Jurnal
Teknologi

Full Paper

EVALUATING THE COOLING RATE OF HOT MIX ASPHALT IN TROPICAL CLIMATE

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Article history
Received
30th April 2015
Received in revised form
2nd August 2015
Accepted
1st October 2015

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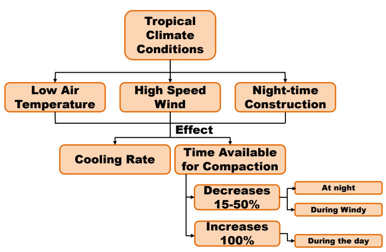
Graphical abstract



Abstract

This paper aims to investigate the environmental effect on cooling rate and to determine the appropriate time available for compaction (TAC) using laboratory tests. This includes the study parameters, namely solar flux, base and ambient temperatures (daytime and night-time paving) and wind velocity, focusing on hot mix asphalt (HMA) asphalt concrete wearing with 14 mm nominal maximum aggregate size (ACW14) mix type for the wearing course and ACB28 mix type for the binder course. Samples were prepared in slab moulds 30.5 cm × 30.5 cm × 5 cm and compacted using a manually operated steel-roller. Readings were taken by averaging the temperature measurements at the middle and surface of the slabs and a temperature of 160 °C was used as the mixing temperature. A control sample was prepared for each mix type and tested in the laboratory without the influence of wind velocity and solar flux. It was found that the cooling rate of HMA is significantly affected by environmental factors, thus influencing the TAC. The TAC tends to decrease by 15-50% during windy and night conditions but increases by up to 100% during daytime conditions compared to the control samples.

Keywords: Hot mix asphalt (HMA); cooling rate; time available for compaction (TAC); surface and ambient temperatures; solar flux

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1.0 INTRODUCTION

Temperature is one of the most important factors affecting the design and performance of both rigid and flexible pavements. Temperature variations within the pavement structure contributes in many different ways to pavement distress and possible failure of that structure [1]. A study was conducted by Lin *et al.* [2], who found that the surface temperature of artificial pavements in Taiwan is 10 °C higher than that of the vegetation surface at noon in the summer, but the difference among the various pavement types is not really significant during winter. Qin and Hiller [3] observed that the daily temperature amplitude affects the temperature distribution across a pavement slab during the daytime more than during the night. Pavements in regions with higher daily temperature amplitude experience greater negative temperature gradients during the night-time hours.

The pavement temperature mainly influences the pavement deflection and medium and high-frequency noise [4-6]. Furthermore, high and low temperatures lead to rutting deformation and cracking respectively in asphalt pavement; water penetrates into the interface of asphalt and aggregate, and the asphalt membrane begins to peel from the aggregates, then the aggregates loosen and turn into pits [7]. The pavement temperature is directly related to the surrounding ambient air temperature, wind speed, relative humidity, solar radiation and cloud cover [3,5,8]. During on-site construction, the temperature of hot mix asphalt (HMA) brought to the field for paving is generally around 160 °C and in a liquid state, making it attach easily to the aggregates [9].

Over time, the mix tends to cool until it reaches the ambient temperature, when it becomes stiff enough to sustain traffic load. After laying onto the pavement surface, HMA needs to be compacted to a specific range of density to ensure that a stable and durable pavement is built [10-12]. HMA compaction is generally begun as soon as the mix can support the roller weight and ends when the mix temperature reaches 80 °C, known as the cessation temperature [9]. The time available for compaction (TAC) is one of the major controlling elements during the compaction process [13]. TAC is defined as a period taken by the HMA to cool and stiffen to the point where it can absorb the applied compaction energy without allowing the aggregate particles to move [14].

However, studies into the TAC of HMA pavement are scarce. This is partly because the study involves many other significant variables such as lift thickness, mix temperature, solar flux and wind speed. It also incurs a high cost and is tedious to perform. The single most important factor that probably affects the compaction of HMA is the temperature at the time of compaction [15-17]. One study of TAC discusses the cooling rate of asphalt pavements, and finds that the factors affecting the cooling rate include the initial temperature at the time of placement, the air temperature of the base, the thickness of the asphalt mix layer and environmental conditions. It is well documented that the time required for HMA compaction decreases with increasing cooling rate. Thus, the ability to predict the cooling rate is more critical during adverse conditions, as the time available for mix compaction is limited [18].

