two components that make up the developed friction: adhesion and hysteresis (47). The adhesion component is generally considered to be the shear strength developed in the area of the actual contact of the rubber with the surfaces of aggregate particles, while the hysteresis component is caused by damping losses within the rubber when the latter is rolling over and around the aggregate particles. Among the many factors which affect the role of these components, the most important are the microtexture and macrotexture of the pavement surface (61, 101). The microtexture controls the adhesion component, while the macrotexture controls the hysteresis component.

In seal coats, the microtexture is the fine-scaled roughness contributed by individual small asperities on the individual coarse aggregate particles. Ideally, for the aggregate particle to sustain a highly favorable microtexture, it should be composed of hard, coarse, angular minerals well bonded into a softer matrix so that gradual differential wear will occur (23). The macrotexture is the large-scale texture at the surface caused by the size and shape of the coarse aggregate particles. Appropriate angularity and proper maximum size and gradation of aggregate particles are essential for achieving adequate macrotexture.

Relative Merits of Each

There had been conflicting claims on the relative merits of macrotexture and microtexture until Kummer and Meyer (77) proposed the classification of pavement surfaces shown in Fig 2.1, which delineates the roles of microtexture and macrotexture in the generation of friction. The figure shows the excellent friction that may be attained by a fine textured gritty surface (high microtexture and low macrotexture) below 30 mph and the loss in friction above this speed. The figure also indicates that a coarse textured gritty surface (high microtexture and high macrotexture) attains high levels of friction at all speeds. Therefore, there seems to be an indication that both microtexture and macrotexture are equally important if enduring friction is to be maintained. However, it appears that the microtexture effect (adhesion) does interact with that of the macrotexture (hysteresis). This

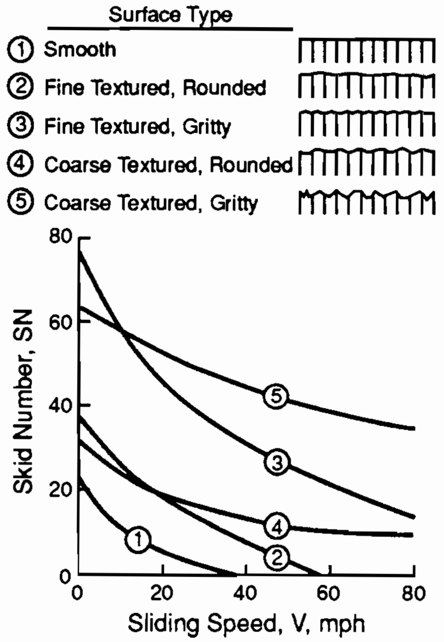


Fig 2.1. Classification of pavement surfaces according to their friction and drainage properties (77).

is because the macrotexture plays the role of providing drainage channels for water expulsion between the tire and the pavement surface, which allows the fine features (microtexture) to penetrate the remaining thin water films and thus permit an intimate contact between the tire and the roadway (43). This role becomes of even greater importance when it comes to providing adequate friction at high speed levels, as shown by comparing the friction of surfaces 3 and 5 in Fig 2.1. Inadequate macrotexture drainage capability may cause the water depth on the pavement surface to increase. This may result in hydroplaning (104), which is a condition in which loss of contact between the tire and the pavement surface occurs.

Quantification Methods

Quantification of Microtexture. Microtexture depends largely on the mineral composition and the rugosity of the aggregates. The quantitative measure of microtexture is a very difficult problem. It is best done when the quantification method can evaluate the effect of the factors contributing to the role of microtexture and can give relative measures on the probable change in the microtexture during surface life.

The most commonly used laboratory method is the PV test (115) in which the friction of the coarse aggregate particles is evaluated with the British Portable Tester (BPT) after nine hours of exposure to accelerated polishing in the presence of water and abrasive grit. The PV is believed to represent the ultimate polish and wear that will be reached by an aggregate when it is placed in field service.

The four-cycle magnesium sulfate soundness (MSS) test (110) used to judge the soundness of an aggregate when it is subjected to weathering action (freeze and thaw) gives indications of the strength (or softness) of the cementing matrix that holds the individual grains in the aggregate particles. If the cementing matrix is strong (reflected by low soundness loss) the individual grains will be expected to be tightly held and thus polished by traffic, resulting in an overall low frictional resistance. On the other hand, if the hardness of the cementing matrix is lower (if the matrix is made up of softer minerals) than that of the minerals bonded into it in such a way that a higher but still reasonably acceptable soundness loss will result, the microtexture of an aggregate may be expected to wear differentially under traffic, resulting in a continually renewed non-polished surface.

Other tests of significance in characterizing microtexture and the degree of retention of such microtexture during service life are the various petrographic tests which describe the aggregate and its mineralogical composition (12, 23). This analysis may prove very helpful if the combinations of the results of such tests (quantitative and qualitative results) can be presented so that they can be correlated with field performance (31, 91, 116).

Quantification Methods of Macrotexture. Several methods have been developed for evaluating or measuring pavement macrotexture (46, 56, 59, 63, 68, 69, 93, 97, 100, 121). Of these, the sand patch and the silicone putty (volumetric measurements), outflow meter (drainage measurement), and stereo photographic interpretation (topography measurement) methods are most commonly used (10, 11, 24). However, since most of these procedures measure only a single attribute, such as depth or drainage characteristics, the correlation of frictional resistance with these measurements is often imperfect (43, 56). In addition, the simplicity, repeatability, and reproducibility are factors affecting the decision to implement any of these methods.

Although the sand patch method is perhaps the most widely used for measuring macrotexture (17, 94), it is difficult to use in wet conditions and has poor reproducibility. Recent work (139) using small glass beads to replace sand has been undertaken by the American Society of Testing and Materials (ASTM), and the findings of the early efforts indicate an improvement in the reproducibility of the test when the work is done in damp conditions.

The Schonfeld method (100) for measuring both microtexture and macrotexture by means of stereophotographs has been used by several researchers, and the photointerpreted values have been found to correlate highly with skid trailer values. While the original method uses visual stereointerpretation to classify the texture of the pavement surface, a study by Howerter and Rudd (123) demonstrated that the method can be automated through the use of electronic stereophotogrammetric techniques coupled with computer processing. The automation has the effect of removing the human subjectivity associated with visual stereointerpretation and leads to more efficient implementation of the method.

Most of these texture measurement methods are slow and involve stationary procedures. Other methods, which measure macrotexture from a moving vehicle, have been developed, and some of these have now evolved into workable systems. Examples of these are the laser sensor methods now being used in Europe. The "Numerisateur," a contactless sensor based system, is in use in France (103). In this method, contactless sensor-measured heights taken at 0.5 mm to 1 mm centers are stored so that a three-dimensional model of the surface can be built up. The stored data are then used to calculated texture depths. In the United Kingdom, the Transport and Road Research Laboratory (TRRL) Mini Texture Meter, a laser based monitoring system, is currently the accepted method for measuring macrotexture on new asphaltic mixes and surface dressings (seal coats) (103). The method has many advantages over the sand patch test, including high correlation with the standard sand patch procedure, a high degree of repeatability, speed of operation, and the ability to work in damp conditions and on warm surfaces. This last aspect has made possible the use of the method as a control tool during construction operations.

In the United States, two indirect methods for measuring texture from a moving vehicle have been evaluated (162). The first method is based on the depolarization of light reflected from a surface whereby the degree of depolarization is a function of the texture. The depolarized light number (DPN), which is the output of the depolarized light system, was found to increase with increasing macrotexture measurements and increasing skid resistance. However, the coefficients of determination of the linear regressions between the DPN and the texture data were too low to provide reliable prediction of texture. The other method is based on the use of skid resistance data measured with blank and ribbed test tires. Two-way regressions with ribbed and blank tire data and macrotexture (determined by the sand patch test) and microtexture (determined by the BPT) produced highly significant results. The procedure was thus recommended for implementation using a two-wheeled tester equipped with a blank tire on one side and a ribbed tire on the other.

Variability in the Frictional Resistance

In the United States, the frictional resistance of highway pavement surfaces (including seal coat surfaces) is generally measured with the locked-wheel skid test standardized in the American Society for Testing and Materials (ASTM) Designation E274 (8). In this method, the friction force on a locked test wheel equipped with a standard test tire, in accordance with ASTM E249, is measured as the locked wheel is dragged over a wetted pavement surface at constant speed (usually 40 mph) and under constant load. The results are expressed as skid numbers (referred to in this report as FNs) that indicate the relative safety of pavements under wet conditions. Variations in the measured friction may occur due to many factors, including tester calibration techniques and operating procedures, lateral positioning of test trailer on the surface and longitudinal uniformity of the surface (45, 80, 124), and long-term and short-term seasonal changes.

Variability Caused by Friction Test Calibration and Operating Procedures

In a study undertaken by the National Cooperative Highway Research Program (NCHRP) (124), the sources of error in skid testing were identified and their magnitudes determined. Recommendations were made for improving skid-testing equipment and the calibration, operation, and data evaluation procedures. The corrective measures formulated in this study involved stressing the need for high-quality instrumentation, recommending a standardized pavement watering method and calibration procedures, and lengthening skid tests to permit evaluation of longer portions of the skid trace, more precise methods of evaluation, and recognition of the statistical uncertainty associated with the data. Through the incorporation of these corrective measures into ASTM E274, the magnitudes of equipment and measurement errors have been minimized.

Variability Caused by Lateral and Longitudinal Changes in Test Surface

The testing for frictional resistance is normally done in the center of the left wheel path (8). The lateral positioning of the test trailer within the path width and the longitudinal uniformity of the test surface along the path have been reported as major sources of variability in measured FNs. An FN difference as high as five between the center line and either edge was indicated by the NCHRP study (124). Errors of this type can be minimized by making the drivers aware of the problem. Since at least five friction measurements are made in a test section, the arithmetic average is expected to represent the average roadway condition and thus take into account any non-uniformity in the test surface. However, if statistical or other criteria applied to the FN for a long test section indicate that it cannot be considered to be uniform, the section is treated as two or more sections (8).

Variability Caused by Seasonal Changes

It has been recognized for many years that pavement surface characteristics undergo seasonal changes which cause variations in the frictional properties. Two types of seasonally caused variations have been observed: long-term and short-term. It has been determined that the long-term variations are caused by changes in the microtexture of the exposed aggregates brought about by polishing during long, dry periods and roughening caused by the rejuvenating effects of long wet periods (25). As a result of this mechanism, friction measurements made in the wet periods have been reported to be much higher than those made in the dry periods. In a five-year study by the Pennsylvania Department of Transportation, summarized by Rice in Ref 96, it was found that the rejuvenating effects tended to offset the polishing effects in that the curves of frictional performance for the last three years showed no consistent upward or downward trends for the annual minimum levels. Similar observations on this tendency are made in a summary of six years of research work done in the Federal Republic of Germany recently reported (103) and from many other studies (18, 19, 26, 35, 117, 120). In one of those studies (26), it was reported that the stabilization of the minimum skid number after two years of pavement exposure to traffic was irrespective of the level or volume of traffic.

In the United States, long-term seasonal variations as high as 30 friction numbers were reported in Kansas, with more typical variations in the order of 5 to 15. In Texas, a study of four aggregate types used in seal coats showed average seasonal decreases (wet to dry) of approximately 10 friction numbers (118). A study in Kentucky (15) indicated that the frictional resistance exhibited an annual sinusoidal cycle similar to the annual precipitation and temperature cycles. In fact, correlations between changes in frictional resistance and temperature suggested that the annual changes in friction resulted from a reaction of the surface to temperature over a period of a few weeks (four and eight-week periods prior to the date of test). In addition, when test sections at the same location were compared, the magnitude of the annual variation in frictional resistance was found to be strongly associated with volume of traffic. In a report by NCHRP (101), this magnitude was reported to differ with type of aggregate, with softer materials such as limestone responding more strongly. Superimposed on these long-term (annual) variations are short-term variations attributable to external factors, such as amount and timing of intermittent rainfall, and possibly to contaminations from oily films, drippings, and other deposits on the surface (57, 65).

In the systematic identification of the levels of frictional resistance, occurrence of these variations makes it difficult to precisely evaluate surfacing materials and practices and to take corrective measures. As an interim measure, it was suggested in Pennsylvania and Kentucky that taking of friction measurements be confined to a period between the first of July and the middle of November, during which the friction is minimum and therefore most critical. However, since it would be difficult, if not impossible, to conduct all inventory surveys of frictional resistance in such a short period, it would be desirable to develop procedures that can be applied to make needed adjustments in measured skid numbers. In this respect, Pennsylvania State University has recently done considerable work (60, 66, 98) in which two models, a generalized predictor model and a mechanistic model, were developed to predict seasonal variations in the skid resistance of asphalt pavements due to rainfall conditions, temperature effects, and time of the year. It has been suggested that the models be used in the geographical area within which the investigation was conducted.

THE AGGREGATE PROPERTIES AFFECTING FRICTIONAL RESISTANCE

Several characteristics should be evaluated in the selection of aggregates for frictional resistant surfaces. For seal coats, the microtexture and the angularity and gradation of the individual coarse aggregate particles composing the surface structure are the main variables controlling the frictional resistance.

Angularity and Gradation

It has long been recognized by paving and construction researchers and engineers that aggregate angularity (shape) and gradation (size) have an important influence on pavement frictional performance (20, 21, 34, 39, 72). The angularity of coarse aggregates contributes to tire-pavement friction in the case of seal coats by establishing points of contact with the tire rubber which protrude above the water level. The contribution lasts as long as the aggregates remain angular. Angularity relates to the rock crushing process, but the retention of angularity depends on such characteristics as mineralogical composition and the amount of polish-wear produced by traffic. In the case of seal coats, the sizes of the aggregate particles in the final surface are a very important consideration in terms of angular projections to different heights so as to provide rubber envelopment and drainage patterns. Variance in maximum aggregate size which is possible even from the same aggregate source, may result in different frictional responses under equivalent traffic exposure (12).

Microtexture

The microtexture or roughness of the coarse aggregate particles in seal coats is a very important characteristic in terms of frictional resistance, but of greater importance is the change in such texture during the service life of seal coats. Fortunately, at this stage of development, there appears to be an agreement on the basic requirement for a satisfactory aggregate microtexture. That is, an aggregate should be composed of sand-size hard grains weakly cemented in a soft matrix so that it will wear differentially under traffic and expose a continually renewed nonpolished surface. On the other hand, if the cementing matrix is strong, the individual grains will be tightly held and consequently polished by traffic. The rate of polish depends on the hardness of the grains, the frequency of contacts with traffic, and the type of abrasive material on the roadway surface(12). The characteristics that describe, to some extent, the microtexture qualities of an aggregate include polish and wear resistance, strength and toughness, and resistance to weathering. Discussions of these characteristics and their evaluation methods follow.

Polish and Wear Resistance. Polishing may be defined as reduction of microtexture whereas wear is the loss of macrotexture. Researchers have found that the two phenomena are not strictly separable (21, 22, 73). That is, wear is promoted by the presence of abrasive material. The finer the particles constituting this material are, the smoother the resulting wear surface and the slower the wear rate will be. Consequently, for similar materials, slower wear means more polishing of the exposed mineral grains.

During the past two decades, several polish susceptibility tests have been proposed and used by various investigators (48, 49, 58, 67, 85, 86, 87, 88, 90, 92). However, progress towards acceptance and universal use of these methods has been slow because many questions remain unanswered. Considerable work has been done in Texas on the polishing properties of coarse aggregates (118). The results of this work led to the adoption of the PV test for ranking aggregates with respect to their frictional characteristics. However, recognizing that some low PV aggregates had exhibited satisfactory performance, experience with the field frictional performance was substituted for the PV requirements.

