

**EFFECTIVENESS OF
ANTISTRIPPING ADDITIVES
VOLUME II
Literature Review**

by

John W. Shute
Graduate Research Assistant
Oregon State University
Corvallis, OR 97331

R.G. Hicks
Professor of Civil Engineering
Oregon State University
Corvallis, OR 97331

James E. Wilson
Research Specialist
Oregon Department of Transportation
Salem, OR 97310

and

Lewis G. Scholl
Technical Studies Coordinator
Oregon Department of Transportation
Salem, OR 97310

May 1989

1. Report No. FHWA-OR-RD-89-03B	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle EFFECTIVENESS OF ANTISTRIPPING ADDITIVES Volume II		5. Report Date May 1989	6. Performing Organization Code
7. Author(s) John W. Shute, et al.		8. Performing Organization Report No.	
9. Performing Organization Name and Address Department of Civil Engineering Oregon State University Corvallis, OR 97331		10. Work Unit No. (TRAVIS)	11. Contract or Grant No. HPR No. 5275
12. Sponsoring Agency Name and Address Materials and Research Division Oregon Department of Transportation Salem, OR 97310		13. Type of Report and Period Covered Feb. 1988 - May 1988	
15. Supplementary Notes		14. Sponsoring Agency Code	
16. Abstract <p>Volume I of this report summarizes the findings on the extent of stripping in 32 Oregon DOT projects and discusses the significant findings from a literature review. Of the 32 projects, 10 had not used an asphalt or aggregate antistripping additive, 19 contained lime-treated aggregate, and 3 contained asphalt treated with an amine-type antistripping additive. These projects range in age from 1 to 9 years. The percent of aggregate coated with asphalt, which was used to determine if a project was stripping, was established from breaking and visually evaluating core samples taken from each project site. Using the criteria that a coating less than 85% classified a project as stripping, the following results were obtained: 7 of the 10 projects without an additive, 5 of the 19 lime-treated aggregate projects, and 2 of the 3 amine-treated asphalt projects were identified as stripping. The conclusion is that lime treatment of aggregate has proven effective in reducing the moisture susceptibility of an asphalt mixture. In addition, a review of mix design test values for the index of retained strength (IRS) (AASHTO T-165) and resilient modulus (M_r) test indicates the IRS test does not reliably predict moisture susceptible mixtures. The M_r test did provide a better indication of moisture susceptible mixtures. This assessment is based on a limited amount of data and is not statistically based; therefore, the results may change with further information. Volume II presents the complete literature review.</p>			
17. Key Words Asphalt concrete, stripping, chemical additives, lime, moisture		18. Distribution Statement This document is available to the public through the National Technical Information Service, Springfield, VA 22161.	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages	22. Price

TABLE OF CONTENTS

	<u>Page</u>
1.0 INTRODUCTION	1
1.1 Problem Definition	1
1.2 Purpose of Paper	1
2.0 BACKGROUND/LITERATURE REVIEW	3
2.1 Overview	3
2.2 Theoretical Considerations of Adhesion	7
2.2.1 Mechanical Theory	9
2.2.2 Chemical Reaction Theory	10
2.2.3 Surface Energy Theory	11
2.2.4 Molecular Orientation Theory	12
2.2.5 Discussion	12
2.3 Control of Stripping	14
2.4 Additives	15
2.4.1 Chemical Additives	15
2.4.2 Lime Additives	20
2.5 Discussion	24
3.0 EFFECTIVENESS OF ADDITIVES	26
3.1 Chemical Additives	26
3.1.1 Laboratory Studies	26
3.1.2 Field Studies	28
3.2 Lime Additives	31
3.2.1 Laboratory Studies	31
3.2.2 Field Studies	32
3.3 Discussion	32
4.0 TESTING PROCEDURES	35
4.1 Overview	35
4.2 Test Procedures	35
4.2.1 NCHRP 246 – Lottman Indirect Tension Test	36
4.2.2 NCHRP 274 – Tunncliff and Root Test	36
4.2.3 Boiling Tests	42
4.2.4 Texas Freeze–Thaw Pedestal Test	42
4.2.5 Immersion Compression Tests	43
4.3 Discussion	43
5.0 REFERENCES	45

LIST OF TABLES

<u>Table</u>		<u>Page</u>
2.1	Commercially Available Antistripping Agents	16
2.2	Methods of Introducing Dry Lime	23
2.3	Methods of Introducing Lime Slurry	25
4.1	NCHRP 246 – Indirect Tension Test and/or Modulus Test with Lottman Conditioning	37
4.2	NCHRP 274 – Indirect Tensile Test with Tunnickliff and Root Conditioning	38
4.3	Boiling Tests	39
4.4	Texas Freeze–Thaw Pedestal Test	40
4.5	Immersion–Compression Tests (ASTM D–1075, AASHTO T–165) . . .	41

LIST OF FIGURES

<u>Figure</u>		<u>Page</u>
2.1	Schematic of the Stripping Process	4
2.2	Classification System for Aggregates	6
2.3	Active Adhesion Mechanism	8
2.4	Mechanisms of Asphalt Adhesion Improvement with Microwave Energy Treatment	13
2.5	Heat Stability of Antistripping Additives in AC-20-1 as Determined by the Boiling Water Test	18
2.6	Excessive Liquid Antistrip Agent	21
3.1	Resilient Modulus and Tensile Strength Ratios	27
3.2	Results for Various Additive, Aggregate and Asphalt Combinations	29
3.3	Effectiveness of Additives vs pH Values	30
3.4	Effectiveness of Lime on Asphalt Oxidation	33

1.0 INTRODUCTION

1.1 Problem Definition

The durability of an asphalt concrete (AC) pavement depends to a great degree on the adhesion between the asphalt cement and the aggregate. Pavement engineers have long recognized that localized shiny areas in pavements (i.e., patch flushing or bleeding), raveling of aggregate at the surface of a pavement, random cracking and potholing are all indicators of loss of adhesion between asphalt and aggregate.

The physical separation, or stripping, of asphalt cement from aggregate is due to the action of water or water vapor (moisture) in the AC pavement. This occurs because the aggregate surface generally has a greater attraction for water than asphalt. Consequently, water may be drawn between the asphalt cement and aggregate surface. This water then strips the asphalt cement film away from the aggregate. The rate at which stripping takes place depends on the temperature, type of aggregate, and the viscosity and composition of the asphalt (Tyler, 1938).

Two characteristic types of pavement failures are associated with stripping. If water enters the asphalt concrete pavement through the upper surface, raveling of the aggregate occurs. This can be easily detected and often remedied with routine maintenance. Stripping can also occur from the bottom of the pavement upwards, resulting in bleeding, random cracking and potholing. This type of stripping is generally not detected until it is too late to prevent.

1.2 Purpose

This report provides insight into the problems of stripping and the effectiveness of additives used to reduce the impact of stripping in roads and highways. Stripping is a complicated phenomenon, and work is still being done to understand more fully its primary causes and how it can be controlled.

An overview of the stripping problem and current theories on the causes of stripping are discussed. Recent work on the effectiveness of additives is presented along with results from field and laboratory studies. It should be noted there are limited data which would allow the correlation of laboratory

and field data. Past research has primarily been laboratory-based using a variety of conditioning and testing procedures to evaluate stripping potential.

Some of the most common research testing procedures were selected in this study for detailed discussion. Other tests may be used, but the selected tests cover the most common methods used to determine the potential for moisture susceptibility in asphalt mixtures.

2.0 BACKGROUND/LITERATURE REVIEW

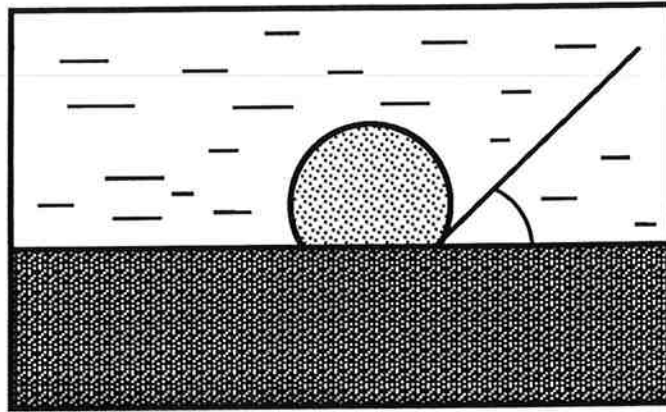
Research to date has provided a beginning for understanding the complex process of stripping in asphalt mixtures. Two general types of additives (chemical and lime) have been used to effectively reduce the stripping potential in asphalt concrete. The following section discusses the stripping process and several theories of how additives and other measures can reduce moisture susceptibility of asphalt mixtures.

2.1 Overview

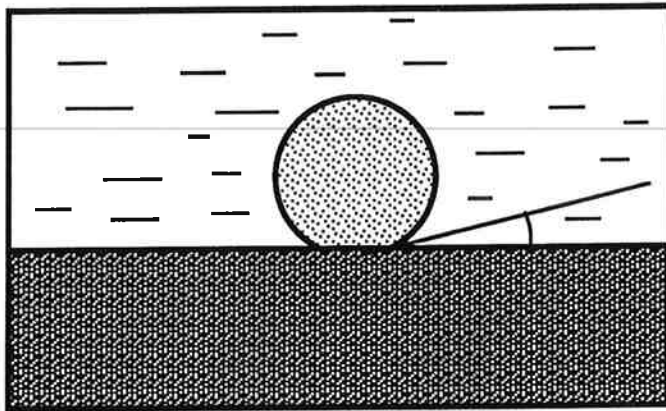
Water or water vapor (moisture) damage in AC pavement may be associated with two phenomena (Kennedy, 1984). First, water can interact with the asphalt cement to cause a reduction in cohesion with an associated reduction in stiffness and strength of the mixture. Secondly, water can get between the asphalt film and the aggregates, break the adhesive bond between the aggregate and asphalt, and "strip" the asphalt from the aggregate. Water typically gets between the asphalt cement film and the aggregate because the aggregate surface has a greater attraction for water than for asphalt. The mechanism associated with stripping may be viewed in terms of a reduction in the contact angle between the asphalt and aggregate surface, as shown in Figure 2.1.

Failure due to stripping occurs in two stages: the first stage is the stripping failure itself; the second stage is the failure of the pavement under traffic. Many asphalt pavements experience stripping failure within the mix without structural failure of the pavement. If stripping within the pavement becomes excessive, severe pavement deformation and failure may occur as a result of repeated loading (Road Research Laboratory, 1962). Stripping failures can take the form of potholes or cracking and surface raveling of the pavement (Fromm, 1974). Wearing courses placed over stripped asphaltic bases are likely to exhibit adhesion failure by raveling and pothole formation (Scott, 1978).

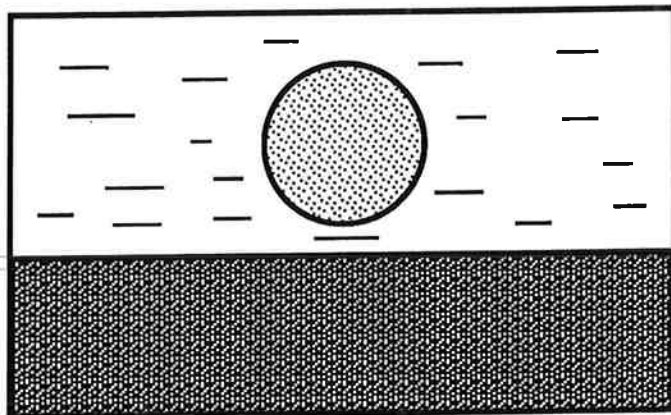
The adhesion of asphalt cement to aggregate is related to the physical and chemical properties of both the asphalt and the aggregate and is reduced by the presence of water. In general, there have been some differences on the contribution of the chemical nature of the aggregate. Siliceous aggregates have been classified as hydrophilic and tend to strip more readily than



- (a) The moment at which the aggregate, with the drop of bitumen, is immersed in water. The contact angle is less than 90° .



- (b) The water begins to remove the bitumen drop from the aggregate surface and the contact angle decreases.



- (c) Finally, the stage is reached where the contact angle is 0° and the bitumen loses contact with the aggregate surface.

Figure 2.1. Schematic of the Stripping Process (after Tyler, 1938).

Limestone aggregates which have been classified as hydrophobic (Taylor and Khosla, 1983). Mertson and Wright (1959) proposed another method of classification of aggregates. They state that both limestone and siliceous aggregates are readily wetted and indicate that both types are truly hydrophilic in character. The terms proposed by Mertson and Wright are "electropositive" for the limestone aggregates and "electronegative" for siliceous aggregates. These two types of aggregates represent the extremes found in aggregate classifications. A schematic classification system for aggregate, based on their system, is shown in Figure 2.2. Selection of an asphalt source and additives to prevent stripping is therefore highly dependent on the aggregate type.

Experience to the contrary has been reported by Mathews (1958). He indicates that relatively few aggregates are known to be completely resistant to the action of water under all conditions of practical use. He also asserts that the notion that "acidic" rocks have a higher potential for stripping than "basic" rocks is inaccurate.

Yoon and Tarrer (1988) report that the chemical and electrochemical interaction between water and the aggregate surface play a greater role in stripping than the physical characteristics of the aggregate. They state the zeta potential of the aggregate surface in water and/or the pH of the water imparted by the aggregate could be used to measure stripping potential. The higher the zeta potential and/or the pH value, the higher the probability for stripping.

Development and evaluation of antistripping agents has been the subject of study by several researchers (Schmidt and Graf, 1972; Ishai and Craus, 1977; Chehovits and Anderson, 1980; Plancher et al., 1977; Tunnicliff and Root 1982; Castedo et al., 1985; Kennedy, 1984; Button, 1985). In many cases, it is stated that the stripping process can be controlled or prevented by the use of an antistripping agent which is added to the binder in small quantities.

Further, evidence suggests that the damage will be minimal if stripping is restricted to the coarse aggregate. If the fine aggregate in the mixture strips, severe damage will result because the fine aggregate constitutes the basic matrix of the mixture (Kennedy et al., 1977). It is apparent that stripping is influenced by many variables related to the materials involved, climate, loading conditions, construction practices, and roadway design techniques.

