NCAT Report 88-02

STRIPPING IN HMA MIXTURES: STATE-OF-THE-ART AND CRITICAL REVIEW OF TEST METHODS

By

Badru M. Kiggundu
Freddy L. Roberts

September 1988

National Center for Asphalt Technology
NCAT
AUBURN UNIVERSITY
277 Technology Parkway • Auburn, AL 36830

STRIPPING IN HMA MIXTURES: STATE-OF-THE-ART AND CRITICAL REVIEW OF TEST METHODS

By

Badru M. Kiggundu
National Center for Asphalt Technology
Auburn University, Alabama

Freddy L. Roberts
Director
National Center for Asphalt Technology
Auburn University, Alabama

NCAT Report 88-02

September 1988

DISCLAIMER

ABSTRACT

This report presents review summaries of the state-of-the-art regarding stripping in hot mix asphalt (HMA) mixtures. The review stresses efforts concerned with methods development, evaluation and presents a critical review of select methods including Lottman (NCHRP 246), Tunnicliff-Root (NCHRP 274), Immersion Compression, 10-minute boil test, and the Nevada dynamic strip method.

The results of the critical review of methods indicated the following ranking order: Lottman test, Tunnicliff-Root test, 10-Minute Boil test, Immersion Compression, and Nevada Dynamic Strip test. The basis of the analysis was a proposed success/failure pattern which was developed using published data on stripping.

Other products of this research include: proposed relationship between stripping theories and mechanisms, and an appended summary of findings from surveys of the users of the stripping tests.

STRIPPING IN HMA MIXTURES: STATE-OF-THE-ART AND CRITICAL REVIEW OF TEST METHODS

Badru M. Kiggundu and Freddy L. Roberts

INTRODUCTION

Background

Stripping is a major distress occurring in hot mix asphalt (HMA) pavements in the United States and in various parts of the world. Pavement performance is adversely affected by stripping and unforeseen increases in maintenance budgets are often incurred. The causes of stripping remain obscure and predictability is relatively non-deterministic. Thus the need to unfold an understanding of the mechanisms, and to develop simple but reliable tests and judgement criteria remains urgent.

Objective

The objectives underlying the National Center for Asphalt Technology (NCAT) Research Project are to:

- Minimize or eliminate stripping of asphalt cements from aggregate by making breakthroughs in the understanding of the mechanisms
- Develop simple laboratory test procedures to reliably measure the stripping potential before the fact
- Evaluate the need, function, and cost-effectiveness of antistripping additives

These objectives shall be accomplished through a coordinated study plan.

Scope

This phase of the study presents the state-of-the-art of stripping technology, definition of mechanisms, outline and discussion of test methods, test criteria, on-going studies, general discussion, future studies, conclusions and recommendations.

Research Plan

A research plan to accomplish the project objectives is outlined in Table 1. Specific tasks undertaken so far and included in this report are:

- Comprehensive Technology Review
  - Literature review - General Concepts
  - Define mechanisms
  - Stripping theories
- Stripping Studies - Past
- Contact Surveys of users of stripping methods
- Review Test Methods
- Review Test Criteria
- Identify Most Promising Test Methods
- Stripping Studies - On-going
  - Commence Limited Fundamental Studies in Stripping - NCAT
    - Develop a Detection Method for Liquid Antistripping Agents in asphalt cement,
    - Explore application of Surface Energy Concepts in Stripping, and
    - Explore application of Selective Adsorption phenomenon in stripping.

Limited information on the initiated NCAT stripping studies shall be presented in this report because the work is still in progress. Further work shall be reported at a later date. The findings from contact surveys are summarized in Appendix A at the end of this report. Portions of the contents in Appendix A shall be included in pertinent sections of this report.

Table 1. Proposed Stripping Study Plan

Task	Description	Products	Projected Target
I	Minimize stripping of asphalt-aggregate mixtures by making breakthroughs in defining the mechanisms of stripping. Identify and evaluate test methodologies: develop criteria for test methodology and method selection.	Comprehensive Report Executive summary report and other interim reports	Sept. 1988
II	Develop test methodology for measuring stripping potential; Evaluate methodology; Define criteria for stripping potential from test measurements; Define modifications to test methodology.	Test methodology Test criteria and report	Sept. 1990
III	Identify criteria for need: test method; function and cost effectiveness of antistripping additives; evaluate effects of antistripping additives using developed test methodology and finalize test development.	Criteria test method. Verified methodology reports ASTM or AASHTO methods standardization efforts commence	Sept. 1991
IV	Field Verification	Adjustments to test methodology and criteria plus report	Variable

NOTE : The plan in this table is subject to variation depending on results of research. Some efforts may be accomplished earlier than planned.

TECHNOLOGY REVIEW

General Concepts

Stripping is a major distress occurring in HMA pavement mixtures in the United States and in many parts of the world. Hubbard (*1*) states that stripping effects have been observed since the advent of paving technology with bituminous materials. Since this phenomenon was detected, many studies, numerous technical papers, articles, and presentations have resulted. The complexity of the problem is evidenced by the fact that these efforts continue through the present day in search of a definitive qualitative and quantitative solution towards understanding and predicting stripping potential of HMA. Unfortunately, stripping continues to occur in our pavements and about 23 percent (Appendix A) of the FHWA regions have recently reported (*2*) occurrence of stripping.

The persistent occurrence of the stripping distress in spite of the numerous studies, theories, evolved test methods, and development of supposedly stripping abating products implies that the basic or fundamental causes are not well understood. This postulation is manifested by the number of definitions which have been offered for the stripping distress, some of which are summarized in Table 2. Secondly, the complexity is manifested by the numerous hypothesized mechanisms, namely detachment, displacement, spontaneous emulsification, film rupture, pore pressure, and hydraulic scouring. These mechanisms are discussed later. Lastly, a number of theories namely mechanical interlock: chemical reaction: molecular orientation or interfacial phenomenon have been postulated to explain stripping. None of the theories is universally accepted and there is no clear definition describing the dominant theory or whether they all act in combination. In summary, Majidzadeh (3) states that stripping due to adhesion failure is an economic loss to society and an engineering design failure of an otherwise sound pavement mixture. Pavement failures attributed to stripping are probably not a result of a single

Table 2. Various Definitions of Stripping in Bituminous Mixtures

Source	Reference	Definition	Completeness
J.C. Peterson	Seminar Auburn University Spring 1987	Deterioration or loss of the adhesive bond between the asphalt and the aggregate from the action of water.	partial
T.W. Kennedy et al.	AAPT, Vol. 51 1982, or CTR-3-9-79-253-1 1984	The physical separation of the asphalt cement from the aggregate produced by the loss of adhesion primarily due to the action of water or water vapor.	partial
D.E. Tunniclif et al.	AAPT, Vol. 51, 1982	The displacement of asphalt cement films from aggregate surfaces by water caused by conditions under which the aggregate surface is more easily wetted by water than by asphalt.	partial
Asphalt Institute	ES-10 (1987)	The breaking of the adhesive bond between the aggregate surface and the asphalt cement.	partial
Khosla et al. and Gharaybeh, F.	TRR 911 (1983) and Dissertation 1987 Auburn University	The loss of the bond between the asphalt binder and the mineral aggregate due to separation of asphalt cement coating in presence of water.	more complete
Kiggundu et al.	NCAT 1987 Auburn University	The progressive functional deterioration of a pavement mixture by loss of the adhesive bond between the asphalt cement and the aggregate surface and/or loss of the cohesive resistance within the asphalt cement principally from the action of water.	

AAPT = Association of Asphalt Paving Technologists
CTR = Center for Transportation Research
ES = Educational Series
NCAT = National Center for Asphalt Technology
TRR = Transportation Research Institute

quantifiable factor. In spite of these variations in definitions, water is the only widely claimed (4,5,6) cause for stripping. This is a very simplistic assertion since there are many variables such as design, material selections, and compatibility considerations which can be considered in explaining the propensity of water action to cause stripping of pavement mixtures. Fromm (*6*) states, "The major problem is to understand how the water penetrates the asphalt film. If it can be retarded, a considerable improvement would result. The development of a good adhesion promoting agent to retard the detachment of the films by water, would also be an improvement." Unfortunately, the results of a recent FHWA Ad Hoc Task Force Study (*2*) revealed the continued occurrence of stripping in various parts of the United States and that renewed efforts are warranted to arrest the causes using available and/or new technology. Mendenhall et al. (*2*) reported results of a survey showing 23 percent of FHWA regional offices indicated that pavement mixtures in their regions experienced moderate to extensive stripping. The regions reporting the most were located in the southeastern, southern, mountain, and northwestern parts of the United States.

Stripping Mechanisms

Numerous mechanisms have been proposed for stripping including detachment, displacement, spontaneous emulsification, film rupture, pore pressure, and hydraulic scouring. These mechanisms are not well understood and there is lack of agreement regarding the relative contribution of each mechanism to stripping in particular cases. Little attention has been given to explain the non-universal application of these mechanisms to the various climatic environments. It is probable that the predominant stripping mechanisms in a hot-dry environment differ from the mechanisms in hot-wet, cold-dry, and cold-wet environments. It is through understanding the possible differences in the stripping mechanisms in relation to the environments, service and material conditions, that appropriate test methods and test conditions can be developed. The above observations concur with the contact survey findings summarized in Appendix A. Fromm (*6*), Taylor et al. (*7*), Scott (*8*) and others discuss the hypothesized mechanisms as follows:

Detachment

This mechanism is defined as the microscopic separation of an asphalt film from the aggregate surface by a thin layer of water with no obvious break in the asphalt film (*3*, *4*, *5*). It is probable the thin film of water could result from a sub monolayer of water which was not dried off the aggregate surface: interstitial pore water which was initially lodged into the pores but vaporized and condensed on the surface; and possibly water which may permeate through the asphalt film and reach the interface region. The proposed and published indicator of this mechanism is that the asphalt film can be readily peeled off the aggregate surface.

Displacement

Displacement is caused by preferential removal of asphalt film from aggregate surface by water. Taylor et al. (*7*), Tarrer (*9*) and others describe displacement occurring due to the presence of a discontinuity or break in the asphalt film, such as pinholes and film rupture, where asphalt, aggregate, and free water are in contact. Hence, water may displace asphalt from the aggregate surface because of the interfacial energy effect. This interfacial energy effect shall be presented later in a section discussing proposed theories governing the stripping phenomenon. Goodrich (*10*) in a personal discussion reported evidence from limited studies which were conducted at Chevron Research Company indicating that asphalt films are not impervious. Therefore penetration of the asphalt film by water would permit moisture to get to the asphalt-aggregate interface and provide opportunity for a displacement mechanism to become active.

Spontaneous Emulsification

Spontaneous emulsification occurs (5) when an inverted emulsion of water droplets in asphalt cement forms rather than the converse. Investigators have noted that this process can be exacerbated under traffic on mixtures laden with free water. Fromm (6) conducted experiments to demonstrate the formation of an emulsion in which he observed that once the emulsion formation penetrated to the substrate, the adhesive bond was broken. Fromm and many investigators have observed the formation of a brownish color on the surface of asphalt films (approximately 1/8 inch) in severely stripped mixtures as well as on asphalt films submerged in water. Kiggundu (11) conducted limited experiments by placing films of virgin AC-5 and AC-10 asphalts in bottoms of beakers, submerging them in distilled water, and placing them on a window sill for observation. Within one week the AC-5 started losing the glossy appearance on the top surface while the AC-10 took slightly longer time to tan. They both assumed a vividly brownish color after a number of weeks of soaking, however, they regained the glossy color after decanting the supernatant and allowing the surface to dry. The presence of some antistripping products and hydrophilic calcareous minerals and some baghouse fines are reported (5, 12) to be materials that enhance the probability of formation of inverted asphalt emulsions.

In summary, the observations by Fromm and other investigators suggest that stripping by emulsion formation may be an important mechanism.

Film Rupture

Film rupture is reported (5, 6) to initiate stripping when film fissures occur at sharp aggregate contact, or points due to dust particles on the aggregate surface. The rupture may occur due to construction loads, operating traffic during service conditions, or could be environmentally induced by freeze-thaw cycling. Once a break in the film occurs, moisture has access to the interface. Thelen (13) reports that presence of dust or other surface coatings on the aggregate can enhance the formation of blisters and pits. These forms of film defects may lead to rupturing of the film and hence easy access to the interface by water.

Pore Pressure

This mechanism precipitates from the presence of water in the pore structure of the HMA locations where segregation is prevalent at layer boundaries when heavy traffic loadings occur and during freeze-thaw cycling. Due to pore pressure pavement layers are known to strip at the interfaces, pavement layers have been observed (contact survey findings) disintegrate usually from bottom upward, and in a few instances disintegration within a layer in both directions. In a majority of cases, the binder layers disintegrate first followed by surface layers. The pore pressure mechanism was postulated by Lottman (14).

Hydraulic Scouring

Hydraulic scouring is caused by the occurrence of a capillary tension/compression phenomenon (5) around a moving heavy traffic wheel on a saturated HMA structure. The asphalt is stripped-off the aggregate producing defects such as surface ravelling. In addition, dust is reported (5) to mix with rain water and, in the presence of traffic, can enhance the abrasion of asphalt films from the aggregate.

