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To cite this article: Sharudin Ismail *et al* 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **220** 012010

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Properties of dense-graded asphalt mixture compacted at different temperatures

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Abstract. Poor compaction work is one of the identified causes of road failure and has always been a concern to the asphalt industry. The use of compaction machinery, compaction temperature, weather factor and the type of mixture used could potentially affect the asphalt pavement performance. This study measures the properties of hot mix asphalt (dense-graded AC10) prepared at different compaction temperatures. Various compaction temperatures were selected for the laboratory slab samples preparation i.e. 152°C, 142°C, 132°C and 122°C. A 60/70 pen bitumen was used to prepare the slab with the size of 305mm x 305mm x 50mm. Thermocouple was used to monitor the temperature of the mix. The slab samples were then cored for cylindrical samples at the approximate size of 100mm diameter for mechanical tests. The core samples were tested for volumetric properties, degree of compaction (DOC), Marshall stability and resilient modulus. It was found that low compaction temperature increases the air void in the total mix (VTM) and decreases the air void filled with bitumen (VFB) due to the increase in bitumen viscosity. In other words, reduction in compaction temperature resists the compactibility of the loose mix and resulted in low final DOC and low modulus.

1. Introduction

Hot Mix Asphalt (HMA) is a hot mixture which involved heating, mixing and coating of aggregates and bitumen at the desired mixing temperature. It is stated in the Malaysian Public Works Department specification (PWD) that the mixing temperature to produce HMA is between 150 to 190°C, depending on the binder type [1-2]. By applying targeted mixing temperature in HMA production, the quality of pavement can be enhanced with good resistance against deformation and longer service life. Other than mixing temperature, compaction temperature also influences the quality of HMA. The temperature of HMA during on-site construction for paving is generally around 150°C in order to ensure the applicability of bitumen in coating the aggregate particles by thin film. This is because as the compaction temperature decreases, the bitumen becomes more viscous and resists compaction, which results in less air voids reduction. It should be noted that the HMA must be compacted to achieve the desired level of density or air voids content as the density controls its durability. Once the temperature cools to 80°C, which is also known as cessation temperature, further compaction should be avoided as suggested by Corlew and Dickson [3] because asphalt pavement may experience fracture of the aggregates, thus leading to the reduction in strength and moisture damage resistance. In fact, it also can contribute to



unevenness of road surfaces and permeability [4]. On the other hand, the time available for compaction (TAC) is one of the major controlling elements during the compaction works [5]. TAC can be defined as a duration taken for HMA to cool and harden to the point where it can absorb the applied compaction force without stripping the aggregates. In recent years, few studies can be found on TAC related with asphalt pavement compaction works. This is because factors such as lift thickness, solar flux, wind speed and asphalt mixture temperature highly influence the TAC value. Generally, the time required for HMA compaction decreases with increasing cooling rate. Study conducted by Chang et al. [6] on the effect of cooling rate for different types of asphalt pavement found that the cooling rate decreased when the air voids in asphalt mixture increases, and thus reduced the TAC. Nevertheless, it has been noted that the cooling rate depends on the initial temperature during placement, temperature of the base, layers thickness and environmental conditions [7]. According to Hashim et al. [8], cooling rate of HMA was highly related with environmental factors, hence affecting the TAC process. On the performance properties of dense-graded asphalt mixture, Perez et al. [9] investigated the different compaction temperature of asphalt mixture from 80°C to 160°C and summarised that the stiffness modulus and density increased when the compaction temperature increased. This shows that high compaction temperature could favour a better pavement performance and extend service life. Proper compaction of asphalt mixture in pavement construction is needed in order to reduce the air voids and to achieve the desired compacted density [10]. Air voids, also known as the small spaces located between the coated aggregate inside the asphalt pavement, is necessary in asphalt pavement to avoid bleeding and to maintain asphalt mixture stability. PWD specification [1] allowed between 3% to 5% of air void in mix for wearing course layer. The lower the air voids, the less permeable the mixture becomes, while high air void content may cause damage to the HMA pavement or reduce its performance. These findings show the importance of understanding the correlation between characterisation of the cooling rate of HMA and the compaction temperature with asphalt pavement properties. Therefore, this study aims to measure the cooling rate and the performance of HMA mixture at different compaction temperature in compliance to PWD specification.