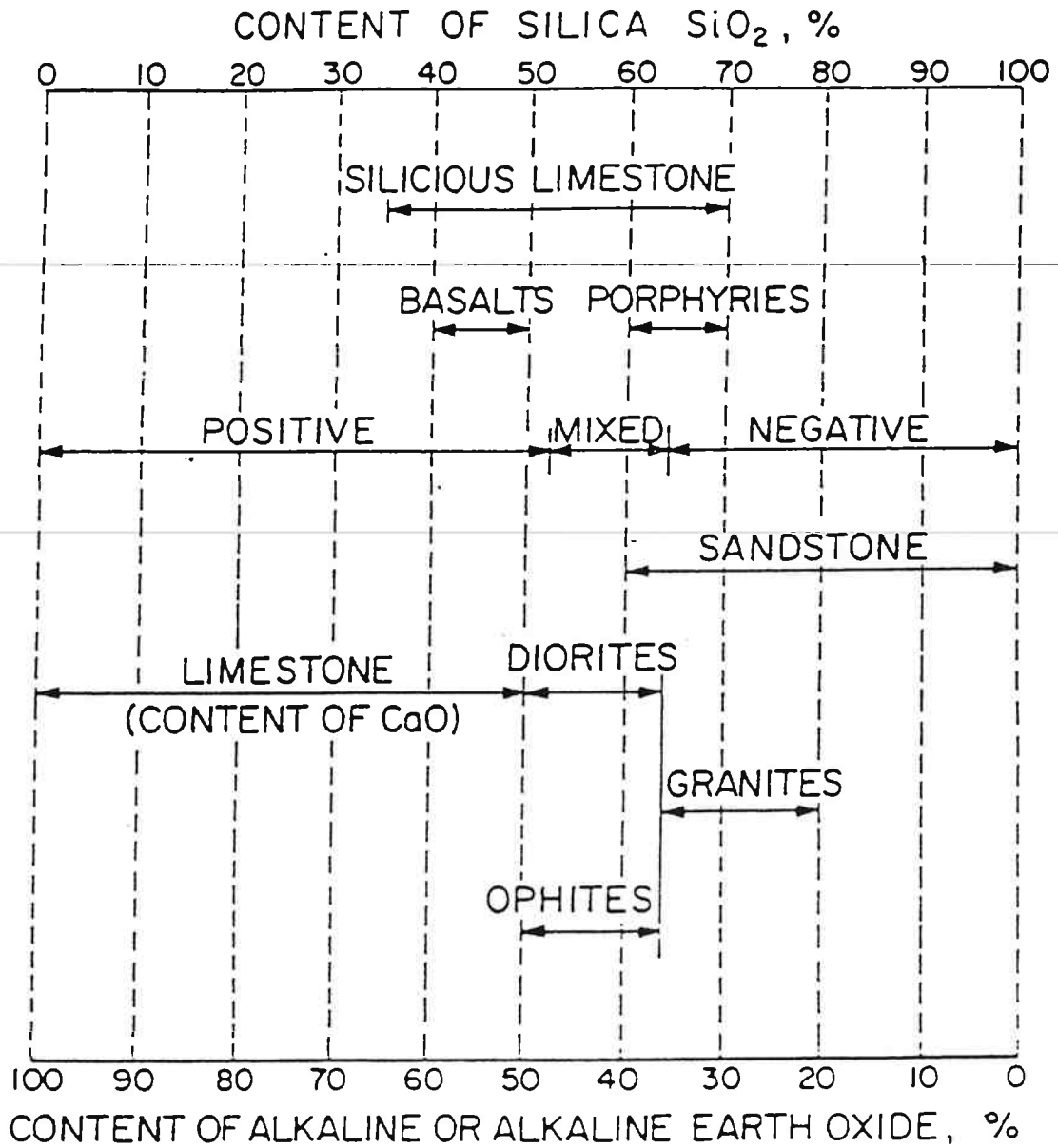


Figure 2.2. Classification System for Aggregates (after Mertson and Wright, 1959).

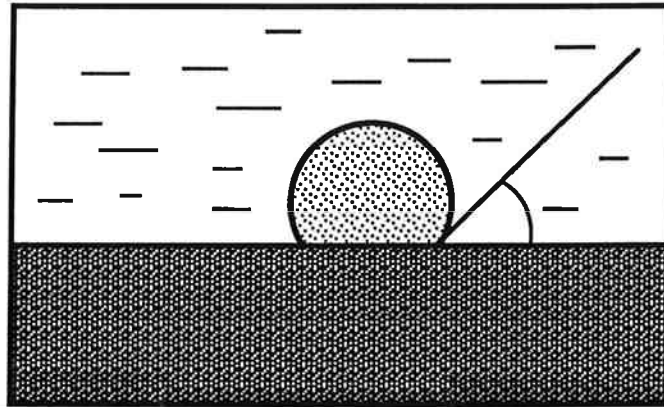
During the past decade, several major research studies have been conducted at the state and federal level to predict the extent of stripping damage in AC mixtures and to evaluate the effectiveness of antistripping additives (FHWA and others). Indeed, no fewer than 18 states have conducted or participated in research projects focusing on stripping (e.g., Alabama, Alaska, Arizona, Colorado, Georgia, Idaho, Kansas, Kentucky, Louisiana, Maryland, Mississippi, Missouri, Montana, Oregon, South Carolina, Texas, Utah and Virginia). To date (1989), however, no universally accepted laboratory test and specimen conditioning procedure, validated by field performance histories, has yet been identified.

2.2 Theoretical Considerations of Adhesion

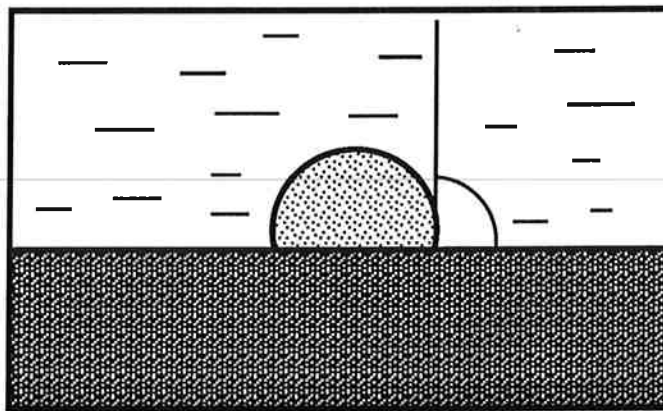
An appreciation of the stripping mechanism is strengthened by a review of theories of adhesion. Adhesion may be defined as "that physical property or molecular force by which one body sticks to another of another nature" (Nicholson, 1932). Several factors which affect the adhesion of the asphalt cement to the aggregate have been identified by Thelen (1958). These factors include: (1) surface tension of the asphalt cement and aggregate, (2) chemical composition of the asphalt cement and aggregate, (3) asphalt viscosity, (4) surface texture of aggregate, (5) aggregate porosity, (6) aggregate cleanliness, and (7) aggregate moisture content and temperature at the time of mixing with asphalt cement.

Adhesion in AC mixes may be either passive or active. Passive adhesion means the asphalt cement coats the dry aggregate surfaces. Active adhesion means the asphalt cement coats the wet aggregate surfaces. Figure 2.3 illustrates the active adhesion mechanism. Very often, active adhesion requires the addition of antistripping agents to the asphalt cement. In general, the required content of antistripping agent is greater for active adhesion than for passive adhesion (Jensen, 1983).

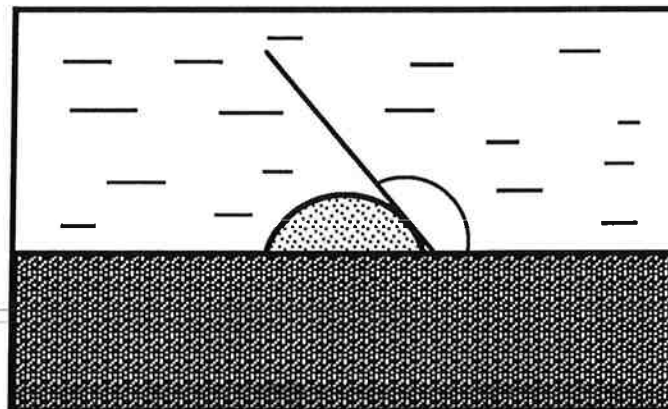
Four major theories have been presented to explain adhesion of asphalt cements to aggregates. These are Mechanical Theory, Chemical Reaction Theory, Surface Energy Theory, and the Molecular Orientation Theory. The actual mechanism by which adhesion works is not fully explained by one theory. Adhesion is partially explained by each theory. Additives primarily address



(a) At the time of immersion the contact angle is smaller than 90° .



(b) The contact angle increases and reaches 90° .



(c) The bitumen drop spreads on the aggregate surface and the contact angle increases, eventually finishing at almost 180° .

Figure 2.3. Active Adhesion Mechanism (after Jensen, 1983).

the chemical, surface energy, and molecular theories. These theories, together with factors affecting adhesion, are discussed in the following sections.

2.2.1 Mechanical Theory

Mechanical adhesion is affected by several properties of the aggregate, including (1) surface texture, (2) porosity (absorption), (3) surface coatings on the aggregate, (4) surface area, and (5) particle size (McBain and Hopkins, 1962; Rice, 1958). Adhesion between the aggregate and asphalt cement takes place primarily at the interface of the two materials. It may be stated that the rougher the surface texture, the greater the adhesion between the asphalt cement and aggregate (Asphalt Institute, 1981). Further, Rice (1958) indicates the stability and durability of the AC pavement is also related to surface roughness of the aggregate. The prevailing theory to explain the influence of surface roughness is that the asphalt cement is forced into the pores and irregularities of the aggregate surface to provide a stronger mechanical interlock. Asphalt retention has been noted to be better with rough, irregular surfaced aggregates compared to smooth, glassy surfaced aggregates (Lee, 1936). Following these arguments, Knight (1938) and McBain and Hopkins (1962) have attempted to relate the adhesion between the asphalt cement and the aggregate to the surface characteristics of the aggregate.

In some instances surface roughness may work against adhesion. For rough-surfaced aggregates, it may be difficult to maintain complete (uniform) coating of the aggregate. Consequently the thin films of asphalt cement at the edges of a rough feature may be most susceptible to stripping (Majidzadeh and Brovold, 1968). Knight (1938) noted that surface texture is influenced by mineralogical composition of the aggregate.

Porosity (the volume of the void space as a percentage of the total volume of the aggregate) and absorption (the volume of water held in the pore space of an aggregate) are believed by many to influence the stripping phenomenon. Although greater porosity and absorption capacity are generally associated with improved adhesion, the pore size is more significant than the total volume of pores in the aggregate (Yoon and Tarrer, 1988).

It is generally held that the penetration of the asphalt into the pores of the aggregate enhances the mechanical interlock. Scott (1978) states that the oily constituents of an asphalt enter the pores or capillaries of the

aggregate and consequently are preferentially absorbed. The asphalt cement on the surface of the aggregate becomes harder and, therefore, has a higher viscosity owing to this preferential absorption. Thelen (1958) suggests that this interlock of the asphalt cement with the pores should cause the asphalt to adhere more strongly to the surface of the aggregate and, therefore, be less susceptible to stripping. Work presented by Zeisman (1963) indicates that the asphalt cement physically interlocks with the aggregate as a result of the penetration of the asphalt cement into pores, crevices, and capillaries in the surface of the aggregate. Yoon and Tarrer (1988) did not find a significant relationship between the physical characteristics of aggregate, pore volume and surface area, and stripping potential due to the influence of chemical properties.

Dust and moisture very often coat aggregates that are used in road construction. Both dust and moisture prevent intimate contact between the aggregate and the asphalt cement and as such, increase the tendency towards stripping. Dust on the aggregate surface is believed to reduce the rate of spreading and often causes an increase in viscosity of the asphalt. To improve asphalt wetting in this case, it is recommended that a lower viscosity asphalt cement be used. In addition, Held (1986) states that excessive fines also form small dams which prevent the penetration of the asphalt cement into the aggregate pores.

The greater the surface area of the aggregate, the greater the amount asphalt cement required for stability (Brown et al., 1959). Results presented by Strauss and Anderson (1942) indicate that aggregates containing appreciable amounts of material finer than the No. 200 sieve require more asphalt cement to completely coat the aggregate than a comparable mix with a lesser proportion of fines. Consequently, a mixture with substantial fines tends to strip more readily because complete particle coating requires more asphalt cement which is more difficult to achieve.

2.2.2 Chemical Reaction Theory

A number of investigators (Tyler, 1938; Rice, 1958, Gzemski, 1948; Saville and Axon, 1937; and Andersland and Goetz, 1956) have noted that stripping is more serious in acidic aggregate mixes compared to basic aggregate mixes. This may be attributed to the fact that when the aggregate

is wetted by the asphalt cement, absorption occurs at the surface which is followed by the chemical reaction between the asphalt cement and the aggregate (Riedel and Weber, 1953). Following this logic, it is argued that the chemical reaction between most asphalt cements and acidic aggregates is not as complete as the reaction between most asphalt cements and basic aggregates. They further state that additives which reduce the acidity of aggregates should improve the chemical reaction between the asphalt cement and the aggregate, thus reducing the tendency to strip.

Several other investigators (Knight, 1938; Becker, 1941; and Douglas, 1947) place much less emphasis on adhesivity and the chemical composition of the aggregate and asphalt. Winterkorn et al. (1937) report good adhesion between an acidic siliceous aggregate and several asphalt cements. Hubbard (1958) and Mertson and Wright (1959) indicate that siliceous aggregates tend to strip more readily than basic aggregates.

2.2.3 Surface Energy Theory

The wetting ability of asphalt cement is defined as the ability of the asphalt cement to make intimate contact with the surface of the aggregate (Hubbard, 1958). The wetting ability of asphalt cement as with other liquids is related to its viscosity (i.e., the resistance to flow associated with molecular friction). For example, water is an excellent wetting agent compared to asphalt cement because it has a much lower viscosity than asphalt cement. Wetting ability is also related to surface tension, which is the stress that tends to hold a drop of liquid in a spherical form.

