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EFFECTS OF OVERHEATING BITUMEN ON HOT MIX ASPHALT PROPERTIES

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Abstract

Hardening of bitumen has long been perceived as one of the main factors that can significantly affect the durability of bituminous paving materials. When the bitumen is hardened, the asphalt mixture will become brittle and its ability to support traffic-induced stresses and strains may significantly reduce. This study will presents a study of laboratory evaluation on the performance of hot mix asphalt (HMA) with (60/70PEN) overheated bitumen at 175°C, 185°C, 195°C, 205°C, 215°C and 225°C for 3 hours, compared with control sample heated at 165°C (virgin bitumen). Bitumen is sensitive to temperature. Thus, bitumen rheological properties have become factors that affect the hot mix asphalt (HMA) properties. The tests conducted are bitumen penetration, softening point, rotational viscometer and Marshall Mix design test. Result obtained from test was compared between control sample and sample of overheated bitumen. Based on the result, it was observed that the performance of HMA mixes was significantly affected with the increase of bitumen heating temperatures. The overheated bitumen was proven to oxidixe and harden more as the heating temperatures increases. This supported by the PI value which is decreases as the bitumen heating temperatures increases and also by the increases of viscosity value as the penetration value decreases. Overheated samples prepared bases on OBC obtained in the Marshall mix design. The tests yielded the maximum heating temperatures for 60/70 PEN bitumen before it start to loss the HMA properties is 189°C. From the verification samples prepared with the maximum heating temperatures show that, by overheated the bitumen the density, stiffness, stability and VFB increases but VTM and flow of HMA decereases. This was expected since by overheating the bitumen, the binder get harder and stiffer than bitumen heated at normal temperature.

Key-word: - Overheating Bitumen; Asphaltic Concrete; Penetration Test; Softening Point Test; Kinematic Viscosity Test; Marshall Test.

1.0 INTRODUCTION

In Malaysia, most of the major road network is bituminous pavement roads. This is because the bituminous pavement providing safe, durable and good riding surface over a desirable period with minimum maintenance. Due to traffic loading and climatic factors such as temperature and moisture, the most common modes of pavement distress are cracking and rutting and more critically some of the bituminous surfacing suffer from surface down cracking as early as four years after laying, much earlier than their normal design life of seven to ten years (Mustafa and Sufian, 1997).

Bituminous pavement materials comprised mainly of aggregates with bituminous binder and a little fillers. Aggregate helps in providing structure to lock together, tolerate the cross and channel load through to the bottom layer. Bitumen is a binding agent to bind the aggregate and produce a mixture that stable and strong.

In order to produce a good asphaltic layer, good quality bitumen which that serves as a binder to the aggregates, must meet the certain standards. Good physical properties of bituminous mixtures can be achieved by proper selection of ingredients of the mixture. Even after the proper selection of materials, specifications and proper mix design, the properties of bituminous mixes are also governed by other factors such as the time and temperature during handling, mixing and in service. The level of performance of service life has a close relationship with the properties of bitumen used in the asphaltic concrete.

1.1 Problem Statement

Bitumen are widely used in road construction largely because they are relatively inexpensive and generally provide good durability in paving mixtures. The properties of bitumen as asphalt binder are dependent on temperature. At high temperatures, the asphalt softens enabling permanent deformation of the pavement. At the low temperatures, the bitumen become stiff and inflexible and can crack as a result of strain and thermal condition. (Kjosavik, 2013). Besides that when a mixture of bitumen lost elasticity, fatigue cracking will occurred due to high load and the aging of bitumen. Meanwhile, low temperature cracking of pavements occurred due to the fragile due to contraction of the pavement (Atkins, 2003).

Bitumen also hardens at the early stages during handling, mixing and in service. The performance level of service life has a close relationship with the properties of bitumen used in the asphaltic concrete. During mixing the asphalt mixture, overheated the bitumen might occcur and this problem also coontributed to bitumen get hardens. Hence, the characteristic of bitumen need to be study, so that an early effective effort can be make in order to prevent any future problems and also can reduce cost for maintaining the roads conditions.

1.2 Objective of the Study

Therefore the aim of this study is to investigate the effects of overheating bitumen on rheological properties and HMA properties**.** With this purpose to be achieved, the objectives of this study are to:

a) compare the rheological properties between virgin and overheated bitumen at different temperatures; and
b) evaluate the hot mix asphalt properties at overheated bitumen samples and with control sample (virgin bitumen).