2. Materials and method

2.1. Aggregates

The crushed granite aggregates used in this study were supplied by the Hanson Quarry in Kulai, Johor and were combined in accordance to the gradation limits of Asphalt Concrete with nominal maximum aggregates size of 10 mm (AC10) as stated in the PWD specification [1]. Figure 1 shows the aggregates gradation limits and Table 1 summarises the aggregates properties tested for the granite aggregates.

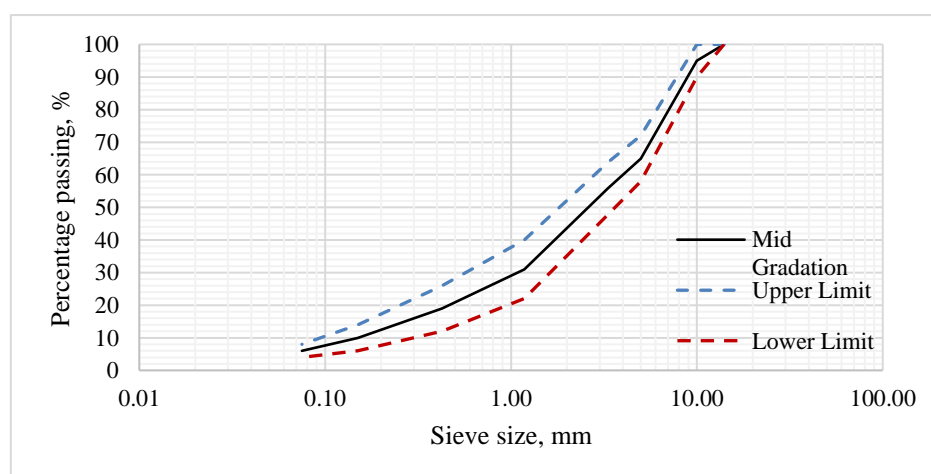


Fig. 1. Aggregates gradation for mixture AC10

Table 1. Aggregates Properties

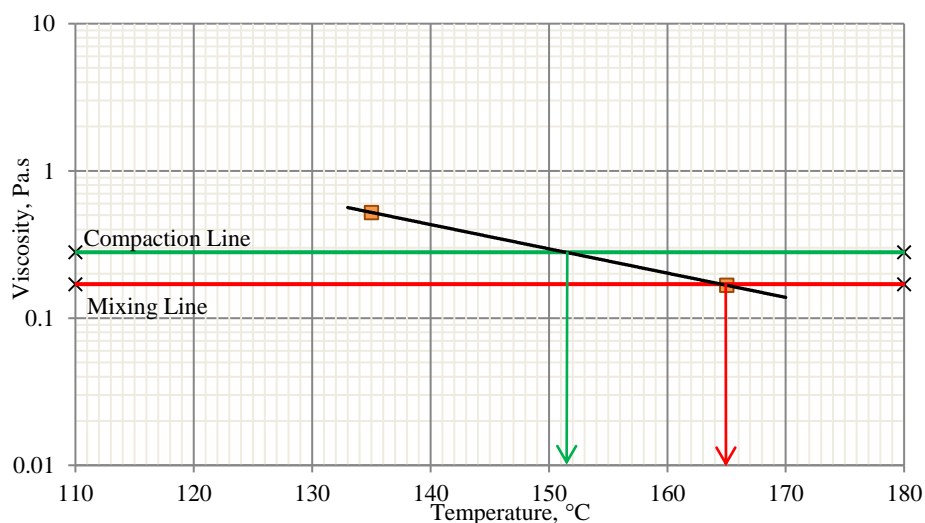
Properties	Standard	Value (%)	Limitation (%)
Aggregate Crushing Value (ACV)	BS 812	17	< 30
Aggregate Impact Value (AIV)	BS 812	15	< 30
Los Angeles Abrasion Value (LAAV)	ASTM C-131	19	< 25
Flakiness Index	MS 30	19	< 25
Elongation Index	MS 30	23	< 25
Water Absorption (WA)	MS 30	0.32	< 2

