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Pavement Stripping in Saudi Arabia: Prediction and Prevention

H.I. Al-Abdul Wahhab*[1], I.M. Asi[1], S.A. Ali[2], S. Al-Swailmi[3] and A. Al-Nour[4]

[1] Department of Civil Engineering, King Fahd University of Petroleum & Minerals, Dhahran 31261, Saudi Arabia.
[2] Department of Chemistry, King Fahd University of Petroleum & Minerals, Dhahran 31261, Saudi Arabia.
[3] Operations & Maintenance, Riyadh Municipality, Riyadh, Saudi Arabia.
[4] M&R Department, Ministry of Communications, Riyadh, Saudi Arabia.

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المستخلص: تعتبر عملية انفصال الحصمة من طبقات الرصف بسبب عوامل التعرية المناخية من الظواهر الرئيسية التي تتعرض لها شبكات الطرق في المناطق القاحلة. لدراسة هذه الظاهرة تم اختيار سبعةعشر طريق بالمملكة منها ثمانية طرق تعاني من ظاهرة انفصال الحصمة بينما تسعة منها تعتبر سليمة. تم تجميع الركام من جميع المصادر التي بنيت منها هذه الطرق وتمت دراستها وتحليلها فيزيائيا وكيميائيا لتحديد الخصائص التي قد يكون لها دور في زيادة قابلية التعرية وتطاير الحصمة من الطرق. ايضا تم اجراء اختبار حساسية المياه على الخرسانة الاسفلتية في العينات المدموكة لتحديد امكانية التمييز بينها. كما تم اجراء اختبار الزجاجة السويدية الدوارة وقد وجد انه يمكن الاعتماد عليه في التمييز بين عينات الركام القابل للتعرية والغير قابل للتعرية. تمت دراسة امكانية تحسين مقاومة الحصمة للتعرية باستخدام مجموعة من المضافات للخلطات الاسفلتية تشمل ١١ مركب كيميائي، الجير المطفي، واسمنت عادي، بالاضافة لنوعين من اللدائن. وجد ان لدائن ايستمان (EE-2) والاسمنت العادي كانت اكثر المواد فعالية في زيادة مقومة الخلطات السفلتية لكل انواع الحصمة ضد التطاير والتعرية.

الكلمات المفتاحية: تطاير الحصمة، الرصف، اللدائن، مضافات كيميائية، اختبار تاثير المياه

Abstract: Pavement weathering or stripping is a major distress in highway networks in arid regions. Using the Saudi Arabian road network as a case study area, seventeen road test sections were selected, out of which eight were stripped and nine were non-stripped. Aggregates from quarries used to build these sections were also collected and subjected to detailed physical and chemical tests to evaluate the ability of these tests to distinguish between stripped and non-stripped sections. The modified Lottman test was used to distinguish between compacted mixes. In addition, the Swedish Rolling Bottle test, was also found to be effective in being able to distinguish between different asphalt-aggregates for stripping potential. Eleven anti-stripping liquid additives, lime and cement, in addition to two polymers, were evaluated for their ability to reduce/eliminate stripping potential of stripping-prone aggregates. It was found that EE-2 Polymer, Portland cement, and their combination were effective with all aggregate sources.

Keywords: Pavement stripping, Roads, Polymer, Anti-stripping agents, Lottman test

1. Introduction

Aggregate chemistry plays a key role in asphalt-aggregate adhesion. It was found (Curtis et al., 1993) that when cohesive asphalt failures do not occur, aggregate chemistry is much more influential than asphalt composition. Active sites on the aggregate surface promote adsorption of polar asphaltic compounds. When these active sites are covered by non-polar compounds or dust that exist naturally on the aggregate surface, the bonding force that maintains the pavement is weakened. Curtis et al. (1991) developed a limestone reactivity test that can determine the number of active sites present on the aggregate surface.

