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16. Abstract

Most asphalt concrete pavements in Texas have been designed to resist a variety of load and environmental stresses. For the most part, these pavements have been successful in this endeavor. However, in the past few years an increasing amount of distress, in the form of rutting, shoving, and bleeding, has been reported. This distress often has been caused by moisture damage or stripping which is attributed to the presence of moisture in the asphalt-aggregate matrix.

This report summarizes the results of a survey of observed moisture problems in Texas, reviews information related to moisture damage and its cause, evaluates test methods used to predict moisture-related distress, and identifies practical solutions to these problems.

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STRIPPING AND MOISTURE DAMAGE IN ASPHALT MIXTURES

by

Robert B. McGennis
Thomas W. Kennedy
Randy B. Machemehl

Research Report Number 253-1

Moisture Effects on Asphalt Mixtures

Research Project 3-9-79-253

conducted for

Texas
State Department of Highways and Public Transportation

in cooperation with the
U. S. Department of Transportation
Federal Highway Administration

by the

CENTER FOR TRANSPORTATION RESEARCH
BUREAU OF ENGINEERING RESEARCH
THE UNIVERSITY OF TEXAS AT AUSTIN

September 1984

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

PREFACE

This is the first in a series of reports dealing with the findings of a research project concerned with moisture effects on asphalt mixtures. This report concerns a survey of moisture damage in Texas, the mechanisms which produce the damage, test methods which potentially can be used to evaluate moisture susceptibility, and possible procedures and techniques to minimize the damage.

The work required to develop this report was provided by many people. Special appreciation is extended to Mr. James N. Anagnos for his assistance in the study. In addition, the authors would like to express their appreciation to Messrs. Paul Krugler, Donald O'Connor, C. Weldon Chaffin, and Billy R. Neeley, all of the Texas State Department of Highways and Public Transportation, for their suggestions, encouragement, and assistance in this research effort, and to other district personnel who provided information related to the performance of actual highway pavements. Appreciation is also extended to the Center for Transportation Research staff who assisted in the preparation of the manuscript. The support of the Federal Highway Administration, Department of Transportation, is acknowledged.

Robert B. McGennis
Thomas W. Kennedy
Randy B. Machemehl

September 1984

LIST OF REPORTS

Report No. 253-1, "Stripping and Moisture Damage in Asphalt Mixtures," by Robert B. McGennis, Randy B. Machemehl, and Thomas W. Kennedy, summarizes a study to determine the extent, nature, and severity of moisture related damage to asphalt mixtures used in pavements in Texas.

Report No. 253-2, "An Evaluation of the Asphaltene Settling Test," by Thomas W. Kennedy and Chee-Chong Lin, summarizes a testing program designed to evaluate the Asphaltene Settling Test, the test procedure, factors affecting the test results, and relationships between settling time and asphalt characteristics.

Report No. 253-3, "Texas Freeze-Thaw Pedestal Test for Evaluating Moisture Susceptibility for Asphalt Mixtures," by Thomas W. Kennedy, Freddy L. Roberts, Kang W. Lee, and James N. Anagnos, includes a detailed description of the Texas Freeze-Thaw Pedestal Test and describes how it can be used to distinguish between stripping and nonstripping asphalt concrete mixtures or individual aggregates.

Report No. 253-4, "Lime Treatment of Asphalt Mixtures," by Thomas W. Kennedy and James N. Anagnos, summarizes information related to stripping of asphalt mixtures and the use of hydrated lime as an antistripping agent and makes recommendations concerning the construction techniques for adding lime.

Report No. 253-5, "Texas Boiling Test for Evaluating Moisture Susceptibility of Asphalt Mixtures," by Thomas W. Kennedy, Freddy L. Roberts, and James N. Anagnos, includes a detailed description and evaluation of the Texas Boiling Test Method and also describes how it can be used to distinguish between stripping and nonstripping asphalt concrete mixtures or individual aggregates.

ABSTRACT

Most asphalt concrete pavements in Texas have been designed to resist a variety of load and environmental stresses. For the most part, these pavements have been successful in this endeavor. However, in the past few years an increasing amount of distress, in the form of rutting, shoving, and bleeding, has been reported. This distress often has been caused by moisture damage or stripping which is attributed to the presence of moisture in the asphalt-aggregate matrix.

This report summarizes the results of a survey of observed moisture problems in Texas, reviews information related to moisture damage and its cause, evaluates test methods used to predict moisture-related distress, and identifies practical solutions to these problems.

KEY WORDS: moisture distress, stripping

IMPLEMENTATION STATEMENT

This report summarizes early findings and experience in the research project entitled "Moisture Effects on Asphalt Mixtures." The purpose of the report is to summarize the information related to the extent, severity, and nature of moisture damage in asphalt mixtures in Texas; the basic background information related to the nature and cause of moisture damage; tests which possibly could be used to evaluate moisture susceptibility; and procedures or techniques to minimize damage.

Thus, the information contained in the report serves as background information related to moisture damage and stripping of asphalt mixtures. Subsequent reports address specific developments and applications.

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CHAPTER 1. INTRODUCTION

During the past few years, asphalt pavement mixtures have suffered extreme damage due to the adverse effects of moisture. Such damage has been reported to occur in two forms, stripping and softening. Of primary concern is stripping, which has become a major cause of distress of asphalt mixtures. Two major pavement failures occurred in Texas during the summer of 1980 (Refs 1 and 2). While many factors contributed to these failures, moisture damage was a definite problem. In addition, other pavements have exhibited lesser damage which has resulted in shortened pavement life, reduced performance, and increased maintenance costs. In recognition of these problems a research study, Project 3-9-79-253, "Moisture Effects on Asphalt Mixtures," was initiated.

Over the years, a great deal of basic and applied research has been conducted on the problem of moisture damage. This research has involved the identification of aggregates and asphalt-aggregate mixtures which are susceptible to moisture-induced damage and the development of treatments and additives to minimize the damage to susceptible mixtures.

More recently, an extensive study was conducted by Lottman at the University of Idaho under NCHRP Project 4-8(3) which led to the development of a practical laboratory test procedure for quantitatively predicting the magnitude and rate of moisture damage in asphalt mixtures (Ref 3). This procedure includes a conditioning procedure for the specimens after which the specimens are tested using the static or repeated-load indirect tensile test developed at the Center for Transportation Research as part of Projects 3-8-66-98, "Evaluation of Tensile Properties of Subbases for Use in Rigid Pavement Design," and 3-9-72-183, "Tensile Characterization of Highway Pavement Materials." Schmidt (Ref 4) also reported using the repeated-load indirect tensile test to evaluate the effects of moisture on strength. Kennedy and Ping (Ref 5) and Kennedy and Anagnos (Ref 6) also investigated the effects of moisture on blackbase mixtures.

A second effort at the Wyoming Research Institute, formerly the Laramie Energy Technology Center, under a contract from the Federal Highway Administration focused on the physical-chemical nature of asphalts and the

surface phenomena at the aggregate-water-asphalt interface. A review of the preliminary results (Refs 7, 8, and 9) and private communication with the researchers indicates potential field application of these methodologies. The main objectives of the portion of the study summarized in this report were to summarize information related to moisture damage in asphalt mixtures, to evaluate the extent and severity of moisture-related distress in Texas, to identify possible methods of detecting asphalt-aggregate mixtures which are susceptible to moisture damage, and to consider potential methods and procedures to alleviate moisture damage problems.

Chapter 2 discusses moisture damage with emphasis on stripping. Chapter 3 reports the results of a survey to determine the extent of moisture damage in Texas. Measures that can be enacted to reduce or eliminate moisture damage are presented in Chapter 4. Test methods to identify moisture susceptible mixtures are discussed in Chapter 5. Conclusions and recommendations are presented in Chapter 6.

CHAPTER 2. MOISTURE DAMAGE MECHANISMS

The distress mechanism that has been observed to result from the detrimental effects of moisture on asphalt mixtures is stripping. Stripping describes the loss of adhesion between aggregate and binder due to the presence of moisture in the asphalt matrix. Many engineers use the terms ravelling and shelling interchangeably with stripping; however, this usage can be not only misleading but incorrect. Whereas ravelling and shelling are also characterized by a loosening of bond between aggregate and binder, the cause may be due to other factors separately or in conjunction with stripping. Based on this apparent ambiguity, the following definitions are presented to eliminate confusion.

Stripping is a distress mechanism which produces physical separation of the asphalt cement and aggregate produced by the loss of adhesion between the asphalt cement and aggregate surface primarily due to the action of water or water vapor. The stripping is accentuated by the presence of aggregate surface coatings and smooth aggregate surface texture.

Ravelling is a distress manifestation that is evident as dislodgement of aggregate particles in the mixture from the surface downward or from the edges inward. Ravelling usually starts within 0.25 to 0.50 inches of the asphalt concrete surface and progresses downward. Possible mechanisms of ravelling include insufficient asphalt binder, hardening of the asphalt binder, wet or dirty aggregate, smooth aggregate surface texture, and surface stripping.

Shelling is a distress manifestation that is evident as loosening and subsequent removal of aggregate from a seal coat or other surface treatment. Possible mechanisms of shelling include the combinations of insufficient embedment of aggregate, insufficient curing of the asphalt, or stripping. Traffic will remove the seal coat aggregate as soon as it is loosened by any of these means.

It should be noted that stripping is a distress mechanism whereas ravelling and shelling are distress manifestations. In fact, as noted in the definitions, stripping can be the mechanism (among others) that is

manifested on the road as ravelling and shelling. Understanding the relationships between distress mechanisms and manifestations is crucial in diagnosing any pavement problem, including moisture damage.

Based on a review of the technical literature as well as on field experience (Refs 1, 2 and 10), three types of failure (Fig 1) can occur due to the action of moisture. Note that in Figure 1, the three distress modes--fracture, distortion, and disintegration--are caused by stripping; however, these can also be caused by other distress mechanisms. For example, rutting can also be caused by a mixture which is over-asphalted, a weak subgrade, or both; shelling can also be caused by insufficient embedment of aggregate, insufficient curing of the asphalt, or excessive traffic; and so on. This fact is probably the reason that stripping often is not recognized as the cause of pavement distress.

Fracture (cracking) is associated with stripping in that moisture collects on the underside of asphalt layers, removes the asphalt binder from the aggregate, and thus destroys the overall cohesion of the mixture (i.e., tensile strength) in this vicinity. This loss of cohesion in the lower part of a bound layer will be manifested by cracking in the wheelpaths. Field experience has shown that stripping in these lower layers may be so pronounced that it becomes impossible to obtain intact cores since the aggregate is free of any binder and appears to be no more than compacted base material.

Distortion of an asphalt mixture due to stripping occurs when water or vapor displaces asphalt on the aggregate surface. As such, the overall fluids content (asphalt cement plus water) is increased and the mixture behaves much the same as one which is over-asphalted. In addition, asphalt cement which is no longer bound to aggregate particles may rise to the surface and produce higher asphalt contents in the upper region. Rutting, shoving, or washboarding will be the most obvious symptom. Small surficial cracks and/or glazing or patch bleeding often accompanies the distortion. The glazed, localized areas of flushed asphalt are not necessarily confined to the wheelpath, as is usually the case with an over-asphalted mixture, but are distributed randomly across the pavement.