Rice (1958) has noted that when asphalt spreads over and wets an aggregate surface, a change in energy takes place. This change of energy, referred to as adhesion tension, is a surface phenomenon that depends upon the closeness of contact and mutual affinity of the asphalt cement and aggregate (ASTM, 1958). Rice (1958) presents data indicating that adhesion tension for water to aggregate is higher than for asphalt to aggregate. Consequently, water will tend to displace asphalt cement at an aggregate asphalt cement interface where there is contact between the water, asphalt, and aggregate. Mack (1935) indicates that interfacial tensions between the asphalt and aggregates vary with both the type aggregate and type of asphalt cement.

2.2.4 Molecular Orientation Theory

The molecular orientation theory states that when asphalt cement comes into contact with an aggregate surface, the molecules in the asphalt orient themselves so as to satisfy the energy demands of the aggregate (Hubbard, 1958). Work by Mack (1935) and McBain and Hopkins (1962) suggest that the alignment of asphalt molecules may be the result of the orientation of ions on the aggregate surface. More specifically, the asphalt cement molecules may orient themselves in the direction of polarization of the aggregate ions.

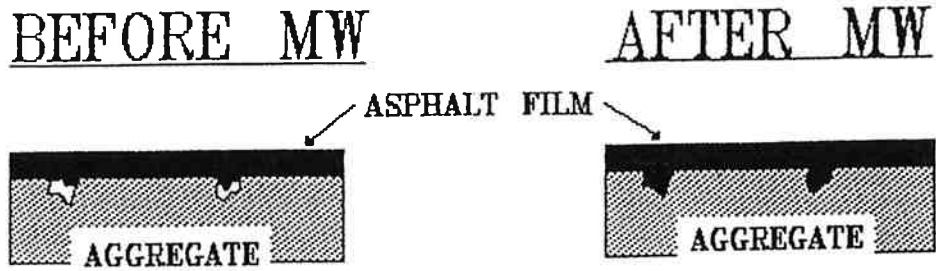
Water molecules are di-polar. Asphalt molecules are predominantly non-polar. Consequently, water molecules may more readily satisfy the energy demands of an aggregate surface. Mack (1935) further notes that the small proportion of asphalt cement molecules that are di-polar may have a greater energy demand for some aggregate surfaces than do water molecules. They would be thus able to displace water from the surface of the aggregates. This effect may not be significant, however, because di-polar molecules are not predominant. Research on this subject has produced variable results.

2.2.5 Discussion

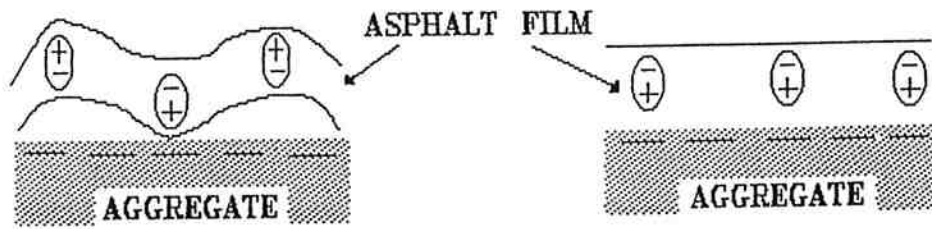
Recent work by Al-Ohaly and Terrel (1988) illustrates how adhesion is best described from an assimilation of the theories just discussed. They have completed some initial work on the effect of microwave heating on the adhesion of the asphalt and aggregate.

Improved adhesion from microwave heating of asphalt mixtures can reduce the moisture susceptibility. They state that microwave radiation creates an alternating electromagnetic field when passing through a material. However, this only occurs if the material is not electrically neutral. Water and aggregate respond to microwaves by heating whereas asphalt does not. When an asphalt mix is subjected to microwave radiation, the aggregates are heated and in turn heat the asphalt cement. This leads to one of the following:

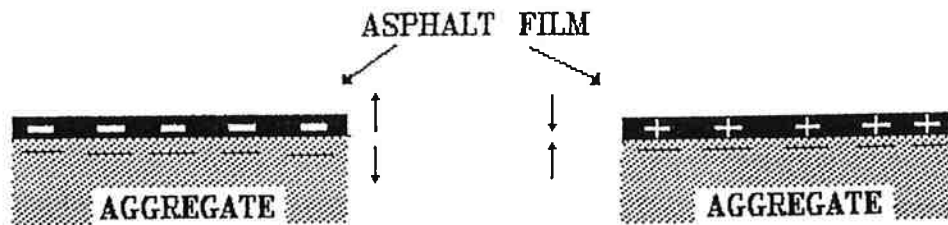
- 1) The heated asphalt becomes less viscous and will redeposit, thereby filling some permeable voids in the aggregate, as shown in Figure 2.4a, and improving the mechanical interlock.
- 2) A reduction of viscosity in the asphalt cement allows for the possibility of reorientation of the molecular polarity,



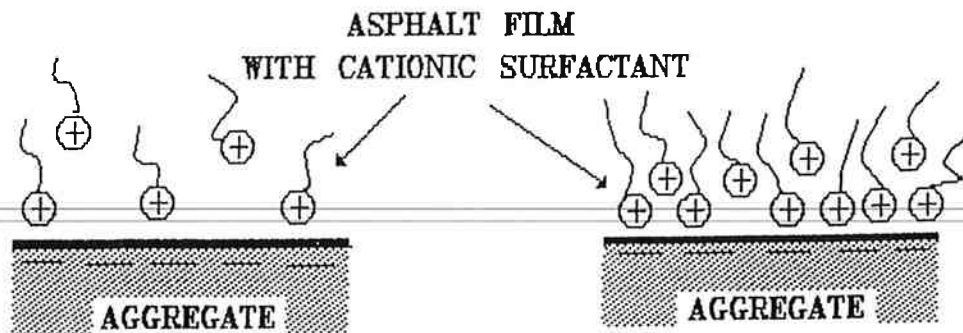
(a) Effect from heating and melting asphalt



(b) Molecular reorientation



(c) Polarization effect



(d) Increased polar additive migration

Figure 2.4. Mechanisms of Asphalt Adhesion Improvement with Microwave Energy Treatment (after Al-Ohaly and Terrel, 1988).

illustrated in Figure 2.4b and 2.4c, which will strengthen adhesion.

- 3) The lower viscosity allows for the migration of the positively charged cations in the antistripping agent to the asphalt/aggregate interface which is shown in Figure 2.4d. The increase in antistripping agent at the interface promotes a stronger bond.

All four theories are involved when the asphalt mixture is subjected to microwave heating. The redepositing of the asphalt in the aggregate pores not only increases the mechanical interlock, but is a function of a decrease in viscosity which increases the wetting ability of the asphalt. Decreasing the viscosity of the asphalt allows for molecular reorientation and chemical additive migration. All processes enhance the adhesion of the asphalt to the aggregate.

2.3 Control of Stripping

While antistripping agents are the major topic here, other measures can also be employed to minimize stripping. These include the use of good aggregate, the use of pavement surface sealants, and the pretreatment of aggregates. These three control measures are discussed briefly in the following paragraphs, followed by a detailed discussion of antistripping agents.

In general, to minimize stripping, aggregates have low porosities of approximately 0.5% and a rough, clean surface (Krebs and Walker, 1971). Initial rounded aggregates should be crushed to produce a rougher texture and coated aggregates should be cleaned through initial processing.

The entrance of water into a pavement structure can be substantially reduced by closing the pores or reducing the air voids. This can be done by using a dense graded mixture or by applying a variety of pavement surface sealants to the asphalt concrete surfaces. Perhaps the most common is "fog sealing" of a pavement structure. This technique consists of spraying a light application of liquid asphalt (typically an asphalt emulsion) without mineral aggregate filler to the pavement surface. Other commercially available sealants are also used. If the source of moisture is from beneath the pavement

then sealing of the pavement surface could be detrimental. The seal could trap moisture vapor inside the asphalt concrete and promote stripping.

2.4 Additives

Pretreatment of aggregates involves modifying the surface properties of the aggregate prior to construction. In general, the pretreatment techniques seek to replace the aggregate surface ions that are likely to be removed by water or to cause weak bonding with the asphalt. Secondly, the pretreatment processes seek to promote a strong bond between the asphalt cement and the aggregate surface.

The chemical interaction at the surface of the aggregate plays an important role in stripping. The aggregate selectively absorbs some components of the asphalt. The bonds formed are generally hydrogen bonds and salt links which is due to the absorption of the more polar components of the asphalt. The ketones and phenolics are thought to be the asphalt components which enhance stripping resistance and the carboxylic acids, anhydrides, and 2-quinolenes the asphalt components which decrease a mixtures resistance to stripping (Yoon and Tarrer, 1988).

2.4.1 Chemical Additives

The majority of liquid antistripping additives are surface active agents which reduce the surface tension of the asphalt cement and, therefore, promote greater adhesion to the aggregate. The adhesion between asphalt cement and aggregate is also improved. This improvement is associated with the fact that the antistripping agents give the asphalt cement an electrical charge that is opposite to that of the aggregate surface.

The properties of asphalt cements containing antistripping agents can vary greatly. A number of antistripping agents that are used in the United States are indicated in Table 2.1. The chemical additives listed have been designed to be effective under certain mix conditions as noted in the description part of the table. Some are designed for use in hot mixes while others are designed to be used with cutbacks or emulsions. Also, the concentration rates vary with the type of mix being used.

Most chemical antistripping additives are classified as being "heat stable" by their manufacturers. This term implies that the chemical additive

Table 2.1. Commercially Available Antistripping Agents.

Supplier	Agent	Description	Cost
Tomah Products 1012 Terra Dr. PO Box 388 Milton, WI 53563	ACRA-500	A 100% active, oil-soluble, cationic surfactant designed to bond to bituminous materials to both acidic and alkaline aggregates. Excellent for use in wet weather. Rate: 0.4-1.0%	50¢/lb in bulk
	ACRA-600L	Same as ACRA-500 but ACRA-600 L is a liquid, easy-to-handle product for drum customers.	
	ACRA-1000	An amine-based, oil-soluble, cationic surfactant that is liquid above 50°F. It can be used in cold mixes and controlled hot mix applications. Rate: 0.30-0.75%	51¢/lb in bulk
	ACRA-2000	An amine-based, oil-soluble, cationic surfactant that is liquid above 35°F. Primary use is hot mixes, but can be used with cutbacks. Rate: 0.30-0.50%	61¢/lb in bulk
	SC-901	A "Super Concentrate" is effective with both alkaline and acidic aggregates in cold mix, hot mix, and recycling applications. Rate: 0.25-0.40%	84¢/lb in bulk
	SC-AT-50	A "Super Concentrate AT-50" that is easier to blend and is effective with alkaline and acidic aggregates in cold mix, hot mix, and recycling applications. Rate: 0.25-0.40%	74¢/lb in bulk
	CATAMINE T-2S	A 100% cationic, talow diamine based additive. Used for with asphalt cement or cutback asphalt. Rate: 0.5-1.0%	78¢/lb in bulk
	TAA-3000	A 100% active oil soluble, cationic, and amine-based. Used with asphalt cement or cutback asphalt. Rate: 0.5-1.0%	76¢/lb in bulk
	TAA-3000 Modified	TAA-3000 in reduced concentration to achieve greater liquidity <O C> and to use when minimum use levels are specified at 0.5%.	62¢/lb in bulk
ScanRoad Inc. PO Box 7677 Waco, TX 76714 ph: 817-772-7677	KLING BETA-LV	Used in asphalt cements and cutbacks. Heat stable. Rate: 0.5-1.0%	NA
	WETFIX SH	A fatty amidoamine for all grades of bitumen. Heat stable and coats wet and dry aggregate. Rate: 0.6-1.5%	NA
Armak Highway Chemicals 8401 W. 47th St. McCook, IL 60525 ph: 312-442-7100	Redicote 82-S	Heat stable, cationic, liquid adhesion agent that produces a water-resistant film of asphalt even on inferior grades of asphalt at use levels as low as 0.5%. Rate: 0.5-0.7%.	NA
	Redicote 90-S	Heat stable cationic, liquid adhesion agent. May be used in either hot mixes or with cutbacks. Rate: 0.5-1.0%	NA
	Redicote 91-S	A polar, heat stable, oil-soluble additive. Can be used with anionic and cationic emulsions. Rate: 0.3-0.6%	NA
Morton Thiokol Inc. Carstab Corp. 2000 West St. Cincinnati, OH 45215 ph: 513-733-2100	Pave Bond Ap and Pave Bond AP Special	All purpose products that are effective with all types of aggregate. Both are heat-stable, liquid, alkaline additives. Rates: AP: 0.5-1.0%; AP Special: 0.25-0.5%	NA
	Pave Bond LP and Pave Bond Special	Free flowing, easy-to-handle liquids that are most effective with siliceous and mixed aggregates. Rates: LP: 0.5-1.0%; Special: 0.25-0.5%	NA
	Pave Bond	A viscous liquid additive that is effective with siliceous aggregates and offers excellent performance and cutback asphalts for winter stockpile. Rate: 0.5-1.0%	NA
	Pave Bond 192	A viscous liquid designed for use wet or dry aggregate. Also, it can be used with asphalt cements, cutbacks, and emulsions. Rate: 0.5-1.0%	NA

does not contain components which might react with some element of the asphalt and render the additive ineffective. The reaction is a function of temperature, increasing as the temperature of the asphalt increases (Tunncliffe and Root, 1982). However, Yoon et al. (1987) found that six of the chemical antistripping additives they tested decreased in concentration and effectiveness after being stored in asphalt at temperatures above 300°F. An illustration of four of these additives and the effect of exposure to 325°F is shown in Figure 2.5.

