TOPIC 5

Material Production, Mix Design, and Pavement Design Effects on Moisture Damage

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Moisture damage has caused many pavement failures throughout the United States. Moisture damage is loss of bond between the asphalt and aggregate or in some cases the loss of cohesive strength of the asphalt. Moisture damage can manifest itself though various failure mechanisms. These include rutting, fatigue cracking, raveling, and potholes. In Colorado, several sections of I-70 failed in just a few short months after placement. A moisture-damage-susceptible mix was placed with high air voids. It was subjected to high rains just before being covered with a plant mix seal and then opened to traffic. This created a section where the moisture was trapped in the high air void mix, covered with a seal that would not let the moisture escape, and then subjected to scour created by high traffic. The open intermediate layer quickly stripped, leaving uncoated aggregate covered by a thin plant mix seal, which quickly disintegrated. This type of failure costs precious dollars to repair, which are needed to improve and upgrade the infrastructure system.

Researchers have been trying to define the causes for moisture damage since the first hot-mix asphalt (HMA) pavements were placed and began to fail. There are many causes of moisture damage. The intent of this paper is to discuss the effects of material production, mixture design, and pavement design on moisture damage. The basic characteristics of materials can change depending on how they are produced. For asphalts, there are many different refining processes, all of which will change its properties and can affect moisture damage. This is also true of the aggregate production process. How the aggregates are crushed and processed will change how they will react to asphalt and water.

The mix design will also affect moisture damage. A coarse-graded mixture and a fine-graded mixture may react differently. Volumetric proportioning will affect compaction, which in turn will affect moisture damage. The relationship between mixture design and structural layers has an effect on moisture damage. Sealing an open layer between two dense layers is likely to trap water and cause moisture damage.

REFINING EFFECTS ON MOISTURE DAMAGE

HMA for paving is produced by combining asphalt binder and aggregates. The chemical interaction between the binder and the aggregate is key to understanding the ability of HMA to resist moisture damage. Understanding this interaction requires an understanding of the production process for the materials.

Asphalt binders are the product of the petroleum crude oil refining process. Two basic items drive the physical and chemical properties of asphalt binders: the crude oil source and the

refining process used to produce the asphalt (*1*). Crude oil pumped from the ground typically contains water, salts, clays, and a variety of mineral mater. Most of these materials are damaging to the refinery and are typically removed before the crude oil is processed. Most of these materials are also detrimental to the moisture performance characteristics of the asphalt binder and should be removed to prevent their inclusion in the final product.

Salts act as emulsifiers (*2*) and if left in the crude oil will end up in the asphalt binder. The water and salts in the crude oil often create emulsions, which have to be removed before the crude oil can be refined. The water and salts can cause significant problems with corrosion in the plumbing of refineries. The salts are typically removed by adding additional water to the crude at an elevated temperature to dissolve them. The water and salts are then separated from the crude by either chemical or electrostatic methods (*1*). This is done in settling tanks just before the refining process.

Crude oil is also acid. These acidic crude oils can also be corrosive to the plumbing in the refinery. To reduce the acid concentration, caustic soda or pulverized limestone is sometimes added to the crude oil. As with the natural salts that are in the crude when it is pumped from the ground, these acid neutralizers must be removed from the crude oil before refining. Salts from caustic soda are strong emulsifying agents and are very corrosive to aluminum tanks.

A diagram of a typical crude oil processing system is shown as Figure 1. The crude oil desalting is done before the crude is heated and sent to the distillation tower. The desalting is typically, but not always, done at the refinery. Some refineries do not desalt. In these cases, very harmful matter can go through the refining process and end up in the residue, which is the asphalt binder.
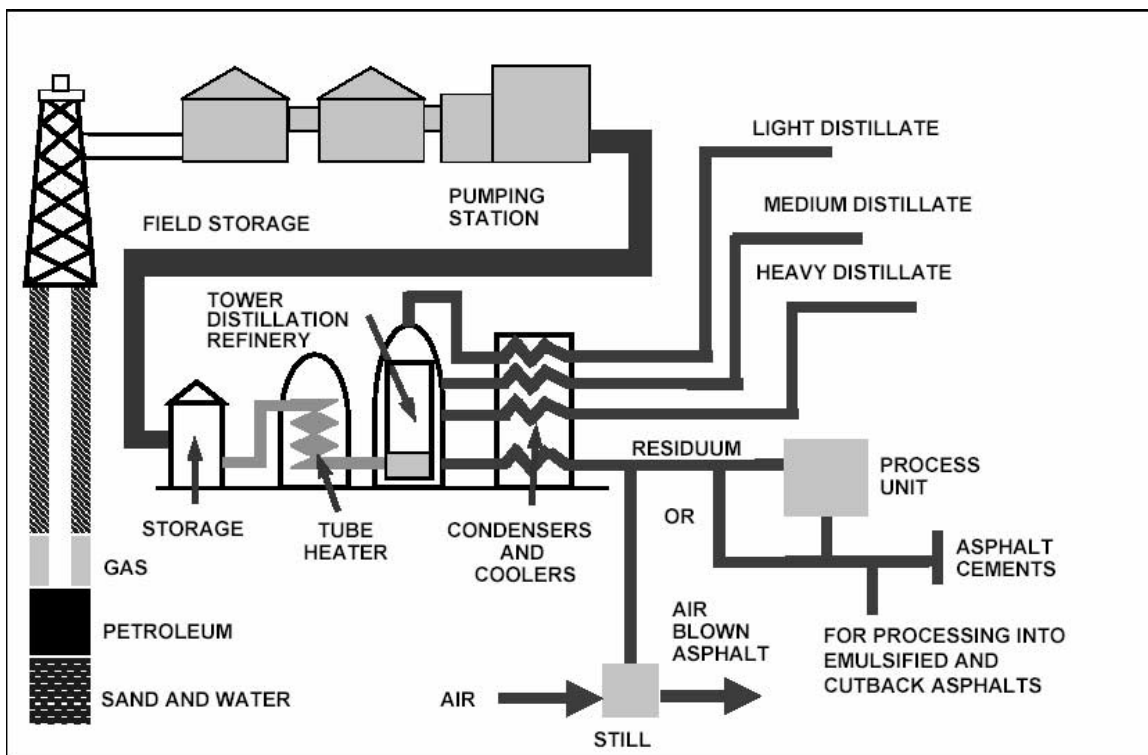

FIGURE 1 Diagram of a typical refining process for the production of asphalt binders.

Acids

The asphalt binder produced during the refining process can be modified in many different ways to meet the specifying agency's specifications. These different modification methods will change the moisture sensitivity of the binder. Such changes can be for the better, but in some cases the changes can be detrimental to the moisture sensitivity of the binder.