Corlew and Dickenson [19] conducted a study of TAC to determine the time limits for compaction by specifying a minimum compaction temperature of 80 °C. At temperatures below 80 °C the probability of significantly increasing density is very low and, in some cases, can result in the fracture of the aggregate in the mix and a decrease in density. In addition, inadequate compaction of HMA leads to a decrease in the fatigue life, reduces strength and stability, increases permanent deformation, accelerates oxidation or ageing, increases moisture-related damage and hence affects long-term pavement performance [20-23].

Tegelar and Dempsey [24] suggest that 10 minutes is the absolute minimum allowable compaction time needed with present-day equipment. In addition, cooling curves were developed to predict the amount of TAC under different combinations of variables. Kari [25] proposes that increasing the lift thickness could allow the mix to retain heat longer, thus improving compactibility. A computer program was produced by Jordan and Thomas [26] to predict the cooling curve for HMA materials. Chadbourn *et al.* [27] developed a new tool to simulate the cooling rate of HMA mat under adverse conditions. Most of the findings are based on work intended for cold climate conditions because of the rapid decline of the temperature of the mix. With the recent developments in asphalt technology there has been widespread use of thin lift surface and performance grade (PG) asphalt, especially in tropical climate countries. Rosli *et al*. [28] found that in tropical climate countries, the thinner the mix layer, the faster the mix cools, thus reducing the TAC.

High demand for new asphalt pavements often requires that paving is done in unfavourable construction conditions. Low air temperatures, high winds and night construction create adverse conditions for HMA paving and these factors subsequently influence the cooling rate and affect the compaction process as well as the TAC. In local practice, the control mechanisms quoted from the locally used specifications are generally at the acceptable limits of delivery and laying completion temperature. There are no items to predict these control elements and specifically related to the local conditions in tropical climate countries. Therefore, this study was conducted to investigate how the cooling rate of the HMA pavement at particular thicknesses of wearing course and binder course is affected by the local conditions such as environmental, construction factors and material characteristics, resulting in the determination of TAC which might lead to significantly better control and specification during the compaction process in the local industry. Environmental effects such as solar flux, base and ambient temperatures (daytime and night-time paving) and wind velocity will be used as the study parameters. The HMA ACW14 mix type for the wearing course and ACB28 mix type for the binder course were prepared in accordance with the Malaysian Public Works Department (PWD) Specifications (JKR/SPJ/2008-S4) [29].

2.0 EXPERIMENTAL DESIGN

2.1 Materials

An asphalt with penetration grade 80/100 was used, in accordance with the Malaysian PWD JKR/SPJ/2008-S4 [29]. The fundamental and rheological properties of the binder are shown in Table 1.

Table 1 Asphalt cement properties for laboratory testing

Penetration @ 25 °C, 0.1 mm	83	ASTM D 5
Softening point, R & B, °C	46	ASTM D 36
Solubility in 1,1,1-trichloroethylene, % wt.	99	ASTM D 2042
Ductility @ 25 °C, cm	100	ASTM D 113
Flash point (Cleveland Open Cup), °C	2.25	ASTM D 92
Loss on Heating, %wt.	0.5	ASTM D 6
Drop in Penetration after Heating, %	20	ASTM D6/D5
Specific Gravity, @ 25 °C	1.03	ASTM D 70
Retained Penetration After Thin-Film Oven Test, %	47	ASTM D 1754/D5

The aggregate type used in this study was well-graded crushed granite aggregate. Like the binder, the HMA ACW14 mix type for the wearing course and ACB28 mix type for the binder course were prepared in accordance with the Malaysian PWD JKR/SPJ/2008-S4. The aggregates for both ACW14 and ACB28 were sieved into their respective size ranges or fractions andbatched to conform to the aggregate grading requirements, as shown in Figure 1 (a and b). The specific gravity (SG) for the fine aggregate (ASTM C 128) and the coarse aggregate (ASTM C 127) and the proportion of required mineral filler content in the aggregate gradation were determined. Finally, the Theoretical Maximum Density (TMD) was measured by means of the Rice Method Test. Table 2 shows the results obtained in this study.