2.2. Bitumen

Bitumen 60/70 pen from Kemaman Bitumen Company Sdn. Bhd. was used in this study for the sample preparation of dense-graded asphalt mixture. Table 2 presents the physical properties of bitumen 60/70 pen as compliance to PWD requirement [1]. On the other hand, the viscosity test was carried out to determine the mixing and compaction temperature by using Brookfield viscometer in accordance to ASTM 4402 [11]. Viscosity is used to measure the internal friction of a fluid during mixing and compaction because high viscosity will lead to difficulty in obtaining the desired mixture density, while low viscosity may cause improper compaction structure for aggregates and bitumen [12]. The result obtained from viscosity test was used to plot the graph as in Figure 2. From the graph, the mixing and compaction temperatures obtained were at 165°C and 152°C, respectively. These temperatures were then used for the samples preparation of dense-graded asphalt mixture. After that, the compaction temperature was reduced at interval of 10°C i.e. 142°C, 132°C and 122°C for other samples produced for comparison.

Table 2. Bitumen properties

Parameter	Result	Test Method
Penetration at 25 °C	66 dmm	ASTM D5 [13]
Softening Point	49°C	ASTM D36 [14]
Ductility at 25 °C	136 cm	ASTM D113 [15]
Dynamic Shear Rheometer (DSR)	$G^*/\sin \delta = 1.544 \text{ MPa}$ at 64 °C	ASTM D7175 [16]

**Fig. 2.** Mixing and compaction temperatures based on viscosity values

2.3. Marshall Mix Design Method

The Marshall mix design procedure was conducted to prepare the AC10 mixture as specified by PWD [1]. The granite aggregates and bitumen 60/70 pen were mixed at the temperature of 165°C with the bitumen content ranged from 5.0% to 7.0%. The OBC of dense-graded asphalt mixture was estimated corresponding to Marshall parameters i.e. bulk specific gravity, VFB, VTM, stability, flow and stiffness. The OBC obtained from the Marshall mix design was 5.6%. It was then verified and found to comply with the PWD specification.

2.4. Slab preparation

A total of 10.5kg of aggregates and 500g of 60/70 pen bitumen were used to produce the dense-graded asphalt mixture. The mass of the mixture was calculated using Equation 1;

$$\text{Mass} = \text{Volume} \times \text{Density} \quad (1)$$

Where;

Mass = weight of asphalt, g
 Volume = volume of mould size 305mm x 305mm x 50mm, mm³
 Density = average SG_{Bulk} at 5.6% OBC

The aggregate and bitumen were mixed thoroughly at 165°C until a proper coated mix was achieved. The mix was then transferred to the slab mould with the size of 305 mm × 305 mm × 50 mm and compacted using a steel-wheel roller over 100 passes to achieve the targeted air void content. The number of roller passes was selected after conducting a few trials i.e. 300, 200, and 100 roller passes. The degree of compaction (DOC), VFB and VTM were determined from the core samples to verify the slab. Detailed results at different rolling pattern were given in Table 3. From the table, it was found that the targeted specification can be achieved after 100 passes. Therefore, this rolling pattern was selected for samples preparation.

Table 3. Rolling pattern results

Properties	Number of passes			PWD Specification [1]
	100	200	300	
Degree of Compaction (DOC), %	99.6	110.1	100.5	98-100
Voids Filled with Bitumen (VFB), %	72.5	74.6	76.5	70-80
Voids in Total Mix (VTM), %	4.3	3.8	3.5	3-5

2.4.1. Cooling rate

Cooling rate is a loss of heat of asphalt mixture into the air and the base ground. It is measured at the laydown time of asphalt mixture until the temperature decreases to 80°C (cessation temperature). This is referred as the time available for compaction (TAC). In road works, TAC is the most important factor to consider, where the accurate estimation of required cooling time will ensure the quality of the pavement and help the contractors to plan their daily production [17]. Based on the aforementioned compaction works, the rolling work was initiated at the temperature of 152°C and the temperature decrement was monitored as the cooling rate using thermocouple. The thermocouple was positioned at the middle of the slab as shown in Figure 3. After 24 hours, the sample was extruded from the mould and cored for cylindrical samples as shown in Figure 4 for further testing. Other slab samples were then prepared at different compaction temperatures i.e. 142°C, 132°C and 122°C, selected lower than 152°C.