After laying the pavement, asphalt-aggregate bonding forces can be weakened by the effects of water. Water molecules intrude or diffuse to the aggregate surface and compete with the polar asphaltic compounds for interactions with the active sites. The affinity or compatibility of an asphalt-aggregate pair is very important for minimization of water induced damage. If the affinity is large, only a small percentage of the asphalt-aggregate interaction sites will be lost to water molecules.

*Corresponding author E-mail: hawahab@kfupm.edu.sa

Pairs of low affinity will lose a large percentage of the asphalt-aggregate interaction sites to the more polar and hydrogen bonding water molecules. This leads to stripping. Tests were devised (Curtis et al., 1993) to determine this important affinity or compatibility for different pairs of asphalt-aggregates. If water is the cause of an asphalt-aggregate problem, these tests will allow one to evaluate the possibility of future pavement stripping based on this affinity.

When an aggregate absorbs water, the asphalt is "stripped" away. This ultimately leads to pavement failure. Moisture degrades the integrity of an asphalt concrete matrix in three areas: loss of cohesive strength in the asphalt film, failure of the adhesive bond between the aggregate and asphalt (stripping), and loss of the chemical bond (integrity) between the asphalt film and the aggregate. Other modes of pavement failure due to the presence of water are also possible. Water can remove the soluble compounds from the asphalt causing it to fail. Failure within the aggregate can also occur. Water can promote phase separation within the asphalt, where the more polar molecules form a separate phase with water.

A reduction in water induced damage can be achieved by selecting asphalt-aggregate pairs of high affinity, modifying the aggregate surface through silylation, or adding antistripping agents. Building roads with low air voids and good drainage reduces water-induced damage by limiting the exposure to water.

The pH of the medium can also affect the asphalt-aggregate bond. It was found (Curtis et al., 1993) that a high pH (basic or alkaline environment) is detrimental to most asphalt-aggregate bonds. Additives such as lime or some liquid anti-stripping agents can improve the performance of some asphalt-aggregate pairs in highly basic environments.

Among the many factors that contribute to the degradation of asphalt concrete pavements, moisture is a key element in the deterioration of the asphalt mix. Since the 1930s, pavement engineers have been working to determine the moisture sensitivity of asphalt concrete mixtures. Since that time, numerous tests have been developed to identify moisture-susceptible asphalt concrete mixtures. In general, there are two categories into which the water sensitivity tests can be divided. The first category includes tests which coat "standard" aggregates with asphalt cement. In these tests, the loose mixture is immersed in water, either at room temperature or at boiling temperature, and a visual evaluation is made of the separation of asphalt from the aggregate. The second category includes those tests that use compacted specimens, either laboratory compacted or cores from existing pavement structures (Terrel and Shute, 1989). These specimens are then water conditioned to simulate the in-service conditions of the pavement structure. The results of these tests are generally evaluated by the ratios of conditioned to unconditioned results using a stiffness or strength test, such as the diametral resilient modulus test.

Several methods have been developed to determine if an asphalt concrete mix is sensitive to water. The main methods can be summarized as follows (Terrel and Shute, 1989; Curtis et al., 1991; Terrel and Al-Swailmi, 1992; AASHTO, 1995):

1. NCHRP 246 – Indirect Tensile Test and/or Modulus Test with Lottman Conditioning.
2. NCHRP 247 – Indirect Tensile Test with Tunnicliff and Root Conditioning.
3. AASHTO T-283 – Combines feature of NCHRP 246 and 247.
4. Boiling Water Tests.
5. Immersion-Compression Tests (AASHTO T-165, ASTM D 1075).
6. Freeze-Thaw Pedestal Test.
7. Static Immersion Test (AASHTO T-182, ASTM D 1664).
8. Conditioning with Stability Test (AASHTO T-245).
9. Net Absorption/Desorption Test (developed by SHRP).
10. Environmental Conditioning System (ECS) (developed by SHRP).