Other mechanisms documented in literature include osmosis (6) and pull-back (6). Osmosis is described occurring due to presence of salts or salt solutions in the aggregate pores and hence creating an osmotic pressure gradient that sucks water through the asphalt film. Some researchers dispute this mechanism like Thelen (13) saying the process is too slow. Many others support the validity of the mechanisms, for example Mark (15). Factors that affect the occurrence of this mechanism include:

- Some asphalts are caustic treated in their manufacture
- Some aggregates compositionally possess ions of salt in the surface
- Incomplete druing of aggregates during mix preparation

- Possibility that asphalt films are permeable, suggest that the hypothesis of an osmosis mechanism may be worth consideration

The pull-back mechanism is evidenced by observations made by many investigators that asphalt mixtures are self-healing or forgiving materials. Fromm (*6*) reports that field stripped mixtures seem to self-heal after laboratory storage. This phenomenon has been observed by Kennedy et al. (*16*), Parker et al. (*17*), and Yoon (*18*) in running the boiling water test on loose mixtures. On completion of the boiling phase, mixtures which are drained while hot tend to recover additional asphalt coating as compared to mixtures which are cooled under water and drained after cooling.

Additional Mechanisms

Many investigators have recognized the complexity of the stripping phenomenon. Defining the mechanisms and causes remains a difficult task. Through NCAT research, discussions with a number of investigators, and contact surveys, stripping mechanisms may be considered asphalt-aggregate specific, environmental or climatic specific, load condition specific and possibly other combinations of variables. On the basis of limited NCAT study data, and literature reviews, the following are suggested additional mechanisms:

1. pH instability mechanism - Adherence of asphalt to the aggregate is strongly influence by the pH of the contact water as has been demonstrated by Kennedy et al. (*19*), Scott (*8*), Yoon (*18*) and others. Kennedy et al. investigated the effects of varying sources of water (tap, distilled, etc.) on the retained coating by a boil test and showed that significant differences in test results occurred as a result of differences in the source of water. Fehsenfeld et al. (*12*) observed that the pH of contact water can cause the value of the contact angle to shift thereby affecting the wetting characteristics of the interface region. Scott (*8*) investigated the pH effects by studying the interfacial tension at the asphalt/water interface and showed that values of interfacial tension between asphalt films and glass at 100°C (212°F) peaked at intermediate pH values, up to 9, but dropped as the pH increased. Scott's tests were run with water having a pH of up to 14 and interfacial tension values were lowest at these high pH values. Yoon used a boil test to evaluate the effects of varying the pH of water on the retained coating. Yoon initially measured the pH tests of the contact water produced by boiling six different aggregates in distilled water. Similar tests were conducted by Scott using a variety of aggregates. The results conclusively indicated that the pH of contact water increased with duration of contact and tended to be aggregate specific. The pH values were observed to stabilize after 5 to 10 minutes of boiling. Yoon then conducted boil tests using asphalt-aggregate mixtures with water of varying pH. The results indicated that coating retention decreased as the pH increased. These results strongly suggest that stabilization of the pH sensitivity at the asphalt-aggregate interface would minimize the potential for bond breakage, provide strong durable bonds and hence reduce stripping. Thus, this proposed mechanism is under continued investigation in order to improve its definition, implication to aggregate surface properties, and HMA performance.
2. In concurrence with findings from the contact surveys, there is a need to define mechanisms inclusive of effects of environment or climate and specificity to the asphalt-aggregate and/or additive material systems. Many studies have showed that changing one component of the aggregate system can improve or worsen the stripping propensity of a mixture. Dunning (*20*) reports that stripping of HMA can be affected by the individual sensitivity of asphalt and/or aggregate to moisture. Hydrophillic aggregates, Dunning and others argue, prefer being wetted by water than by an oil. In this case, the asphalt appears to bead up in the same manner as water beads up in a greased pan. Dunning states that this type of stripping may be alleviated by using an additive which improves the wetting potential of the asphalt for the aggregate surface. Water sensitive asphalts are also discussed by Dunning by

reporting that use of caustic treating of crudes in some refining processes leads to asphalts laden with sodium naphthenates. These naphthenates are believed to work as water-in-asphalt emulsifiers and their presence may be suspect if the asphalt turns brown after say 24-hour water soak of an asphalt-aggregate mixture. Phillips and Marek (*21*) argue that stripping mechanisms in asphalt-aggregate mixtures made with granites and gravels can be characterized by a near total loss of adhesion while carbonaceous mixtures can sustain coherent adhesion but weakened cohesion in the bulk phase of the asphalt. Thus, material selections should be made to optimize compatibility or procedures should be developed to facilitate choosing materials (asphalts, aggregates, and/or additives) on the basis of compatible behavior.

Stripping Theories

Numerous theories have been hypothesized to explain the water-resistance of bitumen-coated aggregate. Rice (*4*) classifies these theories as mechanical interlocking, chemical reaction, and molecular orientation or surface energy theory each of which is discussed below.

Mechanical Interlocking

Thelen (*13*), Rice (*4*) and other researchers postulate that surface texture of the aggregate is the main factor affecting adhesion. Mechanical interlocking assumes the absence of chemical interaction between asphalt and aggregate. The bond strength is assumed to be derived from the cohesion in the binder and interlocking properties of the aggregate particles which include individual crystal faces, aggregate porosity, absorption, surface coating, and angularity. The absence of a sound interlocking network of the above properties is assumed to render the system to the adverse effects of water.

Chemical Reaction

The postulation of this theory arises due to the presence of acidic and basic components in each asphalt-aggregate system. The postulate is that these components react forming water-insoluble compounds. The theory suggests (*4*) the possibility of selective chemical. reaction between the aggregate and asphalt species. Recent investigations by Jeon et al. (*22*) and others have alluded to the possibility of the occurrence of a chemisorption mechanism between some asphalt functionalities and aggregate surfaces. This result was observed from selective adsorption-desorption studies between model asphalt functionalities and model silica aggregate surface. Jeon et al. applied a Langmuir (*23*) model to quantify chemisorption and low coverage physisorption in his study and showed that the strength of adsorptive forces, amount of asphalt adsorbed per unit weight of the adsorbent, and mono-layer coverage of adsorbate can be quantified. Thelen (*13*) had earlier proposed that formation of a chemisorption type bond may be necessary in order to minimize the stripping potential in asphalt-aggregate mixtures. Thelen did not verify this proposition.

Molecular Orientation or Surface Energy

This theory depicts structuring of asphalt molecules at the asphalt-aggregate interface. This theory assumes (*1*, *4*, *24*) that adhesion between asphalt and aggregate is facilitated by a surface energy reduction on the aggregate as the asphalt is adsorbed on to the surface.

Yoon (*18*), Tarrer (*9*) and other investigators observed that aggregates which imparted a relatively high pH value to contact water and/or which had a relatively high zeta potential had a high propensity to strip. Scott (*8*) from reviewing his work and works of other investigators states, “It is reasonable to assume that if water penetrates the asphalt film to the mineral surface under conditions where microdroplets are formed below an asphalt layer, the pH reached may be sufficient to ionize and dissociate adsorbed asphalt molecules in a number of cases.” Thelen (*13*) on the other hand argues that reducing the surface energy of the aggregate is not a sufficient condition to abate the stripping potential in asphalt-aggregate mixtures. However, Thelen does not substantiate his argument.

The three theories discussed above probably act in combination or one dominates another for each asphalt-aggregate system. Thus, more work is necessary to discriminate the contributions described by the three theories.

Combining Theories and Mechanisms in Stripping

In the existing technical literature little attention has been paid to the relationship between theories and mechanisms that have been postulated to explain stripping. Thus an attempt is made in this report to propose an initial set of relationships between theories and mechanisms. Only primary and secondary contribution relationships are suggested in Table 3. The proposed relationships represent only a first attempt and may need adjustments in the sense that possibilities of role reversals are entirely likely and other factors may come into play during the time that a mechanism remains active.

Table 3. Showing Proposed Theory-Mechanism Relationships in HMA Stripping

		THEORY								
		Mechanical Interlock			**Chemical Reaction**			**Interfacial Energy**		
	Proposed Operating Mode	P	C	P-C	P	C	P-C	P	C	P-C
Stripping Mechanism	Detachment	S						S	W	
	Displacement					S		S		
	Spontaneous Emulsification				S	W				
	Film Rupture	S								
	Pore Pressure	S								
	Hydraulic Scouring	S								
	pH Instability					S				

P = Physical
C = Chemical
P-C = Physical-Chemical
S = Primary Contributor
W = Secondary Contributor

The primary reasons that these relationships are proposed are that relations may help with developing which theory-mechanism relationship would be:

- Best dealt with by improvements in mix design
- Best served in material selection techniques using conventional tests/properties
- Best understood by employing special tests/properties, for instance, compatibility properties/tests/considerations

An attempt to completely explain each element in Table 3 has been attempted at the time of this report. However, two stripping mechanisms are described as examples. The first mechanism is detachment which is believed to be explained by physical and chemical aspects of the interfacial energy theory as well as the physical aspects of the mechanical interlock theory. The physical rationale is manifested solely by surface energy considerations whereas the chemical rationale is contributed by the effect of polarity of the molecules present at the common boundary. The physical aspects of the mechanical interlock theory may be due detachment resulting from presence of a thin layer of dust or other foreign matter which prevents bonding between the asphalt and the aggregate. It is also highly likely that the detachment mechanism may precede the displacement mechanism. However the displacement mechanism is likely to be rationalized by both the interfacial and chemical reaction theories.

The last mechanism “pH instability” is more likely to be explained by chemical aspects of the chemical reaction theory and by the physical-chemical aspects of the interfacial energy theory. These arguments concur with the previous assumption that in absence of a clear cut distinction between the contributions of either theory, two or perhaps three theories may as well be acting concurrently at some stage of stripping. A distinct solution remains distant and expectations are directed at potential breakthroughs through the SHRP research efforts.

STRIPPING STUDIES

There are numerous studies which have been conducted to evaluate various aspects of the stripping problem. These studies are categorized based on the measures of stripping presented in the study and are:

- Fundamental studies in stripping
- Qualitative studies in stripping
- Quantitative or engineering based studies in stripping including a list of current studies

Fundamental Studies in Stripping

These studies have predominantly been directed at understanding the interface phenomenon. They are studies whose information cannot be easily used in design but contribute to improved understanding of the stripping phenomenon. Petersen et al. (*25*) have spearheaded the majority of the efforts specifically marked as “asphalt-aggregate interaction as it relates to pavement moisture-damage.” Petersen et al. consider pavement moisture-damage to be related to the rupture of the adhesive bond at the asphalt-aggregate interface in contrast to stripping which was defined in Sections I and II. Thus moisture-induced damage can be considered a subset of stripping where the latter is the terminal manifestation of the effects of water to a pavement mixture. In the moisture-induced pavement damaged condition, both physical and chemical properties of the constituent mixture materials are presumed important.

Petersen et al. (*25*) efforts were directed at determining the physiochemical properties at the asphalt-aggregate interface. In these studies qualitative and quantitative determinations of the types of functionalities at the interface (*26*, *27*), relative adsorption/desorption (*28*, *29*, *30*) of these functionalities were undertaken. The following asphalt functionalities have been quantitatively and qualitatively identified: ketones, carboxylic acids, anhydrides, 2 quinolone and others. The results indicated that carboxylic acids are most selectively adsorbed on the aggregate surfaces. Conversely, carboxylic acids are most easily stripped off aggregate surfaces by the action of water.

In addition, asphalt-aggregate mixtures involving a number asphalt-aggregate systems were selectively desorbed of the asphalt coating by using staged solvent wash with intermittent water saturation freeze-thaw. The freeze-thaw stage was int ended to displace strongly adsorbed water sensitive components off the aggregate surface. The intermittent freeze-thaw stages were followed by final refluxing using pyridine. Each fraction was recovered and analyzed for the distribution of functionalities. The numerical results of the functionalities in the final pyridine wash were divided by corresponding data from the so called “loosely” held asphalt fractions to establish relative distributions of the functionalities in the various fractions called “Ratios.”

Within eight asphalt-aggregate systems, the carboxylic acid functionality had ratios ranging from 12 to 68 percent; and anhydride from 4 to 32 percent; 2 quinolone types from 3 to 10: and the rest of the compounds followed this descending order. These results suggest in concurrence with the authors observation that carboxylic acids and anhydrides have the greatest affinity for aggregate surfaces.

Additional fundamental studies include disbonding studies by Scott (*8*) discussed in Section II, bond energy measurement by Ensley et al. (*31*, *32*) and nitrogen adsorption studies by Plancher (*33*). Ensley et al. measured heat released from interacting asphalt and aggregate by microcalorimetry. Results from these studies suggest that stripping potential could be related to bond strength measurements. Plancher et al. interacted nitrogen compounds with various aggregate surfaces using a range of temperatures. Their results suggest that aggregates which strongly interact with nitrogen compounds may have less stripping potential. More work in these fundamental areas needs to be uncovered.

Qualitative Studies in Stripping

Numerous studies have involved development of indicator tests for stripping. These efforts have produced tests which use semi-subjective and subjective assessments to infer the stripping potential. Tests developed from these studies include the ASTM D 33625 1-minute boil test (to be discussed later), the Texas Freeze-Thaw Pedestal test (*35*), Gagle procedure (*36*), the Quick Bottle test (*37*), the Rolling Bottle Method (*38*), and many others.

The 1-minute boil test is a field oriented test in which a mixture (plant or other) is boiled for 1-minute and visually observed for coating retention. It is considered that 95 percent and higher retained coating indicates a “passing” mixture whereas below 95 percent denotes “failure.” The test is considered unfavorable because of the subjectivity of the rating pattern and rarity of users. Efforts are underway (1988) in ASTM D04-22 to revise this test.