Disintegration of a mixture due to stripping occurs as ravelling or potholes. In such cases, stripping usually begins at the surface as ravelling and progresses downward. When enough water ponds in a ravelled

Distress Mechanism	Distress Mode	Distress Manifestation
	Fracture	Longitudinal cracking
		Alligator cracking
Stripping	Distortion	Rutting
		Shoving
		Washboarding
	Disintegration	Ravelling
		Shelling
		Potholes

Figure 1. Asphalt pavement failure concepts associated with stripping

area for extended periods with heavy traffic, a pothole will form. Disintegration of a seal coat due to stripping occurs as shelling. Although stripping alone can cause shelling of a seal coat, other causative factors are usually involved. Some of these factors include insufficient aggregate embedment, excessive traffic prior to adequate curing of the asphalt, and incompatible asphalt (usually emulsified) and aggregate.

Besides stripping, "softening" is another term which has been associated with moisture-induced damage. Softening is characterized by overall loss of cohesion of the asphalt mixture. Although not well documented in the technical literature, there appear to be two theories that explain softening. The classical theory assumes that certain chemical or other reactions occur which cause the asphalt cement to degrade to a lower viscosity. The second theory states that the asphalt cement and mineral filler (finer than No. 200 sieve) as an intimate mixture function as the binding agent for the larger aggregate particles. Thus, if the mineral filler is stripped of asphalt the overall binding effect is destroyed and the mixture loses cohesion.

The authors tend to believe the second theory for the following reason. Several mixtures that had experienced moisture distress were tested as part of other studies (Ref 2). Penetration tests on extracted asphalt showed that the asphalt actually hardened. In several instances, the penetration value was less than 20 which indicated a rather severe hardening effect. Thus, even though mixture cohesion was affected, the primary cause was still lack of adhesion. In addition, mixtures have been observed wherein the larger aggregate fractions have stripped but the smaller fractions (finer than No. 10 sieve) have not. These mixtures as a whole performed well. Since the small fractions contribute most of the mineral filler, it can again be concluded that the softening phenomenon is highly related to adhesion between the asphalt cement and mineral filler.

Examination of moisture distressed mixtures reveals clean aggregate surfaces. The residual binder has been reported by field personnel to appear "dead" in terms of adhesiveness and lightened in color. It is for this reason that a chemical type or structuring change is assumed to have occurred. It is possible that what is seen as degraded asphalt binder is actually a severely stripped mixture of asphalt cement and mineral filler.

This scenario would explain the apparent lack of adhesion and color in mixtures that have been reported to be softened.

BASIC FAILURE THEORIES

No single mechanism of stripping has been universally accepted and it is possible that different mechanisms occur for different conditions and that more than one mechanism may actually produce failure. The most widely accepted distress mechanisms can be grouped into three types: (1) mechanical, (2) chemical, and (3) thermodynamic.

The mechanical mechanisms suggest that the quality of adhesion is dependent upon how well the asphalt cement intrudes into the pores and irregularities of the surface of an aggregate particle to secure a strong mechanical interlock. Mechanical bond is dependent upon the tensile strength of the asphalt cement and the surface characteristics of the aggregates.

The chemical mechanisms involve chemical reactions that take place on the aggregate surface and involve the asphalt, aggregate, and water. The quality of bond that develops between aggregate and binder depends on factors such as surface charges and pH of the mixture components.

The thermodynamic mechanisms involve the ability of various asphalts to wet aggregate surfaces. Wetting, which is the ability of a liquid to spread over a solid, is a function of the viscosity and surface tension of a binder. During mixing operations a binder of lower viscosity and surface tension will tend to produce better coating of the aggregate particles.

These three mechanisms are usually used singularly or combined to develop failure concepts to explain the stripping phenomenon. Appendix A contains a cursory review of seven failure concepts that have been theorized to cause stripping.

For the most part, it is apparent that the cause or causes are not well known even though the problem has been studied for years. This suggests that additional work related to the cause of stripping should be conducted; however, it should be noted that the probability of success is quite low.

CHAPTER 3. MOISTURE DAMAGE IN TEXAS

Each district within the State of Texas was visited to assess the severity and extent of moisture damage within each district. After field visits and interviews with district personnel, the extent and severity of stripping in each district was categorized as: severe, moderate, or nil, and is summarized in Figure 2. In addition, Figure 3 indicates those districts that experience problems with shelling which may be moisture related.

CAUSATIVE FACTORS

Several factors affect the moisture susceptibility of asphalt mixtures. These factors are related to

(1) environment,

(2) aggregate type, and

(3) mixture properties.

The existence of causative relationships for the first two categories was evaluated through comparisons of the geographic characteristics of each factor and the geographic severity of moisture damage. Causative relationships for the last category were evaluated through field observations of mixture distress and subsequent study of mixture properties of the distressed pavement.

Environmental Factors

The three environmental factors considered are relative humidity, annual precipitation, and Thornthwaite moisture index. These factors represent a quantitative measure of the amount of moisture available in a given geographic region.

Relative Humidity. Relative humidity is the ratio of the amount of moisture that a sample of air contains at a certain temperature to that contained at saturation expressed as a percent. High relative humidities provide an available source of water to activate moisture damage mechanisms.

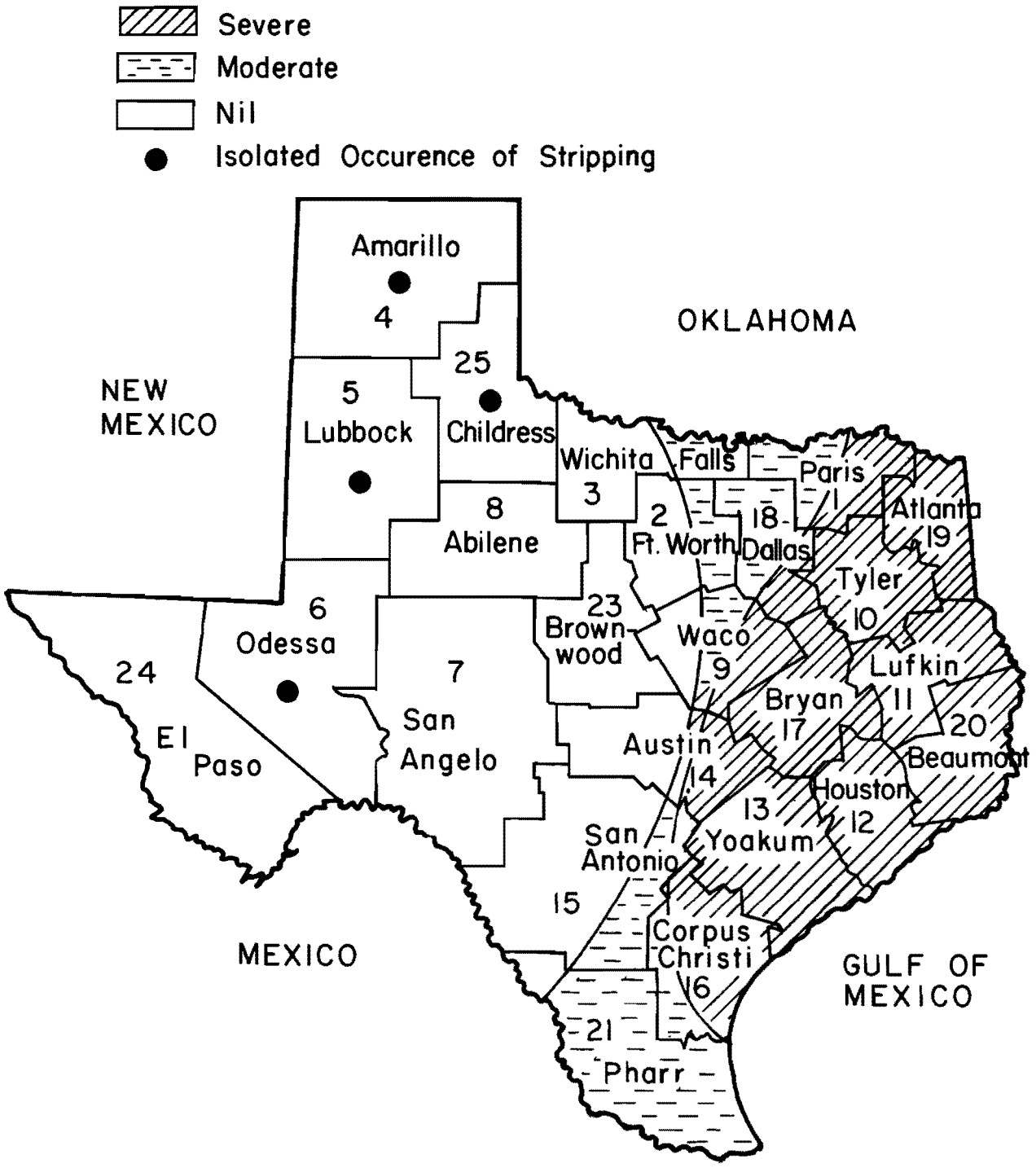

Fig 2. Severity of stripping damage in hot mix, cold mix, and blackbase layers by district.

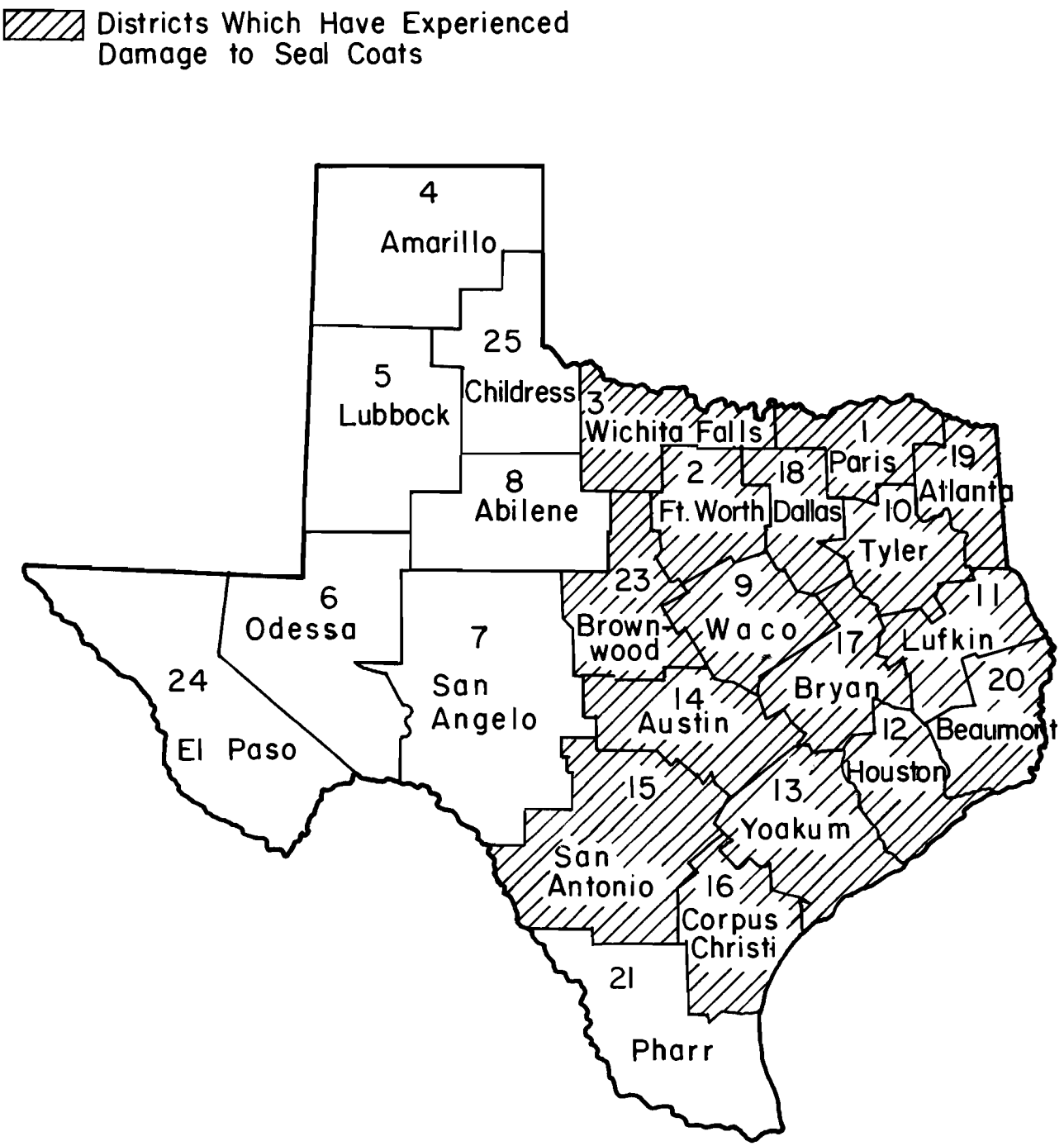

Fig 3. Reported damage to seal coats by district.