The term petrography is used to refer to mineral composition; constituent mineral hardness; mineral grain size, shape, and distribution; grain interlocking; and mineral susceptibility to chemical attack and alteration. Most of these properties were found to have been repeatedly mentioned in the literature as important in terms of resistance to polish and wear (9, 12, 23, 27, 40, 76, 91). Dahir and Mullen (23) found that there exists an optimum proportion of hard to soft mineral content that produces satisfactory and lasting polish and wear properties as evaluated in the laboratory by using the circular track and jar mill methods. The optimum proportion seemed to fall in the range of 50 to 70 percent of hard minerals to 30 to 50 percent of soft minerals. In their study and in many others, it was found that the coarser and the more angular the hard grains were and the more uniform their distribution was in the softer bonding matrix, the more likely that a differential wear would occur in the aggregate. It has been also repeatedly reported in the literature that the petrographic tests may prove very useful in the selection of aggregates if such test or combination of test results are correlated with field performance (31, 91, 116).

In the case of carbonate aggregates, which generally polish very rapidly, the acid insoluble residue test (6) has been explored and currently adopted by many highway agencies. Several investigators found that the amount of sand-sized insoluble residue, the residue gradation, and the total amount of insoluble residue are significant factors in determining the polish susceptibility of carbonate aggregates, with the sand-sized residue tending to be more significant than the total residue (23, 118).

Strength and Toughness. In highway pavement surfaces, particularly in seal coats, the coarse aggregate is in direct contact with the tire. The aggregate is thus subject to forces of shear, abrasion, and impact. These forces may break up the aggregate, altering its gradation, and they may abrade the aggregate particles, reducing their texture. Therefore, the aggregate should provide the mechanical stability and strength to resist these forces over the surface life. The most commonly used test for resistance to abrasion and impact is the Los Angeles abrasion test (109). Typically, not more than 40 percent loss is permitted when this test is used for surface aggregates.

Resistance to Weathering. Resistance to degradation by weathering actions is a major factor affecting the wear rate of aggregates (20, 71, 101). The MSS test (110) is often used in determining this resistance. The test gives a useful indication of the expected aggregate resistance to freeze-thaw and salt recrystallization effects. As indicated earlier, the test is also indicative of the strength and hardness of the cementing matrix that holds the crystal grains of aggregate particles together. As with the many other tests used for determining the suitability of aggregate for incorporation in pavement work, the test does not always appear to be reliable in distinguishing poor from good aggregate performers (89). Recognizing this fact, some agencies use performance history along with the information furnished by the test when judging the soundness of aggregates. Another method currently intended for use only in synthetic aggregates is the freeze-thaw test (112).

PREDICTION OF FRICTIONAL RESISTANCE FROM MATERIALS PROPERTIES

After the dependence of frictional resistance on the polishing and wear properties of aggregates had been established, several researchers attempted to predict the frictional resistance from these aggregate properties. A major advancement in this field was achieved in a study by the British TRRL in 1972. In this study, summarized by Salt (99), a regression analysis was carried out to relate the polished stone value (PSV) and traffic simultaneously to the side friction coefficient measured at 50 km/h (SFC_{50}). One hundred and thirty-nine different sections of bituminous surfaces (including seal coat surfaces) with traffic volumes of up to 4000 commercial vehicles per day were examined for the purpose of the investigation. The following highly significant relationship ($R^2 = 0.83$) was obtained:

$$SFC_{50} = 0.024 - 0.663 \times 10^{-4} q_{cv} + 1 \times 10^{-2} PSV$$

where

q_{cv} = flow of commercial vehicles per lane per day (in one direction). The relationship applies only to tangent sections.

The publication of this finding has been regarded as a major advancement in the field of frictional resistance as it provides a method for nominating at the design stage the properties of the aggregate required to provide a given ultimate frictional resistance provided that the traffic can be estimated. It is believed that the high significance obtained by the TRRL model was due to the use of a low speed measure of skid resistance, SFC, which depends primarily on surface microtexture (140).

In North America, almost all research concerned with the prediction of skid resistance has been on the correlation of friction measured by the ASTM Standard E274 locked wheel skid trailer with laboratory aggregate polishing values. Mullen (87) established a method which allows prediction from laboratory tests of maximum field polish that may be anticipated for a given pavement mixture (open-graded and dense-surface mixes). First, usable correlations were found between field British portable tester measurements, British pendulum numbers (BPN), and skid trailer measurements (FN) at different test speeds. These correlations were used to draw BPN-FN-velocity nomographs for the types of mixes investigated. Second, field wear versus laboratory wear correlation was attempted by coring pavements after field testing and then polishing the cores to terminal polish in the circular-track machine. Then, the unworn portions of the field cores were remixed and molded into laboratory specimens and later polished in the circular track machine to obtain the full "as new" polish curve. The new and worn polish curves when compared gave the extent of circular-track wear experienced in the field. An upper limit for field wear equivalent to three hours or less of machine wear was therefore established. The established limit, in terms of hours, may then be used to obtain the laboratory BPN associated with it, and the BPN when entered in the BPN-FN-velocity nomographs will give the predicted FN values for the different velocity values.

In a study by Dahir et al (26), correlations between the results of laboratory polishing tests on aggregate panels and FN's were poor with correlation coefficients ranging from 0.55 to 0.65. The laboratory tests were the Penn State rotary drum polishing machine (RDM), the modified Penn State reciprocating pavement polisher (RPP), and a modified small drum machine (SDM) used for aggregate wear at Penn State. In the RDM and RPP methods, the frictional resistance was measured by the British portable tester, while in the SDM method the average frictional resistance of ten aggregate particles was measured electronically.

A skid resistance model appropriate for asphaltic concrete mixes was developed in Ontario, Canada, by Heaton et al (140). The model contained parameters associated with the ability of the mixes to resist consolidation under traffic as well as those contained in the TRRL model. The multiple regression model with a multiple coefficient of correlation (R^2) of 0.86 is shown below:

$$SN_{100} = (0.17 \times PSV) + (1.7 \times MS) + (3.6 \times FLOW) + (0.9 \times VOID) - (0.24 \times EQT) - 9$$

where

SN_{100} = skid number at 100 km/h
PSV = polish stone value
MS = Marshall Stability
FLOW = flow of the mix
VOID = void content in the mix
EQT = an equivalent traffic factor

The model was based on 56 independent site cases all of dense-graded asphaltic concrete of 12-mm maximum aggregate size. The cases covered two of the more widely used aggregates in Ontario, limestone and traprock with low and medium PSV, 41 and 45 respectively, and two aggregates of high PSV, blast furnace slag and steel slag, 45 and 59 respectively.

Refinement of this model continued with the analysis of other site cases and extended to include a wider range of mix compositions and aggregate types (35). As a result, improved predictive models have been developed for various traffic volumes and surface types. The work has confirmed the overall importance of mix designs in achieving desired skid resistance with accumulated traffic influences, particularly in preventing coarse aggregate immersion due to traffic compaction. High stability mixes have proven most suitable, and coarse aggregate properties such as PSV and Los Angeles abrasion value are of secondary importance once adequate levels are provided. Continued monitoring of the site cases showed that the SN_{100} values have levelled off rather than continuing to decrease at a reduced rate, which the predictive model could not describe. This was pertained to weathering influences which appeared to be regenerating microtexture at about the same rate that traffic polishing is involved.

In Texas, several researchers have attempted to formulate relationships similar to those discussed above (33, 39, 125, 126); however, reliable relationships could not be established. In a study by Elmore and Hankins (33), it was found that a relationship does exist between the ultimate PV of the aggregate reached in the laboratory and the stable value of skid resistance reached after exposure to traffic. However, one problem with that relationship was that the friction numbers used were those predicted to represent the friction level at 1 x 10^6 traffic applications from traffic-friction regression equations which had poor prediction ability (R^2s for the traffic-friction regressions for all aggregate types investigated were too low). The poor prediction ability was due to the variability found in the measured skid numbers. The variability was indicated to have been probably caused by the effects of seasonal and climatological changes and the effect of different construction techniques. Therefore, it was suggested that the results of the study not be implemented.

In a more recent study (13), which involved aggregates used in many types of pavement surfaces, relationships were obtained between skid number, cumulative traffic per lane, and aggregate properties (PV and Los Angeles abrasion tests). The all-pavement-type model was based on about 600 observations and had an R^2 of 0.40. The model for seal coats was based on about 150 observations and had an R^2 of 0.32. The low predictive ability of the models can probably be attributed to the exclusion of variables such as macrotexture and seasonal variations.

GUIDELINES FOR ACHIEVING AND MAINTAINING ADEQUATE SEAL COAT FRICTIONAL RESISTANCE

Adequate frictional performance of seal coats is achieved mainly by the selection of satisfactory aggregates, by the use of properly designed application rates of asphalt and aggregate, and by assuring a careful quality control of construction operations. Guidelines related to each of these factors are discussed as follows.

Selection of Aggregates

It has been accepted worldwide that, for a natural aggregate to have high, prolonged frictional resistance, it should be comprised of sand-size hard grains weakly bonded in a softer matrix so that differential wear in the aggregate occurs. Generally, it has been proved that sandstone aggregates with high PVs have high, long-lasting frictional resistance, whereas carbonate aggregates with low PVs, such as limestones and dolomites and some siliceous gravels lose their initial frictional resistance rapidly under traffic exposure (28, 29, 36, 84). On the other hand, synthetic aggregates, particularly lightweight aggregates, have proven to be highly superior to most natural aggregates in terms of maintaining comparatively highly favorable frictional resistance (37, 38, 42, 70, 101).

In selecting the aggregate to be used in a seal coat, attention is paid to the level of friction to be maintained on the roadway. The level of friction is, in turn, decided upon in view of the estimated traffic volumes and speed limits (32, 44, 55, 102, 104); the roadway features, such as hills, curves, and intersections, which require unusual vehicle maneuvering (83, 102, 104); and the pavement's drainage capabilities as influenced by the surface cross-slope and the capacity and adequacy of drainage facilities in the vicinity of vertical and horizontal curves and other transition locations (83, 127).

After the required level of frictional resistance has been decided, the aggregate is selected. The aggregate is expected to have the following properties:

(1) adequate polish and wear resistance,
(2) ability to transmit traffic loads to the underlying surface,
(3) abrasion resistance, and
(4) resistance to the deteriorating effects of weather ing.

Due to the lack of reliable frictional resistance predicting models that would relate the aggregate properties to the desired frictional resistance, the several laboratory tests discussed previously and the aggregate performance history can be used to determine the suitability of the aggregate under consideration. The tests may include the PV test, the Los Angeles abrasion test, the four-cycle soundness test, the insoluble residue test for carbonate aggregates, and many others. In Texas, PV guidelines have been used for many years. The SDHPT issues a catalogue of RSPVs to serve as a guide for prospective bidders concerning the furnishing of aggregates for pavement surfaces. Recognizing the fact that some low PV aggregates (especially siliceous gravels) have been observed to show satisfactory frictional performance (44), the SDHPT has permitted the qualification of an aggregate source based on historical friction data as an alternate procedure. Several studies have been conducted in Texas (13, 39, 117) which have resulted in the development of plots of frictional performance history for numerous aggregate sources. As expected, the major problem encountered has been the high variability in the friction data caused by seasonal variations, which makes the qualification procedure not very dependable.

One of the difficult problems in proper selection of aggregates in Texas and many other states is the enormous amount of limestone available as aggregate. As stated previously, most limestone aggregates polish rapidly and lead to low frictional resistance in a relatively short period. Some studies (12, 86, 128) have shown that it is possible through proper combinations of aggregates of different wear rates to use most sources of limestone aggregates. Studies indicated that blending in proportion to the amount blended and the polish and wear resistance of the blending aggregates is effective. In Texas, problems have been experienced with blends of aggregates used to meet PV or soundness requirements. From a production standpoint, blends were reported to be difficult to control (141). For example, in blending a lightweight aggregate with a limestone aggregate, the tendency is to cut back on the amount of the lightweight aggregate. The specific gravity of the resulting mix is used to check the adequacy of blending rates. From a performance standpoint, it was experienced that surfaces constructed with blends may start with improved initial friction, but eventually this will decrease to take on the frictional characteristics of the poorer aggregate (141). Another observation reported (89) was on a highway section overlayed in 1985 with a HMAC blend of a sandstone aggregate and a siliceous gravel aggregate. The blend met the 40 percent soundness requirement, but the individual sandstone soundness loss was much higher. After two years of exposure to traffic, the road suffered deterioration due to rapid degradation of soft sandstone particles. It is recommended that, when blends of aggregates are to be used, each aggregate be required to meet all quality tests (89, 141).

Shape and size of aggregate particles are other features important to satisfactory frictional performance of an aggregate. Angular aggregate particles have proven to provide higher frictional resistance than subrounded or rounded particles, particularly in the case of siliceous gravels (122). Rounded siliceous gravels have provided satisfactory performance on low traffic volume roads. Although lightweight aggregate particles are often not angular, they tend to have the rough surface features desired for good seal coat surfaces. The presence of flat and elongated particles should be minimized and, if possible, avoided.

An aggregate with a "one size" gradation which will produce superior particle interlocking and will result in an optimum contact area between the tire and seal coat surface is preferred for seal coats. In Texas, it is a common practice to select large maximum size aggregate, grade 3 or 4, for high traffic volume roads (122). A large maximum size aggregate improves pavement surface drainage and thus reduces the potential for hydroplaning.

Although precoated aggregates are more expensive than non-coated aggregates, they have been extensively utilized in Texas for many years and found to have the following advantages (104, 122). They

(1) reduce the effect of dusty aggregates, thus promoting the bond with asphalt, and
(2) reduce automobile glass damage due to flying aggregate particles.

Design Method

After the aggregate type has been selected, the asphalt type and the design application rates of asphalt and aggregate are determined. Guidelines for selection of asphalt type and grade are available in the literature (122, 129, 130, 131). The guidelines indicate that a careful selection is one based on the following:

1. the type of aggregate to be spread on the asphalt layer, as related to the percentages of silica and alkali contents;
2. the climatic region in which the seal coat is to be constructed (minimum temperature, rainfall, and humidity); and
3. the limitations on the minimum surface and ambient temperatures for a few days prior to construction, at time of construction, and for several days after construction.

In designing the distribution rate of asphalt and the spreading rate of aggregate, the procedures should be aimed at producing (1) an adequate surface macrotexture in terms of providing uniformly distributed aggregate particles spaced in a way that would assure rapid escape of water from underneath the tire and (2) proper adhesion between the asphalt binder and the aggregate and adequate embedment of the aggregate into the asphalt film in order to minimize loss of aggregate. In practice, large maximum size aggregates require larger amounts of asphalt than small maximum size aggregates (i.e., 0.40 gal/sq yd for a Grade 3 aggregate compared with 0.20 gal/sq yd for a Grade 5 aggregate). It has been evident that Grade 3 aggregates have provided more effective seal coats because of the thickness of the applied asphalt film. In addition, although distributors, when kept in proper condition, are capable of accurately distributing desired amount of asphalt in a uniform transverse and longitudinal direction, experience has shown that field variations in applied asphalt quantities are much less critical for Grade 3 aggregates than for smaller grade aggregates (122, 130, 132). However, under no circumstances should the amount of the applied asphalt be in excess of that required to develop enough bond to the aggregate and produce adequate embedment. Excessive amounts of asphalt may cause the aggregate to be completely embedded into it, inducing bleeding of the surface, which lowers the surface frictional properties. Epps, Gallaway, and Hughes (122) gave excellent guidelines concerning design methods of seal coat surfaces.

Quality of Construction

The performance of seal coats depends to a large degree on the quality of construction. Key factors which may contribute to successfully constructing high quality seal coats include (122, 130, 131):

1. proper preparation of the existing surface upon which the seal coat is to be placed—for example, if the surface is exhibiting a bleeding distress, special corrective measures should be taken to reduce the potential for bleeding in the new seal coat;
2. satisfactory environmental conditions—experience has shown that the ideal environment for the construction of seal coats is hot, dry weather with no rain for the next several days;
3. selection of equipment in good operating condition and proper handling of equipment during construction;
4. carefully planned sequence and timing of construction operations;
5. implementation of an adequate field inspection and quality control plan; and
6. adequate traffic control during construction and in the first hours after completion of construction.