1.3 Scope of the Study

In order to investigate the effects of overheating bitumen on HMA properties, the scope of the study was included preparation of ACW 14 Marshall samples with bitumen content are 4.5%, 5.0%, 5.5%, 6.0% and 6.5% as control samples. The Marshall Test was conducted to determine optimum bitumen content and mix properties. Besides that, overheating bitumen will be stimulated by overheating the bitumen (60/70 PEN) in oven at 125°C, 150°C, 175°C, 200°C, and 225°C for 2 hours of the optimum bitumen content weight into the mixture. The rheological properties of the bitumen will be test by conducting the Penetration Test and Softening Point Test. Meanwhile, the viscosity test measures the viscosity of an asphalt. Both the viscosity test and the penetration test measure the consistency of asphalt at some specified temperatures. As for the hot mix asphalt properties, Marshall test will be conducted and the result on the density, stability, flow, voids in total mix, voids filled bitumen and stiffness from the overheated sample and control sample were compared and analyzed according to specification stated in JKR/SPJ/rev2008-S4.

2.0 LITERATURE REVIEW

2.1 Binder Ageing

The performance of the road pavement is determined by the properties of the bitumen, as bitumen is the continuous phase and the only deformable component (Yuonne et al., 2001). Bitumen is also a viscoelastic material with suitable mechanical and rheological properties for waterproofing and protective coverings for roads, because of its good adhesion properties to aggregates (Garcia-Morales et al., 2004). It has been well established that the rheological properties of the asphalt binder affect the pavement performance (Roberts *et al*, 1996). Since the rheological properties of asphalt binder change during HMA production and continue to change subsequently in service, the phenomenon of ageing (or age hardening) is given higher priority.

Ageing of asphalt binders is induced by chemical and physical changes during the production of the pavement and throughout its service life. The process is usually accompanied by hardening of the binders, which in general influences the deterioration of asphalt pavements. The most important ageing related modes of failure are traffic and thermally induced cracking, and ravelling.

Asphalt binder ageing takes place in two stages: short-term and long-term. Short-term ageing occurs during the production, storage, laying, and compaction of asphalt mixtures. Long-term ageing (in-service ageing) is mainly caused by exposure of binders to oxygen in a pavement. Asphalt binder ageing may be influenced simultaneously by several factors, such as characteristics and content of the binder, nature and particle size distribution of the aggregate, void content of the mixture, production related factors, and external conditions (e.g., temperature and time) (Lu and Isacsson, 1999).

2.2 Asphalt Binder Ageing Contributing Factors

The following six factors have been reported to contribute to the ageing of asphalt binder during mixing and in service (Roberts *et al*, 1996).

a) Oxidation – Complex organic constituents of bitumen react with atmosphericoxygen and UV radiation. This results in surface hardening, cracks and penetration of oxygen into cracks, which ultimately leads to oxidation. In his paper, Sung (2006) examines oxidation of 15 different types of binder. He concludes that the oxidation does not occur on the surface of the pavement only, but it also adversely affects the entire depth of the structure. The binder on the road surface becomes harder and more brittle at a depth section of up to 15 cm
b) Volatilization – The temperature rise in asphalt during its production, transport and placing, leads to the evaporation of lighter constituents of asphalt binder, which is defined as the short-term ageing. Light asphalt volatilisation is linked to the external weather conditions and UV radiation, which constitute an important influencing factor (Man et al, 2013). Volatilisation leads to the degradation of asphalt pavement, thus resulting in the increase in its stiffness and in negative impact on the functional and structural performance of road pavements. In his paper, Lolly (2013) examines the impact of bitumen exposure to high temperatures over time. The corresponding results indicate that the highest growth in bitumen viscosity occurs as the result of increase in exposure time. Significant changes in dynamic modules develop during the first few hours of exposure to elevated temperatures, leading to a rise in the short-term ageing of the binder. In their survey, Cui et al. (2014) analyse properties of two bitumens during their volatilisation at high temperatures. The results indicate that the mass content of bituminous binder decreases as a result of its exposure to high temperatures. A shorter volatilization is followed by the growth in its softening point and fall in its penetration value.
c) Polymerization – the combining of like molecules to form larger molecules, causing a progressive hardening. There is no scientific evidence that this is a significant factor during the low temperature ageing of asphalt in pavements in spite of such speculation in the literature.
d) Thixotropy – the progressive hardening due to the formation of a structure within the asphalt binder over a period of time, which can be destroyed to a degree by reheating and working the material. Thixotropic hardening (also called steric hardening) is generally associated with pavements which have little or no traffic, and its magnitude is a function of asphalt composition.
e) Syneresis – an exudation reaction in which the thin oily liquids are exuded to the surface of the asphalt binder film. With the elimination of these oily constituents, the asphalt binder becomes harder.
f) Separation – the removal of the oily constituents, resins, or asphaltenes from the asphalt binder as caused by selective absorption of some porous aggregates.

