Stripping of Asphalt Pavements: State of the Art

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A comprehensive survey of the literature regarding moisture damage to asphalt pavements as a result of stripping is presented. The literature reviewed was generally limited to readily available publications since 1954. The paper attempts to address the key issues related to stripping of asphalt pavements in a logical order. These issues have been divided into the following categories: Mechanisms of Stripping, Factors Influencing Stripping, Use of Anti-Strip Additives, and Tests to Predict Moisture Susceptibility. Each of these areas has been developed to the extent felt necessary to discuss the current knowledge of the subject adequately, with numerous references cited. A summary entitled "Design and Construction to Reduce the Potential for Stripping of Asphalt Pavements" is provided at the end of the paper to bring together practical implications of the current state of knowledge about stripping and moisture damage of asphalt pavements.

A general definition of stripping is "the breaking of the adhesive bond between the aggregate surface and the asphalt cement" in an asphaltic pavement or mixture (1). Stripping is a complex problem dependent on many variables, including the type and use of mix, asphalt characteristics, aggregate characteristics, environment, traffic, construction practice, and the use of anti-strip additives; however, the presence of moisture is the common factor to all stripping.

A bituminous mixture derives its strength from the cohesional resistance of the binder and grain interlock and frictional resistance of the aggregate. The cohesional resistance is only fully available if a good bond exists between the binder and the aggregate (2). If a good bond exists, failure of the mixture should occur within the binder (2). If the bond is poor, the failure may occur at the binder-aggregate interface and may result in premature failure of the mix.

Failure caused by stripping occurs in two stages: the first stage is stripping failure, and the second stage is failure of the pavement under traffic (3). Many asphalt pavements experience stripping failure within the mix without structural failure of the pavement. If stripping within the pavement becomes excessive, loss of strength may result in excessive deformations caused by repeated loading. This can lead to complete disintegration of the pavement, often in the form of potholes (3). Failure caused by stripping can also result in cracking and surface raveling of the pavement (4). Wearing courses over stripped asphaltic bases are likely to exhibit adhesion failure by raveling and pothole formation (5). With surface treatments, progressive loss of the stripped aggregate causes gradual removal of the entire surfacing (5).

Evidence suggests that a stripped pavement will not fail unless the pavement structure has pronounced flexibility (3). Further evidence suggests that the damage will be minimal if stripping is restricted to the coarse aggregate (6). If the fine aggregate in the mixture strips, severe damage will result because the fine aggregate constitutes the basic matrix of the mixture (6). Numerous investigators have observed that if a stripped asphaltic mixture is exposed to a dry environment, the stripping process is reversed and the mixture will heal itself (4,5,7,8). Failure of a stripped pavement due to traffic is not reversible, however, and prevention is the best and only cure.

MECHANISMS OF STRIPPING

A review of the literature indicates that there may be as many as five different mechanisms by which stripping of asphalt from an aggregate surface may occur. Those five mechanisms include detachment, displacement, spontaneous emulsification, pore pressure, and hydraulic scouring. It appears that these mechanisms may act individually or together to cause adhesion failure in bituminous mixtures. A brief description of each of the suggested mechanisms of stripping follows.

Detachment

Detachment is the separation of an asphalt film from an aggregate surface by a thin layer of water, with no obvious break in the asphalt film (1,2). Where stripping by detachment has occurred, the asphalt film can be peeled cleanly from the aggregate, indicating a complete loss of adhesion (1). The theory of interfacial energy provides the rationale for explaining the detachment mechanism. This widely accepted theory considers adhesion as a thermodynamic phenomenon related to the surface energies of the materials involved, namely, asphalt and mineral aggregates. The surface tension of water is much lower than that of asphalt. The wettability of an aggregate increases as the surface tension (or free surface energy) of the adhesive decreases (2).

Thus, if a three-phase interface consisting of aggregate, asphalt, and water exists, water is better than asphalt for reducing the free surface energy of the system to a thermodynamically stable condition of minimum surface energy (2). The theory of interfacial energy emphasizes the effect of polarity of the molecules present at the surface of the two phases. Most aggregates have electrically charged surfaces. Asphalt, which is composed chiefly of high molecular weight hydrocarbons, exhibits little polar activity; therefore, the bond that develops between asphalt and an aggregate is primarily due to relatively weak dispersion forces (3). Water molecules, on the other hand, are highly polar and are attracted to aggregates by much stronger orientation forces (3).

Displacement

Stripping by displacement results from the penetration of water to the aggregate surface through a break in the asphalt film (1,2,4,5). This break can be caused by incomplete coating of the aggregate initially or by film rupture (1-4). Because the asphalt film at these locations is generally thinner and under tension, rupture of the asphalt film is probable at the sharp edges and corners of angular aggregate pieces as a result of traffic loading. Stripping by displacement can result from pinholes in the asphalt film, which can form soon after coating of a dusty aggregate (4). The concept of stripping by displacement is congruent with the thermodynamic approach to adhesion; that is, water will displace asphalt from an aggregate surface when the three-phase interface exists.

The chemical reaction theory of adhesion can also be used to explain stripping by displacement (5). Changes in the pH of the microscopic water accumulations at the mineral surface can alter the type of polar groups adsorbed, as well as their state of ionization/dissociation, leading to the build-up of opposing, negatively-charged, electrical double layers on the aggregate and asphalt surfaces (5). The drive to reach equilibrium attracts more water and leads to physical separation of the asphalt from the aggregate (5).