2.2 Mix Designs

The standard Marshall mix design procedure from the Malaysian PWD JKR/SPJ/2008-S4 [29] was employed to design the HMA mixes. Fifteen specimens of each mix were prepared with blended mineral aggregates at an increment of 0.5% binder from 4% to 7% by weight of mixture. The mixing temperature was selected at 160 °C for the 80/100 penetration grade asphalt, as recommended by the Malaysian PWD JKR/SPJ/2008-S4 [29]. The optimum binder content (OBC) of these mixtures was estimated, corresponding to 4% design air voids, bulk density, voids filled with asphalt (VFA) and flow values. The OBC for ACW14 and ACB28 are 5.0% and 4.3% respectively. The volumetric properties of all PWD Marshall Mixes conformed to the Malaysian PWD JKR/SPJ/2008-S4 [29], as tabulated in Table 2.

Table 2 Volumetric Properties of ACW14 and ACB28

Volumetric Properties	ACW14	Specification	ACB28	Specification
TMD	2.439	-	2.411	-
$SG_{agg\ (course)}$	2.627	-	2.577	-
$SG_{agg\ (fine)}$	2.601	-	2.557	-
SG_{OPC}	2.439	-	2.411	-
OBC, %	5.0	5.0-7.0	4.3	4.0-6.0
Stability (S), kg	1314	>815	1662	>575
Flow (F), mm	2.27	2.0-4.0	4.53	>2.0
Stiffness, kg/mm	881.9	>203	367.2	>2.80
VTM, %	3.4	3.0-5.0	3.97	3.0-7.0
VFB, %	79.5	70-80	72.6	65-75

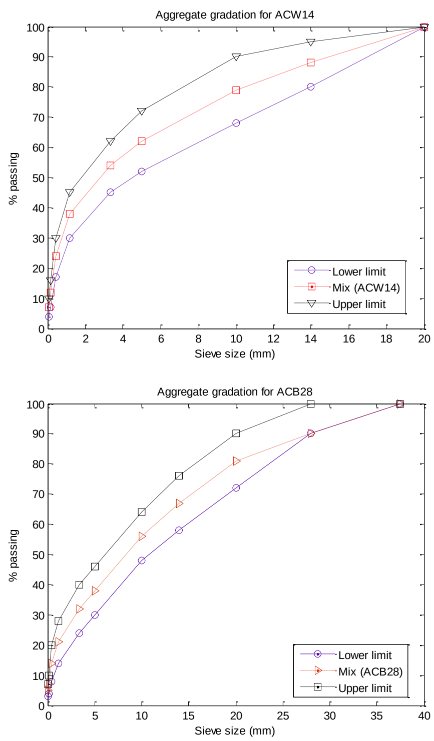

Figure 1 Aggregate gradation for (a) ACW14 and (b) ACB28

2.3 Laboratory Testing

In general, the temperature measurement test includes four main pieces of apparatus: a slab mould, steel roller, thermo heat gun and thermocouple. Test samples were prepared in a slab mould 30.5 cm wide and 30.5 cm long with a height of 5 cm. The slabmould was used to replicate an actual in situ pavement shape. The slab interior surface area was calculated to provide a thickness to length ratio less than or equal to 0.2. This limiting ratio for the square slab is important to ensure that temperature variations at a mid-slab position can be modelled using one-dimensioned plan-wall theory [30]. The sample was compacted by a steel-wheel roller at particular passes and desired air void content. The steel-wheel roller resembles the roller machine usually used in the paving process in the field. The ambient air temperature was then recorded. The temperature at the surface of the slab sample was measured using the thermo heatgun and the temperature at the centre of the slab was measured using thermocouple wires which can be plugged into a multi-channel thermocouple reader.

The temperatures were recorded every minute until the surface of the slab reached the ambient temperature (approximately 29°C). The readings recorded as a graph were the average of slab surface and mid-slab temperatures. The samples were tested under various affecting parameters, namely solar flux, base temperature, ambient temperature and wind speed. The tests for solar flux and base and ambient temperature effect were conducted outside of the highway laboratory at three different times during daytime and night-time. Samples were tested at 9.00 a.m., 1.00 p.m. and 5.00 p.m. and at 9.00 p.m., 1.00 a.m. and 5.00 a.m. to represent both daytime and night-time conditions.

Tests for the effect of wind speed were conducted inside the highway laboratory. Samples were subjected to three different speeds: 5, 10 and 15 km/hr. The speed was simulated by a fan located at a specific horizontal distance from the slab sample. As the wind speed test took place inside the laboratory, the base and ambient temperature for each wind speed variation and mix type test were almost the same. A control sample for each mix type was prepared and tested under laboratory conditions at a base temperature of 28 °C, room temperature of 29 °C and without the influence of wind or solar flux. The control samples were also prepared to compare the difference in cooling rate and TAC at the affecting parameters tested. In general, 20 samples were prepared for the laboratory tests including one control sample for each mix.