In addition, high relative humidity inhibits evaporation from moisture-bearing surface mixtures.

Annual Precipitation. Annual rainfall is a direct indication of the amount of water available to produce moisture-related damage.

Thornthwaite Moisture Index. The Thornthwaite moisture index was first developed by agronomists to quantify potential evapotranspiration. More recently, though, it has been used to relate climate to engineering performance of pavements (Ref 11). High positive values of the Thornthwaite index indicate that there is a surplus of moisture in the soil; that is, the rate of moisture entering the soil from precipitation is greater than the rate of moisture leaving the soil due to evapotranspiration.

Figures 4, 5, and 6 (Ref 12) show the geographic severity of relative humidity, annual precipitation, and Thornthwaite moisture index, respectively, superimposed on the geographic extent of moisture damage. It can be seen that regions with high values of these environmental factors, and thus a readily available source of moisture, have experienced moisture damage to the greatest extent.

Aggregate Type

Another factor considered is the aggregate type used in mixtures. In Texas, siliceous aggregates and rhyolite have shown a greater propensity for stripping than other aggregate types. Therefore, districts that both use large quantities of siliceous and rhyolite aggregates and have relatively high amounts of rainfall should experience greater moisture-related distress problems than those districts with only one of those factors. Figure 7 shows districts that (at the time of the survey) used siliceous and/or rhyolite aggregates superimposed upon the geographic extent of moisture damage. It can be seen that most districts which use these aggregates have had problems, especially if sufficient quantities of moisture are available.

Mixture Properties

The amount and ease with which moisture can enter an asphalt concrete mixture is directly dependent on the density and gradation of the mixture. Dense, well-graded mixtures will more effectively keep water out (Ref 13). Analysis of an overlay project on IH-10 near Columbus, Texas, showed that

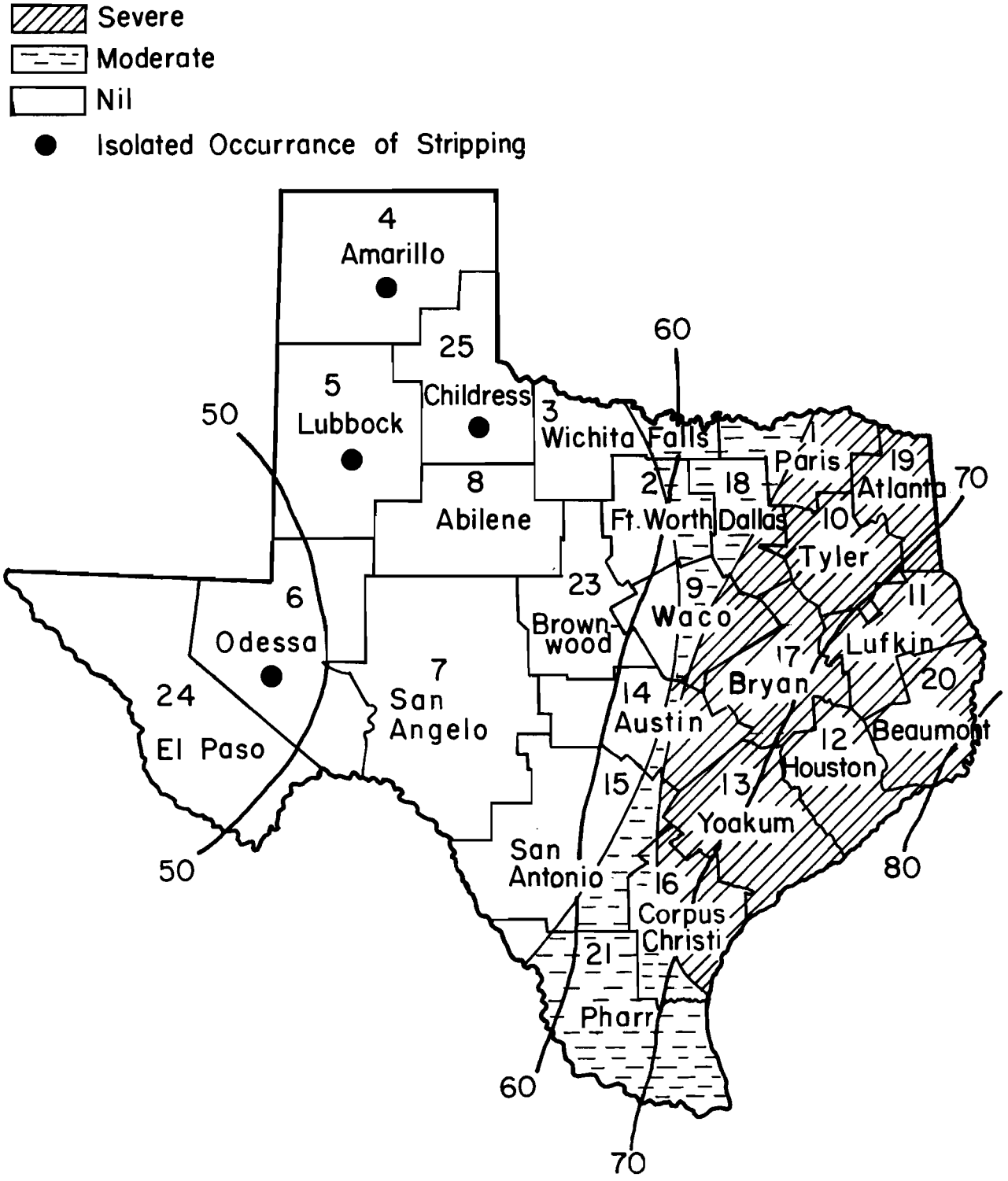

Fig 4. Geographic severity of relative humidity compared to geographic severity of moisture damage.

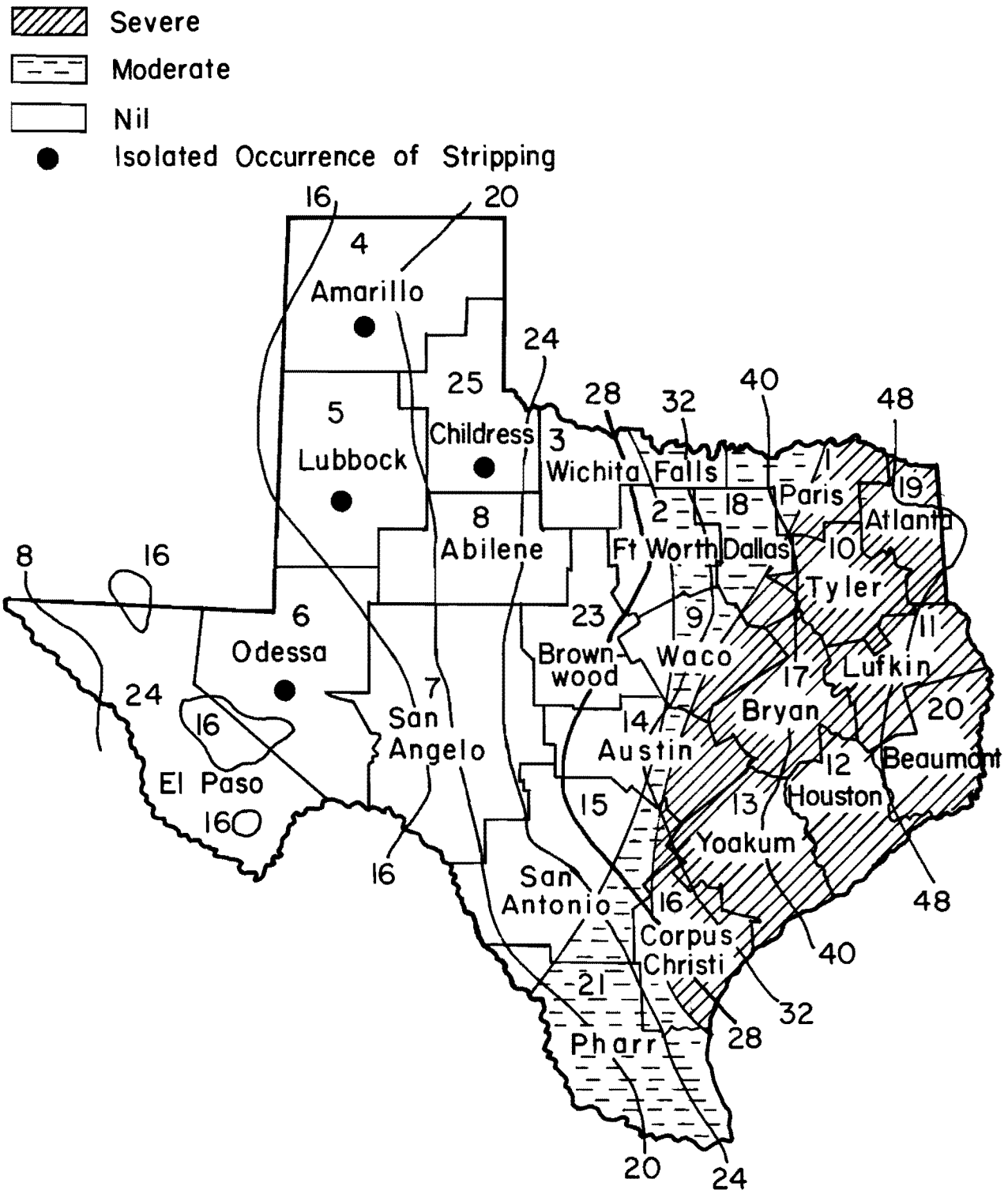

Fig 5. Geographic severity of annual precipitation (inches) compared to geographic severity of moisture damage.

