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A Literature Review of Liquid Antistripping And Tests for Measuring Stripping

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Introduction

The bonding between asphalt and aggregate is of special importance because it is the primary characteristic that influences the integrity of the pavement. This bonding must be established at the initial stages of contact between the asphalt and the aggregate and must endure during the lifetime of the pavement. Loss of bonding results in lowered performance. DiVito and Morris (1982) attribute concrete pavement strength to the "(1) cohesive resistance of the binder, (2) the adhesive bond between the binder and the aggregate, (3) the aggregate interlock and the frictional resistance between aggregate particles." A number of different methods have been used to strengthen the adhesion of asphalt to aggregate and to lower the pavement's propensity to strip from the intrusion of moisture. Some of the methods that have been used include addition of dry lime or portland cement to the mix or lime-slurry treatment of the aggregates, bitumen precoating of the aggregate, careful selection of aggregate using special mineral fillers or not allowing hydrophilic aggregates, washing or blending of aggregates, and addition of chemical antistripping agents (Divito and Morris 1982).

A review of the mechanisms of stripping of asphalt pavements has been performed by Taylor and Khosla (1983). They list five primary mechanisms that either act individually or together to cause the debonding of asphalt from aggregate. These mechanisms are:

(1) Detachment which is the separation caused by water of the asphalt film from the aggregate without any visual break in the asphalt film.
(2) Displacement which results from the intrusion of water to the aggregate surface through a break in the asphalt film or through the film itself.

(3) Spontaneous emulsion which is the formation of a inverted reversible emulsion at the aggregate.
(4) Pore pressure which is the increased pressure caused by circulation of trapped water through the void structure of the aggregate.
(5) Hydraulic scouring which occurs on surface courses because of a compression tension cycle caused by the interaction of tire pressure with surface water.

Of the different ways to minimize the effect of water on the pavement liquid antistripping agents are frequently used. The SHRP A-003B study of asphalt-aggregate interactions at the interface includes a section that evaluates the influence of antistripping agents on the chemistry of the interface. Hence the chemistry of the antistripping agents and the tests that have been used to evaluate their performance in asphalt-aggregate mixes are important background knowledge to performance of the research.

This review of the literature focuses upon the chemistry of the liquid amino base antistripping agents and mineral agents and their contribution to adhesion and resistance of the asphalt-aggregate bond from the intrusion of water. Tests that have been performed to evaluate these agents have also been reviewed. This review and the "Summary Report on Water Sensitivity" by Ronald L. Terrell (1990) of SHRP A-003A are complementary since the A-003A report focuses upon the "state of the practice" of water sensitivity in asphalt paving mixtures. This report provides an information background to the practice that Ronald Terrell so well describes.

Objective and Scope

The purpose of this literature review is to search the literature in the area of chemical and mineral agents used to promote adhesion of asphalt-aggregate mixes. In addition, tests performed to measure the effectiveness of these agents were reviewed. The information gained through this literature search and review provides valuable background information for the research being performed in the SHRP A-003B contract, particularly in Subtasks a1, a3, a6, a8 and a9. The review has been divided into three sections: (1) liquid antistripping agents; (2) lime and other mineral agents; and (3) tests for measuring stripping. The last section entitled "Implications of Research" states how the information gained can provide background and guidance for the research being performed in A-003B.

This literature search was performed using on-line chemical abstracts for documents in the time period of 1967 to present. Key words searched included adhesion, stripping, adhesive, antistrip, asphalt, bitumen, and aggregate.

Liquid Antistripping Agents

Liquid antistripping agents in the form of cationic surface-active agents, principally amines, have been used for many years. In 1964, Mathews (1964) reviewed the use of amines as cationic additives in bituminous road materials and explained the problems associated with each of the materials. At the time of this review, heat stable agents were not available and, hence, the development of a heat stable agent that could be kept in hot storage was essential to the future usage of the antistripping agents. The difficulty of determining the quantity of agent present was expressed. The correlation between the immersion wheel tracking test, the then best available test method, did not agree with full-scale experiments. However, this study found that cationic agents helped to adhere wet stone and bitumen and to prevent stripping. Some agents were more effective than others in specific applications because of differences in asphalt composition and aggregate surface condition.

