

# A Literature Review on Anti-Strip Additives in Asphalt Mixture

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**Abstract:** *The loss of bond between aggregates and asphalt binder that generally begins at the bottom of the HMA layer and progresses upward is known to be stripping of pavement. Stripping has been existent since the advent of paving technology. It causes functional weakening of pavements leading to costly repairs. Adhesion of bitumen onto aggregate is explained based on theories like mechanistic tenacity, molecular orientation, chemical reaction, and thermodynamic balance of interfacial forces. Stripping is elucidated using several mechanisms namely, displacement, detachment, spontaneous emulsification, bitumen film rupture, water pore pressure, hydraulic scouring, chemical disbonding, microbial activity, osmosis; and blistering and pitting. Chemical composition of aggregates is also an important factor of the occurrence. In this paper we have discussed the mechanism of stripping, causes of stripping and finally the solution. Different Anti strip additives may minimize the severity of stripping based on their properties and workability. The goal of this paper is to introduce the readers with different anti strip additives and their workability in a simple way.*

**Keywords:** Stripping, Anti strip additives, Effect, Agent

## 1. Introduction

Moisture damage is the loss of strength and stiffness of asphalt mixtures caused by the existence of moisture. The propagation of moisture damage generally occurs through two main mechanisms: the loss of adhesion (stripping) and loss of cohesion (softening). The loss of adhesion occurs between the aggregate and surrounding asphalt binder film, while the loss of cohesion occurs within the asphalt binder itself. Although moisture damage is not a failure mode, it leads to and accelerates several pavement distresses such as rutting, raveling, shoving, and bleeding. The loss of bond between aggregates and asphalt binder that typically begins at the bottom of the HMA layer and progresses upward. When stripping begins at the surface and progresses downward it is usually called raveling. The aggregate–asphalt binder bond is enhanced through one of three main mechanisms: improvement of aggregate surface; reduction of asphalt binder surface tension, which promotes asphalt binder spreading through the aggregate; and improvement of chemical properties of both aggregate and asphalt binder.



**Fatigue:** cracking caused by stripping at the bottom HMA

Although the displacement of asphalt on the aggregate particle surface by water (stripping) is a complex phenomena

and is not yet fully understood, mineralogy and chemical composition of the aggregate have been established as important contributing factors (Roberts et al., 1996[1]). In general, some aggregates have an affinity for water over asphalt (hydrophilic). These aggregates tend to be acidic and suffer from stripping after exposure to water. On the other hand, some aggregates have an affinity for asphalt over water (hydrophobic). These aggregates tend to be basic and do not suffer from stripping problems. Additionally, an aggregate's surface charge when in contact with water will affect its adhesion to asphalt cement and its susceptibility to moisture damage. In sum, aggregate surface chemistry seems to be an important factor in stripping. However, specific cause-effect relationships are still being established.

### Key factors determine the severity of stripping potential in pavement

1. Aggregate mineralogical composition
2. Asphalt chemical characteristics
3. Aggregate cleanliness
4. Mix design
5. Construction quality
6. Pavement drainage condition
7. Climatic condition

## 2. Mechanism

Stripping in asphalt pavement results from the failure of the asphalt aggregate adhesion bond due to the presence of water. The location of this failure (in the interface region) is crucial to understand the mechanism of stripping. Some major mechanisms that lead to stripping are described below:

*Weak Adhesion Bond-Lack of Bonding Sites on Aggregate Surface:* The adhesion bond may be weak due to the lack of intrinsic chemical interaction between the aggregate and asphalt. The electron donor-acceptor bonding between asphalt and aggregate can be weakened or even reversed by water. This is a known failure mechanism in other material systems.

**Naturally Emulsifiable Asphalt Leading to Unstable Adhesion:** Because of the composition or balance of constituents some asphalts are unstable in water and tend to form stable emulsions. This asphalt type is expected to form unstable interface with aggregates in the presence of water. This has been found to cause water stripping.

