SYSTEMATIC TESTING METHODOLOGY TO PREDICT STRIPPING OF ASPHALT CONCRETE MIXTURE

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Abstract

The stripping of asphalt cement still the most significant reason that causes the deterioration of asphalt concrete pavement. This study aims to compare and develop a systematic method for the results of stripping tests: Texas boiling, resilient modulus, and fatigue. Three types of aggregates and two types of anti-stripping additives were used. Texas boiling test, and then Marshall specimens with (6-8%) air voids subjected to medium or high moisture conditioning were used. The stripping potential evaluated by suggesting sequence tests steps for asphalt coating retained (60-80%) visually and by the resilient modulus (M_R). The visual assessment of the boiling test and the rolling test is not enough to predict stripping. The degree of saturation had a very significant effect on the resilient modulus values. The use of the resilient modulus test for Marshall specimens is a reliable test to predict stripping. For the results of less than the range; add additives and re-evaluate the stripping. For results above the range; run a fatigue test with high saturation. In general, it found that the dosage of lime needed is between 1.5 to 2.0% by weight of aggregate, where for polyamine, it was between 0.75 to 1% by weight of asphalt binder. Lime additive showed better effects on stripping potential than polyamine (liquid) additive. The proposed methodology which organized by a flow chart is a sound step-by-step and practical procedure for predicting the stripping. It could be used as a guideline to assess the water susceptibility for any aggregate type.

Keyword: Asphalt concrete; Stripping; Boiling test; M_R test; Fatigue test; Systematic methodology

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1 Introduction:

The stripping of asphalt cement became the most significant reason that causes the deterioration of asphalt concrete pavement. It may be considered as a major reason for many pavements distresses. Great efforts were done and hundreds of research studies were carried out to determine the nature, mechanism, and measurement of stripping. It was recognized since 1932, and many anti-stripping agents were identified and used since 1947.

The stripping is the breaking of the bond between the asphalt and the aggregate by the action of water. Adhesion of asphalt to aggregate is a surface phenomenon. It depends on the close contact of the two materials and the mutual attraction of their surfaces. Prediction of stripping is usually based on the retained ratio (wet/dry). Because the adhesion properties of asphalt-aggregate mixtures are very complex, many tests have been used. Many factors affect the stripping potential of asphalt concrete mixtures revealed that these factors could be either internal or external. Internal factors may include the mix component characteristics or the mix configuration, the materials used in the mix such as aggregate, asphalt, and additives. External factors may include the environment, construction practice, inadequate pavement drainage, etc. Many test procedures were developed to predict the stripping of asphalt pavement mixture. The stripping phenomenon has not been solved adequately.

Mehrara and Khodaii [1] concluded that for sensitive asphalt mixtures, moisture causing stripping, which causes rutting or cracking. Caro et al. [2] investigated the damage of asphalt mixtures due to moisture transport modes, such as capillary rise, vapor diffusion, and water permeability. Jakarni [3] defined the adhesion as the holding bodies together by the attractive force in the area of contact between bodies. It refers to the energy magnitude required to break the adhesive bond between them. Nejad et al. [4] concluded that the moisture resistance inversely proportional to permeability, saturation (%), and debonding energy.

Roberts et al. [5] listed the following methods "boiling test, static immersion, vacuum saturation and immersion, immersion-compression test, Lottman, modified Lottman, and Tunnicliff- Root." which are usually used to check the stripping of aggregate mixtures

Gharaybeh and Parker [6] and Lottman [7] applied asphalt retained percentage for the boiling test, the tensile strength ratio (TSR) and the ratio of resilient modulus retained (M_{RR}) to check the stripping severity as follows: 60% asphalt retained for the boiling test, 70% TSR and 75% M_{RR}. The authors considered TSR = 70%, as the separation level between stripping and non-stripping mixes. In a severe conditioning process, either a 70% retained value of a TSR is considered as a separation point between damaged and undamaged pavements.

Kennedy et al. [8] classified aggregate that has retained values of less than 70% classified as moisture susceptibility. Kim et al. [9] used the visual assessment for moisture damage and found that the moisture damage increases with the numbers of treatment cycles, and periods.

Gardiner and Epps [10] concluded that visual stripping was not observed in mixtures with or without additives. Both tensile strength and resilient modulus are decreasing with increasing temperature in the absence and the presence of the additives. Maupin [11] found that there was a weak correlation between performance rating and visual stripping.

Alkofahi [12] studied the asphalt stripping for three aggregate types: limestone, valley gravel, and basalt, which are used widely in Jordan as a loose mixture, and Marshal specimens with lime and morelife additives (dark brown viscous liquid). The author concluded that lime dosage of 2% could restore the stripping resistance by about 25% for all types of aggregate that were used in this study, where the morelife dosage of 1% can restore about 29%, 37%, and 46% for basalt, limestone, and valley gravel respectively.

Bagampadde and Karlsson [13] developed a technique to study the water move into bitumen/substrate interfaces based on Fourier Transform Infrared Spectroscopy-Attenuated Total Reflectance (FTIR-ATR). The authors noticed that at least one of three processes occurred: water diffusion, film fracture, and bitumen displacements of water.