2.3 Rheological Properties of Asphalt

Rheology is the study of deformation and flow of matter. Deformation and flow of the asphalt binder in HMA is important in determining HMA pavement performance. HMA pavements that deform and flow too much may be susceptible to rutting and bleeding, while those that are too stiff may be susceptible to fatigue or thermal cracking. HMA pavement deformation is closely related to asphalt binder rheology. Since the rheological properties of asphalt binder vary with temperature, rheological characterization involves two key considerations:

a) To compare different asphalt binders, their rheological properties must be measured at some common reference temperature.
b) To fully characterize an asphalt binder, its rheological properties must be examined over the range of temperatures that it may encounter during its life.

3.0 METHODOLOGY

The purpose of this study was to investigate the effects overheated asphalt binder on its rheological properties and HMA properties. In order to evaluate the quality of asphalt binder on road asphalt, laboratory experiments have to be done to identify the performance of the overheated aspahlt compare to the fresh asphalt. All the laboratory experiment are based on the standard specification on JKR/SPJ/2008-S4 and AASHTO. Study will be carried out by using experimental methods to evaluate the quality of overheated asphalt binder and its suitability in road pavement especially in hot mix asphalt. The sample testing on this overheated asphalt is carried out through the bitumen tests and Marshall AC14 mix design procedures.

Testing on bitumen have to be carried out is Penetration Test, Rotational Viscometer and Softening Point Test in order to ensure it performs well on the specification. Both tests were carried out to test whether the overheated asphalt binder was appropriate. Penetration Test (ASTM D 5-86) is the consistency test to determine the material stiffness meanwhile Softening Point Test (AASHTO T 53-84) is the consistency test to determine the temperature where the phase change occur in bitumen. This study used the Marshall method, and the type of mixes that was designed is ACW 14. Overheated bitumen will be obtain by overheating the bitumen (60/70 PEN) in oven at 175°C, 185°C, 195°C, 205°C, 215°C and 225°C for 3 hours at the optimum bitumen content used in ACW 14. Minimum three specimens for each of the mix was prepared to obtain the optimum temperatures of the bitumen before its change their properties. The process framework for this study is summarized in Figure 1.

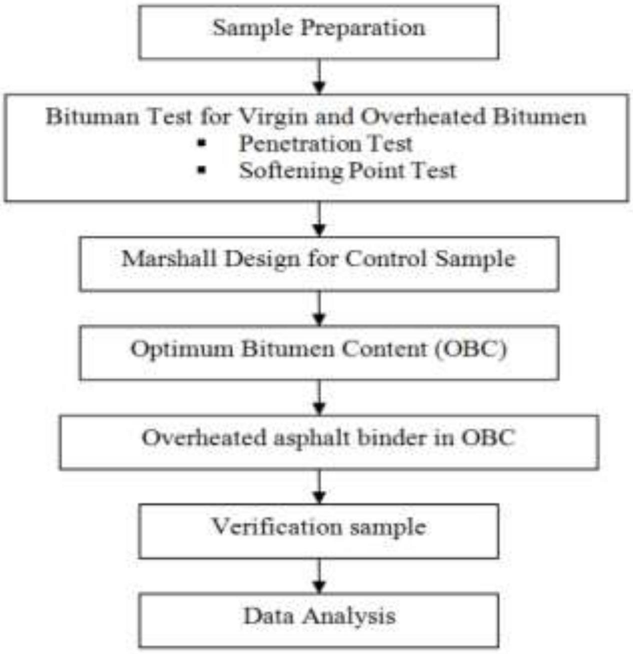

Figure 1 : Flow chart of methodology

4.0 RESULT AND ANALYSIS

Through the laboratory works that had been conducted, the result and data obtained will be used to analyze the effect of overheating bitumen on its rheological and HMA properties. Consistency tests were run to determine the penetration values, viscosity values and the softening points of the virgin and overheated bitumen samples. These data also will be analyzed to determine the relationship between the consistency tests and their effect to HMA properties.