The chemical composition of most commercially produced agents is proprietary information. Tunncliffe and Root (1982), however, indicate that the majority of the surfactants currently in use are chemical compounds that contain amines. Amines are primarily basic compounds ($R-NH_2$, R represents a hydrocarbon chain) that are derived from ammonia. Amines that are produced from fatty acids (fatty amines) have a long hydrocarbon chain. They are generally believed to be the most suitable antistripping agents. When the fatty amines are added to asphalt cement, the asphalt cement is better able to wet the aggregate surface. Further, the fatty amines have the ability to improve the adhesion of the cement to the aggregate owing to the chemical bond that they may make with silica (Hartman, 1983).

The amines will form a positive ion ($R-NH_3^+$) when combined with water or an acid. In cationic surfactants, Held (1986) states that the non-polar end of the hydrocarbon attaches to the asphalt while the amine group forms ammonium salts with hydrogen ions in the aggregate. These cationic surfactants can destabilize the asphalt emulsions which form at the asphalt/aggregate interface.

There are two methods by which antistripping agents are added to asphalt concrete mixes. The simplest and most economical application method is to introduce the additive to the asphalt cement in a liquid state and thoroughly mix the additive with the asphalt cement, prior to mixing the asphalt cement with the aggregate. Although this method is the most commonly used, it is inefficient in that much of the antistripping agent does not reach the aggregates/asphalt cement interface. The second method of application is to apply the antistripping agent directly to the aggregate surface. This method is undoubtedly the most efficient and possibly the most effective.

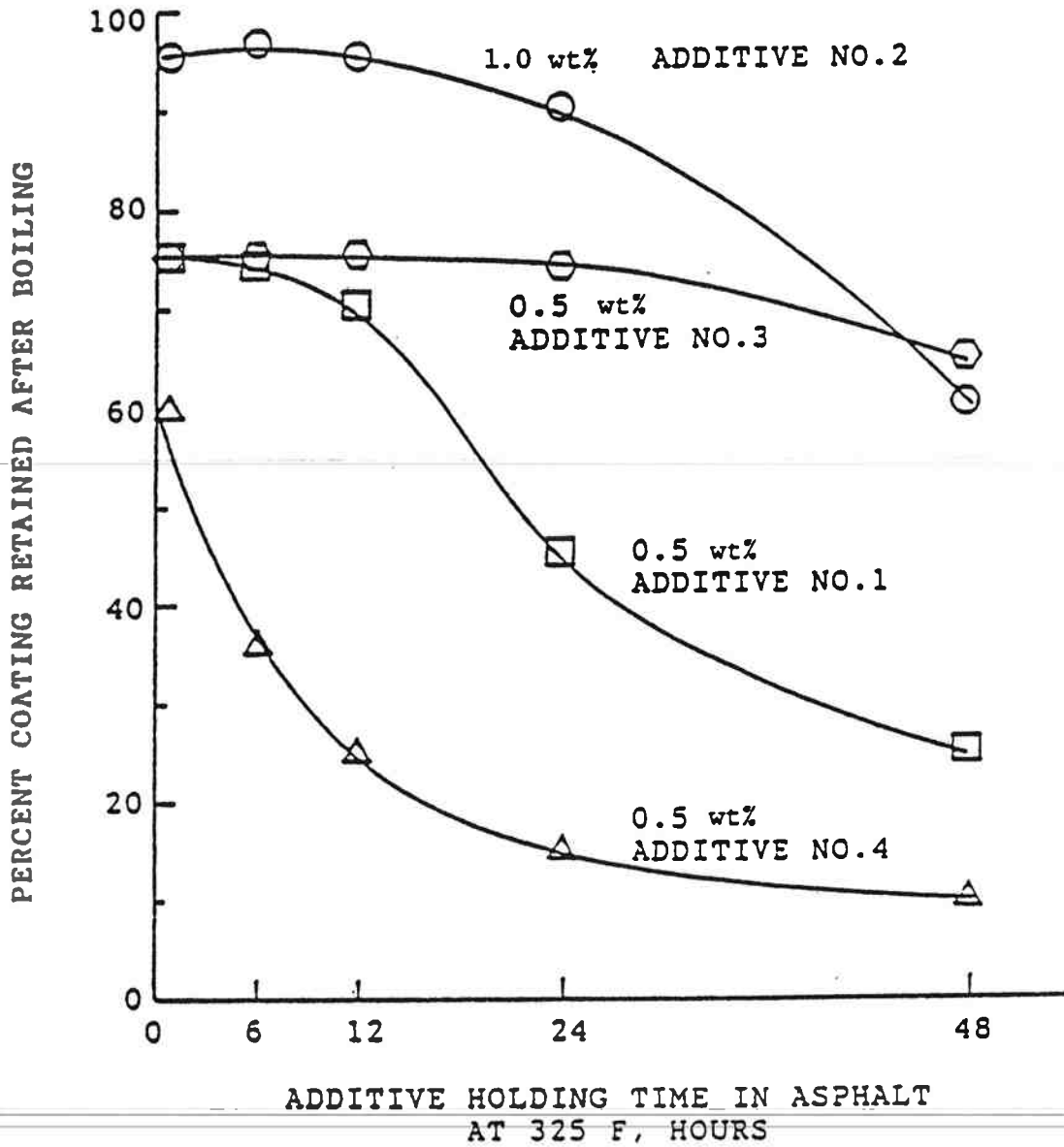


Figure 2.5. Heat Stability of Antistripping Additives in AC-20-1 as Determined by the Boiling Water Test (Yoon et al., 1987).

When the liquid antistrip additive is added to the asphalt cement, the chemicals migrate through the asphalt to the asphalt/aggregate interface. Upon reaching the surface interface, water is displaced and the surface interface becomes hydrophobic and lipophilic (an affinity for oil). When the mix is still hot and the viscosity of the asphalt cement low the amount of chemicals able to migrate to the asphalt/aggregate interface is sufficient. However, when the mixture cools and the viscosity of the asphalt cement increases the amount of chemical additive able to migrate decreases. The ineffectiveness of pre-mixing the additives with the asphalt is a result of this slow migration. The normal time available for migration is approximately 3 hours, while 12 hours is generally needed to obtain the necessary amount of additive at the asphalt/aggregate interface (Dybalski, 1982). In contrast, Yoon et al. (1987) state that the additive concentration at the asphalt/aggregate interface rapidly attains an equilibrium. Through evaluation of the diffusion rate it was estimated for one additive that 2 minutes would be required for 90% of the additive to pass through 1 millimeter of asphalt at a temperature of 300°F. This rate is dependent upon the additive in addition to the state of the asphalt.

The use of microwave radiation or a cutback can help increase the amount of additive reaching the asphalt/aggregate interface. Application of microwaves to the mixture would speed up the migration of the chemical additive to the surface interface by forcing polarization (Al-Ohaly and Terrel, 1988). At a minimum the application of microwave radiation would reduce the molecular orientation randomness that occurs at the interface and thereby improve adhesion. Al-Ohlay and Terrel (1988) caution that weak or complete debonding could result from microwave treatment of mixes in which the asphalt and aggregate are incompatible.

The addition of cutback decreases asphalt viscosity and thereby allows a greater amount of chemical additive to reach the interface. An increase from 30-40% of the original amount to 80-90% can be achieved by this method (Dybalski, 1982). When a cutback is used the additive required is generally 0.3-0.5% and when hot asphalt cement is used the amount is approximately 1.0% by weight of asphalt.

The amount of chemical additive used is important. When not enough is used, the amount of additive reaching the asphalt\aggregate interface will be

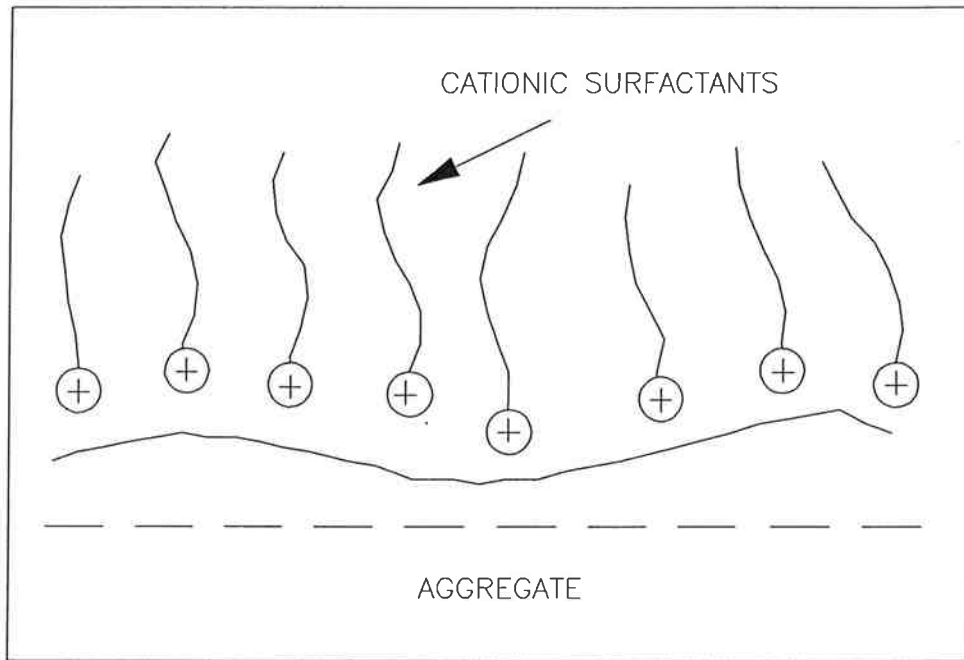
insufficient. However, if an excess amount of additive is used a moisture susceptible shear plane may form which would be detrimental to the mix as is shown in Figure 2.6 (Dybalski, 1982).

2.4.2 Lime Additives

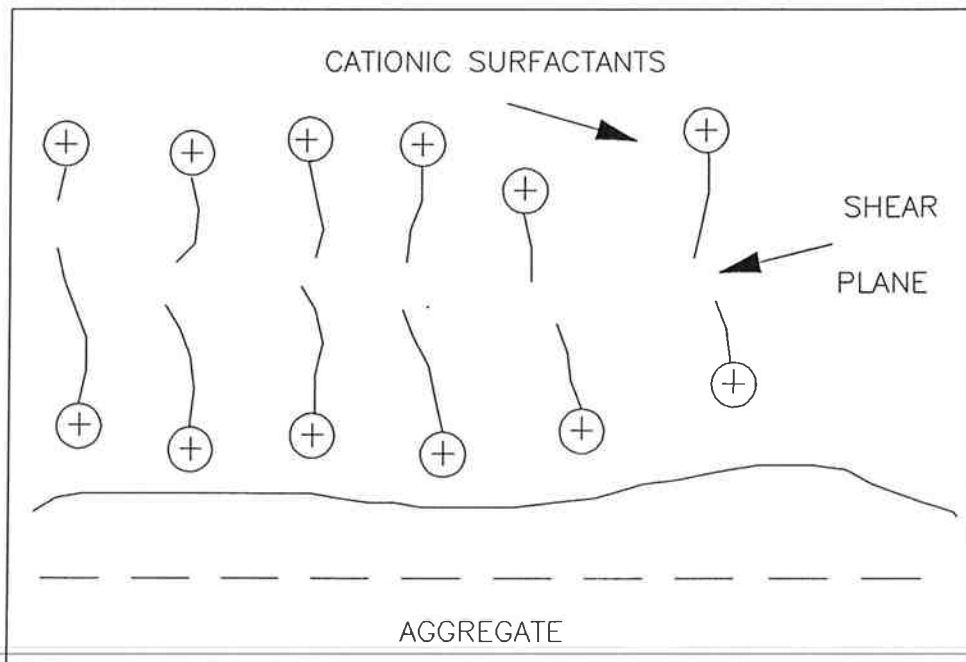
In general, lime is applied in slurry form to the aggregate. The improvement in adhesion provided by the hydrated lime only occurs after moisture has been introduced to activate the lime (Ishai and Craus, 1977). It is generally believed that the lime produces a sharp decrease in the interfacial tension between the asphalt cement and water, thus resulting in good adhesion. Plancher, et al. (1977) suggests that hydrated lime improves stripping resistance as a result of its interaction with acids in the asphalt that are readily absorbed onto the surface of an aggregate. Schmidt and Graf (1972) note that the mechanism by which hydrated lime improves stripping resistance cannot be completely explained by the reaction of the asphaltic acids with the lime. They note that lime, in general, provides calcium ions which can replace hydrogen, sodium, potassium and other cations on the aggregate surface.

Hydrated lime reacts with most silicate aggregates to form a calcium hydroxy silicate crust on the surface of the aggregate. This thin crust, which forms a strong bond to the aggregate, has sufficient porosity to allow penetration of the asphalt to form a strong bond (Held, 1986). The carboxylic acids and 2-quinolenes of the asphalt are absorbed by the lime to form an insoluble calcium salt.

Acidic OH groups are found on the surface of siliceous aggregates. These groups (SiOH) form hydrogen bonds with the carboxylic groups from the asphalt and play a major role in the adhesion between the asphalt and aggregate. However, in the presence of water, the two groups dissociate and associate with the water molecules forming strong hydrogen bonds. The lime forms calcium salts with the carboxylic acid and the 2-quinolenes leaving the Si molecule to bond with the nitrogen groups in the asphalt (Petersen et al., 1987). The bonds formed with the basic nitrogen are strong and promote adhesion.



a) Surface charge saturation



b) Surface charge over-saturation

Figure 2.6. Excessive Liquid Antistrip Agent (after Dybalski, 1982).

The emulsification of the asphalt at the asphalt/aggregate interface can play an important role in the stripping process. Held (1986) states that the highly alkaline hydrated lime causes asphaltenes, which are strong surfactants, to change from a di-polar ion to an anionic ion. This change allows for greater adhesion, lower surface tension, and greatly reduces the potential for water absorption by the asphalt. Hence, reducing the amount of emulsification that is likely to occur.

Use of Lime. Lime has been used in asphalt mixtures since 1910 (Kennedy, 1984). Initially it was primarily used to act as a mineral filler. Gradually, locally available materials replaced the lime and commercially available antistripping agents were used.