Wood [14] found that air voids, permeability, and density tests are valid to predict the stripping after the use of chip seal, he suggested that nuclear density test is the easiest and least invasive test to predict stripping of the pavements.Hammons et al. [15] suggested a procedure involving observation of surface distresses, radar survey for ground-penetrating, and other non-destructive methods test to measure the stripping level and its depth in HMA pavements. The effective rehabilitation could be done due to the identification of the stripping area. Celaya and Nazarian [16] used a rapid seismic nondestructive tool to detect the extent of stripping. They used a portable seismic property analyzer (PSPA) using two methods: ultrasonic surface wave (USW) and impact echo (IE). To predict the stripping of asphalt (extent and depth), it concluded that the USW method was more effective than the IE.

Watson et al. [17] had field tests for a conventional Superpave section that used three different anti-strip agents using multiple 0, 1, 5, 10 freeze-thaw cycles. They used different aging period comparisons to predict the effectiveness of additives: hydrated lime, a liquid additive, and warm-mix asphalt anti-strip. The results showed that hydrated lime was the only additive verified at least 80% of tensile strength ratio (TSR) for all freeze-thaw cycles, and appeared the highest values of tensile strength and TSR.

Bhargava et al. [18] resulted that the tensile strength of warm mix asphalt decreased with moisture and temperature increased. The resistance to permanent deformation will increase due to aging and interestingly moisture conditioning. Jahromi [19] assessed the moisture destruction on asphalt mixtures. An analytical approach based on surface energy was used. To study this, two different chemical bitumen (AC-10 and AC-20), three aggregates represent a considerable range in mineralogy (limestone, siliceous gravel, and granite) and an additive of hydrated lime. Two conditions (dry and wet) were used.

Hamedi and Tahami [20] applied the surface free energy theory test to check the influence of Zycosoil as a bitumen modifier on moisture sensitivity of the asphalt mixtures. Using Zycosoil additive increased the resistance of the asphalt to stripping. Kavussi et al. [21] soaked treated recycled concrete aggregate (RCAs) in Hydrochloric Acid (HCl) and then impregnated with Calcium Metasilicate (CM) which filled the pores of RCAs The results showed that moisture sensitivity and water absorption of mixes were reduced. Hamedi et al. [22] results' indicated that the acidic components decreased and the basic elements increased when adding anti-stripping additives of the base asphalt binder, which could strengthen the bond between asphalt binders and aggregates.

Fallahi et al. [23] used a new anti-stripping additive (styrene-butadiene-styrene nano-composite) to improve the resistance of the asphalt mix. Two types of aggregates (limestone and granite aggregates), bitumen with of 60/70 (PG 64-22), and SBS nano-composite used. The modified Lottman test applied, using surface free energy methods studying nanomaterial affected cohesion and adhesion properties of asphalt mix. Gorkem and Sengoz [24] result's indicated that the stripping resistance of limestone was better than the basalt-limestone mixture, and it increased by adding hydrated lime and polymer. Radovskiy [25] suggested an average film thickness between 8 and 15 µm provides acceptable pavement performance. Hmoud [26] found that the average thickness of asphalt film coating the aggregate of 8 microns will produce a durable mixture; The author focused on evaluating VMA and film thickness. It was recommended to use both parameters of film thickness and the VMA in Iraqi standards to design of asphalt mixture.

2. Objectives

The following are the objectives of this research:

1- Assess and compare different types of stripping tests.

2- Develop a systematic flowchart, that can use to predict the stripping of asphalt concrete mixture

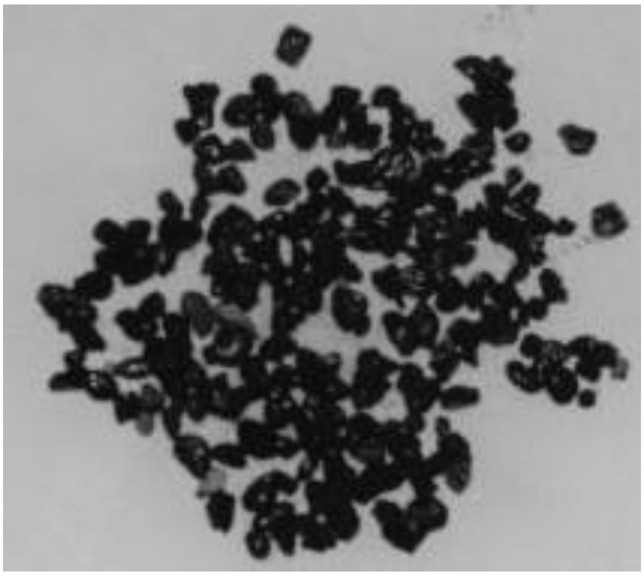
3. Laboratory works

The analyses in this research are based on the data resulted from Alkofahi [16], and Alkofahi et al. [27, 28, 29]. In their researches, four procedures were used to evaluate and predict stripping of asphalt for loose mixes and Marshall specimens which were made for three types of aggregates; limestone, valley gravel, and basalt, which are used for pavement construction in Jordan. Two types of anti-stripping additives were used; lime and morelife which consists of Polyamine and mixed Polycyclo-aliphatic. It contains of 30-60% by weight Polyalkylene Glyco-Polyamines and Alkyloxylated Aliphatic Polyamines (pH=12.3). [30].