The WST procedure measures the number of freeze-thaw cycles an asphalt-aggregate briquette of specified dimensions takes to develop cracks. This test is conducted on reground one-size stone and therefore considered by numerous practical oriented investigators to be unrepresentative of actual conditions. The Texas Freeze-Thaw Pedestal Test is an outgrowth of the WST procedure with modifications introduced to make it more acceptable to engineering applications. However, findings from contact surveys (Appendix A) and literature reviews indicate that this test has worked well on some materials and not so well on others as a predictor of stripping potential.

The Gagle procedure was developed to test the finer portion of the grading for adhesion potential. with asphalts. The amount of tanning an asphalt-aggregate mixture or pellet undergoes after 24 hour immersion in distilled water is reported to be indicative of the adhesion potential of the mixture. It has been a localized test and there is no evidence of continued use of this test in the literature.

The Quick Bottle Test is used to judge coating ability of an asphalt-additive blend on Ottawa sand. The mixture is vigorously shaken under water after which the supernatant is drained and the sand-binder mixture emptied on a paper towel for coating observation. The results are usually reported as pass or fail. The use of this test has been conducted by a number of state departments of transportation.

Rolling Bottle Method - This test was recently reported from Sweden or Nordic region as a predictor for percent coating. A single coated aggregate is dropped in a half-filled bottle of distilled water till the required sample size is obtained. The distilled water is maintained at 41°F (5°C) in order to inhibit agglomeration potential of the coated aggregates. Bottles containing the sample are placed in a rolling machine which turns at 40 rpm if the asphalt mixture is additive free, otherwise 60 rpm. This test runs for three days with two independent evaluations of the coating recommended at 5, 24, 48, and 72 hours after start of the test. These evaluations are used to determine the mean degree of coverage as the test statistic.

Other tests discussed by Taylor et al. (7) include dye adsorption, mechanical integration method, Radioactive Isotope Tracer Technique, Tracer-Salt with Flame Photometer Analysis, Light-Reflection Method, a Chemical Immersion test by Reidel and Weber, Abrasion Displacement, Briquet Soaking, swell, peeling, detachment, and stripping coefficient measurement. The general relative use of these methods is fairly low, and thus a detailed discussion is not included in this report.

Quantitative or Engineering Based Studies in Stripping

This group of studies constitutes the bulk of efforts directed at developing tests for making quantitative predictions, developing criteria for assessing failure, and applying or interpreting laboratory test results to predict field performance. Each of these areas shall be considered in more detail in the subsequent discussions.

Stripping Tests - Table 4 lists tests which have been developed to predict the stripping phenomenon-quantitatively as per literature reviews and contact surveys (Appendix A). In addition to the methods listed in Table 3 is a class of tests used to measure parameters like percent weight loss through an abrasive operation. The results from these tests are used as indicators for stripping potential. These tests include:

- Dynamic Strip Test (Nevada)
- Cold Water Abrasion Test (Minnesota)
- Moisture Vapor Susceptibility Test (California)
- Surface Abrasion Test (California)

Table 4. Quantitative Stripping Tests

Method	**ASTM/AASHTO/ Other Status**	**Relative Use[1] Indication**	**Designated Precision[2] ASTM/AASHTO/ Other**
Immersion Compression Test	D 1075, T 165	High	50% (ASTM/AASHTO)
Indirect Tensile Test • Lottman version • Tunnicliff/Root version	None T 283-85 (parts) T 283-85 (parts), ASTM Efforts complete June 1988	Many versions in use Medium Medium to High	Not 21.4-26% (Ref. 11)[3] 23.0% (Ref. 12)
Marshall Immersion Test • Wet Evacuation • Dry Evacuation	No standard but ASTM draft prepared	Very Low	Localized precision
Resilient Modulus Test	None but use ASTM D 4123	Low to Medium	Not established
Double Punch Method	None - under trial in Arizona	Very Low	Not documented

1 - Use in specification and/or research
2 - Reproducibility on test parameter (multi-laboratory)
3 - Based on coefficient of variation using data from two laboratories
4 - Reproducibility based on multi-laboratory effort

Each test is briefly discussed below.

1. Immersion Compression Test - This test is reported (*39*) to have been standardized around 1945 by the Bureau of Public Roads. The method is currently designated ASTM D 1075 or AASHTO T 165.

   Test specimens which are 4x4 inch are prepared using the procedure ASTM 1074. These specimens are divided into two sets which include a set to be tested dry (control) and another set to be tested after water treatment (wet set). Testing for compressive strength is usually done at 77°F (25°C) at deformation rates ranging from 0.2 to 2.0 inch per minute. The mean compressive strength of the wet set is divided by the mean compressive strength of the dry set resulting in a strength ratio expressed as percent. The minimum value of the strength ratio above which stripping may not occur is 75 percent. From the survey made in this study, this test has a high usage but score low in providing accurate predictions.
2. Lottman Test - This test is often referred to as National Cooperative Highway Research Program (NCHRP) 246. The test was developed (*42*, *43*, *44*) to evaluate the stripping potential of bituminous mixtures. Evaluations using the Lottman Test involve 4x2.5 inch Marshall, 4x2 inch Hveem, and specimens of comparable sizes prepared by other compaction methods including gyratory methods. The tensile strength of test specimen sets are evaluated both dry and after moisture conditioning. The moisture conditioned set is subjected to a freeze-thaw cycle (long Term effect) or Just the warm (140°F or 60°C) cycle (short-term effect) prior to testing for the tensile strength. Testing for strength is conducted at 55°F (12.8°C) at a deformation rate of 0.065 in per minute. The test result is the average wet strength divided by the average dry strength yielding a tensile strength ratio (TSR). The minimum TSR suggested by Lottman is 70 percent. Results form the contact surveys (Appendix A) indicated increading appeal for use of this test because other tests were not adequately discriminating between asphalt-aggregate mixture systems. However, modifications involving test temperature (from 55 to 77°F) and loading rate (from 0.065 in/min to 2 in/min) were the preferred direction of agencies considering use of this procedure.
3. Tunnicliff/Root Test - This test was developed (*45*, *46*) by modifying conditions of test in the Lottman test as follows:
   - Load rate (2 in/min) compared to 0.065 in/min
   - Test temperature 77°F (25°C) compared to 55°F (12.8°C)
   - Presaturation of 55 to 80 percent compared to an unlimited level in the Lottman test
   - Absence of a freeze cycle

   Results from the contact surveys indicated a general preference for this test as compared to the Lottman because the test can be performed faster. However, some contacts indicated that the test lacks the severity of the Lottman conditioning and allowed a number of stripping asphalt-aggregate systems to pass as non-strippers. In fact some contacts indicated that further requirement for a freeze-cycle may be necessary for improved overall utility of the test. The test results and minimum index (TSR) are expressed as those in the Lottman test. This test is currently under consideration for standardization by ASTM.
4. Marshall Immersion Test - This test evaluates Marshall specimens by using the dry or wet evacuation procedures. Stuart (*47*) reports that the dry evacuation procedure involves application of a vacuum head to the dry specimens for say one hour prior to introduction of water. Whereas, the wet evacuation procedure involves application of a vacuum head to specimens which are already submerged in water. These two conditioning procedures produce the wet sets of test specimens. Testing is usually done at 140°F (60°C) using a deformation rate of 2 inch per minute for both the dry and wet sets. The ratio between dry and wet stabilities is expressed as percent retained stability and the minimum value above which stripping is supposedly unlikely to occur is 75 percent.

5. Resilient Modulus - Schmidt et al. (*48*) reported early application of resilient modulus property to HMA mixtures. Compacted specimens of variable size are tested along the diametral plane by using a pulsating stress wave while deformations are being recorded along the ends by linear-variable differential transducers (LVDTs). Both moisture conditioned and dry sets are evaluated and the mean modulus is divided by the mean dry modulus yielding a resilient modulus ratio. The minimum ratio suggested is 70 percent.
6. The Double Punch Method - Compacted asphalt-aggregate mixtures of variable sizes are tested through steel rods placed at either end of the specimen in a punching configuration reported by Jimenez (*49*). Tensile strength is computed from the peak load values. A strength ratio is determined between the wet and dry strengths as the test statistic. Jimenez demonstrated the severity of this test by comparing predictions on similar mixtures using the immersion compression test. The double punch method was reported to produce lower retained strength ratios and hence considered to be more severe than the immersion compression test.

In addition, Jimenez (*49*) developed a stressing procedure simulating traffic loading effects. The procedure involves repeated application of pore water pressure in the range of 5 to 30 psi (34.5 x 10^3 to 206.9 x 10^3 N/m^2) at the rate of 580 times/minute on pre-vacuum saturated specimens. This pore pressure is applied through a rubber line annulus assembly which is not in contact with the test specimens. The conditioned specimens are tested in the double punch set up discussed earlier at 77°F (25°C) applying a head speed of 1.0 in/min (41.5xl0^{-6} m/s).

The subsequent discussion presents the “special class” of tests mentioned earlier by which the HMA stripping potentials are inferred from changes in weight of the test specimens determined through an abrasive operation. These are:

1. Dynamic Strip Method - This test is used predominantly by the Nevada DOT. Hveem. specimens are soaked in a 140°F (60°C) water bath for six days, rapidly cooled to 41°F (5°C) by packing with ice, and tumbled through 1000 revolutions at 33 rpm. The conditioning and tumbling processes subjected to the specimens produce a durability index expressed by the amount of weight loss in percent. The maximum value of this index is 25 percent above which severe stripping is considered likely to occur.
2. Cold Water Abrasion Test - This test is used by Minnesota DOT for evaluating 2x2 inch compacted briquettes for moisture damage susceptibility. A set of six briquettes is first conditioned in 140°F (60°C) oven for 24 hours. The set is then immersed in a 120°F (48.9°C) water bath for six days, cooled to room temperature followed by further cooling at 33°F (0.8°C) for one hour. Then the set is abraded in a tumbling machine at 33°F for 1000 revolutions in 34.5 minutes. The test statistics is the amount of abrasion loss expressed as a percent of the original weight of the set of briquettes and whose maximum value is 25 percent.
3. California Moisture Vapor Susceptibility Test - This test measures the effects of moisture (vapor form) to the Hveem stabilities of 4x2 inch compacted mixtures. The vapor form mimics water migration into pavement mixtures from wet subgrades.

   The test assembly is placed in 140°F (60°C) oven for 75 hours after which the specimens are tested for stabilometer values. Numerical stabilometer values are the test statistic compared to a strength ratio between wet and dry sets as with most conventional quantitative test procedures.
4. Surface Abrasion Test - 4x2 inch Hveem specimens are abraded using rubber balls or steel balls at 1200 cycles per minute for 15 minutes. The rubber balls version test is conducted at 100°F (37.8°C) while the steel balls version is conducted at 40°F (4.4°C). The test statistic is expressed as amount of weight loss in grams.

Other tests which deserve additional discussion include:

1. Texas Freeze-Thaw Pedestal Test - This test was discussed earlier in works by T. W. Kennedy et al. (*50*, *51*). Briquettes made out of a uniformly-sized aggregate (passing No. 20 and retained on No. 35) and asphalt (2 percent higher than the job mix formula) are subjected to freeze-thaw conditioning until cracking is initiated. The number of freeze-thaw cycles is the test statistic used to judge the stripping susceptibility of each asphalt-aggregate mixture.
2. The 10-Minute Boil Test - The Boil Test has been around for a long time. An asphalt-aggregate mixture, usually single size (passing the 3/8 inch and retained on No. 4 sieves), is placed in boiling water. The whole system is kept boiling for 10 minutes. The supernatant liquid is either poured off hot or after the system cools to ambient conditions. The dried mixture is then visually inspected for percent retained coating. A rating board was developed by Kennedy et al. (*16*) to minimize the subjectivity of the rating procedure used in the boil test. The usefulness of the rating board has been demonstrated in recent studies by Parker et al. (*17*, *52*), Tarrer (*9*), and Yoon (*18*). The boil test has been used on while mixtures both in laboratory and field environments. Test standards which apply to laboratory and field whole mixtures exist in some DOTs like Virginia (*53*), Georgia (*54*), Maryland (*55*, *56*), and Louisiana (*57*). Research results determined on whole mixtures have been reported by Kennedy et al. (*16*), Bushing et al. (*57*, *58*), Parker et al. (*59*), Gharaybeh (*60*), and other researchers. The findings from the contact surveys (Appendix A) and an earlier survey by ASTM D04.22 revealed that more than 15 state DOTs have and use the 10-minute boil test in both laboratory and field evaluations. There are currently (1988) efforts by ASTM Subcommittee D04-22 to develop a standard for this 10-minute boil test.

Finally, there are numerous miscellaneous tests which include Taylor et al.'s (*7*) listing as:

- Static Immersion (ASTM D1664)
- Lee
- Holmes Water Displacement
- Oberbach
- German U-37
- Dynamic Immersion Tests of Nicholson
- Dow or Tyler Wash
- Sonic Test (non-destructive)
- English Trafficking
- Test Tracks

Due to limited use and inadequate reference information concerning these tests, no further discussion is given in this report.

Most Frequently Used Tests

From the above discussions of various tests, findings from the contact surveys (Appendix A), the following tests have emerged being the most frequently used:

- Indirect Tensile Test including:
    - Tunnicliff-Root or NCHRP 274 test
    - Lottman test
- Immersion Compression Test - ASTM D1075
- 10-Minute Boil Test

The above test methods and others are the subject of critical review in Section IV.