Lime in its oxide (CaO) and hydroxide (Ca(OH)_2) forms is active and will react with water quite readily. However, as a carbonate (CaCO_3) lime will not provide the benefits desired for antistripping purposes. Hydrated lime has a low specific gravity, 2.3 to 2.8, and about 85% passes the #325 sieve.

Lime is also available in two dolomitic forms. Type S is a compound of calcium hydroxide and magnesium carbonate and Type N is a compound of calcium carbonate and magnesium oxide. Both types of dolomitic lime have been used as antistripping additives.

Generally, the resistance to stripping will increase with increased amounts of hydrated lime. However, if the aggregates are well coated, 1 to 1-1/2% of lime by weight of aggregate normally is adequate. Finer aggregates, however, have larger surface areas and may require higher percentages of hydrated lime to adequately protect the aggregate from stripping.

Methods of application include treatment of the aggregate with: 1) dry hydrated lime, 2) hydrated lime slurry, 3) dry hydrated lime with water, and 4) hot (quicklime) slurry. All of the above produce improved resistance to stripping of asphalt mixtures. Each of the procedures is discussed below.

1) Dry Lime. The primary problem with the addition of dry lime is holding the lime on the surface of the aggregate until it is coated with asphalt. The loss of lime will be greater in drum mixers, which will tend to pick up some of the lime in the gas flow. In addition, a portion of the dry lime may be mixed into the asphalt acting as a filler. Aggregates can be treated by adding dry hydrated lime to the aggregates as shown in Table 2.2.

Table 2.2. Methods of Introducing Dry Lime.

a) Batch Mix Plants		
Methods	Advantages	Disadvantages
On the Cold Feed	- Scalping screen and belt changes can improve mixing	- May produce dusting and some lime loss - Mixing and coating of aggregates is minimized
Premixing Pugmill	- Maximizes coating of the aggregate - Minimizes losses due to dusting	- Some lime loss due to dusting - Some lime may be lost in the asphalt cement
Pugmill Prior to stockpiling	- Maximizes mixing and coating of the aggregate - Minimizes losses due to dust	- Some lime may be lost in the asphalt cement
Prior to Stockpiling	- Lime may be added prior to stockpiling	- Maximizes chance of carbonation occurring - Some lime may be lost due to construction

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

The table lists additional advantages and disadvantages of each method. The addition of dry lime has not proven to be as consistently effective as the other methods described in this paper.

2) Hydrated Lime Slurry. The primary problem with the use of lime slurry is the additional water added to the aggregates since it must be removed by drying, it increases fuel costs and reduces production rates. Thus, application techniques should be directed toward minimizing the amount of water which must be removed when the aggregate enters the dryer of the drum mixer. Table 2.3 summarizes the commonly used techniques.

3) Dry Hydrated Lime with Water. Possibly one of the most common ways to add lime is to increase the aggregate water content to 3-5%. Then add lime using a positive mixing pugmill or tumble mixer to obtain a homogeneous mix.

4) Hot (Quicklime) Slurry. The use of quicklime has some advantages. First, the cost is approximately the same as for hydrated lime. However, when the quicklime is slaked, the hydrated lime yield is about 25% greater (Kennedy, 1984). Also, the chemical reaction produces an elevated temperature which aids in the evaporation of the moisture.

2.5 Discussion

The use of hydrated lime, both in dry or slurry form, has been shown to be an effective means of improving the moisture resistance of asphalt mixtures when applied directly to the aggregate. Initial indications in a study by Tunnicliff and Root (1986) show that applying lime in a wet form provides slightly more resistance. This is consistent with other studies, noted later in this paper, showing the addition of dry lime does not provide consistent results.

Table 2.3. Methods of Introducing Lime Slurry.

a) Batch Mix Plants

Methods	Advantages	Disadvantages
On the Cold Feed	- Scalping screen and belt changes can improve mixing	- Only certain aggregates may be treated - Adding lime at each cold feed bin may be required - Some dust loss may occur during drying
Premixing Pugmill	- Better aggregate coverage and allows for drainage - Minimizes losses due to dusting	
Prior to Stockpiling	- Allows aggregate drainage	- Maximizes chance of carbonation occurring - Only certain aggregates may be treated

b) Drum Mix Plants

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

3.0 EFFECTIVENESS OF ADDITIVES

It is well established that both chemical and lime antistripping additives reduce the moisture susceptibility of asphalt mixtures. Additives are used to prevent stripping when aggregates are known to strip and/or when the pavement will be subjected to climatic conditions that are conducive to stripping. This determination is made from experience and the use of test procedures discussed in Chapter 4. The cost effectiveness of additives is diminished on roads that are low volume or under dry climatic conditions or when the pavement is a properly placed dense graded mix. A road that falls under one or more of these categories will derive even less of a benefit from the incorporation of an additive into the mix. The results cited illustrate both the effectiveness of additives and their variability.

3.1 Chemical Additives

Chemical additives are more sensitive than lime to the specific combination of asphalt cement, liquid antistrip additive, and the aggregate source. To establish the effectiveness of a particular additive requires lab testing of the specific combination of materials to be used. Any changes in either of the variables; the asphalt cement, antistrip agent, or aggregate, would require retesting to determine the effectiveness of the new combination of materials (Kennedy, 1985; Busching et al., 1986).

3.1.1 Laboratory Studies

The effectiveness of liquid chemical agents versus lime in lab studies has produced mixed results. Coplantz and Epps (1985) conducted a lab study with two generations of liquid antistrip additives (Figure 3.1). They found both to be effective in reducing the moisture susceptibility of the mix as measured by resilient modulus ratio. This test, however, did not show them to be as effective as lime slurry. In the figure, additive #1 is a "first generation" and additive #2 is a "second generation" liquid antistripping agent. Since this project is only a year old, the data for field correlation is not available. In a study by Kennedy (1985), liquid antistripping additives (1%) were found to perform better than hydrated lime (1%). This contrasts with the results found by Coplantz and Epps (1985).

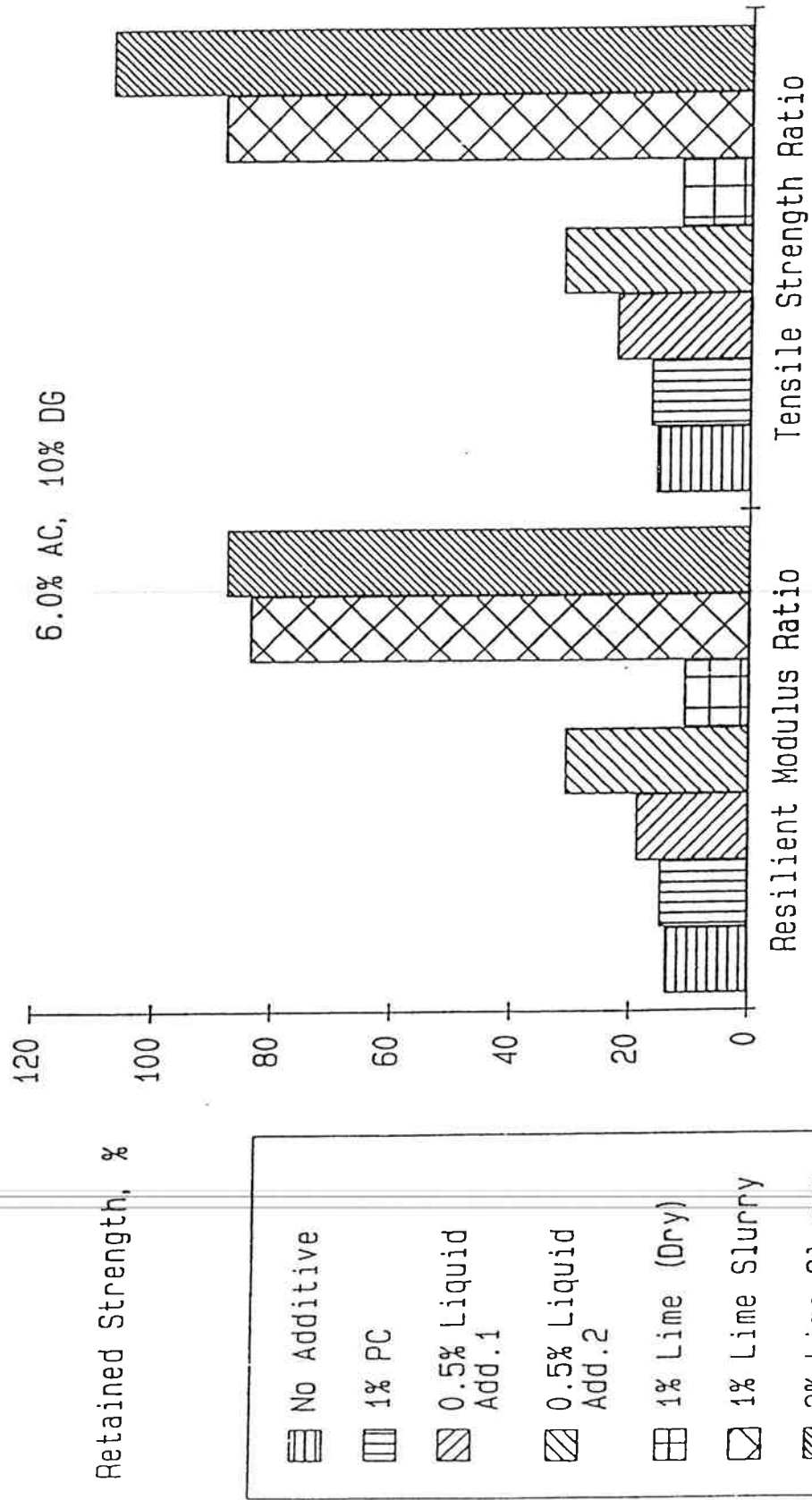


Figure 3.1. Resilient Modulus and Tensile Strength Ratios (after Coplantz and Epps, 1986).

Additional studies have shown lime to be more effective than chemical additives in reducing moisture susceptibility. In testing the use of additives in reducing moisture susceptibility for foamed asphalt mixtures, Casledo et al. (1985) found the use of a saline additive and Inulin improved the stability retention of the mixtures. However, the improvement was not to the same level as the lime additive mixes. Kim et al. (1985) found a liquid antistripping additive (0.5%) to be of some benefit in reducing damage to a mix with high moisture content (3%), however, not to the extent of a lime (1%) additive.

The results of studies have shown that while the effectiveness of a chemical additive versus lime is mixed, it does not indicate that lime should be used in all cases and chemical additives disregarded. While lime is generally shown to be more effective, the studies have shown chemical additives to be effective. In other words, is the extra effectiveness of the lime, for a particular scenario, cost effective.

The variation that can occur in test results when any of the constituents are changed is illustrated in Figure 3.2. The figure, from a study by Parker and Gharaybeh (1988), shows the improvement in tensile strength ratio (TSR) from various combinations of liquid antistripping additives (which vary in concentrations), aggregate, and asphalt source. In the figure, additive BAB is a metalo-amine at 5% by weight of asphalt, while the KBB and KBC additive is an amido-amine at 1% and 5% respectively. HLa is hydrated lime applied at 1% by weight of aggregate. The figure illustrates how a change in the combination of any of the variables in the asphalt matrix can change the results.

Recent research has shown other factors may influence the effectiveness of chemical additives. If the pH of the water surrounding the aggregate is increased, it may reduce the effectiveness of the chemical additive. Figure 3.3 shows the effectiveness of two liquid antistripping additives and hydrated lime when the pH of the water is increased (Yoon and Tarrer, 1988).

3.1.2 Field Studies

There is limited data on the effectiveness of chemical additives in the field. However, lab studies and the limited field data indicate the chemical additives should provide the desired benefits. In a study by Malsch (1985), it was determined the use of a liquid antistripping additive can be effective if the proper care is given when selected. The cost effectiveness of using an

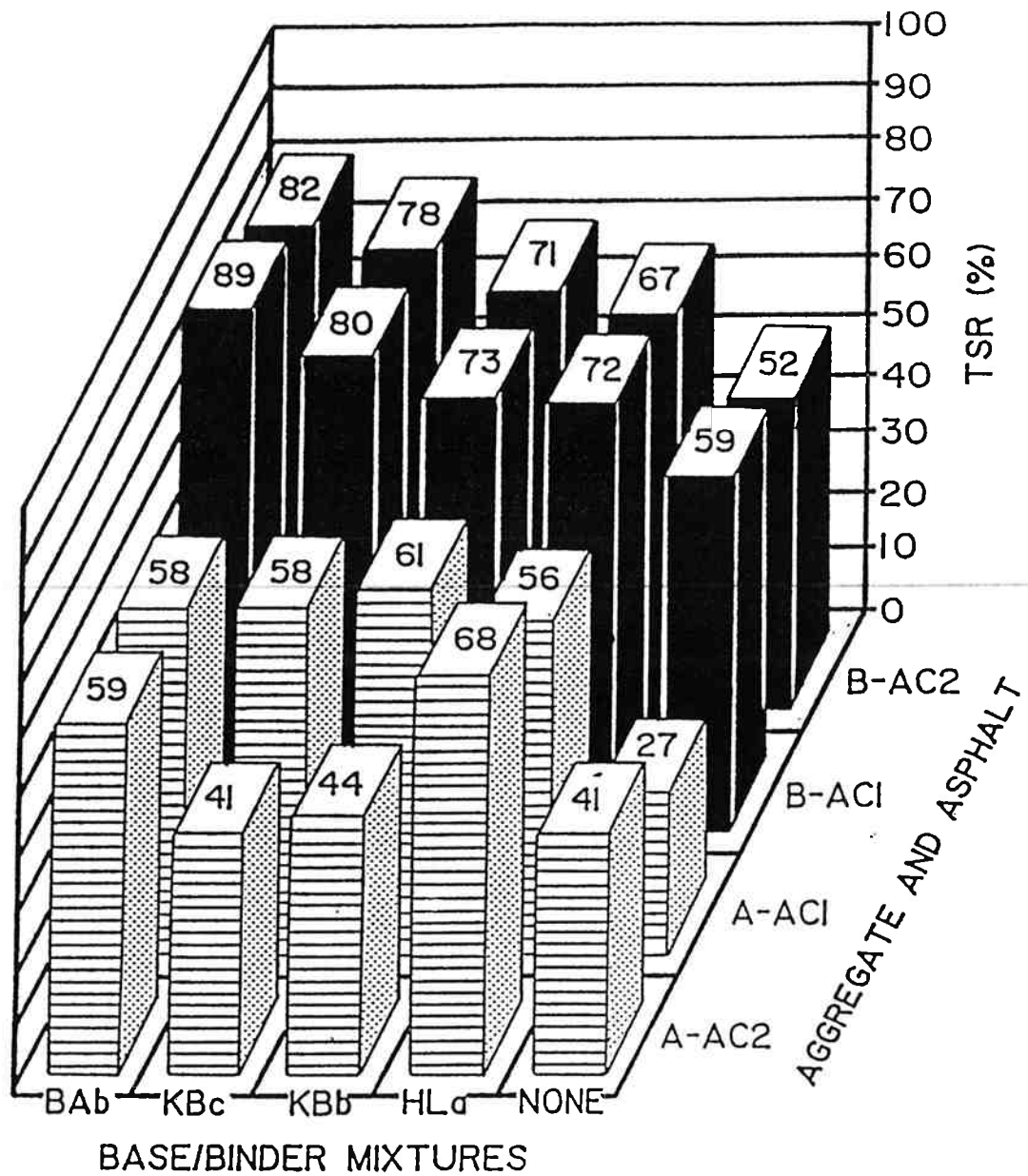


Figure 3.2. Results for Various Additive, Aggregate, and Asphalt Combinations (after Parker and Gharaybeh, 1988).