A number of researchers have studied the effectiveness of antistripping agents on the adhesion of asphalt to different types of rock surfaces. Dybalski (1970) determined that the adhesion water-asphalt dispersions to sand as well as the resistance to leaching of asphalt from sand was improved by the following treatment: the addition of amine or quarterarnized amines of omega-phenylstearic acid to a mixture containing asphalt, Dupont 950 neoprene latex, water and N,N,N,N′,N′,-pentamethyl-N,N′-trimethylene-N-(phenyloctadecyl) diammonium chloride (I). The addition of component I to Ottawa sand resulted in 95% of the asphalt remaining after a one hour leaching compared to 40% for a system not containing I. Component I increased the rate of adhesion.

In a later study, Dybalski (1982) explained the role of cationic surfactants in asphalt adhesion. Two major types of surfactants are used as antistripping agents: fatty diamine/fatty acid salt and fatty amido-diamine/fatty acid salt. To make these materials thermally stable above 100°C the reactive amino hydrogens are chemically substituted with alkyl radicals, so that these materials can be stored at hot mix temperatures. The author pointed out the importance of having the correct or needed amount of antistripping agent to maximize the effectiveness of the agent as an adhesion agent. Overly high addition amounts may oversaturate the aggregate surface and result in weakening the bond. Dybalski (1982) suggested using water soluble cationic homologs of the oil soluble antistripping agents and applying these directly to the surface of the aggregates.

Russian workers (Kartashevskii et al. 1971) prepared additives from polyethylene polyamine and fatty acids ranging from C_12-C_20 at a 1:1 to 15:1 ratio at 160°C. These materials had a high thermal stability. The degree of adhesion required was controlled by varying the ratio of starting materials. Deutzmann et al. (1973) found that the addition of amines and/or amides and acids promoted good adhesion of bituminous materials to wet supports. The adhesion of asphaltic bitumens to aggregates was shown by Kratky (1972) to be also improved by the addition of imidazoline derivatives. Less additive was necessary when the aggregates were coated with an emulsion containing the additive. Sakuma (1972) found the adhesion of asphalt to gravels was improved by adding 0.3 to 0.5 wt% of the product from the reaction of 1 mole $RNHCH_2CH_2NH_2$ with 0.5 to 1.5 moles ethylene oxide where R is an aliphatic hydrocarbon radical of C12-C20. The adhesion was also improved by taking the 1 part product from the above reaction and adding 0.5 to 1.0 part carboxylic acid.

Brown and Swidler (1975) examined the effect of an adhesion agent having the formula $Me(CH_2)_x\ CH(R)(CH_2)_yCH_2NH_2$ in which $y > 3$, $x + y = 15$ and R is an aryl group for bituminous materials. These additives were prepared by alkylation of aromatic species with unsaturated fatty acids and converting the acid to an amine. When using naphthylstearylamine as a parent compound, several amines or diamines produced from it were shown to improve the adhesion of asphalt to aggregate. When naphthylstearyl amine and N,N,N-trimethyl-N-phenylstearylammonium chloride were combined, water removal resistance was improved to 80% and adhesion to 90% compared to 30% and 50%, respectively, for control tests.

The adhesion of asphalt to aggregate was improved by Hellsten et al. (1973) by the addition of alkyloxyalkyleneamines and alkanolamines. Gilmore and Kugele (1987) prepared adhesion promoting additives for asphalt for formaldehyde condensation with polyamines. Formaldehyde adducts with amines, polyamines and amides to yield the additives. These additives are typically introduced at a level of 0.2 to 2.0 or preferably 0.3 to 1.0 parts of additive per 100 parts (by weight) of asphalt. Conditions for the reaction conditions are given in the patent. These additives performed well resulting in high levels of adhesion between asphalt and mineral aggregate that were both hydrophilic and hydrophobic, or glass fibers or glass fiber mesh. An increase in the tensile strength of the asphalt coated filler was observed.