Data analysis for HMA properties will be done according to Marshall test and all the results will be compared to the specification stated in JKR/SPJ/2008-S4. The comparison of HMA properties were observed in terms of density, stability, flow, stiffness, VTM and VFB. This is to ensure the optimum temperatures of bitumen heating before loss its properties.

4.1 Bitumen Test

4.1.1 Viscosity Test Results

From Figure 2, we can clearly see that the viscosity values for all samples decrease with the increase of test temperatures. .

The R² value for the viscosity slope versus temperature line for all samples is above 0.9, indicates the close relationship between viscosity and the temperature of the bitumen. The viscosity- temperatures relationship of a binder helps to identify the temperatures range bitumen workability for successful bituminous mixtures. If the viscosity of bitumen is too high, the binder may not completely coat the aggregate in the bituminous mixture; if the viscosity is too low, binder drainage is likely to occur during the storage and transportation of the mix. Identifying the most suitable temperature range for mixing allows decisions on the suitability of the binder to be made.

We can also see the viscosity of overheated bitumen more viscous than virgin bitumen. When bitumen has been overheated, it caused bitumen get stiffer, hence give high viscosity value as expected since needle can penetrate less through the stiffer bitumen and give lower penetration value as obtained in Penetration test for overheated bitumen.

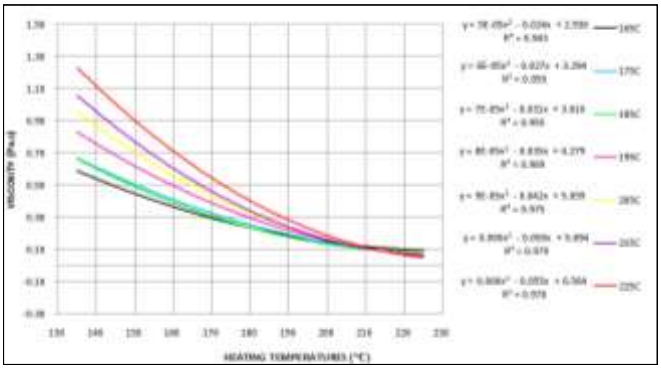

Figure 2: Viscosity versus temperatures

4.1.2 Penetration Index Results

Penetration Index (PI) is determined from Softening Point and Penetration Test. PI is used to predict bitumen and mixture visco-elastic properties. PI shows the suitability of bitumen as pavement binder. The suitable penetration index for bitumen is between -1 and +1 as based on the standard specification on JKR/SPJ/2008-S4 and AASHTO. Table 1 shows the summary of the PI result. The penetration index significantly decreases with the heating temperatures.

Table 1: Penetration Index value

Temperature °C	Penetration Index (PI)
165	-1.50
175	-1.25
185	-1.00
195	-1.25
205	-1.50
215	-1.25
225	-2.00

4.1.3 Relationship Between Viscosity, Penetration, Softening Point and Penetration Index (PI)

The relationship between physical properties studied; viscosity, penetration and softening point and calculated PI related to heating temperatures is analyzed. Table 2shows the summary for all physical properties studied.

Table 2: Summary of bitumen test results

Temperature °C	Viscosity (Pa.s) at 135°C	Penetration (PEN)	Softening Point (°C)	Penetration Index (PI)
165	0.60	55.9	48.0	-1.50

175	0.60	55.4	48.0	-1.25
185	0.60	55.6	48.5	-1.00
195	0.80	54.6	48.5	-1.25
205	0.90	54.7	49.0	-1.50
215	1.00	50.7	48.0	-1.25
225	1.20	49.4	47.5	-2.00

Figure 3 are based on the Table 2, shows the correlation between Viscosity test at 135°C and Penetration value of virgin and overheated bitumen samples. Its shows a good relationship between viscosity and penetration with the R^2 value of 0.858 which is indicates that the when bitumen been overheated, it caused bitumen get stiffer with high viscosity value and with less needle can penetrate will give lower penetration value as illustrated in the figure.