CHAPTER 3. SURVEY OF TEXAS DISTRICTS

PURPOSE

Nine Texas Districts were surveyed to obtain information on the current policies practiced and problems experienced by those Districts concerning methods for laboratory evaluation of coarse aggregate and aggregate frictional performance. Although the research efforts at this phase are directed towards investigating the frictional resistance of seal coat surfaces only, the survey of Districts was intended to gather information on the use and friction of aggregates in seal coat and HMAC surfaces. It is believed that a full understanding of these policies and problems by the researchers would play a vital role in prioritizing and refining the study objectives. This in turn might lead to a better orientation of the research towards solving the current problems. Information sought included requirements regarding PVs of aggregates used, other methods for laboratory evaluation of coarse aggregate, FNs obtained, correlation between PV and FN where applicable, visual inspection of typical sections for high and low polish values and high and low frictional resistance, and personal observations of District personnel.

FINDINGS

Enthusiastic response to the opportunity to participate in this research was observed in all surveyed Districts. Valuable information was gathered and summarized for each District as follows.

District 2

The District uses the MSS and PV tests for evaluating the polish susceptibility of coarse aggregates. District personnel contacted feel that both tests are equally important in determining aggregate properties. The percentage loss in the MSS test should not exceed 30 percent if an aggregate is to be accepted. An aggregate with an MSS loss less than 20 percent is considered good; one with an MSS loss greater than 40 percent is poor. The District's PV requirements are as follows:

ADT	PV
Greater than 30,000	35
30,000 to 5,000	32
5,000 to 2,000	30
2,000 to 750	28
Less than 750	No requirement

District personnel have found that when aggregates meet the soundness test requirement, the FN tends to equal the PV of the aggregate at about 40 million passes; afterwards the FN remains constant. For example, for an aggregate with an MSS loss of 10 percent and a PV of 28, the FN tends to be in the range of 27 to 28 at 40 million passes. They have also found that aggregates with high MSS losses have low FNs even though their PVs are relatively high.

District personnel do not approve the use of aggregate blends as a way to improve FN. They feel that, although the initial FN is improved, it eventually drops and tends to decrease to the PV of the poor material with increases in traffic passes.

The District has the FN incorporated in its pavement management rehabilitation system. Pavements are ranked according to their respective FNs, and their maintenance priorities are set; pavements with the FN less than 20 have a higher priority.

Finally, the District keeps records of aggregate performance. It has 10-year friction data for many seal coat and HMAC projects, along with laboratory information on the results of the MSS, Los Angeles abrasion, PV, and decantation tests performed on the aggregate materials used in the projects documented. Some of the friction data were obtained on hard copies and manipulated along with data from other Districts, as discussed later.

District 3

The District adopts the use of the PV test to determine the aggregate acceptability for use in HMAC and seal coat surfaces. The eastern part of the District produces aggregates with a PV of 38 to 39 while the southern part produces aggregates with a PV of 29. Sometimes, a low PV aggregate is blended with sandstone to improve its frictional resistance. The District personnel indicated that the sandstone improves the PV of the blend but reduces its soundness.

In addition, the District personnel stated that there is no need for an aggregate to meet a high PV requirement because, usually, before the FN drops below the acceptable limit the road is resurfaced for other rehabilitation purposes. However, they reported that in the case of low volume roads where low PV aggregates can be used, the relation between the reduction in FN and accumulative traffic is needed.

Finally, the District has never required the four-cycle soundness test for job control because the limestone aggregates used in the District easily pass the test.

District 4

The District uses the PV test. The aggregates should meet a minimum PV of 32 to be accepted. It also runs the Los Angeles abrasion test on siliceous gravel material. The District does not require the MSS test because its aggregates easily meet the requirement. The primary performance problem the District reported was stripping of aggregates from pavement surfaces.

District 5

The District uses the PV and MSS tests. The maximum allowable MSS loss is 25 percent. The PV requirements are a minimum of 32 for high volume roads and a minimum of 28 for low volume roads. However, past history of aggregates having lower PVs showing good frictional performance could waive these requirements. The District's area has a shortage of aggregates that will meet the PV required for high volume roads. Some of their aggregate must have a softer, unsound material combined with it to come up to a minimum required PV. The lightweight aggregate (high PV) is expensive for their area and tends to crush in the wheel paths of high volume roads.

Additionally, it was related that soft aggregates have high PV but are inadequate in soundness. The personnel contacted believe that soundness of aggregates is more important than PV and, therefore, the MSS test is preferred. It was also stated that soft limestone should be tested for soundness while siliceous gravel should be tested for polishing characteristics.

Factors mentioned to be more important for the FN than the PV were flushing of the asphalt in wheel paths and slipperiness of pavement surfaces right after rainfall. Finally, the District's Pavement Evaluation System does not include the FN. Yet, it is believed that safety regulations will eventually require the inclusion of the FN in such a system.

District 15

The District employs the PV and MSS tests in judging the acceptability of aggregates for usage in pavement surfaces; an aggregate should have a PV greater than 30 and a maximum allowable MSS loss of 30 percent to be accepted. Also, the District allows the use of blended aggregates to meet PV requirements. The District preserves records of aggregate properties and performance upon which such judgments and decisions also depend. Some of these records were acquired for evaluation by the researchers. The District has also set up test sections of seal coat surfaces for investigating aggregate performance.

District 16

The District relies on the PV and MSS tests. The soundness limits used are 30 percent for seal coats and 40 percent for blends in HMAC surfaces. A research project has been undertaken in which twelve HMAC test sections were built with limestone, sandstone, and blends of the two aggregates. The purpose of the study is to relate mixture design data including PV and MSS with FN and pavement performance (cracking, rutting, etc.).

District 18

The MSS test is greatly relied upon in this District with a maximum allowable MSS loss of 30 percent. The PV test is also used, though not relied on as much as the MSS test.

The District has several test sections on which PVs, MSS losses, and five-year friction data are available. Some of the District personnel pointed out that the outside lanes have lower FNs than the inside lanes due to heavier traffic volumes. They also believe that blending aggregates with different PVs (e.g., 30 and 34) gives better performance than using one aggregate with a PV of 32.

District 23

The PV and MSS tests are used in this District with 30 percent being the maximum allowable MSS loss. Two types of aggregates are used in the District, a limestone aggregate with a PV of 28 and a lightweight aggregate with a PV of about 35. A few years ago, both aggregates were used extensively. However, the use of the lightweight aggregate during the last few years was observed to have improved the frictional resistance of the roadways built with this aggregate. As a consequence, the lightweight aggregate has replaced the limestone aggregate almost everywhere.

The FN of roads constructed with the limestone aggregate dropped to around 25 within the first year, whereas roads built with the lightweight aggregate maintained an FN in the range of 50 to 45. The limestone aggregate is mostly used on low volume Farm-to-Market roads and roads that have many bends. The lightweight aggregate was reported to break in bends exposing sharp edges detrimental to rubber tires. The District prefers not to use aggregate blends, but it uses the low PV aggregate and then applies a sealant of lightweight aggregate when the FN drops below the acceptable limits.

A case was reported where two HMAC pavement sections were constructed with aggregates from the same source. In the first section, the aggregate was washed, and the section consequently used less asphalt; in the second, the aggregate was not washed. Performance records have shown that the first section maintained higher friction numbers, which might indicate that asphalt content affects pavement friction.

District 25

Both the MSS and PV tests are used in the District. The MSS test is not performed on aggregates for use in HMAC surfaces, because aggregates can pass it very easily, nor on precoated aggregates. The test is used only for seal coat surfaces with non-coated aggregates, with a maximum allowable MSS loss of 30 percent. The MSS test is relied on since the test gives a relative measure of the extent to which their aggregates will deteriorate due to salt, which they apply when they experience ice and snow.

The requirements for the PV test are a minimum of 32 for high traffic volume and a minimum of 28 for low traffic volume. However, the District allows the use of lower PV aggregates only if the aggregates have good performance history. The PV test is used only for new construction.

A study conducted years ago in the District revealed little correlation between PV and FN while some correlation between sand equivalency of surface texture and FN was found.

OBSERVATIONS FROM OBTAINED FRICTION DATA

Friction data, collected over the past six to eight years, were obtained from several Districts in Texas, not necessarily from the surveyed Districts only. Data from three Districts, for four selected aggregate sources used in HMAC surfaces with various traffic volumes, were combined in order that limited observations could be made. Besides FN, the data included laboratory information on PV and MSS loss. Graphs of the FN versus accumulated traffic per lane are plotted in Fig 3.1 (89). The aggregate types and the laboratory information are shown in Table 3.1.

As can be noted, there are obvious performance differences among the aggregates considered. First, the overall performance of the sandstone aggregate, which had a high PV of 47 and a MSS loss in the range of 9 to 20 percent, was markedly better than that of the limestone aggregates. A comparison between the PVs and MSS losses of the sandstone aggregate with those of Limestone 1 suggests that, since the MSS loss for the limestone aggregates is less than that of the sandstone aggregate, the markedly better performance of the sandstone aggregate is most likely due to the relatively higher PV, 47. Second, up to two million passes, the limestone aggregates exhibited a dramatic decrease in FN compared to the rather flattened decrease exhibited by the sandstone aggregate. Third, Limestone 1, which had the lowest MSS loss, maintained on FN higher than those of the other two limestone aggregates up to about two million accumulated passes, after which the FN of Limestone 2, with a PV of 36 and an MSS loss in the range of 7 to 26 percent, flattened and remained constant. Fourth, Limestone 3, in spite of its good PV of 39, had the worst performance all throughout the life of the road because it was inadequate in soundness (MSS = 52%). Last, the terminal FNs of Limestone 1 and Limestone 3 were about the same at six million passes. Yet, had the roads been resurfaced when the FN dropped below 20, Limestone 1 could have sustained twice as much traffic.

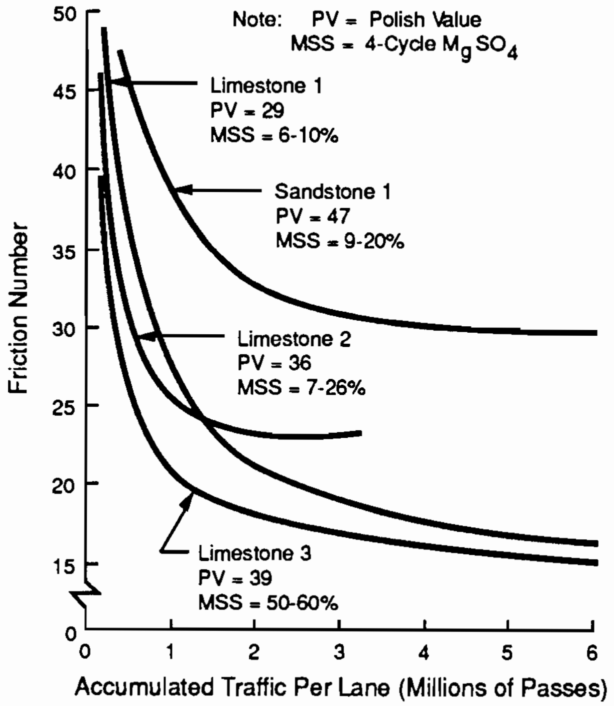


Fig 3.1. Frictional resistance of HMAC surfaces constructed with four aggregates in three Texas districts (89).

TABLE 3.1. AGGREGATE CONSIDERED IN THE ANALYSIS OF OBTAINED FRICTION

Aggregate Material	Aggregate Properties	
	PV	MSS, %
Sandstone	47	9-20
Limestone 1	29	6-10
Limestone 2	36	7-26
Limestone 3	39	50-60

In summary, it seems that good frictional performance could not be achieved with only good polishing properties or with only good soundness characteristics. Two aggregates, Limestone 1 and Limestone 3, exhibited undesirable frictional performances; the former had a low PV and a low MSS loss, and the latter had a high PV and a high MSS loss. Two other aggregates, Sandstone 1 and Limestone 2, with approximately the same range of soundness loss had different frictional performances, with the aggregate with the higher PV maintaining higher FNs. The above discussion seems to indicate that both polishing and soundness properties and the interaction between the two contribute to changes in frictional performances.

It should be reemphasized that the above findings apply only to HMAC surfaces and may not necessarily be valid for seal coat surfaces. Also, it should be mentioned that these observations are to be interpreted cautiously since they are tentative and are based on plots that represent best fit curves. Although the trend of the decrease in FN was traceable, the data of each curve suffered from large, unexplained variations to the extent that overlapping between some of the data was observed. These variations could be attributable to factors unknown to the researchers, which are not easy to determine.

SUMMARY

Several observations can be drawn from the findings of the surveys and the analysis of obtained friction data.

(1) It was found that the PV test is used in all surveyed Districts as a laboratory method for evaluating the

polish susceptibility of coarse aggregates used in pavements. In seven of the surveyed Districts, the MSS test is used along with the PV test (and is even more preferred in Districts 5 and 25). The PV requirements in most of the surveyed districts seemed to be a minimum of 32 for high volume roads and a minimum of 28 for low volume roads. The maximum allowable MSS loss was found to be 30 percent in five of the surveyed Districts.

(2) The soundness of the aggregates was found to be an important aggregate characteristic affecting the frictional resistance of pavement surfaces. It was reported in the surveys and supported by the findings of the analysis of friction data obtained for HMAC surfaces that aggregates that had high PV but were inadequate in soundness did not have good frictional performance on the roads.

(3) Districts 5, 15, and 25 allow the use of aggregates that do not meet the PV requirements only if the aggregates have good frictional performance history. In addition to these districts, District 2 preserves friction data for many seal coat and HMAC projects along with laboratory information on the aggregates used in the documented projects.

(4) Districts 15, 16, and 18 have set up seal coat and HMAC test sections for the purpose of investigating frictional resistance. A study conducted years ago in District 25 revealed little correlation between PV and FN while some correlation between sand equivalency of surface texture and FN was found.

(5) Districts 2 and 23 do not like to use aggregate blends while District 18 does. District 2 personnel feel that although the initial FN is improved, the FN eventually drops and tends to decrease to the PV of the poorer material. District 23 personnel prefer to use the low PV aggregate and then apply a sealant of lightweight aggregate (high PV) when the FN drops below the acceptable limits. However, District 18 personnel believe that blending aggregates with different PVs (e. g., 30 and 34) gives better performance than using one aggregate with a PV of 32.

(6) District 3 reported that there is no need for an aggregate to meet a high PV requirement because, usually, the road is resurfaced for other rehabilitation purposes before the FN drops below the acceptable limit. However, for low volume roads where low PV aggregates can be used, the relationship between FN drop and accumulated traffic was reported to be of value.

(7) Factors mentioned as important for frictional resistance were stripping of aggregates in the wheel paths (District 4), flushing of asphalt in the wheel paths (District 5), and slipperiness of pavement surfaces right after rainfall (District 5). District 18 reported that the outside lanes have lower FNs than the inside lanes due to the heavier traffic volumes passing on the outside lanes.

(8) Finally, only District 2 was found to have the FN incorporated in its pavement management rehabilitation system. Yet, District 5 personnel believe that safety regulations will eventually require the inclusion of FN in such a system.

CHAPTER 4. RESEARCH METHODOLOGY AND TEST SECTIONS

RESEARCH METHODOLOGY

Many coarse aggregate types and sources have been used for placing seal coats on Texas highways. The major types or categories include crushed limestone (LMST), crushed sandstone (SDST), and crushed siliceous gravel (SIGR). Other types include lightweight aggregate (LTWT), limestone rock asphalt (LMRA), traprock (TPRK), granite (GRNT), and rhyolite (RHYO). Differences in field frictional resistance of these aggregates have been observed over the years (13, 28, 29, 36, 39, 84, 117). Numerous factors, including aggregate characteristics, construction variables, traffic volume, and environment, are believed to be major contributors to these performance differences. The objective of this phase of the study was to investigate the effects of these factors on the field frictional resistance of coarse aggregates when used in seal coat surfaces.