3.0 RESULTS AND DISCUSSION

In the paving process, cooling of HMA needs to be well monitored to ensure that there is adequate time to carry out the compaction process, as when HMA cools to ambient temperature it becomes stiff and resistant to compactive effort, which could lead to insufficient compaction. Figure 2 describes the relationship between temperature and cooling time [14].

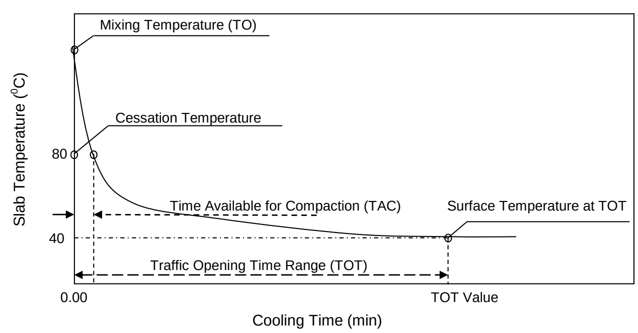

Figure 2 Definition of main analysis element [14]

It is observed that there is a gradual reduction in HMA temperature according to time until it becomes stable.

3.1 Analysis of Cooling Rate (°C/mm)

Cooling rate value was obtained from the slope of the trend line applied to the scatter graph of data acquired at 10-minutes intervals over 30 minutes. Based on the cooling time graph plotted, the temperature reduction of HMA is critical during the first 30 minutes. Cooling rate within this 30-minute period shows the trend of the TAC result obtained; Table 3 shows the result of cooling rate at 10-minute intervals over 30 minutes for each test conducted.

It is observed that there are differences between the cooling rates of HMA under various test conditions. In the wind velocity test, the cooling rate at various wind speeds differed significantly. A wind speed of 15 km/hr resulted in the highest cooling rate, followed by 10 km/hr and finally 5 km/hr.

Table 3 Cooling rate at 10-minute intervals over 30 minutes for ACW14 and ACB28

Mix Type	ACW 14			ACB28		
Test/Time (min)	**10**	**20**	**30**	**10**	**20**	**30**
1. Wind Velocity	**Cooling Rate (°C/min)**					
Control	3.9	2	1.3	4	2.1	1.4
5 km/hr	4.1	2.2	1.4	4.2	2.1	1.5
10 km/hr	4.9	2.4	1.5	5	2.4	1.7
15 km/hr	5.3	2.8	1.7	5.5	2.7	1.9
2. Paving during Daytime	**Cooling Rate (°C/min)**					
Control	3.9	2	1.3	4	2.1	1.4
9.00 a.m.	3.8	2	1.5	3.7	1.9	1.3
1.00 p.m.	3	1.6	1.1	3	1.5	0.9
5.00 p.m.	3.7	1.8	1.3	3.7	1.7	1.1
3. Paving at Night	**Cooling Rate (°C/min)**					
Control	3.9	2	1.3	4	2.1	1.4
9.00 p.m.	4.1	2.1	1.1	4.2	2.1	1.2
1.00 a.m.	4.3	2.2	1.2	4.3	2.3	1.3
5.00 a.m.	4.6	2.5	1.4	4.7	2.5	1.5

In the paving time test, which evaluated the effect of surface and ambient temperature as well as solar flux on the HMA cooling rate, the results obtained indicate that paving work done at 1.00 p.m., results in a lower cooling rate compared to 9.00 a.m. and 5.00 p.m. due to the high value of solar flux as well as the surface and ambient temperatures at that time. Paving work done during the night is not affected by solar flux. Therefore, the results indicate that the cooling rate during the night is higher than during daytime. However, the different value of cooling rate during various periods at night is caused by the effect of surface and ambient temperatures. Due to the low surface and ambient temperatures at 5.00 a.m., the cooling rate is higher compared to 9.00 p.m. and 1.00 a.m.

3.2 Time Available For Compaction (TAC)

The cooling rate during particular tests was ascertained with the result of TAC (min) acquired from the cooling time graph plotted for each test. Furthermore, the percentage reduction and increment in TAC as compared to the control sample was evaluated.

3.2.1 Wind Speed Effect

The wind effect tends to dissipate heat from HMA, thus making it begin to cool. The dissipation process occurs horizontally along the mix surface. Figure 3 (a and b) shows the graph of cooling time for ACW 14 and ACB 28 affected by various wind speeds.