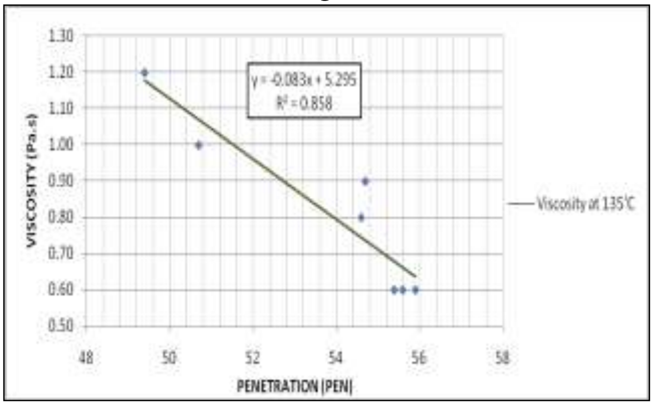

Figure 3: Relationship between Viscosity and Penetration

Figure 4 shows the relationship between Softening Point and Penetration. Acceptable models are obtained based on the linear model employed on the test data with 0.505 R^2 values that indicates that a linear model exactly represents the relationship between them. The penetration and softening point value increases due to the decreases of the bitumen heating temperatures.

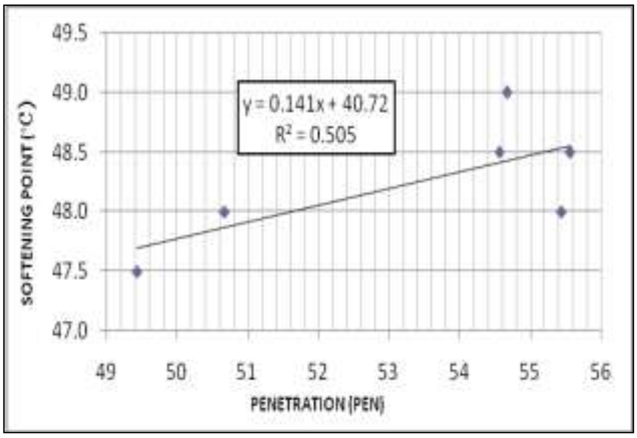

Figure 4: Relationship between Softening Point and Penetration

4.2 Analysis on Effect of Overheated Bitumen in AC14 Mixture

Results of Marshall Test for overheated bitumen were now compared to verification samples. Analysis and discussion on the effects of overheating bitumen in AC14 mixture will be explained.

4.2.1 Density Analysis

Figure 5 shows density versus bitumen heating temperatures. The graph shows that the maximum density for overheated bitumen was when the temperature at 195°C. The graph pattern shows that the density value increases as the heating temperatures increasing. The relationship between density and temperature are good as we can tell from the R^2 value which is more than 0.5.

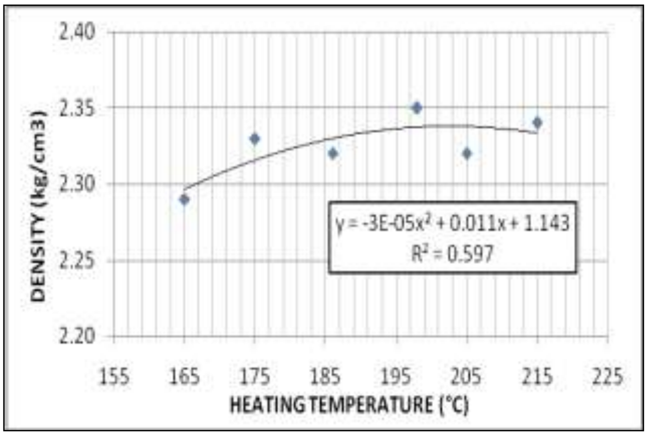

Figure 5: Effect of overheated bitumen on mixture density

Mix using overheated bitumen has higher density value compare to mix using virgin bitumen. The density value of the mix increases with increasing of the heating temperatures until a maximum value is reached, and start to decreases after that. Bitumen act as lubricant and helps the aggregates to slide over each other. Once the optimum value achieved, it only acts to displace over the aggregates and resulting the decreases of bulk density.

4.2.2 Stability Analysis

Figure 6 shows the good relationship between stability and overheated bitumen mixtures with 0.875 R^2 value. The graph shows that the stability value increases gradually with the increase of the bitumen heating temperatures and after 205°C its start decreases. If the stability is too high, it will causes significance effect on mixture. Excess bitumen will cause instability problem. Too high stability value produces a pavement mixture that is too stiff and less durable.