Spontaneous Emulsification

In spontaneous emulsification, water and asphalt combine to form an inverted emulsion, where asphalt represents the continuous phase and water represents the discontinuous phase. The formation of such an emulsion leads to stripping and is further aggravated by the presence of emulsifiers such as mineral clays and some asphalt additives (1,4,5).

Fromm observed that spontaneous emulsification occurs whenever asphalt films are immersed in water but that the rate of emulsion formation depends on the nature of the asphalt and the presence of additives (4). He observed that emulsion formation results in a total loss of adhesion when the emulsion penetrates to the aggregate surface (4). The fact that stripping has been observed to be reversible lends support to the spontaneous emulsification mechanism because evaporation of the water from the emulsion returns the asphalt to its original condition (4).

Pore Pressure

Pore pressure has been suggested as a mechanism of stripping in high void mixes where water may circulate freely through interconnected voids (1,2). Upon densification of the mix from traffic loading, water may become trapped in impermeable voids that previously permitted water circulation. Further traffic may induce high excess pore pressures in the trapped water causing stripping of the asphalt film from the aggregate (1,2).

Hydraulic Scouring

Hydraulic scouring is a mechanism of stripping that is applicable only to surface courses. Stripping due to hydraulic scouring results from the action of vehicle tires on a saturated pavement surface. This causes water to be pressed down into the pavement in front of the tire and immediately sucked away from the pavement behind the tire. This compression-tension cycle is believed to contribute to the stripping of the asphalt film from the aggregate (1).

In addition to the mechanisms outlined above, which have gained varying degrees of acceptance among investigators of the stripping problem, other potential mechanisms for stripping have been proposed. Osmosis has been suggested as a possible mechanism of stripping, but this has not been proved in the laboratory (4). It has been observed that asphalt will creep up an air-water interface, such as an air bubble on the pavement surface, as a result of surface tension (4). If the air-water interface is sufficiently large, this pulling of the asphalt film may result in film rupture or may result in a film that is so thin that spontaneous emulsification is rapid (4).

Related to the mechanisms of stripping is the initiation and progression of stripping in a typical asphalt pavement. Inspection of field specimens of stripped pavements has revealed that stripping begins at the bottom of the layer and works its way up, stripping mostly the coarse aggregate (1,4). This behavior is not surprising because the asphalt at the bottom of a pavement layer is in tension upon the application of load and is often subject to prolonged exposure to moisture from water trapped within a granular base course above the subgrade.

FACTORS INFLUENCING STRIPPING

As stated at the beginning of this paper, stripping of asphalt pavement is a complex problem related to a large number of variables. Those variables, which have been identified through years of study of the stripping problem, can be grouped for purposes of discussion into six categories: type and use of mix, asphalt characteristics, aggregate characteristics, environment, traffic, and construction practice.

Type and Use of Mix

The type and use of an asphalt mixture has been found to be related to the likelihood of stripping of the mix. The majority of pavement failures caused by stripping occur in open-graded mixes, base courses, and surface treatments, all of which are relatively permeable to water when compared with dense-graded mixes (2). Surface treatments have been noted to be particularly vulnerable to stripping (9). Stripping in dense-graded, hot-mix paving mixtures is generally not a problem unless the mixtures exhibit excessive air voids, insufficient bitumen, inadequate compaction, or aggregate with adsorbed coatings (9). The inherent resistance to stripping exhibited by dense-graded, hot-mix paving mixtures may be caused, in part, by the use of hot, dry aggregate in those mixtures (7,10).

The small percentage of air voids normally present in well-compacted, dense-graded hot mixes is probably largely responsible for their excellent moisture resistance because the virtual absence of voids renders the mixes almost impermeable. Full-depth (deep strength) asphalt pavements, as proposed by The Asphalt Institute, have been shown to provide excellent resistance to stripping (4,11). The dense-graded asphalt bases often used in full-depth pavements are observed to act as a vapor barrier so that little or no free moisture accumulates beneath the pavements (11).

Asphalt Characteristics

The most frequently referenced relationship between the characteristics of the asphalt in a paving mixture and the tendency of the mix to strip relates stripping resistance to the viscosity of the binder in service (2,3,8,10). Binders of high viscosity have been observed to resist displacement by water much better than those of low viscosity, although even 60 penetration bitumen has been observed to strip (10). Fromm observed that high viscosity asphalt resisted pulling along an air-water interface and that the pulling of the asphalt film increased as asphalt viscosity decreased (4).

Low viscosity, however, is desirable during mixing operations because a low viscosity fluid has more wetting power than one of high viscosity (1,2). Observations made by Schmidt and Graf indicate that most asphalts appear to behave similarly with respect to moisture, provided they are of the same viscosity; i.e., the effect of asphalt composition is negligible (8). In contrast, Fromm observed that the rate of emulsion formation in an asphalt submerged in water depends on the nature of the asphalt rather than its viscosity (4). Logically, an emulsified asphalt may be more prone to stripping by spontaneous emulsification if some concentration of emulsifier remains in the binder after mixing (4). The presence of paraffin in asphalt is believed to be detrimental to stripping resistance (2).