From the graph, both mixes affected by a wind speed of 15km/hr resulted in the lowest TAC due to the higher cooling rate shown in Table 3. As the wind speed reduces, the cooling rate reduces, thus TAC increases. This finding is in good agreement with the study done by Hainin *et al*. [28]. A thin layer of mix will cool more quickly in a strong wind than when there is little or no wind. Wind has a greater effect at the surface of the mix than within the mix, and can cause the surface to cool so rapidly that a crust will form.

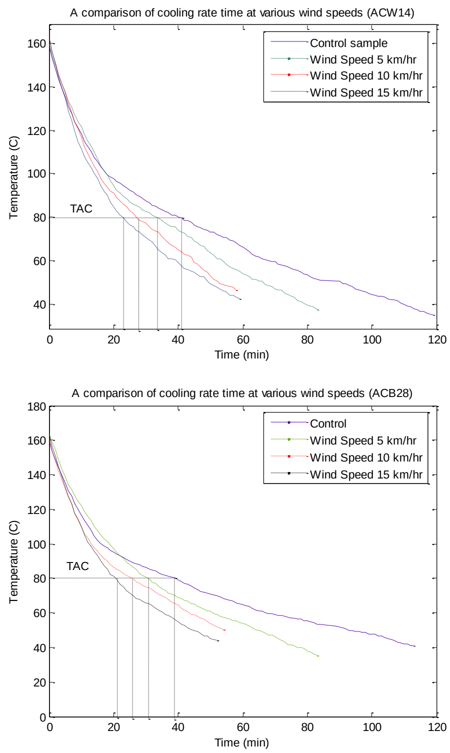

Figure 3 A comparison of cooling rate at various wind speed effects of (a) ACW14 and (b) ACB28 mixes

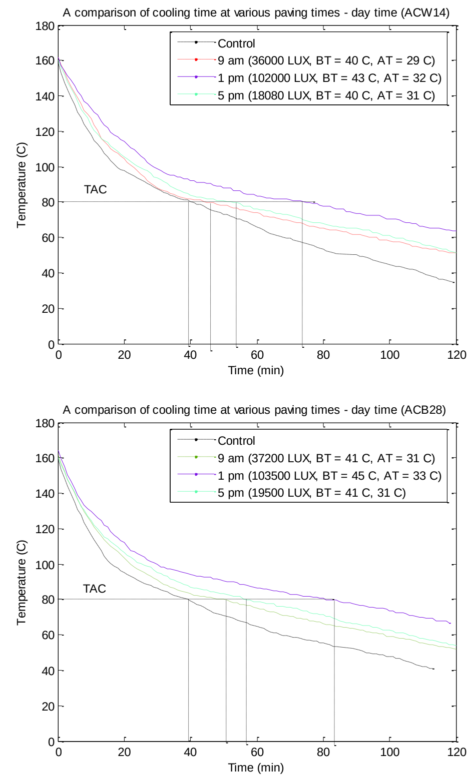

Figure 4 Comparisons of cooling rate at various paving time (day-time) for (a) ACW14 and (b) ACB28 mixes

3.2.2 Paving Time And Flux Effect

Tests were conducted according to paving time (daytime and night-time) to evaluate the effect of solar flux and base and ambient temperature on the cooling rate of HMA. The test took place outside the highway laboratory to resemble a real-time situation. Figure 4 (a and b) shows the cooling time graph for ACW14 and ACB28 respectively at different paving times during the daytime.

The LUX is the unit of measurement of solar flux (radiation), where 1 LUX equals 1.46×10^{-7} watt/cm^2. The TAC for both mixes tested at each paving time tends to increase compared to the control sample with a paving time at 1.00 p.m., resulting in the highest TAC, more than 60 minutes, due to a lower cooling rate caused by higher solar flux and base and ambient temperature compared to 9.00 a.m. and 5.00 p.m. Night-time paving tests were conducted to evaluate the cooling rate of HMA affected by base and ambient temperature, which is relatively lower compared to daytime without the effect of solar flux.

