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MOISTURE SUSCEPTIBILITY OF HMA MIXES: IDENTIFICATION OF PROBLEM AND RECOMMENDED SOLUTIONS

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ABSTRACT

Stripping of hot mix asphalt (HMA) pavements appears to have become a major problem in recent years. More and more states are specifying the use of antistripping (AS) agents. There is a need to identify the problem properly so that decisions are not made based on visual observations of some isolated distressed areas.

External factors and/or in-place properties of the HMA pavements can induce premature stripping in HMA pavements. This paper describes these factors such as inadequate pavement drainage, inadequate compaction of HMA pavement, excessive dust coating on aggregate, inadequate drying of aggregates, and overlays on concrete pavements. Suggestions for alleviating the problems associated with these factors have been given.

An investigative methodology based on forensic experience has been recommended for use by the specifying agencies and industry to establish stripping as a problem on a specific project or statewide.

The current practices of specifying moisture susceptibility tests across the United States have been reviewed. AASHTO T283 (Modified Lottman) test method has been recommended to determine moisture susceptibility of HMA mixes until more suitable and reliable tests are developed and validated by SHRP or other agencies.

MOISTURE SUSCEPTIBILITY OF HMA MIXES: IDENTIFICATION OF PROBLEM AND RECOMMENDED SOLUTIONS

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INTRODUCTION

In recent years stripping of hot mix asphalt (HMA) pavements appears to have become a major problem. Every year more and more states are specifying the use of antistripping (AS) agents. There is a need to identify the problem properly so that decisions are not made based on visual observations of some isolated distressed areas. Premature stripping can result from poor subsurface drainage (causing excessive moisture in the pavement structural layers), use of weak and friable aggregates (fracturing during construction and subsequently in service exposing uncoated surfaces), excessive dust coating around the aggregates, and very poor compaction of the HMA mat during construction.

Among the states which have started to specify AS agents the proliferation of specifications and test methods is large. Different test methods such as immersion-compression, boiling water, Texas pedestal, Lottman, modified Lottman, and Tunnicliff-Root are specified usually with some variations. Different acceptance criteria are used for the same test method.

OBJECTIVES

This study was undertaken to achieve the following objectives:

1. List and discuss the factors which can induce premature stripping in HMA pavements.
2. Recommend an investigative methodology which can be used by the specifying agencies/industry to establish stripping as a problem on a specific project or statewide.
3. Review the current practice of specifying AS agents, test methods and acceptance criteria. Make recommendations; for a viable common strategy on specifications and test methods.

FACTORS RESPONSIBLE FOR INDUCING PREMATURE STRIPPING

Figure 1 shows the estimated percentage of HMA pavements experiencing moisture related distress in the United States according to a 1989 survey of state departments of transportation (*1*). Research conducted at the National Center for Asphalt Technology (NCAT) under the SHRP A-003B Project has shown that the physicochemical surface properties of mineral aggregate are more important for moisture induced stripping compared to the properties of asphalt cement binder. Some mineral aggregates are inherently very susceptible to stripping. However, in many cases external factors and/or in-place properties of HMA pavements induce premature stripping in HMA pavements. A proper knowledge of these factors is essential in identifying and solving the stripping problem. A discussion of these factors follows.

Inadequate Pavement Drainage

Inadequate surface and/or subsurface drainage provides water or moisture vapor which is the necessary ingredient for inducing stripping. If excessive water or moisture is present in the pavement system the HMA pavement can strip prematurely. Kandhal et al. (*2*) have reported case histories where the stripping was not a general phenomenon occurring on the entire project

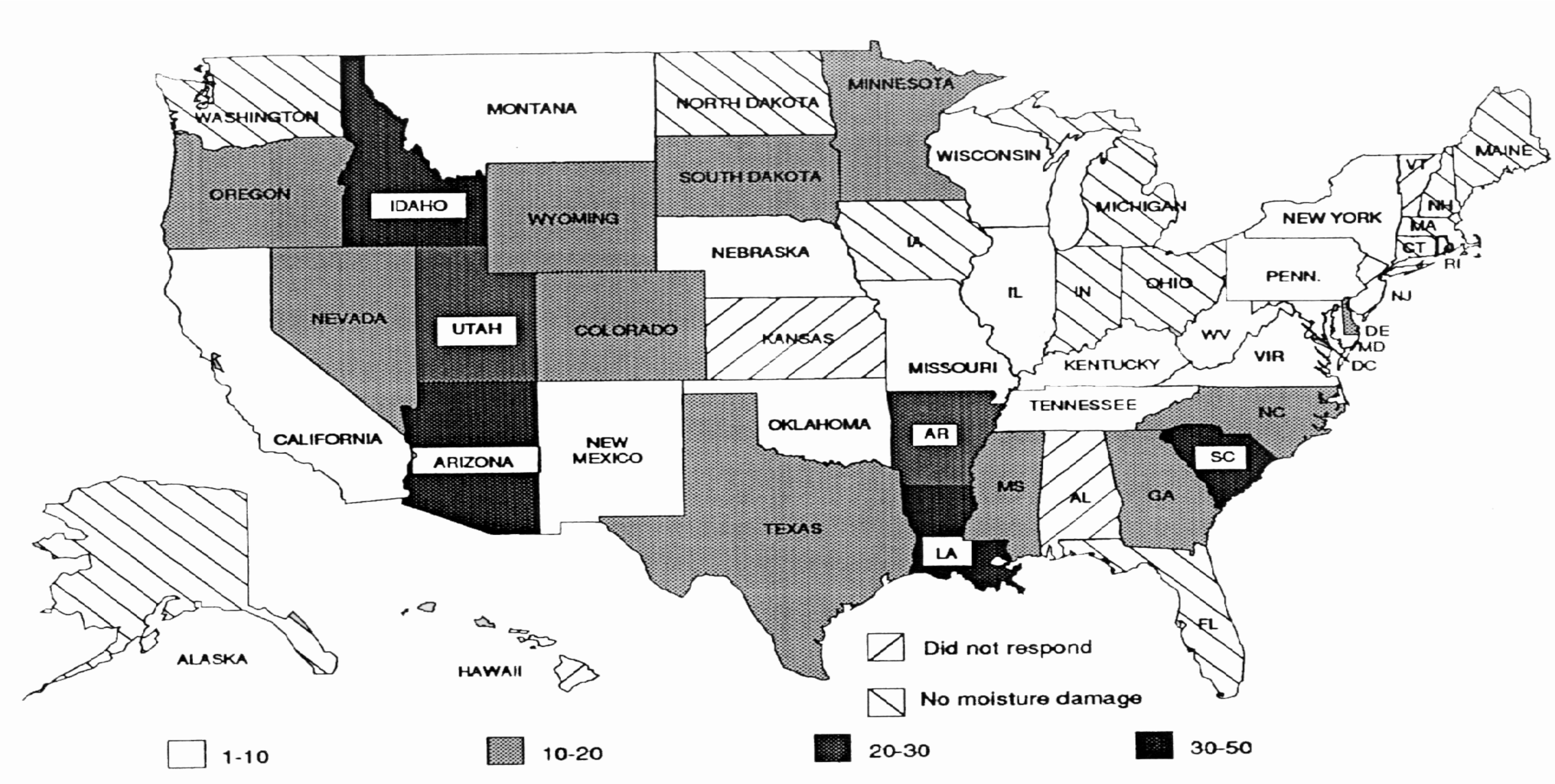

Figure 1. Estimated Percentage of Pavements Experiencing Moisture Related Distress (*1*)

but rather a localized phenomenon in areas of the project over-saturated with water and/or water vapor due to inadequate subsurface drainage conditions.

Water can enter the HMA pavement layers in different ways. It can enter as run-off through the road surface, primarily through surface cracks. It can enter from the sides and bottom as seepage from ditches and high water table in the cut areas.

The most common water movement is upward by capillarity under a pavement. Above the capillary fringe water moves as a vapor. Many subbases or subgrades in the existing highway system lack the desired permeability, and, therefore, are saturated with the capillary moisture. The construction of multilane highways (or widening) to greater widths, gentler slopes and milder curves in all kinds of terrain has compounded the subsurface drainage problem. Doubling the road width, for example, makes drainage about four times as difficult as before (*3*). Quite often, a four-lane highway is rehabilitated by paving the median and shoulders with HMA resulting in a fully paved width of 72-78 feet which is equivalent to a six-lane highway without any increase in the subsurface drainage capability (*2*).

Extensive research has been conducted on the mechanism of asphalt stripping at the University of Idaho (*4*). It has been reported that "air voids in asphalt concrete may become saturated with water even from vapor condensation due to water in the subgrade or subbase. A temperature rise after this saturation can cause expansion of the water trapped in the mixture voids resulting in significant void pressure when the voids are saturated. It was found that void water pressure may develop to 20 psi under differential thermal expansion of the compacted asphalt mixture and could exceed the adhesive strength of the binder aggregate surface. If asphalt concrete is permeable, water could flow out of the void spaces under the pressure developed by the temperature rise and, in time, relieve the pressure developed. If not, then the tensile stress resulting from the pressure may break adhesive bonds and the water could flow around the aggregates causing stripping. The stripping damage due to void water pressure and external cyclic stress (by traffic) mechanism is internal in the specimens, the exterior sides of the specimens do not show stripping damage unless opened up for visual examination."

Majidzadeh and Brovold (*5*) have also stated that the pore pressure from stresses induced by traffic cause the failure of the binder-aggregate bond. Initially, the traffic stresses may further compact the mixture and trap or greatly reduce the internal water drainage. Therefore, the internal water is in frequent motion (cyclic) and considerable pore pressure is built up under the traffic action.

Hallberg (*6*) has reported that "the required internal water pressure causing an asphaltic mixture to have adhesive or interfacial tension failure (stripping) is inversely proportional to the diameter of the pores." Binder course mixtures generally strip more than the wearing course mixtures possibly due to large diameter pores in the binder course. Moreover, the wearing course is exposed to repeated high temperature drying periods when the pavement heals. The asphalt films which debond from the aggregate attach themselves again and the mix regains its strength and water resistance. The humid periods are longer in the underlying binder course and, therefore, the self healing forces during warm periods have much less influence.

Lovering and Cedergren (*7*) have reported that "with insufficient drainage, water may flood the base and rise through the pavement. Many drainage problems and deteriorated pavements can be attributed to water that enters the structural section from below." Apparently the deterioration is caused by premature stripping in many cases.

Telltale signs of water damage to HMA overlays (over concrete pavements) have been described by Kandhal et al. (*2*). They observed wet spots on the HMA overlay surface scattered throughout the project. Usually at these wet spots water oozed out during hot afternoons. Some of the wet spots contained fines suspended in the water which were tracked on the pavement by the traffic and appeared as white spots. Most white spots turned into fatty areas (resulting from asphalt stripping and migrating to the surface) which usually preceded the formation of potholes. Figures 2 and 3 show all three stages: white spots, fatty areas, and potholes on a four-lane highway. Figure 4 shows severely stripped aggregate particles in a pothole.

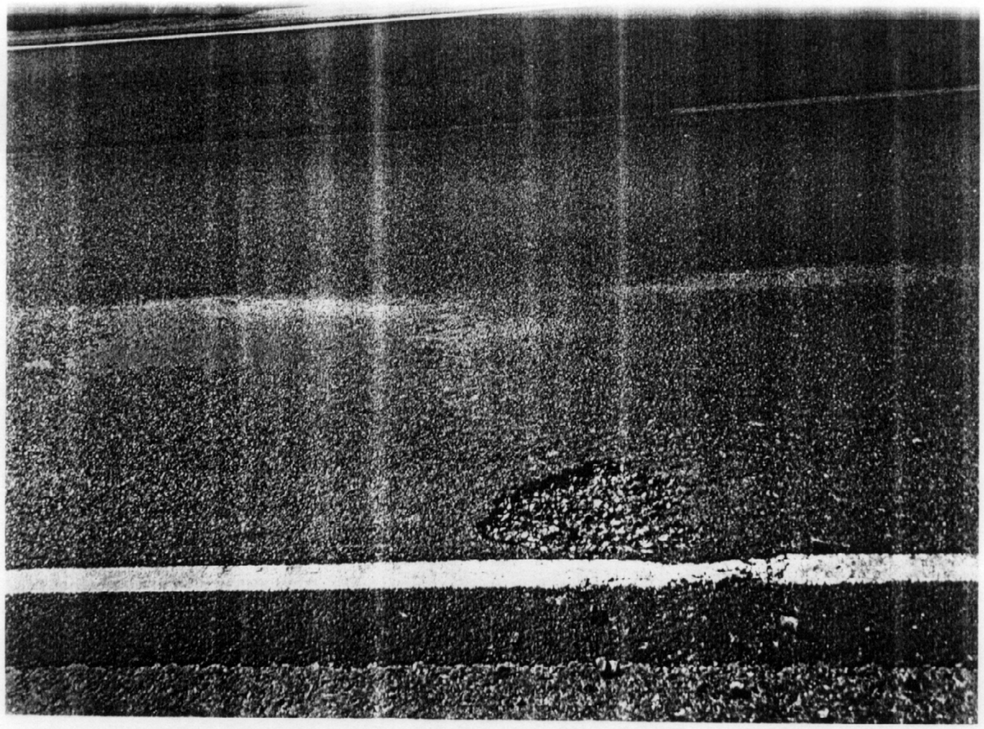

Figure 2. Three Stages of Stripping: White Spots, Fatty Area, and Pothole (a Closeup)

Figure 3. Slow Traffic Lane Showing Three Stages of Stripping

Figure 4. Close-Up of Pothole Showing Severely Stripped Aggregate

Small and large blisters were also observed due to entrapped moisture. A very severe case of blistering from moisture vapor pressure at Emporia Airport, Virginia has been described by Acott and Crawford (*8*) and is shown in Figure 5. However, blisters can occur without any asphaltic globules at the surface.

