Jurnal
Teknologi

Full Paper

AN OVERVIEW OF MOISTURE DAMAGE PERFORMANCE TESTS ON ASPHALT MIXTURES

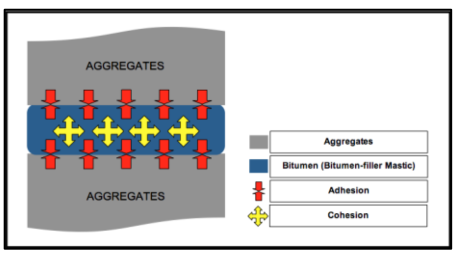
Fauzan Mohd Jakarni[a*], Muhammad Fudhail Rosli[a], Nur Izzi Md Yusoff[b], Md Maniruzzaman A Aziz[c], Ratnasamy Muniandy[a], Salihudin Hassim[a]

[a]Department of Civil Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia
[b]Department of Civil and Structural Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia
[c]Department of Geotechnics and Transportation, Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia

Article history
Received
2 December 2015
Received in revised form
13 March 2016
Accepted
31 March 2016

*Corresponding author
fauzan.mj@upm.edu.my

Graphical abstract



Abstract

This paper presents a review of moisture damage performance tests on asphalt mixtures. The moisture damage remains to be a detriment to the durability of the Hot Mix Asphalt (HMA) pavement. Moisture damage can be defined in forms of adhesive failure between bitumen and aggregates and cohesive failure within bitumen. Aggregate mineralogy, bitumen characteristics and anti-stripping additive dominantly influence the performance of asphalt mixtures towards moisture damage alongside construction methods, climate and traffic loading. Various laboratory test methods have been developed to quantify the moisture damage performance of asphalt mixtures by resembles the action in the field, including qualitative test such as Boiling Water Test (ASTM D3625) and quantitative tests such as Modified Lottman Test (AASHTO T283). Both of these tests consist of two phases, which are conditioning and evaluation phase. This paper will review the effectiveness of the selected available tests based on various asphalt mixtures materials. Generally, this study indicates that asphalt mixtures consisted of limestone aggregates, modified bitumen and addition of anti-stripping additives will provide more resistant towards moisture damage.

Keywords: Moisture damage, adhesion, asphalt mixtures, Boiling Water Test, Modified Lottman Test

1.0 INTRODUCTION

Nowadays, Malaysian feels greatly unsecured when driving on the road mostly because of the presence of road distresses particularly after rainy season. Generally, moisture or water had been associated to this issue. Evaluation of moisture damage or moisture susceptibility in asphalt mixtures remained precedence in the pavement construction almost a few decades ago. In this manner, a speedy, reliable and practical approach for evaluating moisture susceptibility of asphalt mixtures will offer engineers and contractors the competence of testing asphalt mixtures, before, during and after lay down of asphalt mixtures pavement, or to find the right combination and proportion of various asphalt mixture materials [11]. Moisture damage in flexible pavement is regularly known as stripping. Stripping can be illustrated as a loss of bond between aggregates and bitumen. It frequently occurs when moisture permeates the pavement and weakening the bond between aggregates and bitumen. Then, it will cause the reduction of pavement strength and subsequently lead to various distresses such as raveling, rutting, fatigue cracking, and bleeding of the binder to the pavement surface, which could decrease pavement's skid resistance [3, 12, 16].

There are two conditions associated to moisture damage either loss of adhesion between aggregates and bitumen or the weakening of the bitumen called as cohesion failures [9]. For the first mechanism, water permeates the asphalt mixtures and disintegrates the bitumen film from aggregates, leaving the aggregates without bitumen film coating. While for the second mechanism, it can be explained as the loss of stiffness and durability of bitumen due to repetitive effect of water. Alam *et al.* [3] reviewed that various tests had been implemented to assess moisture damage performance of asphalt mixtures since 1930s. Conversely, none of these tests producing a very significant results in evaluating moisture damage performance of asphalt mixtures. These tests can be characterized into two which is those depended on the estimation of the ratio of conditioned to unconditioned strength of the compacted specimen (quantitative determination) either from the laboratory or from the field, while others depend on visual assessment (qualitative determination) of stripping of bitumen from loose asphalt mixtures.

