Asphalt production, paving and compaction techniques

The effect of sample reheating on asphalt properties

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Abstract

Asphalt is typically designed and tested in small trial batches produced in a laboratory before full-scale production in an asphalt plant. Samples are commonly taken from either the laboratory or production plant, for testing in the laboratory. The test specimens may be manufactured immediately or the bulk sample may be allowed to cool and subsequently re-heated prior to specimen manufacture. It is generally assumed that for practical purposes, the cooling and reheating process has insignificant effect on the asphalt properties. To quantity the effect of asphalt sample reheating on specimen properties, nominally identical asphalt was produced and then either not reheated or was reheated in an open or closed vessel. Specimens were manufactured and tested for dynamic complex modulus, dynamic compressive modulus, wheel track rutting and four-point bending fatigue, as well as the normal Marshall properties. The effect of reheating on the various asphalt properties was evaluated by statistical analysis. Conclusions address the importance of bulk sample thermal loading prior to specimen manufacture and testing, particularly when comparing different asphalt mixtures in the laboratory.

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1. INTRODUCTION

Bulk sampling and reheating of loose asphalt is a common practice in production plants. The samples are typically stored and transported in sealed containers and later subjected to compaction and laboratory tests for quality control and assurance purposes, or for forensic or research purposes. Whilst in the containers, the asphalt samples gradually cool to ambient air temperature. For subsequent test specimen fabrication, the loose asphalt must be reheated to the target (compaction) temperature. As such, the loose asphalt is subjected to an extra cycle of heating that increases the ageing of the sample, as shown by the dashed line in Figure 1. The time gap between mixing at the plant and compaction in the laboratory can vary from a few minutes to weeks. Ideally, the pattern of reheating and cooling of the asphalt should be identical to the production temperature and cooling in the plant (the solid red line in Figure 1). The dashed and dotted line illustrates the difference in thermal function shape when the reheating and cooling rates of the asphalt differ.

Further ageing due to reheating not only changes the rheological characteristics of the bituminous binder (bitumen) but also influences the structural performance of the asphalt. Numerous laboratory studies and field investigations have been conducted to characterise the effects of reheating on the engineering properties of bitumen and asphalt. For example, Kidd et al. [1] found that the resilient and flexural strength results of samples stored in closed containers were relatively comparable with plant-compacted samples. Lemke et al. [2] showed that the time required to reheat the asphalt depended on the types of storage and oven used. This is likely due to differing heat distribution between the oven types and temperature maintenance. In another laboratory study, Leng et al. [3] evaluated the effect of reheating warm and hot stone mastic asphalt (SMA). The results indicated that the effect of conditioning time on the fracture potential of warm SMA was not statistically significant. However, reheating increased the fracture energy of both warm and hot SMA. Al-Qadi et al. [4] found that the effect of conditioning time on mixture characteristics was dependent on the mixture type and performance test considered.

Understanding the engineering properties of reheated asphalt is important for predicting its performance in the field [5]. Consequently, some industrial sectors and agencies have developed reheating instructions. In North Carolina for example, testing is conducted using around 70 kg of asphalt mixture which is sampled from the truck and split into four quarters. Half of the asphalt sample is retained by the contractor and the rest goes to the State. The two portions are then split again by each party, half of which is tested and the other half is retained for retesting, if required. The contractor's samples are tested onsite, whilst the State transports their asphalt samples to another location for testing. The distance travelled typically takes between 30 to 45 minutes, which allows the asphalt samples to cool and there is a need to reheat the samples to allow effective laboratory compaction. As mentioned previously, both the contractor and the state retain material from their samples in case the results differ. Should they require testing, the retained samples need to be reheated to a workable temperature for splitting and then undergo additional heating to reach the temperature required for compaction [6]. In an attempt to address similar issues in Australia, Technical Note 167 (TN 167) [7] from Queensland, provides instructions for reheating loose mix for laboratory compaction.

