Field and Laboratory Investigation of Stripping in Asphalt Pavements: State of the Art Report

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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 agents. There is a need to investigate and identify the problem properly so that decisions are not made solely on the basis of observation of isolated distress areas. External factors and in-place properties of HMA pavements can induce their premature stripping. Contributing factors, such as inadequate pavement drainage, inadequate compaction of HMA pavement, excessive dust coating on aggregate, inadequate drying of aggregate, and overlays on concrete pavements, are described. Suggestions for alleviating the problems associated with these factors are given, and an investigative methodology based on forensic experience is recommended for use by the specifying agencies and industry that want to establish whether stripping is a problem either on a specific project or statewide. Current practices of using laboratory moisture-susceptibility tests across the United States are reviewed and the AASHTO T283 (Modified Lottman) test method is recommended for use until more suitable and reliable tests are developed and validated.

Stripping of hot mix asphalt (HMA) pavements appears to have become a major problem in recent years. Stripping can result prematurely 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.

Every year more and more states are specifying the use of antistripping (AS) agents. There is a need to investigate and identify the problem properly so that decisions are not made simply on the basis of observation of isolated distress areas. Within states that have started to specify AS agents, the proliferation of specifications and test methods is great. 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. This study was undertaken, in part, to make recommendations for a viable, common strategy.

OBJECTIVES

- List and discuss factors that can induce premature stripping in HMA pavements;
- Recommend a field investigative methodology that can be used by the specifying agencies and industry to establish stripping as a problem on a specific project or statewide;
- Review current laboratory test methods used by various agencies for determining the stripping potential of HMA mixtures and make recommendations for a common strategy on test methods and criteria.

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 physico-chemical surface properties of mineral aggregates are more important to moisture-induced stripping than the properties of asphalt cement binder. Some mineral aggregates are inherently very susceptible to stripping. However, in many cases, external factors or in-place properties of HMA pavements induce stripping prematurely in HMA pavements. Knowledge of these factors is essential to investigating and solving the stripping problem. A discussion of these factors follows.

Inadequate Pavement Drainage

Inadequate surface or subsurface drainage produces water or moisture vapor, the necessary catalyst to induce stripping. If excessive water or moisture is present in the pavement system, HMA pavement can strip prematurely. Kandhal et al. (*2*) have reported case histories in which stripping was not a general phenomenon occurring on an entire project but instead a localized phenomenon in areas of the project that were over-saturated with water or water vapor because of inadequate subsurface drainage.

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

Water commonly moves upward by capillarity from 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 capillary moisture. The construction of multilane highways, the widening of existing roads, in addition to gentler slopes and milder curves in all kinds of terrain, compound the subsurface-drainage problem. Doubling a road's width, for example, makes drainage about four times as difficult as before (*3*). Quite often, a four-lane highway is