The methodology followed in this investigation involves establishing seal coat test sections in different climatic regions of the State of Texas, using as many of the aggregates which are predominant to the area and which are economically obtainable. For each test section a construction survey is made. The survey is comprised of construction variables such as design application rates of asphalt and aggregate, asphalt and aggregate type, weather condition, type and condition of existing pavement, and type of construction forces. Aggregate samples are obtained from the job sites of test sections and examined in the laboratory to determine their physical properties, polish and wear characteristics, resistance to weathering, resistance to impact and abrasion, and petrographical and mineralogical qualities. Field tests are then performed on the surfaces of test sections twice a year at random intervals. Testing involves measuring surface friction and texture. Finally, annual and periodical weather information on average temperature, total precipitation in inches, and total inches of snow are obtained for each test section.

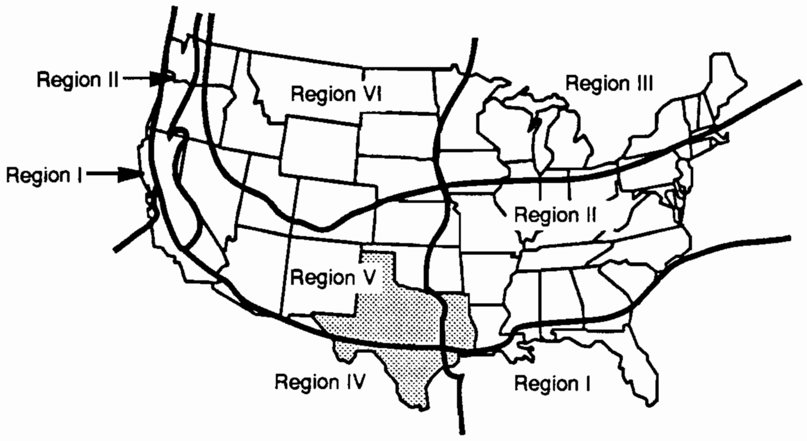
All data are being stored in the data base being created on the IBM PC AT specially purchased for this study. In-depth statistical analysis will be performed on the data in order to formulate probabilistic models for predicting pavement friction, in which the effects of the involved variables on the friction of seal coat surfaces will be assessed.

TEST SECTIONS

Environmental Considerations

Figure 4.1 provides a map that shows six different climatic regions of the United States and the environmental characteristics associated with each (135). The State of Texas lies within four of these regions (I, II, IV, and V), as shown in Fig 4.2. The respective environmental characteristics are wet and no freeze, wet and freeze-thaw cycling, dry and no freeze, and dry and freeze-thaw cycling.

Seal coat test sections have been established in all four climate regions. At least one source of each major aggregate category should have been used in all four regions to allow evaluation of the effect of climate on that aggregate category. However, in the course of building test sections it was felt that this was not possible in most cases because, in practice, no aggregate is currently used in all four regions, and hauling an aggregate to locations far from its source is neither feasible nor practical. To make the experimental design more representative of the current practices, D-9 suggested that sections be constructed using different qualities of the main aggregate categories in regions close to the aggregate source. D-9 reviewed the already established sections and grouped some of the major aggregates, according to their soundness (the MSS test) and polishing characteristics (the polish value test), based on historical laboratory data available at D-9. As a result, regions where it might be practical to construct sections were recommended. Table 4.1 provides a summary of the suggested aggregate groups and recommended regions.



Region	Characteristics
I	Wet and No Freeze
II	Wet and Freeze-Thaw Cycling
III	Wet, Hard Freeze and Spring Thaw
IV	Dry and No Freeze
V	Dry and Freeze-Thaw Cycling
VI	Dry, Hard Freeze and Spring Thaw

Fig 4.1. The six climatic regions in the United States (135).

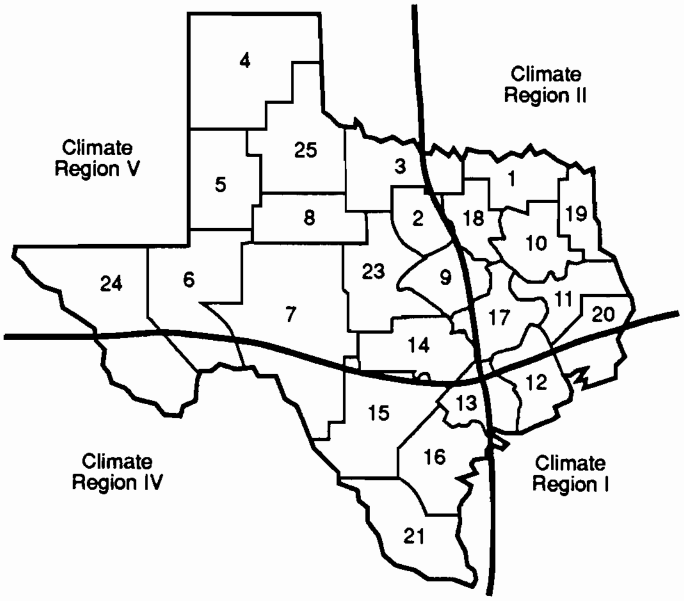


Fig 4.2. Location of the four climatic regions in Texas (135).

TABLE 4.1. SUMMARY OF THE AGGREGATE GROUPS AND REGIONS SUGGESTED BY D-9 FOR EVALUATING THE ENVIRONMENTAL EFFECT

Aggregate Material	Material Group	MSS	PV	Producer	Regions with Sections	Regions to Place Section In	Pit Location
Limestone	1	≤5	<30	Dolese Brothers - Coleman	V	II	Oklahoma
	1	≤5	<30	Gilfford Hill - Ogden	IV, I	-	District 15
	2	10-25	>33	Texas Crushed Stone	II	I, IV	District 14
	2	30-80	>35	White's Mines - Massey	V	-	District 8
Sandstone	1	~5	36-43	Boorhem Fields - Apple, Ok	II	-	Oklahoma
	1	~20	~40	Delta Materials - Marble Falls	II*	I, IV, V	District 14
Siliceous Gravel	1	<5	26-30	Janes-Blackburn	V	II	District 8
	1	<5	25-28	South Texas Aggregate - Knippa	I	IV	District 15
Limestone Rock Asphalt	1	-	-	White's Mines - Uvalde	I, II, IV	V	District 15
Lightweight	1	-	-	Texas Industries - Streetman	I	II, IV, V	District 18

* Since the Marble Falls pit is located in central Texas, it may be possible to place a section in Region II as well.

Statistical Considerations

For the experimental design to be statistically sound, some requirements have been established.

(1) Sections should be at least 1000 feet long to allow five friction or texture values to be measured.

(2) Ideally, for each major aggregate type, as many as four sections with aggregates obtained from four different sources are to be constructed in each environmental region. However, the total number of test sections should not exceed that which may result in effective handling of sections.

(3) Replications of sections should be established wherever possible. These will be used to test for a constant variation in field responses (friction and texture) under various experimental conditions. The variation expected can be caused mainly by the following:

  (a) time: which reflects possible changes in the quality of an aggregate pit with time. For example, an aggregate is used to construct a test section, and later, after a few weeks or few months, the same aggregate is used to build another test section, preferably in the same climatic region and under the same traffic.

  (b) traffic count: in the case of a divided highway, the ADT is provided as a total figure for both directions. Replications built in both directions may clarify whether traffic is divided equally. Also, in the case of more than one lane per direction, replications are built in all lanes to account for differences among the traffic volumes passing over the different lanes.

  (c) less importantly, construction practices: two sections are placed a few miles apart on the same lane to evaluate any variations due to construction equipment, such as changes in application rates of asphalt or aggregate.

However, it should be mentioned that replications are not constructed for all sections. They are considered only for few sections where the circumstances permit.

Criteria for Selection

Several criteria have been followed, when possible, in selecting test sections. These are as follows:

(1) All sections are tangent sections.

(2) Consider only sections with minimal slope, up to two percent.

(3) Have no major intersections within or between sections.

(4) Ideally, have as many sections end-to-end as the number of different aggregates used.

(5) Ideally, select two sections for each aggregate; one constructed by the maintenance forces, and the other by a contractor.

(6) In the case of divided highways, have sections in only one direction, preferably the direction of heavier traffic. Where possible, replications are recommended as discussed earlier.

Selected Test Sections

Fifty-two seal coat test sections have been established in nine districts of the four environmental regions; twelve of them are replications. Various aggregate types and sources have been used. Specifically, aggregates from eight sources of crushed limestone, one source of limestone rock asphalt, two sources of crushed sandstone, eight sources of crushed siliceous gravel, and five sources of lightweight aggregate were placed. More than fifty percent of the aggregates were non-coated and the others were precoated. Different aggregate grades were also considered in view of the effect gradation may have on pavement surface texture and friction.

Table 4.2 provides a comprehensive summary of the selected test sections. The summary shows the region, district, county, and highway designation where each aggregate was placed as well as the ADT to which the aggregate is exposed. The aggregate type, material, grade, producer, and pit are also included.

Table 4.3 exhibits a summary of the aggregates used in the selected test sections. It includes information on the total number of sections constructed with each aggregate and the number of sections per region, along with the average daily traffic associated with each. The table also shows for which sections replications were possible and the type of replication built.

Table 4.4 summarizes the number of test sections and types of aggregates still needed to complete the design of the experiment. The numbers with asterisks represent the sections needed to complete the experimental design for the environmental effect, as discussed earlier. The others represent those additionally needed to ideally complete the experimental design for the aggregate effect. Preferably, these sections are to be built with aggregates obtained from sources different from those already used. A list of these sources, suggested by D-9, is shown in Table 4.5.

As can be noticed, rhyolite, granite, and traprock aggregates are not included in Table 4.4. However, sections with these aggregates will be constructed in some parts of the state, where the aggregates are available. For instance, a rhyolite aggregate available in District 6 in southwest Texas is being used to construct seal coat sections in District 7. Similarly, a traprock aggregate available in District 23 is being placed in the District.

TABLE 4.2. SUMMARY OF SELECTED TEST SECTIONS

			Aggregate							
District	**County**	**Sect No.**	**Type**	**Material and Grade**	**Producer**	**Pit**	**Road**	**Maint/ Contract Job**	**ADT**	**Region**
23 Brownwood	Stephens	1	B	LMST 3	White's Mines	Brownwood	FM 1148	C	680	V
	Stephens	2	B	LMST 3	White's Mines	Brownwood	FM 1287	C	800	V
	Stephens	3	B	LTWT 3	Featherlite	Ranger	US 193	C	1300	V
	Eastland	4	B	LTWT 3	Featherlite	Ranger	SH 36	C	2500	V
8 Abilene	Shackelford	5	B	LTWT 3	Featherlite	Ranger	SH 351	C	2500	V
	Shackelford	6	B	SIGR 3	Janes Gravel	Blackburn	SH 351	C	2500	V
	Shackelford	7	PB	LMST 3	White's Mines	Abilene - Massey	SH 351	C	2500	V
4 Amarillo	Deaf Smith	8	B	SIGR 4	Vega Sand & Gravel	Tom Green	FM 2943	M	240	V
	Deaf Smith	9	B	SIGR 4	Panhandle Gravel Co.	Box Canyon	FM 2943	M	240	V
	Deaf Smith	10	B	LMST 4	Dolese Brothers	Coleman, Ok	FM 2943	M	240	V
	Deaf Smith	11	B	SIGR 4	Western Sand & Gravel	Tascosa	FM 2943	M	240	V
	Deaf Smith	12	PD	SIGR 4	Texas Sand & Gravel	Mansfield Plant	FM 2943	M	240	V
	Deaf Smith	13	B	SIGR 4	Vega Sand & Gravel	Tom Green	FM 1062	M	250	V
	Deaf Smith	14	B	SIGR 4	Vega Sand & Gravel	Tom Green	FM 2943	M	270	V
16 Corpus Christi	Nueces	15	PB	LMST 4	Redland Worth	Beckman	P 22	M	13300	IV
	Nueces	16	PB	SIGR 4	Bay	Kingsville	P 22	M	13300	IV
	Nueces	17	PB	LMST 4	Pioneer	Tradesman Dr	P 22	M	13300	IV
	Nueces	18	PB	LMST 3	Gifford-Hill	Ogden - New Braunfels	P 22	M	13300	IV
	Nueces	19	PB	LMRA 4	White's Mines	Uvalde	P 22	M	13300	IV
	Nueces	20	PB	LMRA 4	White's Mines	Uvalde	P 22	M	13300	IV
	Nueces	21	PB	LMRA 4	White's Mines	Uvalde	SH 358	M	34000	IV
19 Atlanta	Titus	22	B	SIGR 3	Gifford-Hill	Little River	FM 2882	M	1100	II
	Panola	23	B	LTWT 3 Mod	Texas Industries	Streetman	US 59	C	6600	II
	Panola	24	B	LTWT 3 Mod	Texas Industries	Streetman	US 59	C	6600	II
	Panola	25	B	SDST 3	Boorhem-Fields	Apple, Ok	SH 315	C	4000	II
	Bowie	31	B	SDST 3 Mod	HMB Construction	Dequeen, Ark	FM 989	M	2300	II
	Upshur	35	B	LTWT 3 Mod	Texas Industries	Streetman	US 271	M	5500	II

(continued)

TABLE 4.2. (CONTINUED)

			Aggregate							
District	County	Sect No.	Type	Material and Grade	Producer	Pit	Road	Maint/ Contract Job	ADT	Region
1	Delta	26	PB	SDST 3	Boorhem-Fields	Apple, Ok	SH 154	C	680	II
Paris	Hopkins	27	PB	SDST 3	Boorhem-Fields	Apple, Ok	SH 19	C	4400	II
	Hopkins	28	PB	SDST 3	Boorhem-Fields	Apple, Ok	SH 19	C	4400	II
	Grayson	29	PB	LMST 3	Amis Materials	Stringtown, Ok	US 69	C	2700	II
	Grayson	30	PB	LMST 3	Amis Materials	Stringtown, Ok	US 69	C	2700	II
11	Houston	32A	B	LMST 3	Texas Crushed Stone	Feld	US 287	C	3800	II
Lufkin	Houston	32B	B	LMST 3	Texas Crushed Stone	Feld	US 287	C	3800	II
	Houston	33A	PB	LTWT 3 Mod	Texas Industries	Streetman	US 287	C	3800	II
	Houston	33B	PB	LTWT 3 Mod	Texas Industries	Streetman	US 287	C	3800	II
	Houston	34A	PB	LMRA 4	White's Mines	Uvalde	US 287	C	3800	II
	Houston	34B	PB	LMRA 4	White's Mines	Uvalde	US 287	C	3800	II
13	Victoria	36	PB	LMST 4	Colorado Materials	Hunter	US 77	C	3600	I
Yoakum	Victoria	37	PB	LMST 4	Gifford-Hill	Ogden - New Braunfels	US 77	C	3600	I
	Victoria	38	PB	LMST 4	Redland Worth	Beckman	US 77	C	3600	I
	Victoria	39	PB	SIGR 4	South Texas Aggregates	Knippa	US 77	C	3600	I
	Victoria	40	PB	LTWT 4	Texas Industries	Clodine	US 77	C	3600	I
	Victoria	41	PB	LTWT 4	Texas Industries	Streetman	US 77	C	3600	I
	Victoria	42	PB	LMRA 4	White's Mines - Uvalde	Dabney	US 77	C	3600	I
	Victoria	43	PB	LMRA 4	White's Mines - Uvalde	Dabney	US 77	C	3600	I
23	Liberty	44	B	LTWT 3 Mod	Texas Industries	Streetman	US 90	C	6100	I
Beaumont	Liberty	45	PB	LMRA 3	White's Mines - Uvalde	Dabney	US 90	C	6100	I
	Liberty	46	B	LTWT 3 Mod	Texas Industries	Streetman	US 90	C	6100	I
	Liberty	47	PB	LMRA 3	White's Mines - Uvalde	Dabney	US 90	C	6100	I
	Liberty	48	B	LTWT 3 Mod	Texas Industries	Streetman	US 90	C	6100	I
	Liberty	49	B	LTWT 3 Mod	Texas Industries	Streetman	US 90	C	6100	I