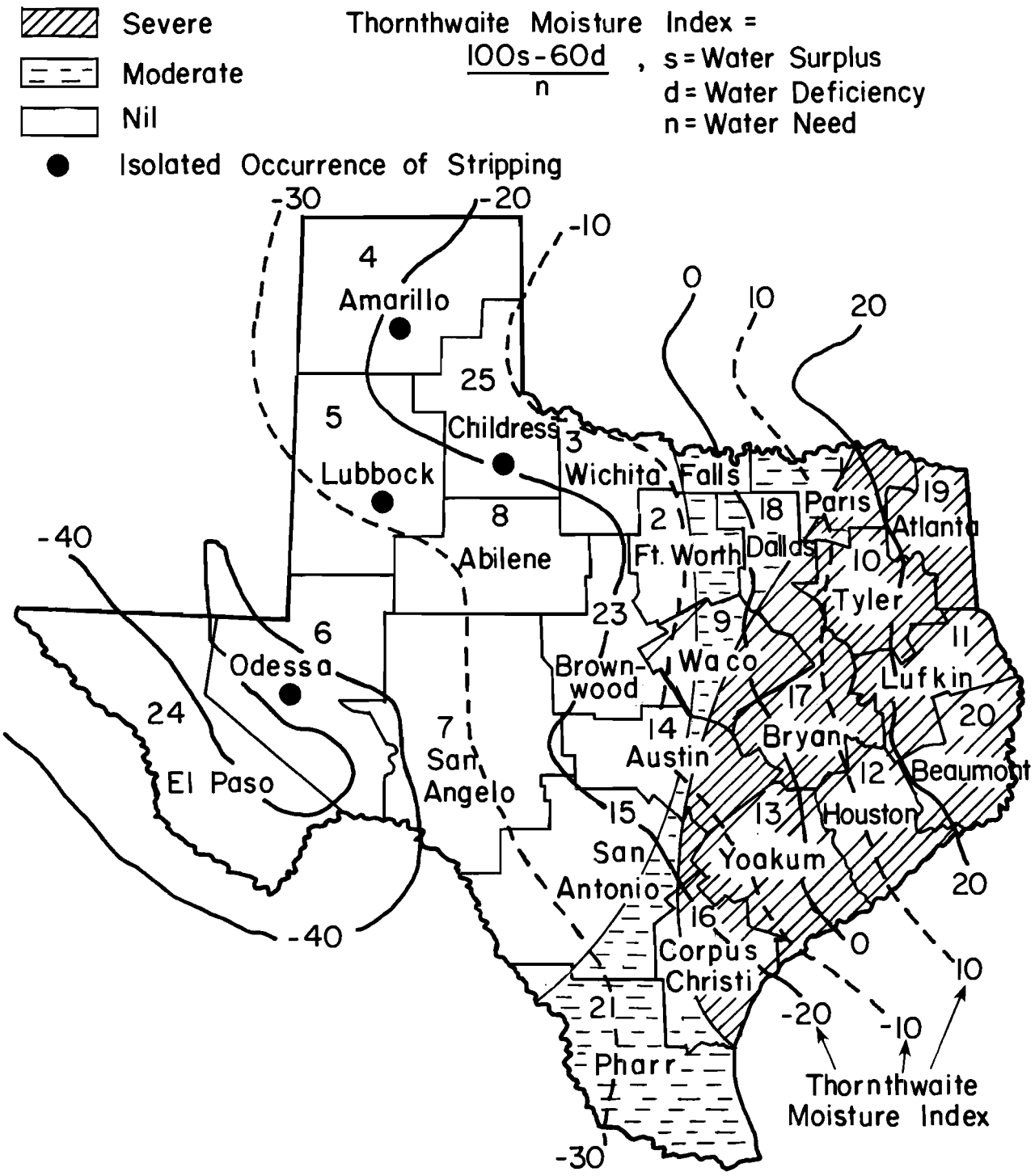

Fig 6. Geographic severity of Thornthwaite moisture index compared to geographic severity of moisture damage.

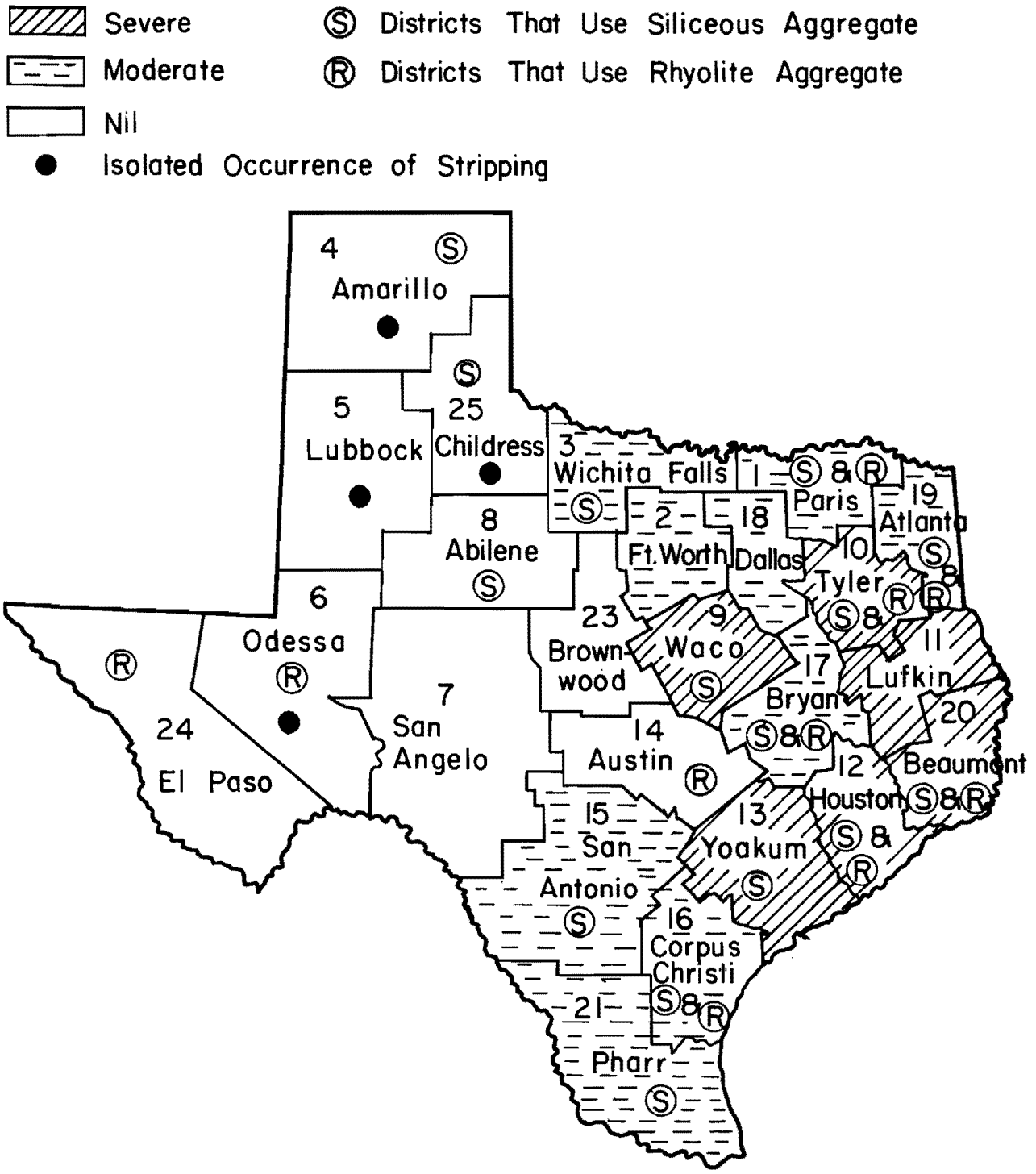

Fig 7. Geographic extent of the use of siliceous or rhyolite aggregates compared to the geographic extent of moisture damage.

mixtures compacted to a high density (150.9 pcf as determined from cores) experienced no moisture-related distress, whereas mixtures compacted to a lower density (146.0 pcf) experienced significant moisture-related distress (Ref 1).

Isolated Occurrences of Moisture Damage

Despite the fact that causative factors (i.e., precipitation, humidity, etc.) are not at high levels, several districts in west Texas have experienced isolated occurrences of moisture damage. An explanation of these occurrences may be hypothesized by examination of the Thornthwaite moisture index.

Russam and Coleman (Ref 14) have related the Thornthwaite moisture index to the equilibrium suction level which develops in the subgrade beneath a pavement. The relationship states that soils with a high negative value of the Thornthwaite moisture index (i.e., high potential for evapotranspiration) also have a large potential for attracting moisture. High suction values such as those observed in west Texas show that those subgrades have a high potential for drawing moisture from either above or below. Therefore, moisture from a perched water table, irrigation adjacent to the roadway, or other local source could provide the aforementioned opportunity to initiate moisture damage.

Figure 8 (Ref 11) illustrates both the Thornthwaite moisture index and the predicted subgrade suction value. From Figure 8 it can be seen that high subgrade suction values occur where the isolated instances of moisture damage reported in west Texas have occurred.

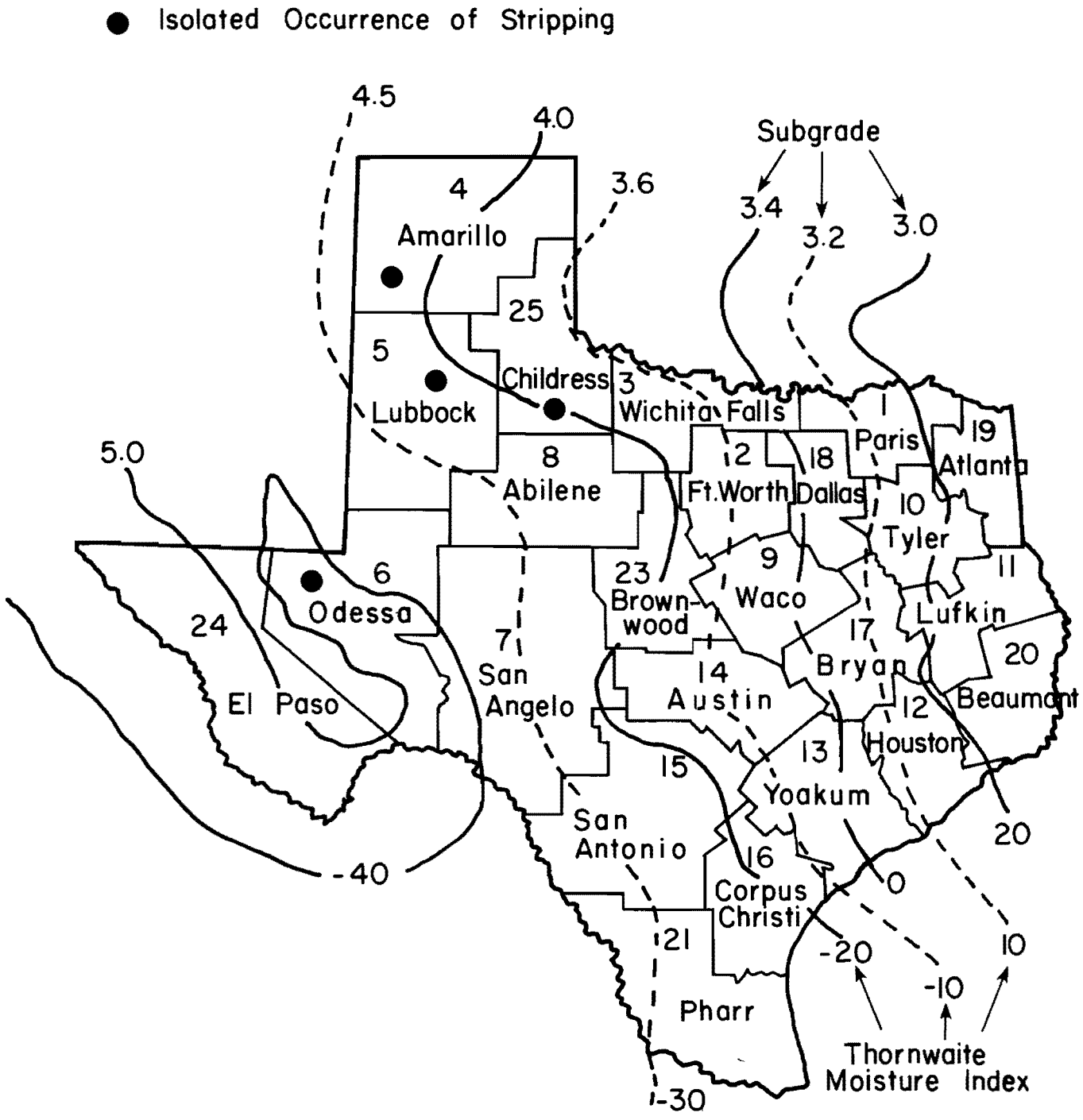

Fig 8. Subgrade suction values based on Thornthwaite moisture index compared to isolated occurrences of stripping in Texas.