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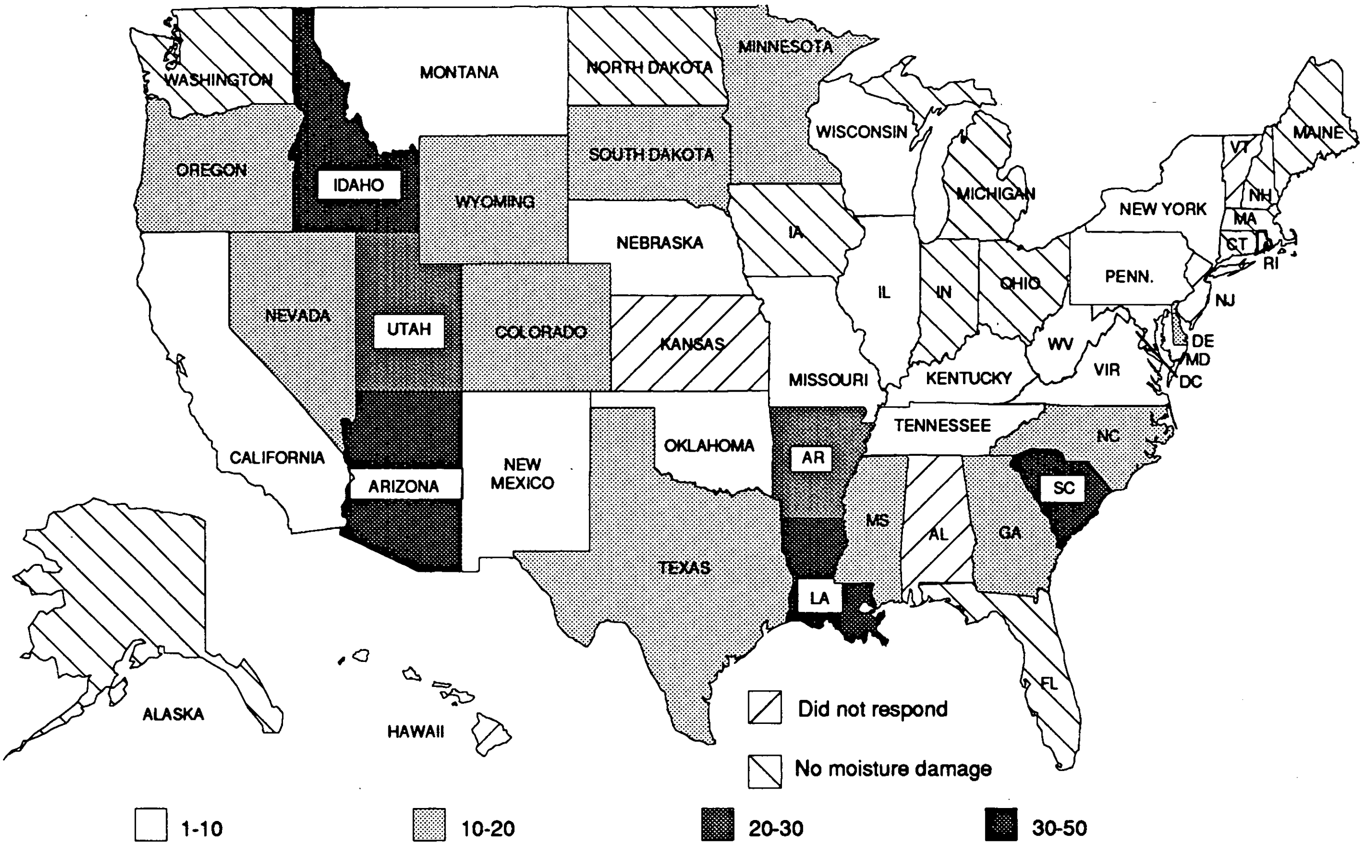

FIGURE 1 Estimated percentage of pavements experiencing moisture-related distress (*1*).

rehabilitated by paving the median and shoulders with HMA, resulting in a fully paved width of 72 to 78 ft. The new surface is equivalent to that of a six-lane highway, without any increase in subsurface drainage capacity (*2*).

Extensive research conducted at the University of Idaho (*4*) on the mechanism of asphalt stripping indicates "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 138 kPa (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 form 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*) also have stated that pore pressure from stresses induced by traffic can cause the failure of the binder-aggregate bond. Initially, 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 traffic action.

Halberg (*6*) has reported "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 wearing course mixtures do, possibly because of large diameter pores in the binder course. Moreover, the wearing course is exposed repeatedly to high temperature drying periods as the pavement heals. Asphalt films that debond from the aggregate attach themselves again, and the mix regains its strength and water resistance. 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*), who observed wet spots on HMA overlay surface scattered throughout a 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 (from asphalt stripping and migration 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 pot-

FIGURE 2 Three stages of stripping: white spots, fatty area, and pothole (close up).

FIGURE 4 Close up of pothole showing severely stripped aggregate.

hole. Small and large blisters caused by entrapped moisture were also observed. Sometimes blisters occurred with asphaltic globules at the surface (*8*).

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

In sum, 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 local conditions (*9,10*); Kandhal et al. (*2*) have reported some such cases in detail.

Inadequate Compaction

Inadequate compaction of HMA mat is probably the most common construction-related factor to cause premature stripping. Studies indicate that at less than 4 to 5 percent air-void content in the HMA, the voids generally are not interconnected and thus are almost impervious to water. Most HMA mixes are designed to have 3 to 5 percent air-void contents. When constructed, a maximum air-void content of 8 percent (at least 92 percent of the theoretical maximum specific gravity) is specified by most agencies. It is assumed that the pavement will become densified to the design air-void content after 2 to 3 years of traffic use. However, some agencies do not exercise good compaction control, resulting in HMA's with air-voids contents higher than 8 percent at the time of construction. This can cause premature surface ravelling, because the mix does not possess adequate cohesion (*11*). Quite often, stripping is blamed for this type of premature raveling although the mixture is not examined closely. However, if the HMA pavement remains pervious for an extended time, stripping is likely to occur because of the ingress of water and hydraulic pore pressures induced by the traffic.