Pavement weathering or stripping is one of the major distresses in the highway network in the case study area, the Kingdom of Saudi Arabia. Pavement stripping severity varies from region to region in the Kingdom. The highway network in Al-Qassim and Hail regions is the most affected by pavement stripping. In certain roads where maintenance programs are not efficient, stripping develops potholes that severely affect road performance. The water sensitivity test used in local road departments is the typical water conditioning and evaluation by the Marshall stability test. The conditioning phase includes partial saturation of specimens with asphalt and then soaking in a water bath. The specimens are then tested for Marshall stability and compared with the results of unconditioned specimens. If the ratio (condition divided by unconditioned) is less than 75%, the mixture is considered sensitive to water. Those roads experiencing stripping and weathering have all passed the water sensitivity test. This has indicated that the water sensitivity test using Marshall stability is not reliable in determining the sensitivity of asphalt mixtures to water. With the recent developments in the design and evaluation as a result of strategic highway research program (SHRP), the Ministry of Transport (MOT) in the case study area has adopted a Superpave mix design that utilizes a gyratory compactor. The northern part of the study area is mostly affected by this phenomenon due to the existence of water sensitive aggregates.

The overall objective of this paper was to assess stripping problems in arid regions using the highway network of Saudi Arabia as a case study. Secifically, current practices by road agencies were reviewed and the tests used by these agencies were included in the test program. Binder aggregate adhesion and susceptibility of that adhesion to water damage were analyzed. Comprehensive tests that predict the resistivity of asphalt-aggregate materials

Table 1. Selected test sections from case study area

Serial #	Crusher	Road name	Pavement condition	Age	Symbol
		Al-Qassim			
1	Al-Swailem	Ring road (North + East)	Excellent	5–6 years	QN-1
2	Burma	Ring road mid-east flange	V. good	5–6 years	QN-2
3	Debiah	414 west road Stat. 45+600	V. good	10 years	QN-3
4	Artic	Al-Jamal Avenue junction road	Medium stripping	3 years	QS-4
5	Al-Fahd	Ring road-West flange Stat. 14+550	High stripping	5–6 years	QS-5
		Hail			
6	Al-Swailem	Bagaà road	Low stripping	3 years	HS-1
7	Al-Hudaires	At Humairah road (Madinah junction) (RD -7771)	Medium to high stripping	5 years	HS-2
8	Al-Namlah	Ring road Stat. 17+000	V. good	14 years	HN-3
		Eastern Province			
9	Road Construction Establishment	Salasel-Abqaiq, KP7	Low stripping	7–8 years	ES-1
10	Al-Hazaà	Nuaireah-Qaysoma road, after Nuaireah intersection bridge	Excellent	6–7 years	EN-2
		Riyadh Region			
11	Shibh Al-Jazira	Riyadh-Dammam Expressway Stat. 980+000	V. good	8 years	RN-1
12	Al-Awaidah	Riyadh-Taif Expressway Stat. 511+00	Medium stripping	5 years	RS-2
		Taif			
13	Al-Harameen	Taif-Baha road, KP 1220	V. good	5-6 years	TN-1
		Abha			
14	Ben-Jarrallah	Prince Salman Sport City road	V. good	7-8 years	AN-1
		Al-Jouf			
15	Al-Swailem	Sakaka Domat Al-Jandal road	V. good	5-6 years	JN-1
16	Al-Harbi	Tabargel Al-Quriyat road	High stripping	15 years	JS-2
		Northern Region			
17	Al-Sagaf	Arar-Taif Highway, km sign 1523	Low stripping	7 years	NS-1

(individually or as a mix) were adapted or modified. Practical treatment methods were suggested to improve stripping resistance of local mixes.

2. Methodology

The work was carried out in three tasks and extended for 30 months.

Task 1: Literature review: Available literature from main research institutions locally and abroad related to the subject of the research were collected, summarized, and utilized to support the knowledge of the researchers in this field.