Fig. 3. Sample preparation

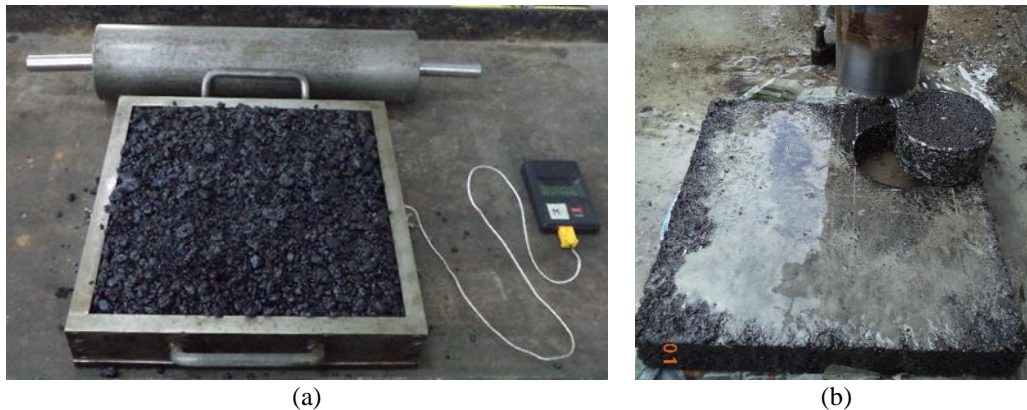


Fig. 4. (a) Slab sample (b) cored sample

2.4.2. Samples testing

The cooling rate and DOC of dense-graded asphalt mixture were investigated in this study for different compaction temperature. The compacted samples were measured for volumetric properties, Marshall stability, flow and stiffness as standardised by the American Society for Materials Testing (ASTM). The resilient modulus test was conducted in accordance to ASTM D4123 at 25°C and 40 °C [18].

3. Results and Discussion

3.1. Cooling rate

Figure 5 shows the result of cooling rate value obtained from the samples of dense-graded asphalt mixture compacted at 152°C, 142°C, 132°C and 122°C. Cooling rate value was obtained from the slope of trend line of data acquired at 5 minutes interval over 80 minutes. Based on the cooling graph, the temperature reduction of HMA is critical for the first 5 to 20 minutes. It can be seen that the TAC obtained for the samples compacted at 152°C, 142°C, 132°C and 122°C is 53 minutes, 49 minutes, 45 minutes and 41 minutes, respectively. On average, the reduction of temperature was recorded at 1°C per minute. This gives less than an hour for the compaction work to be completed within the required temperature as recommended by the specification. Higher initial compaction temperature was identified to provide longer TAC compared to lower compaction temperature, thus indicating more time is available for the compaction process to take place.