Terrel and Shute (*12*) have advanced the concept of "Pessimum" voids content for stripping. Figure 5 shows the general relationship

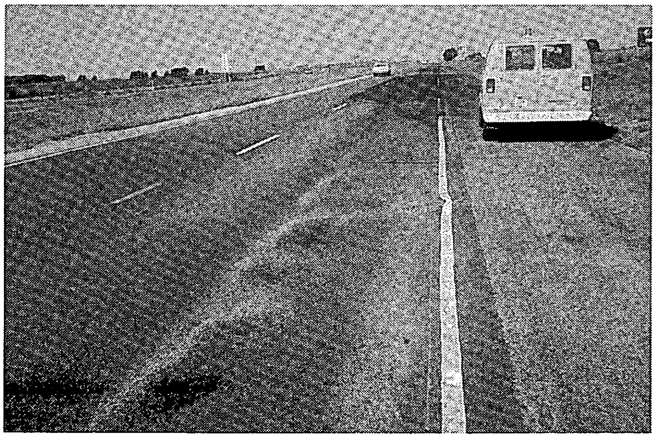

FIGURE 3 Slow traffic lane showing three stages of stripping.

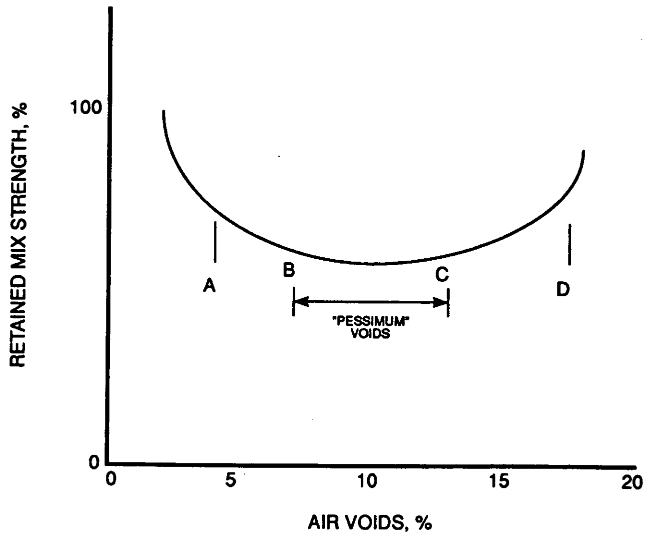

FIGURE 5 Air-void content versus retained mix strength, region of pessimum voids (*12*).

between air voids and relative strength of HMA mixtures following water conditioning. The amount of strength loss depends on the amount and nature of the voids. As shown in Figure 5, at less than 4 percent voids (Region A), the mixture is virtually impermeable to water, so it is essentially unaffected. Unfortunately, many pavements get constructed between Region B and C. As the voids increase to Region D and beyond, the mix strength becomes less affected by water, because the mixture is now free draining. Region B to C in Figure 5 is termed "Pessimum" void content because voids within its range are the opposite of optimum. The objective is to stay out of the "Pessimum" void range in order to minimize stripping problems. This can be done through proper mix design and compaction control procedures.

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. Some very fine clayey material may cause stripping by emulsifying the asphalt cement binder in presence of water.

The author is aware of one project in which stripping occurred by the mechanism of hydraulic scouring, which is applicable only to surface courses. Unlike typical stripping, this scouring starts at the surface and progresses downward, and it 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 is 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 the 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*) also have 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 open-graded 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 also cause flushing, rutting, or shoving at the surface. Several states suspended the use of OGFC in the early 1980s. In South Carolina the statewide average stripping frequency was determined to be 18.7 percent under OGFC compared with a statewide average of 8.5 percent for all pavement layers (*16*). Some studies also have indicated that the stripping in the layers underlying OGFC resulted from the layers' high air-void content (lack of adequate compaction). Evidently, to minimize stripping, it is all the more desirable to have an impervious HMA course below the OGFC. It is recommended that the air-void content of the underlying HMA course should not exceed 4 to 5 percent when 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 of 4 to 5 percent.

Inadequate Drying of Aggregates

Laboratory studies (*17*) indicate that high residual-moisture content in the mineral aggregate before mixing with asphalt cement binder increases the potential for stripping. When drum-mix facilities were introduced to HMA production in the 1970s, low mixing temperatures (and high moisture content in the HMA) were encouraged to facilitate compaction. Now it is hypothesized 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 better adhere to the asphalt cement than a moist or wet aggregate surface.

Weak and Friable Aggregate

If weak and friable aggregates are used in the HMA mix, degradation takes place during rolling and later under heavy traffic. Degradation or delamination exposes new uncoated aggregate surfaces that can absorb water readily and initiates 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, durable aggregate in the HMA is recommended.