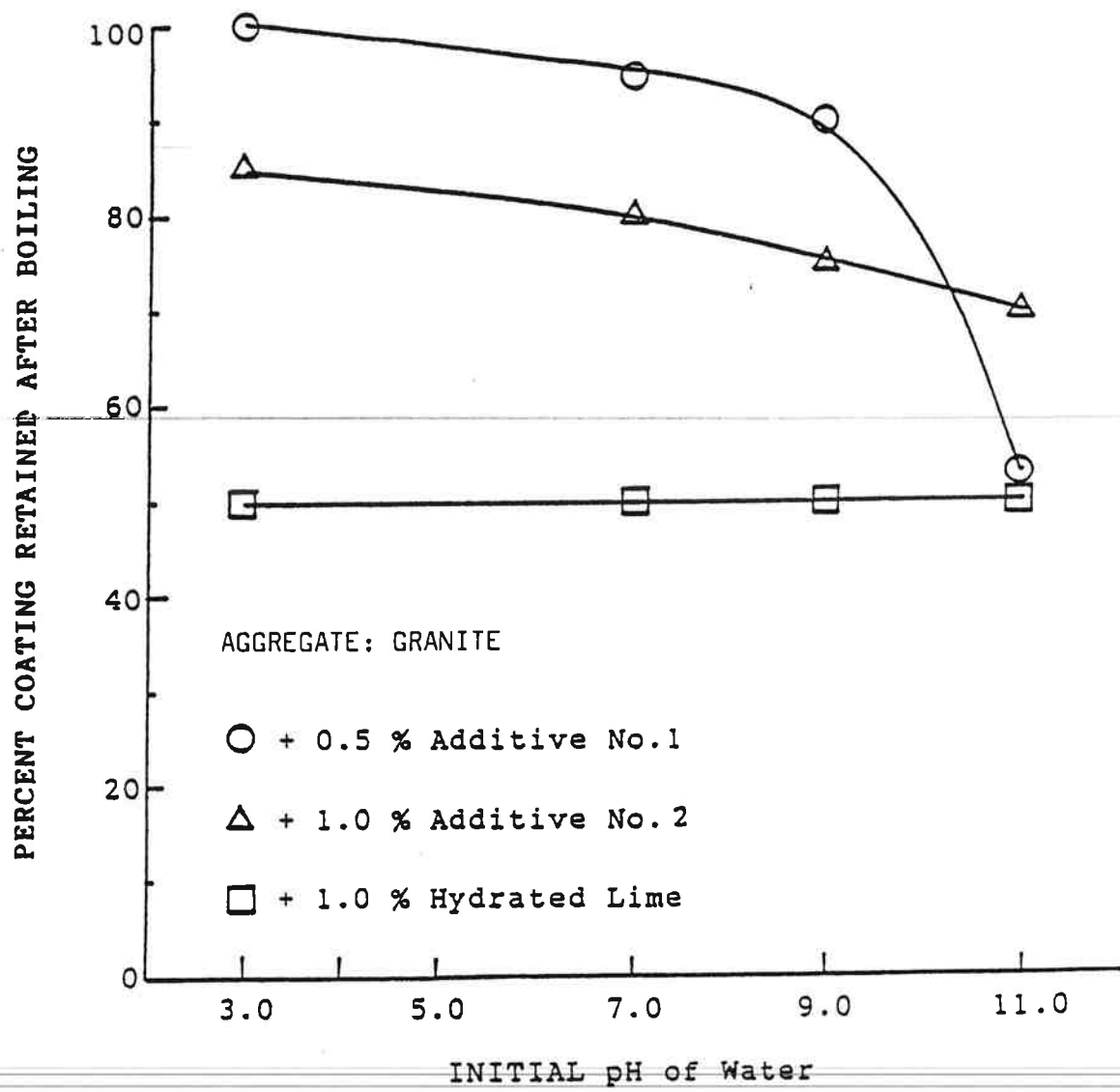


Figure 3.3. Effectiveness of Additives vs pH Values (after Yoon and Tarrer, 1988).

additive is reduced when the climate becomes drier and the traffic volume decreases. An ODOT test section using a liquid antistrip additive (0.5%) in one area and a combination of liquid antistrip additive and lime-treated aggregate on another area report no damage and good results 3 years after placing the mix. Previous experience with pavement constructed without additives on this highway indicates that damage should occur in 2 to 4 years.

3.2 Lime Additives

Recent studies on the effectiveness of lime have substantiated the fact that properly used lime can reduce the moisture susceptibility of an asphalt concrete mixture. Some authors indicate the benefit derived from the use of lime is considered to be instantaneous and therefore, the treated aggregate does not need to be stockpiled prior to mixing. If the treated aggregate is stockpiled too long, then carbonation may occur and render the lime ineffective for antistripping purposes (Kennedy, 1985). The rate of carbonation is dependent upon climatic conditions.

3.2.1 Laboratory Studies

Tunncliffe and Root (1986) report that lime was beneficial in all cases studied and that the accuracy achieved in the laboratory appears not to be required to achieve the same results in the field. The results of lab tests of field samples showed they were not sensitive to the amount of lime added. Therefore, some loss in the actual field procedures, which does not occur in the laboratory, should not significantly affect the results. The type of method (i.e., on the cold feed or in a pre-mix pugmill) system used to introduce the lime was found not to play a significant role in the results.

Studies have shown that greater resistance to moisture damage results from higher concentrations of lime. Coplantz and Epps (1987) found a 2% and 1% lime slurry mixture to be more effective than the liquid antistripping agents that were also tested. The 2% lime slurry mix being slightly more effective than the 1% mix (Figure 3.1). Kennedy (1985) found lime at 1.5% to be more effective than either 1% or at 0.5%. Lee and Al-Jarallah (1986) found the lime slurry effective on all mixes except those that were natural sands. Therefore, it is up to the testing agency to establish a minimum concentration level that is effective for their particular situation.

The addition of dry lime to reduce moisture susceptibility has produced mixed results. Coplantz and Epps (1987) did not note a significant effect in moisture susceptibility reduction when dry lime was added to dry aggregate, Maupin (1983) notes an acceptable improvement in 60% of the tested mixes and Stroup-Gardiner and Epps (1987) tests were successful when hydrated lime was added to the dry aggregate. The lack of moisture to fix the lime to the aggregate contributes to these mixed results.

The addition of quicklime may produce detrimental results if added to the asphalt. Stroup-Gardiner and Epps found the addition of quicklime to the dry aggregate did not improve the moisture susceptibility of the mix. When added to the asphalt cement directly the resistance to stripping was reduced.

If an aggregate has a high moisture content, lime may be used to improve the asphalt mixture. Kim et. al found the use of a 1% lime reduced damage that could be created from excessive moisture (3%) in a mix.

3.2.2 Field Studies

Jones (1971) evaluated several pavements three years after construction. Sections with 1% hydrated lime were significantly better than roadway sections without. The improvement was attributed to increased ductility and lower viscosity of the asphalt with lime. This is illustrated in Figure 3.4. Jones also states that lime reduces the pavement oxidation rate and may reduce the intrusion of water by reducing the amount of fatigue cracking that occurs. The solid line is from actual data and the dashed line represents an extrapolation of the curve. The improvement is expected to extend the life of the pavement approximately 2 years, which exceeds the break even point by 19 months.

In a study by Kennedy (1985), the addition of dry hydrated lime to a drum mixer, just prior to the addition of the asphalt cement, did not improve the resistance to moisture susceptibility of the mix. This was believed to be due to the loss of the hydrated lime prior to mixing.

3.3 Discussion

The moisture susceptibility of an asphalt mixture can be reduced by the use of antistripping additives. The effectiveness of lime and the proven (by testing for specific material combinations) use of liquid antistripping agents

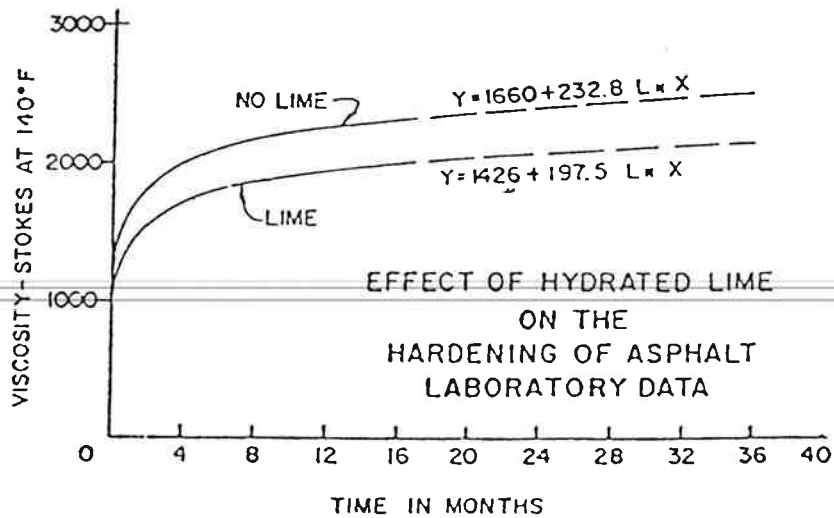
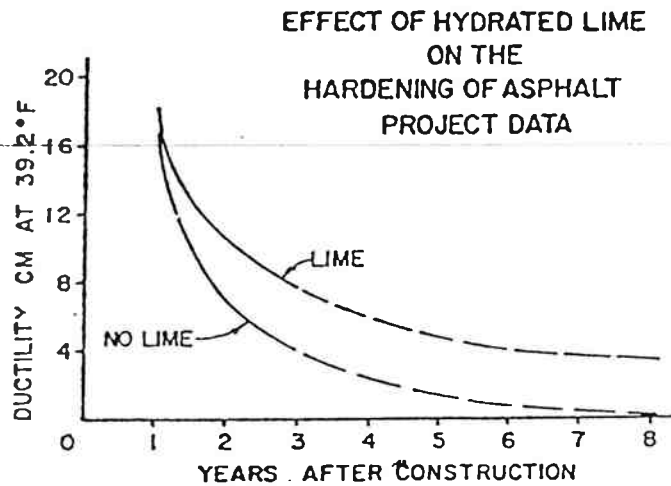
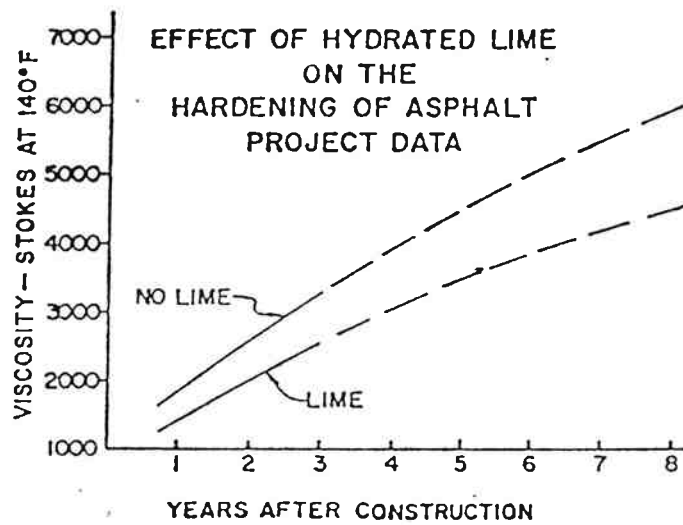


Figure 3.4. Effectiveness of Lime on Asphalt Oxidation (after Jones, 1971).

Malsch (1985) found that there was no satisfactory test procedure to evaluate the concentration of a liquid antistripping agent in the field. No field test is currently available to confirm that the actual concentration is the same as the design concentration. A visual inspection at the time the additive is mixed with the asphalt cement is the only check.

The addition of lime to an asphalt mixture has not appeared to provide any detrimental effects when added in correct concentrations (Schmidt and Graf, 1972). However, the correct concentration and method of application is job dependent. A 1% lime slurry is a common method of application with reports of improved lab results with 1.5% and even 2% concentrations. The addition of lime to wet aggregate or in a slurry form applied to the aggregates appears to consistently provide the desired results.

There is not yet an accepted standard by which an asphalt mixture is tested for moisture susceptibility. In reviewing the test methods, the tests discussed earlier seem to be consistently used. However, it is not uncommon to modify the procedure being used to fit the needs of the people and equipment used to conduct the tests.

The evaluation of the effectiveness of antistripping additives is at this time primarily based on lab test results. The long term effectiveness of certain additives has not yet been established. This process will be accomplished in the following years as results from test areas are analyzed and evaluated.