Air blowing is one method of modifying asphalt binders. Air blowing is a chemical modification of the binder (*1*). Air blowing involves percolating air through the asphalt binder in a large tank for several hours. Passing air through the binder will change the molecular structure and chemical makeup of the binder. Air blowing will change the average molecular size of the binder and increase its stiffness. Air blowing will also cause some oxidation of the binder. This oxidation can create increased amounts of carboxylic acids and sulfoxides (*3*). During HMA production, the carboxylic acids and sulfoxides will attach themselves to the surface of the aggregate and prevent nitrogen compounds from bonding. The carboxylic acids and sulfoxides are also easily displaced from the surface of the aggregate by water, causing moisture damage (*2–4*), as shown in Figure 2. The extent of this problem will vary significantly depending on the properties of the base asphalt binder and the amount of oxidation that occurs during the air-blowing process. Air blowing is not inherently bad. If the base asphalt is low in acid content, the resultant binder will likely be low in acid content.

As noted, there are many methods for modifying binders. Acid compounds have also been used to modify the asphalt binders and extend the temperature range at which they will perform. The most prominent of these is polyphosphoric acid. The addition of polyphosphoric acid will increase the high temperature stiffness of the binder, thereby increasing the high temperature grade. The one concern with acid modification is that in some cases it can be reversible.
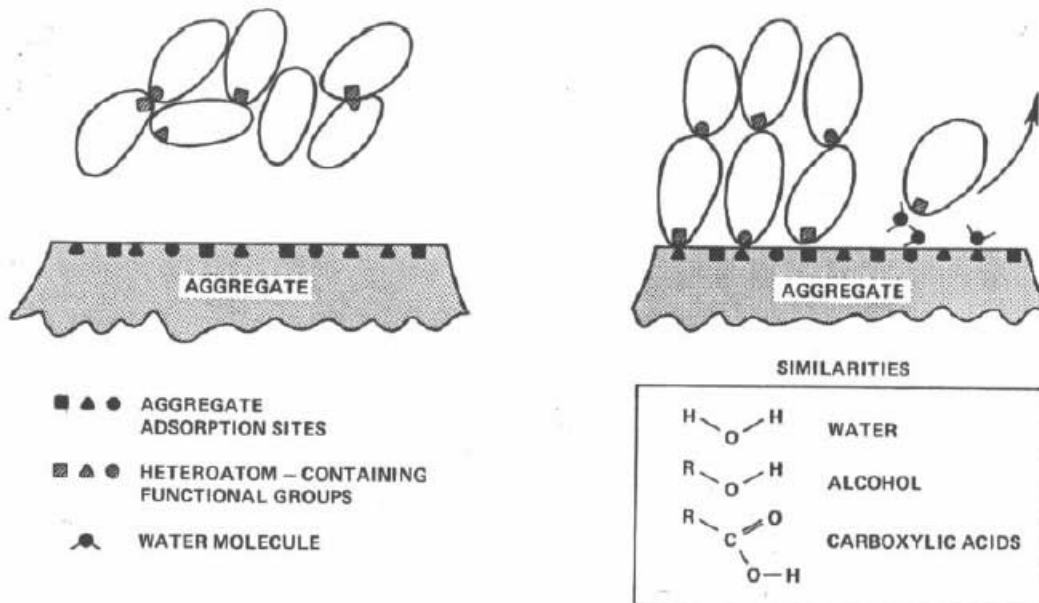

FIGURE 2 Molecular bonding sites of asphalt on aggregates being displaced by water (*4*).

In field applications, there have been occasions in which the acid modification process has been reversible (*5–7*). On several projects in which acid was used as a modifier and an amine antistripping agent was added at the plant site, dramatic changes took place. The amine neutralized the acid, resulting in a softening of the binder. Additionally, the amine antistripping agent was neutralized, which allowed stripping damage to occur in the mix.

During the past 2 years, extensive studies have been done to evaluate acid modification. Several have indicated that the acid modification process is reversible. In these studies, binders modified with acid would revert to the base asphalt binder properties when amine antistripping agents were added. Several other studies indicated that when small amounts of acid, 0.5% by weight of binder, were used to act as stabilizers in polymer-modified asphalts, the changes were not reversible even when hydrated lime was added to the binder as an antistripping agent.

Caustics

Caustics used in the refining process will also cause problems with moisture damage. As noted, most crude oils are acidic. The amount of acidity varies depending on the source of the crude oil. In some locations, sodium hydroxide has been used to lower the pH of the crude, to reduce corrosion of the plumbing at the refinery. Sodium hydroxide is a salt highly soluble in water and one known to act as a strong emulsifier in asphalt binder. If the crude oil is not desalted after the caustic treatment, these salts will remain in the crude oil and end up in the asphalt binder (*4*).

Caustics have also been used to increase the high temperature grade of the binder (*8*). Sodium hydroxide has been used as an agent to create large polar molecules to modify asphalt binder and increase stiffness. When sodium hydroxide is used as a stiffening agent, the caustic salts are left in the asphalt. As noted, these salts are strong emulsifiers and have caused stripping in asphalt mixtures. The use of this type of system to modify asphalt has been discontinued because of extensive problems with corrosion of aluminum tanks.

AGGREGATE PRODUCTION

Minerals

The chemical makeup of aggregates is as complex as that of asphalt. This is demonstrated in Table 1 (*9*). The chemical composition of several aggregates used in the SHRP research is listed along with surface area determinations. These aggregates cover a wide variety of mineralogical composition representing many of the aggregates used across the country.

Depending on the source of aggregate, there is a predominate compound that makes up that aggregate. Silicon dioxide or calcium carbonate is the predominant compound found in most aggregates. As seen in Table 1, one or the other of these compounds makes up a major portion of the aggregate. Those aggregates that are primarily made up of silicon dioxide are typically acid, and those that are primarily calcium carbonate are typically basic. Figure 3 graphically shows the acid-base makeup of typical aggregate used in the United States.
The bonding of the asphalt acid-based molecules to the base molecules of the aggregate has been put forward as the primary form of adhesion for hot-mix asphalt (*10*). However, this acid-base bonding of asphalt to aggregate is not the only important factor in moisture damage (*1, 2*). The physical properties of the aggregate are also important in the asphalt-aggregate bond. The porosity and surface texture will affect the mechanical bond between the asphalt and aggregate (*1, 11*). Aggregates with rough surface texture or a high amount of surface pores, or

TABLE 1 Mineral Composition of the MRL Aggregate Used in SHRP Research (*9*)