CHAPTER 4. SOLUTIONS TO MOISTURE DAMAGE

Solutions to prevent or minimize the effects of moisture-induced damage to asphalt mixtures are as difficult to develop as determining the cause of the damage. Moisture damage may be due strictly to action of the moisture mechanisms or may be due to a combination of the moisture mechanisms and other physical factors such as slick aggregate or surface coatings. Therefore, prevention or reduction of moisture damage to asphalt mixtures may involve either of two basic approaches. The first approach includes solutions to directly improve adhesion at the asphalt-aggregate interface. The second approach includes solutions to improve the material characteristics, construction methods, or any other physical factors which may interact with moisture to produce adverse effects on an asphalt mixture.

IMPROVED ADHESION

There are several practices that reduce the adverse effects of moisture on bituminous mixtures through indirect means. The following practices normally will improve adhesion at the asphalt-aggregate interface:

(1) aggregate preheating,
(2) chemical antistripping additives,
(3) lime,
(4) remove surface coatings, and
(5) avoidance of stripping aggregates.

Each of these techniques is discussed in the following paragraphs.

Aggregate Preheating

Aggregate preheating has been shown (Ref 15) to improve adhesion by removing several molecular layers of adsorbed water, which can disrupt adhesion. This practice, which was common a number of years ago, has largely been eliminated due to increased cost of energy.

Chemical Antistripping Additives

In the past, many chemical agents have been used to improve the resistance of asphalt mixtures to stripping. This practice has achieved mixed results and thus has been and currently remains a controversial topic. Many of the currently used additives are cationic surfactants that enhance adhesion after migrating to the aggregate surface which acts as a cathode. After migration, the surfactants displace moisture and make the aggregate prefer asphalt rather than water. The extent to which this preference occurs depends on the amount of additive used, the quality of the bond between the additive and aggregate, and the effectiveness of the migration (Ref 16). The effect of construction practices, materials, and specifications on these preference factors appears to be the basis of controversy.

For example, chemical additives are usually added to the asphalt cement at a rate of approximately 0.5 to 1.0 percent by weight of asphalt. For a one hundred pound mixture sample this rate corresponds to less than an ounce. As such, some question exists as to whether these additives become dispersed enough in the asphalt cement for the previously mentioned migration to occur. To counter this effect, it has been suggested (Ref 16) that chemical agents should be added directly to the aggregate. Such operations would be more costly, though.

Presently, it is clear from the technical literature that many chemical additives offer a potential benefit in reducing the adverse effects of moisture; however, several important factors need to be addressed when their use is considered. First, numerous studies (Refs 17, 18, and many others) have determined that a certain asphalt mixture will be affected differently by different chemical additives. The resistance to stripping may be drastically changed if either the asphalt cement, aggregate, or additive is changed. Second, addition of an antistripping agent may force an asphalt cement that normally meets specifications into noncompliance. The general effect is one of lowering the asphalt viscosity. Finally, there appears to be a minimum dosage required for a particular additive. This minimum dosage changes for different asphalts.

A secondary, and sometimes overlooked, aspect of antistripping agents is their effect on initial coating of aggregate. Field experience (Ref 19) has proven that some agents do a remarkable job in enhancing aggregate coating, particularly when a wet aggregate is used. In this respect they

are acting primarily as a surfactant. Further, tests such as the generic boiling test, ASTM stripping test (D 1664), and others, when used to evaluate antistripping agents only function to predict the durability of coating during mixing and placement operations. The long term bond enhancing effects may or may not be adequate. This concept will be further addressed in Chapter 5.

Lime

The earliest use of lime in asphalt mixtures dates back to approximately 1910 when it was used primarily as a mineral filler to satisfy gradation requirements. These mixtures produced under the Warrenite patent (Ref 20) were noticeably free of moisture-related problems. Since that time many agencies have used lime both as a mineral filler and as an antistripping agent.

The mechanism by which hydrated lime improves adhesion is not well understood although several explanations exist in the literature. According to Petersen (Ref 21), when lime coats an aggregate particle, it induces polar components in asphalt cement to bond to the aggregate surface. This effect also inhibits hydrophilic polar groups in the asphalt from congregating on the aggregate surface.

Occasionally, lime is added directly to the asphalt cement and thus, becomes an asphalt modifier. The mechanism by which this method of treatment works, as well as the effectiveness, is not well documented.

Laboratory studies performed as part of this project have demonstrated the effectiveness of lime in improving adhesion. These studies have also shown that lime slurry treatment (as opposed to dry lime) of the aggregate is most effective in terms of desired results. There has been a great amount of speculation on the period of time required for the beneficial effects to occur. Based on laboratory studies as part of this project and field studies as part of another project (Ref 22) the effects appear to be immediate. Lime slurry placed on a cold feed belt was found to be effective. A more serious finding was that if lime slurry is placed on an aggregate and subsequently washed off, there will be no benefit. In addition, if the lime carbonates, it is ineffective.

Based on conversations with mixture producers, there seems to be a tendency to treat only the large aggregate fractions since this operation

is easiest. This practice is not recommended since it is adhesion of asphalt cement to the finer fractions which determines whether a mixture will experience a significant amount of distress.

Typical treatment levels range from one to two percent hydrated lime by weight of aggregate. This comparatively large amount of material and treatment operations often render lime more expensive than other antistripping additives.

Remove Surface Coatings

As previously mentioned, aggregate surface coatings such as clay and other fine dust-like material are detrimental to adhesion between the asphalt binder and aggregate. Thus washing of the aggregate prior to mixing often will improve the bond between the asphalt and aggregate.

Avoidance of Stripping Aggregates

A safe, but often expensive, solution is to avoid the use of water-susceptible aggregates. In Texas, the most common moisture-susceptible aggregates are siliceous gravels, sands, and rhyolite; however, other aggregates may be moisture susceptible including some limestones. However, if the moisture-susceptible mixture cannot be protected then the additional cost of transporting quality aggregates may be quite effective when compared to reduced pavement life, poor performance, and excessive maintenance costs.

IMPROVED MATERIAL CHARACTERISTICS AND CONSTRUCTION METHODS

There are several practices that reduce the adverse effects of moisture on bituminous mixtures through indirect means. The following practices normally will enhance the resistance of asphalt mixtures to water damage:

(1) provide adequate surface drainage,
(2) use dense-graded mixtures with the proper asphalt content,
(3) design a mixture that is compactible,
(4) use porous, rough surface textured aggregates, and
(5) compact the mixture to a relative theoretical density of 96 to 95 percent (4 to 5 percent air voids).

Each of these techniques is briefly discussed in the following paragraphs.

Surface Drainage

One of the best methods of minimizing water available to cause stripping is through adequate cross slope to provide good surface drainage. When new, most roadways have an adequate cross slope but with overlays the cross slope may be reduced and allow water to accumulate on the surface. Underground drainage structures may be needed to prevent water from getting into the pavement system when a high water table is encountered.

Construction Practice and Mixture Design

Laboratory and field studies (Refs 1 and 2) have shown the significant effect of air voids on moisture susceptibility. Simply stated, more air voids allow larger quantities of moisture to penetrate the mixture and increase the stripping potential. Well-compacted mixtures with approximately four to five percent air voids have shown remarkable resistance to stripping, even when stripping-prone aggregates were used.

Although good construction practice such as carefully designed rolling patterns, maintenance of cross slope during laydown, etc., definitely reduce moisture susceptibility, mixture design and its effect on construction is often overlooked. Examination of the technical literature over the last twenty years indicates that in terms of construction one of the more important mixture property is voids in the mineral aggregate (VMA). In a given volume of aggregate, the space not occupied by aggregate particles is the VMA. In terms of an asphalt mixture, VMA is equal to the volume of air voids plus the volume of asphalt. In a mixture, VMA is the primary factor which affects workability. A mixture too low in VMA will not allow asphalt cement to completely permeate all of the aggregate void spaces and impart a lubricating effect. A mixture too high in VMA, especially in the finer aggregate fractions, exhibits excessive workability.

In 1962, Goode and Lufsey (Ref 23) presented a chart, since termed the Bureau of Public Roads or BPR chart, that could be used to graphically analyze aggregate gradations; an example is shown in Figure 9. A straight line drawn on the chart from the nominal maximum particle size through the origin theoretically represents the "maximum density" of the aggregate because as many void spaces as possible are filled with successively smaller particles. The validity of this theory is of course dependent on aggregate shape, but does provide a starting point and general guideline. Thus the

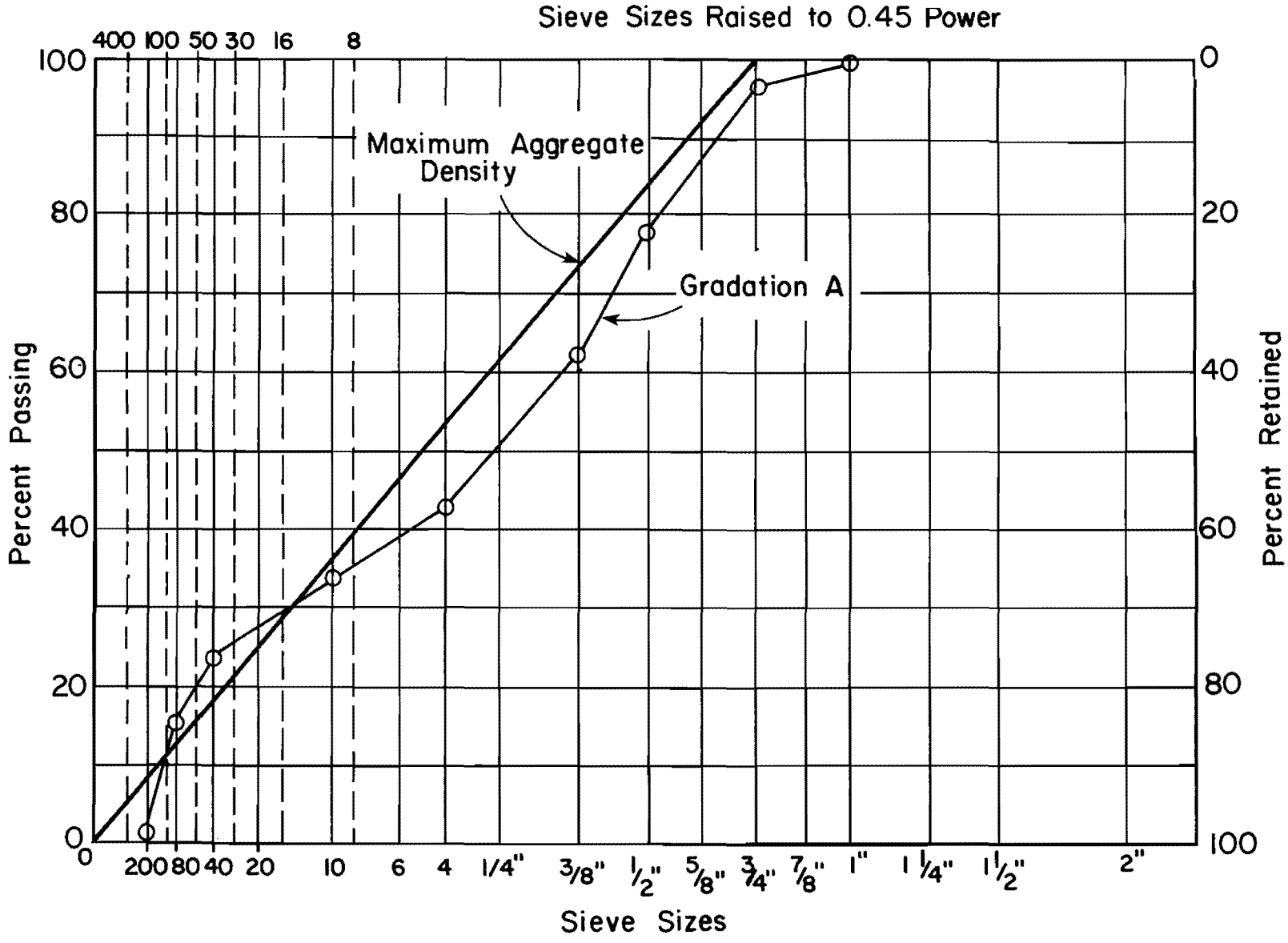

Fig 9. Bureau of Public Roads grading chart for analyzing aggregate gradation with a tender mixture gradation (Gradation A).