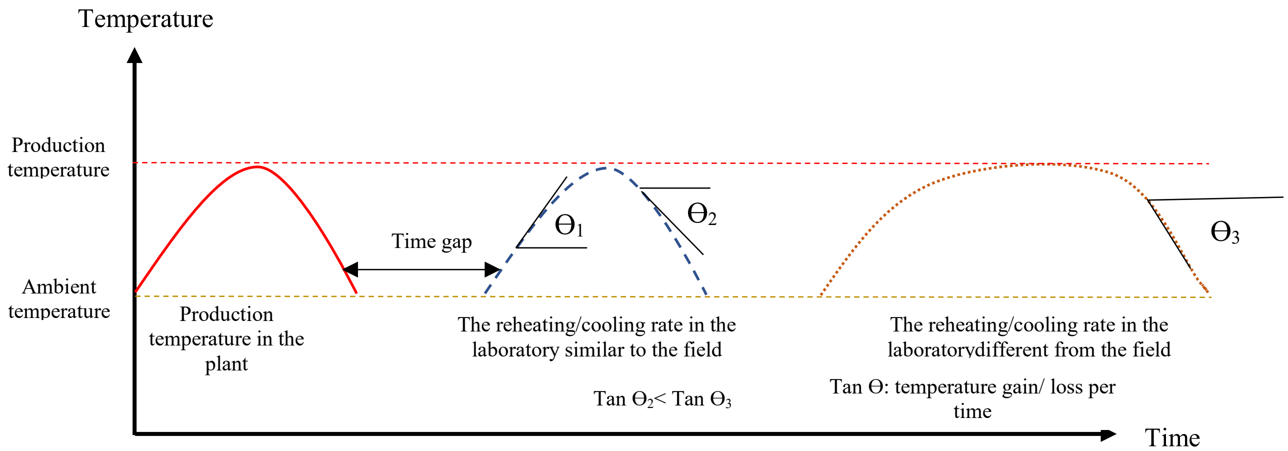


Figure 1: Schematic illustration of cycles of reheating

The type of container used for storing the samples may also affect the results. For instance, if the container is made of copper, which has a high conductivity, the thermal exchange between the loose mix and the environment will occur at a more rapid rate. If contrast, if the container is double layered, the thermal exchange between the loose mix and the environment will be delayed due to the insulating air between the two layers having a low conductivity. There are many other variables that influence the engineering properties of reheated asphalt samples such as bitumen type, optimum bitumen content, filler type, production temperature, use of bitumen modifier/extender, construction technology and aggregate type/gradation and method of sampling and reheating. There is no extensive, accepted instruction or laboratory protocol that correlates all the variables with the engineering properties of the reheated samples. It is therefore necessary to evaluate the effects of one or more variables at a time, on the performance of the asphalt. There is also a lack of research on the effect of the container type and reheating on the engineering properties of asphalt. Furthermore, the effect of laboratory performance test types on the structural response and durability of reheated asphalt samples is unclear. The objective of this research is to fill these gaps.

2. MATERIALS AND METHODS

Brisbane City Council (BCC) asphalt plants are committed to producing high quality asphalt using innovative materials and cutting-edge technologies. To achieve this, BCC has engaged in collaborations with the industrial and academic sectors. In this project, the Aggregate materials and bitumen, as well as laboratory facilities, were supplied by BCC. Figure 2 shows the specification aggregate gradation.