Measures Undertaken to Reduce Stripping
Numerous investigative actions have been undertaken in laboratories and field to reduce the stripping potential in HMA mixtures. The investigative actions have involved use of antistripping (AS) agents and/or additives. The additives tried in mixtures are reported (*61*-*64*) in the following groups:

- Cationic surfactants
- Iron Naphthenate
- Hydrated Lime
- Organo Silane
- Portland Cement
- Other products

The overall hypothesis in using either additive is to convert a hydrophilic (water loving) aggregate surface to a hydrophobic (water hating) condition. Numerous questions remain unanswered regarding the beneficial attributes derived from using additives. Some of the questions are listed in Appendix A and a few are listed below.

- How does one determine that an additive is really needed?
- How does an additive really work?
- What is the most effective method of application of the additive?
- What generic properties should an additive possess to be effective or to influence its selection?
- How is effectiveness measured?
- What test can be used to detect their presence?
- How does an additive contribute to performance?

Tunnicliff et al. (*45*, *46*) presented survey findings regarding the use of AS agents in bituminous mixtures. The results of the survey indicated the following as factors that contribute to stripping:

- Various aggregate types
- Asphalt cement grade and source
- Numerous aspects of mixture design
- Aspects of construction
- Climate

In addition to the above list of variables Tunnicliff found that: there was over 100 AS agents being marketed, and there was a very large number of testing procedures including numerous modifications to these procedures.

A more specific listing of causative factors for stripping was reported in a Canadian publication (*61*) including:

- Mineral nature of chemical composition of aggregates
- Exposure history of aggregates (e.g. freshly crushed versus two months weathering after crushing)
- Original properties of asphalt (physical and chemical)
- Modifications in asphalt during storage and handling
- Interactions between individual aggregates, asphalts, and additives (if included)
- Water content in the mixes
- Curing variables (e.g. time, temperature)
- Nature of water to which mix is exposed (salt content, pH)
- Asphalt content
- Special field variables (e.g. climate, construction quality, etc)

None of the factors listed in this section singly controls the stripping condition manifest in bituminous mixtures. Remedial actions involving use of any one group of additives is looked at as a blanket insurance. Research done by Kennedy (*64*), Petersen (*65*), Petersen et al. (*66*), Collins (*67*) and other researchers suggests that the most effective AS agent is hydrated lime. However, a most effective method of adding lime is still under investigation. In recent investigations by Tunnicliff et al. (*68*, *69*), various lime addition techniques were the subject of study. Preliminary results from laboratory and one-year old field mixtures revealed no significant differences in the stripping resistance of mixtures laid using various lime addition procedures.

Other types of AS agents have been investigated in laboratories and/or field situations as contained in various research reports (*46*, *47*, *71*, *76*, *83*). The reports do not list consistent performance improvements from the use of these products. The possible causes of the inconsistencies may be associated with the methods of adding these liquid AS agents to the liquid asphalt. These methods include:

- In-line blending in liquid asphalt stream at the hot mix plant site
- blending at the refinery

The other possible causes may be the absences of clearly defined material properties and tests for the liquid AS agents. Thus, the adequacy of these additive mixing methods, absence of clear material properties, and absence of well defined contribution to performance remain puzzles to asphalt technologists.

In summary, long term effectiveness derivable from use of AS agents remains unknown. However, the following constitute suggested (*64*, *68*, etc.) methods for improving overall moisture susceptibility characteristics of bituminous mixtures:

- Achieve adequate compaction during construction
- Eliminate the use of moisture-susceptible aggregates and asphalts
- Provide adequate drainage (both surfacial and subsurface)
- Treat the moisture susceptible aggregates and asphalts

The current authors propose the following additional factors to the above list:

- Develop and understand the controlling mechanisms and then develop the appropriate test(s) to assess the identified mechanism(s)
- Use test methods by which undesirable materials can be screened out in advance of the fact
- Optimize materials selections for compatibility

Current Studies in Stripping

Table 5 lists projects which are underway or planned in the area of stripping in bituminous mixtures in various parts of the United States. The information identifying these projects was mainly obtained through reviews and contact surveys made during the course of the NCAT stripping study in FY 1988. The listing of the projects is not comprehensive but includes both laboratory and field efforts. None of these projects is discussed in this report.

CRITICAL REVIEW OF TEST METHODS

The test methods which are the subject of review in this section include those sort-listed in Section III including the Nevada Dynamic Strip Method. These methods are:

- Indirect Tensile Test
    - Lottman conditioning procedure (with modifications)
    - Tunnicliff-Root conditioning procedure
- Immersion Commpression Test
- 10-Minute boil test
- Nevada Dynamic strip test

Table 5. Current Research Efforts in Stripping of Bituminous Mixtures, Continuing and Completed

General Project Description	Nature of Investigation		Client	Duration		Investigator
	Lab.	Field		Start	End	
An investigating of the effects of various additives in projects located in various climatic areas using various test methods	X	X	TX DOT	1986	ND	CTR - Univ. Of Texas
Evaluation of various treatment procedures for stripping improvement	X	X	AZ/ NCHRP	1986	ND	Dr. Jimenez & Dr. Tunnicliff
Asphalt-aggregate mixture analysis system (AAMAS) - Phase II	X	X	NCHRP Project 9-6 (II)	1987	Nov. 1988	BRE, Inc.
SHRP - Contracts A-003A and A-003B	X	X	SHRP	1988	1992	Various
Investigate correlation between TSR and IC Strength Ratio	X	X	AZ DOT	1987	ND	AZ DOT
Investigate fundamental mechanisms and test methods in stripping	X	X	NAPA Ed. Found.	1987	Cont.	NCAT (AU)
A field study of stripping potential of asphalt concrete mixtures	X	X	ALHD	1986	Cont.	HRC (AU)
Investigate stripping phenomenon in various mixtures using various test methods	X	X	FHWA Task Order	ND	ND	LA Trans. & Res. Ctr.
Assessment of stripping asphalt pavement before rehabilitation	X	X	VA DOT	FY 88	FY 89	VA Transport. Res. Ctr.
Investigate effectiveness of antistripping agents	X	X	FHWA Task Order	1988	1988	OR State Univ.
Evaluate antistripping testing procedures	X	X	FHWA Task Order	1988	1989	OR DOT Mtls. Sec.
Evaluate stripping test procedures using mixtures from lime treated test sections	X	X	FHWA	1987	1989	Information unavailable
Antistripping additives in asphalt concrete - Phase II	X	X	NCHRP Project 9-6 (II)	Mar. 1981	July 1989	Tunnicliff Consulting Engineer

CTR = Center for Transportation Research
HRC = Highway Research Center
ND = Not determined during this study
NCAT = National Center for Asphalt Technology
AU = Auburn University

Criteria for Selecting the Above Test Methods

- Contact survey results (Appendix A)
- Availability of documented laboratory and field evaluations
- Availability of information involving common types of materials on which nearly all the above tests were applied
- Availability of standards of the tests at DOT level, AASHTO or ASTM
- Availability of a judgement criteria associated with use of the test
- An additional test which has been successful in a local setting (Nevada Dynamic strip test)

Critical Review Approach

Reviews of literature bases were conducted to establish availability of published data on numerous material types and generated by the test methods under review. The data sought had to contain laboratory evaluations, laboratory predictions, and associated expected or known field behavior of the candidate asphalt-aggregate mixtures.

Material Types and General Locations

1. Aggregates - The following aggregate types were involved in the studies from which the data for the current review were based: Limestones including dolomite, granite, chert, gravels, and sands.
2. Asphalts - Asphalt varied from AC-10 to AC-30 and represented diverse sources.
3. Antistripping agents - Numerous liquid and solid additives were used in the referenced studies.
4. Locations - The data used in this review was obtained on materials combinations from the following states:

a. Alabama	e. Louisiana	i. Tennessee	
b. California	f. Mississippi	j. Texas	
c. Georgia	g. New York	k. Utah	
d. Kentucky	h. Nevada	l. Virginia	m. Washington

Test Results Summaries

Kiggundu et al. (<u>*69*</u>) recently compiled test data for use in this review as shown in Tables 6 through 10. The results are listed in each table showing the following:

1. Test method type
2. Material source and mineral types listed below:

<u>Material Source</u>		<u>Aggregate Type</u>[1]
GA - Grason		Granite
UT - Staker		Not available
GA - Rome		Limestone
MS - Hattiesburg (#1)		Chert gravel
MS - Hattiesburg (#2)		Chert gravel
GA - Kennesaw		Granite
TX - District 9		Coarse gravel-washed & field sand
TX - District 11		Crushed limestone plus sand and gravel
TX - District 12		Gravel-crushed limestone-local field sand
TX - District 13		Sand-gravel
TX - District 5		Crushed caliche
TX - District 14		Crushed limestone-local sand
TX - District 19		Coarse slag-local sand
VA - Aggregate		Granite
WA - Aggregate		Pit aggregate near Spokane
TN - Aggregate		Limestone
KY - Aggregate		Granite
GA - Norcross		Granite
AL - Aggregate	A	Limestone (dolomite)
	B	Crushed gravel-limestone-natural sand
	C	Sliceous gravel (crushed natural sand)
	D	Siliceous gravel (natural sand plus uncrushed gravel)
	E	Limestone
CA - Tel Chert		Chert gravel

CA - P.C.A Fairoaks	
LA - A613 - Mix Z	Crushed gravel
LA - A123 - Mix G	Not available
LA - A070 - Mix H	Not available
1-80 Near Dieth (Nevada)	Pit run aggregate
Elko, Nevada Idaho Street	Pit run aggregate

[1]Other aggregates are identified in Tables 6 to 10

3. Strength or Criteria Ratio listing
   a. Minimum value(s) required, and
   b. Test results.
4. Field performance rating
5. Test performance in predicting the field condition by:
   a. Success - indicating the laboratory prediction was consistent with the expected field condition or
   b. Failure - indicating that the laboratory prediction using the particular test was inconsistent with the field performance condition, and
6. Citation of the reference publication.

Analyses

Data analysis followed the compilation effort shown in Table 6 through 10 by the following operations:

1. Numerical count of the cases for which each test registered success versus failure and represent the result as a percent of the total data in each table.
2. Recounting the success/failure distribution resulting from changes in the minimum test index say from a TSR of 80 percent to a value of 70 percent as seen in Table 6. This operation resulted in a reduction of the success rating from 76 percent at a TSR of 80 percent to a 67 percent at a TSR of 70. Applying the same rationale to the data in Table 7 leads to success ratings of 67 percent. In the latter case (Table 7) using a combined criteria of 70 and 80 percent leads to a combined success rating of 67 percent.
3. Graphical representation of the success/failure ratings - The ratings established by comparing the laboratory predictions to the field performance ratings are graphically represented as shown in Figures 1 through 4. The vertical axis represents successful prediction (0-100 percent). The ordinate is determined by the value of the laboratory predicted retained strength or retained coating (boil test) whereas the abscissa is the compliment, that is 100-success (%).

The data points in the plots in Figures 1-4 fall on the diagonals because of the simplicity of the mathematical function adopted. However, the value of the plot is in the pattern in which the points cluster. If the majority of the points cluster towards the northeast corner of the plot, this trend suggests a test that systematically predicts failure in the laboratory when failure occurs in the field. Such a result would indicate that the test under review predicts fewer failures and vice versa.

Table 6. Test Results on Mixtures Evaluated by NCHRP 246 Test

Test Method	Material Source	Strength or Crit. Ratio (%)		Field Performance Rating	Test Performance		Reference
		Min. Req.	Test Result		Success	Failure	
NCHRP 246	GA - Grayson	80 (70)	6.5	Moderate to Severe	yes		(47)
	UT - Staker		77.2	Moderate to Severe	yes	(yes)	(47)
	GA - Rome	80 (70)	75.2	Slight	yes	(yes)	(47)
	MS - Hattiesburg (#1)	80 (70)	86.9	Slight		yes	(47)
	MS - Hattiesburg (#2)	80 (70)	84.8	Slight		yes	(47)
	GA - Grayson + A	80 (70)	92.9	Good	yes		(47)
	GA - Kennesaw + A	80 (70)	89.9	Good	yes		(47)
	GA - Rome + A	80 (70)	88.0	Good	yes		(47)
	MS - Hattiesburg #2+A	80 (70)	83.7	Good	yes		(47)
	TX - District 9	70	21	Stripper	yes		(72)
	TX - District 11	70	20	Stripper	yes		(72)
	TX - District 12	70	32	Stripper	yes		(72)
	TX - District 13	70	36	Stripper	yes		(72)
	TX - District 5	70	10	Non-Stripper		yes	(72)
	TX - District 12	70	18	Non-Stripper		yes	(72)
	TX - District 14	70	69	Non-Stripper		yes	(72)
	TX - District 19	70	80	Non-Stripper	yes		(72)
	VA - Aggregate	70 or 75	32	Stripper	yes		(73)
	WA - Aggregate	70 or 75	37	Stripper	yes		(73)
	TN - Aggregate	70 or 75	54	Stripper	yes		(73)
	KY - Aggregate	70 or 75	66	Stripper	yes		(73)

A = mixtures made with additive Crit. = criteria
Min. = minimum Req. = required
(Yes) = represent effect of change of TSR criterion from 80 to 70 percent