| Sample	RA Granite	RB Granite	RC Limestone	RD Limestone	RE Gravel	RF Glacial Gravel	RG Sandstone	RH Greywacke	RJ Gravel	RK Basalt	RL Gravel
SiO_2	73.4	56.2	6.49	16.4	93.7	15.8	52.8	66.0	76.5	50.1	63.1
Al_2O_3	13.4	19.8	1.23	2.28	1.86	1.89	2.27	10.4	12.2	13.7	4.66
Fe_2O_3	2.24	6.49	0.78	0.80	1.46	1.17	0.72	12.9	1.09	15.0	1.67
MgO	0.49	2.60	2.52	5.29	0.31	16.7	0.35	2.44	0.27	6.88	0.32
CaO	1.24	8.87	48.9	39.1	0.42	25.9	23.78	2.35	1.45	10.3	14.5
Na_2O	3.41	3.04	0.24	0.16	0.18	0.41	<0.15	2.57	2.91	2.25	0.92
K_2O	4.92	0.44	0.22	1.16	0.23	0.52	0.88	0.99	4.31	0.62	1.72
TiO_2	0.22	0.51	0.03	0.06	0.09	0.08	0.14	0.53	0.07	1.48	0.09
P_2O_5	<0.05	0.06	<0.05	<0.05	<0.05	<0.05	<0.05	0.13	0.09	0.22	0.05
MnO_2	0.05	0.12	<0.02	<0.02	<0.02	0.03	0.04	0.20	<0.02	0.21	<0.02
LOI	0.22	1.98	40.3	35.0	0.43	37.4	18.7	0.96	0.59	−0.36	11.2
Total	99.59	100.11	100.71	100.25	98.75	99.95	99.88	99.47	99.48	100.4	98.23
MRL Surface Area, m³/g	0.19	1.62	2.90	0.72	0.95	1.66	1.99	2.74	1.32	15.73	2.41
Surface Area for −35 to 50 mesh, m³/g			1.78					3.12		17.4	0.93
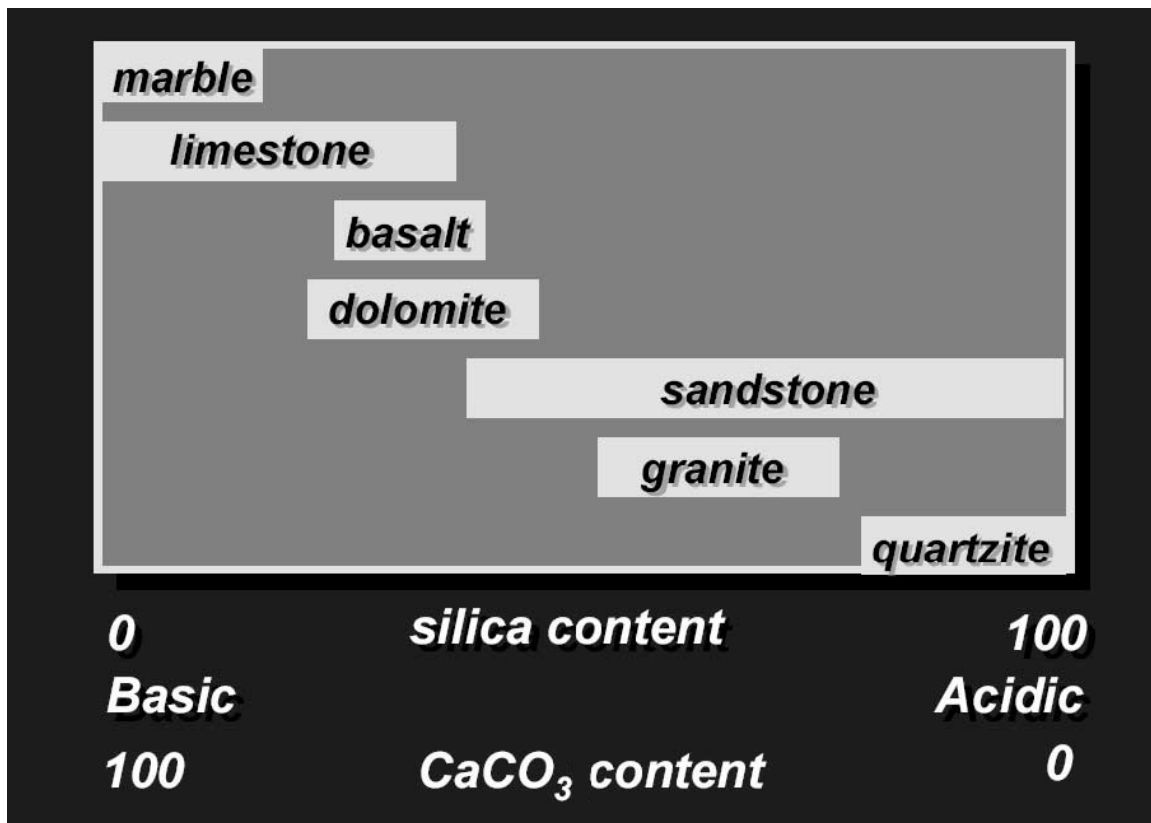
FIGURE 3 Acid-base composition of typical aggregates (*10*).

both, will increase the moisture damage resistance of the asphalt mixture. Aggregates with rough surfaces and high voids provide more surface area for the asphalt to bond to.

Many of the silicate aggregates have low porosity or smooth surface texture, but this is not always the case. Some granites do have very high surface texture and can create good mechanical bonding, but those factors may not be enough to overcome problems with chemical bonds. Not all limestone aggregates have good chemical sites or texture for bonding to the asphalt. Some limestones contain high amounts of calcite. The calcite locks up the calcium carbonate so it is not available for bonding to the asphalt (*4*) and can reduce the aggregate surface area.

Dirty Aggregate

There are many factors that affect the bond between asphalt and aggregate. Chemical bonding, as well as mechanical bonding, has been shown to be important to moisture damage resistance, but it is not the only type of bonding that affects moisture damage.   In the crushing process, dust is generated. The nature and extent of the dust can have a major effect on the moisture damage potential of the hot mix.

Dusty and dirty aggregate can promote moisture damage. Dust coating on the aggregate can prevent the asphalt binder from bonding directly to the surface of the aggregate. Asphalt by osmosis does allow water to pass through it (*8*, *10*). Consequently, water can get between the binder and the surface of the stone, stripping the asphalt from the aggregate surface.

The production process for HMA is affected by dust on the aggregate. In a hot-mix drum plant, the aggregate is heated and dried as it passes through the drum-dryer. Aggregate that is coated with dust will slow the process of allowing the water to escape from the center of the aggregate. In these cases, the asphalt is prevented from bonding well to the surface of the stone by the dust, and then the moisture in the aggregate weakens the bond as it escapes slowly from the mix, a situation shown in Figure 4. This problem is only significant when large amounts of dust are covering the aggregate. All processed aggregate will have some amount of dust, but only when it is caked on does the dust create a real problem with moisture damage.

There are cases when even small amounts of dust can cause a problem. This happens when the dust is made up of small claylike particles. Clay can actually act as an emulsifier (*2*, *3*). Clay will expand in the presence of water, and the expanded clay can lift the asphalt off the surface of the aggregate. If this is combined with the action of traffic, the clay will emulsify the asphalt in the mix and cause severe stripping. This is why it is critical that clay not be allowed in the mix. In some cases, clay is generated in the crushing process. Gravel aggregate may have shale mixed in. When crushed, the shale can break down, reverting to clay and getting into the mix. Figure 5 shows a gravel deposit with large amounts of shale mixed in.

MIXTURE TYPE AND DESIGN CONSIDERATIONS

In addition to materials (aggregates and asphalt binder), the selection of the type of asphalt mixture that will be used on a given project may have an influence on the moisture susceptibility of the asphalt mixture. The three general categories of mixture types are dense graded, gap graded, and open graded.