4.0 TESTING PROCEDURES

4.1 Overview

The development of tests to determine the stripping potential of asphalt mixtures has beginnings back to the 1930's. Since that time numerous tests have been developed to help identify moisture susceptible mixtures. The tests vary in how they test for stripping potential. In general, there are two categories by which the tests can be separated:

- 1) Those tests which coat "standard" aggregate with an asphalt cement (with or without additive). The loose uncompacted mixture is then immersed in water (which is either held at room temperature or brought to a boil). A visual determination is then made of the separation of asphalt from the aggregate.
- 2) The other group uses compacted specimens; either laboratory compacted or cores from existing pavement structures. These samples are then conditioned in some manner to simulate in-service conditions of the pavement structure. The results of these tests are generally evaluated by the ratios of conditioned to unconditioned results of either a diametral resilient modulus test, diametral tensile strength test, or both.

Stuart (1986) and Parker and Wilson (1986), in evaluating test procedures, found that from the tests they were evaluating that a single pass/fail criteria for any test could not be established that would result in 100% success. Therefore, the use of terms of "reasonable" and "good" are often used in conjunction with the description of how well the results of a test correlate with actual field performance, if there is sufficient data to make this determination.

4.2 Test Procedures

From a review of the literature, the following tests have received the most attention. Also, because they cover the variety of methods used to evaluate stripping potential, they were selected for review;

- a) NCHRP 246 – Indirect Tension Test and/or Modulus test with Lottman Conditioning,

- b) NCHRP 274 – Indirect Tensile Test with Tunnicliff and Root Conditioning,
- c) Boiling Tests,
- d) Immersion Compression Tests (ASTM D 1075, AASHTO T-165), and
- e) Texas Freeze–Thaw Pedestal Test.

An outline of each procedure is provided in Tables 4.1 to 4.5. The tables also list some of the advantages and disadvantages associated with each procedure.

4.2.1 NCHRP 246 - Lottman Indirect Tension Test

In the Lottman procedure, the specimens are 4 in. diameter by 2.5 in. height and are compacted to the air void content expected in the field. An index of retained strength (IRS) or modulus (IRM) is obtained by dividing the test values from the conditioned samples by the values obtained from the unconditioned samples. A ratio of 0.70 or greater is recommended by Lottman and Maupin (1982) who reported differentiating between stripping and non-stripping when values were between 0.70 and 0.75.

Some have argued the Lottman procedure is too severe because of internal water pressures that develop from the vacuum freeze to warm water soak.

Stuart (1986) and Parker and Gharaybeh (1987) found a good correlation between the laboratory and field results.

4.2.2 NCHRP 274 - Tunnicliff and Root Test

This test focuses on controlling the degree of saturation in the test specimen. If the test specimen is not at 55% saturation after the initial vacuum soaking, then the specimen is returned for additional soaking until a saturation level between 55% and 80% is reached. If, after the initial vacuum soaking the sample is above the 80%, the sample is discarded. The saturation level is important to ensure that enough moisture is present for stripping to occur.

A tensile strength ratio (TSR) is used to evaluate the test results. As with the IRS, the TSR is obtained by dividing the value for the tensile strength from the conditioned sample by the result for the unconditioned sample. Instead of a minimum ratio, a statistical 't' test is performed and the desired confidence level used to determine the effectiveness of an additive.

Table 4.1. NCHRP 246 – Indirect Tension Test and/or Modulus Test with Lottman Conditioning

Specimens	9 samples divided into 3 groups Size: 4-in. diameter by 2.5-in. height				
Compaction	ASTM Methods: D1559 or D1561 or D3387				
Air Voids (%)	Expected Field Level or Mix Design Value				
Procedure	Group I: • Water bath (in jars) for 5 hours → Test				
	Group II & III: • Vacuum saturation @ 26 in. Hg for 30 min • Atmospheric pressure, submerged, for 30 min				
	Group II: • Water bath @ test temperature for 3 hours → Test				
	Group III: • Freeze @ 0.0°F for 15 hours • Water bath @ 140°F for 24 hours • Water bath @ test temperature for 3 hours → Test				
	Note: Tests can be run at 55°F or 73°F				
Damage Analysis	Ratios: Diametral Resilient Modulus Test Diametral Tensile Strength Test <table style="width: 100%; border: none;"> <tr> <td style="text-align: center; border: none;">$\frac{\text{Group II}}{\text{Group I}}$</td> <td style="text-align: center; border: none;">Short Term (saturation)</td> <td style="text-align: center; border: none;">$\frac{\text{Group III}}{\text{Group I}}$</td> <td style="text-align: center; border: none;">Long Term (accelerated)</td> </tr> </table>	$\frac{\text{Group II}}{\text{Group I}}$	Short Term (saturation)	$\frac{\text{Group III}}{\text{Group I}}$	Long Term (accelerated)
$\frac{\text{Group II}}{\text{Group I}}$	Short Term (saturation)	$\frac{\text{Group III}}{\text{Group I}}$	Long Term (accelerated)		
Advantages	<ul style="list-style-type: none"> • Conducted on lab mixes, field mixes, or core samples • Severe test • Can differentiate between additive levels • Good correlation with field performance • Does not give biased results toward lime or liquid additive 				
Disadvantages	<ul style="list-style-type: none"> • Time consuming (about 3 days for one freeze-thaw cycle) • Amount and type of equipment required is not always readily available 				

Table 4.2. NCHRP 274 – Indirect Tensile Test with Tunnicliff and Root Conditioning

Specimens	6 samples – 2 groups of 3 Size: 4-in. diameter x 2.5 in. height (for aggregate ≤ 1 in.)
Compaction	ASTM Methods: D1559 or D1561 or D3387
Air Voids (%)	6 to 8 or expected field level
Procedure	Sort into groups so average air voids are approximately equal Group I: <ul style="list-style-type: none"> • Store dry at room temperature • Prior to testing, soak 20 min. @ 77°F → Test Group II: <ul style="list-style-type: none"> • Obtain a 55% to 80% saturation level (20 in. Hg for about 5 min in distilled water) • Reject if saturation is > 80% • Soak 24 hours @ 140°F • Soak 1 hour @ 77°F • Test
Damage Analysis	<ul style="list-style-type: none"> • Diametral Tensile Strength (ASTM D 4123) • Visual
Advantages	<ul style="list-style-type: none"> • Can use lab, plant, or field mixes; also cores from existing pavements • Mixtures with or without additives • Time required is moderate • Initial indications show good correlation (based on 80% retained strength)
Disadvantages	<ul style="list-style-type: none"> • May require trial specimens to obtain air void level • May not be severe enough

Table 4.3. Boiling Tests.

Specimens	<p>Field mixture representation @ design AC or Individual aggregate size (coat aggregate with AC)</p> <p>Note: • Use of 200 or 300 gram sample is common • Use of agitation is agency dependent • Specific evaluation techniques vary among agencies</p>
Compaction	None – Loose mix sample
Air Voids (%)	Not applicable
Procedure	<ul style="list-style-type: none"> • Place 500 ml of distilled water in 1000 ml beaker • Heat to boil, then add mixture • Boil 10 min, stirring 3 times with glass rod • Skim asphalt off surface • Cool to room temperature, dry on paper towel
Damage Analysis	<ul style="list-style-type: none"> • Visual assessment • Texas Boiling Test < 70% retained indicates moisture susceptibility
Advantages	<ul style="list-style-type: none"> • Can be used for initial screening • Minimum amount of equipment required • Can be used to test additive effectiveness • May be used for quality control • Can use lab mix or field mix
Disadvantages	<ul style="list-style-type: none"> • Subjective analysis • Uncompacted mix • Water purity can affect coating retention • Assessment of stripping in fines is difficult

Table 4.4. Texas Freeze-Thaw Pedestal Test.

Specimens	3 to 5 briquets 1-5/8-in. diameter x 3/4-in. height AC @ 5% > optimum Aggregate: Passes No. 20 (0.850 mm), Retained No. 35 (0.500 mm) sieve
Compaction	In mold under 6200 lb for 20 min
Air Voids (%)	Not specified
Procedure	<ul style="list-style-type: none"> • Cure briquets @ 75°F for 3 days • Place specimens on stress pedestal in water bottle • Freeze @ 10°F for 15 hours • Place in warm water 75°F (room temperature) for 45 min • Place in 120°F oven for 9 hours • Repeat, beginning at freeze, if cracking is not present
Damage Analysis	<ul style="list-style-type: none"> • Visual observation • If crack develops in < 10 cycles, moisture susceptible • > 20-25 cycles, resists moisture damage
Advantages	<ul style="list-style-type: none"> • Used to test additive effectiveness
Disadvantages	<ul style="list-style-type: none"> • Uses only a small portion of the mix • Only fair correlation between field and lab results • Measures only cohesion • Takes time, 1 day for each cycle

Table 4.5. Immersion-Compression Tests (ASTM D-1075, AASHTO T-165).

Specimens	6 samples – 2 groups of 3 4 in. x 4 in.
Compaction	Double plunger – pressure 3000 psi for 2 min (ASTM)
Air Voids (%)	6
Procedure	Group I: Air cured for ≥ 4 hours @ 77°F → Test
	Group II: <ul style="list-style-type: none"> • Water bath @ 120°F for 4 days • Water bath @ 77°F for 2 hours → Test (Alternate) <ul style="list-style-type: none"> • Water bath @ 140°F for 24 hours • Water bath @ 77°F for 2 hours → Test
Damage Analysis	<ul style="list-style-type: none"> • Visual assessment • Unconfined compression @ 77°F and 0.2 in./min
Advantages	<ul style="list-style-type: none"> • Uses actual mix
Disadvantages	<ul style="list-style-type: none"> • Time required can be extensive • Poor reproducibility • Air void level plays significant role • Water quality (ions and salts) can affect moisture sensitivity • Equipment may not be readily available

Results from the test appear to reflect the field performance results (Stuart, 1986).

4.2.3 Boiling Tests

This test is a result of the assimilation of different boiling tests used by several state agencies (Kennedy, 1983). Kennedy (1983) recommends the test be used as an initial screening procedure because it provides reasonable results for differentiating between stripping and nonstripping mixtures, while others offer its benefits for use in quality control in field laboratories.

In Stuart's (1986) evaluation of the procedure, boiling times of 1 minute and 10 minutes were used. He concluded the 1 minute test provided poor results as did the 10 minute test. However, the 10 minute test may prove useful for field determination for the presence of additives. Lee and Al-Jarallah (1986) and Parker and Wilson (1986) found the test to provide good correlations between the lab results and field performances. Also, the effectiveness of antistrip additives could be established, but the selection of aggregates that were likely to strip could not be determined (Parker and Wilson, 1986). Parker and Gharaybeh (1987) report the boiling test did not evaluate the effects of lime correctly.

Parker and Wilson (1986) found consistent correlation in their results between mixes, antistripping agents, and asphalt cements when using the Texas Boiling Test. They state the results indicate there is a potential for use of the boiling test as an indicator of an antistripping agents effectiveness. This conclusion is supported in a separate study by Lee and Al-Jarallah (1986).

4.2.4 Texas Freeze-Thaw Pedestal Test

This test is empirically based and attempts to simulate viscosity levels at 5 years of pavement life. This test was designed to minimize effects of mechanical properties while emphasizing the strength of the bond, and asphalt cohesion. This is a result of the use of uniform size aggregate in the test.

Parker and Wilson (1986) found the test to provide a poor correlation between the laboratory and field results. Based on the materials available in Alabama the test showed little potential for identifying moisture susceptible mixes or for isolating components that contribute to stripping. In contrast,

Kennedy (1983) asserts the pedestal test has excellent potential and can be used to determine individual stripping components. Also, good results can be achieved in determining the stripping potential of a mix.

4.2.5 Immersion Compression Tests (ASTM D-1075,AASHTO T-165)

This type of test is currently used by many agencies. The loss of cohesion due to stripping is evaluated. The Asphalt Institute recommends that mixtures with an IRS less than or equal to 75% should be rejected.

4.3 Discussion

It is apparent from the literature review that a variety of test methods have been employed to assess (1) the potential for stripping in asphalt concrete mixes, or (2) the benefits offered by agents to simulate moisture induced damage to asphalt concrete mixes. So far, one test has not proven to be "superior." Neither can any test correctly distinguish a moisture susceptible mix in all cases.

In evaluating the results from conditioned and unconditioned samples, the determination of stripping versus nonstripping should not be made based solely on the modulus or tensile strength ratios. Scherocman et al. (1986) and Busching (1986) report that the use of chemical additives can significantly increase the unconditioned strengths of test samples. The increase in strength for the conditioned sample is not proportional and a lower retained strength ratio can occur even though the values for both the conditioned and unconditioned samples have increased.

In reviewing the conditioning procedures, two common methods stand out. One is the use of a vacuum saturation to "force" moisture into the test specimen without freezing and the other is the use of a freeze-thaw cycle to induce moisture damage to the specimen. Coplantz and Newcomb (1988) report, from their evaluation of four different conditioning procedures, that vacuum saturation alone did not induce moisture related damage to the mixture. This is supported in other work by Coplantz (1987). In a report by Busching et al. (1986), after saturation conditioning of the test specimens for 60 days, it was determined that high saturation levels that could occur in wet environments would significantly affect retained strengths even in the absence of freeze-thaw cycles. The use of one freeze-thaw cycle is common (except the

stress-pedestal test and Tunncliffe and Root conditioning procedure). The results from the one cycle can be used to make initial determinations as to the effectiveness of a mixture with or without an additive. However, to obtain an improved indication of the long term effectiveness of the mix multiple freeze-thaw cycles should be evaluated (Coplantz, 1987). As the number of cycles increase the damage per cycle decreases. Also, an order of retained ratios for a given group of additives would likely not remain the same (Coplantz and Newcomb, 1988; Scherocman et al., 1986), for example, for a group of five additives group A may have the highest ratio after one freeze-thaw cycle, but only the third highest retained ratio after three freeze-thaw cycles. Additives which have the higher retained values after several freeze-thaw cycles (5 to 7) would indicate a higher long-term performance.