Similarly, Solaimanian *et al.* [15]pointed out that the tests can be classified into those evaluating the affinity between aggregates and bitumen in loose mixture condition and those accustomed to evaluate the moisture sensitivity in compacted mixture condition. At present, accessible moisture damage performance test that had been recognized, for example, Boiling Water Test (ASTM D3625) and Static Immersion Test (ASTM D1664/AASHTO T182) only depend on subjective evaluation, while Modified Lottman Test (AASHTO T283) and Immersion Compression Test (AASHTO T165) rely on the principle of relative assessment of mechanical properties (indirect tensile strength, resilient modulus, Marshall stability or compression strength) of conditioned sample and unconditioned sample. Meanwhile, other tests such as Saturation Ageing Tensile Stiffness (SATS), Environmental Conditioning System (AASHTO TP34) and Hamburg Wheel Tracking have also been established in order to assess moisture damage performance of asphalt mixtures [7]. This paper presents a review of moisture damage performance tests on asphalt mixtures in terms of the effectiveness of the selected available tests based on various asphalt mixture materials.

2.0 OVERVIEW ON MOISTURE SUSCEPTIBILITY TESTS

Development of tests to evaluate moisture susceptibility of asphalt mixtures has started since 1930s [17]. It has been conclusively shown that since that time, a number of tests had been implemented in order to identify the proneness of asphalt mixtures to moisture damage [4, 6]. Up to now, the test procedures have tried to resemble the loss of strength that possibly occurs in the pavement so that the premature distresses of asphalt mixtures can be recognized prior to construction. Diab and You [10]observes that even though continuous improvement on moisture susceptibility tests has been made in clarifying and understanding the mechanisms of moisture damage, a reliable and practical laboratory method that can simulate moisture damage in the field is still needed. However, theoretically it is almost impossible to invent a laboratory test procedures that can imitate the field conditions including traffic loading, environmental condition and construction practices. Diab and You [10]argues that some efforts have been made so far to develop a test procedure that would precisely determine the susceptibility of asphalt pavement to moisture damage. However, none of the moisture susceptibility test has been accepted widely due to lack of repeatability, difficulty of the process, expensive equipment and lack of quantitative results.

Al-Swailmi [4] founds that moisture susceptibility tests have conditioning and evaluation phases. The conditioning phase is conducted to imitate the deterioration action on flexible pavement in the field including environment conditions, traffic load repetition, climate (humid and hot climates), air voids level and others. While for evaluation phase, the asphalt mixtures sample will then be assessed by visual evaluation (qualitative evaluation) and physical tests (quantitative evaluation). In the visual evaluation, the percentage of retained bitumen coating is then determined after the conditioning process. While, physical tests evaluation consisted of strength or modulus and a ratio between the results from conditioned sample with the result from unconditioned sample is computed. If the ratio is less than standardized value, the sample will be clarified as moisture susceptible.

Conversely, Solaimanian *et al*. [15] and Copeland [8]argued that moisture susceptibility tests could be divided into two categories, which is test on loose mixtures (qualitative test) and test on compacted mixtures (quantitative test). The following are some of the tests that been used by public agencies by referring to AASTHO and ASTM standard.

i. AASHTO T 165/ASTM D 1075 Effect of Water on Compressive Strength of Bituminous Mixtures
ii. AASHTO T 283/ASTM D 4867 Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage
iii. ASTM D 3625 Effect of Water on Bituminous-Coated Aggregate using Boiling Water
iv. ASTM D 4867 Effect of Moisture on Asphalt Concrete Paving Mixtures
v. AASHTO T 324 Hamburg Wheel-Track Testing of Compacted Hot-Mix Asphalt