As we know, the stability of mixtures depends on bitumen cohesion. Cohesion results from the bonding ability of bitumen and the cohesion increase with increasing bitumen content. This occurs due to the high temperatures that liquefied the bitumen (overheated bitumen) and make it sufficiently fluid to coat the mixtures. However when bitumen been overheated at higher temperatures than 205°C, the bitumen get too liquefied and start to change its rheological properties and decrease the stability properties as illustrated in the figure.

From the penetration test, we know overheated bitumen is harder than virgin bitumen. Therefore, asphaltic concrete using overheated bitumen has higher stability than asphaltic concrete using virgin bitumen; hence it also expected to be more resistance to rut regarding to its harder and stiffer mix.

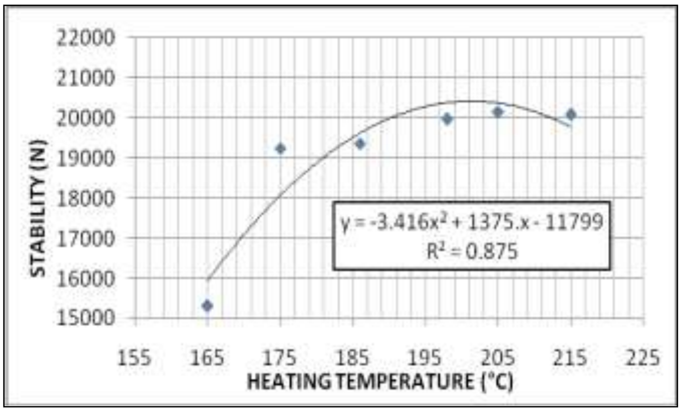

Figure 6: Effect of overheated bitumen on mixture stability

4.2.3 Voids Filled with Bitumen Analysis

Voids filled with bitumen are related to the voids in total mix and density. Figure 7show the graph of VFB versus bitumen heating temperatures from the Marshall test has been done. The percent of air voids filled with bitumen increases with increasing heating temperatures. The increasing amount of bitumen due to overheated it, results in thicker bitumen coating the aggregate particles. This will make the pavement mixture to be more difficult to allow air and water to permeate. Sufficient bitumen provides bonding properties adequate to resist the pavement abrasion and take a longer period of time to reduce a thicker film compared to thin film of bitumen. However if the bitumen content exceeds the optimum value, it will produce the mix that prone to bleed. Besides, it will reduce the stability of the mixture.

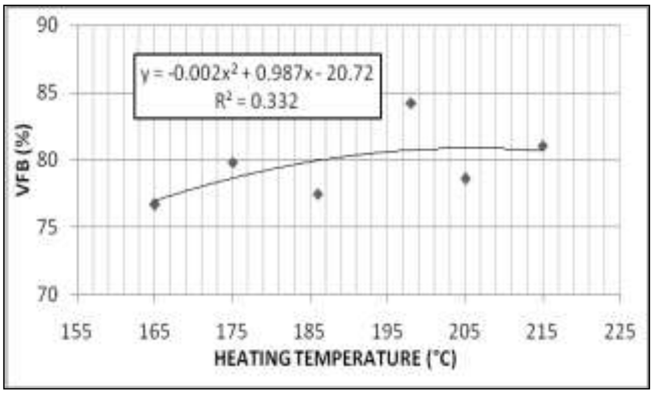

Figure 7: Effect of overheated on mixture VFB

4.2.4 Voids in Total Mix

From the Marshall test that has been done, the trend of the air voids in total mix obtained was decreases as the bitumen heating temperature increasing as shown in Figure 8. The decreasing of VTM value is because the voids are filled with bitumen. Density and VTM are directly related. The higher the value of density means that the lower percentage of voids in mixture. The voids in total mix were highly related to the compaction that has been done. Higher compaction caused the small particles filled between aggregate and reduce the voids in the mix. When the overheated bitumen melt due to the high temperature and high compaction caused the particles proper filled between aggregate and reduced the voids. Lower voids in mix caused bleeding when the extra traffic loads react on the mix surface. Meanwhile, the greater the air voids contents, the more easily air and water (moisture) can attack the bitumen and the adhesive bond between bitumen and aggregate. It leads to premature hardening of bitumen. Besides, it also results in poor durability.

Therefore, the optimum VTM is essential to allow for a compaction under traffic loading without any problems. Besides, the residual voids are used to allow for expansion of the bitumen and entrained air under hot weather condition. Since asphaltic concrete using overheated bitumen has lower VTM, it is expected that its rut depth is lower compared to asphaltic concrete using virgin bitumen when applied with same number of load cycle.