Aggregate Characteristics

The mineralogical and chemical composition of the aggregate is known to be an important factor in the susceptibility of an asphalt pavement to stripping. The mineralogical and chemical composition of an aggregate influences its surface energy and its chemical reactivity; it also accounts for the presence of adsorbed coatings on the aggregate surface (9). With regard to their affinity for water, aggregates are typically classified as being either hydrophilic (water loving) or hydrophobic (water hating). Hydrophilic aggregates are considered to be acidic with regard to their chemical nature and generally exhibit a high silica content. Hydrophobic aggregates, on the other hand, are considered to be chemically basic and exhibit a low silica content. Carbonate rocks, such as limestone, produce hydrophobic aggregates.

It is generally observed that hydrophobic aggregates provide better resistance to stripping of asphalt films than do hydrophilic aggregates; however, acidic quartzite has been shown to be less susceptible to stripping than most basic aggregates (2). Furthermore, stripping was recently observed in Virginia in mixes containing limestone aggregate, which is often considered to be immune to stripping (12). It must be concluded, then, that few if any aggregates can completely resist the stripping action of water.

The physical characteristics of the aggregate surface have been shown to be somewhat related to the occurrence of stripping in asphalt pavements. The surface texture of an aggregate affects its coatability, making it easier to coat a smooth aggregate surface than a rough one (2,9). A complete initial coating of aggregate pieces is obviously necessary to minimize the destructive effect of moisture on the bitumen-aggregate bond.

When an aggregate is coated with asphalt, the asphalt penetrates the pores and cracks of the aggregate surface to some extent (10). It has been suggested, therefore, that an aggregate that has a porous, slightly rough surface will promote adhesion by providing for a mechanical interlock between the bitumen and the surface of the aggregate (2,9). Aggregates that have large pores on exposed surfaces, such as limestone, appear to exhibit stronger bonds with asphalt than aggregates that have fewer or smaller surface pores, such as quartz (10).

Laboratory tests indicate that stripping is more severe when angular aggregates are used (7). This phenomenon is believed to be related to the increased potential for film rupture provided by angular aggregates.

Sometimes a newly crushed aggregate used in asphalt paving mixtures exhibits poor stripping resistance when compared to mixtures made with the same aggregate after it has been stockpiled for some period of time (1). It is a characteristic of many aggregates that one or more layers of water molecules are strongly adsorbed on the aggregate surface as a result of electro-chemical attraction. Upon aging, the outermost adsorbed water molecules may be partially replaced or covered by organic contaminants present in air, such as fatty acids and oils, that reduce the stripping potential of the aggregate. This contamination process is believed to be the reason why an aged or weathered aggregate provides better stripping resistance than one that is freshly crushed (10).

Adsorbed coatings are often present on the surface of aggregates, and the nature of the adsorbed coatings present on a given aggregate is related to its mineralogical and chemical composition. A partial list of substances that have been encountered on the surface of aggregates includes clay, silt, calcium carbonate, iron oxides, opal, gypsum, manganiferous substances, soluble phosphates, dust from crushing, ferruginous coatings (on gravel), oil, fatty acids, oxygen, and water (9). Of these coatings, clay, silt, dust from crushing, and water have been found to be detrimental with regard to the susceptibility of an aggregate to stripping, whereas ferruginous coatings, oil, and fatty acids have been found to be beneficial (9).

Aggregates that have a dry surface provide better adhesion with asphalt and increased stripping resistance than damp or wet aggregates (2,7). Heating aggregates that contain free water and adsorbed water films, under conditions permitting vapor escape, will remove the free water and the outermost adsorbed water molecules, causing the interfacial tension between the asphalt and the aggregate surface to decrease (2,10). This results in a decrease in the stripping potential of the aggregate-binder interface. It has also been observed that asphalt adheres better to hot aggregate, resulting in a stronger bond (2,10).

Environment

The environment of an asphalt pavement is largely responsible for whether or not stripping will occur. Variations in the environment, such as wetting and drying, freeze and thaw, and temperature fluctuations, have notable effects on the resistance of the pavement to moisture damage. It is helpful to examine the ways moisture can have access to the pavement in service so that provisions can be made during pavement design to minimize the amount of water available to the mixture. Schmidt and Graf have shown that the rate and extent of moisture damage to an asphalt mixture is proportional to its water content (8). If one can assume that the pavement surface is properly sealed to prevent infiltration of surface water, the movement of moisture into the subgrade and base courses becomes of great concern with respect to stripping. It has been found that water can enter the subgrade on which an asphalt pavement is supported in one or more of the following ways: seepage from adjacent higher ground, rising of the water table, capillary rise from the water table (moisture suction), from the shoulder (moisture suction), and hydrogenesis (vapor movement) (1,11,13).

Hydrogenesis has been suggested as the primary cause of moisture entering granular bases in flexible pavements (11). Most stripping begins where the bottommost layer of an asphalt pavement meets a wet granular base (1). It has been observed that asphalt pavements placed over untreated granular bases with well-designed and properly operating drainage have not stripped, even when mixtures were made with aggregates known to be prone to stripping (1).

Traffic

Traffic has been shown by numerous investigators to be an important variable in the stripping problem (1-4,7,14). There have been many cases where stripping has occurred only in highway lanes which are subject to heavy traffic (4,7). The role of traffic in asphalt stripping is not well understood; however, it is obvious that traffic imposes cyclic loading on the pavement structure as well as abrasion of its surface.