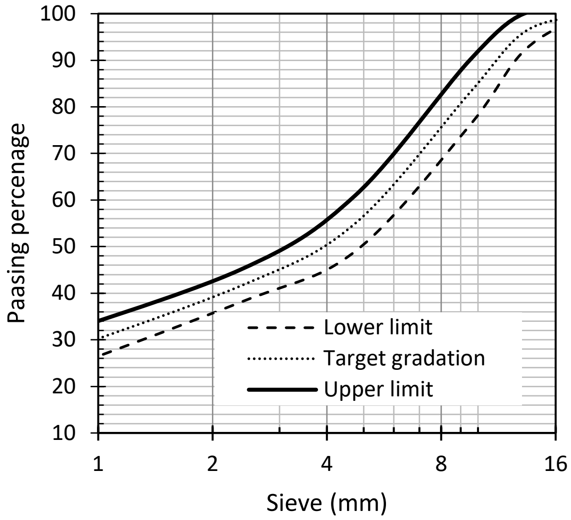


Figure 2: Aggregate size distribution of BCC Type 3

Aggregate and bitumen were mixed at 160°C at the asphalt production plant. A fraction of loose mix was then compacted at 155°C using a gyratory compactor in the BCC laboratory. The rest of loose asphalt was then split between open steel containers and closed steel containers. The closed containers were sealed tightly with a small hole provided to monitor the thermal gradient of the sample over time, as well as to allow for the ventilation of gas. The closed container was single-walled. Figure 3 shows the containers used in this study. The size of steel trays used for the open and closed method were 500 x 410 x 65 mm and 530 x 325 x100 mm, respectively.

The tray in the closed has a lid, which avoids thermal exchange with the air (Figure 4 (a)). Therefore, the rate of thermal of loss (Tan Ө) decreases. It can result in residual thermal stresses in the mix. The open method is a simple tray. Therefore, the loose mix exposes to the air. The temperature of surface of mix in the open method decreases quickly due to relatively rapid thermal exchange (Figure (4b)). Due to the convention phenomenon, the thermal energy from depth of the mix is transferred to the surface. However, it should be noted that thermal loss through the wall of both trays are identical.

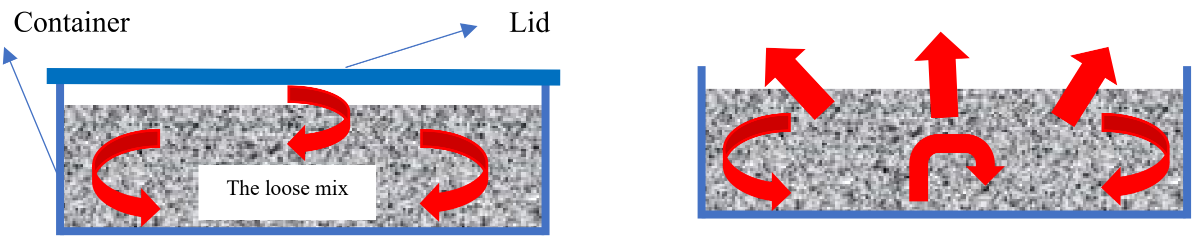
The trays were filled with 14-15kg. After one week, the loose asphalt samples were reheated up to the compaction temperature in an oven (2 hours) in their respective containers and compacted with the same gyratory compactor. Figure 5 shows difference between samples stored in the open and closed container in terms of heat energy gaining. It can be seen that the samples stored at the closed container researched to the target temperature with a 10-minite gap compared to the open sample. From the figure, the rate of temperature increase (Tan Ө in Figure 1) for the samples stored in the open container is 0.70°C/min, while it is 0.53°C/min in the closed samples.

Samples were tested for indirect tensile strength (ITS), compressive dynamic modulus (E*), indirect tensile modulus and wheel tracking in accordance with DTMR [8]. The indirect tensile (known as resilient) modulus (MR) test was carried out according to AS2891.2.2 [8] and at 32°C, using the universal testing machine. The temperature of wheel tracking test was 60°C. For evaluation moisture sensitivity, the samples were conditioned according to Q 315

procedures [9]. Therefore, compacted samples were saturated with 55% to 80% under vacuumed condition. Then, the samples were covered with plastic and conditioned in freezer for 18 hours. After removing plastic cover, samples were submerged at the water bath at 60°C for 25 hours. Followed by that, the samples were conditioned at 25C for two hours before testing using ITS machine.
The dynamic modulus test was conducted using the universal testing machine, according to AG:PT/T220 [8]. The test was conducted at five frequencies (0.1, 0.2, 0.5, 1, and 10 Hz) and five temperatures (5, 15, 25, 30 and 40°C). The master curves were developed using the Williams–Landel–Ferry method and reference temperature was 25°C [10]. Three replicate specimens were prepared for each stage (production-sampling-reheating-test), the mean value was recorded as the final result.