The adhesion of nonpolar bitumen to polar aggregates was improved by adding a compound containing N-alkylpropylenediamine, 1-aminoethylimidazoline or 2-alkyl-imidazoline (Porubszky and Dobozy, 1973). These compounds were more effective additives than those containing amides or alkylated tertiary polyalkylpolyamides.

In another study, Kartashevskii and Kashina (1973) discovered that the addition of 0.5 stearic acid and 3-octadecylamine to bitumen enhanced adhesion of the bitumen to marble and sand, respectively. Other additives also had good adhesion: anionic additives such as stearic acid and synthetic fatty acids; cationic additives and anionic-cationic additives.

Norbornane amino derivatives were added to bitumen that was mixed with sand and gravel (Katanoaka 1975). The asphalt with the norbornane derivative additive showed no desorption of the asphalt in 80°C after 5 hours in water while asphalt not containing the derivative showed 50% desorption.

Long chain amine derivatives, hydroxylalkylamines, were prepared by Smith and Joy (1980) by a condensation reaction of aliphatic aldehyde with alkanolamines in the presence of Raney nickel. They hydroxyalkylamines showed promise as adhesive agents for bituminous materials. In a patent, Dalter and Gilmore (1983) mixed bituminous materials and an antistripping containing a hydroxyalkylated polyamine. When an amount of 0.07 wt% hydroxyalkylated polyamine was added, the adherence of the asphalt to the aggregates was greater in the 10-minute boiling water test that 0.5 wt% of the commercial agent N,N-dimethylaminopropylamines and 0.33 wt% for epoxylated polyamines.

In a study in which the binder was composed of 30-60% blown asphalt, 35-70% diluents and 0.05 - 5% fatty acid esters, alkylamines, acrylamines, acrylaminoamides, substituted alkylimidazolines and N-alkyl-polypropylene polyamines, Buchta et al. (1982) found that a binder with 0.7 wt% N-alkylpolypropylenepolyamine adhered well to different wet and dry aggregates.

Chang and Treybig (1987) prepared a blend of bituminous materials and 0.05 -1.0 wt% of the reaction of $\geq$ 1 aldehyde with $\geq$ 1 organic amine, 1 organic polyamine and 1 or $\geq$ hydrohalides. Specifics concerning the preparation of the product are given in the patent. The addition of the additives resulted in 100% retention of the asphalt aggregate surfaces in boiling water while only 5% was retained without additive for the same length of time. Substantial improvement in retention after freeze-thaw, 40 versus 6%, were obtained.

Buocz and Nemedy (1987) evaluated the adhesion and elongation of bitumen-based fillers for airports and roads by adding 0.6 - 2.0 wt% of condensation products from linear polyamine with fatty acids. The product elongation was improved by 5% at -20°C and by 97% at +20°C.

Mullins (1988) increased the adhesion between a dolomitic-limestone aggregate (Utah Staker) and an AC-10 asphalt by adding a conventional antistripping agent and pretreating the aggregate surface with an acidic salt such as 0.01% $CaHPO_4$ and 0.01% H_3PO_4. The improvement is based on an amine-acid salt reaction at the asphalt-aggregate interface. The antistripping agent can consist of any commercial amine type agent while the salt should be a di- or trivalent metal of an inorganic acid and may also include its acid. The preferred metal is a divalent metal calcium and the preferred acid is phosphoric. Aggregates composed of quartzite, granite, chalcedony, feldspar, limestone, silicates, hornblende, quartz, jasper, agate, and rhyolite are suitable for use. The method for producing the desired effect consists of "coating the aggregate with a divalent or trivalent metal salt of an inorganic acid, drying the coated aggregate, admixing said dried aggregate with the asphalt containing an amine antistrip to form an insoluble reaction product at the interface between said asphalt and said aggregate in an amount sufficient to bind said asphalt to said aggregate." A substantial improvement was observed in that 15% stripping was observed with treatment while 90% was observed without treatment.