Overlays on Deteriorated Concrete Pavements

Many concrete pavements on interstate and primary highways are deteriorating before their design life. In recent years, HMA overlays have increasingly been put over existing concrete pavements, some of which have faulted, spalled, cracked, and water-pumping slabs. Dense-graded subbase material under concrete pavements can hold considerable water, which can escape through cracks or longitudinal and transverse joints. Once the concrete pavement is overlaid with an impervious HMA course, the water is trapped underneath. Excessive pore pressure builds under the traffic, initiating stripping, and then potholes form at the worst spots. Whenever a concrete pavement is due to be overlaid for the first time, it is necessary to evaluate existing drainage conditions. It may be necessary for the project to include installation of a positive drainage system, especially in troubled spots. Unless this is done, the problem of stripping and potholing will persist forever.

Usually edge drains are not sufficient to drain the entire roadway width. Transverse (lateral) drains are necessary, especially on steppe grades where water tends to flow longitudinally rather than toward the edge drain. Lateral drains can be installed at or near the existing transverse joints of concrete pavements before overlay and connected to the edge drain.

If an existing concrete pavement is badly deteriorated, cracked, and pumping were because of inadequate subsurface drainage, putting a 4-in. drainage layer of open-graded asphalt-treated permeable material (ATPM) directly above it before placing the dense-graded HMA overlay is recommended. The 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. 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 that have been subjected to crack and seat, break and seat, and rubblizing operations. Details on the design and use of ATPM are provided elsewhere (*9,10*).

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 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 [McKesson] 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 observed this phenomenon of induced stripping in the pavement layers underlying waterproofing membranes and seal coats. The potential for stripping should, therefore, be considered whenever such sealing systems are used.

FIELD INVESTIGATIVE METHODOLOGY

It is necessary to apply an investigative methodology based on forensic experience with HMA pavements is to establish whether stripping is a problem either on a specific project or statewide. Surface distresses such as ravelling, flushing, and rutting can be caused by factors other than stripping. Visual investigation of the road surface alone is often inconclusive; it should not be used as the sole basis for determining whether stripping has occurred. The following field methodology is suggested.

Sampling

Inspect the whole project and select a 152.5-m (500-ft) long section that represents the "distressed area." Most projects also will have relatively better areas, with minimal or no distress. Select another 152.5-m (500-ft) long section from the same project that can be termed a relatively "good area." Document the type and extent of the observed distress (such as ravelling, flushing, rutting, and potholing) in both areas.

Obtain at least seven cores 102-mm (4-in.) in diameter at random locations in each area. A minimum sample size of seven 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 four-lane highway, obtain all cores from the inside wheel track of the slow-traffic (outside) lane. If it is a two-lane highway, obtain all cores from the outside wheel track of the lane. Stripping usually occurs first at these locations, across the roadway pavement. Cores 4-in. in diameter are recommended so that an indirect tensile test can be conducted. An additional eighth core also can be obtained, if the aged asphalt cement binder is to be recovered and tested for penetration and viscosity.

It is necessary to drill the cores without using water as a coolant, so that the in-situ moisture contents can be determined. Compressed air and CO_2 can be 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 water-cooled core drill, but valuable information on 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 Public Transportation (SCDHPT) in an investigation of stripping of HMA in the state (*16*). Cores should be sealed in air-tight containers so that the in-situ moisture content can be determined later in the laboratory. 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 a jack hammer in investigating stripped pavements on the Pennsylvania Turnpike.

Testing

The recommended testing plan is shown in Figure 6. 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 an 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 using the specification AASHTO T166. Determine the indirect tensile strength of the dry specimens at 25°C (77°F) using AASHTO T283 (Sections 10 and 11) or ASTM D4867 (Sections 8 and 9).

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 (DOT) and used by 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