(a) The closed container (b) The steel tray

Figure 3: The containers used to restore the loose mix from the plant and reheat in the laboratory



(a) The closed container (b) The steel tray

Figure 4: Schematically difference of closed and open method in term of thermal exchange

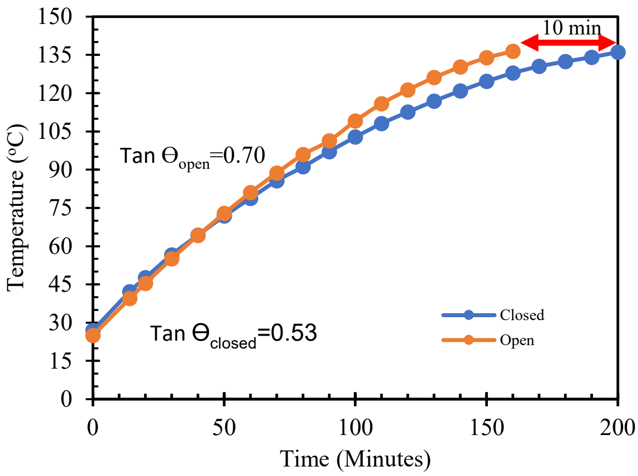


Figure 5: Relationship between temperature and time in the laboratory

3. RESULTS AND DISCUSSIONS

3.1. Effects of the reheating on the volumetric properties

Table 1 shows the volumetric properties of the control and reheated mixes in terms of air void percentage (Va), voids in the mineral aggregate (VMA) and the percentage of voids filled with bitumen (VFB). The Va of reheated asphalts was higher than that of the control sample, due to their lower density. Asphalt that was stored in the open container had the maximum air voids, this was due to the bitumen ageing, and subsequently stiffening. Consequently, the VFB of the reheated samples was lower than that of the control asphalt. A possible reason for this could be that the aggregate in the control samples was gradually able to absorb the bitumen after mixing and compaction. Whereas the temperature of stored samples decreases, increasing bitumen viscosity, and thus lowering the absorption potential of the aggregate particles. Although reheating decreases viscosity, the bitumen has experienced double ageing, and is therefore not fluid enough to be absorbed by the aggregate. In addition, the increased viscosity reduces workability of mix, which results in the higher air voids. However, the volumetric properties were still within the ranges prescribed by the standards.

Table 1. The volumetric properties of the control and reheated asphalts

Asphalt type	Va (%)	VMA (%)	VFB (%)
Control	5.5	15.8	66.6
Open	7.0	17.2	59.4
Closed	6.9	17.0	60.1

Figure 6 shows box plots of the volumetric properties of the asphalt samples. From the plots, the scatters among the data of the control asphalts are observed to be higher than the reheated samples for all volumetric properties. Therefore, variations in the control samples or sample compaction should be considered. Table 2 shows the T-test results and confidence intervals. The results indicate that the reheating method had a significant impact on the volumetric properties of the asphalt mix. Additionally, the open reheating method had a greater effect on the results compared to the closed container. This is likely as a result of the higher level of oxidative ageing when using an open container. Michael et al. [6] reported that reheating has no noticeable effect on volumetric properties, which is inconsistent with the findings of this study; however, it should be noted that their study used a different storage time (0, 3- and 20-hours storage), binder type, aggregate gradation and compaction temperatures. The main difference in this study is type of container is considered as a variable in analysis of volumetric properties of mix.