Meanwhile, Figure 5 (a and b) shows the cooling time graph for ACW 14 and ACB 28 at different paving times during the night. The TAC for both mixes tested at each paving time tends to decrease compared to the control sample with a paving time at 5.00 a.m., resulting in the lowest TAC due to a higher cooling rate caused by lower base and ambient temperatures compared to 9.00 p.m. and 1.00 a.m. Table 4 summarises the TAC obtained from each test conducted. A comparison was made between each TAC, including the reduction and increment of TAC as compared to the control sample. As shown in this table, due to wind speed effects, which result in a high cooling rate, the TAC in the wind velocity test is lower than in other tests. A wind speed of 15km/hr for both types of mixes results in a lower TAC, reduced by more than 40% compared to the control sample's TAC at 5km/hr a reduction of 16-21% and 10km/hr with reduction between 30 and 34%.

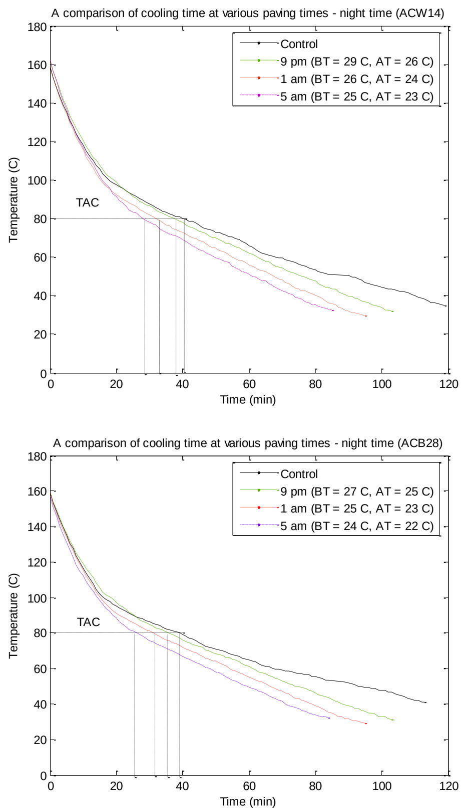

Figure 5 Comparisons of ACW 14 cooling rate at various paving time (night-time) for (a) ACW14 and (b) ACB28 mixes

The test conducted on the cooling rate of HMA according to time of paving shows quite a different value for TAC. During daytime when cooling rate is lower, the TAC is much higher compared to paving work during the night. The TAC increased by 17-33% at 9.00 a.m., 90-108% at 1.00 p.m. and 30-44% at 5.00 p.m. compared to the control sample. Paving works during the night will reduce the TAC, as no solar flux effect occurs and the surface and ambient temperatures are much lower than during the daytime. The amount of solar flux is more important in its effect on base temperature than on the mix temperature. It is also said that incident solar flux has little effect on cooling rate [31]. Result from the test shows that paving at 5.00 a.m. has the lowest TAC. This occurred because surface and ambient temperatures are lower compared to paving at 9.00 p.m. and 1.00 p.m. The TAC at 5.00 a.m. is 30-35% less than the control sample's TAC, while at 9.00 p.m. the TAC is reduced by 5-8% and by 20-21% at 1.00 a.m. compared to the control sample.

The time available for the compaction process to take place is critical, as it depends on the cooling rate, which is easily affected, especially in windy conditions or during night-time construction, as shown by the results of the tests conducted. Therefore, two recommendations are suggested to lead to better control of TAC under adverse conditions: (i) compaction to be done immediately after the laying process; and (ii) the roller/compactor should be right behind the paver for better compaction and to waste no time.

Table 4 TAC and percentage difference between test and control samples for ACW 14 and ACB 28

Test	**ACW 14**				**ACB2 8**			
1. Wind Velocity	**Control**	**5 km/hr**	**10 km/hr**	**15 km/hr**	**Control**	**5 km/hr**	**10 km/hr**	**15 km/hr**
TAC (min)	40	33	27	23	39	31	26	21
Reduction (%)	-	17.5	32.5	42.5	-	20.5	33.3	46.2
2. Paving during Daytime	**Control**	**9.00 a.m.**	**1.00 p.m.**	**5.00 p.m.**	**Control**	**9.00 a.m.**	**1.00 p.m.**	**5.00 p.m.**
TAC (min)	40	47	77	52	39	52	81	56
Increment (%)	-	17.5	92.5	30	-	33.3	107.7	43.6
3. Paving at Night	**Control**	**9.00 p.m.**	**1.00 a.m.**	**5.00 a.m.**	**Control**	**9.00 p.m.**	**1.00 a.m.**	**5.00 a.m.**
TAC (min)	40	38	32	28	39	36	31	26
Reduction (%)	-	5	20	30	-	7.7	20.5	33.3

4.0 CONCLUSIONS

Based on the limited observations and result of this study, the following conclusions are drawn:

(a) The results clearly indicate that paving works done in windy conditions have an increased cooling rate, thus reducing the TAC of HMA because less time is available for the compaction process to take place. Furthermore, the results also indicate that there is a significant difference in cooling rate and TAC of HMA between paving works done during the daytime and night-time. Paving works done during the daytime when surface and ambient temperatures are generally higher because of solar flux, have a reduced cooling rate, thus increasing the TAC of HMA pavement compared to paving during the night. At night, without solar flux occurrence and lower surface and ambient temperatures, the cooling rate will increase, thus reducing the TAC.