Gilmore and Kugele (1988) improved the physical properties of bitumen-aggregate combinations by either adding > 0.05 wt% of an antistripping agent composed of one or a combination of the following: imidazoles, polyamines, alkoxylated polyamines, aminocarboxylic esters, or amides-amines; or by adding $\geq$ 0.25 wt% of portland cement or by blending the antistripping agents with portland cement. To the asphalt was added 0.22 wt% bis (hexamethylene-triamine); to the aggregate was added 0.25 wt% portland cement. When added together with the additives, the dry and wet tensile strengths were higher than without the additives. These improvements are not seen when fly ash, hydrated limestone or limestone dust are used as aggregates.

Grossi et al. (1983) found that incorporating a chemically modified asphalt molecule into a hot mix asphalt increased the bond energy between asphalt and aggregate. The chemically modified asphalt compound was obtained by heating a mixture of organic species with an acrylamide. The chemically modified asphalt was between 1 to 10 wt% of the total weight of asphalt and modified asphalt.

Odgen and James (1988) have shown that the adhesion of bitumens and road oils is improved by the addition of 0.2 - 0.8% C_8 to C_12 carboxylic amides of N-aminoethyl - piperazine. When the same test procedure was used, the aggregate remained 100% covered by road oil with the addition of adhesive compound to <10% coverage without the amine.

Several Russian researchers (Khudyakova et al. 1987) evaluated how to predict adhesion of asphalt concrete mixes. The various combinations which were tested were oxidized petroleum tars with sand, marble and granites. The adhesion of petroleum tars with different grades and degrees of oxidation was good with marble. However, the adhesion of the asphalt to sand and gravel was poor. The authors recommended that the adhesion of asphalt-aggregate mixes be evaluated according the type of aggregate in the mix.

Treybig and Chang (1988) in a recent patent have prepared antistripping additives from hydrocarbyl substituted nitrogen containing aromatic heterocyclic compounds, aldehydes, or ketones and amines. These additives were synthesized from monoamine having from 1 to 36 carbon, nitrogen, oxygen or sulfur atoms, with $\geq$ 1 active H alone, and/or a polyamine with $\geq$ 1 active H alone, an aromatic heterocyclic material with $\geq$ 1 ring N and $\geq$ 1 active H; and an aldehyde or ketone. When combined at a mole ratio of (0.25-5):1: (0.25-5) and reacted from 25 to 250°C and usually at 60 to 200°C usually in a water medium with hydrochloric acid serving as a catalyst, these additives when combined with asphalt show stripping resistance especially with a siliceous aggregate such as granite. The asphalt composition did not affect the results; materials such as natural and air blown petroleum asphalts, gilsonite, and coal tars can be used. The aggregates used were Gifford-Hill, granite, or Helms or combinations of these materials. For example, when an antistripping agent prepared from a mixture of C10-18 primary amines, 2, 4, 6,-trimethylpyridine and HCHO, and a Gifford-Hill aggregate was sieved and heated and then combined with asphalt containing 1 wt% of the additives, stripping was reduced. The additive resulting from the reaction of a hydrocarbyl substituted nitrogen-containing aromatic hydrocarbon and an amine with an aldehyde was effective for asphalt-aggregate mixtures containing any of the three aggregates used. A boil test showed that 100% of the asphalt was retained on the aggregate compared to 40% without the additive. A freeze-thaw test showed that the material with additive survived >30 cycles compared to 6 cycles without the additive.

The addition of antistripping agents affected properties of asphalts. In a study by Anderson et al. (1982), ten antistripping agents were added to three asphalts and the effect of the antistripping agent was measured before and after the thin film oven. The asphalts selected varied in their asphaltene content from 4.1 to 25.7% and in their paraffin content from 26.4 to 6.4%. The antistripping agents ranged in titrable nitrogen from 2.5 to 14.1%. They found the effect of the antistripping agents was to change the molecular interactions among the polar constituents of the asphalt, usually causing the asphalt to soften. Aging seemed to improve while temperature susceptibility decreased. The interaction of a particular asphalt with an antistripping agent appeared to be specific and may change the characteristics of the asphalt sufficiently to cause the asphalt not to remain with specifications. The idea of an additive threshold for a particular asphalt was presented on the basis that doubling the amount of antistripping agent more than doubled its effectiveness.