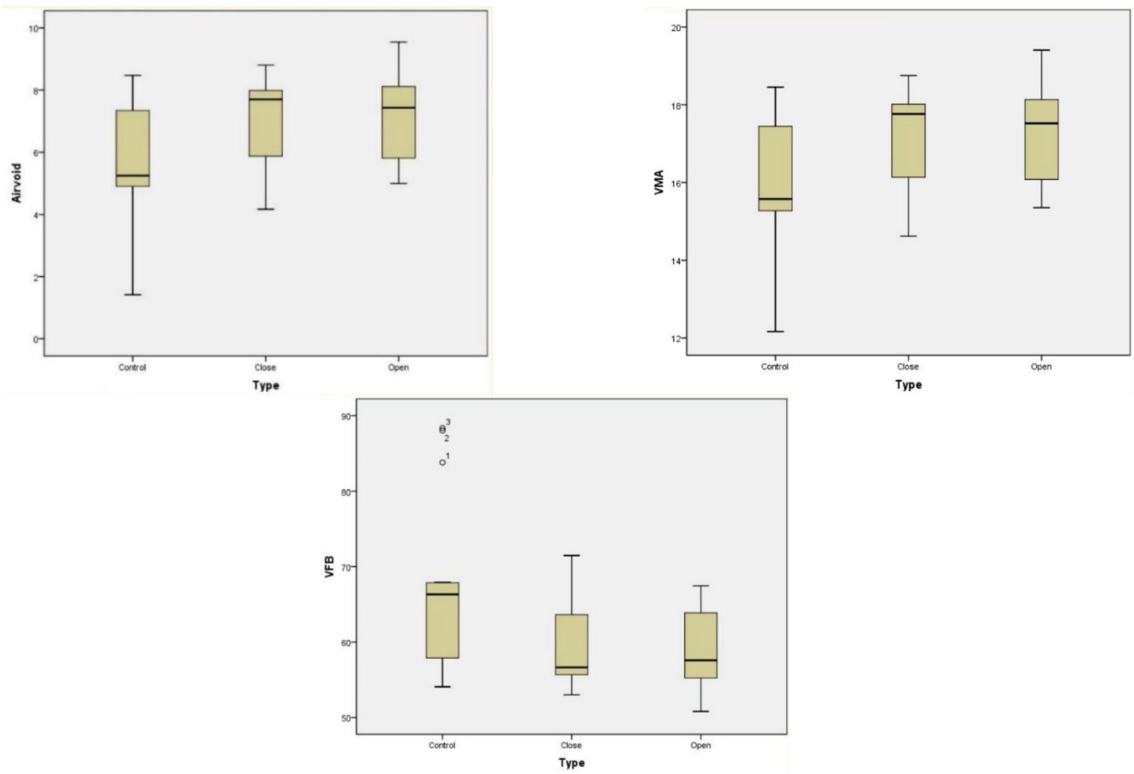


Figure 6: Boxplot of the volumetric properties of samples

Table 2. T-test results and confidence intervals for volumetric properties

Reheating method	t	df	Significant difference	Mean	95% confidence interval	
					Lower	Upper
	Va					
Open	18.9	14	No	7.0	6.2	7.8
Closed	17.8	14	No	6.9	6.0	7.7
	VMA					
Open	51.67	14	No	17.2	16.41	17.9
Closed	49.4	14	No	17.0	16.27	17.8
	VFB					
Open	42.4	14	No	59.4	56.4	62.4
Closed	39.0	14	No	60.1	56.8	63.4

3.2. Resilient modulus

Resilient modulus testing is a non-destructive method which measures the indirect tensile modulus of asphalt under sinusoidal loading. This is an important characteristic of the material for mechanistic pavement design. A high MR enhances the load bearing capacity of a pavement structure. An overestimation of the resilient modulus can therefore undermine the pavement thickness design. Figure 7 presents the MR of the asphalt samples, it indicates that the control and open asphalt samples are comparable, while the resilient moduli of the closed container samples is 17.5% and 18.5% higher than the control and open samples, respectively. Therefore, the resilient modulus measured of the closed sample could be misleading for pavement design, analysis and quality control.