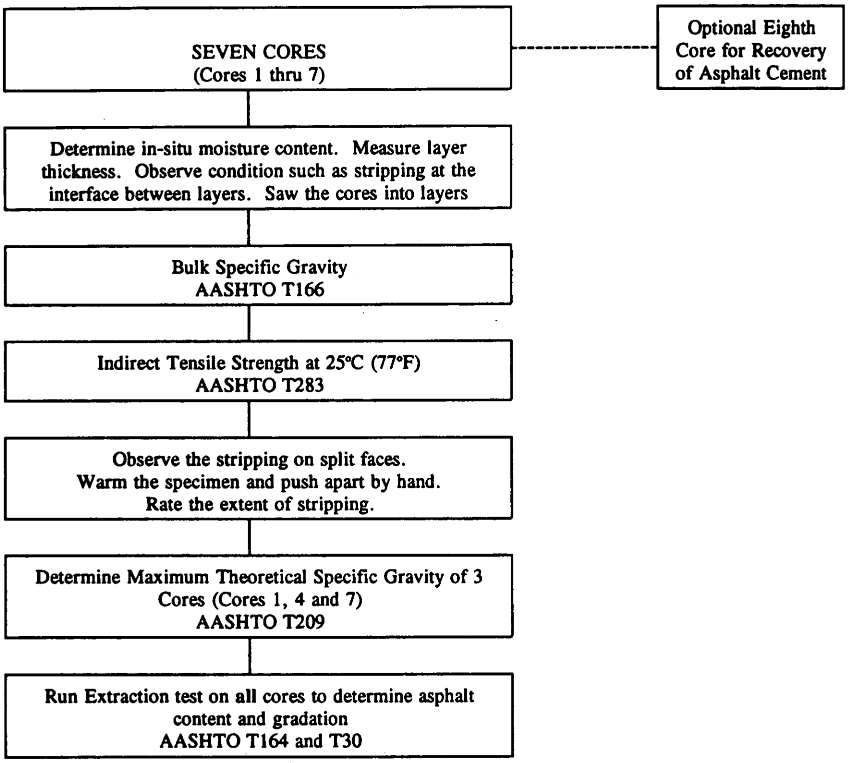

FIGURE 6 Testing plan.

stripping of the fine aggregate matrix and the coarse aggregate fraction separately. Stripping of the fine aggregate matrix is considered 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 the values of C and F are as follows:

Values of C	*Values of* F
C = Coarse Aggregate Stripping	F = Fine Aggregate Stripping
1 = less than 10 percent	1 = less than 10 percent
2 = 10–40 percent	2 = 10–25 percent
3 = more than 40 percent	3 = more than 25 percent

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

An average stripping rating of 2.5 and 3.0 was 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 three cores (Cores 1, 4, and 7 are recommended because in combination they encompass most of the representative area).

Conduct an 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 7 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 each of the seven cores using the average effective specific gravity and the cores' 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:

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

Tabulate all calculated and observed data separately for "good" and for "distressed" areas. Calculate the mean, standard deviation, and 95-percent 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 3-year old distressed project. Table 1 represents test data obtained by this investigative methodology from a "good" area whereas Table 2 has data

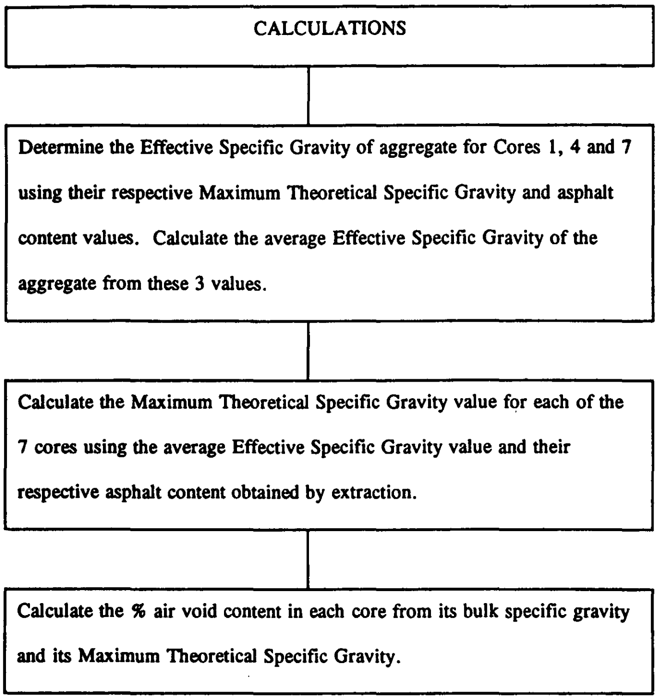

FIGURE 7 Calculation of air-void content.

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) that are likely to induce stripping. Therefore, this can be considered the worst-case scenario. The "distressed" area in this example has the following problems:

- Very high and inconsistent air void content,
- Deficient and inconsistent asphalt content,
- Excessive and inconsistent minus-200 material, and
- Very high in situ moisture contents or saturation levels.

These 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 was also indicated by lower tensile strengths compared with those in the good area.

When data such as those in Table 2 are obtained, one should not immediately presume that an antistripping agent is needed; instead, remedial measures should be taken to remove the cause(s). For example, the data in Table 2 indicate the following needs:

- 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 to 5 percent) in 3 years.
- 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 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 especially variable considering the standard deviation of 1.97 percent.
- Positive drainage system. The project has a water-drainage problem in the distressed area; saturation is as high as 100 percent.