Lime and other Mineral Agents

Rao and coworkers (1968) examined the effect of adding lime to aggregates on the stripping of bitumen from the aggregate. By coating wet aggregates with lime, the adhesion and stripping resistance of the bitumen is improved. This method allows for coating wet aggregates, resulting in shorter setting times and quicker utilization of new road surfaces.

The improvement of adhesion between waste glass aggregate and bituminous materials when exposed to water was examined by Day et al. (1970). A comparison was made between the effectiveness of three commercial antistripping agents and $Ca(OH)_2$ by using the immersion-compression test on graded glass samples containing 5.5 wt% asphalt cement. Immersions in 140°F water for 24 hours seriously damaged the specimens containing 1 wt% commercial antistripping agents. When the amount of the two most effective agents was increased to 4%, the retained strength of the immersed specimens was 70% of the dry control samples. When 5% $Ca(OH)_2$ was substituted for the fine glass aggregate, the strength retained after the immersion-compression test was greater than for the dry samples. In this test system, the commercial antistripping agents reduced stripping while $Ca(OH)_2$ eliminated it. The relationship between the immersion-compression test and field performance is unknown. A bituminous mix containing 4% antistripping agent and waste glass showed no significant stripping after six months of service in Toledo, Ohio. The traffic load was several hundred cars and trucks daily.

Dusdorf and coworkers (1970) sprayed glassy aggregates with saturated $Ca(OH)_2$ solutions and heated the treated aggregates for 10 minutes in a CO_2 atmosphere to promote adhesion. The process formed a layer of $CaCO_3$ on the surface of the aggregate and yielded better adhesion.

Al-Jarallah and Lee (1987) examined the addition of hydrated lime to relieve stripping problems in asphalt mixes. Their study used Saudi asphalt cements and local aggregates. The lime slurry was directly added to the aggregate when it appeared to react chemically immediately. The effectiveness of different types of additives was examined using the Texas Boil Test. For all of the aggregates tested, the lime slurry treatment was most effective except for two kinds of sand.

Four variables that are important to lime performing well as an adhesion agent in asphalt-aggregate interactions were examined by Stroup-Gardiner and Epps (1987). The four variables were method of addition, type of lime product, aggregate type and source, and air voids. The effect of these variables on sensitivity to moisture was evaluated by determining the resilient modulus and tensile strength of samples before and after a one cycle Lottman test with accelerated aging. The effect of these variables on temperature susceptibility was evaluated by determining the resilient modulus at four temperatures. They found that (1) quicklime added to the asphalt was detrimental to the asphalt-aggregate mix; (2) dolomitic lime and hydrated lime were equivalent in their effectiveness; (3) hydrated lime enhanced mixture properties regardless of the moisture susceptibility of the mix; (4) the presence of more lime can improve mixture properties; and (5) air voids affected the mixture properties substantially regardless of the amount or effectiveness of the lime.

A Japanese patent (1985) presented the treatment of granular slag by sulfate salt to form a $CaSO_4$ coating on the slag particles. The coating keeps the Ca containing components in the slag from dissolving in the asphalt. This helped to adhere the slag to the asphalt. Improved adhesion was determined by comparing Marshall stability with untreated slag.

A method for improving strength, stability and water resistance of asphalt concrete pavements was developed by Hopkins (1988). The additives which he used were (1) a metallic organic compound comprised either of Mn, Co, Cu, V, Mo, Ce, Fe, Ni, Pb, Zr, Ba, Ca or Zn and the organic part derived from $\geq$ 1 carboxylic acids, phenols and ketones, either separately or in combination with other metallic organic compounds to increase strength, and (2) $\geq$ 10 wt% antistripping agent synthesized from tall oil acid and amines or polyamines. The asphalt cements contained $\geq$ 90 wt% asphalt cement, and $\geq$ 0.5 wt% of the metallic organic compound and $\geq$ 0.1 wt% of the amine antistripping agent. As measured by Marshall stability, the strength, stability, and water resistance was improved by the addition of these additive compounds.