TABLE 4.3. SUMMARY OF AGGREGATES USED FOR TEST SECTIONS

Aggregate Material	Type	Grade	Producer	Pit	No. of Sects	No. of Sections/ADT By Region			
						I	II	IV	V
LMST	PB[d]	4	Redland-Worth	Beckman	2	1/3,600		1/13,300	
LMST	PB	4	Gifford-Hill	Ogden	1	1/3,600			
LMST	PB	4	Colorado Mat.	Hunter	1	1/3,600			
LMST	PB	3	Amis Mat.	Stringtown, Ok	2		2 [a]/2,700		
LMST	B[c]	3	Texas Crushed Stone	Feld	2		2 [a]/3,800		
LMST	PB	4	Pioneer	Tradesman Drive	1			1/13,300	
LMST	PB	3	Gifford-Hill	Ogden	1			1/13,30	
LMST	PB	3	White's Mines	Abilene - Massey	1				1/2,500
LMST	B	4	Dolese Bros.	Coleman, Ok	1				1/240
LMST	B	3	White's Mines	Brownwood	2				2/1-680
LMRA	PB	3	White's Mines	Dabney	2	2 [a]/6,100			
LMRA	PB	4	White's Mines	Dabney	7	2 [a]/2,800	2 [a]/3,800	3/2 [a]-13,300 1-34,000	
SDST	PB	3	Boorhem - Fields	Apple, Ok	3		3/2 [a]-4,400 1-680		
SDST	B	3	Boorhem - Fields	Apple, Ok	1		1/4,000		
SDST	B	3 Mod	HMB Const	Dequeen, Ark	1		1/2,300		
SIGR	PB	4	South Texas Aggregates	Knippa	1	1/3,600			
SIGR	B	3	Gifford-Hill	Little River	1		1/1,100		
SIGR	PB	4	Bay	Kingsville	1			1/13,300	
SIGR	PD[e]	4	Texas Sand & Gravel	Mansfield Plant	1				1/240
SIGR	B	4	Vega Sand & Gravel	Tom Green	3				3/1-240 1-250 1-270
SIGR	B	4	Panhandle Gravel	Box Canyon	1				1/240
SIGR	B	4	Western Sand & Gravel	Tascosa	1				1/240
SIGR	B	3	Janes Gravel	Blackburn	1				1/2,500
LTWT	PB	4	Texas Industries	Streetman	1	1/3,600			
LTWT	PB	4	Texas Industries	Clodine	1	1/3,600			
LTWT	B	3 Mod	Texas Industries	Streetman	4	4[b]/2 [a] -6100 2 [a]-6100			
LTWT	B	3	Featherlite	Ranger	3				3/2 [a]-2,500 1-1,300
LTWT	B	3 Mod	Texas Industries	Streetman	3		3/2 [a]-6,600 1-5,500		
LTWT	PB	3 Mod	Texas Industries	Streetman	2		2 [a]-3,800		

[a] Sections consist of one section and one replication (twelve of the sections are replications).

[b] Each two of the four sections were constructed with a different asphalt type.

[c] An aggregate which consists of crushed gravel, crushed slag, crushed stone, or natural limestone rock asphalt.

[d] The same as above but precoated.

[e] A precoated aggregate which consists of crushed gravel, crushed slag or crushed stone.

TABLE 4.4. SUMMARY OF NUMBER OF TEST SECTIONS AND AGGREGATE TYPES STILL NEEDED TO COMPLETE THE EXPERIMENTAL DESIGN

Region	Number of Sections Needed	Aggregate Material	Producer/Pit	Pit Location
I	1 [a]	LMST	Texas Crushed Stone, Feld	District 14
	1 [a]	SDST	Delta Materials, Marble Falls	District 14
	3	SDST	Any Type	-
	3	SIGR	Any Type[b]	-
II	1 [a]	LMST	Dolese Bros. Coleman	Oklahoma
	1 [a]	SIGR	Janes, Blackburn	District 8
	1	LMST	Any Type [c]	-
	2	SDST	Any Type	-
	2	SIGR	Any Type [b]	-
IV	1 [a]	LMST	Tx Crushed Stone, Feld	District 14
	1 [a]	SDST	Delta Materials, Marble Falls	District 14
	1 [a]	SIGR	South Texas Aggr, Knippa	District 15
	1 [a]	LTWT	Texas Industries, Streetman	District 18
	3	SDST	Any Type	-
	2	SIGR	Any Type[b]	-
	3	LTWT	Any Type	-
V	1 [a]	SDST	Delta Materials, Marble Falls	District 14
	1 [a]	LTWT	Texas Industries, Streetman	District 18
	1 [a]	LMRA	White's Mines, Uvalde	District 15
	1	LMST	Any Type[c]	-
	3	SDST	Any Type	-

[a] Sections needed to complete the experimental design for the environmental effect.

[b] Uncrushed and crushed siliceous gravel aggregates are needed.

[c] Limestone material of the Texas Crushed Stone Co., Feld pit, is most preferred.

TABLE 4.5. LIST OF AGGREGATES TO BE CONSIDERED FOR FUTURE TEST SECTIONS SUGGESTED BY D-9

Producer	Pit	Aggregate Material
White's Mines	Weatherford	Limestone
Reese Albert	Wileke	Limestone
Pioneer Aggregate	Bridgeport	Limestone
Trans Pecos Materials	Hoban	Rhyolite
Granite Mountain Quarry	Little Rock, Ark	Granite
Appian Corporation	Thrasher	Siliceous Gravel
Fordyce	Spaulding	Siliceous Gravel
Janes, RE Gravel	Woods	Limestone/Siliceous Gravel
Parker Brothers	New Braunfels	Limestone
Dolese Brothers	Richards Spur	Limestone
Dolese Brothers	Coppertone	Limestone
East Texas Stone	Blue Mountain	Sandstone
Texas Crushed Stone	Feld	Limestone

CHAPTER 5. DATA COLLECTION

Field, laboratory, and weather data are being collected. The field data and the weather data are related to the established test sections and their geographical locations, respectively. The laboratory data involve the aggregates used in establishing the test sections.

FIELD DATA

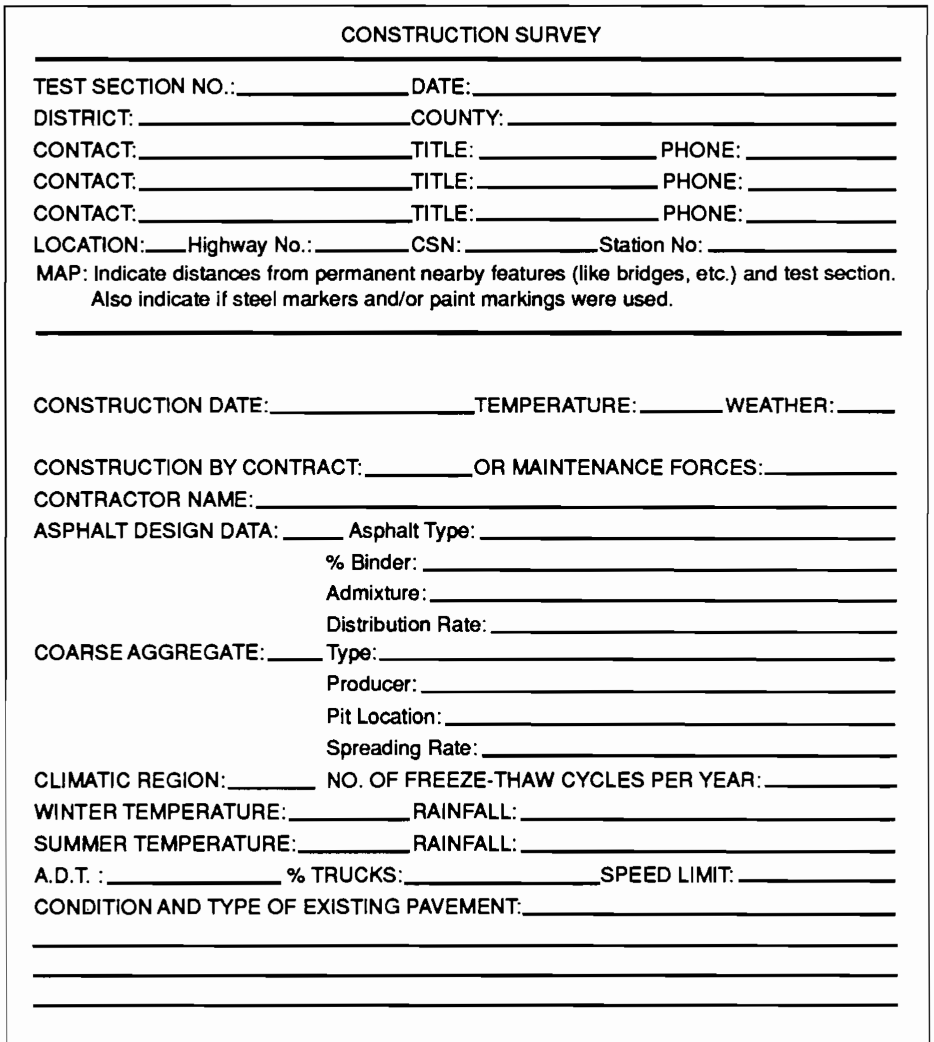
Field data are gathered on all established test sections. They constitute information obtained by monitoring the sections since the date of construction. Specifically, the data for each test section consist of a survey of construction variables performed at the construction sites, results of field testing obtained twice a year, and evaluations of a visual condition survey done concurrently with field testing. The 3- to 6-month and the 12-month field data on field testing and visual condition surveys have been gathered for almost all test sections.

Construction Survey Data

A construction survey has been made for each test section. The survey consists of information on the location of each section, condition and type of existing pavement, personnel contacted at the site, type of construction forces, coarse aggregate material and asphalt type used, design application rates of aggregate and asphalt, weather conditions, and traffic volume. In addition, coarse aggregate samples have been obtained from the aggregate piles at the construction sites, and asphalt samples have been taken from the asphalt distributors. Also, photographs of the construction operations and notes on any problems encountered have been documented. The form shown in Fig 5.1 has been utilized for collecting the construction data.

Field Testing Data

Three tests are being performed on the surfaces of test sections for evaluating their frictional properties and texture



CONSTRUCTION SURVEY

TEST SECTION NO.: DATE:
DISTRICT: COUNTY:
CONTACT: TITLE: PHONE:
CONTACT: TITLE: PHONE:
CONTACT: TITLE: PHONE:
LOCATION: Highway No.: CSN: Station No:
MAP: Indicate distances from permanent nearby features (like bridges, etc.) and test section.
Also indicate if steel markers and/or paint markings were used.

CONSTRUCTION DATE: TEMPERATURE: WEATHER:

CONSTRUCTION BY CONTRACT: OR MAINTENANCE FORCES:
CONTRACTOR NAME:
ASPHALT DESIGN DATA: Asphalt Type:
% Binder:
Admixture:
Distribution Rate:
COARSE AGGREGATE: Type:
Producer:
Pit Location:
Spreading Rate:
CLIMATIC REGION: NO. OF FREEZE-THAW CYCLES PER YEAR:
WINTER TEMPERATURE: RAINFALL:
SUMMER TEMPERATURE: RAINFALL:
A.D.T. : % TRUCKS: SPEED LIMIT:
CONDITION AND TYPE OF EXISTING PAVEMENT:

Fig 5.1. Seal coat construction survey form.

depths. These are the skid resistance test and the British pendulum test for measuring friction and the sand patch test for measuring texture. The skid resistance test is being conducted by the Research Division (D-10) of the SDHPT while the other two tests are being performed by the researchers.

The testing is normally done in the center of the left wheel track of a highway test section. Friction and texture measurements are taken only on parts of the surfaces that are free of obvious contamination. For each of the tests considered, five measurements are made at intervals of about 200 feet in each test section with the instrument of each test at the same lateral position in any one test section. The arithmetic average of the five measurements is considered to be the representative friction or texture measure of a test section.

The three tests are being conducted twice a year. According to the findings in Chapter 2, it was first thought that it would be best to conduct the tests after long periods of dryness when the pavement surface is expected to exhibit a minimum frictional resistance and texture depth. Later, it was felt that this would eliminate the chance of detecting and understanding the effects of long-term seasonal variations, caused by long periods of wetness or dryness. Then the decision was made to perform the tests on a random basis, and the season in which the tests are undertaken is being regarded as a variable affecting the obtained measurements and expected to explain the anticipated variations. Yet, properly defining and understanding this weather-caused variable is believed to be a matter of importance, as will be further discussed later in this chapter.

Skid Resistance Test. The test provides a method for characterizing the capability of pavements to contribute to tire-pavement friction under wet conditions. The test is conducted in accordance with the ASTM E274 (8) using the SDHPT research skid trailer. The test apparatus consists of an automotive vehicle with a test wheel forming part of a suitable trailer towed by a vehicle. The test wheel is equipped with a standard pavement test tire according to ASTM E501. The apparatus contains a transducer and instrumentation which feeds into a computer, a water supply and proper dispensing system, and actuation controls for the brake of the test wheel.

The test apparatus is brought to the desired speed, 40 mph for the purpose of this research. Water is delivered to the surface ahead of the test tire and the test wheel brake is applied so as to lock the wheel completely. The magnitude of friction is then measured, and the result is expressed as a FN.

The FN is determined from the resulting friction force acting between the test tire and the pavement surface. It is the force required to slide the locked test tire at the stated speed, divided by the effective wheel load, and multiplied by 100.

Both microtexture and macrotexture contribute to the measured FN. The relative merits of each were discussed in Chapter 2.

British Pendulum Test. This test is performed with a modification to ASTM Designation: E 303, Measuring Surface Frictional Properties Using the British Pendulum Tester. The tester, suited for laboratory as well as field friction measurements, is used in this test in an attempt to obtain field friction values for the seal coat test surfaces equivalent to the laboratory PVs of the specimens from the accelerated polish test.

ASTM describes the tester as "a dynamic pendulum impact type tester used to measure the energy loss when a rubber slider edge is propelled over a test surface." To elaborate, the test surface is freed of loose particles, and sufficient clear water is applied to flush the surface thoroughly. The pendulum slider is positioned to allow a specified length of slider path to make contact with the test surface. The pendulum is raised to a near horizontal position as it is locked, then released to swing freely, allowing the slider to make contact with the test surface. A drag pointer is carried by the pendulum arm to maximum upswing, where it remains in place to indicate the British pendulum number (BPN). Five swings are made with the test surface rewet each time, and the modification to ASTM Standard Method is that only the BPN of the last swing is recorded.

The significance of the test lies in the fact that it describes the microtexture of the surface, i.e., the fine-scaled roughness contributed by individual small asperities on the individual aggregate particles.

Sand Patch Test. The sand patch test is a volumetric method used for determining the average texture depth (ATD) of a selected portion of a pavement surface. The test is being performed according to Test Method Tex-436-A, described in the Manual of Testing Procedures of the SDHPT, D-9 (114).

A known volume of dry natural silica sand is spread over a circular dry area until it is flush with the aggregate peaks of the pavement surface. The area of the formed patch is determined from an average of four or more diameters measured at equally spaced locations. Then, the average texture depth (ATD), calculated as the ratio of the volume to the area, is considered to be a measure of surface texture.

The measured ATD does not adequately assess the degree of roundness or grittiness the individual aggregate particles possess. However, it does represent the large scale texture of the pavement surface caused by the size and shape of the surface aggregate particles.

Visual Condition Survey Data

The visual condition survey is made for the purpose of determining the condition of a test section at the time of field testing. The survey is qualitative in nature in that subjective evaluations are made of those surface distresses whose occurrence would undoubtedly influence the friction and texture measurements. The evaluations are made mainly in the wheel paths of a test section, but more attention is given to the left wheel path, where field testing normally takes place.

Three types of distress have been found to affect the friction and texture measurements of seal coat surfaces. These are poor aggregate retention, inadequate aggregate embedment, and bleeding or flushing of asphalt (122, 138). The form shown in Fig 5.2 is used for gathering data on the extent of these distresses in each test section (122). In addition, slides of each test section are taken to show the surface condition, particularly the distressed areas.