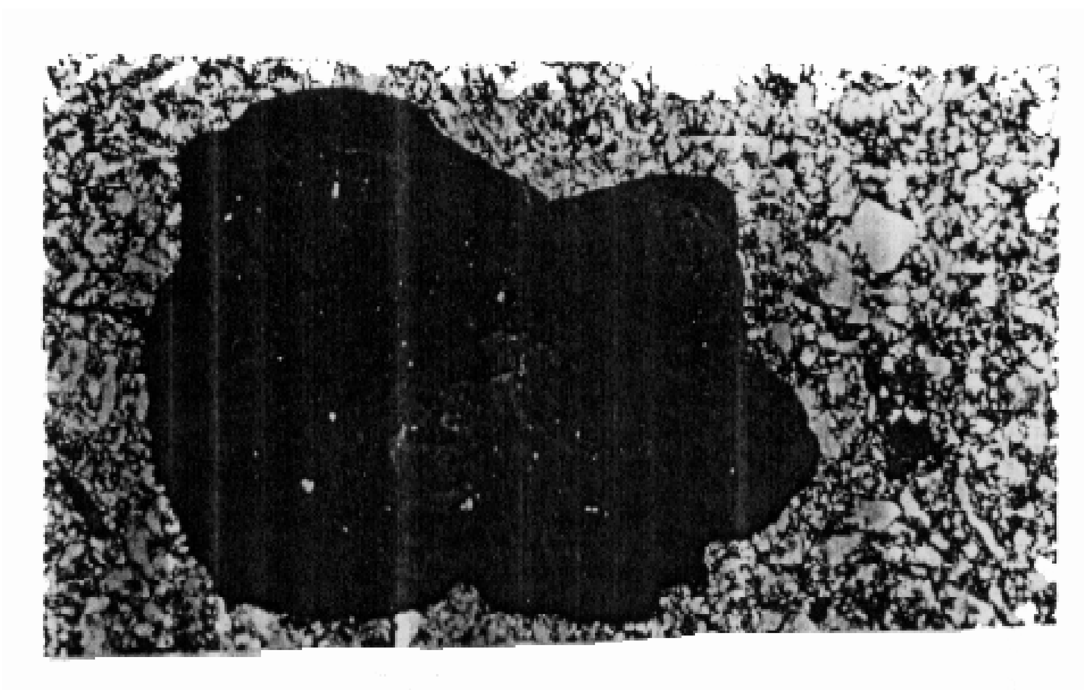

Figure 5. Moisture Vapor Blisters Within Stripped Asphaltic Globules (*8*)

Usually stripping in a four-lane highway facility occurs first in the slow traffic lane as evident in Figure 3 because it carries more and heavier traffic compared to the passing lane. Typically, stripping starts at the bottom of HMA layer and progresses upwards.

It is evident from the preceding discussion that inadequate subsurface drainage is one of the primary factors inducing premature stripping in HMA pavements.

Subsurface drainage problems can be alleviated in different ways depending on the local conditions. Kandhal et al. (2) have reported some case histories in detail where it has been done. These are described briefly here. Figures 6a and 7a show typical median and cut sections of the East-West Pennsylvania Turnpike, respectively. This section received a 4-inch HMA overlay on the main line in 1977 and its median was also paved for the first time with a 3-inch HMA binder and wearing course. The work also included the installation of new pipe in the median. However, the new subbase above the pipe was almost impermeable. Stripping was observed in this pavement during the summer of 1978 when small potholes started to develop mainly in the inside wheel track of the slow traffic lane. It was observed from extensive trenching and sampling that water and/or water vapor was getting into the pavement structural system from underneath primarily through the longitudinal and transverse joints, cracks in the concrete pavement and the disintegrated concrete itself at some places. There was also evidence that moisture was being drawn from the subbase under the paved median into the HMA overlay layers probably in the form of water vapor during the heat of the day (Figure 6a). Water vapor which accumulated in the pavement layers during the day condensed during the night until the HMA pavement layers become saturated with water. With saturation the pore water pressure developed by differential thermal expansion and cyclic stresses from the traffic ruptured the asphalt-aggregate bond causing stripping.

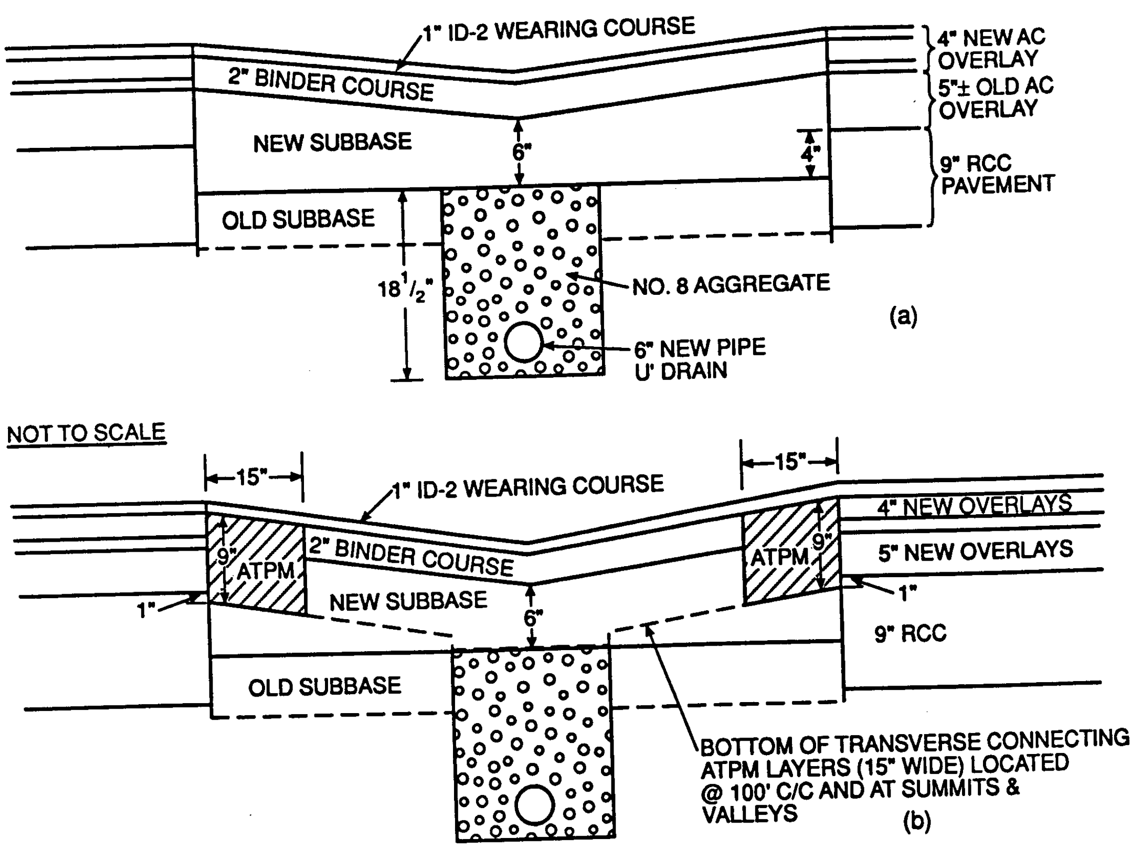

Figure 6. Typical Median Section of East-West Pennsylvania Turnpike (2)

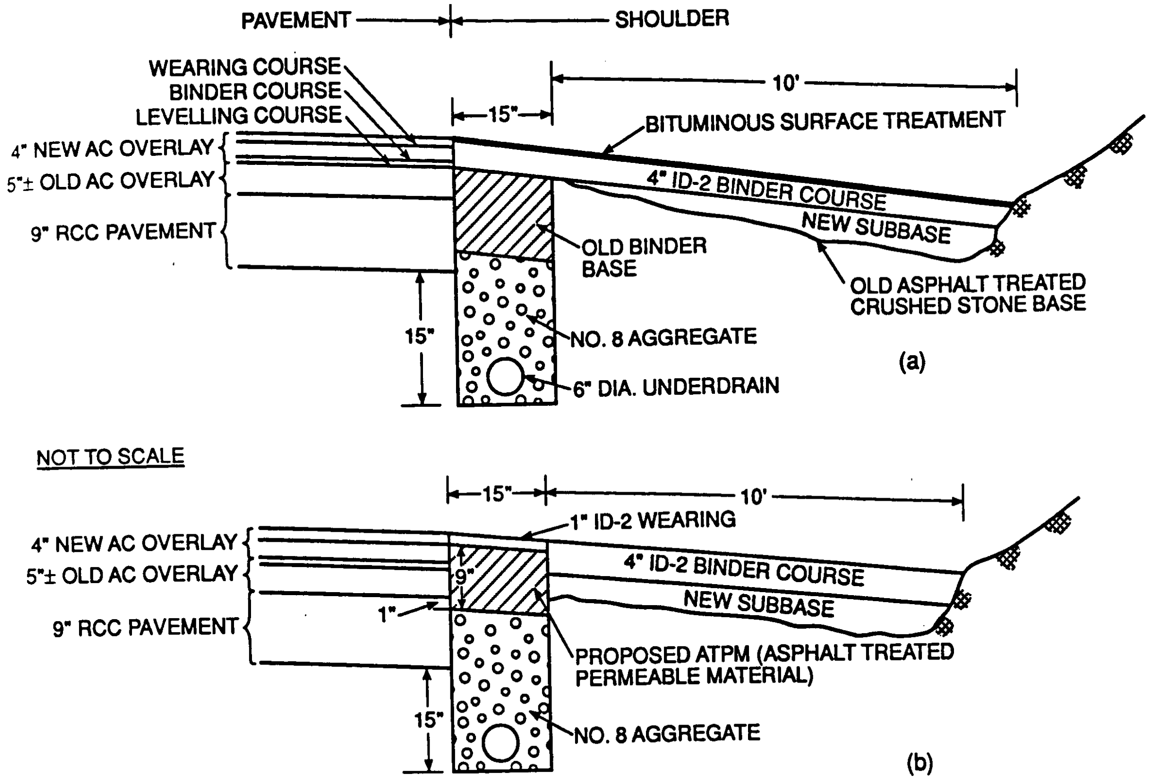

Figure 7. Typical Cut Section of East-West Pennsylvania Turnpike (2)

It is difficult to prevent the ingress of water and/or water vapor from underneath an existing pavement. However, the HMA overlay layers should at least be made freely draining on both sides to prevent the buildup of pore water and/or water vapor pressure in these layers. These layers sloped towards the shoulder, but there was no outlet due to the presence of 15-in. wide HMA binder course abutting against these layers (Figure 7a). One proposed solution was to provide a layer of Asphalt Treated Permeable Material (ATPM) on both sides of the two-lane pavement (Figures 6b and 7b). ATPM is a highly permeable mix (more than 10,000 feet/day) made from AASHTO No. 57 or 67 aggregate (no fine aggregate) and about 2 percent AC-20 asphalt cement. ATPM towards the median (Figure 6b) should be connected to the existing No. 8 aggregate at the summit and bottom of vertical curves and every 100 ft. (arbitrarily chosen) so that accumulated water and/or water vapor can be drained or released from the system. The use of ATPM in subsurface drainage systems has been discussed by other researchers (3, 7, 9, 10).

Although the new subbase layer in the shoulder in cut areas (Figure 7b) is sandwiched between two impermeable layers, at least the excessive water vapor should be able to escape through the ATPM at its upper end.