The most commonly used asphalt mixture type in the United States is the dense-graded asphalt mixture. The *HMA Pavement Mix Type Selection Guide* (*12*) notes that dense-graded asphalt mixtures are "considered the workhorse of HMA, since they may be used effectively in
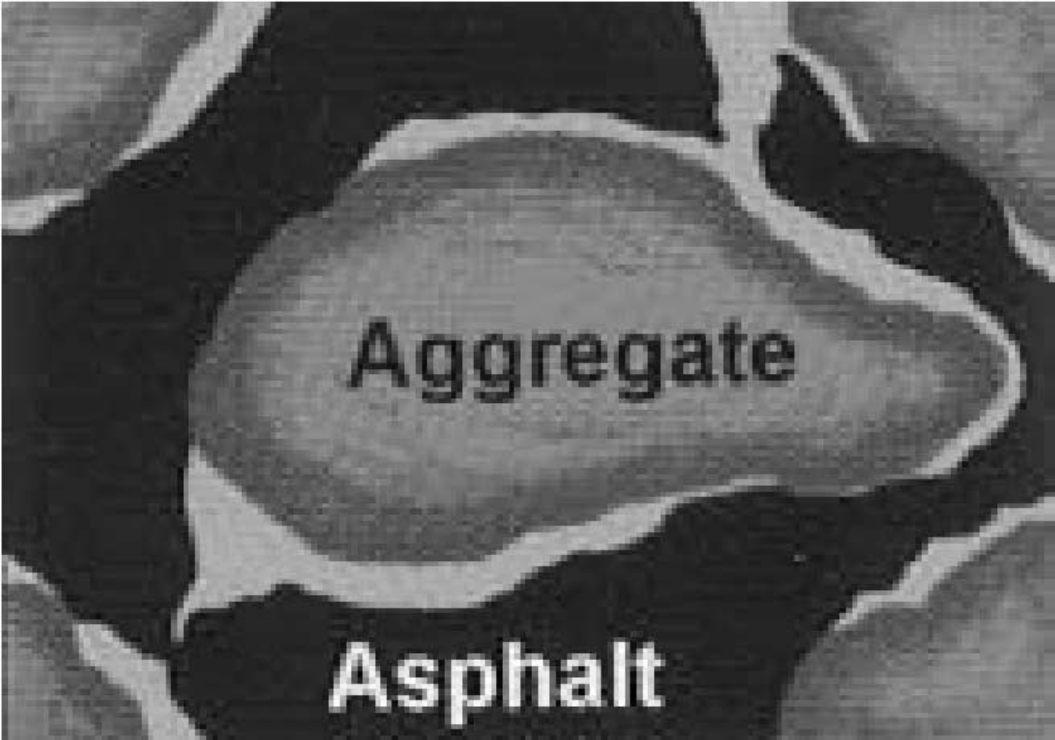
FIGURE 4 Asphalt separated from the surface of the aggregate.

FIGURE 5 Gravel aggregate with large quantities of shale.

all pavement layers, for all traffic conditions." Dense-graded mixtures may be classified generally as either fine or coarse mixtures, with the definition based on the percentage of the combined gradation on the 2.36-mm sieve (or 4.75-mm sieve for mixtures with a nominal maximum aggregate size of 25 mm or 37.5 mm) compared with the defined maximum density line. Generally, mixtures with a gradation having a higher percentage passing the 2.36-mm sieve than the maximum density line are considered fine-graded mixtures. These mixtures are usually well graded with a continuous distribution of particle sizes. Figures 6 and 7 are examples of dense-graded mixtures that are considered fine and coarse, respectively.

Stone matrix asphalt (SMA) is a type of gap-graded asphalt mixture that is used most often as a premium surface (wearing) course mixture for high-volume roadways. By definition, gap-graded mixtures do not maintain a continuous grading (like dense-graded mixtures), but have a "gap" in the gradation where there is a predominance of single-sized material (material retained on one or two sieves). As shown in Figure 8, this SMA gradation has over 50% of its combined aggregate pass the 12.5-mm sieve, but it is retained on the 4.75-mm sieve. Another characteristic of the SMA is the high dust content compared with those of the dense-graded mixtures. The high dust content allows the matrix (manufactured sand, mineral filler, asphalt binder, and additives) to be stiff, thereby assisting in the rutting resistance of the asphalt mixture.

The last general category of asphalt mixture type is the open-graded asphalt mixture. The open-graded friction course (OGFC) is the most common open-graded mixture type used in the United States for surface courses (*12*). The asphalt-treated permeable base (ATPB) is an open-graded mixture that is used as a base course to assist with drainage of water from below the pavement surface. The OGFC is a permeable layer that allows water to quickly pass through the pavement surface for drainage. The ATPB also allows water to be quickly drained from the pavement structure.
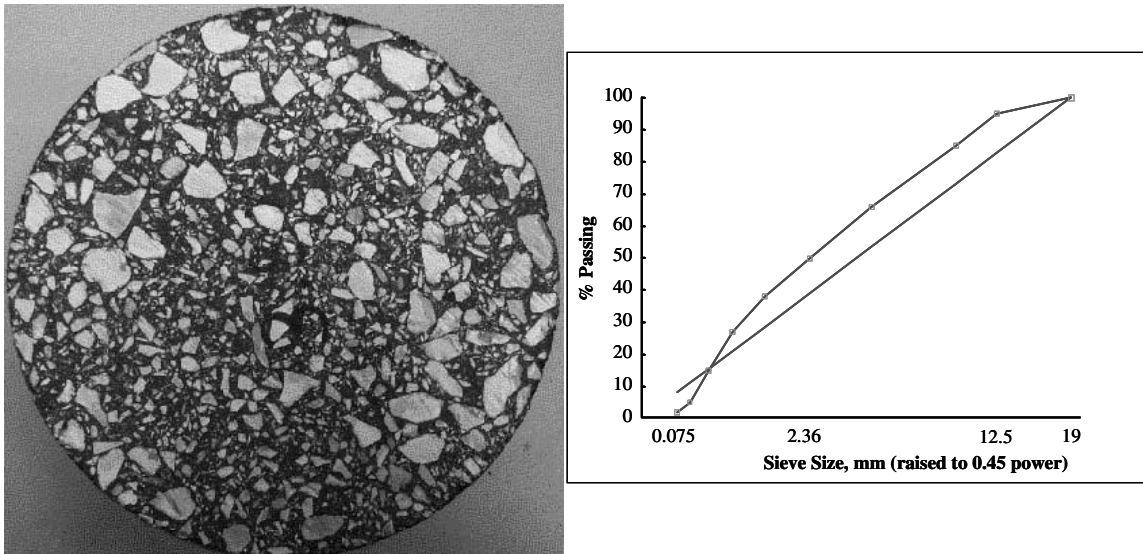