DiVito and Morris (1982) compared the effectiveness of a silane coupling agent, Dow Corning Z-6020, an aminoalkyl functional silane $(CH_3O)_3SiCH_2NHCH_2\ CH_2NH_2$, with a commercial liquid amine antistripping agent, Pavebond Special. The tests used were immersion-compression which followed a AASHTO T165 and double-punch debonding tests developed by Jimenez. Silane was added to two Arizona aggregates using two different methods. First, when the aggregate was in an oven-dried state, a 3 percent treatment of silane of four different concentrations was used. Second, when the aggregate was in a surface saturated dried state, the aggregate was heated with one weight percent of silane at the same four concentration levels as used with the other method. The aggregates used were Salt Lake and Agua Fria and the asphalt was AR 2000, whose source was Edgington Asphalt in California. The antistripping agent, however, was added to the asphalt. The silane performed better on Agua Fria than on Salt River aggregate and improved the bonding of asphalt. The treatment of the aggregate influenced the efficacy of the silane treatment. Other researchers (Marzocchi et al. 1977) found that treatment of glass flakes used in road paving improved surface adhesion to the organic phase.

Russian researchers (Khudyakova et al. 1987) examined the promotion of adhesion by modifying the aggregate surface. They found that the best adhesion was observed with $FeCl_3$; lesser results were obtained by an amine-type water-polyethylene emulsion, shale tar (with 30% phenols), $CaCl_2$, and $AlCl_3$. Acid tar did not promote adhesion. Stefanczyk (1968) found that both good cohesion and high adhesion were obtained by adding 0.8 to 2.0% Fe naphthenate to the aggregate and mixing with asphalt. Adhesion was also promoted by the addition of 0.1 to 8.0% Fe oxides to a bitumen foam which was then mixed with aggregate (Navratil et al. 1982).

Tests for Measuring Stripping

The debonding of asphalt concrete subjected to water and to cyclic stresses has been examined by Lottman (1971). The interfacial bond between the asphalt and aggregate is weakened in the presence of moisture and cyclic stresses. Changes in pavement temperature result in changes in pressure in the void water in asphalt concrete leading to bond failure. External cyclic stress can also cause bond failure. Scherocman and coworkers (1986) used multiple freeze-thaw cycles incorporated in the Lottman indirect tension test to measure moisture damage and the efficacy of different additives. Four liquid commercial antistripping agents and Carstab BA-2000 were used. Aggregate was obtained from six different states: Georgia, Virginia, Washington, Tennessee, Kentucky, and Iowa. By using multiple freeze thaw cycles with the indirect tensile strength test the effectiveness of the different additives could be discerned.

The adhesion of asphalt to aggregate was measured by heats of immersion using a microcalorimeter (Ensley and Scholz, 1970, 1972). Heats of immersions were determined with Arkansas penetration grade 36 asphalt and using specimen-grade quartz and calcite, silicate rocks from Glacier County and Lewis and Clark County, a limestone aggregate from Teton County, and a phosphate slag from Silver Bow County, all of Montana. The aggregates were tested both untreated and treated with 1 percent Armour Diamine-Redicote 80-S, a fatty acid salt of a long chain fatty diamine. The immersional energy data observed with the asphalt-aggregate systems showed that the energy was much greater and released over a longer time period than for typical liquids. The characteristic curve shape obtained was a peak followed by a long tail. The peak was ascribed to a monolayer and a multilayer buildup produces the tail. For both untreated and amine treated aggregates, a high tail height correlated with resistance to stripping by stripping tests.

The adhesive properties of bituminous materials to different aggregates such as quartzite, gabbro, basalt, or limestone were evaluated by Lassalle (1973) using ultrasonics. The minerals were coated with asphalt and then soaked in water for three (3) days. The coated mineral chips were subjected to ultrasonic energy while being agitated. The asphalts loosened by the ultrasonic energy were collected while the strongly adhered material was removed by trichloroethylene. The amounts of each material were determined by weighing and the adhered mineral matter was corrected by ashing the samples.