Table 7. Test Results on Mixtures Evaluated by NCHRP 274 Test

Test Method	Material Source	Strength or Crit. Ratio (%)		Field Performance Rating	Test Performance		Reference
		Min. Req.	Test Result		Success	Failure	
NCHRP 274	GA - Grayson	70	10.5	Severe Stripper	yes		(47)
	GA - Rome	70	65.2	Slight Stripper	yes		(47)
	GA - Rome	80	76.8	Slight Stripper	yes		(47)
	MS - Hattiesburg (#1)	80	81.7	Slight Stripper		yes	(47)
	MS - Hattiesburg (#2)	80	75.9	Slight Stripper	yes		(47)
	GA - Grayson + A	80	92.7	Good	yes		(47)
	GA - Kennesaw + A	80	74.7	Good		yes	(47)
	GA - Norcross + A		89.4	Good	yes		(47)
	GA - Rome + A	80	83.8	Good	yes		(47)
	MS - Hattiesburg + A	80	90.9	Good	yes		(47)
	AL - Aggregate A	80	87	Non-Stripper	yes		(60)
	AL - Aggregate B	80	80	Severe Stripper		yes	(60)
	AL - Aggregate C	80	109	Moderate Stripper		yes	(60)
	AL - Aggregate D	80	107	Severe Stripper		yes	(60)
	AL - Aggregate E	80	85	Good or Non-Stripper	yes		(60)

A = mixtures made with additives Crit. = criteria
Min. = minimum Req. = required

Table 8. Test Results on Mixtures Evaluated Using Immersion Compression Test

Test Method	Material Source	Strength or Crit. Ratio (%)		Field Performance Rating	Test Performance		Reference
		Min. Req.	Test Result		Success	Failure	
I/C	CA - Telchert	70	88.5	Very Good	yes		(75)
	CA - P.C.A. Fairoaks	70	56	Very Good		yes	(75)
	CA - Watsonville Granite	70	32	Very Good		yes	(75)
	NY - Crushed Granitic Gravel	75	80	Stripper		yes	(76,77)
	NY - Crushed Limestone & Quartz Gravel Blend	75	71	Stripper	yes	yes	(76,77)
	NY - Crushed Limestone & Gravel Blend	75	56	Stripper	yes		(76,77)
	NY - Crushed Dolomite	75	41	Non-Stripper		yes	(76,77)
	GA - Grayson	75	16.4	Moderate to Severe Stripper	yes		(47)
	UT - Staker	75	55.7	Moderate to Severe Stripper	yes		(47)
	GA - Rome	75	84.6	Slight Stripper		yes	(47)
	GA - Grayson + A	75	96.8	Good	yes		(47)
	GA - Rome + A	75	83.7	Good	yes		(47)
	LA - A613 - Mx Z	75	87.4	Stripper		yes	(78)
	LA - A123 - Mx G	75	103.0	Stripper		yes	(78)
	LA - A070 - Mx H	75	107.8	Stripper		yes	(78)

A = mixtures made with additives Crit. = criteria
Min. = minimum Req. = required

Table 9. Test Results on Mixtures Evaluated by Ten-Minute Boil Test

Test Method	Material Source	Strength or Crit. Ratio (%)		Field Performance Rating	Test Performance		Reference
		Min. Req.	Test Result		Success	Failure	
Boil Test	AL[1] A	90	70	Non-Stripper		yes	(60)
	B	90	55	Severe Stripper	yes		(60)
	C	90	95	Moderate Stripper		yes	(60)
	D	90	95	Severe Stripper		yes	(60)
	E	90	95	Non-Stripper	yes		(60)
	GA - Grayson	90	85	Mod. to Severe	yes	yes	(60)
	GA - Kennesaw	90	15	Mod. to Severe	yes		(60)
	UT - Staker	90	2.5	Mod. to Severe	yes		(60)
	GA - Rome	90	5	Slight		yes	(60)
	MS - Hattiesburg #1	90	15	Slight		yes	(60)
	GA - Grayson + A	90	12.5	Good		yes	(60)
	GA - Rome + A	90	2.5	Good		yes	(60)
	Field Sand, 9E	85	55	Stripper	yes		(72)
	Coarse Field Sand, 13C	85	65	Stripper	yes		(72)
	Gem Sand, 13M	85	26	Stripper	yes		(72)
	Coarse Sand, 13N	85	65	Stripper	yes		(72)
	Sand Stone, 13L	85	85	Non-Stripper	yes		(72)
	Field Sand, 13D	85	85	Non-Stripper	yes		(72)

[1] Surface mixes only without additives
A = mixtures made with additives Crit. = criteria
Min. = minimum Req. = required

Table 10. Test Results on Mixtures Evaluated by Nevada Dynamic Tumbling Test

Test Method	Material Source	Strength or Crit. Ratio (%)		Field Performance Rating	Test Performance		Reference
		Min. Req.	Test Result		Success	Failure	
Dynamic Tumbling	I-80 near Deeth, Nevada	less than 25% weight loss	6.5-12.1%	Non-Stripper		yes	(79)
	Elko, Nevada Idaho Street	less than 25% weight loss	8.2–16.8%	Severe Stripper		yes	(80)
	GA - Grayson	less than 25% weight loss	18.2%	Moderate Stripper		yes	(47)
	GA - Kennesaw	less than 25% weight loss	3.0%	Mod. to Severe		yes	(47)
	GA - Norcross	less than 25% weight loss	2.7%	Mod. to Severe		yes	(47)
	GA - Rome	less than 25% weight loss	0.7%	Slight		yes	(47)
	MS - Hattiesburg #1	less than 25% weight loss	5.6%	Slight		yes	(47)
	GA - Grayson + A	less than 25% weight loss	1.5%	Good	yes		(47)
	GA - Kennesaw + A	less than 25% weight loss	1.5%	Good	yes		(47)
	GA - Norcross + A	less than 25% weight loss	1.5%	Good	yes		(47)
	GA - Rome + A	less than 25% weight loss	0.4%	Good	yes		(47)

A = mixtures made with additives Crit. = criteria
Min. = minimum Req. = required

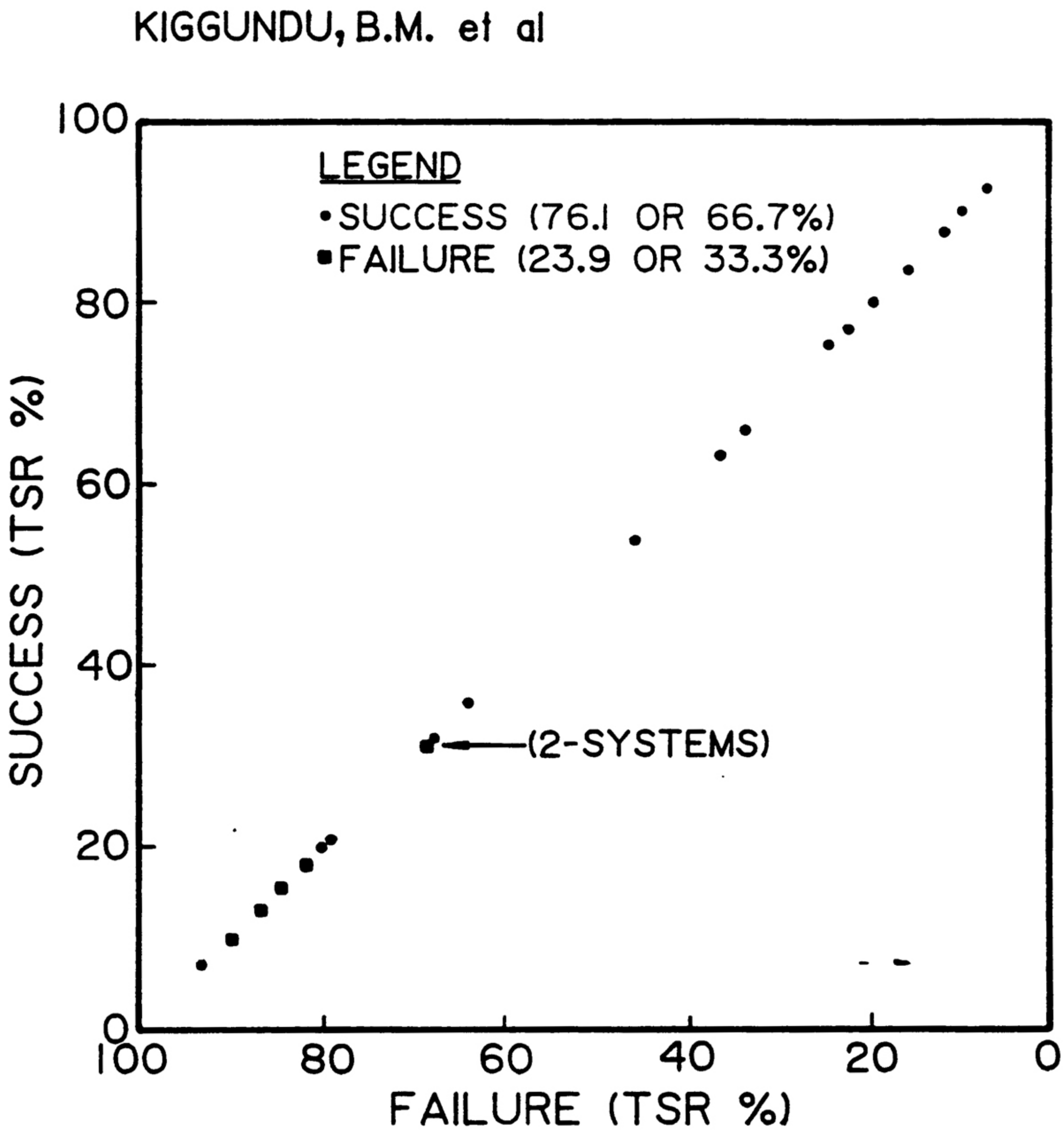

Figure 1. Success vs. Failure Predictions Using NCHRP 246 Test (Table 1)

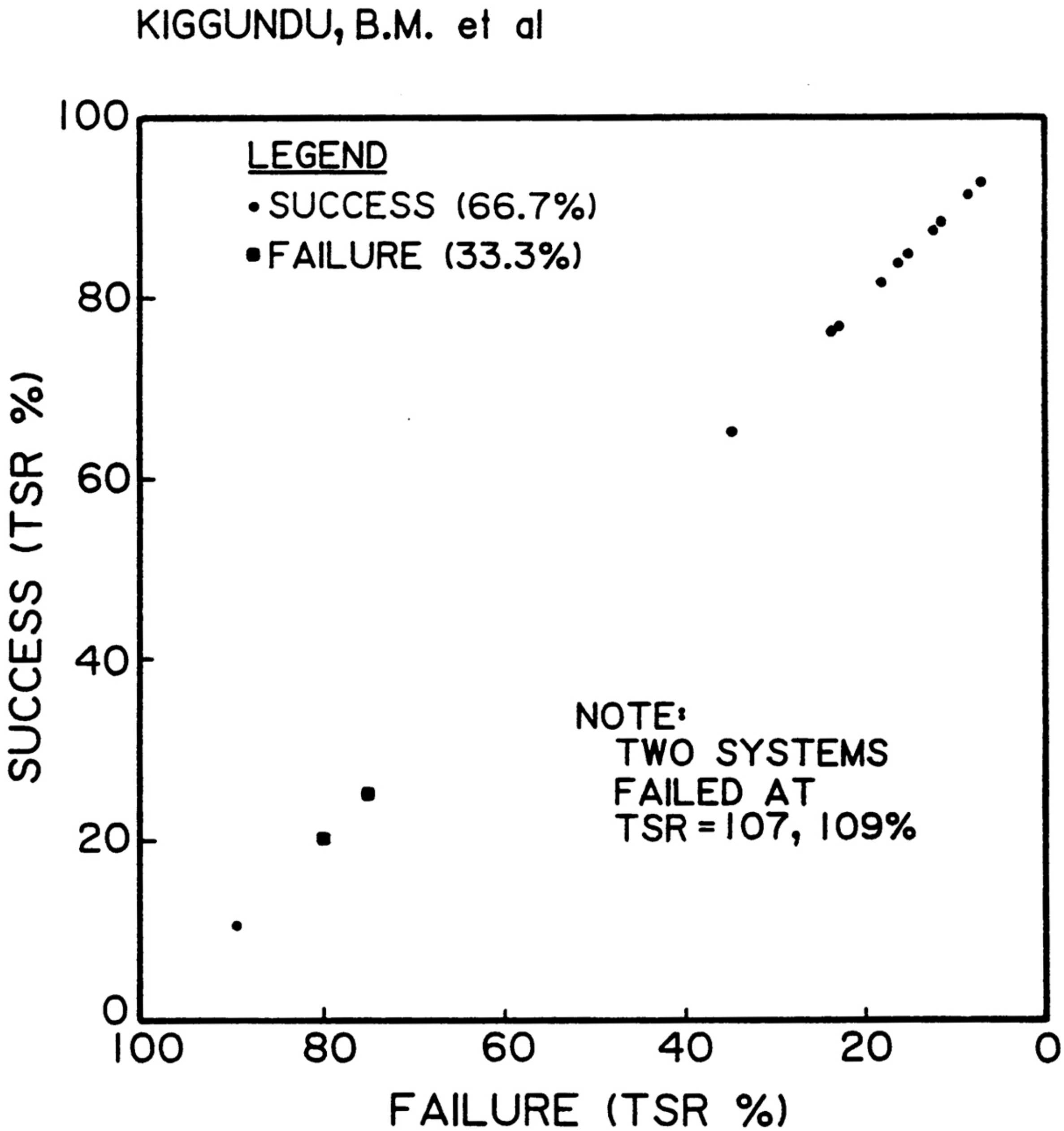

Figure 2. Success vs. Failure Predictions Using NCHRP 274 Test (Table 2)