2.1 Tests on Loose Asphalt Mixtures (Qualitative Tests)

These types of tests are conducted on bitumen-coated aggregates by immersing samples into water. Some examples of these tests are boiling test, filmstrip, and static/dynamic immersion tests. Benefit of these tests is they are only consuming short time and less costly to conduct comparing with tests on compacted samples. Besides, these tests also only need simple equipment and procedures. However, these tests are not able of simulate pore pressure, traffic conditions and mix design properties to justify moisture susceptibility of asphalt mixtures. The results are mostly qualitative and clarification of the results tends to be subjective as it is reliant on the evaluator's judgment and experience. Besides, correlation between these types of tests to field performance of flexible pavement is still unreliable.

In addition, these tests are suitable to be used for comparative purpose between different asphalt mixtures or uses of different anti-stripping additive to evaluate compatibility, stripping and strength of adhesion of asphalt mixtures. Mixtures that not achieved the required standard of these tests will be considered fail and have higher probability to strip and should not be used. Though, successful results not necessarily mean that the asphalt mixtures can be used, as the effects of other factors are not taken into consideration in these tests. Most popular test conducted on loose samples that are currently used such as Static Immersion Test (AASHTO T182) and Boiling Water Test (ASTM D3625). Table 1 provides explanation on the only established standard tests on loose asphalt mixtures according to AASTHO and ASTM.

Table 1 Test methods on loose asphalt mixtures

Tests	Measured Parameter	Approaches of the Test	Description of Test Procedures
Static Immersion (AASHTO T182)	Percentage of aggregate remain coated after static immersion in water	Focusing on adhesion bond failure	The test required a sample of asphalt mixtures been immersed in a jar filled with 600 mL of distilled water after been cured for 2 hours at 60oc and cooled to room temperature. The jar is then capped left settled in a 25oc water bath for 16 to 18 hours. The degree of stripping is visually evaluated while the mixture still in the jar.
Boiling Water (ASTM D3625)	Percentage of aggregate remain coated after boiling in water	Focusing on adhesion bond failure	The test involves placing loose sample of asphalt mixtures into boiling water and being stirred using glass rod. After 10 minutes, the mixture is left to cool while the stripped bitumen is detached away. Then, the mixture is removed from the water and being dried in room condition

2.2 Tests on Compacted Sample of Asphalt Mixtures (Quantitative Tests)

Solaimanian *et al.* [15] states that this type of test is performed on laboratory-compacted samples or taken from field in the form of cores or slabs. Some of the tests that currently established as standard tests and widely used according to ASTM or AASHTO are Immersion-Compression Test (ASTM D1075/AASHTO T165), Modified Lottman Test (AASHTO T283) and Tunnicliff-Root Test (ASTM D4867). Other tests such as Hamburg Wheel Tracking Test (AASHTO T324), Environmental Conditioning System (AASHTO TP34), Simple Performance Test (SPT), Asphalt Pavement Analyser (APA), Moisture Induced Sensitivity Test (MIST) and Saturated Ageing Tensile Stiffness (SATS) are also taken into consideration but rarely used due to lack of standardization in the procedures used (i.e. in terms of sample preparation, complexity of the procedures and also involve quite high cost of conducting the test). The main benefits of these tests is that it can assess the physical and mechanical properties while the traffic action and pore pressure effects can also be considered [15]. The results provided are measured quantitatively and this will reduce the higher variability of the test results as compare to visual evaluation. However, the weaknesses from these tests are it involved very expensive and complex testing equipment, take longer time to perform and require more laborious test procedures. Summary for some of these tests that currently been widely used is briefly explained in Table 2.