A simple test called the Texas boiling water test was developed by Kennedy and coworkers (1984) to evaluate the stripping potential of materials that are moisture sensitive. Tests were performed on eight asphalt-aggregate mixes which had field performance data. Five of the mixes had previously shown stripping and were composed of siliceous river gravel and sand while the nonstripping mixes were composed of crushed limestones, caliche, or slag. Eleven different additives were used including amidoamines, alkyl fatty diamine, imidazole, organofunctional silanes and amido amine silane and a lime slurry. The results indicated that in most cases the Texas boiling water test could delineate the moisture-susceptible mixtures. Less than 70 percent retention by the test indicates a stripping mix while more than 85 percent indicates a nonstripping mix. Those mixes with retention less than 85% should benefit from the addition of an additive. Of the additives used the lime slurry and silanes were most effective on the basis of the Texas boiling water test.

The stripping of Alabama asphalt concrete mixtures was evaluated by Parker and Gharaybeh (1987) by using the indirect tensile test. The test consisted of determining strength loss of mixtures that had been moisture conditioned and contained 6 to 8% air voids. These tests were performed to determine if stripping was a cause of premature damage and if the indirect tensile test provided an adequate measure of stripping potential. The significant variables found in the study were asphalt cement content and type of mix. Generally accepted "truths" concerning stripping potential of different aggregate sources, types and combinations were not shown to be correct by the indirect tensile test. This test also did not differentiate clearly between combinations of asphalt and aggregate that have been reported in the literature to be stripping or nonstripping.

Parker and Wilson (1986) evaluated the boiling water test and stress pedestal test for determining the stripping potential of Alabama asphalt concrete. The various mixes were composed of (1) 85% crushed dolomite and 15% natural coarse sand that showed little sign of stripping; (2) 70% crushed gravel, 20% natural sand, 10% crushed limestones; (3) 60% crushed gravel, which had severe stripping without antistripping agents, 25% natural coarse sand, 15% fine sand composed of quartzite and quartz, that had minor stripping problems without antistripping agents; (4) a Texas limestone with published 75 to 85% retention after boiling; and (5) Ottawa sand composed of medium to fine grains. The antistripping additives used were hydrated lime and two liquid antistripping agents, and metals-amine at 0.5 weight percent and an amino at 0.5 to 1.0 weight percent. The asphalts used were AC-20 grade that fulfilled State of Alabama Highway Department requirements. Parker and Wilson's results showed that the stress pedestal test results did not correlate with the field performance data since the aggregate with both stripping and nonstripping performed the same in the test. The boiling water test showed that important variables for retaining coating of asphalt onto the aggregate included aggregate, asphalt cement, and additive type and properties. The different antistrip additives gave different amounts of coating retention. No model could be developed by which to rank the stripping propensity of each combination; hence, each combination had to be tested to evaluate coating retention.

The effectiveness of antistripping agents was evaluated, utilizing the Texas boiling test, by Lee and Al-Jarallah (1986). The study used Saudi asphalt of 60 to 70 penetration grade and local aggregates in conjunction with different types of additives. Four types of aggregates from construction projects were used: (1) sandstone and sand, (2) crushed stone and sand, (3) granite and (4) limestone and sand. The antistripping agents used were hydrated lime, amidoamine antistripping agent, and mixtures of alkyl and alkylene amines. The hydrated lime was added in three ways: to the asphalt, to the aggregate as a mineral filler and to the aggregate as a slurry. The liquid antistripping agents were added to the asphalt at 0.3 weight percent of the asphalt and then heated to 163°C before being mixed with aggregate. The field performance of the aggregates agreed with the test results from the Texas boiling test. Lime was the most effective agent on all materials, except for two types of sand. This effectiveness is observed immediately after adding lime slurry to the aggregate. The amidoamine antistripping agent was the best additive for several sands. These results indicate that the efficacy of particular combinations of asphalts, aggregates and additives should be evaluated prior to their use.