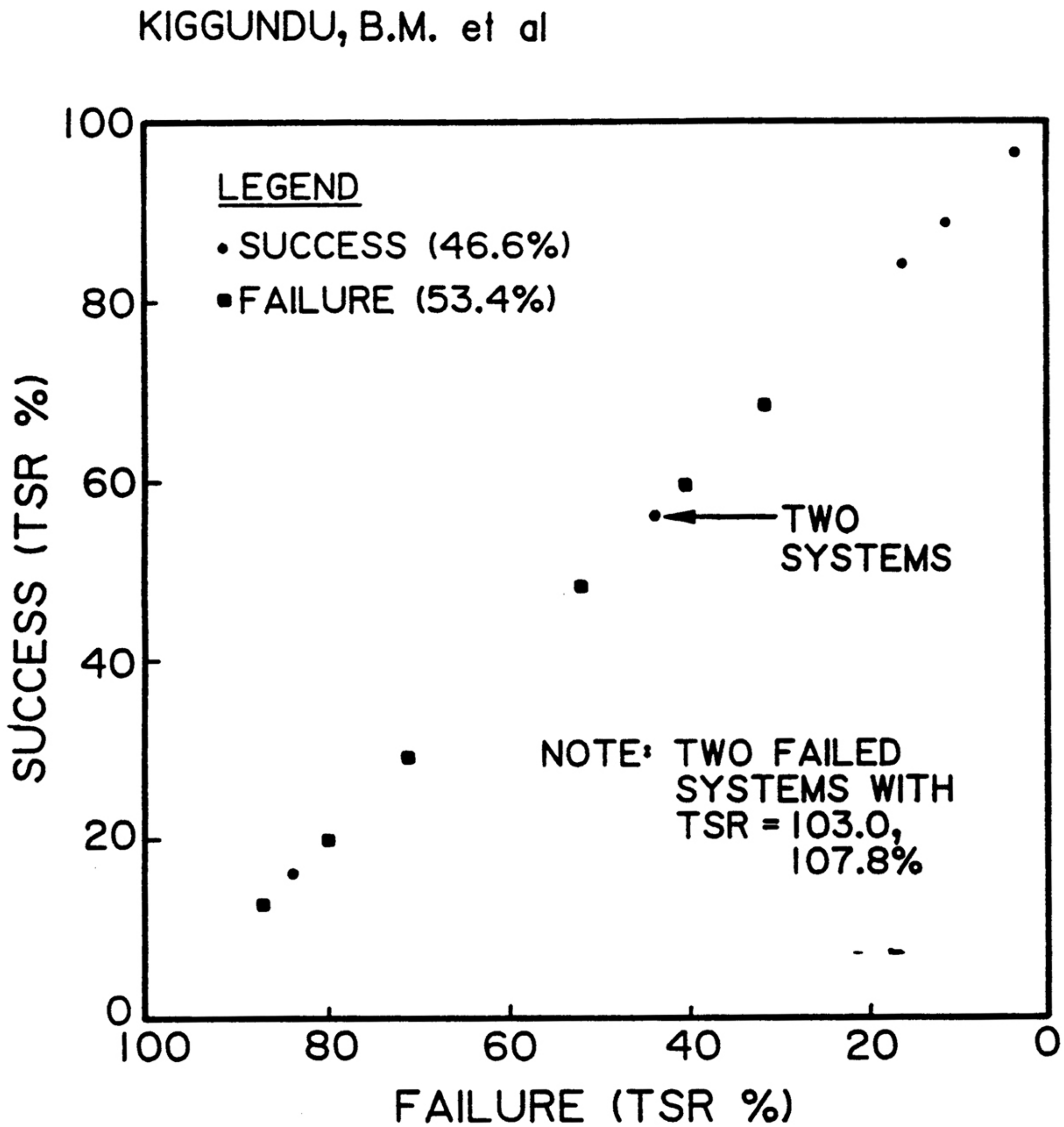

Figure 3. Success vs. Failure Predictions Using Immersion-Compression Test (Table 3)

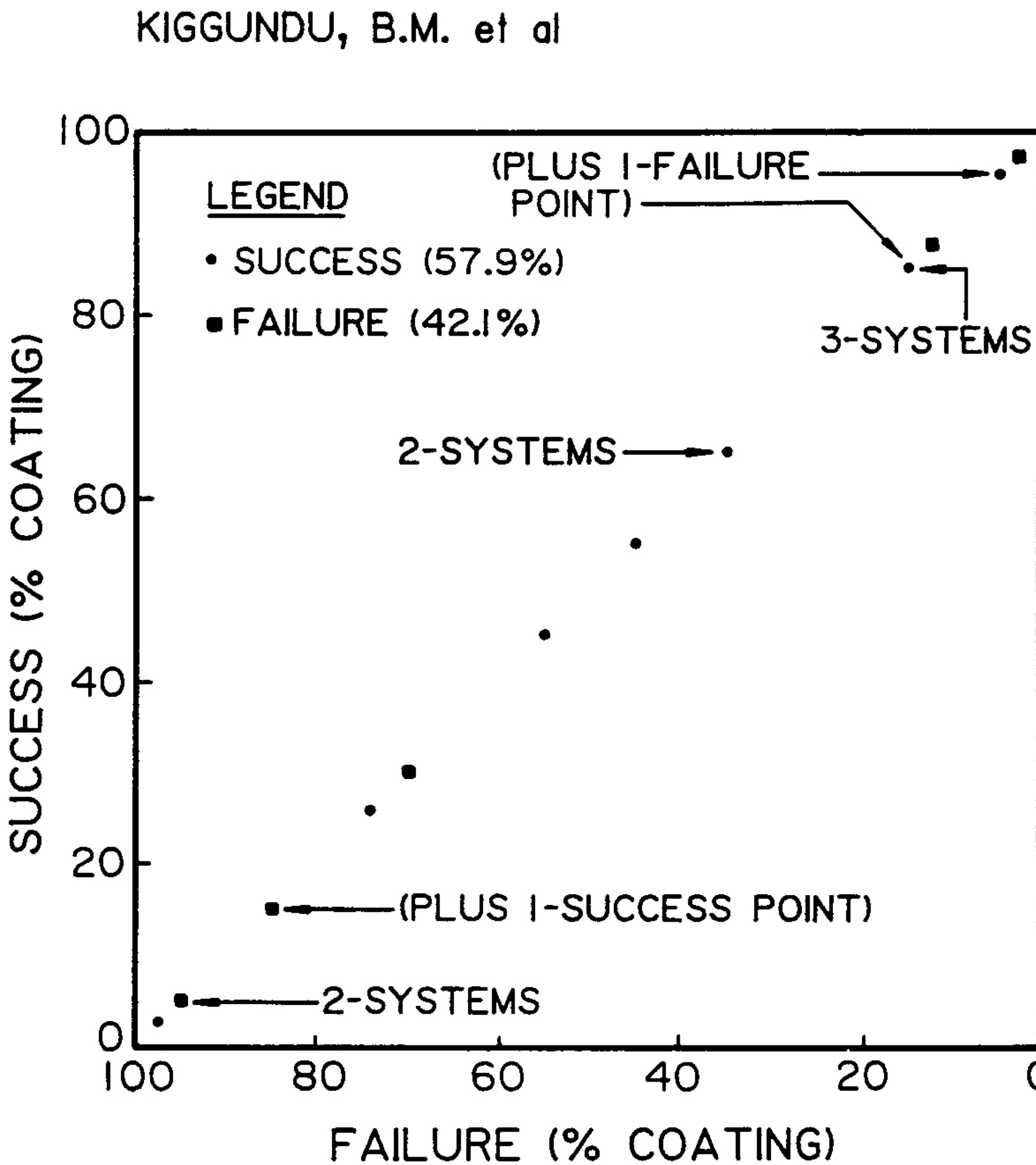

Figure 4. Success vs. Failure Predictions Using the Boil Test (10-Minute) (Table 4)

Discussion

The results of the analyses presented above using information in Tables 6-10 and Figures 1-4 are summarized in Table 11. It is probable that the success ratings (Table 11) between the Lottman and Tunnicliff-Root procedures are not significantly different. This is so because the reproducibility for the TSR criteria in the Tunnicliff procedure (*41*) is 23 percent. This value implies that an asphalt-aggregate mixture evaluated by two independent laboratories may be Judged to be of the same stripping potential if the mean TSR values satisfy the 70 ± 23 percent criteria range.

Table 11. Summaries of Success Ratings of Various Results

Test Method	Min. Test[1] Index	% Success
Lottman (NCHRP 246)	TSR = 70%	67
	TSR = 80%	76
Tunnicliff-Root (NCHRP 274)	TSR = 70%	60
	TSR = 80%	67
	TSR = 70-80%	67
Immersion Compression (ASTM D1075)	Strength Ratio = 75%	47
10-Minute Boil Test	Retained Coating 85-90%	58
Nevada Dynamic Strip Test	Weight Loss (less than 25%)	36

[1] Test index represents the established value by which performance of an HMA mixture has been judged.

However, the results of this analysis concur with the user information contained in the contact survey (Appendix A) as well as the findings presented by Stuart (*47*). The findings of Stuart indicated that the Lottman and Tunnicliff-Root tests offered the best predictions. Preference was cited by Stuart for the Tunnicliff-Root test because of expediency.

A preferred ranking of the methods based on results in Table 11 is as follows:

- Lottman test
- Tunnicliff-Root test
- 10-Minute Boil test
- Immersion Compression
- Nevada Dynamic Strip test

In this report, the results of the analysis, contact surveys, and, extensive reviews indicate that at the moment, the Lottman test (with modifications) may be the best choice with at least one freeze-thaw cycle. Coplantz et al. (*81*) reported that freeze-thaw cycling was necessary to determine the water sensitivity of HMA mixtures. This finding agrees with the earlier results by Kennedy et al. (*72*) and Stuart (*47*). Maupin (*82*) proposed the current set of modifications to the Lottman test which include:

- Speed of loading of 2 inch per minute, and
- Test temperature of 77°F (25°C)

These modifications comply with most readily available test equipment in most user laboratories and thus make use of the test that readily without undue equipment requirements.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

From the reviews summarized in this report, the following conclusions are made:

1. Stripping has been related to a very large number of factors and combinations of factors. Thus, the complexity of this condition remains unresolved and the distress continues to cause serious problems with performance of HMA mixtures.
2. Numerous mechanisms have traditionally been documented in the literature. Additional mechanisms have been proposed in this report resulting from work at the National Center for Asphalt Technology and other research organizations. These mechanisms are briefly listed here:
    - pH instability mechanism - that is asphalt-aggregate interface regions are sensitive to varying pH of the contact water. Reduction of this sensitivity to pH can enhance formation of a strong bond and hence reduced stripping potential.
    - An awareness has been raised that future definitions need include effects of environment or climate and specificity to each asphalt-aggregate material system.
3. Fohs et al. (*83*) concluded as follows:
    a. "No general or universally applicable rules of thumb for identifying or predicting stripping problems such as siliceous aggregates strip, calcareous don't, or crushed aggregated don't, uncrushed do, etc. For a given aggregate, stripping increases with increasing air voids."
    b. "In environments where pavements will be subjected to moisture, mixtures should be evaluated for stripping potential."
4. A number of subject areas in stripping have been reviewed including fundamental, qualitative, and quantitative. On-going research efforts have been briefly listed including some known and recently completed efforts.
5. Numerous test methods have been critically reviewed in this report. Results of the critical review indicated the following preferential ranking:
    a. Lottman test (NCHRP 246) with modification of saturation, loading rate, and testing temperature
    b. Tunnicliff-Root test (NCHRP 274)
    c. 10-Minute Boil test
    d. Immersion Compression test (ASTM D 1075)

    The ranking positions a and b above coincide with the results of the survey (Appendix A) and in reverse order with the ranking in reports by Fohs et al. (*83*) and Stuart (*47*). The ranking established in the present report was established by developing success/failure profiles of a number of tests using published data. The Lottman test showed 76 percent success versus the Tunnicliff-Root test at 67 percent using a TSR of 70% as the bench mark. The rest of the results are summarized in Table 11.
6. A universal criteria value could not be established in this study. This value would depend on the asphalt-aggregate system, test used, environment, anticipated traffic loading, design variables, and stress. Fohs et al. (*83*) reports, "Although not adequately verified at this time (April 1987), "a Tensile Strength Ratio of 80 percent using the NCHRP 274 methodology is recommended acceptable criteria."
7. Regarding the use of additives, the following have been observed in the reviews: Hydrated limes is reportedly the most effective additive. However, it may not work well with all types of aggregate systems. Also, a most effective procedure for adding

lime to mixtures remains a subject of investigation. The long term effectiveness of liquid additives remains unresolved. Neither is the chemical interaction of the additive-asphalt-aggregate complex system understood at the present time.

Recommendations

1. A thorough understanding of the mechanisms should be prerequisite to developing test methods.
2. An applied phase II research effort is necessary to quantify the effects of the proposed mechanisms.
3. A predictive test should be developed which will consistently identify materials that are strippers during the laboratory evaluation phase and before construction. Repairs to stripped pavements are expensive and disruptive to normal flow of economic activities.
4. A reliable criteria cognizant of such factors as materials, traffic loading, environment, etc. need to be developed.