Figure 8a shows a typical cut section of the North-East Pennsylvania Turnpike which experienced stripping problems. Water and/or water vapor was entering the pavement structural system from beneath through the longitudinal and transverse joints, cracks and disintegrated portions of the concrete pavement. Since the two longitudinal underdrains are only 3 ft. deep and are spaced 70 ft. apart at the shoulder edges in tangent cut section their effectiveness in lowering the water table (especially in the middle of the roadway) and draining the subgrade was questionable (Figure 8a). This lack of effectiveness was confirmed by the observations in cut areas where the pavement layers were wetter near the concrete median barrier than in the area near the center line. Most of this North-East Extension section is mountainous and is predominantly built in cut areas.

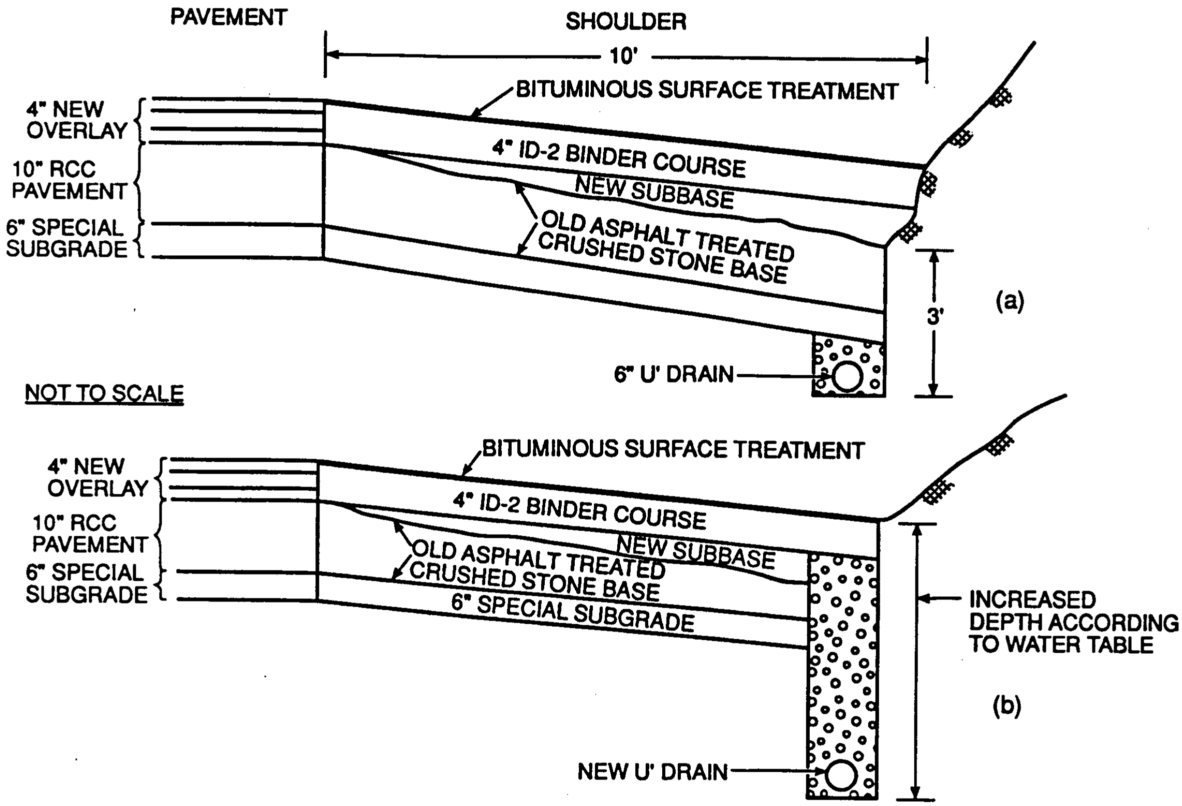

Figure 8. Typical Cut Section of North-East Pennsylvania Turnpike (2)

The subsurface drainage can be improved in this instance by increasing the depth of the two longitudinal underdrains at the shoulder edge in cut areas. The proposed improvement as shown in Figure 8b will also drain the new shoulder subbase, which is sandwiched between two impermeable layers and is causing asphalt stripping in the overlying new binder course.

Inadequate compaction

Inadequate compaction of HMA mat is probably the most common construction related factor responsible for premature stripping. Studies have shown that at less than 4-5% air void content in the HMA the voids are generally not interconnected and thus almost impervious to water. Most HMA mixes are designed to have 3 to 5% air void contents. When constructed, a maximum air void content of 8% (at least 92% of the theoretical maximum specific gravity) is specified by most agencies. It is assumed that the pavement will get densified to the design air void content under 2-3 years traffic. However, some agencies do not exercise good compaction control resulting in air voids content higher than 8% at the time of construction. This can cause premature surface raveling because the mix does not possess adequate cohesion. The relationship between air void content and extent of ravelling obtained from eight paving projects is shown in Figure 9 (*11*). Quite often, stripping is blamed for this type of premature ravelling without closely examining the mixture. However, if the HMA pavement remains pervious for an extended period of time, stripping is likely to occur due to ingress of water and hydraulic pore pressures induced by the traffic.

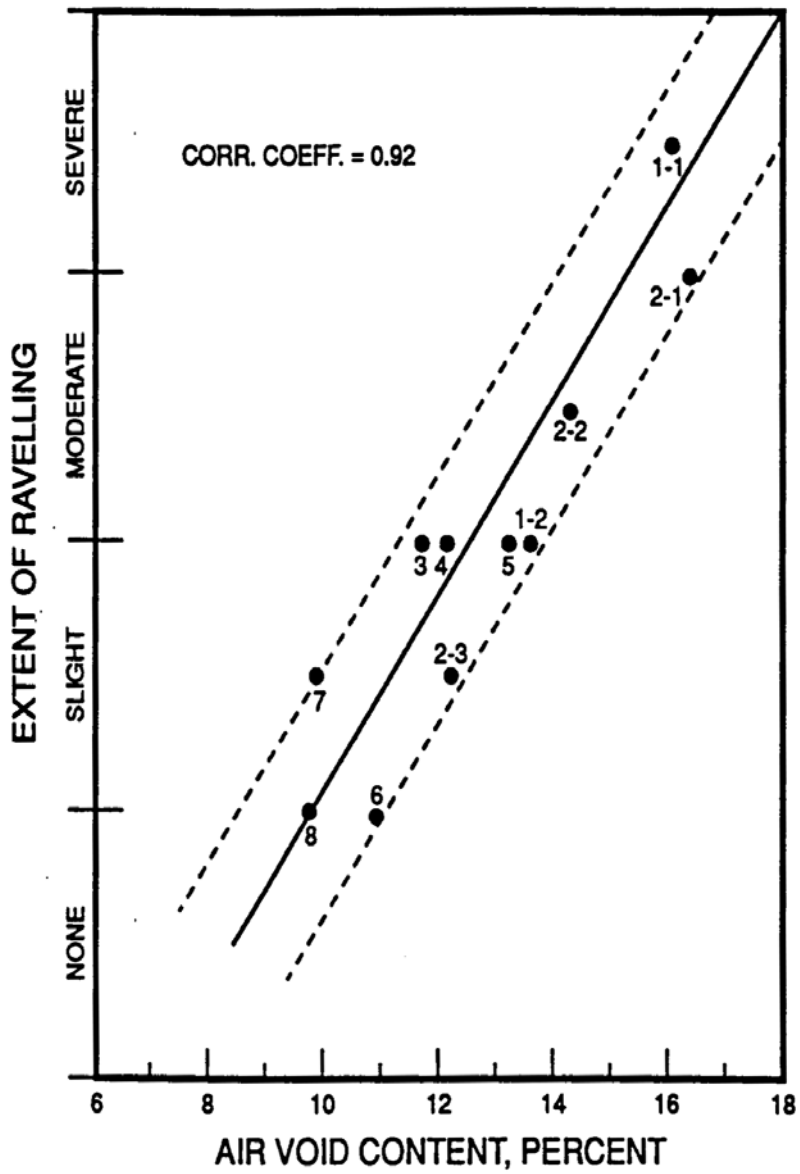

Figure 9. Air Void Content versus Extent of Raveling (*11*)

Terrel and Shute (*12*) have advanced the concept of “Pessimum” void content for stripping. Figure 10 shows the general relationship between air voids and relative strength of HMA mixtures following water conditioning. The amount of strength loss depends upon the amount and nature of the voids. As shown in Figure 10, at less than 4 percent voids, the mixture is virtually impermeable to water, so is essentially unaffected. Unfortunately, region B to C is where many pavements get constructed. As the voids increase to D and beyond, the mix strength becomes less affected by water because the mixture is now free draining. The region B to C in Figure 10 can be called “Pessimum” void content because it represents the opposite of optimum. The objective is to stay out of the “Pessimum” void range to minimize stripping problem. This can be done through proper mix design and compaction control procedures.

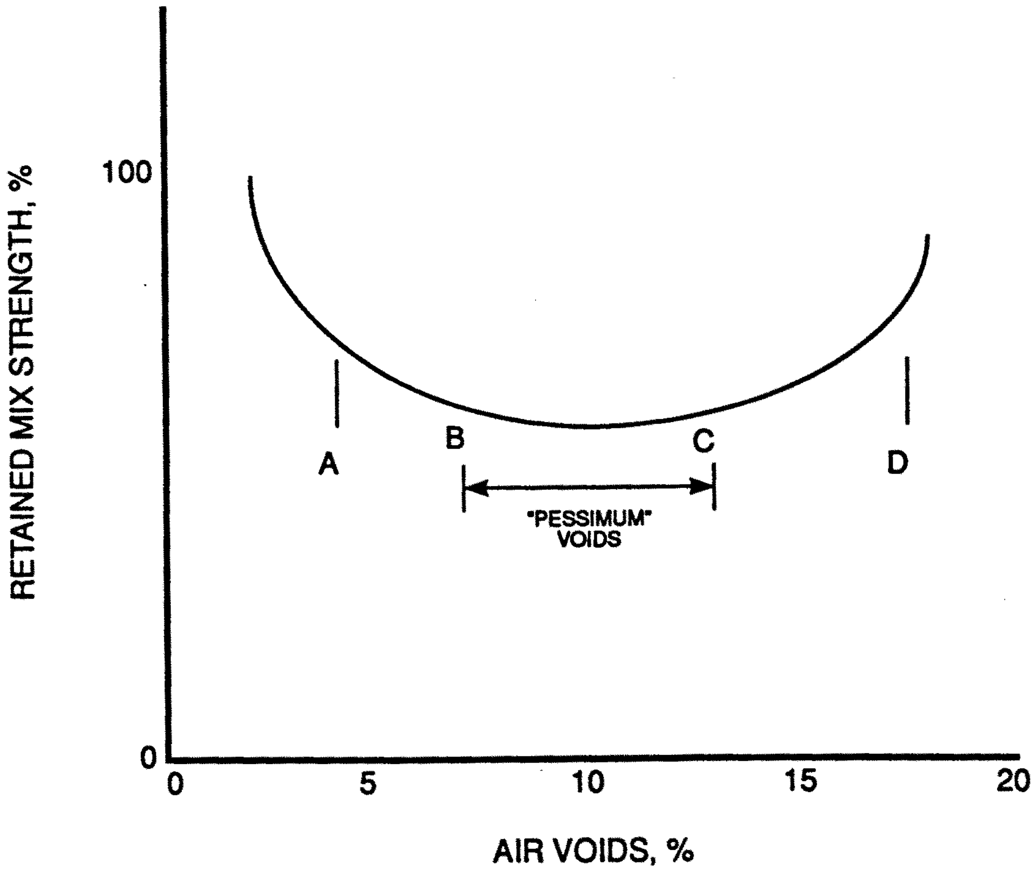

Figure 10. Air Void Content versus Retained Mix Strength-Region of Pessimum Voids (*12*)

Excessive Dust Coating on Aggregate

The presence of dust and clay coatings on the aggregate can inhibit an intimate contact between the asphalt cement and aggregate and provide channels for penetrating water (*13*). The asphalt cement coats the dust coating and is not in contact with the aggregate surface. It has also been hypothesized that some very fine clayey material may cause stripping by emulsifying the asphalt cement binder in presence of water, but this appears to be an insignificant and uncommon factor.

The author is aware of one project on which stripping occurred by the mechanism of hydraulic scouring which is applicable only to surface courses. Unlike typical stripping, such a stripping starts at the surface and progresses downward. Hydraulic scouring results from the action of vehicle tires on a saturated pavement surface. The water gets pressed down into the pavement in front of the tire and immediately sucked away from the pavement behind the tire. This compression-tension cycle contributes to the stripping of the asphalt film from the aggregate (*14*). The aggregate used on that project had excessive amounts of a very fine dust coating. When the aggregate was washed in the quarry and used again the problem went away. Laboratory studies (*15*) have also shown improved adhesion characteristics of some dust contaminated coarse aggregates when washed.