It has been suggested that the role of traffic may be in the mechanical breaking away of asphalt films that have already stripped from the aggregate (7). It has also been suggested that densification of the paving mixture as a result of traffic loading may close voids in the mix that were formerly permeable to water and that subsequent stress imposed by traffic creates high pore pressures in the trapped water resulting in stripping (1,2,4). Traffic is directly responsible for the mechanism of stripping known as hydraulic scouring (1,7).

Construction Practice

Two aspects of pavement construction practice are of particular importance in stripping: compaction and weather conditions during construction. Proper compaction of asphalt mixtures during pavement construction is a necessity in order to minimize the potential for stripping. Excessive air voids in paving mixtures, resulting from inadequate compaction, can provide passages that permit the movement of water and water vapor through the mix (1).

It has been shown that pavement construction in the late fall results in asphalt pavements that are more susceptible to stripping because of the likelihood of aggregates being damp and weather conditions being cool and wet (15). Regardless of the season, if rain immediately follows pavement construction, stripping of the pavement is more likely to occur because the asphalt viscosity remains low for several hours after paving operations cease.

USE OF ANTI-STRIP ADDITIVES

A review of the literature indicates that the types of anti-strip additives currently being used with reasonable frequency in the United States can be grouped into the following categories: surface active agents (commercial additives), hydrated lime, portland cement, and fly ash.

This is by no means a complete list of the various chemicals and compounds experimented with in the past and probably overlooks a few additives currently being used on a trial basis or with relative infrequency. Rather, the additives listed represent those that have attained general acceptance throughout the country and are believed to be effective in reducing the potential for moisture damage in asphalt pavements (15). Discussions regarding the operative mechanisms, application and dosage, and effectiveness of portland cement and fly ash as anti-strip additives were not encountered in the reviewed literature. It is speculated, however, that these additives are effective and are applied in much the same way as hydrated lime. Of the four additives, only the first group, surface active agents, needs explanation regarding its constituents.

Tunnicliff and Root concluded that all of the surface active agents in current use are amines or chemical compounds containing amines, which are strongly basic compounds derived from ammonia (15). Most of the surface active agents (or surfactants) are cationic; however, some contain both cationic and anionic compounds and a few are strictly anionic compounds (15). Lists of approved commercial additives provided by responding agencies in the Tunnicliff and Root survey revealed at least 27 different manufacturers of anti-strip additives in the United States providing at least 116 approved products (15). The number of commercial additives on the market are constantly changing as some additives are discontinued and new ones introduced, but the number of additives available remains large (15). The additive manufacturers who responded to the inquiries of Tunnicliff and Root all claim that their additives are heat stable at usual working temperatures (15). An additive that is heat stable theoretically does not contain compounds that will react with some component of asphalt cement and render the additive ineffective as a surfactant (15). The rate of such reactions is significantly increased with increased temperature, thus the term "heat stable."

Operative Mechanisms

Tunnicliff and Root define anti-strip additives as "substances designed to convert the aggregate surface to one that is more easily wetted with asphalt than water" (15); however, anti-strip additives may also increase the resistance of an asphalt pavement to stripping by means other than electrochemical modification of the aggregate surface. Surface active agents work by reducing the interfacial tension between the aggregate and bitumen by adsorption at the aggregate-bitumen interface, thereby strengthening and reducing the stripping potential of the aggregate-bitumen bond (2,7,16). The intent of this modification is to convert the aggregate surface to one that is more easily wetted by asphalt than water (15). Cationic surfactants, upon migration to the aggregate surface, displace water and render the surface hydrophobic and lipophilic (having an affinity for oil) (17).

Lime is usually considered to function as an anti-strip additive by means of a reaction in which the hydrogen, sodium, potassium, and other cations on the aggregate surface are replaced by calcium from the lime (8). It has been suggested by Plancher and others that the effect of hydrated lime in improving the stripping resistance of asphalt mixtures is, in part, a result of its interaction with certain asphaltic acids that are readily adsorbed to aggregate surfaces (18).

Schmidt and Graf concluded that the mechanism by which lime operates in asphalt mixtures cannot be fully explained by reaction with asphaltic acids or cation exchange at the aggregate surface (8). Based on their observations, Schmidt and Graf concluded that hydrated lime improves the stripping resistance of asphalt mixtures to a large extent by the formation of a separate, crystalline, lime-mortar bond between aggregate particles that appears to be synergistic with the binding action of asphalt (8).

Application and Dosage

There are two methods of introducing anti-strip additives into asphaltic paving mixtures. The additive may be added to the asphalt while in a liquid state and thoroughly mixed before mixing the asphalt with the aggregate or aggregates (2,17). This method is inefficient because much of the additive never reaches the aggregate-bitumen interface; however, it represents a simple and economical application method and is generally the method by which commercial additives are currently used.

The second method consists of applying the additive directly to the aggregate surface (2,17). This is the most efficient and most effective method; however, it requires more labor and probably more additive and is, therefore, more expensive. It has been shown that hydrated lime is most effective when applied as a slurry to the aggregate before heating and drying (4,8).

It has been observed repeatedly by investigators working with anti-strip additives that the dosage of the additive employed in a mix is extremely important to its effectiveness. Anderson and others indicate that a minimum dosage for surface active agents exists, such that "the demand of the asphalt for the anti-strip additive must be satisfied before the additive is effective as an anti-strip agent" (19).