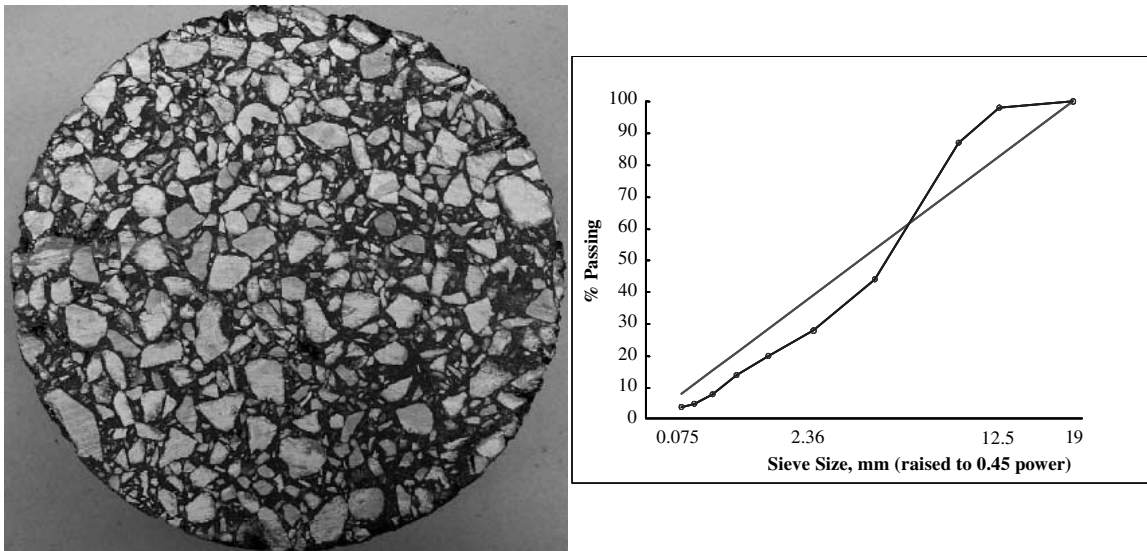**FIGURE 6 Dense-graded asphalt mixture (12.5-mm fine).**

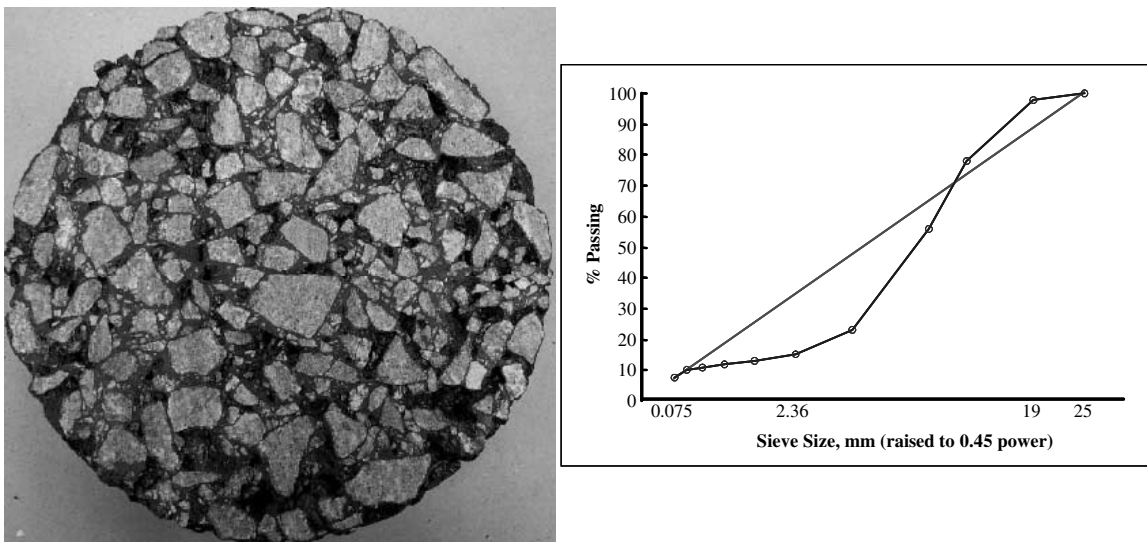**FIGURE 7 Dense-graded asphalt mixture (12.5-mm coarse).**

FIGURE 8 Gap-graded asphalt mixture (19-mm SMA).

Of the three major mixture types (dense-graded, SMA, and OGFC), moisture damage is least likely to be associated with SMA for several reasons that will be outlined in the following section. Even though dense-graded and OGFC mixtures may be more likely, in general, to be associated with stripping problems than SMA mixtures are, it does not mean that these mixtures cannot be effectively used without exhibiting moisture damage.

Causes of Stripping Related to Mixture Design

The selection of material—aggregates and asphalt binder—has a large impact on the stripping potential of an asphalt mixture. Likewise, the type of asphalt mixture required by the project influences the material selection. Because it is considered a premium mixture for high-volume roadways, the SMA mixture uses high-quality crushed aggregate for both the coarse and fine portions of the mixture. The crushed fine aggregate is combined with mineral filler and, if required, fibers to produce a stiff matrix. In many cases, user agencies will also increase the grade of the asphalt binder to compensate for the high traffic loading. This may result in a premium asphalt binder, such as a polymer-modified asphalt, being used in the mixture. The combination of high-quality crushed aggregate and premium asphalt binder grade helps lessen the possibility of stripping problems in SMA mixtures compared with other mixture types.

Another potential cause of stripping related to mixture design is excess dust coating of the aggregates. Both the National Asphalt Pavement Association (NAPA) and Asphalt Institute (AI) recognize that dust coating of the aggregates can inhibit the adhesion of the asphalt binder, thereby allowing water to penetrate to the aggregate surface (*13*, *14*). This is a problem most associated with dense-graded mixtures using crushed aggregates (particularly limestone).

Although SMA mixtures have a much higher total dust content than dense-graded mixtures do, they are not expected to experience this same problem as dense-graded mixtures. The principal reason that high dust content could negatively affect dense-graded mixtures, but not SMA mixtures, is that the SMA mixture, being gap graded, has a high percentage of voids in the mineral aggregate compared with the dense-graded mixtures. Usually high dust content reduces the void space in the combined aggregate. This void space, identified as the percentage of voids in the mineral aggregate or VMA, is the total volume in a combined aggregate that is available for air voids and asphalt binder. A mixture that is expected to perform adequately in service must balance the volume of air voids and the volume of asphalt binder for rutting resistance and durability.

Because of the gap-graded nature of an SMA, the VMA remains high even though the dust content is high. Assuming that the percentage of air voids stays the same in both SMA and dense-graded mixtures, the SMA mixture will have a higher volume of asphalt binder, or a thicker film coating on the aggregates compared with the dense-graded mixture. This reduces the potential of water penetrating the asphalt film.

By contrast, a high dust content in a dense-graded mixture typically reduces the VMA of the mixture. At the same percentage of air voids, the dense-graded mixture will have a lower volume of asphalt binder (thinner film coating on the aggregates) than will an SMA mixture. This increases the potential of water penetrating the asphalt film.

Because VMA is the total volume of void space in the aggregate structure, it changes based on the compaction effort used. At high compaction levels, such as those used to simulate heavy traffic loading, the aggregates are packed together more tightly, leaving less room for air voids and asphalt binder. Because the percentage of air voids is usually fixed, the volume of

asphalt binder used in the mixture must decrease as the compaction effort increases, to maintain the same VMA.