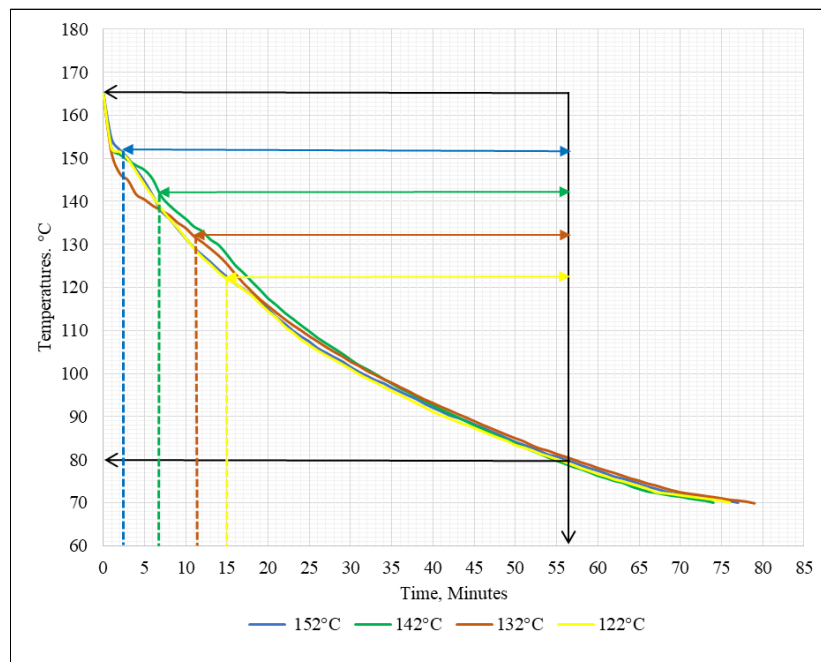


Fig. 5. Cooling time at different compaction temperatures

3.2. Degree of compaction (DOC)

Figure 6 shows the DOC of dense-graded asphalt mixture against the compaction temperature. At 152°C compaction temperature, the DOC is 99.5% and is slightly reduced to 98.9%, 98.5% and 98.2% at 142°C, 132°C and 122°C compaction temperature, respectively. This shows that the decrease in compaction temperature has lowered the DOC since the compaction works become harder as the asphalt mixture starts to cool. In addition, this also contributes to the increase in air voids in the asphalt mixture. Nevertheless, despite the decrease in compaction temperature from 152°C to 122°C, the DOC is still within the allowable limit (more than 98% for wearing course) as specified by the PWD.

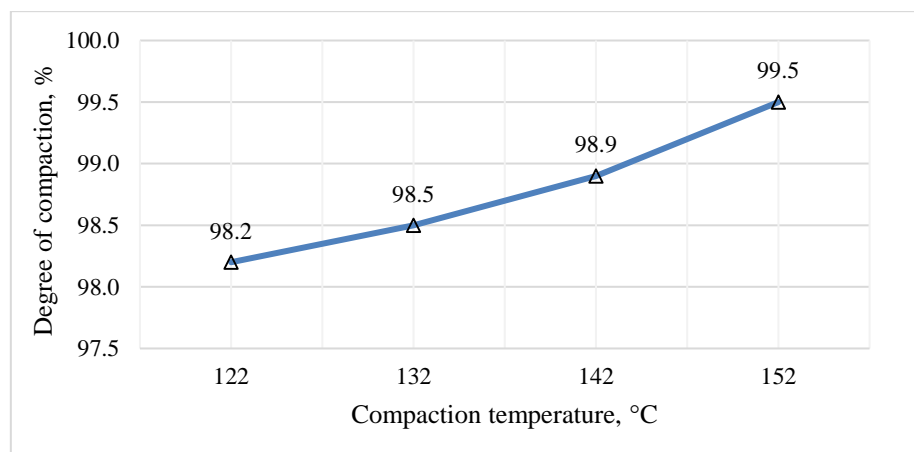


Fig. 6. Degree of compaction at different compaction temperatures

3.3. Marshall Properties

3.3.1. Voids in total mix (VTM) and voids filled with bitumen (VFB)

The effects of compaction temperature on VTM and VFB are shown in Figure 7. The VTM increases gradually with the decrease in compaction temperature and the value remains at 132°C and 122°C. At 152°C compaction temperature, the VTM value is 4.7% and decreases to 4.9% when compacted at 122°C. This clearly shows that reducing the compaction temperature slightly increases the air void content in the compacted samples. The mixture compacted at lower temperature become less dense compared to those compacted at higher temperature, thus resulted in high air voids. On the other hand, the percentages of VFB slightly decrease as the compaction temperature reduces from 152°C to 122°C. The percentage of VFB is 72.6% when compacted at 152°C and reduced to 72.0% as the compaction temperature decreases to 122°C. This is due to the increase in bitumen viscosity that reduces the flow and makes it difficult to fill the mixture's voids. Overall, all the values are found to comply with the PWD specification.