Table 2 Test methods on compacted asphalt mixtures

Tests	Measured Parameter	Description of Test Procedures
Immersion-Compression Test(ASTM D1075/ AASHTO T165)	Ratio of average strength of conditioned specimens over controlled specimens is being used as a parameter to measure loss of strength cause by moisture damage	General procedures involve six specimens which been divided equally into two group known as control group and conditioned group. The control group is dried while specimens in conditioned group is being immersed in water bath at 120°F (49°C) for four days or at 140°F (60°C) for one day. Compressive strength of the specimens from both groups is measured at 77°F (25°C) at a loading rate of 0.05 inches/minutes per inch of height.
Lottman Test	Ratio of test values conditioned specimen to control group specimen (tensile strength ratio,TSR) including freeze and thaw cycle	Nine compacted Marshall specimens of 100 mm in diameter and 63.5 mm in height are equally divided into 3 groups (i.e. Group 1: Control group, dry; Group 2: Vacuum saturated at 660mmHg with water for 30-minutes and Group 3: Vacuum saturation followed by freeze cycle at -18°C for 15 hours and then subjected to a thaw at 60°C for 24 hours). After the conditioning procedures, Resilient Modulus (MR) and/or Indirect Tensile Strength Test (ITS) are conducted on each specimen based on the specified testing conditions.
Tunnicliff–Root Test (ASTM D4867)	Ratio of test values conditioned specimen to control group specimen without freeze and thaw cycle	Improvising from Lottman Test (i.e. Load rate increases to 2 inches/minutes from 0.065 inches/minutes; test temperature increases from 55°F (12.8°C) to 77°F (25°C); pre-saturation of 55%-80% compared to an infinite level in Lottman test and removing freeze cycle conditions).
Modified Lottman Test (AASHTO T283)	Ratio of test values conditioned specimen to control group specimen with/without freeze and thaw cycle	Procedure combines features of both the Lottman and Tunnicliff and Root procedures. Lottman procedures attempts to achieve 100% saturation level, while the Tunnicliff and Root procedures attempts to control the level of saturation between 55%-80%. Modified Lottman procedures have set the degree of saturation to between 60%-80%. As the saturation level achieved by partial vacuum is primarily responsive to the magnitude of the vacuum and relatively independent of the length of time, this reduced saturation was achieved by reducing the partial vacuum from 600 mm Hg to 508 mm Hg.

3.0 ANALYSIS ON PREVIOUS MOISTURE SUSCEPTIBILITY TESTS ON VARIOUS ASPHALT MIXTURES

As can be seen from the Tables 3 to 5, it can be concluded that asphalt mixtures consist of limestone aggregate will give more resistant to moisture damage. From Table 3, the results generated by Khosla *et al.* [13] shown that asphalt mixtures consisted of limestone produce the highest tensile strength ratio (TSR) which is 61.7% compare to asphalt mixtures consisted of slate which is 48.6% and granite which is 58.5%, with the same type of bitumen without any anti-stripping additives after conditioning by Modified Lotmann Test. By referring to Table 4 after Immersion Compression Test, those findings are consistent with those of study by Kumar and Anand [14]. Kumar and Anand [14] shown that asphalt mixtures consisted of limestone give the highest Marshall stability ratio which is 98% compared to asphalt mixtures consisted of granite (89.1%), sandstone (87.8%) and Harwar Quartzite (86.5%). Whereas in Table 5, after Boiling Water Test being conducted on loose asphalt mixtures, the results hown that asphalt mixtures consisted of limestone produce the highest percentage of aggregates remain coated by bitumen which is 98.7% and 98.4% compared to other asphalt mixtures which consist of quartzite (59.7%), granite (84.2%) and andesite (13.5%).