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

Statewide Survey

Before specifying antistripping agents or moisture-susceptibility test methods statewide, it is prudent first to establish whether stripping is a statewide problem or only occurring in isolated cases. Georgia and South Carolina have each completed a statewide survey and evaluation of the stripping problem through an extensive coring program. South Carolina sampled 805 km (500 mi) of pavements, coring 1,324 cores and testing 4,503 pavement layers(*16*). A random sample, consisting of two pavement cores, was taken from every 3.2-km (2-mi) segment for each highway section sampled. Two-lane and multilane highways, and HMA pavements with and

TABLE 1 Core Test Data—Good Area

Test	Job-Mix Formula	Core No.							$\bar{X}$	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	4.6	0.63	3.3 - 5.9
Tensile Strength, psi	---	118	130	110	128	98	121	90	114	15.1	84 - 144
% Asphalt Content	6.9	6.7	7.0	6.6	7.2	7.0	6.8	6.7	6.8	0.21	6.4 - 7.2
% Minus 200	5.2	5.8	6.1	5.3	4.3	4.8	6.0	4.5	5.3	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	0.27	0.076	0.1 - 0.4
% in-situ Saturation	---	15.2	11.7	14.6	10.8	13.0	11.5	16.1	13.3	2.05	9.2 - 17.4
Stripping Rating	---	1.0	1.0	1.0	1.0	1.5	1.0	1.5	1.14	---	---

TABLE 2 Core Test Data—Distressed Area

Test	Job-Mix Formula	Core No.							$\bar{X}$	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	2.434	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.

without open-graded friction courses (OGFC), were sampled. A similarly unbiased, statewide testing program is recommended for others. Ideally, however, one would obtain at least three 102-mm (4-in.) diameter cores randomly from each project to obtain preliminary data on in-situ moisture content, air-void content, mix composition, tensile strength, and the extent of stripping, if any. If 100 projects were selected across the state, testing would involve 300 cores; that does not appear to be an unreasonable number to establish whether or not stripping is a statewide problem.

Data from 100 projects would not only help assess the average frequency for severe stripping (that is, visual ratings of 2.5 and 3.0) within a state, it would also indicate whether there were other problems to be addressed statewide, such as inadequate compaction, lack of HMA-production quality control, or inefficient subsurface drainage systems.

Selected projects could be revisited, sampled, and tested every year to assess increasing moisture-induced damage, if any. Georgia DOT has such a program, which has been successful.

Since materials, mix design, construction practices, maintenance procedures, and climatological conditions vary from state to state, it is essential that each state conduct its own statewide survey to assess and quantify the "stripping" problem, as recommended. Calling for antistripping agents as "insurance" against stripping, without establishing the extent or cause of the problem is not justified. Not only is such a policy uneconomical, it may be ineffective if underlying causes responsible for stripping are not addressed adequately.

LABORATORY INVESTIGATIVE TESTING METHODS

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 gained wide acceptance because they have low reliability and lack a satisfactory relationship between laboratory and field conditions. Selected test methods, only those commonly used by certain agencies, are discussed briefly.

Qualitative or Subjective Tests

- Boiling Water Test (ASTM D3625 or a variation): Loose HMA mix is added to boiling water. Although the current ASTM D3625-83 specifies 1 min. of boiling, most agencies use a 10-min. boiling period. The percentage of the total visible area of the aggregate that retains its original coating after boiling is estimated as either above or below 95 percent. 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.
- Static-Immersion Test (AASHTO T182): A sample of HMA mix is immersed in distilled water at 25°C (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 that remains coated as above or below 95 percent. Again, this method does not involve any strength test.

Quantitative Strength Tests

- Lottman Test (NCHRP 246): This method was developed by Lottman (*20*) under the National Cooperative Highway Research Program 246. Nine specimens (102-mm or 4-in. in diameter and 64-mm or 2½ in. high) are compacted to expected field air-void content. Specimens are divided into three groups of three specimens each. Group 1 is treated as a control, without any conditioning. Group 2 specimens are vacuum saturated (660 mm or 26 in. Hg) with water for 30 min. Group 3 specimens are vacuum saturated like those in Group 2 and then subjected to a freeze (−18°C or 0°F for 15 hr) and a thaw (60°C or 140°F for 24 hr) cycle. All nine specimens are tested for resilient modulus (M_R) and indirect tensile strength (ITS) at 13°C (55°F) or 23°C (73°F). A loading rate of 1.65 mm/min. (0.065 in.) 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:

$$\text{TSR} = \frac{\text{ITS of conditioned specimens}}{\text{ITS of control specimens}}$$

A minimum TSR of 0.70 is recommended by Lottman (*20*) and Maupin (*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).