**Soluble Cations Forming Displaceable Soap at Aggregate-Asphalt Interface:** Most aggregates contain a large concentration of soluble ions that are leachable in water. These ions are known to form soaps (with asphalt carboxyl) at asphalt-aggregate interface. These soaps are displaceable and can cause water stripping. Evidence is present to support better performance of experimental pavements made with thoroughly washed and dried aggregates.

**Aggregate With Weak Boundary Layers:** It has been demonstrated by Podoll that the location of failure of some asphalt-aggregate pairs occurs in the aggregate side of the bond. The responsible weak boundary layer may be intrinsic to the aggregate or can be developed by surface complexation as described below.

**Dissolution of Aggregate-Asphalt Surface Complexes:** The exterior surface layers of aggregate may be weakened due to the formation of complexes between the aggregate surface sites and asphalt surface groups. These complexes are known to dissociate and dissolve from the aggregate surface. For different asphalt-aggregate pairs a combination of mechanisms may explain differences in pavement performance.

#### Problems due to stripping

- Decreased structural support
- Corrugation and Shoving
- Raveling
- Cracking including fatigue and longitudinal

**Corrugation and Shoving:** A form of plastic movement typified by ripples (corrugation) or an abrupt wave (shoving) across the pavement surface. The distortion is perpendicular to the traffic direction. Usually occurs at points where traffic starts and stops (corrugation) or areas where HMA abuts a rigid object (shoving).

**Raveling:** The progressive disintegration of an HMA layer from the surface downward as a result of the dislodgement of aggregate particles.

#### Possible Causes of Stripping

Bottom-up stripping is very difficult to recognize because it manifests itself on the pavement surface as other forms of distress including rutting, shoving/corrugations, raveling, or cracking. Typically, a core must be taken to positively identify stripping as a pavement distress.

- Poor aggregate surface chemistry
- Water in the HMA causing moisture damage
- Overlays over an existing open-graded surface course. Based on experience, these overlays will tend to strip

**Anti-Strip Additives:** Additives that are used to mitigate the stripping of pavement in HMA are known as anti-strip additives or simply anti-strip. Different types of anti-strip are

used in reducing stripping of pavement. But the anti-strip additives are broadly divided into two categories. They are:

- Liquid Anti-Strip Additives
- Hydrated Lime

**Liquid Anti-Strip Additives:** There are many different types of liquid anti-strip additives; most are surfactants. Sometimes liquid anti-strip additives are added to the asphalt binder at the terminal prior to delivery to the hot mix plant. Some plants are equipped to add liquid anti-strip to the HMA during mixing.

**Hydrated Lime:** Hydrated lime is quicklime that has been hydrated with water and pulverized. It should not be confused with agricultural lime, which is powdered calcium carbonate and is not effective as an anti-strip agent. There are various ways of adding hydrated lime to HMA at the plant. In some cases, a lime solution is sprayed on the aggregate. Some plants "marinate" aggregate stockpiles in a lime slurry. The hydrated lime can be added to the aggregate on the cold feed belt. In general it is considered more effective if the aggregate is somehow coated with the hydrated lime prior to mixing with the asphalt binder.

#### Different Anti-Strip Additives

##### 1. Liquid Anti-Strip

One of the most popular approaches for mitigating moisture susceptibility of asphalt mixes is adding Liquid Anti-Strip to asphalt binder. LAS's are surface active agents that can be added to asphalt binder, emulsion, and cutbacks. Generally, LAS's reduce the surface tension and increase the wettability of aggregates. Which produces better adhesion between the asphalt binder and aggregate surface. The selection of the most effective LAS product is time consuming and no selection guidelines are available with respect to asphalt concrete composition.

##### 2. Styrene Butadiene Styrene (SBS)

SBS is a thermoplastic polymer that improves the overall performance of asphalt pavement by reducing potential rutting in summer and cracking in winter by increasing stability, elasticity, and stiffness of asphalt binders (Tarefder and Zaman 2010). SBS softens under high temperature; therefore, it can be easily added and mixed with asphalt binder. The effect of SBS-modified binders on moisture sensitivity remains undetermined. It has not yet been confirmed whether SBS modification increases or decreases the moisture damage potential (Tarefder and Zaman 2010). In the current study, 1.5% SBS was added to PG 64-22 by the weight of asphalt binder to bump the grade to PG 70-22.