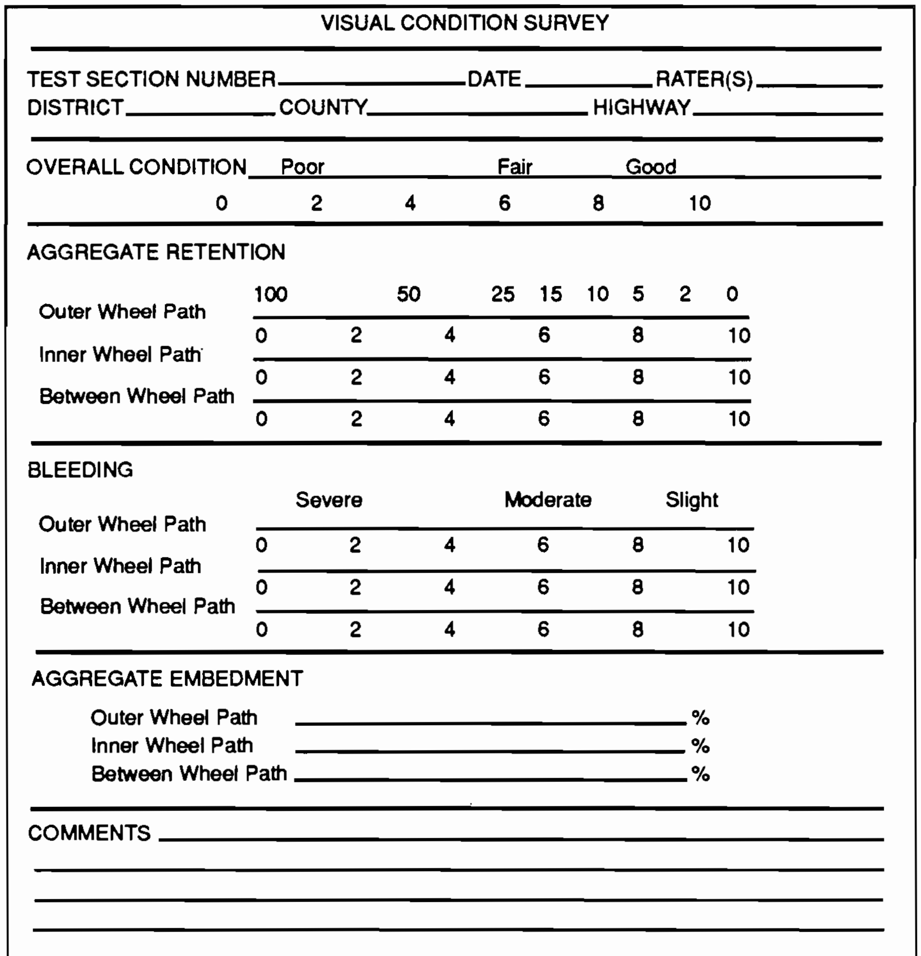
If, at a certain testing time, a distress of the types mentioned is observed to be severe in a test section, the results of field testing would be questionable in that they might not properly represent the frictional properties of the surface aggregate. Only if a test section displays a differential or discontinuous type of distress along a wheel path may field testing still be considered; it may be then carried on parts of the wheel path where the distress seems to be minimal. Otherwise, monitoring of the distressed section would be terminated.

Aggregate Retention. Aggregate retention is measured by the percent loss of aggregate particles from seal coat surfaces. As shown in Fig 5.2, a score of six for aggregate retention refers to aggregate loss in 15 percent of a wheel path area. Factors which may cause poor aggregate retention include unsuitable design rates of spreading asphalt and aggregate, poor construction methods, improper adhesion between the asphalt binder and the aggregate, and inadequate embedment of the aggregate into the asphalt film. Excessive loss of aggregate may result in loss of surface friction.

Aggregate Embedment. Aggregate embedment is determined as a percent of the depth of the aggregate is embedded into the asphalt film. The seal coat design methods, the construction operations, and considerations for climatic conditions and traffic should be aimed at providing proper embedment of aggregate particles throughout the life of a seal coat surface. However, if during the life of seal coats the aggregate particles sink excessively into the asphalt, the surface loses texture and friction and may suffer from bleeding of the asphalt.

Bleeding. Bleeding or flushing is the presence of excess asphalt or a film of asphalt on the pavement surface. The extent of distress for bleeding is defined by three levels of severity, as shown in Fig 5.2: slight, moderate,and severe.

Bleeding of asphalt on seal coat surfaces can be caused by a variety of factors, including bleeding in the old surface of the roadway, improper design value of asphalt spreading



VISUAL CONDITION SURVEY

TEST SECTION NUMBER ____________ DATE __________ RATER(S) __________
DISTRICT __________ COUNTY ______________ HIGHWAY __________

OVERALL CONDITION Poor Fair Good
0 2 4 6 8 10

AGGREGATE RETENTION
100 50 25 15 10 5 2 0
Outer Wheel Path
0 2 4 6 8 10
Inner Wheel Path
0 2 4 6 8 10
Between Wheel Path
0 2 4 6 8 10

BLEEDING
Severe Moderate Slight
Outer Wheel Path
0 2 4 6 8 10
Inner Wheel Path
0 2 4 6 8 10
Between Wheel Path
0 2 4 6 8 10

AGGREGATE EMBEDMENT
Outer Wheel Path ______________ %
Inner Wheel Path ______________ %
Between Wheel Path ______________ %

COMMENTS ______________________

Fig 5.2. Seal coat evaluation form (122).

rate, asphalt too soft for the climate, and poor construction method. Moreover, the bleeding defect is traffic related and occurs in the wheel paths. That is, heavy traffic and/or high traffic volumes can force the asphalt to the surface, especially in hot weather. In any case, bleeding is very detrimental to the surface friction and causes problems when measuring the frictional properties of the surface aggregate is of concern.

LABORATORY DATA

Two types of laboratory data are being collected. The first type, which constitutes the larger portion, is concerned with the physical properties of the aggregates and is obtained from the results of numerous tests performed at the engineering laboratories. The other type deals with aggregate mineralogy and petrographic characteristics and is gathered from examinations done at the geology laboratories.

Data of Aggregate Physical Properties

Four groups of tests were found applicable for measuring the degree of deterioration an aggregate may exhibit when placed in field service. These are:

Group One: testing for basic properties,

Group Two: testing for polish and wear characteristics,

Group Three: testing for resistance to disintegration due to weathering action, and

Group Four: testing for resistance to degradation due to abrasion, impact, and grinding.

In the engineering laboratories, the samples are first reduced to testing sizes, required by each of the tests considered, according to the procedures described in ASTM C702. Next, the asphalt coating of precoated aggregates is extracted according to Test Method Tex-210-F (105). Then, most of the selected tests are performed on all prepared samples in conformity with the Test Methods described in the Manual of Testing Procedures of the SDHPT, D-9. Most of these methods are modifications of Standard Test Methods of the ASTM; some have procedures identical to those prescribed by ASTM. Two of the selected tests, the insoluble residue test and the Aggregate Durability Index, are preformed in accordance with ASTM Standards.

Testing of the non-coated aggregates is almost completed while that of the precoated ones is in progress. The following is a review of the selected tests and their grouping and significances.

Group One: Testing for Basic Properties

a. Sieve Analysis

This procedure is performed in accordance with Test Method Tex-401-A (106). it is used for the determination of the particle distribution, gradation, of the obtained aggregate samples. The gradation of an aggregate is a primary factor in the forming of the texture of a seal coat surface and thus affects surface friction.

b. Specific Gravity and Absorption Test

The test is performed according to Test Method Tex-403-A (107) to determine the saturated surface-dry specific gravity and water absorption of natural aggregates and according to Test Method Tex-433-A (113) to determine the dry bulk specific gravity and absorption of lightweight aggregates. The specific gravity and absorption give an indication of the porosity of an aggregate. Both characteristics are viewed as important factors influencing aggregate frictional properties.

c. Decantation Test

This test is performed in conformity with Test Method Tex-406-A (108). During the test, the amount of material finer than the No. 200 sieve is removed from an aggregate by washing and the percentage by weight is calculated. The removed materials include water-soluble materials as well as aggregate particles and silt and clay particles that can be dispersed by water.

The amount of material removed may be related to the relative stability of aggregate particles in seal coat surfaces (adhesion between aggregate particles and asphalt) and to the amount of asphalt needed to assure a desired stability. This measure along with some of the construction variables may explain some of the problems pertaining to surface texture, particularly to dislodgement or loss of aggregates from seal coat surfaces.

Group Two: Testing for Polish and Wear Characteristics

a. Accelerated Polish Test

Test Method Tex-438-A (115) for the accelerated polish test is employed; it provides an estimate of the extent to which coarse aggregates in the wearing surface of the roadway are likely to polish when subjected to traffic. The aggregate samples are prepared to required size and placed in metal molds. A polyester resin and a catalyst are used to bond the aggregate particles together in the mold. Seven specimens are made for each aggregate type. The specimens are then mounted around the periphery of a specimen wheel and subjected to accelerated polish by the rolling action of a rubber tire in the presence of water and abrasive grit used to accelerate the rate of wear. The state of polish reached by each sample after nine hours of accelerated polish is expressed as the PV, and it is measured by the BPT. The PV is calculated as the average of the seven specimens.

The PVs of aggregates could be a helpful tool in predicting the frictional characteristics of aggregates if placed in field service. The idea is based on the concept that the limiting PV of an aggregate, which occurs after nine hours of polishing, may match or correlate well with the terminal frictional resistance of a roadway after exposure to a certain traffic volume.

b. Insoluble Residue Test for Carbonate Aggregates

This test is conducted in accordance with ASTM D-3042 (6). It provides an estimate of the amount of non-carbonate (insoluble) material in carbonate aggregate and involves a grain size distribution of these insoluble particles. This is done by chemically separating the non-carbonate minerals from the carbonate particles. The procedure is based on the chemical reaction that occurs when dilute hydrochloric acid is allowed to react with the carbonate portion of the aggregate. The leaching process dissolves the carbonate fraction, leaving the non-carbonate fraction in the form of a residue, which must not be destroyed or altered in any manner. Then the grain size distribution of the residue is analyzed and the plus No. 200 sieve fraction (sand-sized fraction) determined. This sand-sized fraction is believed to be a major factor affecting the polish susceptibility of a carbonate aggregate (118).

The aim of the test is to establish a relationship between the friction properties exhibited by a carbonate aggregate and the physical characteristics measured by this test. The theory is based on the concept that the frictional resistance of carbonate aggregates is related to the differential hardness of the minerals that comprise the structure of the aggregate (118). According to this concept, when a carbonate aggregate is subjected to polish, the softer minerals will wear away at a faster rate than the harder ones, and there will be some attrition in the aggregate caused by loss of the softer minerals. The result will leave the wearing surface of the aggregate with a rough, uneven texture, which increases or maintains the friction properties of the carbonate aggregate.

c. Crushed Particles in Gravel Aggregates

This test is performed in accordance with Test Method Tex-413-A (111) and is used to determine the percentage by weight of crushed particles in aggregates. This characteristic is of interest because the asperities of the texture of crushed particles as opposed to the smooth texture of non-crushed particles are very important features of an aggregate's polish susceptibility.

Group Three: Testing for Resistance to Disintegration Due to Weathering Action.

a. Four-Cycle Magnesium Sulfate Soundness Test

In this test, the aggregates are examined according to Test Method Tex-411-A (110) to estimate their soundness when subjected to weathering action. In each of the four cycles of this test, the aggregate samples are immersed in saturated solutions of magnesium sulfate followed by oven drying to partially or completely dehydrate the salt precipitated in permeable pore spaces. The dehydration of salt upon re-immersion causes internal expansive forces which simulate the expansion of water on freezing. When water repeatedly freezes in the pore spaces of an aggregate in field service, the expansive forces created cause the aggregate particles to disintegrate, resulting in increased deterioration in surface texture and decreased frictional resistance.

b. Coarse Aggregate Freeze-Thaw Test

This test is performed in accordance with Test Method Tex-432-A (112) which was developed for testing synthetic coarse aggregates. As in the MSS test, the aggregates are tested to judge their soundness when subjected to weathering action. This is accomplished by subjecting the aggregates to 50 cycles of freezing and thawing in the presence of water. The internal expansive forces created by repeated freezing of water in the pore spaces cause the aggregate to disintegrate. This action is supposed to simulate what happens to the aggregates placed in the environmental regions characterized by freeze-thaw cycling.

The soundness and freeze-thaw losses are believed to be indicative of the strength and hardness of the cementing material that holds the crystal grains of aggregate particles together.

Group Four: Testing for Resistance to Degradation Due to Abrasion, Impact, and Grinding.

a. Los Angeles Abrasion Test

The Los Angeles abrasion test provides a measure of degradation resulting from a combination of actions, including abrasion or attrition, impact, and grinding. This is done, in accordance with Test Method Tex-410-A, by placing the aggregate in a rotating steel drum containing a specified number of steel spheres, the number depending upon the gradation of the test sample. As the drum rotates, the sample and the steel spheres are picked up by a shelf plate and carried around until they are dropped to the other side of the drum, creating an impact-crushing effect. The contents then roll within the drum with abrading and grinding actions until the shelf plate impacts and the cycle is repeated. After the prescribed number of revolutions, the aggregate is removed and then sieved to measure the degradation as percent loss.

b. Aggregate Durability Index

This test is performed in compliance with ASTM D-3744 (7). The test establishes an empirical value, the durability index, indicative of the relative resistance of an aggregate to generating detrimental clay-like fines when subjected to mechanical degradation in the presence of water. The coarse aggregate test sample is agitated in a mechanical washing vessel for a period of 10 minutes. The resulting wash water and minus No. 200 size fines are collected and mixed with a stock calcium chloride solution and placed in a plastic cylinder. After a 20-minute sedimentation time, the height of the sediment is read and then used to calculate the durability index of the aggregate.

c. Aggregate Degradation Test

This test was developed as a part of Research Project 3-9-85-438 (89). It is intended for determining the resistance of aggregates to degradation in HMAC and seal coat surfaces. The test includes information from Test Methods Tex-116-E, ASTM C-132, ASTM D-3744, and California Test 229 and research reports "Modification of the Standard Los Angeles Abrasion Test" (HRB), and "Concrete Aggregate Durability Tests" (California Department of Transportation).

The procedure is to subject an aggregate to mechanical degradation by agitation in the wet ball mill apparatus in the presence of water. Two measures are then assigned to the aggregate: the durability index and the percent loss of minus No. 16 material. The durability index is based on the height of the sediment of the clay-sized fines generated by the agitating action. The percent loss of minus No. 16 represents the percent loss by weight in aggregate created by the resulting interparticle impact, abrading, and grinding actions.

The mechanical degradation an aggregate is subjected to in this group of tests is expected to simulate (1) the impact action of axle loads on aggregate particles in the wearing surface of a roadway and (2) the abrasive and grinding actions created between the rubber tires and aggregate particles in the presence of fines and grits accumulated on the roadway surface.

Data of Aggregate Mineralogy and Petrographic Examinations

A preliminary investigation has been made to determine the feasibility of performing petrographic analyses on the obtained aggregate samples. A complete examination was done of one aggregate, and a methodology for testing was developed. For each major aggregate category, two of the aggregate sources used will be selected and petrographically examined in the first phase of this analysis. The results of this phase will be evaluated, and a decision will then be made in light of the evaluation's outcomes as to whether the analysis should proceed, to include all aggregate sources used in the test sections. The following are discussions on the purposes, preliminary procedures, and significance of this analysis.

Purposes. The petrographic examinations are intended to provide information helpful in judging the mineralogical and the petrographic characteristics of an aggregate as related to the aggregate's frictional resistance. Specifically, the petrographic examinations are made for the following purposes:

(1) to determine the physical properties of an aggregate that may be observed by petrographic methods and that have a bearing on the performance of the aggregate in seal coat surfaces,
(2) to identify, describe, and classify the constituents of the aggregate sample, and
(3) to determine the relative amounts of the constituents of the samples when the constituents differ significantly in a property, such as hardness, that may be expected to influence the frictional behavior of the aggregate when used in pavement surfaces.