The Tunncliffe and Root procedure (NCHRP 274) is a recent development. Stuart (1986) reported favorable results from the test data. The use of a freeze-thaw cycle is not incorporated into the test. The focus is on saturation of the test specimen, which for a short duration (approximately one day for the Tunncliffe and Root procedure), has been reported as not sufficient to induce moisture related damage (Coplantz and Newcomb, 1988). However, this testing procedure is currently undergoing further evaluation and these results should provide a better understanding of the procedure and its use in evaluating the moisture susceptibility of asphalt concrete mixtures.

5.0 REFERENCES

- Al-Ohaly, A.A. and Terrel, R.L., "Effect of Microwave Heating on Adhesion and Moisture Damage of Asphalt Mixtures," presented at the Jan. 11-14, 1988, Transportation Research Board Meeting, Washington, D.C.
- American Society for Testing Materials, Symposium on Effect of Water on Bituminous Paving Mixtures, *ASTM STP 240*, 1958.
- Becker, W., "Improvement of the Adhesiveness of Bituminous Binders to Stone by Addition to the Binder," *Strasse*, 1941, pp. 7-8, 154-159.
- Brown, A.B., Sparks, J.W., and Marsh, G.E., "Objective Appraisal of Stripping of Asphalt from Aggregate," *Special Technical Publication No. 240*, ASTM, 1959, pp. 59-74.
- Busching, H.W., Amirhanian, S.N., Burati, J.L., Alewine, J.M., and Fletcher, M.O., "Effects of Selected Asphalts and Antistrip Additives on Tensile Strength of Laboratory-Compacted Marshall Specimens - A Moisture Susceptibility Study," *Proceedings*, Association of Asphalt Paving Technologists, vol. 55, 1986, pp. 120-148.
- Busching, H.W., Corley, G.C., Buralti, J.L., Amirhanian, S.N., and Alenine, J.N., "A Statewide Program to Identify and Prevent Stripping Damage," *ASTM STP 899*, American Society for Testing and Materials, Dec. 1985, pp. 7-21.
- Button, J.W., "Maximizing the Beneficial Effect of Lime in Asphalt Paving Mixtures," *ASTM STP 899*, American Society for Testing and Materials, Dec. 1985, pp. 134-146.
- Castedo, A., Beaudoin, C.C., Wood, L., and Attschaeffl, A.G., "A Laboratory Study of the Effectiveness of Various Mixtures on the Alternation of Moisture Damage Upon Various Foamed Asphalt Mixtures," *ASTM STP 899*, American Society for Testing and Materials, Dec. 1985, pp. 104-118.
- Chehovits, J.G. and Anderson, D.A., "Upgrading of Marginal Aggregates for Improved Water Resistance of Asphalt Concrete," *TRR 727*, Transportation Research Board, Washington, D.C., Jan. 1980.
- Coplantz, J.S., "Laboratory Test Methods to Predict Water Induced Damage to Asphalt Concrete", "*Masters Thesis*", submitted to the Graduate College of University of Nevada-Reno, 1987.
- Coplantz, J.S., Epps, J.A., and Quilici, L., "Antistrip Additives: Background for a Field Performance," *TRR 1115*, Transportation Research Board, Washington, D.C., 1987, pp. 1-11.
- Coplantz, J.S. and Newcomb, D.E., "Water Sensitivity Test Methods For Asphalt Concrete Mixtures - A Lab Comparison," presented at the Jan. 11-14, 1988, Transportation Research Board Meeting, Washington, D.C. (Preprint 870224).
- Douglas, J.F., "Adhesion Between Binders and Aggregates," *Journal of Institution of Civil Engineers*, England, No. 3, Jan. 1947, p. 292.

- Dybalski, J.N., "Cationic Surfactants in Asphalt Adhesion," *Proceedings, Association of Asphalt Paving Technologists*, vol. 51, 1982, pp. 293-297.
- Fromm, H.J., "The Mechanisms of Asphalt Stripping from Aggregate Surfaces," *Proceedings, Association of Asphalt Paving Technologists*, vol. 43, 1974, pp. 191-223.
- Gzemski, F.C., "Factors Affecting Adhesion of Asphalt to Stone," *Proceedings, Association of Asphalt Paving Technologists*, vol. 9, 1937, pp. 87-101.
- Hartman, J., "Anti-Stripping Agents," *Technical Bulletin 1*, Scan Road International Ltd., Singapore, 1983.
- Held, A., "Considerations of Aggregate Surface and Asphalt Cement Surface Chemistry Relative to Stripping of AC Pavements," Appendix to "Test Method to Determine the Degree of Asphalt Stripping from Aggregate," Kelly, P.B. et al., USDOT DTRS-57-85-C-00170, Mar. 1986, pp. B1-B8.
- Hubbard, P., "Adhesion in Bituminous Road Materials: A Survey of Present Knowledge," *Journal of the Institute of Petroleum*, vol. 44, no. 420, Dec. 1958, pp. 423-432.
- Ishai, I. and Craus, J., "Effect of the Filler on Aggregate-Bitumen Adhesion Properties in Bituminous Mixtures," *Proceedings, Association of Asphalt Paving Technologists*, vol. 46, 1977, pp. 228-258.
- Jensen, H., "Anti-Stripping Agents - Function, Applications and Methods," *Technical Bulletin 1*, Scan Road International, Singapore, 1983.
- Jones, G.M., "The Effect of Hydrated Lime on Asphalt in Bituminous Pavements," presented at the May 22, 1971, National Lime Association Meeting, Colorado Springs, Colorado.
- Kennedy, T.W., Roberts, F.L., Lee, K.W., "Evaluation of Moisture Effects on Asphalt Concrete Mixtures," *TRR 911*, Transportation Research Board, Washington, D.C., Jan. 1983.
- Kennedy, T.W., "Use of Hydrated Lime in Asphalt Paving Mixtures," Bulletin #325, National Lime Association, Mar. 1984.
- Kennedy, T.W., "Prevention of Water Damage in Asphalt Mixtures," Evaluation and Prevention of Water Damage to Asphalt Pavement Materials, *ASTM STP 899*, B.E. Ruth, Ed. American Society for Testing and Materials, Philadelphia, 1985, pp. 119-133.
- Kim, O.K., Bell, C.A., and Hicks, R.G., "The effect of Moisture on the Performance of Asphalt Mixtures," Water Damage of Asphalt Pavements: Its Effect and Prevention, *ASTM STP 899*, B.E. Ruth, Ed., American Society for Testing and Materials, Philadelphia, 1985, pp. 51-72.
- Knight, B.H., "The Adhesion of Bituminous Binders to Road Aggregates," *The Surveyor*, vol. 93, no. 2300, Jan. 1938, pp. 77-80.
- Krebs, R.D. and Walker, R.D., *Highway Materials*, McGraw-Hill Book Company, 1971.
- Lee, A.R., "Adhesion in Relation to Bituminous Road Materials," *Journal of the Society of Chemical Industry*, Feb. 1936, pp. 23-29.

- Lee, K.L. and Al-Jarallah, M.I., "Utilization of Texas Boiling Test to Evaluate Effectiveness of Antistripping Additives in Saudi Arabia," *TRR 1096*, Transportation Research Board, Jan. 1986, pp. 81-89.
- Lottman, R.P., "Predicting Moisture-Induced Damage to Asphaltic Concrete," *NCHRP Report 192*, Transportation Research Board, 1978.
- Lottman, R.P., "Predicting Moisture-Induced Damage to Asphaltic Concrete - Field Evaluation," *NCHRP Report 246*, Transportation Research Board, Washington, D.C., May 1982.
- Mack, C., "Physio-Chemical Aspects of Asphalt Pavements: Energy Relations at Interface Between Asphalt and Mineral Aggregate and Their Measurement," *Industrial and Engineering Chemistry*, Dec. 1935, pp. 1500-1505.
- Majidzadeh, K. and Brovold, F.N., "State of the Art: Effect of Water on Bitumen-Aggregate Mixtures," *Highway Research Board Special Report 98*, 1968.
- Malsch, D.A., "Evaluating the Effectiveness of Liquid Antistrip Additives in Asphalt Cement," *WA-RD-85.1*, Washington State DOT, 1986.
- Mathews, D.J., "Adhesion in Bituminous Road Materials: A Survey of Present Knowledge," *Journal of the Institute of Petroleum*, vol. 44, no. 420, Dec. 1958, pp. 423-432.
- Maupin, G.W., "Final Report - Laboratory Investigation of Hydrated Lime as an Antistripping Additive," *FHWA/VA-84/14*, 1983.
- McBain, J.W. and Hopkins, D.G. "Adhesives and Adhesive Action," Appendix IV. Second Report of the Adhesive Research Committee, *Department of Scientific and Industrial Research*, London, 1962, p. 34.
- Mertson, E.W. and Wright, J.R., "Cationic Asphalt Emulsions: How They Differ from Conventional Emulsions in Theory and Practice," *Proceedings*, Highway Research Board, 1959, pp. 386-397.
- Nicholson, V. "Adhesion Tension in Asphalt Pavements, It's Significance and Methods Applicable in It's Determination," *Proceedings*, Association of Asphalt Paving Technologists, vol. 3, 1932, pp. 29-49.
- Parker, F. and Wilson, M.S., "Evaluation of Boiling and Stress Pedestal Tests for Assessing Stripping Potential of Alabama Asphalt Concrete Mixtures," *TRR 1096*, Transportation Research Board, Jan. 1986, pp. 90-99.
- Parker, F. and Gharaybeh, F., "Evaluation of Tests to Assess Stripping Potential of Asphalt Concrete Mixtures," Presented at the Jan. 11-14, 1988 Transportation Research Board Meeting, Washington D.C. (Preprint 870063).
-
- Petersen, J.C., Plancher, H., and Harnsberger, P.M., "Lime Treatment of Asphalt - Final Report," National Lime Association, 1987.
- Plancher, H., Dorrence, S.M., and Peterson, F.C., "Identification of Chemical Types in Asphalts Strongly Absorbed at the Asphalt-Aggregate Interface and Their Relative Displacement by Water," *Proceedings*, Association of Asphalt Paving Technologists, vol. 46, 1977, pp. 151-175.

- Rice, J.M., "Relationship of Aggregate Characteristics to the Effect of Water on Bituminous Paving Mixtures," *ASTM STP 240*, American Society for Testing and Materials, 1958, pp. 17-33.
- Riedel, W. and Weber, H., "On the Adhesiveness of Bituminous Binders on Aggregates," *Asphalt und Teer*, vol. 33, 1953.
- Road Research Laboratory, "Bituminous Materials in Road Construction," *Department of Scientific and Industrial Research*, Her Majesty's Stationery Office, London, 1962, pp. 68-88; 316-333.
- Saville, V.B. and Axon, E.O., "Adhesion of Asphaltic Binders to Mineral Aggregates," *Proceedings*, Association of Asphalt Paving Technologists, vol. 9, 1937, pp. 87-101.
- Schmidt, R.J. and Graf, P.D., "The Effect of Water on the Resilient Modulus of Asphalt Treated Mixes," *Proceedings*, Association of Asphalt Paving Technologists, vol. 41, 1972, pp. 118-162.
- Scott, J.A.N., "Adhesion and Disbonding Mechanisms of Asphalt Used in Highway Construction and Maintenance," *Proceedings*, Association of Asphalt Paving Technologists, vol. 47, 1978, pp. 19-48.
- Strauss, F.H. and Anderson, A.P., "Stripping Versus Coating of Mineral Aggregates," *Proceedings*, Association of Asphalt Paving Technologists, vol. 13, 1942, pp. 1-8.
- Stroup-Gardiner, M. and Epps, J.A., "Four Variables That Affect Lime in Asphalt-Aggregate Mixtures," *TRR 1115*, Transportation Research Board, Washington, D.C., Jan. 1987, pp. 12-22.
- Stuart, K.D., "Evaluation of Procedures Used to Predict Moisture Damage in Asphalt Mixtures," FHWA/RD-86/091, 1986.
- Takallou, H.T., "Stripping of Asphalt Pavements: State of the Art," *Masters Thesis*, submitted to the Department of Civil Engineering, Oregon State University, 1984.
- Taylor, M.A. and Khosla, N.P., "Stripping of Asphalt Pavements. State of the Art," *TRR 911*, Transportation Research Board, Washington, D.C., Jan. 1983, pp. 150-158.
- Thelen, E., "Surfacing Energy and Adhesion Properties in Asphalt-Aggregate Systems," *Highway Research Board, Bulletin 192*, 1958, pp. 63-74.
- Tunnickliff, D.H. and Root, R.E., "Anti-Stripping Additives in Asphalt Concrete State of the Art," *Proceedings*, Association of Asphalt Paving Technologists, vol. 51, 1982, pp. 265-289.
- Tunnickliff, D.G. and Root, R.E., "Use of Antistripping Additives in Asphaltic concrete Mixtures," *NCHRP Report 274*, Transportation Research Board, Washington, D.C., Dec. 1984.
- Tunnickliff, D.G. and Root, R.E., "Introduction of Lime Into Asphalt Concrete," FHWA/RD-86/071, 1986.
- Tyler, O.R., "Adhesion of Bituminous Films to Aggregates," *Purdue University Research Bulletin*, no. 62, vol. 22, Sep. 1938.

- Winterkorn, H.F., Eckert, G.W. and Shipley, E.B., "Testing the Adhesion Between Bitumen and Mineral Surfaces with Alkaline Solutions," *Proceedings*, Association of Asphalt Paving Technologists, vol. 9, 1937, pp. 63-85.
- Yoon, H.H. and Tarrer, A.R., "Effect of Aggregate Properties on Stripping," presented at the Jan. 11-14, 1988, Transportation Research Board Meeting, Washington D.C. (Preprint 870077).
- Yoon, H.H., Tarrer, A.R., Roberts, F.L., and Kiggundu, B.M., "Thermal Degradation Properties of Antistripping Additives and Enhanced Performance by Curing," presented at the Jan. 1989, Transportation Research Board Meeting, Washington, D.C.
- Zeisman, W.A., "Influence of Constitution on Adhesion," *Industrial and Engineering Chemistry*, vol. 55, no. 10, Oct. 1963, pp. 18-38.