Use of Open-Graded Asphalt Friction Course

Several states in the southeastern United States experienced stripping in the HMA course underlying opengraded asphalt friction course (OGFC) during the late 1970s. It has been hypothesized that the OGFC retains moisture for a longer time and does not dry out after rain as fast as a conventional dense graded HMA surface. The water in OGFC is also pressed into the underlying course by the truck tires initiating the stripping action which can cause flushing, rutting or shoving at the surface. Several states suspended the use of OGFC in early 1980s. In South Carolina the statewide average stripping frequency was determined to be 18.7 % under OGFC compared with a statewide average of 8.5 % for all pavement layers (*16*). Some studies have also shown that the stripping in the layers underlying OGFC resulted from their high air void content (lack of adequate compaction). Evidently, it is all the more desirable to have an impervious HMA course below the OGFC to minimize stripping. It is recommended that the air void content of the underlying HMA course should not exceed 4-5 percent when the OGFC is placed to minimize stripping in the underlying course. Quite often, the air void content in the HMA course can be as much as 8 percent just after construction. The construction of OGFC in such cases should be delayed until the traffic densifies the HMA course to an air void content of 4-5 percent.

Inadequate Drying of Aggregates

Laboratory studies (*17*) have shown that high residual moisture content in the mineral aggregate prior to mixing with asphalt cement binder increases the potential for stripping. When drum mix facilities were introduced for HMA production in the 1970s, low mixing temperatures (and high moisture content in the HMA) were encouraged to facilitate compaction. It is hypothesized now that this might have caused some of the stripping problems. However, most states have now increased the mix temperature requirements for drum mix facilities to those required for batch mix facilities. Undoubtedly, a dry aggregate surface will have increased adhesion with the asphalt cement compared to a moist or wet surface.

Weak and Friable Aggregate

If weak and friable aggregates are used in the HMA mix, degradation takes place during rolling and subsequently under heavy traffic. Degradation or delamination exposes new uncoated aggregate surfaces which can readily absorb water and initiate the stripping phenomenon in the mix. Also, if not observed carefully, these uncoated aggregate surfaces can mistakenly be deemed as stripped aggregate particles. Obviously, use of sound and durable aggregate in the HMA is recommended.

Overlays on Deteriorated Concrete Pavements

Many concrete pavements of interstate and primary highways are deteriorating before the design life. Recent years have seen increased HMA overlays over these existing concrete pavements some of which have faulted, spalled, cracked, and water-pumping slabs. Dense graded subbase material under concrete pavements can hold considerable amounts of water which escape through cracks, longitudinal and transverse joints (Figure 11). Once the concrete pavement is overlaid with an impervious HMA course the water is trapped underneath. Excessive pore pressure is built under the traffic initiating stripping and subsequently potholing at worst spots (Figure 12). Whenever a concrete pavement is due to be overlaid for the first time, it is necessary to evaluate the existing drainage conditions. If necessary, the project must include installation of a positive drainage system especially in the worst spots like shown in Figure 11. Unless this is done, the problem of stripping and potholing will persist forever. Usually the edge drains are not efficient to drain the entire roadway width. Therefore, transverse (lateral) drains are necessary

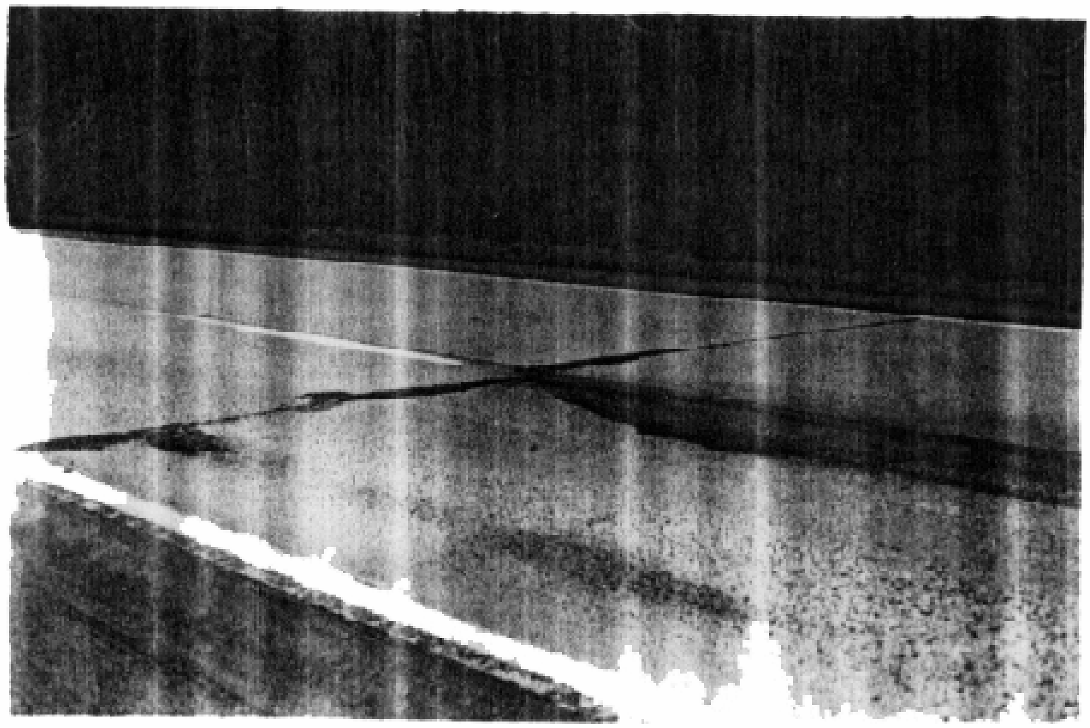

Figure 11. Water Pumping from Transverse Joint of Concrete Pavement

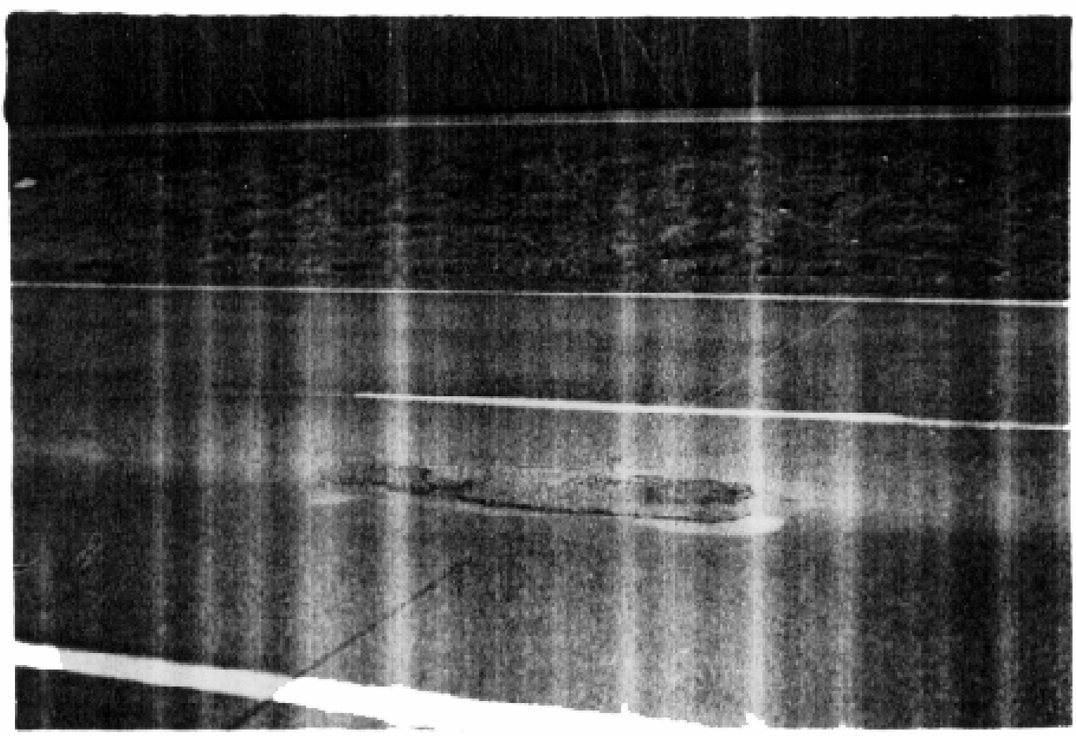

Figure 12. Patched Potholes in HMA Overlay on Either Side of Transverse Joint of Underlying Concrete Pavement

especially on steep grades where water will tend to flow longitudinally rather than towards the edge drain. Such lateral drains can be installed at or near the existing transverse joints of concrete pavements prior to overlay, and connected to the edge drain.

If the existing concrete pavement is badly deteriorated, cracked and pumping water due to inadequate subsurface drainage, it is recommended to provide a 4-inch drainage layer of open-graded ATPM directly above it prior to placing the dense graded HMA overlay. This drainage layer should be connected to the edge drain(s). The ATPM will not only drain the water very efficiently, it will prevent any moisture vapor buildup in the pavement system. A typical road cross-section showing such usage of ATPM is shown in Figure 13. The ATPM has been used successfully in such applications. It will also help to minimize reflection cracking emanating from the concrete pavement. If required, the ATPM can also be placed over concrete pavements which have been subjected to crack and seat, break and seat, and rubblizing operations. References *9* and *10* give details on the design and use of ATPM.

Waterproofing Membranes and Seal Coats

If the source of moisture is from beneath the pavement, which is usually the case, then sealing of the road surface can be detrimental. Use of some waterproofing membranes (such as stress absorbing membranes to minimize reflection cracking) and seal coats between the pavement courses or at the surface acts like a vapor seal or a vapor barrier. McKesson (*18*) has made some interesting observations. He observed that "ground water and water entering the roadbed from the shoulders, ditches and other surface sources, is carried upward by capillarity under a pavement. Above the capillary fringe water moves as a vapor and, if unimpeded at the surface, it passes to the atmosphere. This method of reduction of moisture has been termed Drainage by Evaporation, and it is the considered opinion of this writer that the Drainage by Evaporation is usually as important as drainage downward by gravitation. If the pavement or seal coat constitutes a vapor seal or a vapor barrier, the moisture during cool nights and in cool weather condenses beneath the surface. When the pavement absorbs solar heat, the water is again vaporized and, if not free to escape, substantial vapor pressure results because water as vapor has more than a thousand times the volume of water in liquid form. Vapor pressure forces the moisture up into the pavement and through the surface. Blistering in bituminous pavements is a well known example of the effect of entrapped moisture and moisture vapor."

Many asphalt paving technologists have experienced the preceding phenomenon which induced stripping in the pavement layers underlying waterproofing membranes and seal coats. The potential for stripping should, therefore, be considered whenever such systems are used.

INVESTIGATIVE METHODOLOGY

An investigative methodology based on forensic experience with HMA pavements is needed to establish if stripping is a problem on a specific project or statewide. Mere visual observations of the road surface is often misleading because the HMA surface distresses such as ravelling, flushing and rutting can be caused by factors other than stripping. The following methodology is suggested.

Sampling

Inspect the whole project and select a 500 ft long section which represents the "distressed area." Most projects will also have relatively better areas with minimal or no distress. Select another 500 ft long section from the same project which can be termed relatively "good area." Document the observed distress (such as ravelling, flushing, rutting and potholing) in both areas.