Not all mix design methods use the same compaction effort for mixtures. For instance, a mixture designed using the Marshall mix design procedure for heavy traffic requires 75 blows per side of the specimen with the Marshall compaction hammer (*15*). The same mix designed for medium traffic only requires 50 blows per side. Assuming that both mixes are designed at the same percentage of air voids and VMA, the mix designed using 50 blows will have a higher volume of asphalt binder (asphalt binder content) than the same mix designed using 75 blows. Similarly, mixes designed by the Superpave® mix design method using 75 gyrations will have a higher asphalt binder content than the same mix designed using 125 gyrations (again, assuming the same percentage of air voids and VMA). In both cases, the mixes with the lower asphalt binder content will have a lower film thickness, plus an increased potential for water penetrating the asphalt film to the aggregate surface. Excess dust on the aggregates and in the mixture can exacerbate this condition.

Causes of Stripping Related to Construction
The major construction variable that can increase the stripping potential of an asphalt mixture in service is compaction (*13*). It is generally accepted from various studies that air voids are not interconnected when there are less than 4% to 5% air voids in the mixture. This value depends somewhat on the type of mixture, because the connectivity of the air voids in a fine dense-graded mixture may be different than in a coarse dense-graded mixture.

Generally, user agencies specify that the compacted asphalt mixture must have at least 8% air voids in place immediately after construction. The mixture is then assumed to densify normally under traffic to its final percentage of air voids (approximately 4%) after a few years of traffic loading.

The SHRP A-003A researchers at Oregon State University proposed the concept of a "pessimum" (defined as the opposite of "optimum") voids content in an asphalt mixture that relates to its stripping potential (*16*). At low percentages of air voids (less than 4% to 5%), the voids are not connected and the potential for water intrusion and stripping is low. At high percentages of air voids (greater than 15% to 20%), the voids are interconnected such that the mixture is free draining. In between these percentages of air voids (greater than 5% and less than 15%) is the pessimum range, where some of the air voids are interconnected and water may become trapped in the mixture, thereby increasing its stripping potential. This concept is illustrated in Figure 9.

Unfortunately, most mixtures are constructed near the middle of this pessimum range, causing an increase in stripping potential early in the pavement life. After several years of traffic, the mix is assumed to densify normally to the impermeable range (4% to 5%). However, if the mixture does not densify as expected, the mixture will be left with high enough air voids to still be in the pessimum range. This lack of expected densification can be caused by several factors including the following:

- The asphalt binder is too stiff (or modified) to allow normal densification for the climate and traffic.
- The laboratory compaction effort is too high for the traffic loading, resulting in a "harsh" mixture (low asphalt binder content).
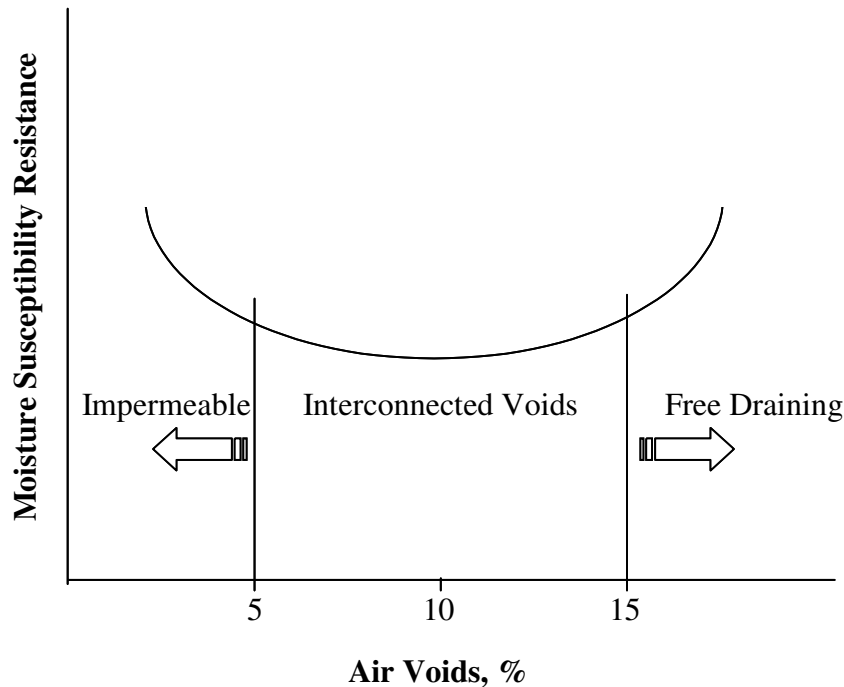
FIGURE 9 SHRP A-003A research concept of pessimum air voids.

       Thus, proper selection of materials and mix design procedures in the design phase has an important impact on the percentage of air voids after initial compaction and densification under traffic.

       For all mixture types, adequate compaction is important. However, by nature, SMA mixtures are often tighter (have lower air voids in place) and impervious immediately after compaction than are typical dense-graded mixtures. By contrast, OGFC mixtures have a much higher percentage of air voids in place to permit adequate drainage. In either case, the SMA and OGFC mixtures are more likely to be outside of the pessimum air voids range suggested by the SHRP A-003A researchers than are dense-graded mixtures.

       Another variable that may have an impact on the stripping resistance of a mixture is residual moisture in the aggregate after being processed through the mixing facility. Aggregates with moisture retained after passing through the dryer may affect the adhesion of the asphalt binder to the surface of the aggregate.

PAVEMENT DESIGN CONSIDERATIONS
The most important pavement design variable that affects the moisture damage potential of an asphalt mixture is pavement drainage. The conclusion to AI's ES-10, *Cause and Prevention of Stripping in Asphalt Pavements*, treats the stripping problem quite simply as "water is the culprit causing stripping. Anything that allows it to stay around long enough to damage the pavement is an accomplice" (*14*). This same publication notes that "It has been observed that asphalt pavements over untreated granular bases *with well-designed and properly operating drainage* have not stripped, even when made with aggregates that are prone to stripping." NAPA's QIP 119, *Moisture Susceptibility of HMA Mixes: Identification of Problem and Recommended Solutions*, notes that "Kandhal et. al. (*17*) have reported case histories where the stripping was not a general phenomenon occurring on the entire project, but rather a localized phenomenon in

areas of the project over-saturated with water and/or water vapor due to inadequate subsurface drainage conditions" (*13*).

More recently, NCHRP published the key findings from the NCHRP 1-34 project, *Research Results Digest No. 268: Performance of Subsurface Pavement Drainage*. This research summarized the effects of subsurface drainage on flexible pavements. In one conclusion, it was stated, "The inability to drain a permeable layer leads to increased fatigue cracking and rutting; increased stripping may also result" (*18*).

Because water and water vapor may move in both vertical directions—down by gravity and up by capillary action—it is important that designers be aware of these concerns when selecting mix types. For instance, it may be advantageous to use an ATPB (a type of open-graded mixture used as a base course) as the bottom layer in a pavement structure. This permeable layer may allow water to escape from the pavement structure more quickly than does a conventional unbound dense aggregate base.