Typical dosages of surface active agents in current use range between 0.3 and 0.5 percent by weight of asphalt when used with cutback asphalts and are on the order of 1 percent or greater by weight of asphalt cement when used in hot-mix (17). Manufacturers of commercial anti-strip additives recommend dosages ranging from less than 0.1 percent to 3 percent by weight of asphalt cement (15). Schmidt and Graf suggest that amounts of lime greater than 1 percent by weight of asphalt are required to form mortar bonds (8).

Effectiveness

Several investigators have reached the same conclusion about effectiveness of anti-strip additives: anti-strip additives are asphalt and aggregate-specific (2,4,12,15,16,19). Previous work to evaluate anti-strip additives has generally shown that hydrated lime is the most effective additive in reducing moisture damage of asphalt mixtures, especially when applied as a slurry to the aggregate prior to drying (6,8).

As reported by Schmidt and Graf, commercial additives that showed dramatic improvement in adhesion (apparent stripping resistance), when tested by usual stripping tests, did not reduce the drop in resilient modulus caused by water saturation when present in concentrations of 1 percent by weight of asphalt (8). However two surface active agents tested by Dalter and Gilmore showed dramatic improvement in retention of diametral tensile strength of compacted specimens, upon vacuum saturation followed by freeze-thaw conditioning, when compared to untreated specimens of the same mix, using both limestone and granitic aggregate mixtures (16).

It has been suggested that commercial anti-strip additives may be ineffective if stripping is initiated and accelerated by externally induced physical damage (e.g., traffic, freeze-thaw, and so on) rather than by spontaneous stripping (15). Commercial additives have been shown to be effective in promoting good initial coating of the aggregate and resisting spontaneous stripping by emulsification, detachment, and so on. At present, no published data appears to be available about the effect of anti-strip additives on the long-term field performance of asphalt pavements.

Problems

Problems with some commercial anti-strip additives have been encountered. Some commercial anti-strip additives can reduce the viscosity of the asphalt in a paving mixture (3,12,19). The largest changes in asphalt viscosity that have been observed approach the magnitude of the specification band for asphalt viscosity; therefore, the use of an anti-strip additive could result in an asphalt which does not meet viscosity specifications (19).

The time required for an adequate amount of surfactant to migrate to the aggregate-binder interface, when dissolved in the binder, may be greater than the period of time during which the asphalt viscosity is sufficiently low to permit such migration (7,15,17). If this occurs, the amount of surfactant that reaches the aggregate surface may be inadequate to satisfy the aggregate's demand and perform as an effective anti-strip agent.

Some commercial anti-strip additives exhibit low heat stability regardless of manufacturer claims (2,8). Some commercial surfactants can act as emulsifiers, particularly if excessive dosages are used (1,4). Although these additives may promote good initial coating and adhesion, they can accelerate stripping by promoting spontaneous emulsification (4). If the concentration of cationic surfactant in an asphalt binder is in excess of that needed to satisfy the aggregate's adsorption sites, a mechanically weak, water-susceptible shear plane can occur within the binder (15,17). This weak condition can promote stripping in asphalt pavements, or could conceivably result in premature failure of the mix in the binder itself (15,17). Some commercial additives may interact with certain compounds in the asphalt without undergoing a chemical change; this may prevent their migration to the aggregate surface, thereby making them ineffective (15).

Given the state of the art concerning commercial anti-strip additives, it is apparent that no foolproof commercial additive is currently available. (15).

TESTS TO PREDICT MOISTURE SUSCEPTIBILITY

Numerous tests have been developed to evaluate properties that affect the stripping potential of a bituminous mix and to predict the moisture susceptibility of a given mixture. None of the tests developed to date has received wide acceptance; this is due, for the most part, to their low reliability. The reliability of a majority of the test procedures proposed to date is poor because of a lack of a direct relationship between laboratory and field conditions. The development and use of laboratory tests to predict an asphalt mixture's susceptibility to moisture began around 1930 or possibly a few years earlier (9). Moisture susceptibility tests serve three purposes:

1. To determine the degree of resistance provided by a mixture against the action of water for a particular combination of asphalt and aggregates (mix design),
2. To compare mixes composed of different types or quantities of asphalt and aggregate, and
3. To evaluate the effectiveness of one or more anti-strip additives in a given mix and determine the optimum dosage.

Literally dozens of laboratory test procedures have been developed in an effort to determine the susceptibility of asphalt paving mixtures to moisture damage. Some of the better known tests that have been developed and are referenced in the literature but that may or may not remain in use today are listed below.