##### 3. Polyphosphoric Acid (PPA)

PPA is a liquid mineral polymer that has many applications in industry, including as a modifier to asphalt binder to reduce or slow the effects of oxidative aging undergone by bituminous materials. PPA is a modifier that needs more evaluation, especially in determining its impact on moisture damage to asphalt concrete. PPA can be used alone or with other additives such as hydrated lime or LAS and also with polymers such as SBS. Another important aspect of PPA is that it does not react efficiently with limestone aggregates. However, it is efficient with acidic aggregate

such as granite (Buncher 2010; TFHRC 2010). In this study, 1.25% PPA was added to PG 64-22 by the weight of asphalt binder to bump the asphalt binder grade to PG 70-22.

#### 4. Hydrated Lime

One of the early approaches to mitigate moisture susceptibility of asphalt mixes is the use of hydrated lime additive. Hydrated lime is thought to improve the stripping resistance of the asphalt mix by two methods: first by increasing the adhesion energy between the aggregate and asphalt binder and second by decreasing the interfacial tension between the asphalt binder and water. The hydrated lime reacts with the carboxylic acids in asphalt binder, forming insoluble compounds that are absorbed onto the aggregate surface. Hydrated lime dosage usually falls in a range of 0.5% to 2% by the weight of the aggregate (Expert Task Group 1990). Four methods for adding hydrated lime to asphalt mixtures can be used:

**Hydrated lime slurry:** Slurry is a combination of water and hydrated lime. The water, as per specifications, should be approximately 3% to 4% by weight of dry aggregate. Hydrated lime content is measured by weight of dry aggregate. Slurry is added to the aggregate in its saturated surface dry (SSD) condition. The aggregate with slurry is immediately placed in an oven at  $230 \pm 9^\circ\text{F}$  ( $110 \pm 5^\circ\text{C}$ ) until the sample weight is constant, then the oven temperature is increased to the mixing temperature of  $295 \pm 5^\circ\text{F}$  ( $146 \pm 3^\circ\text{C}$ ) for 2 hr. The normal mixing and compaction process is then followed.

**Hydrated lime slurry with marination:** The procedure used for hydrated lime slurry with marination is the same as for hydrated lime slurry except that after adding slurry to the SSD aggregate, the sample is left for 24 hr to marinate. Then the sample is placed in an oven at  $295 \pm 5^\circ\text{F}$  ( $146 \pm 3^\circ\text{C}$ ) for 2 hr. The normal mixing and compaction process is then followed.

**Dry hydrated lime to dry aggregate:** In this method, hydrated lime is added to aggregate preheated for 2 hours at a mixing temperature of  $295 \pm 5^\circ\text{F}$  ( $146 \pm 3^\circ\text{C}$ ). The blend of aggregate and hydrated lime is placed back in the oven until the temperature returns to the mixing temperature. Asphalt binder is added to the blend, and the normal mixing and compaction process is then followed.

**Dry hydrated lime with moist aggregate:** The difference between this method and the dry hydrated lime to dry aggregate method is that the dry hydrated lime is added to SSD aggregate as in the case of preparing hydrated lime slurry. The sample is then placed in the oven at  $230 \pm 9^\circ\text{F}$  ( $110 \pm 5^\circ\text{C}$ ) until the sample weight is constant, then the oven temperature is increased to  $295 \pm 5^\circ\text{F}$  ( $146 \pm 3^\circ\text{C}$ ) for 2 hr. The normal mixing and compaction process is then followed.

#### Effect of Antistrip Agents

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 pre-coating 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 anti stripping 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 an 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 anti-stripping agents are frequently used. The SHRP A-003B study of asphalt-aggregate interactions at the interface includes a section that evaluates the influence of anti-stripping agents on the chemistry of the interface. Hence the chemistry of the anti-stripping 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 anti-stripping 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.