OGFC mixtures, likewise, should be selected in conjunction with the underlying mixture types. Because the OGFC allows water to pass down through the surface to the underlying mixture, it is important that the lower layer mixture be well compacted and impermeable. Otherwise, the OGFC mixture may simply channel water into the semipermeable mixture, and, following the repeated loading of traffic, allow the water to rapidly scour the lower layer mixture, resulting in stripping. By contrast, the use of seal coats on the surface may create an impermeable barrier, trapping water in the underlying layers.

The pavement designer should be aware of these potential problems of trapping moisture when selecting mixture types for the project. After all, it seems logical that the simple truth stated from the first paragraph in this section is the most important: do not let the water stay in the pavement system and the potential for moisture damage will be greatly reduced.

CONCLUSIONS AND RECOMMENDATIONS

Moisture damage can be a significant problem that severely shortens a pavement's life. The causes of moisture damage are many and varied, ranging from the basic materials to the design and construction process. Thus, it is critical that each aspect of the production process be managed properly.

Asphalt binders are produced from crude oils that contain materials that can cause moisture damage problems. These are natural salts that, when exposed to water and mechanical action such as traffic, can cause the asphalt to emulsify and strip from the aggregate.

Asphalt modification, depending on how it is done, can also aggravate moisture damage problems. Acids and caustics have been used to stiffen the binder to improve high temperature rut resistance. Depending on the nature of the crude and the extent of the modification, these methods can be effective in improving the binder or can create binders that may react with other additives to cause stripping.

To avoid such situations, it is very important that the binder be tested with all additives in it, including binder modifiers for performance and any antistripping agents. If there is an interaction between the different modifiers, the only way to identify it is through testing with all additives included.

Even more critical in determining if the mix is susceptible to moisture damage is evaluating the binder aggregate combination. The only way to determine if the aggregate will provide good bonding sites for the binder is to measure the mixture properties. Even limestone

aggregate can have problems with moisture damage if the calcium carbonate is locked up by calcite.

Tests for clay should be performed on the crushed aggregate as it is to be used in the mix. Clay can come from many sources, and the only way to ensure that it does not get into the mix is to test for its presence in the combined aggregate as it is delivered to the plant site.

Asphalt technologists should be aware of the potential effects of mixture type on stripping potential in a pavement structure. Judicious selection of appropriate mix types for the project can help minimize the potential for moisture damage in the pavement structure.

Finally, adequate compaction and pavement drainage are needed to ensure that water entering the pavement structure will have an opportunity to leave before causing significant damage.

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Questions and Answers

JOHN D'ANGELO
FHWA, Speaker

Q1—Gayle King, Koch Pavement Solutions
John, excellent presentation! You've addressed a lot of important issues. Your point regarding inappropriate application of chip seals to seal moisture into the pavement brings back some particularly unpleasant learning experiences from the past. More importantly, you've really captured some of the pressing binder chemistry issues we don't handle well as an industry. I've followed four projects in which surface mixes failed due to stripping within 8 months, and each was caused by specific binder chemistry problems. In each case, good performance was achievable when other binders of similar grade were substituted for the problem material. Although each failure was related to binder chemistry, the causes were different. One was an acid/amine compatibility problem, one was a crude source problem, one was caused by the addition of absurdly high concentrations of emulsifiers, and the fourth is still under investigation. Three of these projects were built using the current AASHTO T283 or agency equivalents thereof. One was CDOT's project on Copper Mountain, with more recent failures about 2 years ago in Oklahoma and last year in Nebraska. In all cases, Hamburg wheel tracking indicated disintegrator mixes, and the binder always showed some signs of reemulsification. To make an emulsion, one needs asphalt, an emulsifier (chemical salt, surface active clay), water, heat, and mechanical energy. In mixes, mechanical energy creates pore pressure, and the resulting shear stresses cause the binder to strip/emulsify. No mechanical energy, no emulsion. We are consistently missing such stripping mechanisms with T283. Wet wheel-tracking tests can predict these problems. For example, when clay acts as the asphalt emulsifier, Hamburg tends to cause much more damage than might be presumed from static immersion tests. Aschenbrener's and Kandahl's Hamburg/methylene blue studies emphasize this point. I apologize for the long comment, but I believe we are missing critical stripping mechanisms by relying on laboratory tests that do not create damage caused by pore pressure.

A—John D'Angelo
Thank you, Gayle. I'll have to sort of agree with you. I agree that the existing AASHTO T283 doesn't have any mechanical action per se and it doesn't cause the problem where you can get reemulsification of the asphalt. Also, the pore pressures cause some of the separations of asphalt from the aggregate even if it's not emulsification. I think it's critical to have the mechanical action. I'm not a big fan of the Hamburg, though, because I think it's too severe a test. If it passes with the Hamburg test, you've probably got a pretty indestructible mix. I'll grant you that one, but it might be a little too severe. That's why I'm holding great hopes for the NCHRP 9-34 procedure.

Q2—Bill Bailey, Rock Binders
I've always wondered over the years—you had an excellent slide here, by the way—why the ratios of the tensile strength numbers being high didn't really relate to the control, on the control

being 800 tensile strength and then the ratio failing but the failing tensile strength would be 800 or higher because the original in that failing sample would be higher. Nobody's ever really addressed that. I'm just a kind of dumb old country boy who doesn't understand a lot of this so I appreciate your letting me be here. I do understand mathematically that if you take the square feet of a ton of mix and measure it for the area, 5 microns will cover that substantially. But anyway, I'd like answers to the other questions.

A—John D'Angelo
In the development of the tensile strengths ratio, that was one of the things that was a relatively easy test, the indirect tensile strength of a mix. You can do it with some very simple equipment and you get a result. One of the best ways to look at the response of the material between an unconditioned and a conditioned was to evaluate the ratio between the strengths. The next issue is how do you then add the effect of the overall total strength of the mixture. To do this, it becomes a lot more complicated. Some states have put minimum strength requirements on the mix, so that if you don't get a minimum strength, you won't pass the test. No one has figured out how to really address that issue of total strength, unless you go into some of the other criteria. You're looking at things like modulus, which then makes the test much more difficult to run.

Q3—Dick Root, Root Pavement Technology
Just a quick comment. When we start fooling around with allowing a reasonable level of air voids to work with and you start taking absolute tensile strengths, then if you did have 6% air voids versus 8%, you had noncomparable results. So we ignored absolute tensile strength and looked at the ratios for that very reason.

Q4—Bob Humer, Asphalt Institute
First of all, John, thank you very much for an excellent paper. I really appreciate your stressing some of the very basic points as a first line of defense against moisture sensitivity. If we can't do those basic things right, then maybe after that there is some chemical stuff we can look at. Especially stressing good mix design, good compaction, and proper lift thickness to get compaction. One of your slides shows the minimum lift thickness and a maximum lift thickness. The minimum we've talked about, so we don't have to argue about the three times the nominal maximum aggregate size. But you have a maximum lift thickness there of five times the nominal maximum aggregate size. Where does that come from, and why is there such a maximum limit, other than for compaction energy? Why would there be such a tight limit on the maximum lift thickness?