(b) There is only a slight difference between the value of the cooling rate and TAC for ACW14 and ACB28. This indicates that the same mix type (fine/dense graded) with different gradations will not really affect the cooling rate and TAC. However, this needs to be verified by conducting more research that focuses on the effect of gradation on cooling rate.

(c) It can be concluded that the cooling rate of HMA is significantly affected by environmental factors, thus influencing the time available for the compaction process to take place. Therefore, more emphasis should be put on the TAC for paving works under adverse conditions such as windy areas or construction done at night. This is to ensure that there is enough time for compaction to be done to a specified density to provide a stable and durable pavement.

Acknowledgement

The authors express their sincere thanks to the Universiti Teknologi Malaysia and Universiti Kebangsaan Malaysia for encouragement and support in conducting this research work.

References

[1] Ramadhan, R.H. and Al-Abdul Wahhab, H.I. 1997. Temperature Variation of Flexible and Rigid Pavements in Eastern Saudi Arabia.*Building and Environment*. 32(4): 367-373.

[2] Lin, T. P., Y.F, Ho, and Huang, Y.S . 2007. Seasonal Effect of Pavement on Outdoor Thermal Environments in Subtropical Taiwan.*Building and Environment*. 42(12): 4124-4131.

[3] Qin, Y. and Hiller, J.E. 2011. Modeling Temperature Distribution in Rigid Pavement Slabs: Impact of Air Temperature.*Construction and Building Materials*. 25(9): 3753-376.

[4] Ramos García, J.A. and Castro, M. 2011. Analysis of the Temperature Influence on Flexible Pavement Deflection.*Construction and Building Materials*. 25(8): 3530-3539.

[5] Bueno, M., Luong, J.,Vinuela, U., Teran, F.and Paje, S.E. 2011. Pavement Temperature Influence on Close Proximity Tire/Road Noise.*Applied Acoustics*. 72(11): 829-835.

[6] Anfosso-Lédée, F. and Pichaud, Y. 2007. Temperature Effect on Tyre–Road Noise. *Applied Acoustics*. 68(1): 1-16.

[7] Yang, Q. and Ning, J. 2011. The Environmental Influence of Asphalt Pavement and Countermeasures. *Energy Procedia*. 5: 2432-2436.

[8] Schindler, A.K., Ruiz, J.M., Rasmussen, G.K., Chang, G.K. and Wathne, L.G. 2004. Concrete Pavement Temperature Prediction and Case Studies with the FHWA HIPERPAV Models. *Cement and Concrete Composites*. 26(5): 463-471.

[9] Roberts, L.F., Kandhal, P.S., Brown, R.E., Lee, D.Y. andKennedy, T.W. 1996. *Hot-Mix Asphalt Materials, Mixture, Design and Construction.* NAPA Education Foundation. Maryland.

[10] Brown, R.E., Hainin, M.R., Cooley, A. and Hurley, G. 2004. *Relationship of Air Voids, Lift Thickness, and Permeability in Hot-Mix Asphalt Pavement.* National Cooperative Highway Research Program, Report No 531: Washington DC.

[11] Hainin, M. R., Cooley Jr, L.A. and Prowell, B.D. 2003. An Investigation of Factors Influencing Permeability of Superpave Mixes. *International Journal of Pavements*. *2*(2): 41-52.

[12] Oluwasola, E.A., Hainin, M.R. and Aziz, M.M.A. 2015. Evaluation of Asphalt Mixtures Incorporating Electric Arc Furnace Steel Slag and Copper Mine Tailings for Road Construction. *Transportation Geotechnics*. 2: 47-55.

[13] Newcomb, D.E., Chadbourn, B.A., Luoma, J.A. andVolleri, V.R. 1996. *Consideration of Hot-Mix Asphalt Thermal Properties during Compaction*. American Society for Testing and Material, ASTM STP 1299.