maximum density line yields the smallest possible VMA and any deviation will introduce VMA, e.g., Gradation A, Figure 9.

Examination of actual mixtures indicates two grading conditions that exist and each can lead to moisture damage from their effect on placement and compaction operations. The first grading condition is that which results in a "tender" mixture. Tender mixtures are evidenced by a hump in the grading curve in the vicinity of the Nos. 40 and 80 sieves (Gradation A, Fig 9). This hump indicates an excess of fine sand in relation to total sand. The fine particles tend to float the larger particles apart which inhibits aggregate interlock and renders the mixture excessively workable. Adequate density is often difficult to achieve for tender mixtures since the mixture shoves under rollers. Thus, high air void contents which can promote stripping often result. In addition, there is a tendency for roller operators to allow a mixture to cool substantially so that the viscosity of the asphalt binder increases to a value which allows the mixture to support the roller. Unfortunately, the asphalt viscosity is often too high to facilitate compacting to an adequate density and again, a large amount of air voids results.

The second grading condition is that which results in a "harsh" mixture. Harsh mixtures are evidenced by either too little VMA or an excess of coarse aggregate with small amounts of sand (Gradations B and C, respectively, Fig 10). Harsh mixtures are difficult to compact because their workability is so low. In the case of Gradation C, Figure 9, harsh mixtures often tend to segregate since there are too few fine particles to bind the large particles together during placing operations. Since harsh mixtures are so difficult to compact, they are often left with high air void contents which results in stripping. In addition, segregated mixtures tend to ravel since in the area of segregation, no fine particles fill the spaces between coarse particles resulting in a localized high void mixture.

Therefore, one of the most effective means of reducing moisture susceptibility is by careful mixture design with careful attention paid to those parameters which affect construction. Using gradation analysis techniques, mixtures should be designed to facilitate placement and compaction with emphasis on avoiding harsh or tender mixtures (Ref 24).

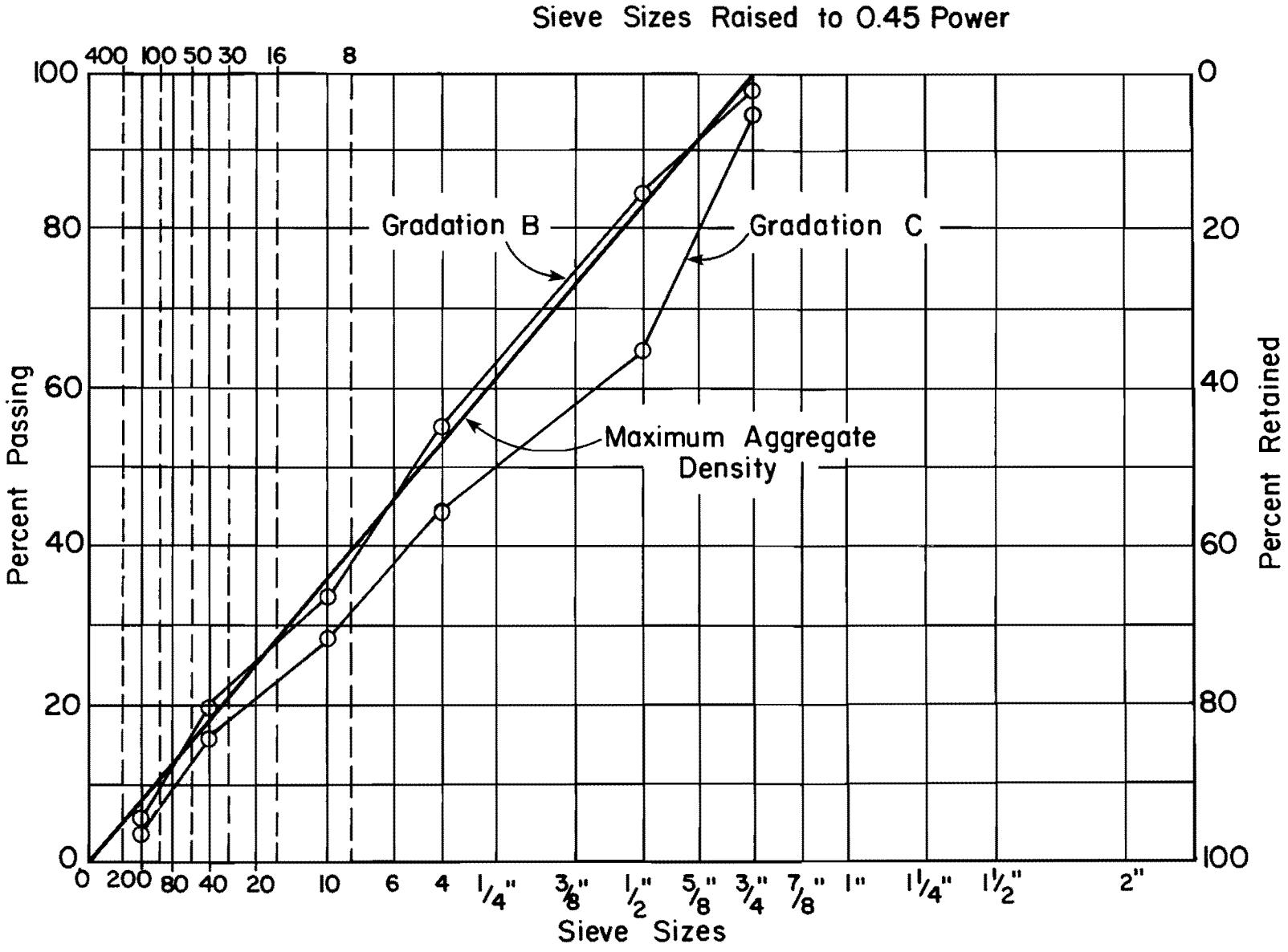

Fig 10. Bureau of Public Roads grading chart for analyzing aggregate gradation showing harsh mixture gradations (Gradations B and C).

Surface Texture

Adhesion will be improved if the aggregate used is porous with a rough surface texture. These two characteristics have a highly significant effect upon the mechanical bond of the asphalt to the aggregate. Therefore, selection of an aggregate with a rough surface is highly desirable. However, the benefits of better bond may be offset because porous aggregates usually absorb considerable quantities of asphalt cement with a resulting higher cost mixture.

CHAPTER 5. TEST AVAILABLE FOR EVALUATING MOISTURE DAMAGE

In the past, there have been numerous attempts to develop laboratory test methods which can be used to predict the moisture susceptibility of asphalt mixtures. These tests have also been used to evaluate the effectiveness of the various antistripping agents. Although not generally recognized, these laboratory tests can usually be placed in two predictive categories. The first category of tests predicts the initial quality of coating and bond of asphalt cement to aggregate during mixing, placement, and compaction operations. The second category attempts to predict the long term adhesion of asphalt to aggregate throughout the service life of the pavement.

The following section briefly describes some of the more common test methods currently in use or proposed for use. It should be noted that in order to classify these as well as other tests into the aforementioned categories the tests must be evaluated on the basis of which field phenomenon is being simulated. Based on test descriptions in the technical literature, this is not always stated or even clear.

TESTS TO EVALUATE INITIAL COATING AND ADHESION

Even though one of the major asphalt concrete production steps is aggregate drying, relatively high moisture contents have been measured in samples taken immediately after mixing (Ref 25). Resistance of asphalt mixtures to early stripping from the presence of this moisture can be evaluated by using the following tests.

ASTM Stripping Test

This test estimates the percentage of the total visible area of the aggregate which remains coated after water immersion: ASTM D 1664-69 (AASHTO T182-70). The intent is to determine the retention of a binder film by an aggregate in the presence of water soon after coating. It is applicable to cut-back asphalts, emulsified asphalts, asphalt cements, and tars. In this test the selected and prepared aggregate is coated with

binder at a specified temperature appropriate to the grade used. After oven-curing for 2 hours, the coated aggregate is immersed in the water for 16 to 18 hours. The test result is reported in terms of whether the total visible area of the aggregate which remains coated is above or below 95 percent (Refs 26 and 27).

Texas Film Stripping Test

The extent of asphalt film stripping is visually inspected by estimating the percentage of uncoated aggregate surface (Tex-218-F). This test provides an indication of the resistance of asphalt mixtures to stripping of the asphalt immediately after mixing and in the presence of water. The asphalt mixture is processed in a manner that simulates plant mixing conditions using Test Method Tex-205-F (Ref 28). A jar containing a sample of mixture and water is agitated for 15 minutes in the apparatus. The material is poured from the jar, and a visual estimate is made of the amount of asphalt removed from the aggregate. Test results are categorized into one of three classes: (1) no stripping, (2) slight stripping ($\leq$25 percent of the aggregates are stripped), and (3) serious stripping (>25 percent of the particles are stripped). Currently this test is being deleted from the Manual of Testing Procedures.

Boiling Test

In this test a visual observation is made of the extent of stripping of the asphalt from aggregate surfaces after the mixture has been subjected to the action of water at elevated temperatures for a specified time. Many agencies have used different versions of the boiling test to evaluate the potential stripping of asphalt mixtures (Refs 29 and 30). To perform this test the cool, loose asphalt mixture, either plant or laboratory mixed, is boiled for 10 minutes in a pot or beaker. After boiling the water is drained, the contents emptied on paper, and the extent of stripping is visually rated. The method can also be used to evaluate the effectiveness of candidate antistripping additives in asphalt-aggregate mixtures (Refs 29, 31, and 32). Several of these test methods are compared in Table 1.