3.1. Boiling Test

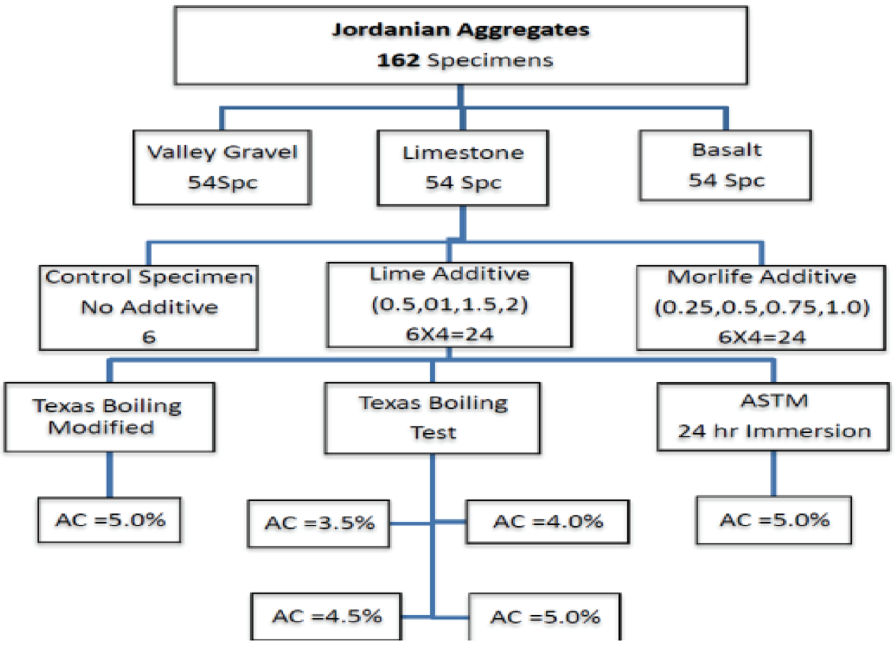
Alkofahi et al. [27] used this test to give a preliminary indication of the moisture susceptibility of the mixes. In this test, the aggregate mix with different % AC with a gradation of 3.5 to 5.5% exceeds by 0.5% each time to obtain the effect of % AC as the effective film thickness on aggregate, and the obtained mixture tested under certain conditions. The result obtained is the qualitative percent of asphalt coating the aggregate and is determined by visual inspection. Although this type of test is simple to perform needs little equipment and performed in a short time. This test performed using ASTM D 3625, the mix immersed in boiling water under certain conditions and the percentage of asphalt retaining estimated visually and used as stripping indicator. Fig. 1 shows the stripped aggregates due to the boiling test; the process of the boiling test is shown in Fig. 2.

(a) Group of test specimens

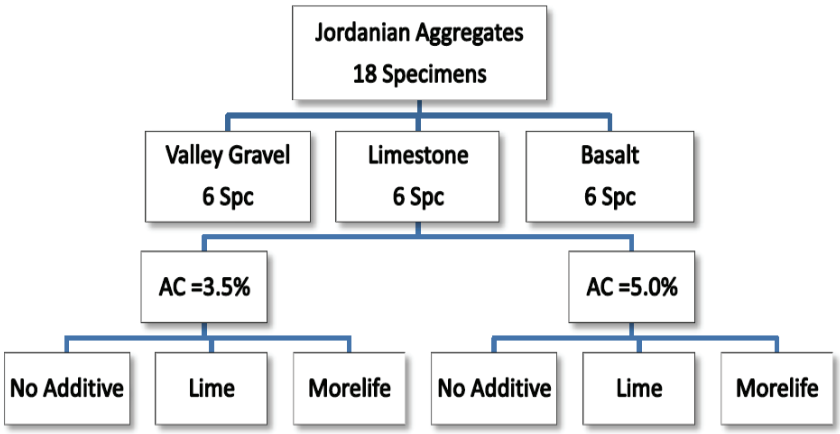


(b) Stripped aggregate

Fig. 1. Stripping of specimens by boiling test



(a): boiling tests



(b): rolling tests

Fig. 2 . Loose mixes samples (by a visual evaluation). [12, 27]

3.2. Resilience modulus (M_R) test

Alkofahi et al. [28] used the resilience modulus test to imply preparation of cylindrical specimens according to ASTM (D 4876) and applying five-pulse (non-destructive test) by using the universal testing machine (UTM) on conditioned and unconditioned (controlled) specimens. Fig. 3 shows the UTM and the environmental chamber. The ratio between the resilient modulus for both test and control specimens was used as a stripping indicator.

The resilient modulus (M_R) is a measure of a material deflection behavior, and it is a fundamental and rational material property, which is included in pavement design. When stress is reduced, the strain is also reduced, but not all strain is recoverable, where the strain consists of two components; permanent (plastic), and temporary recoverable (resilient).

Three hundred and seventy-eight specimens were mixed with different dosage of lime or morelife additives as anti-stripping agents as shown in Fig. 4. Eighteen specimens were considered as control samples, so they were tested without any conditioning. Other specimens were subjected to two types of conditioning: a medium degree of saturation (30-50%), which is called condition1, and a high degree of saturation (60-80%), which is called condition 2. The specimens that were compacted to have 6-8% air void were immersed into water for 60 minutes at 60 °C and then tested for a five-pulse indirect tensile test at 60 °C, by using the UTM. The resilient modulus ratio (M_{RR}) of a specimen is defined as follows:

M_{RR} (%) = {M_R (saturation condition) / M_R (dry condition)} X 100 (1)

This assessment shows a decrease in M_R for each aggregate regardless of their values. For example, M_R for valley gravel has a larger M_R value than that of basalt, but MRR for valley gravel has a lesser M_R value than that of basalt. M_{RR} for limestone is greater than 70%, but M_{RR} for valley gravel and basalt are less than 70%.