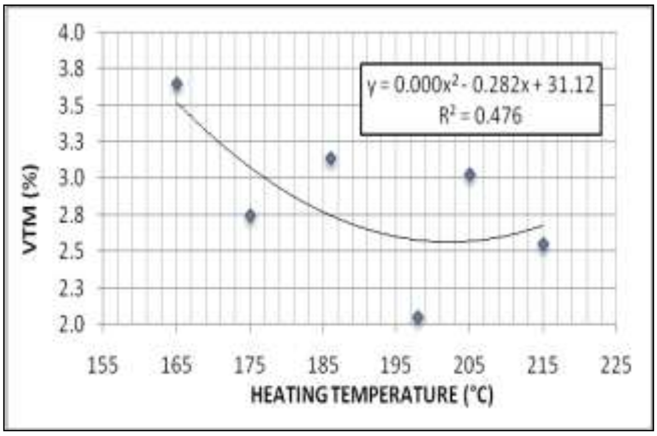

Figure 8: Effect of overheated on mixture VTM

4.2.5 Flow Analysis

Figure 9 shows the relationship between flow and bitumen heating temperatures. Flow was related to the flexibility of the mix. High value of flow shows high flexibility. According to the JKR/SPJ/2008-S4, the minimum flow of the wearing course was 2mm. The graph shows that the flow value decreases with increasing of the heating temperatures. This is expected since, the stiffer the bitumen, the viscous and the lower its flow.

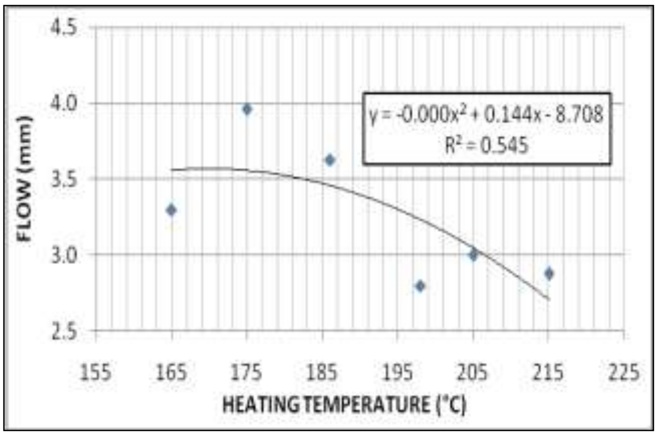

Figure 9: Effect of overheated bitumen on mixture flow

4.2.6 Stiffness Analysis

Stiffness of the mixture is important to limit the occurrence of rutting. Higher stiffness value shows that the mixture can take the load without changing in shape. Figure 4.10 shows the good relationship of stiffness and the bitumen heating temperatures by giving a 0.991 R^2 value. The stiffness value increases with increasing the heating temperatures and this result met the expectation based on the penetration test as bitumen get stiffer as the temperature increases. In term of rut resistance, the asphaltic concrete with overheated bitumen will has higher rut resistance depth compared to asphaltic concrete using virgin bitumen.

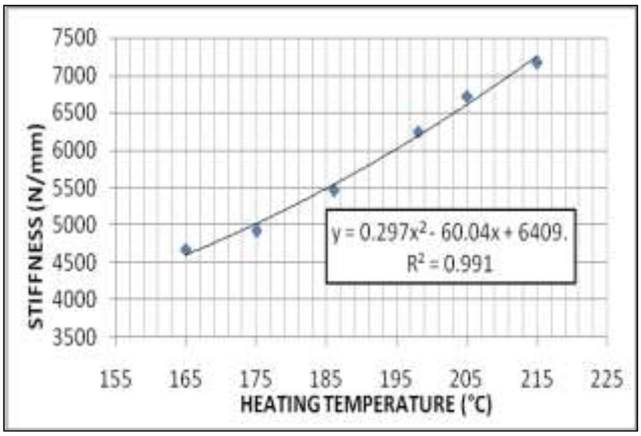

Figure 10: Effect of overheated bitumen on mixture stiffness

4.3 Data Analysis Conclusion

From the bitumen test and Marshall test analysis, the maximum heating temperatures for 60/70 PEN that meet the JKR/SPJ/2008-S4 specification is 189°C. Table 3 shown the result obtained for AC14 mixtures with bitumen heated at 189°C, fulfilled all the Marshall properties from the specification.