Task 2: Stripping test selection and evaluation: Different tests (physical and chemical) that might be used to detect susceptibility of pavement mixes and/or materials to stripping were evaluated (Table 1). Construction materials (fresh aggregates, slabs, and cores) from known performance road sections were collected, in consultation with government personnel. These materials were subjected to different tests to evaluate their ability in predicting stripping potential. A total of seventeen test sections were selected: eight stripped and nine unstripped.

In selecting the study sections several criteria had to be met Adequate drainage had to be present for the pavement surface. Construction had to be according to specifications, (i.e. percent air voids (AV%) had to be

Table 2. Experimental design

		NUMBER OF REPLICATES																			
		Stripped Sections										Non-Stripped Sections									
		Field Samples					Laboratory Samples					Field Samples					Laboratory Samples				
Laboratory Test/Road Section Number		1	2	3	.	8	1	2	3	.	8	1	2	3	.	9	1	2	3	.	9
Aggregate-Asphalt Blend	Swedish Rolling Bottle	X	X	X	.	X	2	2	2	.	2	X	X	X	.	X	2	2	2	.	2
	Absorption-Desorption	X	X	X	.	X	2	2	2	.	2	X	X	X	.	X	2	2	2	.	2
Asphalt Concrete Mix	Volumetric Properties	3	3	3	.	3	3	3	3	.	3	3	3	3	.	3	3	3	3	.	3
	Marshall Compaction, Vacuum Saturation Conditioning a nd Resilient Modulus Testing	3	3	3	.	3	3	3	3	.	3	3	3	3	.	3	3	3	3	.	3
	Marshall Compaction, Vacuum Saturation Conditioning and Split Tensile Testing	3	3	3	.	3	3	3	3	.	3	3	3	3	.	3	3	3	3	.	3
	Marshall Compaction, Marshall Conditioning and Split Tensile Testing	3	3	3	.	3	3	3	3	.	3	3	3	3	.	3	3	3	3	.	3
	Gyratory Compaction, Vacuum Saturation Conditioning and Split Tensile Testing (7% Air Voids)	3	3	3	.	3	3	3	3	.	3	3	3	3	.	3	3	3	3	.	3
	Marshall Stability Loss	3	3	3	.	3	3	3	3	.	3	3	3	3	.	3	3	3	3	.	3
	Environmental Conditioning System (ECS)	2	2	2	.	2	2	2	2	.	2	2	2	2	.	2	2	2	2	.	2

X = Test is not applicable

within design limits, compaction temperature within allowable limits, no overheating of asphalt, aggregate gradation within limits). Aggregate quarry used for supplying aggregate in the asphaltic concrete layers had to be known and active so that fresh aggregate could be obtained similar to that used in the section.

The collected materials were subjected to a number of chemical and physical evaluation tests to evaluate the ability of those tests to predict stripping. These tests included compacted mix evaluation methods such as environmental conditioning system (ECS), modified Lottman test and Marshall durability test.; Asphalt/aggregate blend evaluation methods such as net adsorption in the presence of moisture and the Swedish Rolling Bottle test and aggregate tests such as methylene blue value (MBV), soundness and physical properties.

Experimental design for the first phase of the project is shown in Table 2. The response variables measured on individual materials, mixtures, compacted specimens, pavement cores were used for selection of applicable physical and/or chemical tests that are able to predict stripping and used for evaluation of the different mixes in the second phase of the study.

***Task 3: Material collection, mix designs and evaluation*:** In the second phase, different additives that are known from literature of being useful in preventing stripping were collected and used with the collected aggregate from stripped sections to prepare asphalt mixes using different percentages of additives and combinations. The Marshall mix design procedure was used to determine the optimum asphalt content for each aggregate source as shown in Table 1. Different percentages of anti-stripping agents (as recommended by the manufacturer) were added to each mix. Mixes were evaluated using the stripping tests.

3. Results and Discussion

As an initial step in the statistical analysis, the normality assumption of the distribution of the test results was checked by drawing normal probability plots of the data. The statistical data analysis was then carried out in three stages.