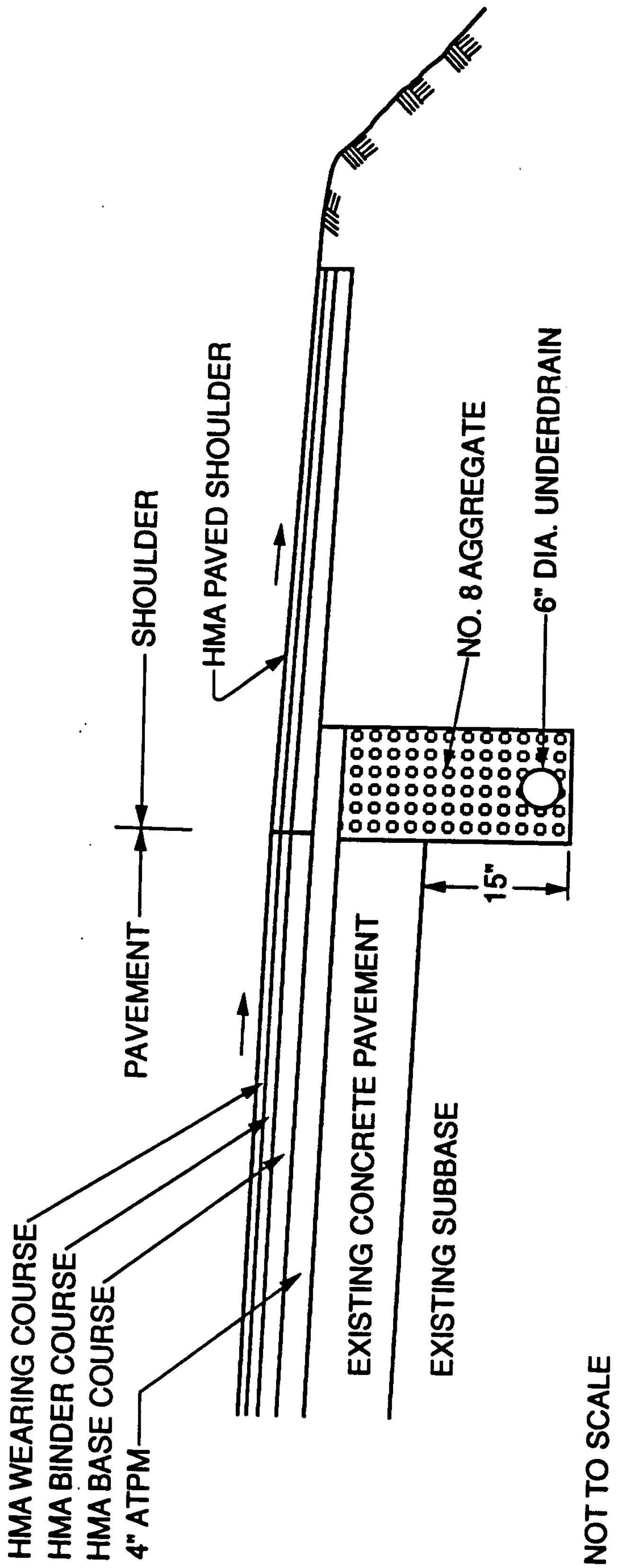

Figure 13. Use of ATPM between existing concrete pavement and HMA overlay

Obtain at least seven 4-inch diameter cores at random locations in each area. A minimum sample size of 7 for each area is necessary for reasonable statistical analysis of the data and to represent the sampled population with an acceptable degree of confidence. If it is a 4-lane highway, obtain all cores in the inside wheel track of the slow traffic (outside) lane. If it is a 2-lane highway obtain all cores from the outside wheel track of the lane. According to author's experience stripping usually occurs first at these locations across the roadway pavement. Four-inch diameter cores have been suggested so that the indirect tensile test can be conducted. An additional eighth core can also be obtained if the aged asphalt cement binder is to be recovered and tested for penetration and/or viscosity.

It is necessary to drill these cores without using water as a coolant so that the in-situ moisture contents can be determined. Compressed air and C02 are introduced under pressure to cool the inside of the core drill. The advance rate of the gas-cooled core drill is usually slower than that of the watercooled core drill but the valuable information of moisture content cannot be obtained from wet coring. Similar procedures have been used by Chevron Research Company in studies of asphalt emulsion mixtures in California (*19*) and by the South Carolina Department of Highways and Transportation in investigation of stripping of HMA in South Carolina (16). Cores should be sealed in air-tight containers for determining the in-situ moisture content in the laboratory later. Seasonal variations of the in-situ moisture content in HMA layers must be taken into account.

If dry coring cannot be done then additional pavement layer samples should be obtained adjacent to the wet coring sites using a jack hammer. The HMA chunk samples loosened by the jack hammer from each layer should also be sealed in air-tight containers so that the in-situ moisture content can be determined in the laboratory later. Kandhal et al. (*2*) used jack hammer in investigating stripped pavements as shown in Figure 14.

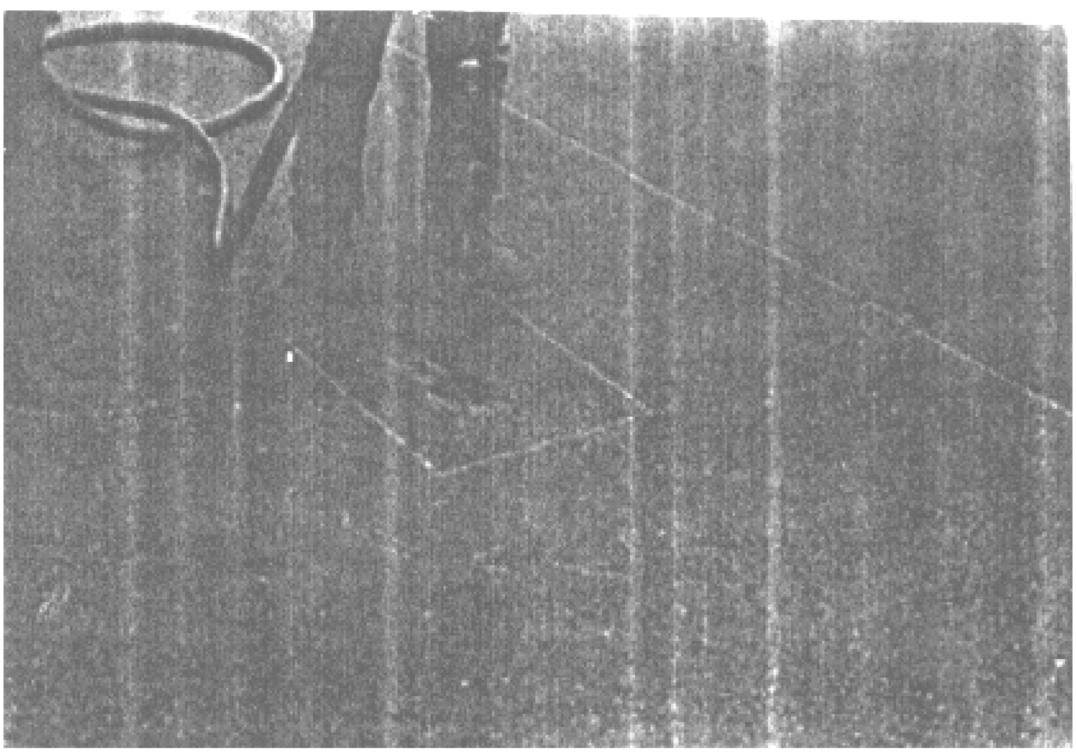

Figure 14. Using Jack Hammer to Obtain Sample for Moisture Content

Testing

The recommended testing plan is shown in Figure 15. The in-situ moisture content should be determined by weighing the cores before and after drying to constant weight. It is preferable to dry the cores at ambient temperatures with a fan. Measure the thickness of all layers in the core. Observe the condition of the core especially any evidence of stripping in the layer(s) or at the interface between the layers. It is not always possible to see the stripping on the outside of cores.

Saw the cores to separate the HMA layers so that the individual layer(s) can be tested. Measure the average thickness of each layer specimen after sawing.

Determine the bulk specific gravity of all specimens (AASHTO T166). Determine the indirect tensile strength of the dry specimens at 77°F using AASHTO T283 (Sections 10 and 11) or ASTM D 4867 (Sections 8 and 9).

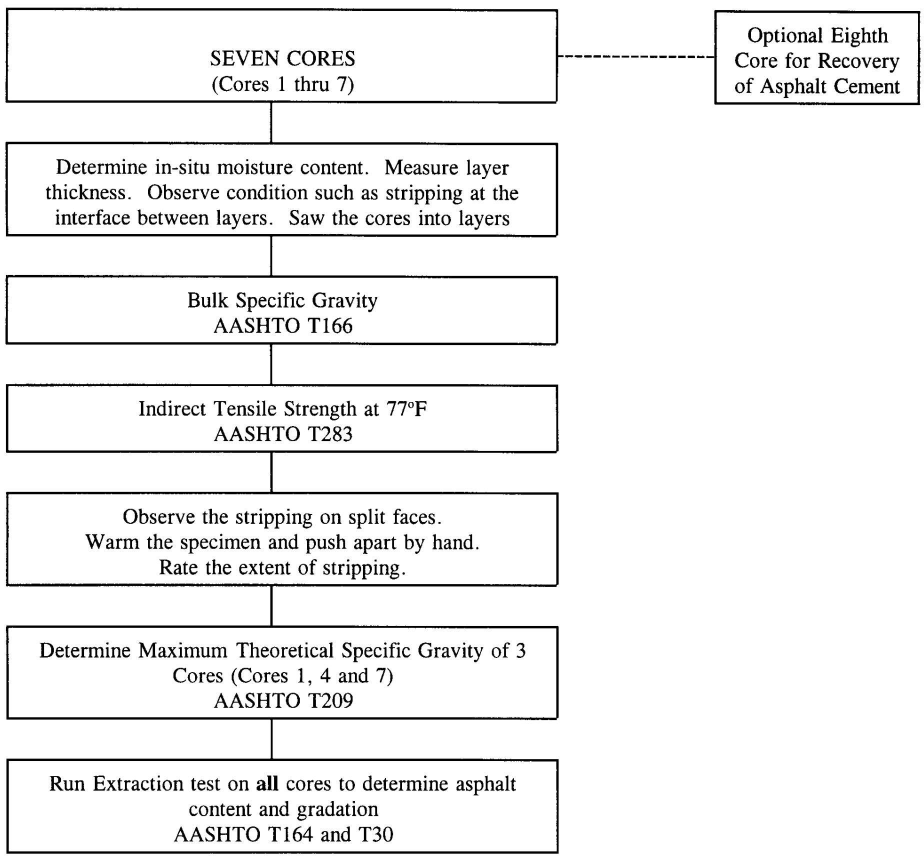

Figure 15. Testing Plan

Examine the split exposed surfaces of the tested core specimens for stripping. Disregard the fractured and crushed aggregate particles. Heat the specimen just enough to push it apart by hand and observe the extent of stripping. A visual rating of the stripping on the exposed surface should be made and documented. A rating system developed by the Georgia Department of Transportation and used by the South Carolina Department of Highways and Public Transportation (SCDHPT) in their statewide stripping survey (*16*) is recommended. This visual stripping rating is based on broad, easily assessed range estimates of stripping. The rating system considers the stripping of the fine aggregate matrix and the coarse aggregate fraction separately. Stripping of the fine aggregate matrix is considered to be more critical than a comparable percentage of stripping in the coarse aggregate fraction. The procedure, however, does require some training for consistent interpretation of observations.

The Georgia DOT stripping rating, S, is calculated by assigning values to C and F in the expression S = (C + F)/2 where C and F are:

Values of C	Values of F
C =Coarse Aggregate Stripping 1 = less than 10% 2 = 10 - 40% 3 = more than 40 %	F = Fine Aggregate Stripping 1 = less than 10% 2 = 10 - 25% 3 = more than 25 %

If possible, have at least three evaluators note the striping in each core and then calculate the average stripping rating.

An average stripping rating of 2.5 and 3.0 were used by SCDHPT to identify pavements for which stripping was considered severe.

After all seven cores from an area have been rated for stripping, determine the maximum theoretical specific gravity (AASHTO T209) of the paving mixtures from 3 cores (Cores 1, 4 and 7 are recommended to encompass most of the representative area).

Conduct extraction test (AASHTO T164) and gradation of extracted aggregate (AASHTO T30) on all seven cores to determine the mix composition (asphalt content and gradation).

Calculations and Tabulation

Figure 16 shows the flow diagram for calculations. The effective specific gravity of aggregates in Cores 1, 4 and 7 should be calculated using their maximum theoretical specific gravity values and their respective asphalt content values. Calculate the average effective specific gravity of the aggregate from these three values. Calculate the maximum theoretical specific gravity values for

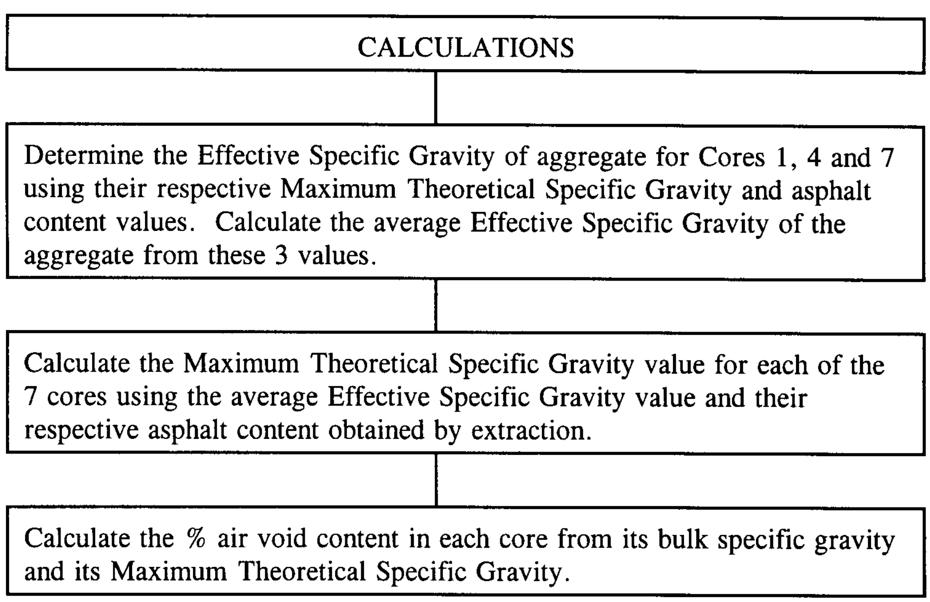

Figure 16. Calculation of Air Void Content

each of the seven cores using this average effective specific gravity and their respective asphalt contents obtained by extraction. Calculate the air void content in each core from its bulk specific gravity and its maximum theoretical specific gravity.