Busching and coworkers (1986) examined the effects of different asphalts and antistrip additives on the tensile strength and moisture susceptibility of Marshall specimens using procedures developed by Tunnicliff and Root. The four asphalts used were AC-20 grades used widely in South Carolina. The aggregates were from South Carolina quarries; two were granitic while the third was siliceous coastal plains sand and gravel. Lime and three liquid antistripping agents whose properties are listed in the paper were used. Aggregate mixtures of crushed granite were usually stronger than gravel mixtures under dry conditions. The indirect tensile strength of granite mixtures that had been wet-conditioned decreased more than gravel mixtures for all of the asphalts used. When the different asphalts cements were compared under wet conditions their differences became more apparent and may result from differences in asphalt chemistry. Antistripping additives were necessary to protect the granite and siliceous mixture against loss of strength due to moisture. The authors felt that the

Root Tunnicliff procedure enabled moisture to penetrate the system and could be performed in a rapid efficient manner.

The relationship of antistripping agents to field performance was examined by Coplantz et al. (1987). The highway under study was the reconstruction of Nevada State Highway 207. The asphalt used was a AR-4000 that came from a San Francisco Bay area refinery. The aggregate came from a river deposit near Gardnerville, Nevada and a granite pit at the junction of US-50 and US-395; and the additives used were portland cement, hydrated high-calcium lime; and two proprietary liquid antistripping agents. Test samples from the materials and cores from the pavement were laboratory conditioned using vacuum saturation and one cycle freeze thaw. The data were obtained on laboratory prepared samples and compared to results obtained from test core samples. The laboratory samples showed a significant decrease in water sensitivity due to lime; much smaller decreases were obtained with liquid antistripping agents; and the liquid antistripping agents showed less sensitivity to moisture than portland concrete. Test results from the road core samples agreed with the laboratory samples in terms of moisture sensitivity. Visual survey of the road one year after reconstruction showed that the pavements containing liquid antistripping agents or portland cement had performed well.

Graf (1986) examined the factors affecting moisture susceptibility of asphalt concrete mixes, using the freeze-thaw pedestal test and the resilient-modulus and indirect tensile strength of laboratory cores that had been water-conditioned. Limestone mixes showed superior resistance to water-induced freeze-thaw damage while silicas did not. The granites ranged from good to bad. The key factors appeared to be size, shape, surface area, and porosity. Lime improved performance when a threshold amount had been added, amidoamine antistripping agents did not, and Carstab BA-2000 showed significant improvements while Union Carbide's diaminosilane was even more effective in wetting the asphalt onto the aggregate. Increased number of cycles were observed in those cases where wetting of the aggregate surface by the asphalt was promoted. Asphalts were very similar in behavior except for those that showed a sharp break in their temperature susceptibility that showed better adhesion. Asphalt chemistry appeared to play only a small role. The effects of asphalt and aggregate composition on the pedestal test were not reflected in the tensile strength ratio tests of core materials. No correlations were observed between the pedestal test and actual field performance.

Implications for Research

A substantial amount of research has been performed in the area of antistripping agents. Many different organic species have been tried in an attempt to bind asphalt more tightly to aggregates. Most of the antistripping agents contain nitrogen and are in the form of amines, fatty amines, substituted amines, and polyamines. The antistripping agents are effective in promoting the adhesion of asphalt onto aggregate. Since these agents have been shown to be effective, their effect on the asphalt aggregate chemistry must be understood. Several aspects of the chemistry must be known including how the antistripping agent interacts at the interface with both the asphalt and aggregate, how the antistripping agent affects the interphase and how the antistripping agent affects the chemistry as well as the dispersion of the asphalt.

Lime has also been used effectively as an antistripping agent. Comparative studies between lime and amine antistripping agents showed the lime to be generally more effective. The differences in mechanisms between lime and amine antistripping agents needs to be elucidated to capitalize on the effective chemistry for adhesion.

Tests have been developed with varying degrees of success to evaluate the efficacy of antistripping agents in terms of their ability to deter moisture and reduce moisture susceptibility. A number of tests have been attempted including the cyclic stress tests, Texas boiling water tests, indirect tensile strength, Marshall stability and heats of immersion. The effectiveness of the tests for correlating with field performance appear to vary with the particular asphalt-aggregate mix. Perhaps through a more thorough understanding of the effect of antistripping agents on the chemistry and mechanisms of antistripping agents a more predictive test can be developed to evaluate the efficacy of a combination of antistripping, asphalt and aggregate.

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