TABLE 1. COMPARISONS OF BOILING TEST PROCEDURES FROM DIFFERENT SOURCES

Test Factors		Shah (Ref 29) I	Shah (Ref 29) II	Louisiana DOT (Ref 32) TR 3/7-77	Virginia DOT (Ref 31) VTM-13	Texas DHT (Ref 30)
Evaluation of		Stripping or Additives		Additives Only	Additives Only	Stripping or Additives
Aggregate		Complete Mixture	-3/8 + #4	-3/8 + #4	Standard aggregate 50:50 of #8 and #10 Quartzite (141g ea)	Tex-205-F
Asphalt		Desired asphalt content by TR 3-3-71	4% AC-40 & AC-10	AC-40 5g (AC + additive)	AC-20 6% treated asphalt (18g)	
Additive		0.5%	0.5%	0.5%	Not to exceed 1.0%	----
Temperature and Time	Aggregate	----*	----	325°F for 1 - 1½ hrs	----	275°F
	Binder	----	----	325°F for 24 - 26 hrs	275°F for 96 hrs	250°F
Mixing Method		Manually or mechanically	----	Manually	Manually on hot plate	Manually or mechanically
Mixture, Weight		----	----	100g	300g	Approx. 500g
Cooling Before Boiling		----	----	2 hrs	----	24½ hrs
Specimen Weight		----	----	----	----	100g
Boil in Water		10 min	10 min in 60°C water bath	10 min in 400cc beaker half full	10 min	10 min in 400 cc beaker half full
Report		Avg. visual ratings from panel. No more than 5% stripping acceptable.	Avg. visual rating from panel.	Compare stripping of test mixture to that of reference mixture. Accept if less.	No signs of stripping acceptable.	Visual estimate immediately and after 24 hrs.

* No statement in test procedure on this factor.

Thin-Layer Chromatography Test

The streak of asphalt on a silica gel plate or plate composed of ground aggregate is observed in both natural and ultraviolet light. This test was suggested by the Wyoming Research Institute as a compatibility test based on thin-layer chromatography. For this test, asphalt cement is spotted onto a silica gel plate. The spot is developed by immersing the edge of the plate in a solvent such as toluene which produces a streak originating from the asphalt spot as the solvent moves upward through the adsorbent. A more uniform continuum from beginning to end of the streak is supposed to indicate a more compatible asphalt system. That is, a more uniform streak indicates a more uniform continuum from polar to nonpolar components and suggests a better dispersion of the highly polar or associating species to yield a better "peptized" system (Ref 33).

TESTS TO EVALUATE LONG TERM ADHESION

Even when initial adhesion between asphalt cement and aggregate is achieved, the long term effect of moisture may remain unknown. Recognition of this fact has led the industry to develop the following test methods to predict this long term behavior. Most of the tests involve singular or combinations of fabrication of test specimens to field conditions, moisture conditioning, and either static or repeated load until failure.

California Swell Test

This test measures the potential of a mixture to convey and/or retain a volume of water that has percolated into the mixture (CALIF. 305B, 1963). To conduct the test a compacted specimen confined in a mold is placed in a pan and a perforated bronze disc and tripod with dial gauge are placed on top of the specimen. Water is poured into the mold and allowed to stand undisturbed for 24 hours. The dial gauge is read, and the volume of water remaining above the specimen is measured. These values are interpreted as an indication of the ability of the mixture to resist permeation and degradation by water. The fundamental test assumption is that moisture damage is probable if a mixture is highly permeable to water (Ref 34).

Compression Test on Dry and Wet Specimens

All specimens are tested in compression and the index of retained strength calculated as the ratio of the compressive strengths of the immersed specimens to those of the dry ones (Refs 26 and 27): ASTM D1075-75 (AASHTO T-165-77).

This test measures the overall loss of cohesion resulting from the action of water on compacted asphalt mixtures. To perform this test, called the immersion-compression test, six 4-inch diameter by 4-inch high specimens are prepared. Three of the specimens are cured at 77°F in a dry condition (dry specimen). The other three specimens are immersed in a water bath at 120°F for 4 days to produce a moisture saturated condition (immersed specimen).

Texas Freeze-Thaw Pedestal Test

This test determines the number of freeze-thaw cycles required to induce cracking on the surface of a specimen (Refs 35, 36, and 37). This test procedure involves subjecting miniature asphalt-aggregate briquets immersed in water to repeated freeze-thaw cycles. The briquets are highly permeable to allow easy penetration of water and are designed to minimize mechanical interlocking of the aggregate particles by using a uniform aggregate size. The moisture susceptibility of an asphalt concrete mixture is evaluated by determining the freeze-thaw cycles required to crack a briquet seated on a beveled pedestal. The major test assumption is that cracking of the briquet is largely determined by the asphalt-aggregate bond.

Indirect Tensile Test on Dry and Wet Specimens

All specimens are tested in indirect tension, and the moisture susceptibility is determined by the ratio of tensile strength in a wet condition to that in a dry condition. Some of the earliest work in applying the indirect tensile test to the study of moisture damage was performed by Lottman (Ref 3) for the National Cooperative Highway Research Program (NCHRP).

In the indirect tensile test a cylindrical specimen is subjected to compressive loads distributed along two diametrically opposed loading strips that create a relatively uniform tensile stress perpendicular to and along

the diametrical plane which contains the applied load that leads to a splitting failure (Refs 38 and 39). Estimates of the tensile strength, modulus of elasticity, and Poisson's ratio can be calculated from the applied load and corresponding vertical and horizontal deformations (Refs 40 to 44).

Wet specimens are prepared by subjecting 4-inch diameter specimens to various vacuums in water, releasing the vacuum, and thus forcing by atmospheric pressure water into the voids available in the mixtures (Refs 45 to 47). After vacuum saturation and depending on the exact procedure used, specimens are placed in a plastic bag along with a small amount of water and subjected to a varying number of thermal cycles. Most procedures require specimens to be submerged in a water bath immediately before testing.

Summary

Of these tests it is felt that the Texas boiling test, Texas freeze-thaw pedestal test, and the indirect tensile test have the greatest potential for detecting and evaluating potential moisture-susceptible asphalt mixtures.

CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS

Based upon the results of this qualitative study, the following set of conclusions and recommendations has been prepared.

CONCLUSIONS

(1) The following definitions have been presented to eliminate confusion in identifying moisture distress types.
   (a) Stripping--a distress mechanism characterized by physical separation of asphalt cement and aggregate produced by the loss of adhesion between the asphalt cement and aggregate surface primarily due to the action of water or water vapor.
   (b) Softening--a distress mechanism thought to be related to stripping and characterized by overall loss of cohesion of the asphalt mixture and caused by degradation of the binder that separates aggregate particles.
   (c) Ravelling--a distress manifestation characterized by dislodgement of aggregate particles in the mixture from the surface downward or from the edges inward and that begins within 0.25 to 0.50 inches of the asphalt concrete surface and progresses downward.
   (d) Shelling--a distress manifestation characterized by loosening and subsequent removal of aggregate from a seal coat or other surface treatment.

(2) Stripping can be manifested on the road as:
   (a) fracture,
   (b) distortion, and
   (c) disintegration.

(3) The majority of observed moisture-related damage to asphalt mixture in Texas is confined to the eastern half of the state where wet environmental conditions and stripping-prone aggregate sources are present.

(4) Isolated occurrences of moisture-related damage have occurred in the western half of the state where local environmental and aggregate source conditions have combined to cause certain mixtures to strip.

(5) The following procedures are believed to directly improve adhesion and thus reduce water damage:
   (a) aggregate preheating,
   (b) use of chemical antistripping additives,
   (c) use of hydrated lime as an antistripping additive,
   (d) washing of aggregate, and
   (e) avoid siliceous and rhyolite aggregates.

(6) The following procedures are believed to reduce the adverse effects of moisture on bituminous mixtures through improved material characteristics or construction methods:
   (a) provide adequate surface drainage,
   (b) use only dense-graded mixtures that have about 3 to 5 percent air voids,
   (c) design a mixture that is compactible, and
   (d) use porous, rough surface textured aggregate.

RECOMMENDATIONS

(1) Practicing engineers should be trained to recognize moisture related distress so that positive steps can be taken in the rehabilitation stages to eliminate future distress.

(2) Local materials that contribute to observed moisture related distress should be positively identified so that corrective measures can be implemented in the design stages.

(3) Particular attention should be paid to determining which antistripping agents are effective with local materials. Treatment levels should be defined and specifications written to ensure efficient use.

(4) Every effort should be made in the design phase to develop a mixture which can be mixed, placed, and compacted in a manner to achieve approximately 3 to 5 percent air voids when in place. Particular attention should be paid to the aggregate gradation in order to avoid harsh or tender mixtures.

(5) Test methods should be developed which will accurately predict the moisture susceptibility of various asphalt aggregate combinations and identify the effectiveness of proposed antistripping agents. For mixtures common to Texas, the Texas Boiling Test, Texas Freeze-Thaw Pedestal Test, and the Indirect Tensile Test on wet and dry specimens can be used to perform this task.

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APPENDIX

FAILURE CONCEPTS

APPENDIX. FAILURE CONCEPTS

DISPLACEMENT CONCEPTS

The displacement concept uses as a model an aggregate particle embedded in an asphalt film as shown in Figure A1. Equilibrium of the contact point of the binder-aggregate system is considered. In the dry state, the contact point is in position A. During moist periods the contact point is in position B (Ref 48). This retraction from position A to position B decreases the contact areas of the binder-aggregate system thus allowing traffic to remove aggregate from a roadway surface (Ref 49). In addition, displacement has been shown to be a function of viscosity whereby high viscosity binders demonstrate more resistance to displacement (Ref 50). Viscosity effects can be observed through damage to new asphalt surfaces caused by early release of traffic. Asphalt cement in such a surface requires appropriate curing time and conditions in order to reach a planned viscosity.

DETACHMENT CONCEPTS

The detachment concept indicates that an aggregate particle may be coated with a bitumen but no adhesive bond exists between the two phases. This lack of bond may be explained by "thermodynamic replacement" of the bitumen by a thin film of water (Ref 51).

Aggregates having a high quartz or feldspar content have been shown to demonstrate a greater propensity of detachment. However, laboratory experimentation has shown that coated aggregates which are in a detached state will usually reattach when air dried (Ref 52).

Water causing detachment through thermodynamic replacement may come from three sources: (a) moist air circulating through open graded mixtures, (b) direct contact with water, and (c) capillary flow among the aggregate.

The molecular lattice structure of siliceous aggregate reacts with water molecules near the aggregate surface elevating the pH of the mixture. Hydroxyl ions formed by the reaction of water with the silica in certain minerals, creating the elevated pH, has been shown to accelerate the detachment mechanism. Thus, any silica mineral (such as quartz or feldspar) used as an aggregate may be susceptible to moisture related damage (Ref 53).