To find the effect of additives for each of the six mixtures at saturation conditions the ratio of resilient modulus increase (M_{RI}) due to the addition of lime or morelife was compared to the case where no additive used; it is calculated as follows:

M_{RI} (%) = {M_R (with additive) / M_R (without additive)} X 100 (2)

Fig. 3. Universal testing machine

3.3 Fatigue test

Alkofahi et al. [29] stated that many factors affect the fatigue potential due to the stripping of the aggregate mixtures. Statistical analysis were carried out to show the relationships between the aggregate type and effect and type of additive from one side with cycles to failure from another side. These variables had significant effects on cycles to failure. There was some relationship between the tensile-strength ratios and pavement fatigue life ratios. Sixty-three specimens were prepared for all three aggregate types with different dosage of additives and with variable loads including the control samples as shown in Fig. 5.

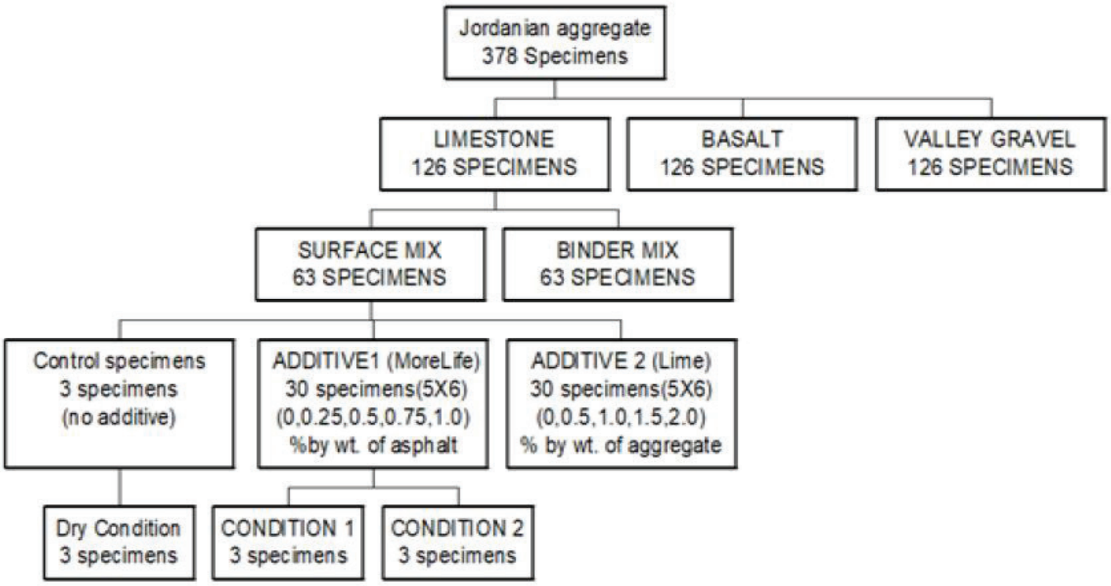


Fig. 4. Marshall specimens distribution for M_R test. [12, 28].

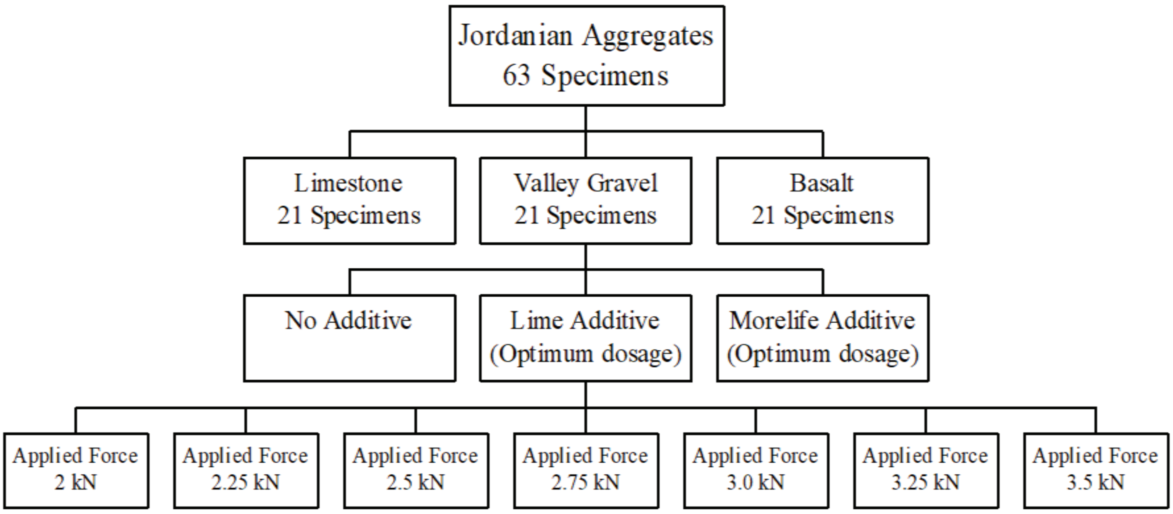


Fig. 5. Marshall specimens for the fatigue test (BS). [12, 29].

3.4 Resistance of asphalt mixtures to moisture-induced damage AASHTO T 283

"The tensile strength is a measure of the force required to pull apart a material. The test is performed by compacting specimens to an air void level of 6-8 %. Three specimens are selected as a control and tested without moisture conditioning, and three more specimens are selected to be conditioned by saturating with water undergoing a freeze cycle and subsequently having a warm-water soaking cycle. The specimens are then tested for indirect tensile strength by loading the specimens at a constant rate and measuring the force required to break the specimen as shown in Fig. 6. The tensile strength of the conditioned specimens is compared to the control specimens to determine the tensile strength ratio (TSR)" [31].