- Tunnicliff and Root Conditioning (NCHRP 274): This method was proposed by Tunnicliff and Root under the NCHRP Project 274 (*24*). They proposed that six specimens be compacted to a 6 to 8 percent air-void content and then divided into two groups of three specimens each. Group 1 specimens are treated as a control, without any conditioning. Group 2 specimens are vacuum-saturated (508 mm or 20 in. Hg for about 5 min.) with water to attain a saturation level of 55 to 80 percent. Specimens attaining more than 80 percent saturation are discarded. The saturated specimens are then soaked in water at 60°C (140°F) for 24 hours. All specimens are tested for ITS at 25°C (77°F) using a loading rate of 51 mm/min. (2 in)/min. A minimum TSR of 0.7 to 0.8 usually is 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*).
- 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 the Lottman test (NCHRP 246) and Tunnicliff and Root test (NCHRP 274). Six specimens are compacted to a 6 to 8 percent air-void content. Group 1 (three specimens) is used as a control. Group 2 specimens are vacuum saturated (55 to 80 percent saturation) with water and then subjected to one freeze and one thaw cycle as proposed by Lottman. All specimens are tested for ITS at 25°C (77°F) using a loading rate of 51 mm/min. (2 in)/min., and the TSR is determined. A minimum TSR of 0.7 is usually specified. This method is gaining acceptance by the specifying agencies.
- Immersion-Compression Test (AASHTO T165): Six specimens (102-mm or 4-in. diameter times 102-mm or 4-in. high) are compacted with a double plunger at a pressure of 20.7 MPa (3,000 psi) for 2 min. to about 6 percent air-void content. Group 1 (three specimens) is treated as control. Group 2 specimens are placed in water at 49°C (120°F) for 4 days or at 60°C (140°F) for 1 day. All specimens are tested for unconfined compressive strength at 25°C (77°F) using a 5.1 mm/min. (0.2 in/minute) loading rate. The retained compressive strength is determined. Many agencies specify at least 70 percent retained strength. This test has produced retained strengths near 100 percent, even when stripping is evident. Stuart (*13*) has attributed this to the internal pore water pressure and insensitivity of the compression test in measuring the moisture-induced damage. Lack of precision is a major problem with this test.
- Other Tests: Moisture-vapor susceptibility, a swell test, and a film stripping test are used by Caltrans. 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 moisture susceptibility was conducted in 1989 by Hicks for NCHRP Topic 19-09 (*1*). Figure 8 shows the relative effectiveness of different test methods on a zero to nine scale, according to this survey. Zero means "not effective" and 9 means "100-percent effective." The results are given in Table 3.

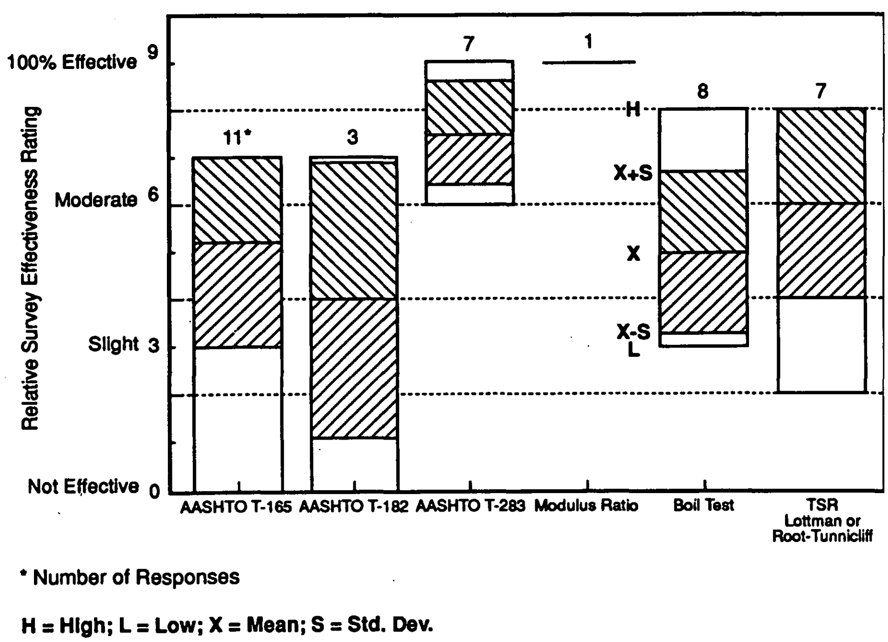

FIGURE 8 Relative effectiveness of mixture test procedures to identify moisture-related problems (*1*).

TABLE 3 Survey of Test Methods and Their Effectiveness

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 Lottman (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.

Evidently, a wide variety of test methods are being used by various agencies. However, no test has proven "superior" at correctly identifying a moisture-susceptible mix in all cases. Kiggundu and Roberts (*27*) quantified the success rate of several tests, based on test data available from various research reports and papers, as given in Table 4.