Calculate the percentage of in-situ water saturation by the following formula:

$$Percent\ Saturation = \frac{Percent\ moisture\ in\ Core \times bulk\ specific\ gravity\ of\ core}{Percent\ air\ void\ content\ in\ core} \times 100$$

Tabulate all calculated and observed data separately for “good” and “distressed” areas. Calculate the mean, standard deviation, and 95 % confidence limits for each parameter. A high standard deviation would indicate lack of uniformity (or consistency) for that test parameter.

Compare the mean and standard deviation of each test parameter obtained in “good” and “distressed” areas to identify the differences, if any. In a majority of cases, the deficiencies in the “distressed” area will stand out by this comparison.

Example

Tables 1 and 2 show some hypothetical data from a three-year old distressed project. Table 1 represents test data obtained by this investigative methodology from a “good” area whereas Table 2 has data from a representative “distressed” area of the project. The hypothetical data in Table 2 has been presented purposely to illustrate **most** of the HMA related factors (or deficiencies) which are likely to induce stripping. Therefore, this can be considered as the worst scenario. This “distressed” area has the following problems:

1. Very high and inconsistent air void content;
2. Deficient and inconsistent asphalt content;
3. Excessive and inconsistent minus 200 material; and
4. Very high in-situ moisture contents or saturation levels.

The above problems can be identified easily by comparing the data from Table 2 with that of Table 1. In this example, severe stripping was observed in the “distressed” area, which is also indicated by lower tensile strengths compared to good areas.

When data like in Table 2 is obtained, one should not start specifying an antistripping agent as a cure but take remedial measures to remove the cause(s). In this example, the following needs would be indicated:

1. Adequate compaction level at the time of construction. An average air void content of 8.9 percent after 3 years' service is unacceptable. The HMA pavement should have achieved its design air void content (3-5%) by now.
2. Quality control of mix composition. The average asphalt content of 6.4 percent is deficient by 0.5 percent from the job-mix formula, and also the standard deviation of 0.45 percent is too high. The average minus 200 content is excessive by 1.9 percent from the job-mix formula and is also very variable based on the standard deviation of 1.97 percent.
3. Positive drainage system. The project has water drainage problem in the distressed area with saturation as high as 100 percent.

Table 1. Core Test Data - Good Area

Test	Job-Mix Formula	Core No.								Std. Dev.	95% Confidence Limits
		1	2	3	4	5	6	7	○		
Bulk Specific Gravity	2.290	2.286	2.287	2.285	2.271	2.256	2.293	2.260	2.277	0.0145	2.248 - 2.306
Max. Specific Gravity	2.385	2.394	2.380	2.398	2.371	2.380	2.389	2.394	2.386	0.0098	---
% Voids	4.0	4.5	3.9	4.7	4.2	5.2	4.0	5.6	5.6	0.63	3.3 - 5.9
Tensile Strength, psi	---	118	130	110	128	98	121	90	90	15.1	84 - 144
% Asphalt Content	6.9	6.7	7.0	6.6	7.2	7.0	6.8	6.7	6.7	0.21	6.4 - 7.2
% Minus 200	5.2	5.8	6.1	5.3	4.3	4.8	6.0	4.5	4.5	0.74	2.6 - 8.0
% in-situ Moisture in Core	---	0.3	0.2	0.3	0.2	0.3	0.2	0.4	0.4	0.076	0.1 - 0.4
% in-situ Saturation	---	15.2	11.7	14.6	10.8	13.0	11.5	16.1	16.1	2.05	9.2 - 17.4
Stripping Rating	---	1.0	1.0	1.0	1.0	1.5	1.0	1.5	1.5	---	---

Table 2. Core Test Data - Distressed Area

Test	Job-Mix Formula	Core No.								Std. Dev.	95% Confidence Limits
		1	2	3	4	5	6	7	○		
Bulk Specific Gravity	2.290	2.154	2.213	2.213	2.212	2.135	2.211	2.205	2.192	0.0329	2.126 - 2.258
Max. Specific Gravity	2.385	2.385	2.411	2.380	2.407	2.429	2.385	2.407	2.408	0.0202	---
% Voids	4.0	11.5	8.2	7.0	8.1	12.1	7.3	8.4	8.9	2.02	4.9 - 12.9
Tensile Strength, psi	---	76	52	107	83	72	97	56	78	20.1	38 - 118
% Asphalt Content	6.9	5.8	6.3	7.0	6.4	5.9	6.9	6.4	6.4	0.45	5.5 - 7.3
% Minus 200	5.2	4.5	7.2	9.6	9.2	7.1	4.7	7.3	7.1	1.97	3.2 - 11.0
% in-situ Moisture in Core	---	5.2	4.5	0.8	3.5	5.1	1.1	5.8	3.7	2.02	0.3 - 7.7
% in-situ Saturation	---	97.4	121.4 *	25.3	95.6	90.0	33.3	152.2 *	87.9	45.30	0 - 178.5*
Stripping Rating	---	2.5	3.0	2.0	2.5	2.5	2.0	3.0	2.5	---	---

* Calculated saturation can exceed 100% because part of the water has been absorbed by the stripped aggregate particles.

If test data like in Table 1 is obtained throughout a project and there is evidence of stripping, the HMA mix is most likely sensitive to moisture damage. In such cases, a suitable antistripping agent should be considered.

Statewide Survey

Before specifying antistripping agents and/or moisture susceptibility test methods statewide, it is prudent to first establish if stripping is a statewide problem or just isolated occurrences. Both Georgia and South Carolina completed a statewide survey and evaluation of the problem through an extensive coring program. For example, South Carolina sampled 500 miles of pavements by coring 1,324 cores and tested 4,503 pavement layers (*16*). A random sample, consists of two pavement cores, was taken from every two-mile segment for each highway section sampled. Both two-lane and multi-lane highways, and HMA pavements with and without open-graded friction courses (OGFC) were sampled. A similar unbiased statewide testing program is recommended. However, it is suggested to obtain at least three four-inch diameter cores randomly from each project to obtain preliminary data on in-situ moisture content, air void content, mix composition, tensile strength, and extent of stripping, if any. If 100 projects are selected across the state, testing of 300 cores does not appear unreasonable to establish if stripping is a statewide problem or not.

The data from 100 projects will not only assess the statewide average frequency for severe stripping (that is, visual ratings of 2.5 and 3.0), it will also indicate if there are some other statewide problems to be addressed such as inadequate compaction, lack of HMA production quality control, and inefficient subsurface drainage systems.

Some selected projects can be revisited, sampled, and tested every year to assess increasing moisture-induced damage, if any. Georgia DOT has a similar successful program.

Since the materials, mix design, construction practices, maintenance procedures and climatological conditions vary from state to state, it is very essential that each state conduct its own statewide survey to assess and quantify the "stripping" problem as recommended. Specifying antistripping agents as an "insurance" without establishing the extent and cause(s) of the problem is not justified. Not only is it uneconomical, it can also be ineffective if the underlying causes responsible for stripping have not been addressed properly.

CURRENT PRACTICES FOR MINIMIZING STRIPPING

Test Methods

Numerous test methods have been developed and used in the past to predict the moisture susceptibility of HMA mixes. However, no test has any wide acceptance. This is due to their low reliability and lack of satisfactory relationship between laboratory and field conditions. Only selected test methods which are commonly used by some agencies will be discussed briefly. An outline of each test is given in Tables 3 through 7 which have been prepared by Hicks (*1*). The tables also summarize the advantages and disadvantages (some modified by the author) associated with each test procedure.

Table 3. Boiling Water Tests - ASTM D3625 (*1*)

Specimens	Field mixture representation @ design AC
Compaction	None
Air Voids (%)	None
Procedure	- Place about 950 ml of distilled water in 1500-2000 ml beaker - Heat to boil, then add mixture - Bring mix back to boil and hold for 1 min - Decant asphalt from vessel and refill with cold water
Damage Analysis	- Visual assessment - < 95% retained indicates moisture susceptibility problem
Advantages	- Can be used for initial screening - Minimum amount of equipment required - Can be used to test additive effectiveness - May be used for quality control - Can use lab mix, drum mix, or batch mix from field
Disadvantages	- Subjective analysis - Uncompacted mix - Water purity can affect coating retention - Assessment of stripping in fines is difficult - Highly dependent on asphalt viscosity - Does not coincide with field experience - Generally favors liquid A.S. agents over lime

Table 4. NCHRP 246 - Indirect Tensile Test and/or Modulus Test With Lottman Conditioning (*1*)*

Specimens	9 samples divided into 3 groups Size: 4-in. diameter by 2.5-in. height
Compaction	ASTM Methods: D1559 or D1561 or D3387
Air Voids (%)	Normally 3 to 5
	Group I: - Water bath for 5 hr - Test** (Unconditioned)
	Group II & III: - Vacuum saturation @26 in. Hg for 30 min (Conditioned) - Atmospheric Pressure, submerged, for 30 min
	Group II: - Test temperature water bath for 3 hr - Test** (Conditioned)
	Group III: - Freeze @ 0°F for 15 hr (Conditioned) - Water bath @ 140°F for 24 hr - Test temperature water bath for 3 hr - Test**
Damage Analysis	Ratios: Diametral Resilient Modulus Test Diametral Tensile Strength Test Group II / Group I Short Term (saturation) Group III / Group I Long Term (accelerated)
Advantages	- Conducted on lab mixes, field mixes, or core samples - Severe test - Can differentiate between additive levels - Fair correlation with field performance - Does not give biased results toward lime or liquid additive
Disadvantages	- Time consuming - Amount and type of equipment required is not always readily available

* There are a umber of modifications to this test method.
** Test can be run @ 55°F or 73°F.

Table 5. ASTM D4867 - Indirect Tensile Test with Tunnicliff and Root Conditioning (*1*)

Specimens	6 samples - 2 groups of 3 Size: 4-in. diameter by 2.5-in. height (for aggregate #1 in.)
Compaction	ASTM Methods: D1559 or D1561 or D3387
Air Voids (%)	6 to 8% or expected field level
Procedure	Sort into groups so average air voids are approximately equal
	Group I: (unconditioned) store dry at room temperature
	Group II: (conditioned) soak 20 min @ 77°F - Test - Obtain a 55% to 80% saturation level (20 in. Hg for about 5 min in distilled water) - Reject if saturation is > 80% - Soak 24 hr @ 140°F - Soak 1 hr @ 77°F - Test
Damage Analysis	- Diametral Tensile Strength (ASTM D 4123) - Visual
Advantages	- Can use lab, plant, or field mixes; also cores from existing pavements - Mixtures with or without additives - Time required is moderate - Initial indications show good correlation (based on 80% retained strength)
Disadvantages	- May require trial specimens to obtain air void level or degree of saturation - May not be severe enough (major limitation)

Table 6. AASHTO T283 - Indirect Tensile Test (*1*)

Specimens	6 samples/set of mix conditions Size: 4-in. diameter by 2.5-in. height
Compaction	ASTM Methods: D1559 or D1561 or D3387
Air Voids (%)	6 to 8% or expected field level
Procedure	Sort specimens into two subsets of three specimens
	Group I: (unconditioned) store @ room temperature - Place in water bath @ 77°F for 2 hr prior to testing
	Group II: (conditioned) partial vacuum (20 in. Hg) for 5 min then soak for 30 min or until the degree of saturation is 55-80% - Freeze @ 0°F for 16 hr followed by soaking in a 140°F bath for 24 hr - Place in water @ 77°F for 2 hr prior to testing
Damage Analysis	- Diametral Tensile Strength (ASTM D 4123) - Visual
Advantages	- Conducted on lab mixes, field mixes, or core samples - Severe test - Can differentiate between additive levels - Good correlation with field performance - Does not give biased results toward lime or liquid additive
Disadvantages	- Time consuming - Amount and type of equipment required is not always readily available

Table 7. Immersion-Compression Tests - AASHTO T165 or ASTM D1075 (*1*)

Specimens	6 samples - 2 groups of 3 Size: 4-in. diameter by 4-in. height
Compaction	Double plunger - final pressure 3000 psi for 2 min (ASTM)
Air Voids (%)	Varies
Procedure	Group I: Air cured @ 77°F - Test @ 77°F
	Group II: Water cured @ 120°F for 4 days or 140°F for 1 day - Test @ 77°F
Damage Analysis	- Visual assessment - Unconfined compression @ 77°F and 0.2 in./min
Advantages	- Uses actual mix
Disadvantages	- Time required is 4 days plus - Poor reproducibility - Air void level plays significant role - Water quality (ions and salts) can affect moisture sensitivity - Equipment may not be readily available

Qualitative or Subjective Tests

1. Boiling Water Test (ASTM D3625 or a variation): Loose HMA mix is added to boiling water. Although the current ASTM D3625-83 specifies one-minute boiling, most agencies use a 10-minute boiling period. The percentage of the total visible area of the aggregate that retains its original coating after boiling is estimated as above or below 95%. This test can be used for initial screening of HMA mixes. Some agencies use it for quality control during production to determine the presence of antistripping agent. This test method does not involve any strength analysis. Also, determining the stripping of fine aggregate is very difficult.
2. Static-Immersion Test (AASHTO T182): A sample of HMA mix is immersed in distilled water at 77°F for 16 to 18 hours. The sample is then observed through water to estimate the percentage of total visible area of the aggregate which remains coated as above or below 95 percent. Again, this method does not involve any strength test.