3.5. Evaluation of materials

The purpose of using different types of aggregates and additives was to use more than

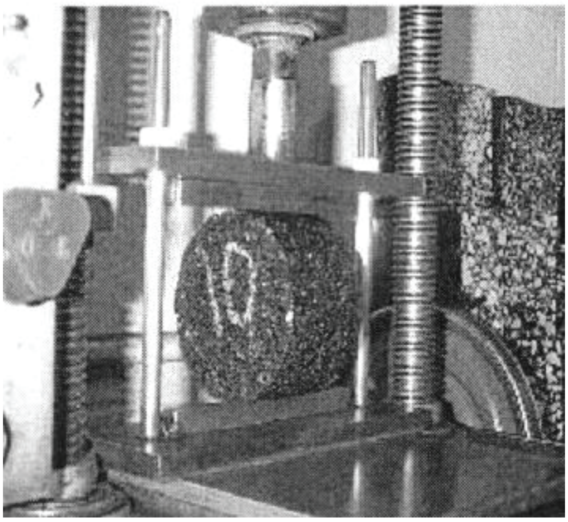


Fig. 6. TSR testing machine (AASHTO T 283) [32]

one variable that may affect the stripping potential of the Jordanian materials as shown in Figs. 2, 4, and 5. The results of these researches showed that all aggregates types had shown a tendency for stripping at a high degree of saturation. Limestone found to have high stripping resistance and smooth, rounded valley gravel aggregate produce asphalt mixtures of high moisture susceptibility with relatively low stability. The basalt aggregate has better resistance to stripping than valley gravel, but a lower resistance when compared to limestone as shown in Table 1. In Jordan, the majority of the pavements made with limestone, being highly resistant to stripping; limestone pavement is expected to be less prone to a water attack. Valley gravel and basalt aggregate are not commonly used, may resist stripping if they are treated with additives, which have a great effect on valley gravel and basalt aggregates.

The use of hydrated lime is economical, simple and it is available in the local market. The liquid additive is hardly available (imported from outside) and sometimes not safe to use (pH=12.8). The required percent of both additives needed to restore the original stripping potential of each aggregate type are shown in Tables 1, 2, and 3. In general, it was found that the dosage of lime needed to restore the resilient modulus is between 1.5 to 2.0% by weight of aggregate, where for morelife it was between 0.75 to 1% by weight of asphalt cement. These percentages are expected to counteract the action of moisture. In places where moisture is not expected to reach a high level, additive dosage may be decreased as in Table 2. The use of additives very significant in reducing the stripping potential of all mixtures and lime additive showed better effects on stripping potential than morelife (liquid) additive.

It noted that wearing course mixtures have better stripping resistance than the binder course mixtures for the same aggregate type. The percentages shown in Table 2 are suitable for the gradation and material used in the study. If other gradations or materials are to be used, other percentages have to be set. The results have shown that the resilient modulus of limestone is higher than that of basalt which is less than that of valley gravel. The asphalt mixture that has the highest resilient modulus has the highest M_{RR}.

3.6. Evaluation of Conditioning Methods

It is very hard to simulate field conditions in the laboratory, so it was decided to expose the mixtures to a medium degree of saturation 30-50% (condition 1), and a high degree of saturation 60-80%, which called condition 2, were immersed into water for 60 minutes at 60 °C. These conditions would force the mix to strip; the Marshall specimens were distributed as shown in Fig. 4. A stripper aggregate can be detected early in a low degree of saturation. A high degree of saturation was applied to verify that non-stripper aggregate still resists water action. Non-stripper aggregate can resist severe water saturation conditioning regimes as shown in Table 2. For high moisture susceptible mixtures, condition 1 and condition 2 provide less difference in ratios retained. Therefore, the medium degree of saturation (condition 1) would be enough to detect stripping. For low moisture susceptible mixtures, the more severe of saturation condition (condition 2) may be needed to make sure the stripping process is fully developed. The degree of saturation had a very significant effect on the M_R values. Condition 2 (high degree saturation) is very effective in distinguishing between a stripper and non-stripper aggregate. To make these conditions compaction of Marshall specimens having 6-8% air voids are essential to ensure adequate saturation for M_R testing, to estimate the effect of stripping potential on asphalt mixtures.

3.7. Evaluation of Tests

Researchers commonly used standardized tests, such as Modified Lottman, ASTM immersion, and Texas boiling tests (TBs). It was suggested to modify the TBs as shown in Fig. 2-a. The modification came because of a deficiency of the standard test and ASTM test as shown in Table 1. The modified test more able to detect stripping of valley gravel and basalt aggregates due to using nine times stirring with a glass rod. Fig. 2-b shows the distribution of loose mixes for all types of aggregates and both additives. The visual assessment of the boiling test and the rolling test (RT) is not enough to predict stripping. The RT was time-consuming and gave similar results to those of the TBs as shown in Table 1. Therefore, the RT could be used as an alternative to the boiling test.

Five pulse indirect tensile test (ITS) applied pulses to simulate fatigue stresses that are sustained by pavement due to traffic loading. The use of M_R test for Marshall specimens is a reliable test to predict stripping as shown in Fig. 4. Some results of this test for the effects of additive types are shown in Table 2. The Universal Testing Machine (UTM) has proven to be a multipurpose-testing machine where the ITS and British fatigue test were done.