Data on success rates indicate that many HMA mixes that might otherwise perform satisfactorily in the field, are likely to be unacceptable if these tests and criteria are used. Use of these tests has encouraged the increased use of antistripping agents in many states.

Many concerns and requirements related to the test methods still need to be addressed:

- Proliferation of test procedures and criteria.
- Unsatisfactory reproducibility of most test methods. For example, small variations in air-void content of the specimens can significantly affect the TSR results.
- Sole reliance on the TSR value instead of considering minimum wet strength (if the desired value can be established) of the conditioned specimens. For example, some additives increase both dry and wet strengths but might have a low TSR value.
- Lack of satisfactory correlation between laboratory and field performance.

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

Strategic Highway Research Program (SHRP) had 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" was needed to develop an improved test method to evaluate moisture susceptibility. A second contract, 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 under SHRP A-003B and completed by the National Center for Asphalt Technology. It is a preliminary screening test for matching mineral aggregates and asphalt cement (*28*) and is based on the principles of adsorption and desorption. A solution of asphalt cement and toluene is introduced and circulated in a reaction column containing the aggregate sample. Once the solution temperature has been stabilized, 4 ml of solution is removed and the absorbance is determined with a spectrophotometer. Fifty grams of minus No. 4 aggregate is then added to the column, and the solution is circulated through the aggregate bed for 6.5 hours. A second 4-ml sample of the solution then is removed from the column and the absorbance is again determined. The difference in the absorbance readings is used to determine the amount of asphalt that has been removed from the solution (adsorption) because of the chemical attraction of the aggregate for the molecular components of the asphalt cement. Immediately after the second solution sample is taken, 575 μm of water is added to the column. The solution is then circulated through the system for an-

TABLE 4 Success Rates of Test Methods

Test Method	Minimum Test Criteria	% Success
Modified Lottman (AASHTO T283)	TSR = 70% TSR = 80%	67 76
Tunnicliff-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

other 2 hr. A final 4 ml of solution is taken from the column at the end of this time. The increase in the absorptivity is a measure of the amount of asphalt cement that is displaced by water molecules (desorption). Additional validation data are needed for the NAT.

An Environmental Conditioning System (ECS) was developed in SHRP A-003A (*29*) in which HMA samples are exposed to wetting and accelerated hot-cold cycling to represent actual field exposure, including repeated loading to simulate traffic. The modulus of the HMA specimen and change in air and water permeability are monitored during the conditioning after each cycle, and tensile strength and stripping are measured at the conclusion of conditioning. Both warm- and cold-climate conditioning can be performed. Modulus ratio and water permeability ratio are calculated after completing each conditioning cycle. A provisional AASHTO standard, Designation TP34, "Standard Test Method for Determining Moisture Sensitivity Characteristics of Compacted Bituminous Mixtures Subjected to Hot and Cold Climate Conditions," is available. The ECS system is expensive but versatile; however, sufficient field-validation data are not available to warrant its use in lieu of AASHTO T283.

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 were reviewed in this paper, especially field investigation of the problem and laboratory test methods. The following conclusions and recommendations are warranted:

- External factors and in-place properties of the HMA pavements can induce premature stripping in HMA pavements. A proper knowledge of these factors is essential to identifying and solving the stripping problem.

Some factors were discussed in detail: inadequate pavement drainage (especially subsurface drainage); inadequate compaction of HMA pavement; excessive dust coating on aggregate; inadequate drying of aggregates before 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 the possible use of open-graded asphalt friction courses. Suggestions for alleviating problems associated with these factors were offered.

- An investigative field methodology based on forensic experience is recommended for use by the specifying agencies and industry in establishing whether stripping is a problem either on a specific project or statewide. [Details of sampling, testing, and interpretation of test results (along with examples) were included.] The recommended methodology will help to determine the causes of stripping, if present, take remedial measures to remove the causes, and specify antistripping agents only when absolutely necessary.
- [Current practices of specifying laboratory moisture-susceptibility test procedures (and acceptance criteria) were reviewed.] Until more suitable test procedures are developed and validated with field performance, Modified Lottman test (AASHTO T283) is recommended to determine potential moisture susceptibility of HMA mixes. Furthermore, a minimum TSR of 0.70 is recommended when using the test. The criterion should be applied to field-produced instead of the laboratory-produced HMA mixes.
- AS agents (both liquid and lime additives) should not be specified across the board in all HMA mixes or from an approved list of sources as "insurance." Some agents are aggregate and asphalt specific and, therefore, may not be effective in all mixes; they could even be detrimental at times. The practice also is uneconomical because some HMA mixes are inherently resistant to moisture damage and do not need an AS agent.
- 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 the moisture susceptibility of HMA mixes.

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