Quantitative Strength Tests

1. Lottman Test (NCHRP 246): This method was developed by Lottman (*20*) under the National Cooperative Highway Research Program 246. Nine specimens (4" diameter and 2 1/2" high) are compacted to expected field air void content. Specimens are divided into 3 groups of 3 specimens each. Group I is treated as control without any conditioning. Group 2 specimens are vacuum saturated (26 inches Hg) with water for 30 minutes. Group 3 specimens are vacuum saturated like Group 2 and then subjected to a freeze (0°F for 15 hours) and a thaw (140°F for 24 hours) cycle. All 9 specimens are tested for resilient modulus (M_R) and/or indirect tensile strength (ITS) at 55°F or 73°F. A loading rate of 0.065 inch/minute is used for the ITS test.

   Group 2 reflects field performance up to 4 years. Group 3 reflects field performance from 4 to 12 years. Retained tensile strength (TSR) is calculated for Group 2 and Group 3 specimens as follows:

$$TSR = \frac{ITS\ of\ Conditioned\ Specimens}{ITS\ of\ Control\ Specimens}$$

   A minimum TSR of 0.70 is recommended by Lottman and Maupin (*20*, *21*) who reported values between 0.70 and 0.75 differentiated between stripping and nonstripping HMA mixtures. It has been argued that the Lottman procedure is too severe because the warm water soak of the vacuum saturated and frozen specimen can develop internal water pressure. However, Stuart (*22*) and Parker and Gharaybeh (*23*) generally found a good correlation between the laboratory and field results. Oregon has successfully used this test with modulus ratio in lieu of tensile strength ratio (TSR).

2. Tunnicliff and Root Conditioning (NCHRP 274): This method was proposed by Tunnicliff and Root under the NCHRP Project 274 (*24*). They proposed six specimens to be compacted to 6-8% air void content and divided into two groups of three specimens each. Group 1 is treated as control without any conditioning. Group 2 specimens are vacuum saturated (20 inches Hg for about 5 minutes) with water to attain a saturation level of 55 to 80 percent. Specimens saturated more than 80 percent are discarded. The saturated specimens are then soaked in water at 140°F for 24 hours. All specimens are tested for ITS at 77°F using a loading rate of 2 inches/minute. A minimum TSR of 0.7 to 0.8 is usually specified. Evidently, the use of a freeze-thaw cycle is not incorporated into ASTM D4867-88 which is based on this method. The freeze-thaw cycle is optional. The primary emphasis is on saturation

of the specimen which for a short duration of about 24 hours has been reported to be insufficient to induce moisture related damage (*25*).

3. Modified Lottman Test (AASHTO T283): This method was proposed by Kandhal and was adopted by AASHTO in 1985 (*26*). It combines the good features of Lottman test (NCHRP 246) and Tunnicliff and Root test (NCHRP 274). Six specimens are compacted to 6-8% air void content. Group 1 of 3 specimens is used as a control. Group 2 specimens are vacuum saturated (55 to 80% saturation) with water, and then subjected to one freeze and one thaw cycle as proposed by Lottman. All specimens are tested for ITS at 77°F using a loading rate of 2 inches/minute, and the TSR is determined. A minimum TSR of 0.7 is usually specified. This method is gaining acceptance by the specifying agencies.

4. Immersion-Compression Test (AASHTO T165): Six specimens (4" diameter x 4" high) are compacted with a double plunger with a pressure of 3,000 psi for 2 minutes to about 6% air void content. Group 1 of three specimens is treated as control. Group 2 specimens are placed in water at 120°F for 4 days or at 140°F for 1 day. All specimens are tested for unconfined compressive strength at 77°F using a 0.2 inch/minute loading rate. The retained compressive strength is determined. Many agencies specify at least 70% retained strength. This test has produced retained strengths near 100% even when stripping is evident. Stuart (*13*) has attributed this to the internal pore water pressure and the insensitivity of the compression test to properly measure the moisture induced damage. Lack of satisfactory precision has been a major problem with this test.

5. Other Tests: Moisture-vapor susceptibility, swell test, and a film stripping test are used by California DOT. Retained Marshall stability is used in Puerto Rico and some other states.

Survey of Test Methods Used

A survey of test methods used in the United States and their effectiveness in predicting the moisture susceptibility was conducted in 1989 by Hicks for NCHRP Topic 19-09 (*1*). Figure 17 shows the relative effectiveness of different test methods on a 0 to 9 scale according to this survey. 0 means not effective and 9 means 100% effective. Briefly, the results are as follows:

Test Method	**No. of Agencies Using**	**Average Rating**	
		Number	**Description of Effectiveness**
Boiling Water	9	5	slight to moderate
Static-Immersion (AASHTO T182)	3	4	slight
Lottman (NCHRP 246)	3	7.5	high
Tunnicliff and Root (ASTM D4867)	9	5	slight to moderate
Modified Lotman (AASHTO T283)	9	7.5	high
Immersion-Compression (AASHTO T165)	11	5	slight to moderate

Although the Tunnicliff and Root procedure is used by nine agencies, only four rated its effectiveness (range of 2 to 8 with an average value of 5) apparently from lack of sufficient experience.

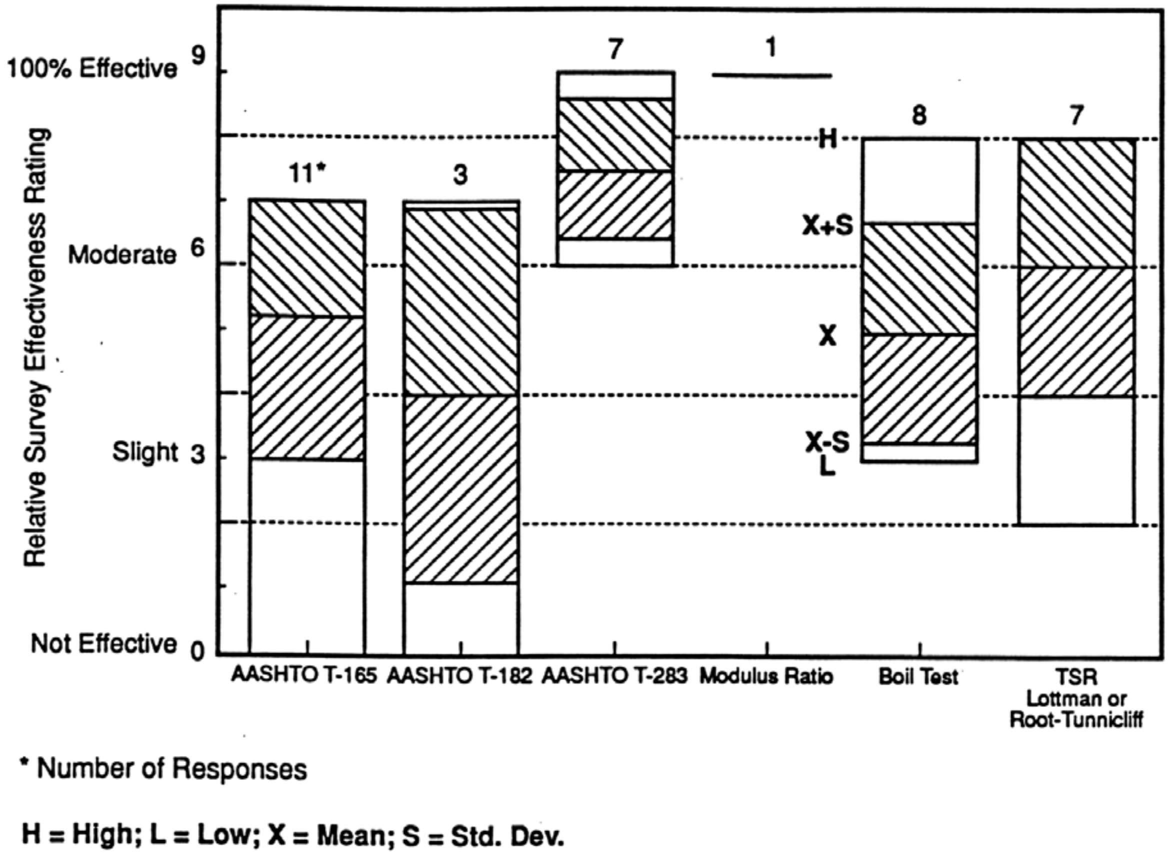

Figure 17. Relative Effectiveness of Mixture Test Procedures to Identify Moisture-Related Problems (<u>1</u>)

Evidently, a wide variety of test methods are being used by various agencies. However, no test has proven to be "superior" and can correctly identify a moisture susceptible mix in all cases. Kiggundu arid Roberts (<u>27</u>) quantified the success rate of some tests, based on test data available from various research reports and papers, as follows:

Test Method	Minimum Test Criteria	% Success
Modified Lotman (AASHTO T283)	TSR = 70% TSR = 80%	67 76
Tunnicliff and Root (ASTM D4867)	TSR = 70% TSR = 80% TSR = 70-80%	60 67 67
10-Minute Boil Test	Retained Coating 85-90%	58
Immersion-Compression (AASHTO T165)	Retained Strength 75%	47

The data on success rates indicates that many HMA mixes which might otherwise perform satisfactorily in the field, are likely to be rendered unacceptable if these tests and criteria are used. The use of these tests has simply encouraged the increased use of antistripping agents in many states.

There are still many concerns and requirements related to the test methods which need to be addressed:

1. Proliferation of test procedures and criteria.
2. Reproducibility of most test methods is not satisfactory. For example, small variations in air void content of the specimens can significantly affect the TSR results.
3. Need to consider minimum wet strength (if the desired value can be established) of the conditioned specimens rather than relying solely on the TSR value. For example, some additives increase both dry and wet strengths but might have a low TSR value.
4. Lack of satisfactory correlation between laboratory and field performance.

However, based on the preceding discussion it appears that the Modified Lottman Test (AASHTO T283) is the most appropriate test method available at the present time to detect moisture damage in HMA mixes. A minimum TSR of 0.70 is recommended when using this test method. This criterion should be applied to the field produced rather than laboratory produced mixes.

Strategic Highway Research Program (SHRP) has two research contracts dealing with moisture susceptibility of HMA mixes. SHRP project A-003A "Performance Related Testing and Measuring of Asphalt-Aggregate Interactions and Mixtures" is developing an improved test method to evaluate moisture susceptibility. SHRP project A-003B "Fundamental Properties of Asphalt-Aggregate Interactions Including Adhesion and Adsorption" studied the fundamental aspects of asphalt-aggregate bond. A Net Adsorption Test (NAT) was developed in SHRP A-003B completed by the National Center for Asphalt Technology. This is a preliminary screening test for matching mineral aggregates and asphalt cement. Considerable work will be required to validate SHRP developed tests in the field.

Antistripping Agents

Antistripping agents might be needed if it has been established that a HMA mix is inherently prone to stripping based on the results of the methodological investigations and moisture susceptibility tests discussed earlier.

Liquid Antistripping Additives

Most of the liquid antistripping (AS) agents are surface active agents which when mixed with asphalt cement reduce surface tension and, therefore, promote increased adhesion to aggregate. The chemical composition of most commercially produced AS agents is proprietary. However, the majority of AS agents currently in use are chemical compounds that contain amines (*28*). These AS agents must be “heat stable,” that is, they should not lose their effectiveness when the modified asphalt cement is stored at high temperatures for a prolonged period of time.