The British fatigue test was selected among a variety of tests that could be run on the UTM to determine other properties of the mixtures as shown in Fig. 5. The fatigue test was selected because it could determine the resistance to cracking under repeated traffic loads. The use of the fatigue test gives a necessary indicator of the performance of moisture potential and additives effect as shown in Table 3.

Table 1: Percentage of asphalt cement-retained, [12].

A. Modified boiling test

Aggregate Type	Condition/ stirring	AC (%)	Asphalt cement-retained (%)		
			No additive	Lime 2%	Morelife 1%
Limestone	ASTM	5/Fresh	94	96	100
	Boiling, St.9*	5.0/24h	69	86	95
Valley gravel	ASTM	5/Fresh	90	98	100
	Boiling, St.9	5/24h	63	79	92
Basalt	ASTM	5/Fresh	91	95	100
	Boiling, St.9	5/24h	72	80	93

B. Rolling test

Aggregate Type	Immersing condition	AC** (%)	Asphalt cement-retained (%)		
			No additive	Lime 2%	Morelife1%
Limestone	6 hr.***	3.4	75.0	85	87
	6 hr.	5.0	80.0	92	92
Valley Gravel	6 hr.	3.4	55.0	75	70
	6 hr.	5.0	60.0	85	80
Basalt	6 hr.	3.4	65	75.0	83
	6 hr.	5.0	68	85.0	92

* St.9: Nine-time stirring, ** AC: Asphalt cement, ***hr.: hours

Table 2: Additive dosage needed to restore the M_R, [12, 28].

Additive type	Degree of saturation	Aggregate type					
		Limestone		Basalt		Gravel valley	
		Wearing	Binder	Wearing	Binder	Wearing	Binder
Lime % (by wt. of agg.)	Medium	1.50	1.34	1.53	1.15	1.14	1.5
	High	1.73	1.89	1.77	2.00	1.83	2.25
Morelife % (by wt. of AC)	Medium	1.03	0.78	0.65	0.70	0.80	0.87
	High	1.12	0.97	0.92	0.88	0.95	1.17

Table 3: Average increase in cycles to failure and accumulated strain ratios for all mixtures.[12, 29].

Aggregate Type	Additive type			
	Lime		Morelife	
	Cycles to failure	Accumulated strain	Cycles to failure	Accumulated strain
Limestone	175 %	231 %	97 %	166 %
Valley	175 %	109 %	139 %	91 %
Basalt	214 %	98 %	225 %	106

4. Results and Discussion

4.1. Boiling test

From the results, it seems that limestone has proven to be stripping resistant aggregate, and smooth, rounded valley gravel aggregate produces asphalt mixtures of high moisture susceptibility, because of its fracture and rough surface and chemical composition which agree with previous researches. The basalt aggregate has better resistance to stripping than valley gravel, because of its fracture and rough surface but lower than limestone due to its chemical composition. The use of additives was very significant in reducing the stripping potential of all mixtures. ratio for six different aggregate mixtures. It found that the dosage of lime needed is between 1.5 to 2.0% by weight of aggregate Where for polyamine, it was between 0.75 to 1% by weight of asphalt binder, and lime additive showed better effects.

4.2. Resilient modulus (M_R)

The results indicated that the resilient modulus was very sensitive to mix design parameters. Table 4 summarizes the M_{RR}. From the results, it was found that wearing course mixtures have better stripping resistance than binder course mixtures for the same aggregate type Limestone aggregate has a higher M_R than basalt, and valley gravel has the lowest M_R value.

Table 4. M_{RR} (%) for mixtures at optimum asphalt contents. [28]

Aggregate Type	Course type and degree of saturation					
	Wearing course			Binder course		
	Dry	Medium Sat.	High Sat.	Dry	Medium Sat.	High Sat.
Limestone	100	79	75	100	89	73
Basalt	100	72	62	100	78	60
Valley gravel	100	70	60	100	66	58

Therefore, the asphalt mixture that has the highest M_R has the highest M_{RR}. The degree of saturation had a very significant effect on M_R values. Where a high degree of saturation is very effective in distinguishing between the stripper and non-stripper aggregates. To estimate the effect of stripping potential on asphalt mixtures, which need Marshall specimens with 6-8% air voids are essential to ensure adequate saturation for M_R testing.

*4.3. **Fatigue** test*

Many factors affect the stripping potential of asphalt concrete mixtures revealed that these factors could be either internal or external. Internal factors may include the mix component characteristics or the mix configuration, the materials used in the mix such as aggregate, asphalt, and additives. From the results, the following are the most effective on the fatigue.

4.3.1. Effect of Aggregate Type

According to the results, limestone showed the best resistance to a failure of the three types of aggregate. That is because limestone has large pores on the exposed surfaces and a small percentage of SiO_2 content. The high cohesion and adhesion of limestone with asphalt cement affect the fatigue performance of aggregate. The physical nature of the aggregate- surface affects its resistance to stripping. The aggregate coatability affected by the surface texture. A complete initial coating minimizes the destructive effect of moisture on the mixes. In the presence of water, limestone bears positive charges as other calcareous materials. Typical aggregate that carries mixed charges includes trap rock, basalt, and siliceous limestone.

Aggregates shape affects asphalt mixture performance; angular-shaped particles give more mechanical stability, because of intensive interlock and internal friction. The basalt has better resistance to stripping than smooth, rounded valley gravel, but lower than limestone.