Table 3 : Marshall test result for AC 14 with bitumen heated at 189°C

Marshall Properties	JKR/SPJ/2008-S4	Modified AC 14
Stability	> 8000 N	18499
Flow	2 - 4 mm	3.40
Stiffness	> 2600 N/mm	5418
VTM	3% - 5%	3.01
VFB	70% - 80 %	77.6
Density	-	2.331

5.0 CONCLUSION

From this limited assessment, it was concluded that by increasing the bitumen heating temperatures before mixing procedure proven to oxidize and harden the bitumen at earlier stages. Meanwhile, maximum heating temperatures for 60/70 PEN bitumen before loss it HMA properties should be less or equal to 189°C. Asphaltic concrete with overheated bitumen which is not exceeded the maximum heating temperatures do increase the adhesion between the aggregate particles, durability and possibility to minimize the deformation of road wearing course.

Stated below are a few suggestions that may give some idea to continue the study of the effect of overheated bitumen on hot mix asphalt properties:

i) Various types of Bitumen Test should be done to determine the effects of overheated bitumen on its rheological properties.
ii) Study can be tested on different mixing and compaction temperature to identify the effects of the mixing and compaction temperature to the virgin and overheated bitumen based on viscosity – mixing/compaction temperature diagram.
iii) Besides that, varies the compactive effort to study the effect on the Marshall volumetric properties of virgin and overheated bitumen mixtures.

REFERENCES

American Association of State Highway and Transportation Officials, AASHTO (2000). Standard Specification for Transportation Materials and Method of Sampling and Testing. Washington D.C.: American Association of State Highway and Transportation Officials.

Atkins, H. N. (2003). *Highway Materials, Soils and Concretes*. 4th edition. Upper Saddle River, New Jersey: Prentice Hall.

Cui, P.Q, Zhang, H.H., Wu, S.P. (2014): Influence of High-Temperature Volatilization on Performance of Bituminous Binder, Key Engineering Materials, 599, pp. 164-167, http://dx.doi.

Garcia-Morales, M., Partal, P., Navarro, F. J., Martinez-Boza, F., Gallegos, C., González, N., González, O. and Muñoz M. E. (2004). Viscous Properties and Microstructure of Recycled Eva Modified Bitumen. Fuel, Vol.83, No.1, pp. 31-38.

Jabatan Kerja Raya (JKR) (2008). *Standard Specification for Road Works*. Kuala Lumpur, Malaysia, JKR/SPJ/2008.

Jung, J. S., Kamil, E. K., and George, B. W. (2002). Life Cycle Cost Analysis: Conventional Versus Asphalt-Rubber Pavements, Arizona, Rubber Pavements Association.

Kjosavik, A. M. (2013). *Determining the Rheological Properetis of Neat and Rubber Modified Soft Bitumen. Norway: Norwegian University of Sicence and Technology.*

Lolly, R (2013).: Evaluation of Short Term Aging Effect of Hot Mix asphalt Due to Elevated Temperatures and Extended Aging Time, Arizona State University.

Lu, X. and Isacsson, U. (1999). Characterization of Bitumen Modified with SEBS, EVA and EBA Polymers, *Journal of Materials Science*, Vol. 34, No. 15, pp. 3737–3745.

Man, Y., Shaopeng, W., Meizhu, C. (2012): Experimental Investigation of the Volatization of Asphalt under Different Conditions, Advanced Materials Research, 463-464 (2012), pp. 69-75,http://dx.doi.org/10.4028/www.scientific.net/AMR.463-464.69

Mustafa, M. Sh. and Sufian, Z. H. (1997). Prospects of Rubberized Bitumen Pavements in Malaysian Roads and Highways, *Proceeding Conference on the Use of Rubberized Bitumen in Road Construction*, Petaling Jaya, Selangor.
Roberts, F. L., Kandhal, P. S., Brown, E. R., Lee, D. Y., dan Kennedy, T.W. (1996). *Hot Mix Asphalt Materials, Mixture Design and Construction. 2nd ed.* Lanham Maryland, NAPA Education Foundation.
Sung, H. J. (2006): The effects of asphalt binder oxidation on hot mix asphalt concrete mixture rheology and fatigue performance, Texas A&M University.
Yuonne, B., Maryro, P. M. and Yajaira, R. (2001). Polymer Modified Asphalt. Vision Technological, Vol 9, No,1, pp. 39-48.