Table 3 Results of Modified Lottman Test

Mixtures Design	Aggregates	Bitumen	Additives	Strength Ratio (%)		
				Minimum Requirement	Water Immersion	Freeze-thaw @ -18°C for 16 Hours
Marshall	Granite	Penetration 60/70	Quarry Dust	70.0	82.0	70.9
			Portland Cement	70.0	83.3	74.6
			Polymer Modifier	70.0	86.2	76.7
	Lime stone (Medium Limits of Dense Graded)	Penetration 60/70	Calcium Hydroxide	80.0	NA	68
			Limestone Dust	80.0	NA	96
			No Additives	80.0	NA	48
		Penetration 80/100	Calcium Hydroxide	80.0	NA	60
			Limestone Dust	80.0	NA	96
			No Additives	80.0	NA	40
Superpave	Granite	PG 64	Not Available	80.0	82.2	NA
		PG 70	Not Available	80.0	94.7	NA
Marshall	Granite	PG 64	Not Available	80.0	99.8	NA
		PG 70	Not Available	80.0	97.3	NA
Superpave	Slate	PG 64-22	No Additive	80.0	48.6	NA
			Hydrated Lime	80.0	80.8	NA
			Amine	80.0	95.2	NA
			Phosphate Ester	80.0	83.5	NA
	Limestone	PG 64-22	No Additive	80.0	61.7	NA
			Hydrated Lime	80.0	80.9	NA
			Amine	80.0	81.2	NA
			Phosphate Ester	80.0	72.0	NA
	Granite	PG 64-22	No Additive	80.0	58.5	NA
			Hydrated Lime	80.0	85.7	NA
			Amine	80.0	81.2	NA
			Phosphate Ester	80.0	79.0	NA
	Limestone and Gravel (Less Angular)	PG 64-22	No Additive	80.0	NA	69
			Hydrated Lime	80.0	NA	77
	Limestone and Gravel (More Crushed)	PG 70-28	No Additives	80.0	NA	79
			Hydrated Lime	80.0	NA	85
			Fly Ash	80.0	NA	91

Note: NA – Not Available

Table 4 Results of Immersion Compression Test

Mixtures Design	Aggregates	Bitumen	Additives	Strength Ratio (%)	
				Minimum Requirement	Test Results
Marshall	Granite	Viscosity Grade 30	No Additives	70.0	89.1
			Hydrated Lime	70.0	96.8
	Limestone		No Additives	70.0	98.0
	Sandstone		No Additives	70.0	87.8
			Hydrated Lime	70.0	97.0
	Harwar Quartzite		No Additives	70.0	86.5
			Hydrated Lime	70.0	94.5
Superpave	Crushed Stone	PG 64-16	Class C Fly Ash	70.0	95.0
			Class F Fly Ash	70.0	112.0
			Cement Kiln Dust	70.0	95.0
			Hydrated Lime	70.0	93.0
			HP Plus (Amine chemical)	70.0	97.0
			No Additives	70.0	97.0

Table 5 Results of Boiling Water Test

Mixtures Design	Aggregates	Bitumen	Additives	Strength Ratio (%)	
				Minimum Requirement	Test Results
Superpave	Limestone and Gravel (Less Angular)	PG 64-22	No additive	90.0	85.0
			Hydrated lime	90.0	94.0
			Fly ash	90.0	95.0
	Limestone and Gravel (More Crushed)	PG 70-28	No additives	90.0	98.0
			Hydrated lime	90.0	99.0
			Fly ash	90.0	99.0
Marshall	Granite	Viscosity Grade 30	Hydrated lime	95.0	>95.0
	Sandstone		Hydrated lime	95.0	>95.0
	Limestone		Hydrated lime	95.0	>95.0
	Delhi Quartzite		Hydrated lime	95.0	>95.0
	Harwar Quartzite		Hydrated lime	95.0	>95.0
Superpave	Quartzite	Penetration 60/70	No additives	95.0	59.7
			Hydrated lime	95.0	96.5
			Zycosoil	95.0	98.6
	Granite		No additives	95.0	84.2
			Hydrated lime	95.0	98.6
			Zycosoil	95.0	98.6
	Andesite		No additives	95.0	13.5
			Hydrated lime	95.0	98.6
			Zycosoil	95.0	99.2
	Limestone		No additives	95.0	98.4
	Slag limestone		No additives	95.0	98.7
Marshall	Lime stone (Medium Limits of Dense Graded)		Calcium Hydroxide	95.0	96.0
			Limestone dust	95.0	96.0
			No additives	95.0	89.0
		Penetration 80/100	Calcium Hydroxide	95.0	95.0
			Limestone dust	95.0	95.0
			No additives	95.0	90.0