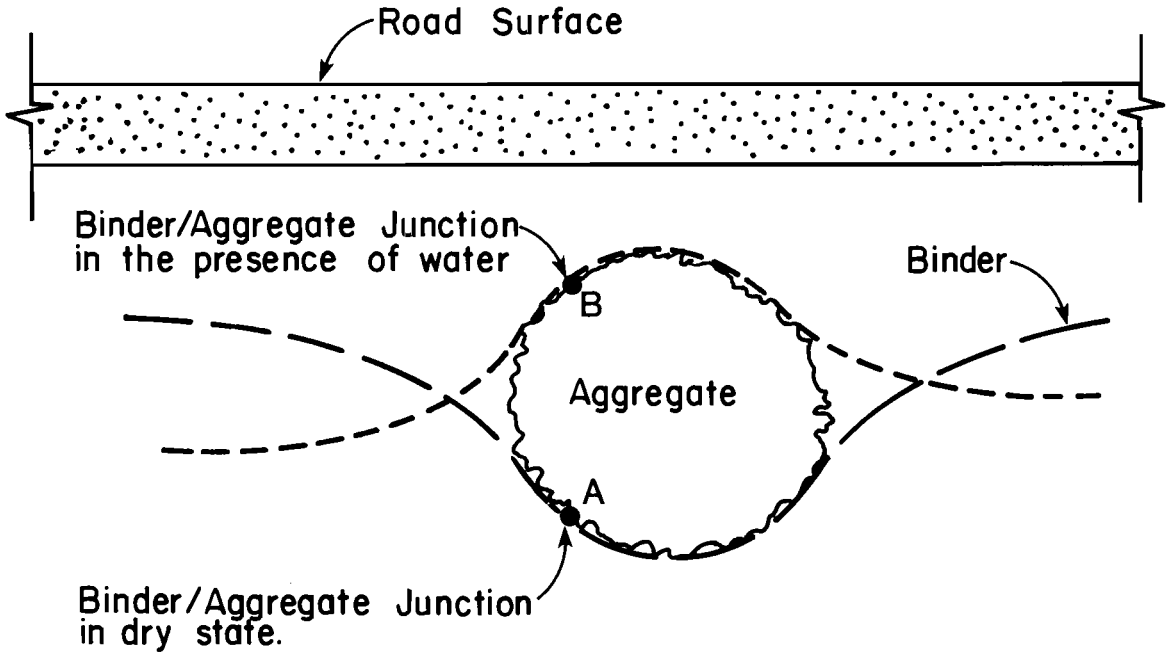


Fig A1. Schematic of interfaces of asphalt and aggregate in the presence and absence of water (Ref 48).

PORE PRESSURE

The pore pressure concept theorizes that asphalt concrete mixes that have void spaces completely saturated with water are especially prone to stripping when pressure is applied. There are two sources of void water pressure: (a) pumping action due to traffic loads, and (b) thermally induced void water pressure.

Pumping action through loading causes high pore pressures and additional compaction (Ref 49). Low void ratio mixes are particularly susceptible to high pore pressures since the water is not free to move throughout the mix. High temperatures may also induce high pore pressures. Water contained in pores expands when heated. Again, in a low void ratio mix the movement of expanding water is constrained creating even higher pressures.

Void water pressure caused by either pumping or heat creates void paths between binder and aggregate particles. These void paths eventually surround an aggregate causing a complete loss of adhesion. This is illustrated in Figure A2 (Ref 54).

CHEMICAL DISBONDING

The chemical disbonding concept considers "double layers" of water molecules that may build up between aggregate minerals and asphalt surfaces. In this theory it is believed that water diffuses through the asphalt layer surrounding an aggregate particle. Siliceous aggregates take on a negative charge to resist this alkaline aqueous environment. Any unabsorbed anionic asphalt near the aggregate surface is negatively charged. Thus, in this environment, two negatively charged surfaces will be in contact causing a mutual repulsion. As more water is attracted to the double layer, asphalt-aggregate disbonding increases. Eventually, the quantity of disbonded surface around an aggregate particle will encompass its entire periphery and complete separation results (Ref 55).

BLISTERING AND PITTING

The blistering and pitting concept theorizes a mechanical mechanism by which water can penetrate an asphalt coating and act on an aggregate particle. Sunlight normally raises the temperature of a pavement and lowers

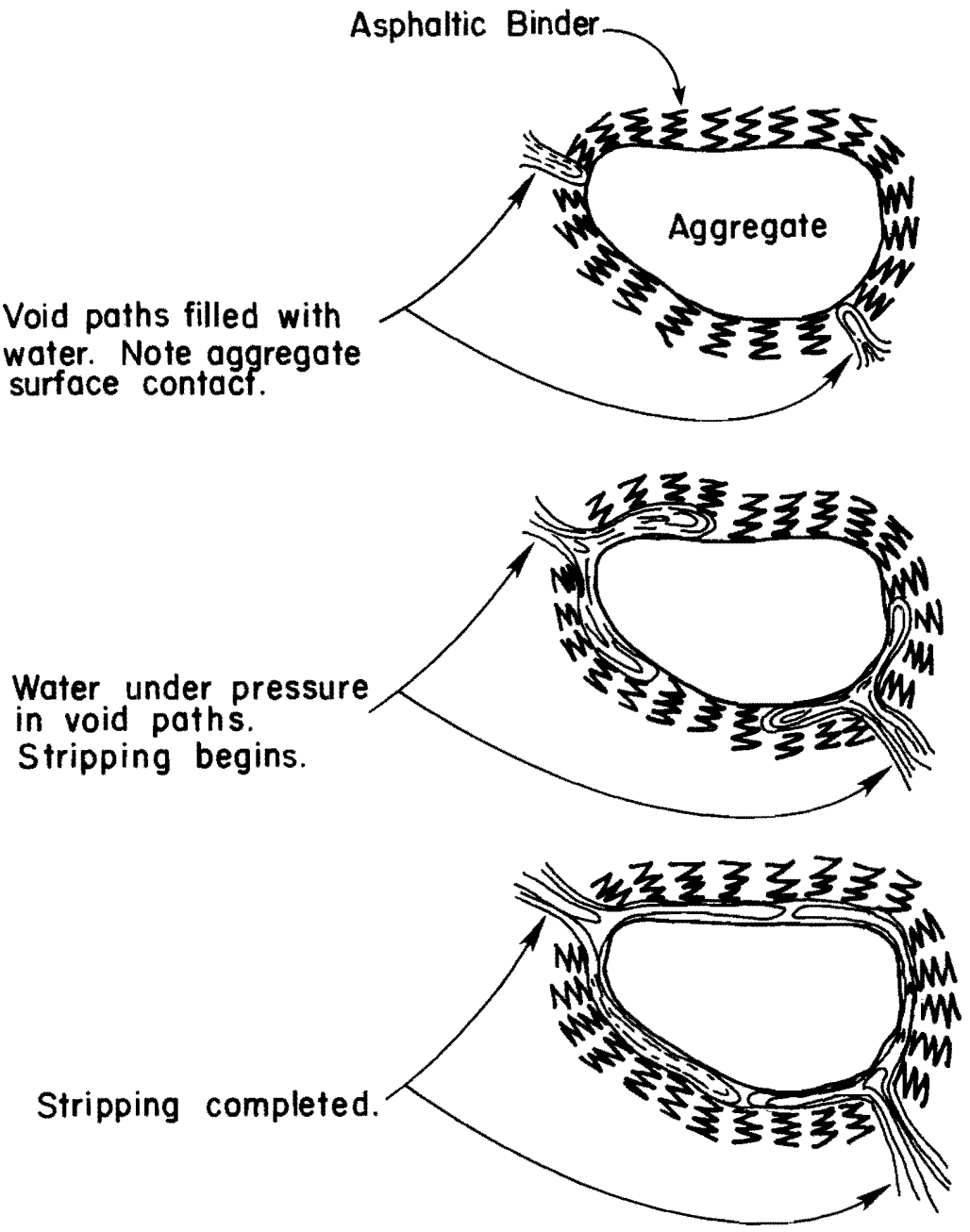


Fig A2. Hypothesized void pressure mechanism (Ref 54).

the viscosity of the asphalt binder. If the pavement is covered by water from recent rainfall the less viscous asphalt may tend to flow around a water droplet creating a blister. With increased heating the blister grows, eventually breaks, and leaves a pit. This may allow more water to enter the asphalt-aggregate system (Ref 56). Figure A3 demonstrates the blistering and pitting concept.

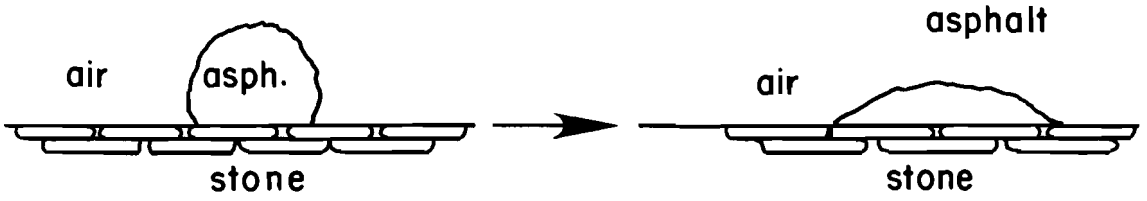
FILM RUPTURE

The film rupture attempts to explain how water may penetrate an asphalt coating. The magnitude of surface tension at an air-water interface is approximately twice as large as the surface tension of an asphalt. Therefore, when asphalt is in the presence of an air-water interface, it is drawn up along the interface. This effect is known as "interfacial pulling."

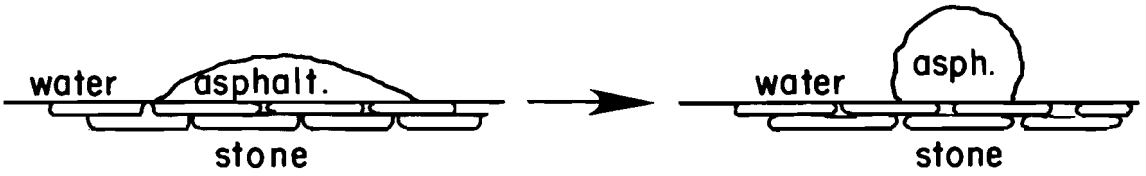
Since there are many air voids in asphalt concrete, when water enters a pavement system, junctions form at the air-water-asphalt interface. At these junctions, interfacial pulling may create breaks in the asphalt film thus allowing successively deeper water penetration (Ref 57).

EMULSION FORMATION

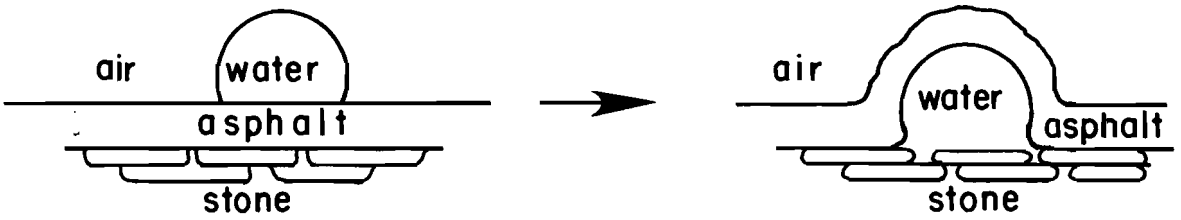
The emulsion formation concept suggests that when water enters the asphalt-aggregate system an electronically charged asphalt emulsion forms. This emulsion has the same charge as that of the aggregate and the like charges create disbonding (Ref 57).



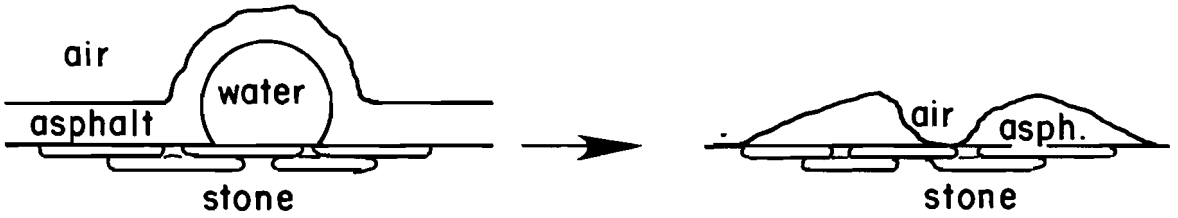
(a) Spreading in air.



(b) Normal stripping.



(c) Blister formation.



(d) Pitting.

Fig A3. Blistering and pitting (Ref 56).