It was clear from the results, no remarkable differences in fatigue potential between valley gravel and basalt aggregates were detected. The low cycles to failure in valley gravel mixtures could be explained by that a rounded shape of valley gravel, smooth and dense surface, and the high percentage of silica (SiO_2) content, which reduces the strength of bonding between the asphalt cement film and surface of the aggregate. This because basalt aggregate has a rough and porous surface aggregate. In general, the number of cycles to failure is inversely proportional to accumulate strain as shown in Table 3.

4.3.2. Effect of Additives

The main objective of any anti-stripping agent is to strengthen the bond between the asphalt cement and the aggregate surface, which may prevent or minimize stripping. The improvement in stripping potentials of all mixtures due to adding a different additive dosage of a hydrated lime additive as shown in Table 3.

(a) Hydrated lime

Hydrated lime has a significant positive effect on increasing the cycles to failure, which increased by 175 %, 175 %, and 214 % for limestone, valley gravel, and basalt respectively. A 1000 accumulated strain was taken as a limit to accept the mixture. The flexural stiffness and fatigue life have decreased by the conditioning of specimens without hydrated lime. The improvement in fatigue resistance is due to the hydrated lime addition. The mechanism of the hydrated lime effect is due to the roughness increase of aggregate surfaces, filler enhancing the viscosity of binder, and an increase in the stiffness of the mixture, which resulted in reducing the cracks in asphalt pavement as shown in Tables 3.

a) Polyamine

Polyamine has a less significant positive effect of increasing the cycles to failure than hydrated lime additive; the improvement in fatigue resistance is due to polyamine additions and increase in the contact area between the asphalt and aggregate surface. The increase in cycles to failure has many reasons: the mechanism of polyamine included the effect of the surface-active agent, increasing the wettability of asphalt cement to aggregate, and an increase the cohesion between coated aggregates in asphalt pavement. All aggregates types have shown a tendency for stripping at a high degree of saturation as shown in Tables 3.

5. Suggested Systematic Testing Procedure

To achieve the objectives of this research, a step-by-step procedure together with pass-fail criteria by which stripping was predicted. The research has compiled tests and materials that are dominant in Jordan. Although some of the tests are very simple and require minimum laboratory pieces of equipment and time, other types are sophisticated and need high technology.

5.1. Pass-fail Criteria

It is very hard to standardize pass-fail criteria that could be applied to all mixtures where a stripper from a non-stripper aggregate could be distinguished. Researchers have suggested values that could be used for the above purpose for each test separately. It is obvious that when the test is so severe, the threshold line should below. However, the use of asphalt retained percent for the boiling test, the tensile strength ratio, and the ratio of retained modulus of resilience could be satisfactorily applied. Jordan specifications require a loss in Marshall stability, not more than 25%, based on this, the 70% M_{RR} ratio considered for the separation purposes [32].

5.2. Systematic Flow Chart

The flowchart is shown in Fig. 7 described a systematic testing procedure that could be used to predict the stripping potential of asphalt concrete mixtures. The flowchart was developed based on the results of the tests resulted from Alkofahi [12].

The selected material or aggregate type has to pass the following several stages before it is considered acceptable for construction as a non-stripper aggregate:

- Select the aggregate type and obtain the optimum asphalt content by using the Marshall procedure.
- Run the Texas boiling test on the selected aggregate mixture.
- Evaluated the retained coating as done by Gharaybeh and Parker [6] and Lottman [7]:

a) If the retained coating ≤ 60% of the aggregate is a stripper, it has to be changed or combined with another type of aggregate, and additives in this stage are not recommended, thus checking the moisture susceptibility of aggregate. Adding anti-stripping agents to this aggregate type will not give a guaranteed water susceptible mixture,

b) If the retained coating > 60%, then: run five-pulse indirect tensile test (ITS) condition 1, to verify that the aggregate will not strip,

c) If $M_{RR} \geq 80$ %, then the aggregate type is a non-stripper, it needs no additives,

d) If M_{RR} < 60 %, then the aggregate type is a stripper, it has to be treated with additives,

e) If 60% ≤ M_{RR} < 80%, then run five pulses ITS condition 2 for verification,

f) If M_{RR} ≥ 70%, then the mixture type is a non-stripper,

g) If M_{RR} < 70%, then the mixture type is a stripper, and it needs additives treated.

- When additives are added to a mixture, condition 2 should be used, and 70% of M_{RR} should be used as a pass-fail criterion. Jordan specifications require a loss in Marshall stability, not more than 25%. Based on this, the 70% M_{RR} ratio was considered for separation purposes [32].

- The non-stripper mixture needs a fatigue test check to verify its resistance to cracking.

5.3. Application Example

The following illustrates the use of the flowchart shown in Fig. 7. If an aggregate type has to be used in road construction, it should be first tested for moisture susceptibility before it is considered as a non-stripper aggregate. The following steps are applied:

1- Select aggregate type and asphalt content with the conventional design procedure (Marshall).

2- Run a Texas boiling test on this aggregate mixture. Assumed retained coating =84%, so the aggregate is preliminarily considered as non-stripper, then;

3- Run a five-pulse indirect tensile test condition 1, to verify that the aggregate will not strip. Assumed M_{RR} =77%, so the aggregate type is considered as a stripper aggregate according to the flowchart (Fig. 7), it needs additives,

4- Lime added as a slurry to the mixture with a dosage of 1.5% by weight of aggregate.