1. Static Immersion Tests
   ASTM D1664-80 (20)
   Lee (2)
   Holmes Water Displacement (2)
   Oberbach (2)
   German U-37 (2,9)

2. Dynamic Immersion Tests
   Nicholson (2,9)
   Dow or Tyler Wash (2,9)

3. Boiling Tests
   ASTM D3625-77 (21)
   Reidel and Weber (2,9)

4. Chemical Immersion Test
   Reidel and Weber (2,9)

5. Quantitative Coating Evaluation Tests
   Dye Adsorption (22)
   Mechanical Integration Method (2)
   Radioactive Isotope Tracer Technique (2,9)
   Tracer-Salt with Flame Photometer Analysis (9)
   Light-Reflection Method (2,9)

6. Abrasion Tests
    - Cold Water Abrasion (2)
    - Abrasion-Displacement (2)
    - Surface Water Abrasion (22)
7. Simulated Traffic Tests
    - English Trafficking (2,3)
    - Test Tracks (2)
8. Immersion-Mechanical Tests
    - Immersion-Compression [ASTM D 1075-76 (23) or AASHTO T 165-77 (24)]
    - Indirect Tension (Diametral Compression) (14)
    - Water Susceptibility (22)
    - Moisture Vapor Susceptibility (22)
    - Marshall Immersion (15)
9. Nondestructive Tests
    - Sonic (25)
    - Resilient Modulus (8)
10. Miscellaneous Tests
    - Detachment (2)
    - Briquet Soaking (2,9)
    - Swell (2,9)
    - Stripping Coefficient Measurement (10)
    - Peeling (2)
    - Texas Freeze-Thaw Pedestal (6)

Discussions are presented below for some of the more widely accepted and recently developed moisture susceptibility tests in current use in the United States.

Qualitative Coating Evaluation Tests

All of the qualitative coating evaluation tests, including static immersion, dynamic immersion, boiling tests, and chemical immersion tests, involve the immersion in water of loose coated mixtures, with or without agitation of the immersed mix, typically having a specified aggregate gradation. In each test, the asphalt mixture remains immersed for a specified period of time, and at the end of that time the percentage of coating retained on the aggregate is estimated visually.

Of all the tests included in this category, the standardized static immersion test, ASTM D1664, is probably the most widely used. The main advantage of qualitative coating evaluation tests is that they are simple to perform, require little equipment, and can be performed in a short time. Perhaps the most frequent criticism of qualitative coating evaluation tests is that no correlation has been shown to exist between observations made during the tests and the field performance of pavements made with the same mixtures (2,9,20,21).

Quantitative Coating Evaluation Tests

Quantitative coating evaluation tests are very similar in procedure to qualitative coating evaluation tests except that in quantitative tests an attempt is made to measure the percentage of aggregate surface exposed rather than to estimate it visually. The basis for such a determination is that exposed aggregate surfaces in the mix will adsorb a dye or tracer introduced into the system, or reflect light, whereas coated aggregate surfaces will not. Therefore, by measuring the concentrations of tracer or dye in the stripping solution after exposure to both coated and uncoated mixtures, or by measuring the light reflected, the percentage of coating can be determined quantitatively. The same advantages and disadvantages of qualitative coating evaluation tests generally apply to these tests.

Immersion-Mechanical Tests

Immersion-mechanical tests measure changes in a specified mechanical property of compacted mixtures, such as shear strength, tensile strength, flexural strength, compressive strength, and so on, caused by exposure to moisture. Because of their wide acceptance and use throughout the United States, the Immersion Compression Test, Marshall Immersion Test, and Indirect Tension Test are discussed separately. The Water Susceptibility Test and Moisture Vapor Susceptibility Test are not discussed because of their relative infrequency of use.

The main benefit of immersion-mechanical tests is that they allow the use of a mixture that is representative of the mix to be used in the field, and that can be compacted to a density comparable to the proposed field density. One restriction of immersion-mechanical tests, however, is that they are limited to mixtures made with penetration grade asphalt cement. Because all of the tests require a relatively large number of test specimens, they are subject to inherent difficulties in producing identical specimens for comparison of strength behavior before and after moisture conditioning (2,9). No quantitative correlations between the results of immersion-mechanical tests and field performance of bituminous pavements have been developed, perhaps because of difficulties in establishing realistic exposure conditions.

Immersion-Compression Test

The Immersion-Compression Test measures the compressive strength of compacted asphalt mixtures before and after moisture conditioning. According to the ASTM D1075-76 procedure, six cylindrical specimens are prepared and cured in accordance with ASTM D1074 (23). The cured specimens are separated into two groups of three specimens by bulk specific gravity so that the average bulk specific gravities of both groups are similar.

One group of specimens is submerged in a constant temperature bath for 4 days at 120°F before compression testing at 77°F (23). The unconditioned group is compression tested dry at 77°F (23). Compression testing is performed in accordance with ASTM D1074. The compressive strengths of specimens within each group are averaged, and an Index of Retained Strength is calculated, which is the ratio of the average compressive strength of the immersed specimens to the average compressive strength of the dry specimens. The Asphalt Institute recommends that an Index of Retained Strength equal to 75 percent be used as the acceptance/rejection criterion for the Immersion-Compression Test (1).

Marshall Immersion Test

The Marshall Immersion Test is virtually identical to the Immersion-Compression Test except that Marshall stability is the mechanical property that is measured. In the Marshall Immersion Test, moisture conditioning is usually accomplished by soaking the specimen for 24 hr at 140°F (15). Moisture damage is evaluated based on a ratio of Marshall stabilities for conditioned and unconditioned samples. Field and Phang developed this test method, but many variations of the test are in current use (8,15).

Indirect Tension Test

The Indirect Tension Test for predicting moisture susceptibility, as developed by Lottman, determines the tensile strength and instantaneous E-modulus of cylindrical specimens by use of a diametral compression test at a specified loading rate and temperature (14). The resulting data is normalized by expressing it in the form of a tensile strength ratio (TSR) and an E-modulus ratio (E-modR), where the tensile strength and E-modulus of dry specimens are used as reference bases.