Addition of anti-stripping additive will increase asphalt mixtures resistant to moisture damage exponentially. It can be seen from the research carried by Abo-Qudais [1] in Table 3 that the Tensile Strength Ratio (TSR) value recorded by asphalt mixtures with addition of anti-stripping additives such as limestone dust is very high which is 96% compared to asphalt mixtures without anti-stripping additives which is recorded to be 48% and 60% with constant type of bitumen and aggregates. This circumstance also can be seen in research by Khosla *et al.* [13] that also shown high Tensile Strength Ratio (TSR) ranging from 72% to 95.2% in asphalt mixtures with addition of anti-stripping additives compared to without any additives, which is in range of 48% to 61.7%. While in other test such as Immersion Compression Test, addition of anti-stripping additive also give the same results. With respect to Table 4, it was found that with the same type of aggregates and bitumen, the Tensile Strength Ratio (TSR) value for asphalt mixtures in addition of anti-stripping additives is higher than without any addition of anti-stripping additives [14]. Referring to Table 5, results from Boiling Water Test also shown the same situation. Percentage of aggregates remain coated with bitumen is higher in asphalt mixtures with the addition of anti-stripping additives compared to the asphalt mixtures without any additives with the fixed aggregates and bitumen.

In general, types of bitumen also have a significant impact in moisture resistant to moisture damage. Uses of modified bitumen will increase the moisture resistant towards moisture damage. This is supported by Airey *et al.* [2], which explains that that increasing of binder grade will then lead to reducing of retained stiffness of bitumen. This circumstance will resulted in reduction of resistant towards moisture damage on asphalt mixtures. The research done by Abo-Qudais [1] after conducting Modified Lottman Test also found that asphalt mixtures consist of bitumen with Penetration 80/100 produce lower Tensile Strength Ratio (TSR) value compared to asphalt mixtures consisted of bitumen with Penetration 60/70 as the aggregates and anti-stripping additives remained the same. However, it was later shown by Abo-Qudais [1] that after testing with Boiling Water Test, asphalt mixtures consisted of bitumen with Penetration 80/100 produce slightly higher percentage of aggregate remain coated with bitumen which is 90% compared to asphalt mixtures consisted of bitumen with Penetration 60/70 which is 89%. This contradiction might be because of this test is relying totally on visual evaluation.

4.0 CONCLUSION

Generally, this study indicates that asphalt mixtures consisted of limestone aggregates, modified bitumen and addition of anti-stripping additives will provide more resistant towards moisture damage. These results are supported by studies conducted by Uddin [18] and Aman *et al.* [5]. Hydrated lime tends to be the most popular among others anti-stripping additives because it had been proven effective in increasing resistance of asphalt mixtures towards moisture. While lower penetration grade of bitumen and polymer-modified bitumen are most popular to be used in asphalt mix design because it can sustain moisture damage more than commonly used asphalt binder. Generally, Modified Lottman Test, Immersion Compression Test and Boiling Water Test can be expected to be reliable test on evaluating the moisture susceptibility of asphalt mixtures based on the analysis of the result of various combinations of asphalt mixtures.

Acknowledgement

The authors would like to thank the Department of Civil Engineering of Universiti Putra Malaysia and to all the people whom are directly and indirectly involved in this study.

References

[1] Abo-Qudais, S. 2007. The Effects Of Damage Evaluation Techniques On The Prediction of Environmental Damage In Asphalt Mixtures. *Building and Environment,* 42**:** 288-296.

[2] Airey, G., Collop, A., Zoorob, S. & Elliott, R. 2008. The Influence Of Aggregate, Filler And Bitumen On Asphalt Mixture Moisture Damage. *Construction and Building Materials,* 22**:** 2015-2024.