In stage I, the preliminary analysis, was to confirm that

Table 3. Summary of analysis of variance results for significant tests

Test	P-value	Non-Stripped Sections		Stripped Sections		Discriminant test limit	Probability of not being stripped if observation is less than set limit*
		Avg.	S.D.	Avg.	S.D.		
% Loss of resilient modulus	4.3E-05	38.13	10.01	60.84	23.57	45	75%
% Loss of split tensile strength + (vacuum saturation)	8.6E-07	41.49	7.65	63.63	18.34	48	80%
% Loss of split tensile strength (no vacuum saturation)	0.00017	32.25	10.03	53.31	24.29	38	73%
Marshall stability loss, %	9.4E-08	20.05	4.77	52.13	25.87	25	80%
% Loss of split tensile strength ++ (gyratory compaction)	4.6E-09	38.20	9.26	66.40	17.48	48	86%
Environmental Conditioning System (ECS), after first loading cycle (%)	0.00082	16.67	6.99	32.48	15.80	22	78%
Environmental Conditioning System (ECS), after second loading cycle (%)	0.00455	30.63	10.77	45.94	16.49	37	72%
Environmental Conditioning System (ECS), after third loading cycle (%)	0.01452	42.99	7.40	54.78	17.04	47	71%
Swedish Rolling Bottle value after 12 hrs.	0.02715	36.33	17.52	56.92	12.21	48	75%
Aggregate soundness test	0.0023	7.64	1.65	13.36	4.35	9	83%

* Similarly, the probability of being stripped if observation is greater than set limit
\+ Conventional Lottman test
++ Modified Lottman test (AASHTO T-283)

there was a difference in behavior between stripped and non-stripped sections and that the grouping of the sections was correct. Therefore, the statistical evaluation tests for this stage were performed on the test results of the extracted field cores. Single factor analysis of variance (ANOVA), using STATISTICA statistical program, was carried out for the test results of the field cores to find if there was a significant difference between the means of the different performed tests of stripped and non-stripped sections. The null hypothesis for the ANOVA test is (Lapin, 1997):

$$H_o : \text{m-stripped} = \text{m- non-stripped}$$

vs.

$$H_a : \mu\text{-stripped} \neq \mu\text{-non-stripped}$$

where,

H_o = null hypothesis

H_a = alternate hypothesis

μ = mean value of the test results for the specific test.

Table 4. Collected liquid antistripping agents

S.N.	Product name	Physical state	Recommended dosage (wt%)*	Stability	Chemical name	Flash point
1	Lilamin VP 75E	Liquid	0.2–0.4	heat stable	mixture of alkyl and alkylene amines	120°C
2	WETFIX AD-4F	m.p. 63ºC			fatty amine salt	>150ºC
3	WETFIX® BE	viscous liquid; b.p. >200ºC	0.2–0.5	heat stable (upto 170ºC)	fatty acid + polyamine	>100ºC
4	ITERLENE IN/400-S	liquid	0.2–0.4	heat stable (170ºC)	alkylamido-imidazo-polyamine	>180ºC
5	CECABASE® 260	liquid	0.2–0.4	heat stable	alkylamido-imidazo-polyamine	>100ºC
6	POLYRAM® L200	liquid		heat stable	N-alkyl'tallow' dipropylene triamine	>100ºC
7	EC9194A (EXXON Energy chemicals)	liquid	0.2–0.4	heat stable (<250ºC)	alkyl imidazoline in aromatic hydrocarbons	
8	ITERLENE IN/400	liquid	0.3–0.6	heat stable (upto 170°C)	alkylamido-imidazo-polyamine	>180°C
9	ITERLENE IN/400-R	liquid	0.2–0.4	heat stable (upto 170°C)	fatty alkylamido-imidazo-polyamine	>180°C
10	ITERLENE IN/400-R-1	liquid	0.2–0.4	heat stable (upto 170°C)	fatty alkylamido-imidazo-polyamine	>180°C
11	MORELIFE 3300	viscous liquid	0.2–0.5	heat stable (upto 150°C)	polycyclo-aliphatic polyamines	170°C
12	POLYBILT	granules	2.0–5.0	heat stable >200°C		>200°C
13	EE-2 Polymer	granules	2.0–5.0	heat stable >200°C	modified olefin	>200°C
14	Cement	powder	2.0–4.0	–	Portland cement	–
15	Lime	powder	2.0–4.0	–	hydrated lime (calcium hydroxide)	–