REFERENCES

1. Hubbard, P., "Adhesion of Asphalt to Aggregate in the Presence of Water," Proceedings, Highway Research Board, Vol. 8, Part 1, 1938.
2. Mendenhall, W.S., Jr., et al., Executive Summary, ADHOC Task Force Report on Asphalt Pavement Rutting and Stripping, August 14, 1987.
3. Majidzadeh, X., and Brovold, P.N., "State-of-the-Art: Effect of Water on Bitumen-Aggregate Mixtures," Special HRB Report No. 98, Highway Research Board, 1968.
4. Rice, J.M., "Relationship of Aggregate Characteristics to the Effect of Water on Bituminous Paving Mixtures," Symposium on Effect of Water on Bituminous Paving Mixtures, ASTM STP No. 240, 1958, pp. 17-34.
5. Cause and Prevention of Stripping in Asphalt Pavements, Asphalt Institute, Educational Series No. 10, Second Edition, 1987.
6. Fromm, H.J., "The Mechanisms of Asphalt Stripping from Aggregate Surfaces," Proceedings, Association of Asphalt Paving Technologists, Vol. 43B, 1974.
7. Taylor, M.A., and N.P. Khosla, "Stripping of Asphalt Pavements: State-of-the-Art," Transportation Research Record 911, 1983.
8. Scott, J.A.N., "Adhesion and Disbonding Mechanisms of Asphalt Used in Highway Construction and Maintenance," Proceedings, Association of Asphalt Paving Technologists, Vol. 47, 1978.
9. Tarrer, R.A., "Stripping of Asphalt Concrete: Chemical Testing," Report #2, Project #930-111, Alabama Highway Department, September 1986.
10. Goodrich, J.L., Personal Communication, May 1987.
11. Kiggundu, B.M., "Effects of Submergence in Distilled Water on the Surface Coloration of Asphalt," Unpublished data, NMERI, June-December 1986.
12. Fehsenfeld, F.M., and Kriech, A.J., "The Effect of Plant Design Changes on Hot Mix Asphalt," Heritage Research Group (undated).
13. Thelen, E., "Surface Energy and Adhesion Properties in Asphalt-Aggregate Systems," Highway Research Board Bulletin 192, Highway Research Board, 1958. p. 63.
14. Lottman, R.P., "The Moisture Mechanism That Causes Asphalt Stripping in Asphaltic Pavement Mixtures," Final Report, Engineering Experimental Station, Detpartment of Civil Engineering, University of Tdaho, Moscow, Idaho, February 1971.
15. Mack, C., Bituminous Materials, Vol. 1, Editor: Arnold Hoiberg, New York, MY, USA, Interscience Publishers, 1964.
16. Kennedy, T.W., Roberts, F.L., and Lee, K.W., "Evaluation of Moisture Susceptibility of Asphalt Mixtures Using the Texas Boiling Test," Transportation Research Record 968, 1984.
17. Parker, F., Jr., "Stripping of Asphalt Concrete-Physical Testing," Final Report, #930-111, Alabama Highway Department, January 1987.
18. Yoon, H.H., "Interface Phenomenon and Surfactants in Asphalt Paving Materials," Dissertation, Auburn University, 1987.
19. Kennedy, T.W., Roberts, F.L., and Anagnus, J.N., "Texas Boiling Test for Evaluating Moisture Susceptibility of Asphalt Mixtures," Research Report 253-5, Center for Transportation Research, The University of Texas at Austin, January 1984.
20. Dunning, R.L., Water Sensitivity of Asphalt Concrete, Personal Prepared Discussion, December 4, 1987.
21. Phillips, R.S., and Marek, C.R., "HMA Moisture Susceptibility Problems: The Need to Test and Specify Via a Common Procedure," Symposium Presentation, ASTM, New Orleans, Louisiana, December 1986.
22. Jeon, W. Young, Curtis, C.W. and Kiggundu, B.M., "Adsorption Behavior of Asphalt Functionalities on Dry and Moist Silica," Submitted to TRB, July 1988.
23. Froment, G.F., and Fischoff, K.B., Chemical Reactor Analysis and Design, John Wiley and Sons, 1979.

24. Sanderson, F.C., “Methylchlorosilanes as Antistripping Agents,” Proceedings, Highway Research Board, No. 31, 288, L952..
25. Petersen, J.C., Plancher, H., Ensley, E.K., VenableR.I., and Mikane, G., “Chemistry of Asphalt-Aggregate Interaction: Relationship with Pavement Moisture-Damage Prediction Test,” Transportation Research Record, No. 843, 1982.
26. Petersen, J.C., “A Quantitative Method for the Determination of Compound Types in Asphalts Absorbing in the Carbonyl Region of the Infrared Spectra,” Analytical Chemistry, Vol. 47, 1975, pp. 112-117.
27. Petersen, J.C, and Plancher, H., “Quantitative Determination of Carboxylic Acids and Their Salts and Anhydrides in Asphalts by Selective Chemical Reactions and Differential Infrared Spectrometry,” Analytical Chemistry, Vol. 53, 1981, pp. 786-789.
28. Petersen, J.C., Dorrence, S.M., Ensley, E.K., Barbaus, F.A., Barbour, R.V., and Raines, W.E., “Paving Asphalts: Chemical Compositon, Oxidative Weathering and Asphalt-Aggregate Interactions: Part II,” FHWA, Interim Report, FHWA-RD-74-71, June 1974.
29. Petersen, J.C, Ensley, E.K., and Barbour, F.A., “Molecular Interactions of Asphalt in Asphalt-Aggregate Interface Region,” Transportation Research Record No. 515, 1974, pp. 67-78.
30. Plancher, H., Dorrence, S.M., and Petersen, J.C., “Identification and Chemical Types in Asphalts Strongly Adsorbed at the Asphalt-Aggregate Interface and Their Relative Displacement by Water,” Proceedings, Association of Asphalt Paving Technologists, Vol. 46, 1977, pp. 151-175.
31. Ensley, E.K., Petersen, J.C., and Robertson, R.E., “Asphalt-Aggregate Bonding Energy Measurements by Microcalorimetric Methods,” Thermochimica Acta 77, 95, 1984.
32. Ensley, E.K., and Scholz, H.A., “An Investigation of Asphalt-Aggregate Adhesion by Measurements of Heat of Immersion,” Highway Research Record No. 340, 38 (1970).
33. Plancher, H., Chow, C., Holmes, S.A. and Petersen, J.C., “MoistureInduced Damage in Bituminous Pavement - A Study of Nitrogen Compound Interactions with Aggregates,” Proc., International Symposium, Progressi Nella Technologia. Dei Bitumi (Milano), Italy, 1981, pp. 263-273.
34. Plancher, H., Miyake, G., Venable, R.L., and Petersen, J.C., “A Simple Laboratory Test to Indicate Moisture Susceptibility of Asphalt-Aggregate Mixtures to Moisture Damage During Repeated Freeze-Thaw Cycling,” Canadian Technical Asphalt Association, V1. 25, 1980, pp. 247-262.
35. Kennedy, T.W., Roberts, F.L., Lee, K.W., and Anagnos, J.N., “Texas Freeze-Thaw Pedestal Test for Evaluating Moisture Susceptibility for Asphalt Mixtures,” Research Report 253-3, Center for Transportation Research, University of Texas, February 1982.
36. Gietz, R.H., “Mineral Fines Effect on Asphalt Viscosity,” Interim Report, Washington Department of Transportation Materials Office, April 1980.
37. Maupin, G.W., Jr., “Detection of Antistripping Additives with Quick Bottle Test,” Final Report, Virginia Highway and Transportation Research Council, Charlottesville, VA, October 1980.
38. Isacsson, W., and Jorgensen, T., “Laboratory Methods for Determination of the Water Susceptibility of Bituminous Pavements,” VITrapport, Swedish Road and Traffic Research Institute, No. 324A, 1987.
39. Goode, F.F., “Use of Immersion Compression Test in Evaluating and Designing Bituminous Paving Mixtures,” ASTM STP 252, pp. 113-126, 1959.
40. Dukatz, E.K., Jr., and Phillips, R.S., “The Effect of Air Voids on the Tensile Strength Ratio,” Proceedings, Association of Asphalt Paving Technologists, Vol. 56, 1987.
41. Tunnicliff, D.G., and Root, R.E., “Precision Study of Standard Test Method for Effect of Moisture on Asphalt Concrete Paving Mixtures,” June 1987, Attachment, ASTM D04-22 Subcommittee Minutes, November 13, 1987.
42. Lottman, R.P., “Predicting Moisture-Induced Damage to Asphalt Concrete,” NCHRP 192, 1978.

43. Lottman, R.P., “Predicting Moistures-Induced Damage to Asphaltic Concrete Field Evaluation,” NCRP 246, May 1982.
44. Lottman, R.P., “Predicting Moisture Induced Damage to Asphaltic Concrete Ten Year Field Evaluation,” NCHRP Research Digest 167 (in print).
45. Tunnicliff, D.G. and Root, R., “Antistripping Additives in Asphalt Concrete-State-of-the-Art,” Proceedings, Association of Asphalt Paving Technologists, Vol. 51, 1982.
46. Tunnicliff, D.G., and Root, R.E., “Use of Antistripping Additives in Asphaltic Concrete Mixtures Laboratory Phase,” NCHRP Report 274, TRB, December 1984.
47. Stuart, K.D., “Evaluation of Procedures Used to Predict Moisture Damage in Asphalt Mixtures,” FHWA/RD-86/091, Draft Report, March 1986.
48. Schmidt, R.J., and Graf, P.E., “The Effect of Water on the Resilient Modulus of Asphalt Treated Mixes,” Proceedings, Association of Asphalt Paving Technologists, Vol. 41, 1972, pp. 118-162.
49. Jimenez, R.A., “Testing for Debonding of Asphalt from Aggregates,” Transportation Research Record, No. 115, January 1974.
50. Kennedy, T.W., Roberts, F.L., and Kang, W.L., “Evaluation of Moisture Susceptibility of Asphalt Mixtures Using the Texas Freeze-Thaw Pedestal Test,” Proceedings, Association of Asphalt Paving Technologists, Vol. 51, 1982, pp. 327-341.
51. Kennedy, T.W., and Anagnos, J.N., “Modified Test Procedure for Texas Freeze-Thaw Pedestal Test,” CTR 3-0-79-253-7, University of Texas at Austin, November 1984.
52. Parker, F., Jr., and Wilson, M.S., “Evaluation of Boiling and Stress Pedestal Tests for Assessing Stripping Potential of Alabama Asphalt Concrete Mixtures,” Transportation Research Record, No. 1096, January 1986.
53. Virginia Test Method for Antistripping Additive, VTM-13-85.
54. Test Method for Heat Stable Anti-strip Additive, GDH-56, April 1980.
55. Laboratory and Field Strip Test for Bituminous Mixes, MSMT Designation 410, May 1983.
56. Test Method Tex. 530C, “Effect of Water on Bituminous Paving Mixtures,” Texas State Department of Highways and Public Transportation, September 1984.
57. Bushing et al., “A Statewide Program to Identify and Prevent Stripping Damage,” ASTM STP 899, December 1985.
58. Bushing et al., “An Investigation of Stripping in Asphalt Concrete in South Carolina,” Report No. FHWA-SC-86-02, Final Report, South Carolina Department of Highways and Public Transportation, July 1986.
59. Parker, F., Jr., and Gharaybeh, F.A., “Evaluation of Tests to Assess Stripping Potential of Asphalt Concrete Mixtures,” Presented for Publication, TRB, January 1988.
60. Gharaybeh, F.A., “Evluation of Tests to Assess Stripping Potential for Asphalt Concrete Mixtures,” Dissertation, Department of Civil Engineering, Auburn University, Alabama, August 1987.
61. Pavement Management Systems Limited, “Study of Asphalt Cement Additives and Extenders,” Roads and Transportation Association of Canada, January 1983.
62. ScanRoad, “Antistripping Agents for Bituminous Surfaces,” Technical Bulletin 1, Singapore, October 1982.
63. Dybalski, J.N., “Cationic Surfactants in Asphalt Adhesion,” Proceedings, AAPT, Vol. 51, 1982.
64. Kennedy, T.W., “Use of Hydrated Lime in Asphalt Paving Mixtures,” National Lime Association, Bulletin #325, March 1984 (Rep. December 1987).
65. Petersen, J.C., “Lime-Treated Pavements Offer Increased Durability,” ASPHALT 88 <u>or</u> Roads & Bridges Magazine, January 1988.
66. Petersen, J.C., Plancher, H., and Harnsberger, P.M., “Lime Treatment of Asphalt to Reduce Age Hardening and Improve Flow Properties,” Proc. AAPT, Vol. 56, 1987.