[14] Jendia, S. and Jarada, A. 2005. Traffic Opening Time and Time Available for Compaction for Fresh Asphalt Layer using Slab Specimens Model.*The Islamic University Journal* (Series of Natural Studies and Engineering). 14(1): 11-35.

[15] Hughes, C.S. 1989. *NCHRP Synthesis of Highway Practice 152: Compaction of Asphalt Pavement*. Transportation Research Board: Washington, D.C.

[16] Idham, M. K., Hainin, M.R., Yaacob, H., Warid, M.N and Abdullah, M.E. 2013. Effect of Aging on Resilient Modulus of Hot Mix Asphalt Mixtures. *Advanced Materials Research*. *723*: 291-297.

[17] Ahmad, J., Rahman, M.Y.A and Hainin, M.R. 2011. Rutting Evaluation of Dense Graded Hot Mix Asphalt Mixture. *International Journal of Engineering & Technology (IJET-IJEN)*. *11*(05): 56-60.

[18] Chang, C.M., Chang,Y.J. and Chen, J.S. 2009. Effect of Mixture Characteristics on Cooling Rate of Asphalt Pavements. *ASCE J Tran Eng*.135: 297-304.

[19] Corlew, J.S. and Dickson, P.F. 1968. Methods for Calculating Temperature Profiles of Hot-Mix Asphalt Concrete as Related to the Construction of Asphalt Pavements. *Proc Assoc Asphalt Paving Technol.* 37: 101-140.

[20] Scherocman, J.A. and Martenson, E.D. 1984. *Placement of Asphalt Concrete Mixtures.* ASTM STP829: Philadelphia. 3–27.

[21] Oluwasola, E. A., Hainin, M.R., Aziz, M.M.A., Yaacob, H. andWarid, M.N.M.2014. Potentials of Steel Slag and Copper Mine Tailings as Construction Materials. *Materials Research Innovations*. 18(S6): S6-250-S6-254.

[22] Abdullah, M.E., Zamhari, K.A.,Buhari, R. Nayan, M.N. and Hainin, M.R.2014. Short Term and Long Term Aging Effects of Asphalt Binder Modified with Montmorillonite. *Key Engineering Materials*. 594: 996-1002.

[23] Sufian, Z., Aziz, N.A., Matori, M.Y., Hussain, M.Z., Hainin, M.R. and Oluwasola, E.A.2014. Influence of Active Filler, Curing Time and Moisture content on the Strength Properties of Emulsion and Foamed Bitumen Stabilized Mix. *Jurnal Teknologi*. 70(4): 135-141.

[24] Tegelar, P.A. and Dempsey, B.J. 1973. A Method of Predicting Compaction Time for Hot Mix Bituminous Concrete. *Proc Assoc Asphalt Paving Technol.* 42: 499-523.

[25] Kari, W.J. 1967. Mix Properties as They Affect Compaction. *Proc Assoc Asphalt Paving Technol*. 36: 295-309.

[26] Jordan, P.G. and Thomas, M.E. 1976. *Prediction of Cooling Curves for Hot-Mix Paving Materials by a Computer Program.* Transport and Road Research Laboratory Report 729.

[27] Chadbourn, B.A., Newcomb, D.E., Voller, V.R., Desombre, R.A., Luoma, J.A.and Timm, H.D. 1998. *An Asphalt Paving Tool for Adverse Conditions*. Final Report 72632: Minnesota Department of Transportation.

[28] Hainin, M.R., Md. Yusoff, N.I.,Mohd Satar, M.K.I. and Brown, E.R. 2013. The Effect of Lift Thickness on Permeability and the Time Available for Compaction of Hot Mix Asphalt Pavement under Tropical Climate Condition. *Construction and Building Materials*. 48: 315-324.

[29] Malaysian Public Works Department. 2008. *Standard Specification for Road Works Section 4: Flexible Pavement. JKR/SPJ/2008-S4*: Kuala Lumpur.

[30] Fwa, T.F., Low, B.H. and Tan, S.A. 1995. *Laboratory Determination of Thermal Properties of Asphalt Mixture by Transient Heat Conduction Method*. A Paper Presented at the Annual Meeting of the Transportation Research Board: Washington DC.

[31] Hunter, R.N. 1986. Cooling of Bituminous Material during Laying. *Journal of The Institute of Asphalt Technology*. 38: 19-26.