Summary of Procedure. The aggregate samples are sieved in accordance with Test Method Tex-401-A (106) in order to get samples of each sieve fraction. The results of sieve analysis of each sample are provided to the petrographer making the examinations and used afterwards in calculating the results of the petrographic examination. At least 300 particles of each sieve size are provided to the petrographer, according to ASTM C-295 (136), in order to obtain reliable results. The particles are first washed and the water dried from the surfaces. Then, each sieve fraction is examined separately, starting with the largest size available, where minerals are more easily recognized. If a fraction apparently consists of more than one rock type or color, representative particles are obtained and thin sections prepared for each of the variations recognized.

A systematic petrographic examination of each prepared thin section is made under a polarizing microscope equipped with a point counter to determine the percentages of mineral constituents. Then the compositional proportion of each sieve fraction of a heterogeneous sample and the weighted average mineral composition of the whole sample are calculated.

The microscopical examination also reveals information on the size and shape of crystal grains, the ground mass formation, and the grain distribution of different minerals. This information is supported by photomicrographs taken for later comparison among the aggregates.

In addition, other relevant features of the aggregate are described during the examination. These include particle surface texture and particle shape. Particle surface texture is assessed using a binocular microscope to determine the degree of roundness of grittiness the aggregate particles possess. Particle shape is evaluated by roundness and sphericity of particles. Roundness is concerned with the curvature of the corners of a particle, and six classes, from very angular to well rounded, are distinguished. Sphericity is a measure of how closely the particle shape approaches that of a sphere.

After all different aggregates have been examined and mineral types determined, a hardness scale is developed which constitutes all major minerals found and their hardnesses based on Mohs scale of hardness. Then, the calculated compositional proportion of the whole sample and the developed hardness scale are used to determine the approximate percentage of hard mineral content (e. g., mineral harder than 5 on Mohs scale) in each of the aggregates under examination. These percentages are the basis of comparison between aggregate performance and mineralogy.

Significance of Findings. The results can be used in many different ways. First, by correlating or regressing the percentages of hard mineral content with the respective FNs of the aggregates, a conclusion might be reached as to whether or not a relationship between the two exists. Another possible finding could be the determination of what the optimum compositional proportion of hard to soft minerals should be for an aggregate to have highly favorable skid resistance. Aggregates having mixed composition of hard and soft minerals are expected to have higher skid resistance than do aggregates consisting predominantly of minerals of the same type or having the same hardness (23, 116). The concept is that the soft ground mass wears away relatively fast, exposing the hard grains to provide a sandpaper-like surface. Before the asperities of these hard grains have a sufficient wearing action to cause them to polish, the matrix has been worn down to where it can no longer hold the hard particles, allowing them to be dislodged to expose fresh, unpolished particles. This continuous renewal of the pavement surface is believed to give highly favorable skid resistance properties. However, it should be noted that the influence of the compositional proportion might be modified by the effects of other features, such as size, shape, and distribution of the hard grains.

Second, the photomicrographs of two aggregates grouped in the same classification (e.g. sandstone) and with approximately the same percentages of hard mineral may reveal markedly different grain sizes. The more angular and the larger are the mineral grains or crystals in individual aggregate particles, the higher is the expected skid resistance of aggregate particles when incorporated in pavement surfaces. Also, the coarser and the more angular are the hard mineral grains, and the more uniform is their distribution in the softer mineral matrix, the higher is the expected skid resistance.

Finally, the results of particle surface texture and particle shape may turn out to be valuable indications of micro-texture and macro-texture of the surfaces where aggregates were placed.

WEATHER DATA

There are many recording weather stations in the State of Texas for which climatological data are published. The primary components of the climatic description furnished by the majority of these stations include precipitation, snowfall, snow on ground, temperature, evaporation, and wind. Eighteen major stations, which are basically located in the large cities, provide more detailed meteorological data.

Climatological data are published by the National Oceanic and Atmospheric Administration and are accessible to the researchers through the Texas Water Development Board (TWDB). Annual averages of the climatic components are being obtained for each test section from the publications of the nearest recording weather station. Detailed climatological data for the periods prior to and during field testing are also sought. Specifically, the data are concerned with the length of the last rainfall period, the number of days between the last rainfall that occurred in that period and the day of field testing, and the total inches that fell in that period. This information is to serve as the basis for understanding the effects of short-term weather variations, caused mainly by localized showers, on the frictional properties of roadway surfaces.

It was stated earlier in this chapter that the season, dry or wet, in which field testing is undertaken is regarded as a variable affecting the obtained field measurements, and that may account for long-term seasonal variations in pavement surface frictional properties caused by long periods of dryness or wetness. For the purpose of properly defining this weather-caused variable, detailed information on climatic, precipitation related patterns in the State of Texas was searched for (78). The state was found to have ten climatic subdivisions formed by blocks of counties having similar rainfall amounts (16). The climatic subdivisions are East Texas (ET), Upper Coast (UC), South Central (SC), North Central (NC), Southern Division (SD), Lower Valley (LV), Edwards Plateau (EP), Low Rolling Plains (LR), High Plains (HP), and Trans-Pecos (TP). These can further be grouped to form three climatic regions having common seasonal rainfall characteristic: summer maximum, summer drought, and May and September maximum. The climatic subdivisions, the climatic regions, and the rainfall characteristics associated with each region are shown in Fig 5.3.

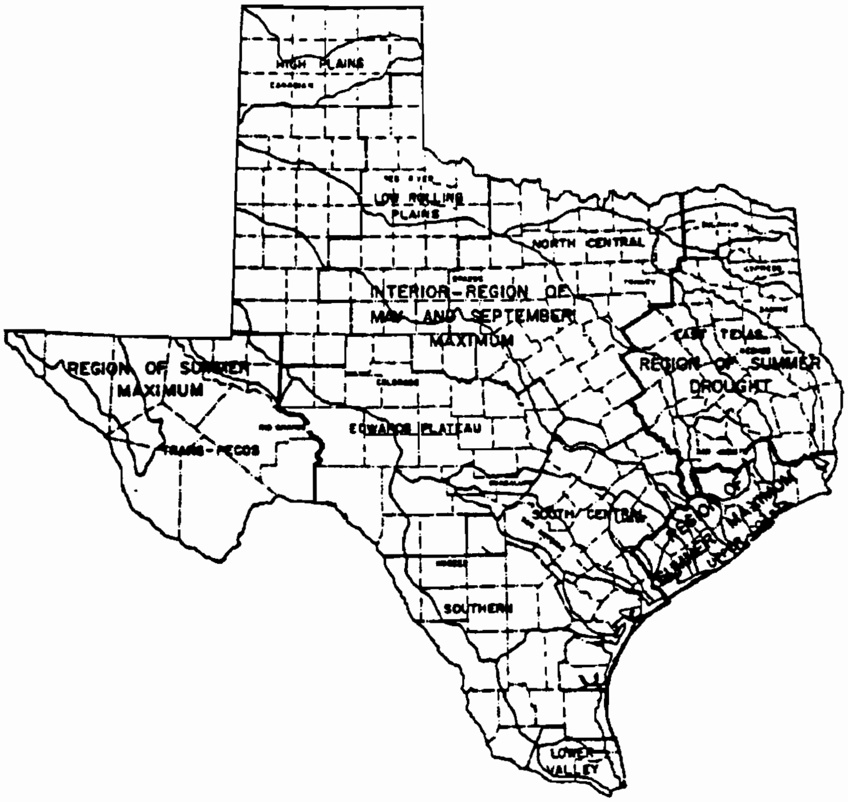


Fig 5.3. The ten climatic divisions (blocks of counties having similar rainfall amounts) and the three climatic regions (blocks of climatic divisions having common seasonal rainfall characteristics—summer maximum, summer drought, and May and September maximum) in Texas (16).

Monthly precipitation data based on the averages for the 30-year period 1951 to 1980 were obtained from the TWDB; use of the 30-year data, as currently computed by the U.S. Weather Bureau, was suggested to be a more realistic approach than use of long-time averages when describing the climate of an area. The data were manipulated and Fig 5.4 generated. Each curve in the figure represents a climatic subdivision of Texas. It seems that most of the curves agree with the rainfall patterns of their respective climatic regions, shown in Fig 5.3. Exceptions are made for the ET curve because of the unusually, relatively high precipitation that occurred in September; for the HP curve, owing to the unsupposedly decreased precipitation which happened in September; and, to some extent, for the UC curve due to the relative decrease in the precipitation trend which occurred in the months of July and August as compared with that of the TP curve. The figure also shows the 30-year average annual precipitation amounts for each subdivision.

Based on these observations, the following will be warranted. First, the HP subdivision will be considered to have manifested a rainfall pattern somewhat similar to that of the TC subdivision. It will thus be grouped with the TC and UC subdivisions in the region of summer maximum as far as the determination of wet and dry periods is concerned. Next, tentative segmentation of a year into wet and dry seasons will be as follows:

(1) For the UC, TP, and HP subdivisions, from the beginning of May until the end of October is wet, while from the beginning of November until the end of April is dry.

(2) For the ET region, from the middle of March until the end of June and from the beginning of September until the middle of December are wet, whereas from the beginning of July until the end of August and from the middle of December until the middle of March are dry.

(3) For the Interior-Region excluding the HP Subdivision, from the middle of March to the middle of June and from the middle of August until the end of October are wet, while from the middle of June until the middle of August and from the beginning of November until the middle of March are dry.

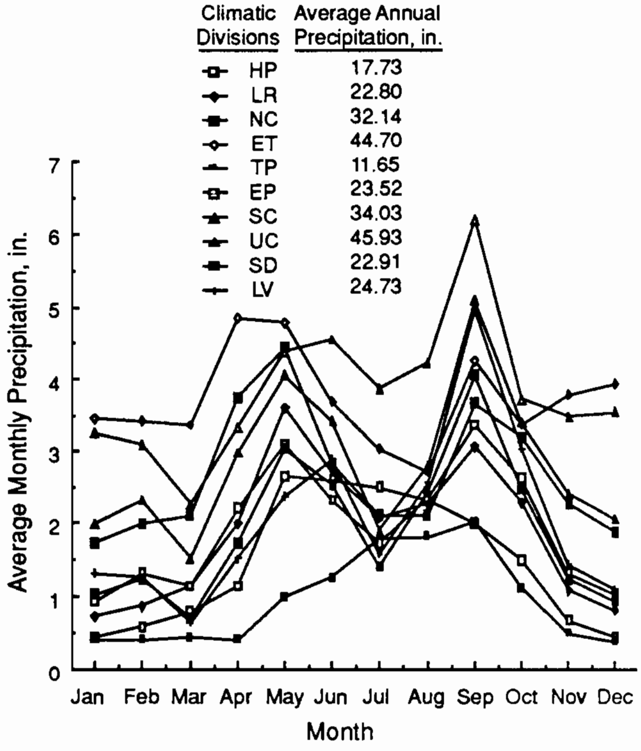


Fig 5.4. Average monthly precipitation (1951-1980).

Finally, it should be noted that the climatic regions described in this section are not to be confused with the four environmental regions discussed in Chapter 4 which are based on precipitation and temperature freeze-thaw cycling. In fact, it is worthwhile to mention that the 30-year average annual precipitation amounts, shown in Fig 5.3, do justify how the state was divided vertically into dry and wet zones as shown in Fig 4.2. That is, the ET and UC subdivisions have average annual precipitation amounts of 44.7 inches and 45.93 inches respectively, which by far exceed those of all adjacent subdivisions. Moreover, the western borders of these subdivision in Fig 5.3 almost coincide with the vertical dividing line in Fig 4.2.

CHAPTER 6. ANALYSIS OF DATA

DATA BASE AND STATISTICAL METHODS

All data will be stored and manipulated in the database being created on the IBM-PC AT using the Statistical Analysis System (SAS) program. In-depth statistical analysis will be performed on the data to formulate multivariable probabilistic models for predicting the frictional resistance or performance of seal coat surfaces. The literature review in Chapter 2 revealed that, under the effects of the long-term seasonal changes, the magnitude of which depends on traffic volume and aggregate type, the curves of frictional performance in numerous studies showed no consistent upward or downward trends for the annual minimum trends after about two years of exposure to traffic. Accordingly, a preliminary analysis may be performed on the data after the two-year friction measurements are obtained. The analysis will basically involve analysis of covariance (ANCOVA), which combines the analysis of variance (ANOVA) and regression analysis, and multivariable regression analysis.

VARIABLES INVOLVED

There are two types of variables involved, dependent and independent. While the dependent variables are all quantitative, the independent variables that contribute information for the prediction of the dependent variables are of two types: quantitative and qualitative. The former, as the name implies, are those familiar variables that can be measured. Qualitative variables cannot be measured; they can only be described and thus assume few discrete values. As will be seen subsequently, the way an independent variable is entered into a prediction equation depends on its type.

Dependent Variables

The friction and texture measurements or performance responses of test sections are the dependent variables - criterion variables. Performance is measured by FN, BPN, and ATD, all of which are quantitative dependent variables. These responses will be dealt with, one at a time, to evaluate the portion of their variations that can be explained by the independent variables. All of the performance measurements obtained for each test section and their associated accumulative traffic volumes will be used when an analysis is performed. This will be done in order to better estimate the effect of traffic on the changes in friction and texture with time.

Independent Variables

A wide range of factors affecting frictional resistance of seal coats has been identified for inclusion in the analysis. These factors are viewed as independent variables which will be used to test the predictability of pavement friction. These are as follows.

Traffic and Age. Traffic is a quantitative variable represented by the ADT passing over each test section. Age is also a quantitative variable which reflects accumulation of traffic from the day of construction until day of field testing.

Construction Variables. Qualitative construction variables include type, grade, and coating of aggregate; type, percent binder, and admixture of asphalt; and construction forces (construction by contract versus maintenance forces). The distribution rate of asphalt and the spreading rate of aggregate are quantitative variables.

Laboratory Variables. Laboratory tests and petrographic examinations give relative measures of the extent to which aggregates will degradate, disintegrate, wear, and polish under the exposure to traffic. Accordingly, they are thought to have a considerable influence on the significance of the prediction models being investigated.

All laboratory tests are quantitative in nature, while the majority of the petrographic variables are descriptive and thus subjectively evaluated. The percentage of mineral composition of a sample aggregate and the percentage of hard mineral constituent are quantitative variables, whereas the size and shape of crystal grains, distribution of hard minerals, and particle shape and surface texture are qualitative variables.

Weather Variables. Climate is a qualitative variable which may assume only four discrete values- four climate regions. The climatological effect will be investigated using both the ANCOVA and the multivariable regression analysis, with the ANCOVA believed to give a better estimation of the significance of the variable. The season of the year during which field testing is performed is also a qualitative variable that can be described as a wet or dry season. On the contrary, the length of the last rainfall period, the number of days between the last rainfall that occurred in that period and the day of field testing, and the total inches that fell in that period are all quantitative variables.

STATISTICAL ANALYSIS

Assumptions

There are certain assumptions that should be approximately satisfied before the ANCOVA and multivariable regression analysis techniques can be used. These assumptions are as follows (5, 51, 95):

1. The response y can be represented by the probabilistic model

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \_\_\_\_\_ + \varepsilon$$

in which no exact linear relationship exists between two or more of the independent variables (for multivariable regression).

2. For each value of a predictor variable, there is a normally probabilistic distribution of independent values of the criterion variable y. From each of these y distributions one or more values are sampled at random.

3. The variances of the response y for various experimental conditions are equivalent, a condition referred to as homoscedasticity or homogeneity of variances.

4. The error term (ε) possesses a normal probability distribution, has an expected value of zero, and is random (does not exhibit any systematic trends).

The normality and homoscedasticity assumptions will be tested using the five readings obtained for each response and the established replications, respectively. It may happen that one of these assumptions is not satisfied. For example, the response variances may not be homogeneous. This situation can be sometimes remedied by transforming the response measurements (5, 74, 119). That is, instead of using the original response measurements, their square roots, logarithms, or some other function of the response might be used. Similarly, transformation will be done if the normality assumption of the response measurements is not satisfied. In fact, transformations that tend to stabilize the variance of a response have been found to make the probability distribution of the transformed response more nearly normal (82).