*weight (5) of the antistripping agent added to the bitumen

ANOVA analysis was performed for the test results of the extracted field cores as shown in Table 2. Results indicated that at $\alpha = 0.05$ (the higher the α value, the lower the significance of the difference), for all the performed tests, except the ECS, the means of the stripped and non-stripped sections were significantly different. This implied that the tests were capable of differentiating between stripped and non-stripped sections and therefore indicated a good matching between the classification of the different sections into stripped and non-stripped sections and the test results.

Stage II was to find which of the laboratory tests was capable of predicting the stripping potential of the asphalt concrete mixes. Therefore, the single factor ANOVA statistical evaluation was performed on the test results of the fresh aggregate and the laboratory prepared mixes, Table 2. Table 3 shows only tests that were significant and that had a P-value (Probability to reject H_o when H_o is true) less than 0.05 in differentiating between mixes that were prone to stripping from sound mixes (Lapin, 1997). The most significant test in predicting stripping (having the smallest P-value) was the loss in split tensile strength when performed on gyratory compacted samples that had 7 ± 1% air voids followed by vacuum saturation then soaking at 60^{oC} for 24 hours (i.e. modified Lottman test). The other tests in a decreasing order of significance were: Marshall stability test; split tensile strength of Marshall compacted specimens soaked @ 60^{oC} for 24 hours after

Table 5. Effect of different antistripping agents using modified Lottman test

Antistripping Agent Code	Hail	Al-Jouf	Eastern Province	Riyadh	Hail
	(HS1)	(JS2)	(ES1)	(RS2)	(HS2)
	% Loss	% Loss	% Loss	% Loss	% Loss
Lilamin VP 75E	36.45%	61.47%	100.0%*	100.0%	48.00%
WETFIX AD-4F	71.15%	100.00%	38.4%	100.0%	40.30%
WETFIX® BE	32.98%	69.10%	100.0%	100.0%	44.90%
ITERLENE IN/400-S	58.40%	79.20%	100.0%	100.0%	51.20%
CECABASE® 260	40.54%	55.80%	100.0%	47.6%	48.00%
POLYRAM® L200	44.30%	72.90%	100.0%	100.0%	53.00%
EC9194A	29.24%	64.60%	100.0%	100.0%	41.20%
ITERLENE IN/400	45.80%	76.80%	100.0%	100.0%	53.70%
ITERLENE IN/400-R	32.59%	57.40%	100.0%	100.0%	44.50%
ITERLENE IN/400-R-1	52.80%	86.40%	100.0%	69.0%	32.40%
MORELIFE 3300	21.54%	67.80%	100.0%	31.7%	36.60%
POLYBILT	70.46%	80.80%	100.0%	100.0%	39.21%
EE-2 Polymer	28.75%	32.30%	35.8%	41.9%	42.40%
Cement	35.85%	40.80%	38.5%	46.9%	46.00%
Lime	41.80%	49.20%	75.5%	74.9%	48.30%
Control	49.40%	77.40%	100.0%	100.0%	58.30%

% loss of 100 means that conditioned samples have collapsed, resulting in ITS of zero and 100% ITS

vacuum saturation; resilient modulus of Marshall compacted specimens soaked @ 60°C for 24 hours after vacuum saturation; split tensile strength of Marshall compacted specimens soaked @ 60°C for 24 hours without vacuum saturation; resilient modulus of gyratory prepared samples having a target air void between 6 and 8% after one cycle in ECS; aggregate soundness test; resilient modulus of gyratory prepared samples having a target air void between 6 and 8% after two cycles in ECS; Loss of resilient modulus of gyratory prepared samples having a target air void between 6 and 8% after three cycles in ECS; and Swedish Rolling Bottle value after 12 hrs. rolling.