The effect of Anti-Strip additives can be described under two broad categories. Namely

- Liquid Anti-Strip Agents
- Lime and other Mineral Agents

**Liquid Anti-stripping Agents:** Liquid anti-stripping 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. A number of researchers have studied the effectiveness of anti-stripping agents on the adhesion of asphalt to different types of rock surfaces. Dybalski (1970) determined that the adhesion of 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 quartered 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 anti-stripping 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 anti-stripping 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 anti-stripping 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 C12-C20 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 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 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-alkylimidazoline (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 aminoderivatives 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 hydroxylalkylamines showed promise as adhesive agents for bituminous materials. In a patent, Dalter and Gilmore (1983) mixed bituminous materials and an anti-stripping containing a hydroxylalkylated polyamine. When an amount of 0.07 wt% hydroxylalkylated polyamine was added, the adherence of the asphalt to the aggregates was greater in the 10-minute boiling water test than 0.5 wt% of the commercial agent N, N-dimethylaminopropylamines and 0.33 wt% forepoxyalkylated 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  $> 1$  organic amine, 1 organic polyamine and 1 or  $>$  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.

Bucz and Nemedi (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 anti-stripping agent and pretreating the aggregate surface with an acidic salt such as 0.01% CaHPO<sub>4</sub> and 0.01% H<sub>3</sub>PO<sub>4</sub>. The improvement is based on an amine-acid salt reaction at the asphalt aggregate interface. The anti-stripping 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 anti-strip 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 anti-stripping agent composed of one or a combination of the following: imidazoles, polyamines, alkoxylated polyamines, aminocarboxylic esters, or amides-amines; or by adding > 0.25 wt% of portland cement or by blending the anti-stripping 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% Ca to C<sub>2</sub> 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 to the type of aggregate in the mix.

Treybig and Chang (1988) in a recent patent have prepared anti-stripping 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 > 1 active H alone, and/or a polyamine with > 1 active H alone, an aromatic heterocyclic material with > 1 ring N and > 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 anti-stripping 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 hydroarbyl 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 additives survived >30 cycles compared to 6 cycles without the additive. The addition of anti-stripping agents affected properties of asphalts. In a study by Anderson et al. (1982), ten anti-stripping agents were added to three asphalts and the effect of the anti-stripping agent was measured before and after the thin film oven. The asphalt selected varied in their asphaltene content from 4.1 to 25.7% and in their paraffin content from 26.4 to 6.4%. The anti-stripping agents ranged in titrable nitrogen from 2.5 to 14.1%. They found the effect of the anti-stripping 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 anti-stripping 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 anti-stripping 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 anti-stripping agents and Ca(OH)<sub>2</sub> 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 anti-stripping 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)<sub>2</sub> was substituted for the fine glass

aggregate, the strength retained after the immersion-compression test was greater than for the dry samples.

Commercial anti-stripping agents reduced stripping while Ca(OH)<sub>2</sub> eliminated it. The relationship between the immersion-compression test and field performance is unknown. A bituminous mix containing 4% anti-stripping 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)<sub>2</sub> solutions and heated the treated aggregates for 10 minutes in a CO<sub>2</sub> atmosphere to promote adhesion. The process formed a layer of CaCO<sub>3</sub> 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<sub>4</sub> 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 >1 carboxylic acids, phenols and ketones, either separately or in combination with other metallic

organic compounds to increase strength, and (2) > 10 wt% antistripping agents synthesized from tall oil acid and amines or polyamines. The asphalt cements contained > 90 wt% asphalt cement, and > 0.5 wt% of the metallic organic compound and > 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 Coming Z-6020, an aminoalkyl functional silane (CH<sub>3</sub>)<sub>2</sub>SiCH<sub>2</sub>NHCH<sub>2</sub>CH<sub>2</sub>NH<sub>2</sub>, with a commercial liquid amine antistripping agent, Pavabond 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 a 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 anti-stripping 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<sub>3</sub>; lesser results were obtained by an amine-type water-polyethylene emulsion, shale tar (with 30% phenols), CaCl<sub>2</sub>, and AlCl<sub>3</sub>. 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).

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