67. Collins, R., Private Communication, 1987; also “Georgia’s Experience with the Use of Hydrated Lime in Asphalt Concrete Mixtures,” SASHTO Meeting Proceedings, Mobile, AL, 1982.
68. Tunnicliff, D.G., and Root, R.E., “Introduction of Lime into Asphalt Concrete Mixtures,” Final Report, FHWA/RD-86/071, U.S. Department of Transportation, FHWA, Research and Equipment Division, Washington, D.C., July 1986.
69. Tunnicliff, D.G., “Introduction of Lime into Asphalt Concrete Mixtures,” Presentation, 24th Annual Laramie Asphalt Research Meeting, Western Research Institute, Laramie, Wyoming, July 8, 1987.
70. Kandhal, P.S., Lubold, C.W., Jr., and Roberts, F.L., “Water Damage to Asphalt Overlays: Case Histories,” Submitted to AAPT, July 1988.
71. Kiggundu, B.M. and Roberts, F.L., “The Success/Failure of Methods Used to Predict the Stripping Potential in the Performance of Bituminous Pavement Mixtures,” Submitted to TRB, July 1988.
72. Kennedy, T.W. and Anagnog, J.N., “Wet-Dry Indirect Tensile Test for Evaluating Moisture Susceptibility of Asphalt Mixtures,” Research Report 253-8, Center for Transportation Research, The University of Texas, Austin, TX, November 1984.
73. Scherocman et al., “The Effect of Multiple Freeze-Thaw Cycle Conditioning on the Moisture Damage in Asphalt Concrete Mixtures,” Proceedings AAPT, Vol. 55, 1986.
74. Kiggundu, B.M., and Newman, K.J., “Asphalt-Aggregate Interactions in Hot-Recycling: A Laboratory Study,” Final Report, ESL-TR-87-07, Air Force Engineering & Services Center, Tyndall AFB, FL., July 1987.
75. “Film Stripping Study,” Final Report, CalTrans., February 1971.
76. Gupta, P.K., “Evaluation of the Immersion Compression Test for Asphalt-Stripping Potential,” Report FHWA/NY/ST-84/77, March 1984.
77. Gupta, P.K., “Evaluation of Asphalt Stripping Associated with Selected New York Aggregates,” Report FHWA/NY-SR-85/83, July 1985.
78. Paul, J.R., “Identification and Qualification of the Extent of Asphalt Stripping in Flexible Pavements, Phase I - Laboratory Evaluation,” Louisiana Department of Transportation and Development, August 1983.
79. Epps, J.A., et al., “An Investigation of Premature Pavement Distress on 1-80 Near Deeth, Nevada,” Report #4-331-504-1, Civil Engineering Department, University of Nevada-Reno, December 1984.
80. Epps, J.A., et al., “An Investigation of Premature Pavement Distress on Idaho St. Elko, Nevada, Report #4-331-504-1, Civil Engineering Department, University of Nevada-Reno, 1984.
81. Coplantz, J., and Newcomb, D.E., “Water Sensitivity Test Methods for Asphalt Concrete Mixtures -- A Laboratory Comparison,” Presentation, Transportation Research Board, January 1988.
82. Maupin, G.W., Jr., “Implementation of Stripping Test for Asphaltic Concrete,” Transportation Research Record No. 712, pp. 8-12, 1979.
83. Fohs, D., et al., “Research on Asphalt Pavement Rutting/Stripping,” Task Force on Asphalt Pavement, April 15, 1987.
84. Parker, F., Jr., Personal Communication, Highway Research Center, Auburn University, AL, 1987.
85. Brown, E.R., Personal Communication, National Center for Asphalt Technology, Auburn University, AL, 1987.
86. McGinnis, R.B., Kennedy, T.W., and Machemehl, R.B., “Stripping and Moisture Damage in Asphalt Mixtures,” Research Report 253-1, Center for Transportation Research, The University of Texas at Austin, September, 1984.

APPENDIX A

CONTACTS SURVEY SUMMARY

APPENDIX A

CONTACTS SURVEY SUMMARY

Contacts made in this study included FHWA Regional Construction/ Material engineers, state material/research engineers, researchers from academia, asphalt/additives producers, consultants, and members from construction industry. Material/research engineers from states which were designated heavy users of antistripping additives in the Tunnicliff and Root (45) report were specifically contacted and earmarked for personal visitation, and some states without any or minimal stripping distress were contacted to explore the possible reasons for their privileged positions.

Contacts were sought primarily from the United States and other parts of the world where efforts in stripping were identified. The modes of contact were by phone, letter, personal visits and discussions with select technologists during technical meetings.

A list of questions was always used during the discussions, a typical set of which is listed below. Some questions regarding additives and use were borrowed from the questionnaire by Tunnicliff and Root (45) which was prepared prior to their antistripping agent study. However, many other unlisted questions were customized to suit the background and experience of the parties involved in the discussion.

1. Do you experience stripping in your flexible pavements?
2. What is the extent of stripping in your pavements (None/Slight/Moderate/ Severe/ etc)?
3. How do you describe stripping or what pavement surface features typify a stripped pavement?
4. Which pavement layer(s) does stripping start and how do you attest its origin?
5. What do you think is the cause(s) of stripping in your area?
6. What are you doing to remedy the problem? (Design/material/ construction/ test(s)/ etc.)
7. What test(s) do you use and why?
8. How do you evaluate the test results to determine if stripping is significant?
9. What test criteria have you developed and what's your rationale?
10. Do you use any additives and how do you select them?
11. How do you measure the durability of additive-modified mixtures?
12. What do you think remains to be done to solve the stripping problem?

Another set of questions which were selectively discussed are borrowed from a report by Don Fohs et al. (83) and include:

13. What chemical phenomenon causes stripping, i.e., what happens between the aggregate and asphalt bond chemically?
14. How, chemically, do antistripping agents work?
15. Which anti-stripping agents work the best? Lime seems to be the best - is this true?
16. What's the relationship between quality control and stripping?
17. What are the best test methods to predict stripping?

The products from the contact survey included:

- Unpublished personal reports
- Sharing of personal and local experience
- Local publications not centrally available
- Information on test methods and criteria in use plus information regarding modifications
- Information on use and class of additives, and
- Selection and approval of additives.

A summary of the responses to some of the questions is presented without disclosing the identity of the exact source unless the source is from a publication.

<u>Do you experience stripping in your flexible pavements?</u>

The responses to this question were usually yes or no.

<u>What is the extent of stripping in your pavements?</u>

The responses ranged from none to severe. The following degrees were expressed in the responses: none, slight, moderate, and severe. The responses which expressed NONE stripping attributed their success to good construction control with regard to quality of materials, good drainage, densities compliant to specifications, a bit of luck, and predominant use of batch plant mixes. Most of the NONE stripping cases use no additives.

The states reporting slight, moderate, and severe stripping all reported using liquid and/or mineral additives to minimize the stripping potential.

<u>How do you describe stripping or what pavement features indicate stripping potential?</u>

The responses to this question listed the following features being indicative of a stripping prone pavement.

- Surface raveling
- Fat spots on pavement surface
- Ringlets consisting of dried up fines deposited on the surface
- Potholes
- Rutting
- Shoving
- Washboarding
- Blistering and pitting
- Raveling, pitting, and slight transverse depressions at locations of reflective cracks, and
- Wet spots along pavement surface and blisters (70)

<u>What pavement layers does stripping start and how do you attest the location?</u>

The following were the locations within the pavement structure where initiation of stripping was observed.

1. Bottom layers (Binder layers) - mostly started from bottom and moved upwards. Parker (84) obtained cores from an Alabama highway whose bottom third of the pavement depth was totally disintegrated. Disintegration from bottom of overlays on old portland cement pavements was recently observed on cores taken by Brown (85) from 1-95 in South Carolina and documented in a recent report by Kandhal (70) regarding similar observations in Pennsylvania.
2. Mid-Layers - It has been observed in a number of pavements that stripping can start in the middle of either layer and spread the stripping effects in all directions. This particular mode was reported from observations made on cores. Bulges were noted at mid-layer locations using cores obtained from a number of projects.
3. Interface boundaries - Interface regions between layers have been observed as locations where stripping initiates. Pronounced delaminations have been widely observed at interfaces.
4. Surface stripping - This is primarily located on the surface and includes surface raveling which can be longitudinal, edge, transverse strips or whole lane width in extent.

The delineation of origin of stripping was generally confirmed from observations made on field cores or slabs. The stripping initiation zones were generally lean in binder content or contained loose aggregate and zones of progression were generally rich in binder content. The upward migration of the binder would eventually lead into fat spots on the surface.

<u>What do you think is the cause(s) of stripping in your area?</u>

McGinnis et al. (86) and other researchers list the following causes for stripping in Texas:
- environment
- aggregate type, and
- mixture properties

The above list of causes was also noted from discussions with many contacts in addition to the following:
- asphalt type
- extensive use of large amounts of natural field sands
- aggregate coatings
- mix design (material selection, analysis, compatibility, etc.)
- test inadequacies
- complexity of the phenomenon
- construction quality and control
- quality assurance programs
- plant mix production technology (that is batch versus drum plants)
- use of ill-understood additives
- high minus 200 content

Paul (78) reports the following causes for stripping in Louisiana:
- Predominant use of water-deposited, smooth hydrophillic chert gravel, and
- use of water-deposited rounded silica sand

Busching et al. (57-58) and Collins (67) credit stripping exacerbation in South Carolina and Georgia to widespread use of porous friction courses. Kandhal et al. (70) credits absence of proper subsurface drainage systems for increased stripping potential

<u>What are you doing to remedy the problem? (Design/Material/Construction/ Test(s))</u>

First of all a number of state Departments of Transportation and/or Highways were issued Task orders since the early 1980s to identify and quantify the extent of stripping in their jurisdictions. Some of these DOTs include most of the southeastern states, and states from other regions of the country. Specific states from which compiled documentation were obtained are cited below:
- Louisiana - Paul (78) reports that the following remedies were considered in Louisiana: use of an anti-stripping agent at 0.5% level in all mixes involving gravel, 0.5% anti-stripping additive level in all friction courses, and strict application of the 10-minute Boil Test. A dismal reduction in the stripping problem was realized. Thus, more research effort was considered and is currently in progress.
- Georgia - Collins (67) discussed Georgia DOT’s experience with stripping in bituminous pavements. A three year extensive field identification and quantification survey program was started in 1979 through 1981. Each survey revealed presence of stripping from slight to severe stages leading to a ban regarding use of open graded friction courses, development of a modified Lottman test procedure, an evaluation criteria, and a dedicated use of hydrated lime in bituminous mixtures.
- New York - Gupta (76) reports results from an FHWA funded cooperative study involving identification and quantification of stripping materials in the state. A number of crushed gravels were identified with which prior use of liquid additives

had been fruitless. These gravels were studied in the laboratory for moisture sensitivity using the immersion compression test. The results from the test were not decisively discriminative between stripping and non-stripping behavior about the 75 percent retained strength criteria and reported field performance. The use of dry hydrated lime did not seem to improve the stripping potential, discarding the aggregate sources was considered uneconomical, but improved construction quality made a difference.

Many other states from which documentation was not obtained participated in the FHWA cooperative study. The conduct of the study was generally similar, the experiences varied, and remedial measures were specific to the jurisdiction concerned.

<u>What tests do you use and why?</u>

The predominant tests used include:

- Tunnicliff/Root or NCHRP 274 test
- Lottman Test or NCHRP 246 test
- Immersion compression test, and
- Boil Test (10-minute or other version)

Reasons for use of either test varied from historically in use to a request by FHWA to commence an investigation of a particular or alternate test for potential application.

<u>How do you evaluate the test results to determine if stripping is significant?</u>

This was always a difficult question. The stripping potential was mostly judged initially based on the laboratory test results. The mixture whose strength ratio fell below the criteria value was always denoted a potential stripper. However, for tests whose criteria had precision limits established, the significance of level of stripping could be inferred when the criteria index fell out side (lower end) of the precision band.

<u>What test criteria have you developed and what is your rationale?</u>

Those using the Immersion compression test use a strength index ranging from 60 percent and higher. Those using the Tunnicliff/Root and/or Lottman test use indices exceeding 70 percent although the use of a 60 percent index (Lottman) has been documented in limited cases in base courses. The boil test (10-minute) criteria has varied from a minimum of 70 percent up to 100 percent retained coating.

The rationale has ranged from “the recommended value” to “one value established using local materials.” The latter argument is the dominant one.

<u>Do you use any additives and how do you select them?</u>

A few respondents reported no use of additives. The positive respondents indicated that the choice of an additive is based on:

- Additive’s improvement of the strength index, or
- Additive’s improvement of the coating ability indicated by the quick bottle test or boil test, and/or
- Additive’s documented and successful use elsewhere using similar materials.

<u>How do you measure the durability of additive-modified mixtures?</u>

The general response was that there was no adequate field information to validate the durability of additive-modified mixtures.

<u>What do you think remains to be done to solve the stripping problem?</u>

Numerous general responses to this question indicated the following deficits:

- An accurate predictive test was unavailable,
- Use of additives remains a mystery because not enough is known about them; there is no test to establish their presence in asphalt qualitatively and quantitatively; long-term field effectiveness is unknown,
- Complexity of the stripping phenomenon remains unfolded, and
- A most effective additive remains undefined.

Many questions similar to those raised by Don Fohs et al. (83) remain unanswered. The general hope is that the SHRP efforts shall unfold most of the unknown phenomena. Don Fohs et al. (83) report lists research efforts which have been undertaken recently, on-going or proposed in the area of stripping as summarized in Table A-1.

Table A-1. Studies Related to Stripping (80)

Title	Org. Funding	Comments
Predicting Numerous Induced Damage to AC-Ten-Year Field Evaluation	NCHRP	Draft final report indicates Lottman test good predictor.
Use of Antistripping Additives in AC Mixes - Part II	NCHRP	Root Tunnicliff commercial additives field tests.
Evaluation of Antistripping Additives	VA-HPR	Field evaluation of lime and liquid anti-strips. Compare with Boil and Tensile Lab tests.
Compatibility of Aggregate, and Anti-Strip Materials	LA-HPR	Correlate Lottman, Pedestal, Boil tests with field performance.
Treatment of AC Mixes with Lime and Antistripping Agents	TX-HPR	Field study of lime and liquid antistrips.
Mix Design Modifications to Improve AC Durability	CA-HPR	Field and lab study to look at premature cracking and rutting.
AC Stripping Problems and Corrective Treatments	FHWA $400K	Evaluate test methods and anti-stripping additives from FHWA/RD-86-091.
Water Sensitivity of AC-Aggregate Systems	SHRP 2.2(3)e	Evaluate tests and reliability and establish criteria.
Evaluation of Procedures Used to Predict Moisture Damage in Asphalt Mixtures	FHWA Staff $100K	Compare various test methods for predicting stripping.