Although all tests were statistically significant, it can be seen that they can be divided into three groups: com-

Table 6. Effect of combined antistripping agents using modified Lottman test

Antistripping Agent Code	Sample* ID	Initial ITS Kg/cm^2	Final ITS Kg/cm^2	Ave. Initial ITS. Kg/cm^2	Ave. Final ITS. Kg/cm^2	Average % Loss
CECABASE® 260 + Cement	RS2	12.1 11.9 12.3	8 7.9 8.3	12.1	8.1	33.33%
MORELIFE 3300 + Cement	RS2	12.9 11.2 11.6	9.2 8.3 9	11.9	8.8	25.77%
EE-2 Polymer + Cement	RS2	11.9 12.1 12.4	7.6 7.7 8.1	12.1	7.8	35.71%
WETFIX AD-4F + Cement	ES1	13.7 12.9 13.5	9.6 9.3 9.3	13.4	9.4	29.68%
EE-2 Polymer + Cement	ES1	13.9 13.5 13.2	9.9 10 9.7	13.5	9.9	27.09%
CECABASE® 260 + Cement	JS2	12.7 13.4 13.1	7.7 8 7.6	13.1	7.8	40.56%
EE-2 Polymer + Cement	JS2	12.2 13.1 12.6	8.8 9.4 9.1	12.6	9.1	27.97%
MORELIFE 3300 + Cement	HS1	12.1 13 11.6	7.6 8.2 8.1	12.2	8.0	34.88%
EE-2 Polymer + Cement	HS1	15.5 15.8 15.1	11.4 11.1 10.8	15.5	11.1	28.23%
MORELIFE 3300 + Cement	HS2	11.4 10.9 11.8	7.3 7.1 8.1	11.4	7.5	34.02%
EE-2 Polymer + Cement	HS2	14.7 14.2 15.1	9.6 9.4 8.9	14.7	9.3	36.59%

* RS: Riyadh aggregate JS: Al-Jouf aggregate
ES: Eastern Provience aggregate HS: Hail aggregate

pacted mix, asphalt/aggregate blend and aggregate. From the first group, it can be seen from Table 3 that both the modified Lottman test (AASHTO T-283) and the Marshall stability loss test (MOT-MRDTM 410) had the lowest discriminant probability P-value of 4.6E-09 as compared to a P-value of 9.4E-08 for Marshall stability loss. Moreover, the government in the case study area is in the process of adopting the Superpave mix design. This will eliminate the use of the Marshall mix design. Lottman, on the other hand, is a simple test that has proven effectiveness and is currently used widely in the United States. The Lottman test was therefore selected as the best mix evaluation test to discriminate between compacted mixes. The Swedish Rolling Bottle test was the only one in the second group that was significant (P=.02715) in evaluating loose aggregate-asphalt blends stripping tendencies. In the third group, aggregate soundness, which was a significant test (P=0.0023), had the ability to distinguish between aggregates prone to stripping. This test, however, did not have the capability to evaluate additives to asphalt mixes and therefore was eliminated.

Stage III was to find the test limits that could be set to screen mixes that were prone to stripping. This was based on the test results of the fresh aggregate and the laboratory prepared mixes. Specification limits were calculated for each of the significant tests. These limits could then be used to test if the mix was prone to stripping (i.e. if the result of the evaluation test was higher than the set limit, then the mix would be prone to stripping). Assuming a normal distribution of the results, the average and standard deviation values for the samples Table 3, were used to find the test limits. The aim was to find the limit that would produce an equal probability of classifying the mix as not being prone to stripping if the test value was lower than the limit, to the probability of classifying the mix as being prone to stripping if the test value was higher than the limit. For example, Table 3 shows that for the modified Lottman test (AASHTO T-283) and the Marshall stability loss test (MOT-MRDTM 410), the discriminating limits were 48% and 25%, respectively.