A—John D'Angelo
On the maximum of five times the nominal aggregate size, that's typically the relationship for coarser-graded mixes. What you have there is when there is a lot more of the stone or the stone content as a larger percentage of the materials, you have to be careful. When the lift thicknesses for coarse-graded mixes get a little bit too high, they'll have a tendency to push around some. It's almost like pessimum voids with permeability. If you get too much lift thickness in these very coarse-graded mixes, they'll have a tendency to shove around significantly and even uncompact themselves, so you have to be careful with that. Again, it depends on the type of mixtures you have. I know the French typically use a dense-graded mix in a lot of the work that they do. They actually go up to seven times the normal maximum aggregate size. However, they don't usually use these very coarse-graded mixes. The contractors won't want to work in France,

because I guarantee you, as contractors, you'd hate it. The French will tell you exactly the lift thickness, the type of roller you'll have, how many passes to make to compact the mix, and then they'll hold you to the compaction.

Q5—Don Goss, Valero
Thank you, John, for your presentation. I thought you included a lot of good information. I just have a couple comments to make. One, earlier in the presentation you mentioned asphalt as the bottom of the barrel of the crude, and you implied that maybe it was waste material, and that hurt, John!

A—John D'Angelo
I would never really consider it waste.

Q6—Don Goss, Valero
Just for the record, there are other uses for the material—as a base oil in marine fuel, of course, in roofing products, and as coker feed, which would create a higher fuel yield from the barrel of crude. So, I just wanted to make that comment, and say that with the development of a lot of the recent tests that reflect the fundamental engineering properties of the binder, many of us who produce asphalt consider it no longer as a by-product but as an engineered product in its own right, and we think it's a very valuable material. I guess on a little bit more serious note, with respect to testing the binder with everything in it, I think you make a good point in respect to grading the binder. With respect to reflecting moisture sensitivity, I just want to comment that I think it is important that we test the mix because the binder may not contain everything that's going to impact moisture sensitivity. Thank you for allowing me to comment.

A—John D'Angelo
I agree with you wholeheartedly. Basically, I tried to stress through the whole presentation that you want to test all the products, and more important than anything it's the final product, the hot-mix asphalt on the roads, that's key to test. You've got to look at the details of the components, but most important of all, you have to look at how they go together and what the product looks like as it's going to be used.

Q7—Dale Rand, Texas Department of Transportation
Two quick comments. We've seen over the last couple of years a problem with the TSR, particularly with the polymer-modified asphalts. For example, you can have a wet strength that is 150 psi and yet the mix still fails the tensile strength ratio. This has been a big problem and a big frustration. I know from the industry side and from the TxDOT side trying to get tests that pass when we are at the same time pushing the use of more and more polymer-modified asphalts in the applications for high-traffic areas. When you take a test that's got 25% variability and you start adding all these polymers and lime to it and all these other additives, it's been a big frustration for us. So for whatever it's worth, we made the decision never to run that test again and we had zero opposition from industry or TxDOT. We were waiting for somebody to say, "Wait, you are doing the wrong thing." The other comment I wanted to make was on your concern about the Hamburg being too severe a test. I'd go back to what you said about one size does not fit all. With the Hamburg and what we are doing now, one criterion does not fit all also.

You really have to look at it based on the PG grade of the asphalt. Anyway, I just wanted to comment on it.

A—John D'Angelo
Thank you, Dale. I'm not trying to attack the Hamburg. I used tensile strength for the slides because that's the data we have for the most part. Though I'm not a fan of the Hamburg test, I don't think that the TSR is the answer, but it's what's being used today predominantly because we have a lot of data on it. The ultimate test will have some kind of mechanical action. You've elected to use the Hamburg and work with it. That test has its problems, too; that's why I want to continue to look for something new. Of course, my thing is that I'm sort of into research and technology transfer. I'm always looking for something new; nothing is good enough for me. I always have to find something new. Otherwise, I'd be out of a job or I'd be bored.

Q8—Gayle King, Koch Pavement Solutions
Run your 1.2% acids through the Hamburg. I predict you won't like the results.

A—John D'Angelo
I'm not saying they are good or bad. Go ahead, Tim.

Q9—Tim Aschenbrener, Colorado Department of Transportation
I had a question regarding the pavement design, and I didn't see it covered in this area, but I think it's really critical. I was wondering if you could make a few comments on the importance of an aggregate base course.

A—John D'Angelo
Are you talking about just the general graded aggregate base?

Q10—Tim Aschenbrener, Colorado Department of Transportation
Yes. Our asphalt industry conducted a survey of the 10 best-performing asphalt pavements in Colorado and came up with a series of lessons learned. One of the common features in all those pavements was the existence of an aggregate base course between the subgrade and the asphalt pavement. In areas where we constructed full depth asphalt on the subgrade, we continuously found severe moisture damage at that interface. Where aggregate base course existed, it did not. So when repair is needed to the full depth asphalt, it is extremely expensive. So I think one area that is critical in the pavement design is to ensure that good-quality aggregate base course is in place.

A—John D'Angelo
There has been a lot of discussion on specifically base type and moisture damage. Should the pavement be full depth asphalt with a black base or a thinner asphalt layer with an aggregate base? To address the problem with moisture, an asphalt permeable base that's the drainage layer to make sure you don't have the moisture that's being brought up from the subgrade, which causes significant problems, was developed. That's one of the approaches taken to address that problem. Then again, even with aggregate bases, you run into problems with drainage. You have to be sure you have a good drainage layer to get that water out of that base or it can cause significant problems, either full depth asphalt or aggregate. There are different ways to tackle any one of these issues. I don't know if the issue is if it's good to have an aggregate base. I think

it's better to not have a lot of moisture sitting in a layer that has high stresses, and if you are at the bottom of that asphalt layer, that's where the stresses start to develop. Probably some of the aggregate bases are reasonable in making sure that layer doesn't stay saturated continuously, I would guess.

Q11—Bob Rea, Nebraska Department of Roads
We use a lot of liquid antistrips and plan on using them a lot more in the future also, but we also agree with your concern that early on we saw a lot of the tensile strength ratios get much tighter with the liquid antistrips, but at the same time they were lowering the tensile strength of the mix. Just wondered if there are some threshold values that one would look at for a minimum tensile strength and then use a ratio from there or anything like that.

A—John D'Angelo
Well, there is not really a minimum ratio. I think Jim Anagnos sort of talked about that. Originally, a lot of these liquid antistrips would soften the asphalt and you would get better ratios, but they actually softened the asphalt, and that is part of what caused the problem with lower tensile strengths. That's why if you are going to use liquid antistrips, it is critical that you test the binder for the binder properties to make sure it meets specs with the liquid antistrip in it, to make sure you didn't soften the binder. He showed several slides earlier where the newer materials don't do that anymore, but that's based on a limited study. I would imagine there are some suppliers out there that are supplying things that will cause problems. To avoid that kind of problem involves more than just setting a minimum value for a tensile strength ratio. It is to make sure that binder you are testing to meet a certain stiffness value has the amine in it to make sure it's really not reducing that strength.