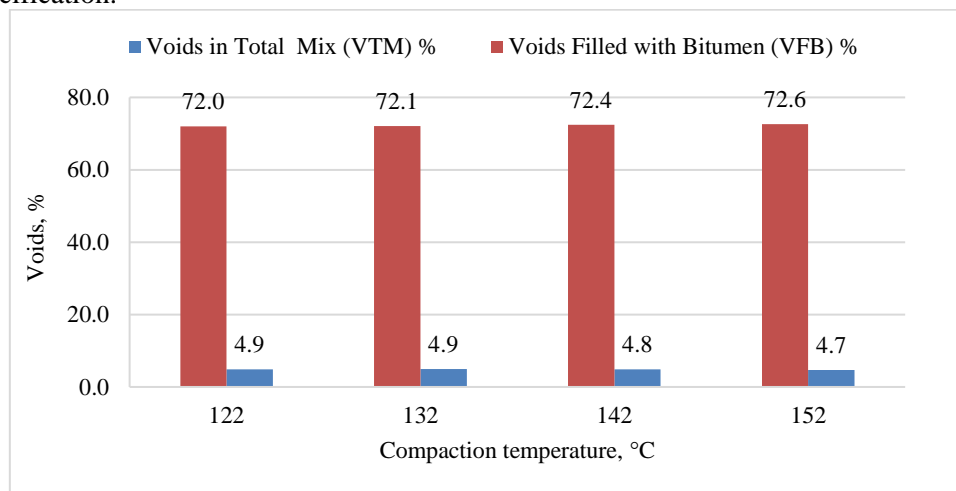


Fig. 7. VTM and VFB at different compaction temperatures

3.3.2. Marshall stability, flow and stiffness

Figure 8 shows the Marshall stability, flow and stiffness of dense-graded asphalt mixture with different compaction temperature. The stability decreases from 8879N to 8117N with the decrease in compaction temperature from 152°C to 122°C, which satisfies the PWD specification of greater than 8000N. The reduction in stability is due to the increase in the air voids content. In addition, the flow values of the compacted samples also slightly increase from 3.9% to 4.3% at compaction temperature of 152°C to 122°C, which tally with the stability results. It is stated in the PWD specification [1] that the flow value must be in the range of 2 to 4 mm. Therefore, it is clearly shown that the decrease in compaction temperature less than 152°C passes the allowable requirement. The reduction in Marshall stability and increase in flow value with the reduction of compaction temperature shows that the stiffness of the asphalt mixture decreases. This can be observed at the compaction temperature of 122°C with the stiffness value of 1892 N/mm, which fails to fulfil the PWD requirement. However, the stiffness value for other compaction temperatures comply the specification as it exceeds 2000 N/mm. From the Marshall properties testing, it can be concluded that compaction undertaken at 152°C fulfils all the requirements specified for the asphalt mixture.