In addition to lime and cement dust, several liquid antistripping agents were purchased and specifications of the products as provided by the companies were also obtained, Table 4.

The Marshall mix design was used to arrive at the optimum asphalt content for the four selected stripped locations. Eleven liquid antistripping agents were collected from the original manufacturers and administered at the maximum recommended percentage. Moreover, cement, lime and two polymers (Polybilt 101 and Eastman EE-2) were used at a dosage of 4% as recommended by government guidelines and polymer manufacturers. Work was carried out in two stages. The maximum recommended dosages of the antistripping additives were used to quantify the effect of the additive on stripping phenomena and to screen the additives, Table 5. In the second stage , additive combinations of promising mixes were evaluated. Combinations included dry additives (Portland cement and/or lime) and liquid additives or polymers. Liquid additives were not mixed with polymers. This was done to avoid adverse chemical reactions, Table 6. The modified Lottman test and the Swedish Rolling Bottle test were used to evaluate the effectiveness of the different treatments.

Table 5 shows the typical stage I test results for the Hail, Al-Jouf, Eastern Province and Riyadh region. The results show the loss in the indirect tensile strength values (ITS), according to the modified Lottman test procedure, for all treatment combinations. The effectiveness of the treatments was evaluated based on the level of ITS improvement for each aggregate as compared to the control mix (no additive). It should be noted that 100% ITS loss indicated that samples failed during the conditioning phase ,indicating severe stripping. This resulted in a final ITS of zero and therefore a 100 % ITS loss.

Table 6 shows the results of the combined additives. In general, it can be seen that the ITS of each mix was dependent on the aggregate type. The results of the second phase indicated that for Hail aggregate, treatments EC9194A, Iterlene IN/400, Iterlene IN/400-R, Polyram L200, CECABASE 260, WETFIX BE, Lilamin VP 75E, Morelife 3300, EE-2 Polymer, cement, and lime were effective in eliminating the stripping potential of the aggregate. For Al-Jouf aggregate, only EE-2 Polymer and cement were effective in eliminating the stripping potential of the aggregate. For Eastern Province aggregate, only WETFIX AD-4F, EE-2 Polymer, and cement were the effective additives. With the Riyadh aggregate, only Morelife 3300 and EE-2 Polymer were effective additives. The EE-2 Polymer was effective in eliminating the stripping potential of all aggregates from all sources. Eastman EE-2 Polymer and Portland cement and their combination proved to be effective with all studied aggregate sources. Morelife 3300 antistripping additive combined with cement was the most effective with Riyadh and Hail aggregates. WETFIX AD-4F combined with cement was the most effective with the Eastern Province aggregate. Finally CECABASE® 260 combined with cement was effective with the Al-Jouf aggregate.

For each type of aggregate, there were specific additives that were effective in eliminating the stripping potential. However, cement and EE-2 Polymer combinations were effective in eliminating or effectively reducing the stripping potential of all the tested aggregates.

4. Conclusions

Based on the Analysis of Variance (ANOVA) results, the modified Lottman test, the Marshall stability loss test, Environmental Conditioning System (ECS), and the resilient modulus loss were effective in distinguishing between stripped and non-stripped mixes. ECS had the lowest significance (P = .00082) among these tests while the modified Lottman had the highest significance (P = 4.6E–09). The Swedish Rolling Bottle was found to be effective in screening asphalt-aggregate materials for stripping potential. Eastman EE-2 Polymer and Portland cement and their combination proved to be effective with all studied aggregate sources. Morelife 3300 anti-stripping additive combined with cement was the most effective with Riyadh and Hail aggregates. WETFIX AD-4F combined with cement was the most effective with the Eastern Province aggregate. CECABASE® 260 combined with cement was effective with Al-Jouf aggregate.

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