After exposing two-thirds of the prepared specimens to vacuum saturation, one-half of the vacuum-saturated specimens are exposed to secondary moisture conditioning consisting of a single freeze-plus-soak cycle (0-140°F) or repeated freeze-thaw cycling (18 cycles of 0-120-0°F) (14). Lottman recommends a separation point of 0.7 for tensile strength ratio or E-modulus ratio, as determined for the specimens subjected to vacuum saturation plus thermal cycling, to distinguish between moisture susceptible mixtures and moisture resistant mixtures; the former category is associated with the lower values (14). The procedure has the potential for providing a quantitative measure of the rate of moisture damage progression by providing for strength and modulus determinations at three distinct phases of moisture conditioning (14)

Lottman's method has been criticized for being too severe with regard to moisture conditioning; however, this appears to be a procedural matter rather than a problem inherent in the test method. Moisture conditioning could be modified to simulate more accurately the climatic conditions that prevail locally (15). No special equipment is needed for the proposed test method because most of the needed equipment is available in the majority of highway materials laboratories (14). Correlation studies performed by Lottman, involving 17 pavements in service in 14 states, indicate that the indirect tension method gives good reliability in identifying asphaltic concrete mixtures that are prone to severe moisture damage and in identifying those that are strongly resistant to moisture damage. It is less reliable in predicting intermediate moisture resistance (14).

A limited correlation study by the Virginia Department of Highways and Transportation compares tensile strength ratio values obtained from laboratory specimens prepared from job mixtures before construction with observed stripping of core samples taken from the pavements after 2.5 years of service (12). The results of that study indicate that tensile strength ratio values correlate well with the observed stripping and performance, assuming that a tensile strength ratio of 0.70 to 0.75 serves as the separation point between good performance and stripping (12).

With further refinement, the moisture damage test system recommended by Lottman may provide quantitative predictions of moisture damage to asphaltic concrete mixtures (14).

Resilient Modulus Test

The Resilient Modulus Test, used by Schmidt and Graf to evaluate the effect of water on asphalt mixtures, uses a 0.1 sec duration pulsing load applied across one diameter of a cylindrical specimen made in accordance with ASTM D1561-65 using the Hveem kneading compactor (8). During application of the pulsing load across one diameter of the specimen, the resultant elastic deformation across the perpendicular, or opposite, diameter is measured. The resilient modulus, M_R, is then calculated from the loading and deformation values, the sample thickness, and an assumed value of Poisson's ratio.

Schmidt and Graf subjected test specimens to various forms of moisture conditioning and then compared the resilient moduli determined for the conditioned specimens to those determined for dry specimens. The resilient modulus is a property that is directly related to the load carrying ability of a flexible pavement; therefore, the Resilient Modulus Test offers great potential for correlating moisture damage observed in the laboratory with field performance.

Because the test is nondestructive, it can be used to measure changes in the resilient modulus of the same specimen with time. The progressive deterioration of asphaltic paving mixtures in service caused by stripping can be related to changes in the elastic constants of the mix (2). By using moisture and thermal conditioning procedures modeled closely after conditions that could be expected to prevail in service, the Resilient Modulus Test may predict moisture damage in an asphalt pavement, and its consequences, with sufficient reliability to make it a valuable design tool.

One factor that may limit use of the Resilient Modulus Test, however, is the cost and availability of the necessary testing equipment.

Texas Freeze-Thaw Pedestal Test

The recently developed Texas Freeze-Thaw Pedestal Test evaluates the moisture susceptibility of an asphalt mixture by determining the number of freeze-thaw cycles that a specimen can endure before cracking (6). The test method uses a compacted cylindrical specimen, approximately 3/4-in. thick by 1-3/8-in. diameter, composed of a uniformly-sized fraction of the proposed job aggregate and 2 percent more asphalt than proposed for the field mix. The compacted specimen is immersed in water contained in a sealed jar and subjected to thermal cycling (10-140-10°F). Kennedy, Roberts, and Lee, who proposed the test method, have concluded that the dividing line between stripping-prone and stripping-resistant mixtures lies between 10 and 20 cycles to failure (6).

A limited correlation study performed during development of the Texas Freeze-Thaw Pedestal Test revealed that the test results showed good correlation with previous field experience using the tested aggregates; however, at this stage, the test method remains empirical and has only been tested on and correlated with a limited number of mixes (6). The need for further study of this test method is indicated.

At present no one test method has been found to be totally reliable in its prediction of the moisture susceptibility of a given paving mixture; however, the evolutionary advancement toward that goal has resulted in new test methods that are predicting moisture damage with increasing degrees of accuracy and confidence.

DESIGN AND CONSTRUCTION TO REDUCE THE POTENTIAL FOR STRIPPING OF ASPHALT PAVEMENTS

Based on the findings of this study, recommendations are presented below that should serve as general guidelines for both the design and construction of asphalt pavements and mixtures to reduce the potential for stripping and related failures. No originality is claimed for the recommendations; in fact, they generally follow recommendations outlined in ES-10 of The Asphalt Institute (1).