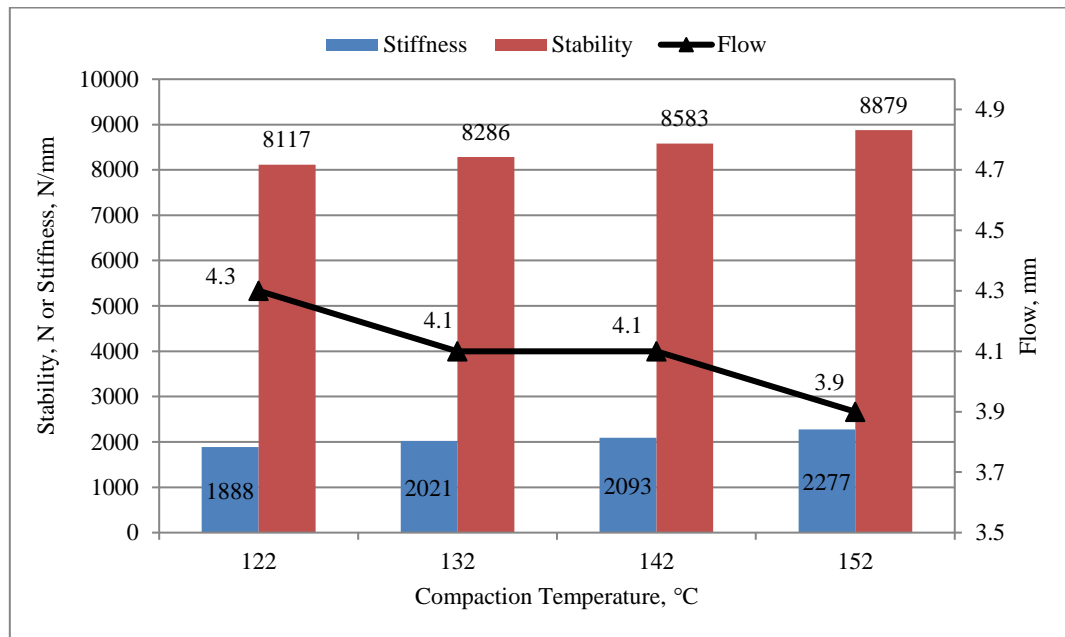


Fig. 8. Stability, stiffness and flow value

3.4. Resilient Modulus

Figure 9 shows the resilient modulus tested at 25°C and 40°C at different compaction temperature. Basically, the resilient modulus of asphalt mixture samples tested at 25°C is higher compared to sample tested at 40°C. At the temperature of 25°C, the resilient modulus of dense asphalt mixture decreases from 2770 MPa to 2564 MPa with the decrease in compaction temperature. All the values are greater than 2500 MPa and comply with the PWD specification. Similar trend can be observed as the testing temperature increases to 40°C, where the resilient modulus decreases from 717 MPa to 629 MPa when compacted at 152°C and 122°C, respectively. Overall, the reduction in compaction temperature will reduce the resilient modulus of the asphalt mixture at both testing temperatures.

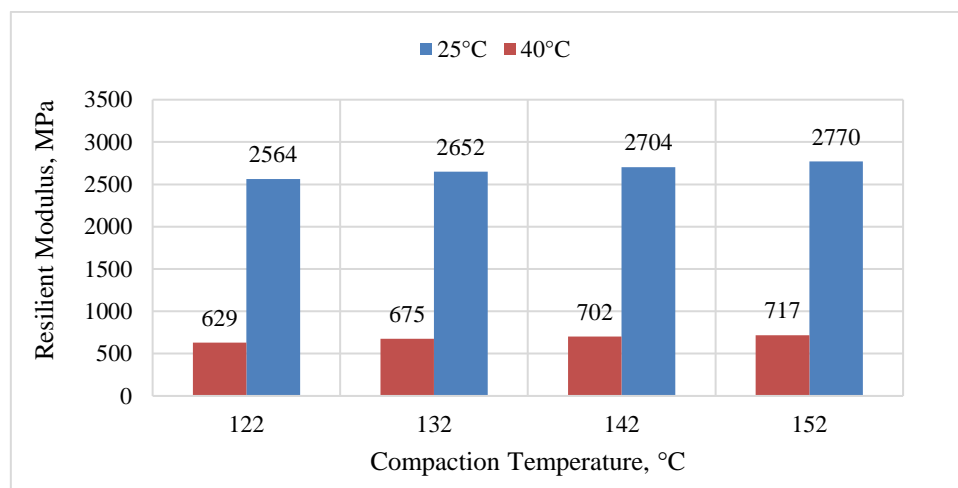


Fig. 9. Resilient modulus at different compaction temperature

4. Conclusions

The effect of different compaction temperature was investigated based on the performance of HMA, particularly dense-graded mix. From the results, it can be concluded that the reduction in compaction

temperature decreases the DOC, VFB, stability and stiffness. On the other hand, compaction at higher temperature gives more time available for the compaction works as observed at 152°C, which gives the highest performance among all. Based on the monitored cooling time, the compaction work must be completed within 1 hour after the mixing process if exposed to the ambient temperature. Overall, all the properties measured for the samples compacted at 152°C, 142°C, 132°C and 122°C comply with the specification except the flow value slightly exceeds the limit.

Acknowledgement

The support provided by Malaysian Ministry of Higher Education (MOHE) and Universiti Teknologi Malaysia (UTM) in the form of a research grant number Q.J130000.2522.19H82 for this study is very much appreciated.

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