Analysis of Covariance

Design of the Experiment for the Environmental Effect. The design of this experiment is aimed towards better understanding of the effect of environment on the frictional resistance of seal coat surfaces. In this experiment, the field responses- FN, BPN, and ATD- are the criterion or dependent variables, while climate and aggregate type are the main predictors considered. Climate is a fixed qualitative independent variable which has four levels, with "fixed" meaning that all levels of interest to the investigators- climatic regions I, II, IV, and V- are included in the experiment. Aggregate type is a random qualitative independent variable which assumes six levels or categories, with "random" meaning that fewer than the population of levels of this variable are to be examined in this experiment and those levels are selected at random from all possible levels of interest to the investigators. Some of the selected levels are aggregates of the same type but from different sources grouped together in terms of their historical laboratory characteristics, as discussed in Chapter 4. The aggregate variable is included in the design of this experiment primarily to investigate whether there is interaction between aggregate type and region; interaction is referred to as being something unique about the combination of a certain climatic region with a certain aggregate category.

The layout of the design of this experiment is shown in Table 6.1. The number of sections built in each region with each of the aggregate categories considered is shown inside the cells. Actually, these numbers mean the numbers of observations obtained for each of the criterion variables, with each observation being a set of five readings. The superscripts indicate the type of replication built for some of the aggregates; the superscript "a" is for traffic count and/or construction replications, "b" for time or pit replications, and "c" for those replications which comply with both "a" and "b."

One may notice that there are cells in the table that are still to be filled. Several districts have been requested to help establish additional test sections so that the design will be complete. However, it may happen for some reason that test sections for some of these cells cannot be established. In such a situation, some of the observations will be missing, and the designed experiment will no longer be balanced and will loose its symmetry. Moreover, if enough observations are missing, not all of the usual parametric functions will be estimated. Dodge (30) has suggested three approaches to this problem that might be employed by the researchers if such a problem is encountered.

Formulation of Model. In addition to the two predictors, climate and aggregate type, considered in the design of the experiment, there are several uncontrolled independent variables, qualitative or quantitative, that may contribute to the prediction of the criterion variables and therefore should be considered in the analysis. These variables, often referred to as covariables, include ADT, age, and perhaps some of the weather and construction variables.

A methodology that takes into account the relationships among the covariables, predictors, and criterion variables is referred to as analysis of covariance, often abbreviated ANCOVA. The model generated by applying the ANCOVA technique has the following form:

$$\begin{aligned} Y = {} & AGE + ADT + WTV + CSV + CLR + AGT \\ & + CLR*AGT + R(CLR\ AGT) \end{aligned}$$

where

1. The criterion variable Y could be any of

$$Y_1 = \text{FN (Friction Number)},$$

TABLE 6.1. DESIGN OF THE EXPERIMENT FOR THE ENVIRONMENTAL EFFECT

Aggregate Material	PV	Climatic Zones I	II	III	IV
Limestone	< 30	1^b	-	1^b	1
	> 33	-	2^a	-	2^b
Sandstone	~ 40	-	4^a	-	-
Siliceous Gravel	< 30	1	-	-	1
Limestone Rock Asphalt		4^c	2^c	3^c	-
Lightweight		5^c	-	-	-

[a] Traffic count and/or construction replication(s)
[b] Time or pit replication(s)
[c] Replications that comply with both "a" and "b"

Y_2 = BPN (British Pendulum Number), or
Y_3 = ATD (Average Texture Depth)

2. The predictors are

CLR = climatic regions, and
AGT = aggregate type

3. CLR * AGT is the interaction term between climatic regions and aggregate type
4. R(CLR AGT) is a term used to account for the fact that replications exist for some aggregates within regions
5. The covariables are

AGE = age of section
ADT = average daily traffic
WTV = weather variables, and
CSV = construction variables

The F-test is used to test the statistical significance of the whole model as well as that of each individual term of the right-hand-side terms. Of course, 'CLR' is of prime concern. If this term is found to be statistically significant, climate will have been found to have an effect on the frictional resistance of the aggregates examined in this experiment; if not, climate may still be investigated in the multivariable regression analysis. In any case, making generalized conclusions on the significance or insignificance of the environmental effect will be avoided, and caution will be taken if such conclusions are ever to be made. This is because the method of aggregate selection made the randomness of the variable questionable. The same is valid for the interaction term CLR*AGT; the interaction term may be found to be significant even though none of the interacting variables is significant.

Regression Analysis

Formulation of Prediction Model. In general, this analysis is intended to find the best general linear regression model of the type

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \_\_\_\_ + b_k x_k + \varepsilon$$

to describe the relationship between the frictional performance of seal coat surfaces (y) and all of the independent variables involved ($x_1, x_2, \_\_\_ x_k$). Since an explanation of causal effects of each individual independent variable is the primary thrust of this investigation, the stepwise regression procedure, an available option in the SAS program, is used for building the prediction model. The stepwise regression procedure is a selection and an elimination algorithm which allows for a two-stage review of variables at each step of the analysis. That is, at the first step, a simple linear model is formed by regressing the frictional performance against the variable with which it is most correlated. Then, the explanatory ability of each remaining variable is examined (through its partial F statistic), and a new model is formed by adding the variables that possess the greatest marginal explanatory ability. In addition to the selection of a new variable to enter into the model, there is a reexamination of all variables previously entered. If the partial F test value of any variable within the model is found to be insignificant, the associated variable is removed from the analysis. This procedure is continued until the point where all remaining variables are judged to be insignificant in their ability to contribute information for the prediction of the frictional performance, that is, where all partial F statistics for variables not yet entered into the model are small.

Qualitative independent variables, such as types and grades of aggregates, will be entered into the model by using dummy variables, the number of dummy variables always being one less than the number of levels (categories) associated with the independent variable. For example, if the frictional performance depends on the variable "type of aggregate", and if, for simplicity, there are only three types, limestone, sandstone, and lightweight, the first few terms of the model will be

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \_\_\_\_ + \{\text{terms associated with other}\} + \varepsilon \text{ prediction variables}$$

where

x_1 = 1 if the response is for a "sandstone aggregate" or $x_1 = 0$ if not and
x_2 = 1 if the response is for a "lightweight aggregate" or $x_2 = 0$ if not

Thus, when a friction measurement is taken for a "limestone aggregate", x_1 and x_2 will assume zero values. If type of aggregate is found to be a significant variable, a prediction model may then be obtained for each aggregate category or type.

The Problem of Multicollinearity. Multicollinearity is a problem that arises when two or more of the independent variables are found to be highly correlated with each other. When such a problem is encountered, the respective individual contribution of the correlated variables to the reduction in the error sum of squares cannot be determined. Therefore, the contribution of information by a particular independent variable to the prediction of y depends on the other independent variables included in the model. If two variables contribute overlapping information, the first β parameter may be overestimated while β_2 tends to be underestimated (82). In fact, multicollinearity may even cause the algebraic sign of one or more regression parameter estimates to be contrary to logic. Thus, if a multicollinearity problem is faced, the explanation of the causal effects of individual variables on the frictional performance will be undertaken with great caution.

To tell whether multicollinearity is causing problems, the standard errors of the coefficients are examined. If several coefficients have high standard errors and dropping one or more variables from the equation lowers the standard errors of the remaining variables, multicollinearity will usually be the source of the problem (95).

Two approaches to dealing with multicollinearity are applicable to the data being collected (81, 98). The first approach is to drop one of the two correlated variables from the equation and to reestimate it. This can cause bias in the reestimated model, but it may be justified if the bias can be argued to be small. The second approach is to combine the two variables into an index variable by standardizing their effects. The variables should be conceptually and theoretically related for this approach to be used.

Measuring the Goodness of Fit of the Model. The term R^2, the multiple coefficient of correlation, provides a measure of the fit of the multivariable regression model (82). That is, R^2 gives the proportion of the total sum of squares that is explained by the predictor variables. The remainder is explained by the omission of important information-contributing variables from the model, an incorrect formulation of the model, and experimental error. R^2 takes values in the interval

$$0 \leq R^2 \leq 1$$

A small value of R^2 means that the predictor variables contribute very little information for the prediction of frictional performance; a value of R^2 near 1 means that the predictor variables provide almost all the information necessary for the prediction of frictional performance.

A relatively poor fit of the model (a small R^2) may result if the predictor variables are not entered properly into the model (perhaps interaction terms x_1x_2, x_1x_3, x_2x_3, etc. and quadratic terms x_1^2, x_2^2, x_3^2, etc. should be included), or perhaps frictional performance is a function of many other variables besides the ones already considered. Interaction terms are considered in the analysis to evaluate their ability to contribute information for the prediction of frictional performance, and residual analysis is performed to identify new variables that may improve the fit of the model.

Residual Analysis. Residual analysis, a capability of the SAS program, examines the degree to which the model satisfies the random error assumption of multivariable regression analysis and thereby suggests the inclusion of additional variables that may improve the fit of the model (82, 95). The analysis involves plotting the residuals against each independent variable. There might be a case where a residual plot suggests the inclusion of a second-order term, say x_2^2, into the analysis as an additional independent variable. Another plot might depict a case where the variance in the response (frictional performance) increases proportionally to the independent variable x_3. Usually the addition of the variable $\mathrm{Log}(x_3)$ will accommodate this problem (5).

Investigation of Other Relationships. Regression analysis is used to investigate the relationships that may exist among the field responses, FN, BPN, and ATD, in order to determine how microtexture and macrotexture, reflected by BPN and ATD respectively, influence the traditional friction measure, FN. Also, a friction curve for each aggregate source is developed which shows how friction decreases with accumulation of traffic. The curves are generated by regressing friction against accumulative traffic and weather-related variables.

USE AND SIGNIFICANCE OF FINDINGS

The prediction model will be of value in three ways:

(1) It can be used to estimate the mean value of frictional performance for given values of the predictor variables.

(2) It can be used to predict some future value of frictional performance for given values of the predictor variables.

(3) If the predictor model provides a good fit to the set of data (if R^2 is large) and the number of predictor variables is not too large, the model will help the engineer or researcher understand the relationship between the predicted value of frictional performance and the set of predictor variables. For example, if two predictor variables, say PV and MSS loss, are found to be interacting, the model will show how the relationship between frictional performance and PV is dependent on the soundness loss.

Estimates of the mean value or predictions of specific values of frictional performance (to be observed in the future) for given values of the predictor variables can be obtained by substituting values of the predictor variables into the prediction model. A confidence interval for the mean value and a prediction interval for the specific value of frictional performance can then be constructed. For the same confidence level and the same values of predictor variables, the prediction interval for the specific value is wider than the confidence interval for the mean value. This is a reflection of the fact that the variance of the error of predicting a particular value of frictional performance exceeds the variance of the error of estimating the mean value (82).

The significance of the model lies in the fact that it will provide a method for nominating at the planning or design phase of seal coat projects the physical properties and petrographic characteristics of the aggregate as well as the design values of the construction variables required to provide or maintain a given acceptable frictional resistance under a certain projected traffic volume in a specific climatic region. In addition, the findings will likely have an immediate impact on specifications relating to aggregate laboratory pre-conditioning methods for the benefit of frictional resistance.

A friction curve will provide an idea of how the frictional resistance of a particular aggregate source may decrease with time. Therefore, the curves may be used to predict the frictional resistance of that aggregate at any particular time or level of accumulative traffic. However, great caution should be taken with the future use of such curves because, if the quality of an aggregate pit is known to have been varying with time, the frictional resistance predicted using the friction curve may underestimate or overestimate the future frictional performance of the aggregate.

CHAPTER 7. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

SUMMARY

This study was initiated with the overall objective to investigate and develop criteria which will provide and maintain adequate pavement friction. In this phase of the study, the prediction of the frictional resistance of seal coat surfaces was investigated. The investigation included the following:

(1) Gathering and assimilating the pertinent literature available on the subject.
(2) Conducting surveys in nine selected districts in Texas.
(3) Establishing fifty-two seal coat test sections in nine districts of the four environmental regions of Texas with various aggregate types and sources and under various traffic volumes.
(4) Performing laboratory and petrographic tests on the collected aggregate samples and field tests on the established test sections.
(5) Collecting climatological data on the conditions at time of construction and time of field testing.
(6) Designing the layout of the analysis to be performed on the data.

CONCLUSIONS

The following conclusions can be drawn at this stage of the study:

(1) It was found that, in Texas, the PV test is the most widely used method for evaluating the polish susceptibility of coarse aggregates used in pavements. The MSS test was found to be used along with the PV test in the majority of the surveyed districts.

(2) The soundness of the aggregates was found to be an important characteristic affecting the frictional resistance of highway surfaces. The findings of the survey of Texas districts and the analysis of friction data obtained for HMAC surfaces indicated that aggregates that had high PVs but were inadequate in soundness did not have good frictional performance.

(3) It was repeatedly reported in the literature that the petrographic tests may prove to be very useful in selection of aggregates if such tests or combination of test results can be correlated with field performance.

(4) It was found that long-term and short-term seasonal changes are a major cause of variation in the frictional resistance of highway surfaces. In addition, it was found in numerous studies that the rejuvenating effects of wet-periods tended to offset the polishing effects of dry periods in that the curves of frictional performance showed no consistent upward or downward trends for the annual minimum levels after about only two years of exposure to traffic. The magnitude of variation was found to be strongly associated with traffic volume and type of aggregate. Pennsylvania State University has developed models that treat these seasonal variations, but is has been suggested that the models be used only in the geographical area within which the investigation was conducted.

(5) There has as yet not been found any reliable relationship that can predict with confidence the field frictional resistance from aggregate properties. This is largely attributable to the fact that there has not been an attempt in any study to relate field friction with microtexture and macrotexture laboratory properties. It was repeatedly mentioned in the literature that the inclusion of a field-measured macrotexture variable in predicting models would not serve any purpose in design (the current art of construction methods cannot assure a predesigned macrotexture). Another reason for the lack of reliable friction predicting models is that the effects of seasonal variations have never been corrected.

(6) Concerning the approach used in this study to formulate prediction models of seal coat frictional resistance, it is believed that the consideration of all relevant laboratory and petrographic tests in determining the aggregate properties hypothesized to have an influence on the frictional performance would answer many of the questions as to which tests (or properties) have to be used in the evaluation of an aggregate.

(7) Recognizing the undisputed effect of macrotexture on frictional resistance and the fact that the inclusion of field-measured macrotexture in the formulation of prediction models would decrease their design value, the methodology followed in this study introduced, instead, the factors that contribute to the formation of macrotexture (aggregate gradation and shape, application rates of asphalt and aggregate) and those believed to be governing the rate of wear in such texture under traffic exposure (resistance to abrasion, soundness, petrographic properties, and others.)

(8) The randomized selection of the seal coat projects and aggregate sources for the construction of test sections gives confidence as to the area in which the results of this study may be implemented.

(9) The construction of test sections end-to-end as number of different aggregates used was found very convenient for performing field testing. One-thousand-foot-long sections were found of sufficient length to make five friction and texture measurements.

(10) It has been difficult to build test sections for the completion of the experiment designed for separately evaluating the climatic effects. If the experiment is not satisfactorily completed, testing for the climatic effects will be incorporated only in the multiple regression analyses.

(11) It is hoped that the climatological data being collected and the suggested tentative segmentation of a year into dry and wet periods will help account for the variability in frictional resistance caused by short-term and long-term seasonal variations, respectively.

RECOMMENDATIONS

Only a few recommendations are made at this stage of the study. These are as follows:

(1) Until a reliable relationship is established between field frictional resistance and aggregate characteristics, the selection or evaluation of aggregates on the basis of the PV and soundness requirements along with the frictional performance history, if available, should be continued.

(2) When decisions are to be made as to whether or not resurfacing of an existing pavement surface is required, it is suggested that reliance be on friction measurements taken in the dry period(s) of the climatic division where the roadway is located.

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