1. Pavement and mix design practice should consider the loss of pavement strength and stiffness, and thus performance, that results from exposure to moisture. This might best be accomplished by incorporating an immersion-mechanical test into the design procedure, so that a quantitative evaluation of strength or stiffness loss due to moisture condi-

tioning can be made, and a reduced strength or stiffness value can be used in the design.

2. Specify a well-compacted, dense-graded hot mix whenever possible.

3. Consider a Full-Depth (Deep Strength) design in which all of the pavement layers use asphalt mixtures. Use dense-graded asphalt mixtures for base and intermediate courses where possible.

4. Provide positive drainage, both surface and subsurface, unless a Full-Depth design is specified. In conjunction with providing good drainage, maintain a well-sealed surface on the roadway to minimize infiltration of surface water.

5. Assure thorough compaction of all courses.

6. Select a grade of asphalt that will wet the aggregate thoroughly during mixing but will have a viscosity in service that is as high as practical for other mix considerations.

7. Use as high an asphalt content as is practical to meet stability and flow requirements. Thick asphalt films can best be accommodated by selecting an aggregate gradation that provides a high percentage of voids in the mineral aggregate (VMA) after compaction (8). The design asphalt content should result in a low percentage of air voids in the compacted mix.

8. Use hot, dry, clean aggregate (not freshly crushed).

9. Do not use highly hydrophilic aggregate if a choice is available.

10. If the apparent stripping resistance of a mix is less than desired, treat it with hydrated lime or a heat-stable surface active agent in an amount determined by mix design and thorough laboratory testing. Hydrated lime is most effective when applied as a slurry to the aggregate before drying. Make sure commercial additives are compatible and effective with the mix materials by testing and observe manufacturer dosage guidelines.

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Discussion

Waheed Uddin

In the state-of-the-art report on stripping of asphalt pavements, the authors have presented an excellent overview of the different types of tests to evaluate the stripping potential of an asphalt concrete mix. In their comments on qualitative coating and stripping evaluation tests, it is mentioned that the ASTM D1664 standard test is frequently criticized. Nevertheless, this test is treated as a standard in many countries around the world and is a quick way to examine the stripping potential while using the material testing facilities on a paving site.

In Saudi Arabia, on the projects of the Civil Aviation Department, a modified stripping test is included in the standard specifications prepared by their consultants, Netherlands Airport Consultants. This test falls in the same category as ASTM D1664. The test is performed on laboratory-prepared as well as plant-mix samples. The test procedure is outlined below.

> In the laboratory, samples of asphaltic concrete mixture are prepared using the same procedure as for Marshall specimens. The optimum asphalt content is used in the preparation of the test samples. The mixture is then spread in loose thin layers to be cured in air for 24 hours. Half of a 600 ml clean glass jar is filled with the sample and covered with distilled water at the room temperature. After 24 hours immersion in water, the jar is vigorously shaken for about 15 minutes and the sample is then examined visually for stripping. This is done by looking through the water in the standard way. Further examination is done by spreading the mixture again on a clean flat surface.

This test method has been successfully used during the construction of pavements on civil aviation projects. The writer used this procedure along with ASTM D1664 on some of these jobs. The modified test has two distinct advantages over the ASTM standard method: (a) The test sample is prepared according to the design mix at the optimum asphalt content, and (b) the test is also performed on the plant mix samples. In general the modified procedure gives a better estimate of stripping potential of the design asphalt concrete mix under conditions closely related to actual field condition.

Qualitative test methods are still necessary especially in the developing countries or anywhere when the more sophisticated testing facilities are not readily available. A qualitative test method can also be used to develop a rating scheme for various aggregate sources in a project area.

Author's Closure

Mark A. Taylor

Uddin's defense of qualitative coating evaluation tests is well received and certainly justifiable. Our intent was not to discredit this classification of stripping tests, but rather to point out the dissatisfaction of many investigators with the reproducibility of the tests and their correlation with field performance. Limitations on the paper's length prevented a thorough discussion of many aspects of the stripping problem. Uddin's discussion is greatly appreciated since it provides a different perspective on one of the many categories of stripping tests.

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Investigation of Moisture Damage to Asphalt Concrete and the Effect on Field Performance–A Case Study

THOMAS W. KENNEDY, ROBERT B. McGENNIS, AND FREDDY L. ROBERTS

An investigation of premature distress and failure of an asphalt concrete overlay placed in 1979 and 1980 is summarized. The primary objective of the study was to determine the probable cause of the distress. The investigation involved an analysis of construction records and laboratory test results performed during and after construction. In addition, specimens and material were obtained from the roadway for use in a laboratory evaluation. The sampling program included the collection of cores, slabs, and stockpile or pit materials. A description and summary of the pavement and distress, construction procedures, and mixture characteristics, along with the findings related to the probable causes of the distress is presented. The basic causes were that (a) all aggregates and the resulting aggregate-asphalt combinations were highly susceptible to moisture damage and (b) the antistripping additive used in the mixture was not effective.

In the fall of 1979, an overlay project was undertaken to rehabilitate a section of roadway that had been in service for 13 yr. The project was 9 miles long and consisted of overlaying a continuously reinforced concrete pavement (CRCP) with hot-mix asphalt concrete.

In June 1980, before completion of the contract, distress began to develop on certain sections of the highway (Figures 1-4). Distress was in the form of rutting, shoving, and bleeding. Initially, distress occurred in small areas of the outside westbound lanes; however, distress subsequently developed in