[3] Alam, M., Vemuri, N., Tandon, V., Nazarian, S. & Picornell, M. 1998. *A Test Method For Identifying Moisture Susceptible Asphalt Concrete Mixes. Research Project 0-1455.* Center for Highway Materials Research, University of Texas at El Paso: El Paso, Texas.

[4] Al-Swailmi, S.H. 1992. *Development of a Test Procedure For Water Sensitivity Of Asphalt Concrete Mixtures.* PhD Thesis, Oregon State University, Corvallis, United States.

[5] Aman, M.Y., Shahadan, Z. & Noh, M.Z.M. 2014. A Comparative Study of Anti-Stripping Additives in Porous Asphalt Mixtures. *Jurnal Teknologi,* 70(7): 139-145.

[6] Choi, Y. 2007. *Case Study And Test Method Review on Moisture Damage. Austroads Project AT1135.* Austroads: Sydney.

[7] Collop, A., Choi, Y., Airey, G. & Elliott, R. 2004. Development of the Saturation Ageing Tensile Stiffness (SATS) Test. *ICE Journal of Transport,* 157(3): 163-171.

[8] Copeland, A.R. 2007. *Influence of Moisture On Bond Strength Of Asphalt-Aggregate Systems.* PhD Thesis, Vanderbilt University, Nashville.

[9] Copeland, A.R., Youtcheff, J. & Shenoy, A. 2007. Moisture Sensitivity Of Modified Asphalt Binders: Factors Influencing Bond Strength. *Transportation Research Record: Journal of the Transportation Research Board,* 1998**:** 18-28.

[10] Diab, A. & You, Z. 2013. Development of a Realistic Conditioning and Evaluation System to Study Moisture Damage of Asphalt Materials. *Airfield and Highway Pavement:* 1008-1017.

[11] Jakarni, F.M., Muniandy, R., Hassim, S. and Mahmud, A.R. 2010. Analysis of Stone Mastic Asphalt (SMA) Slab Dimensions For Evaluation Of The Newly Developed Roller Compactor (Turamesin). *Pertanika Journal of Science and Technology (JST),* 18(1):13-22.

[12] Jakarni, F.M., Yusoff, N.I.M., Wu, J. and Aziz, M.M.A. 2015. Utilization of Sewage Sludge Molten Slag As Aggregate Substitute In Asphalt Mixtures. *Jurnal Teknologi Special*

Edition (Highway and Transportation Engineering), 73(4): 105-110.

[13] Khosla, N.P., Birdsall, B.G. & Kawaguchi, S. 2000. Evaluation of Moisture Susceptibility Of Asphalt Mixtures: Conventional and New Methods. *Transportation Research Record: Journal of the Transportation Research Board,* 1728**:** 43-51.

[14] Kumar, P. & Anand, P. 2012. Laboratory Study on Moisture Susceptibility of Dense Graded Mixes. *Journal of Transportation Engineering,* 138**:** 105-113.

[15] Solaimanian, M., Harvey, J., Tahmoressi, M. & Tandon, V. 2003. Test Methods To Predict Moisture Sensitivity Of Hot-Mix Asphalt Pavements*,* in Moisture Sensitivity of Asphalt Pavements:A National Seminar, San Diego, California, February 4-6, 2003.*Transportation Research Board*: Washington DC: 77-110.

[16] Terrel, R.L. & Al-Swailmi, S. 1994. Water Sensitivity Of Asphalt-Aggregate Mixes: Test Selection*: Strategic Highway Research Program Report A-403.* Oregon State University: Corvallis, Oregon.

[17] Terrel, R.L. & Shute, J.W. 1989. *Summary Report On Water Sensitivity*. *SHRP-A/IR-89-003,* Strategic Highway Research Program, National Research Council: Washington DC.

[18] Uddin, W. 2003. Viscoelastic Characterization Of Polymer-Modified Asphalt Binders Of Pavement Applications. *Applied Rheology,* 13**:** 191-199.