5- Run five pulse indirect tensile test condition 2 for more verification. Assumed M_{RR} = 75%, then the aggregate mixture type is non-stripper.

6- The mixture has to be checked with a fatigue test to verify its resistance to cracking:

7- The selected aggregate type can be used for this road project, with the recommendation of using lime additive by a dosage of 1.5% by weight of aggregate.

6. Conclusions

The study has revealed the following conclusions related to the materials, additives, moisture saturation, and testing procedures which are:

1) The visual assessment of the boiling test is not enough to predict stripping.

2) The additives used, have a great effect on all aggregates, especially valley gravel and basalt. In general, it found that the dosage of lime needed is between 1.5 to 2.0% by weight of aggregate, where for polyamine, it was between 0.75 to 1% by weight of asphalt binder. Lime additive showed better effects on stripping potential than polyamine (liquid).

3) A high degree saturation condition is very effective in distinguishing between a stripper and non-stripper aggregates. The degree of saturation had a very significant effect on M_R.

4) The range of 60% to 80% of asphalt retained is considered a separate limit between a stripper needs an additive and non-stripper

aggregates.

5) Fatigue test gives a good indicator of the performance of moisture potential and additive effects. The number of cycles to failure is inversely proportional to accumulate strain.

6) The use of the M_R test for Marshall specimens is a reliable test to predict stripping.

7) The developed systematic testing procedure is a step-by-step procedure. It is a viable technique to avoid misleading tests in predicting stripping, and it could be used as a guideline to assess the water susceptibility for any aggregate type.

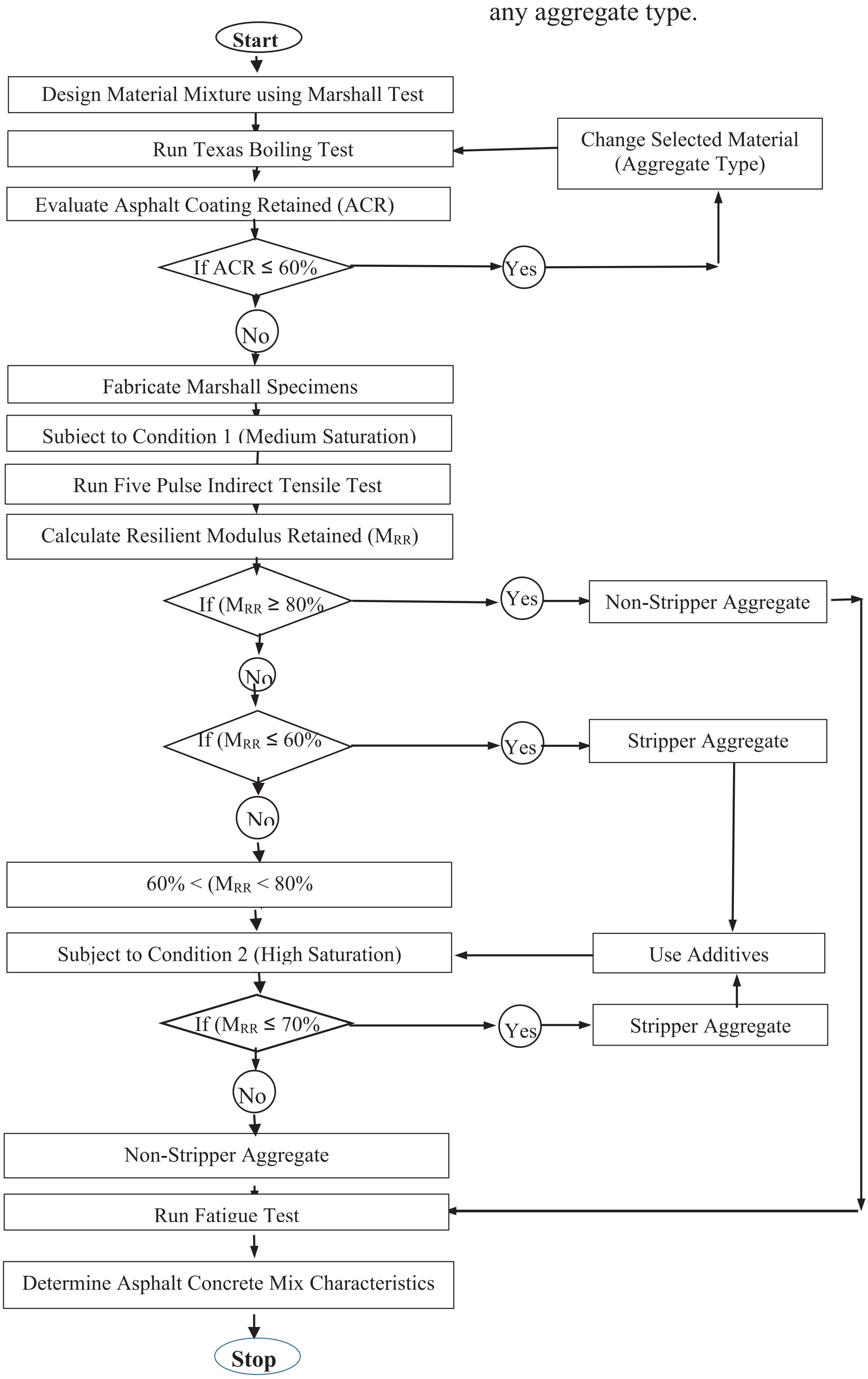


Fig. 7. Systematic testing methodology flow chart

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