The simplest and most economical way is to mix the AS agent with the asphalt cement in a liquid state prior to mixing the asphalt cement with the aggregate. Although this method is most commonly used, it is inefficient because only a portion of the AS agent reaches the aggregate-asphalt cement interface. Direct application of the AS agent to the aggregate surface is undoubtedly the most efficient and possibly the most effective (*1*). However, a uniform dispersion is not possible because very small amounts of AS agents (for example 0.5% by weight of asphalt cement) are normally used, and the HMA mix contains substantial amount of fines.

The amount of AS agent to be used in important. Too little may not be effective and too much may be detrimental to the HMA mix. The long range effectiveness of liquid AS agents during the service life of the HMA pavements has not been established.

Some agencies maintain an approved list of AS agents and require the contractors to use any AS agent in **all** HMA mixes without conducting any moisture-susceptibility test. This practice has many serious disadvantages. Some HMA mixes do not need any AS agent and, therefore, it is uneconomical (and sometimes detrimental) to use these agents. Some AS agents are asphalt cement and aggregate specific and, thus, are not effective in all HMA mixes unless verified by tests. It should be left to the contractor to select a suitable AS agent and its dosage to meet the test criteria of the specified moisture susceptibility test. Such criteria should be constantly modified to reflect technological advancements and product developments from the suppliers of AS agents.

Lime Additives

Unlike liquid AS agents which are usually added to the asphalt cement, lime is added to the aggregate prior to mixing with asphalt cement. Many studies indicate that lime is a very effective antistripping agent. However, its antistripping mechanism is not well understood. Various mechanisms have been postulated: (a) lime interacts with acids in the asphalt cement that are readily adsorbed on the aggregate surface, (b) lime provides calcium ions which can replace hydrogen, sodium, potassium and other cations on the aggregate surface, and (c) lime reacts with most silicate aggregates to form a calcium silicate crust which has a strong bond to the aggregate and has sufficient porosity to allow penetration of the asphalt cement to form another strong bond (*1*).

Both hydrated lime $Ca(OH)_2$ and quick lime CaO are effective, although the former is most commonly used. Dolomitic limes (both Type S and N) have also been used as antistripping additives. However, as a carbonate CaC03 lime is not as effective. Generally, 1 to 1½ % of lime by weight of dry aggregate is used. Finer aggregates may require higher percentages because of increased aggregate surface area.

Aggregates have been treated with lime by the following four methods (*1*):

1. Dry hydrated lime: The main problem in using dry lime is to maintain its coating on the aggregate surface until it is coated with asphalt cement. It is more critical in drum mixers which tend to pick up some of the lime in the exhaust gas flow. However, Georgia DOT has successfully used dry hydrated lime in drum mixers by injecting lime into the drum just ahead of asphalt cement. The pick up of lime by the gas stream is prevented by modifications of the flights and providing suitable baffles inside the drum (*29*). Dry hydrated lime can be added to the aggregate at different points in batch and drum mix facilities as shown in Table 8 which also lists the advantages and disadvantages (*30*). Some asphalt paving technologists believe that use of dry lime is not consistently effective although Georgia DOT has had very satisfactory results with dry lime.
2. Hydrated lime slurry: This method required additional water to be added to the aggregates which results in increased fuel costs and reduced HMA production rates. The commonly used techniques of introducing lime as a slurry are given in Table 9 (*30*). Additional mixing equipment is also needed.
3. Dry hydrated lime to wet aggregate: In this method dry hydrated lime is added to wet aggregate, usually containing 3-5% water, and then mixed in a pugmill or tumble mixer to obtain a homogeneous mix. Dry lime can also be added to dry or moist aggregate and then sprayed with water. Unless the water content is low, increased fuel costs and reduced HMA production rates will result.
4. Hot (Quicklime) slurry: The use of quicklime (CaO) has at least two advantages: (a) its cost is equal to that of hydrated lime but when slaked the hydrated lime yield is 25% greater, and (b) the heat from slaking results in an elevated temperature which helps in the evaporation of the added moisture. It should be handled with caution because it can cause burns on humans.

Table 8. Methods of Introducing Dry Lime (*30*)

Methods	Advantages	Disadvantages
a) Batch Mix Plants		
On the Cold Feed	- Scalping screen and belt changes can improve mixing	- May produce dusting and some lime loss - Mixing and coating of aggregates is minimized
Premixing Pugmill	- Maximizes coating of the aggregate - Minimizes losses due to dusting	- Some lime loss due to dusting - Some lime may be lost in the asphalt cement
Pugmill Prior to Stockpiling	- Maximizes mixing and coating of the aggregate - Minimizes losses due to dusting	- Some lime may be lost in the asphalt cement
Prior to Stockpiling	- Lime may be added prior to stockpiling	- Maximizes chance of carbonation occurring - Some lime may be lost due to construction
b) Drum Mix Plants		
On the Cold Feed	- Scalping screen and belt changes can improve mixing	- May produce dusting and some lime loss - Mixing and coating of aggregates is minimized
Premixing Pugmill	- Maximizes coating of the aggregates - Minimizes losses due to dusting	- Some lime loss due to dusting - Some lime may be lost in the asphalt cement
Prior to Stockpiling	- Allows aggregate drainage	- Maximizes chance of carbonation occurring - Only certain aggregates may be treated
Prior to Adding Asphalt	- Dust loss is minimized	- Not recommended without special equipment

Table 9. Methods of Introducing Lime Slurry (*30*)

Methods	Advantages	Disadvantages
a) Batch Mix Plants		
On the Cold Feed	- Scalping screen and belt changes can improve mixing	- Only certain aggregates may be treated - Adding lime at each cold feed bin may be required - Some dust loss may occur during dyring
Premixing Pugmill	- Better aggregate coverage and allows for drainage - Minimizes losses due to dusting	- High cost*
Prior to Stockpiling	- Allows aggregate drainage	- Maximizes chance of carbonation occurring - Only certain aggregates may be treated
b) Drum Mix Plants		
On the Cold Feed	- Scalping screen and belt changes can improve mixing	- Only certain aggregates may be treated - Adding lime at each cold feed bin may be required - Some dust loss may occur during drying
Premixing Pugmill	- Better aggregate coverage and allows for drainage - Minimizes losses due to dusting	- High cost*
Prior to Stockpiling	- Allows aggregate drainage	- Maximizes chance of carbonation occurring - Only certain aggregates may be treated
On a Slinger Belt	- Minimizes the amount of mixing	- Maximizes the amount of moisture to be removed

* Added by the author.

The relative effectiveness of the preceding four treatments based on a 1989 survey is shown in Figure 18 taken from Reference *1*. However, comparative laboratory and field studies have been generally inconclusive and, therefore, increased fuel and equipment costs and decreased HMA production rates associated with the wet process may not be justified at the present time.

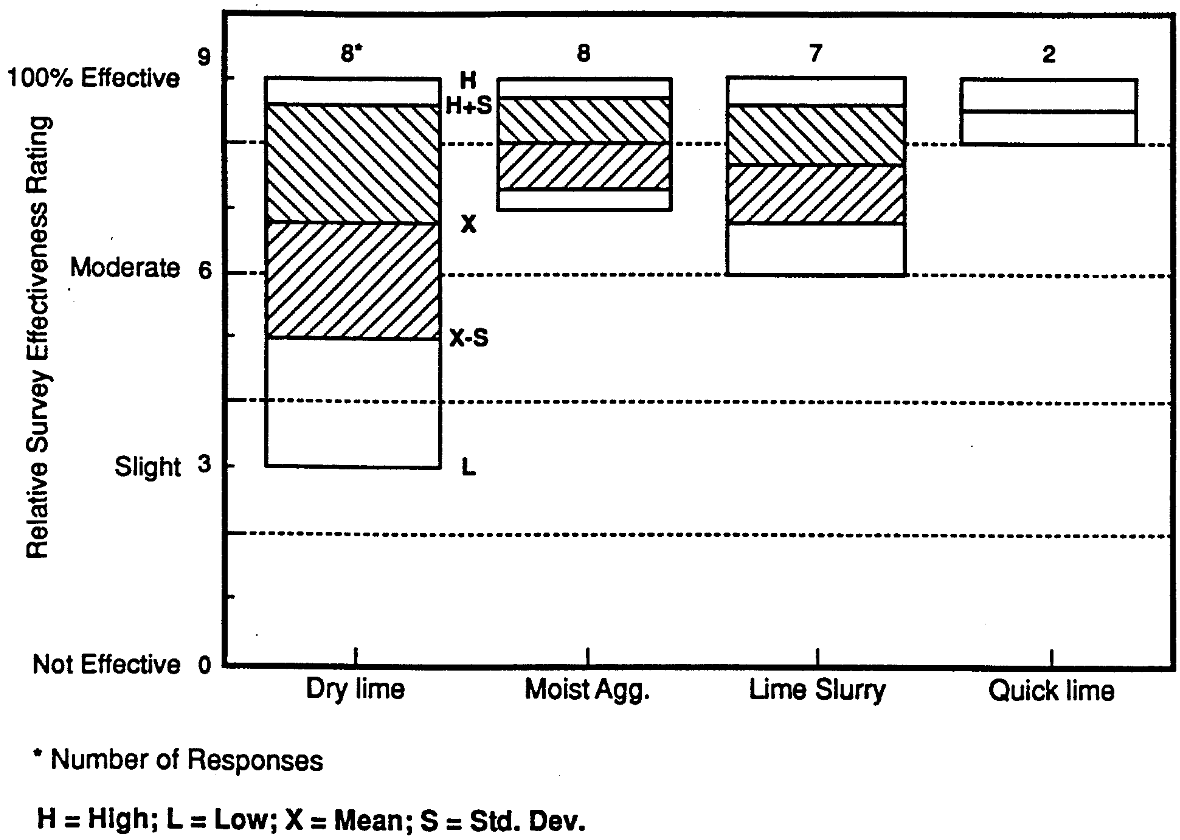

Figure 18. Relative Effectiveness of Lime Treatment of Aggregate by Method of Lime Addition (*1*)

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Stripping of hot mix asphalt (HMA) pavements appears to have become a major problem in recent years. More and more states are specifying the use of antistripping (AS) agents. Moisture susceptibility of HMA mixes has been reviewed in this paper in terms of identification of the problem and recommended solutions. The following conclusions and recommendations are warranted:

1. External factors and/or in-place properties of the HMA pavements can induce premature stripping in HMA pavements. A proper knowledge of these factors is essential in identifying and solving the stripping problem. Some of these factors which have been discussed in detail are: inadequate pavement drainage (especially subsurface drainage); inadequate compaction of HMA pavement; excessive dust coating on aggregate; inadequate drying of aggregates prior to mixing with asphalt cement; use of weak and friable aggregates in HMA; overlays on deteriorated concrete pavements; use of waterproofing layers and seal coats when the source of the moisture is from beneath the pavement; and possibly the use of open-graded asphalt friction courses. Suggestions for alleviating the problems associated with these factors have been given in the paper.
2. An investigative methodology based on forensic experience has been recommended for use by the specifying agencies and industry to establish stripping as a problem on a specific project or statewide. Details of sampling, testing, and interpretation of test results (along with examples) are included. This methodology will help determine the

cause(s) of stripping (if present), take remedial measures to remove the cause(s), and specify antistripping agents only when absolutely necessary.

3. The current practices of specifying moisture susceptibility test procedures (and acceptance criteria) and antistripping agents have been reviewed. Until more suitable test procedures are developed and validated by the SHRP, Modified Lottman test (AASHTO T283) has been recommended to determine potential moisture susceptibility of HMA mixes. A minimum TSR of 0.70 is recommended when using this test. This criterion should be applied to the field produced rather than the laboratory produced HMA mixes.
4. Antistripping (AS) agents (both liquid and lime additives) should not be specified across the board in all HMA mixes and/or from an approved list of sources as an "insurance." Some agents are aggregate and asphalt specific and, therefore, may not be effective (and could be detrimental at times) in all mixes. This practice is also uneconomical because some HMA mixes are inherently resistant to moisture damage and do not need any AS agent.
5. Various laboratory and field studies indicate that lime is a very effective antistripping agent for most aggregates. Lime can be added to the aggregate in dry form or as a lime slurry. It is generally believed that the wet process is more effective than the dry process. However, comparative laboratory and field studies have been generally inconclusive and, therefore, increased fuel and equipment costs and decreased HMA production rates associated with the wet process may not be justified at the present time.
6. A thorough and fundamental understanding of mechanisms (especially asphalt cement aggregate interactions) involved in moisture induced damage is necessary to develop improved and more reliable laboratory test methods and criteria to predict moisture susceptibility of HMA mixes. Such methods which are being developed by SHRP will then need to be correlated and validated with field performance.

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