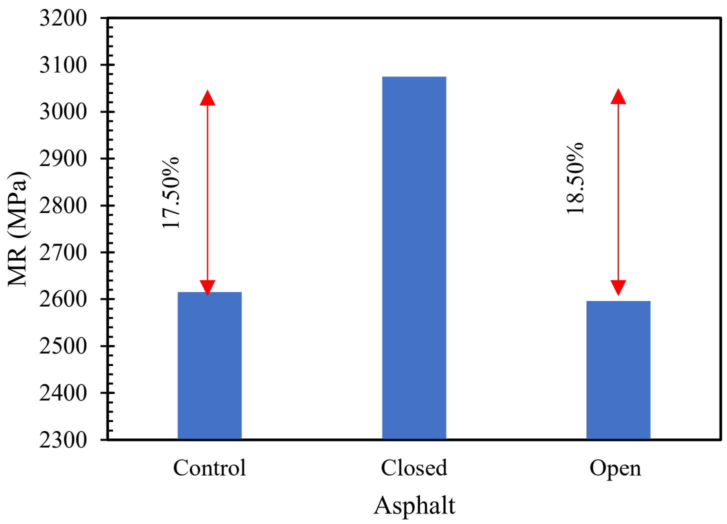


Figure 7: The resilient modulus of asphalt samples

The MR of the open sample was comparable to the control sample after reheating. This could be due to the similar thermal exchanges experienced during storage. The 'thermal shock' on exposure to open air was identical for the control and the open sample, and hence the ageing or increase in bitumen stiffness over time could be similar. The thermal exchange for the closed asphalt was limited, and it is likely that this gradual heat loss resulted in the steady evaporation of bitumen oil, thereby allowing for enough time for transformation of maltenes to asphaltenes. The higher asphaltene content, containing longer hydrocarbon chains [11], increases the structural capacity of the asphalt resulting in more stable, resilient bitumen. However, the steady formation of asphaltenes in the bitumen is unrealistic under current field conditions due to the thermal shock or rapid thermal exchange with the air. In addition, the closed asphalt sample is neither exposed to light nor fresh air. For a more detailed assessment, it is recommended that a Fourier-transform infrared spectroscopy test be undertaken in the future, to determine the effect of reheating and container type on chemical bonds and the mechanism of asphaltene formations in bitumen.

3.3. Indirect tensile strength

Asphalt ITS can be used to analyse the potential for cracking in asphalt samples. Figure 8 presents the ITS results for the asphalt samples. The maximum ITS result was obtained under dry conditions using an open container. This was found to yield only slightly (around 4%) higher ITS than for the closed asphalt sample. This 4% can be attributed to the container type and therefore can be said to have no significant effect on the ITS of asphalts. This means that for the destructive test, where samples are tested for failure or macrocracking, the storage method and reheating was not significant.

The reheated asphalts were found to have a higher ITS than the control sample because of the higher ageing of the binder. This means that the greater stiffness of the binder increases the ITS of reheated samples, in the dry state. In wet conditions, the difference between the control and reheated sample decreased. The ratio of wet and dry conditions is 82% for all the samples, indicating they are all equally moisture resistant.

Although the results showed that storage method and reheating were insignificant factors, the trend may be different for different asphalt types, aggregate gradations and asphalt additives. For example, the natural wax in bitumen, stemming from crude oil, may affect the ageing process. The stiffening effect of natural wax and reheating raises the ITS. Therefore, the effect of the chemical components of the asphalt binder on the stiffening effects of reheating should not be undermined. To avoid this, it is recommended that the natural wax content of the bitumen should be less than 3% [12].

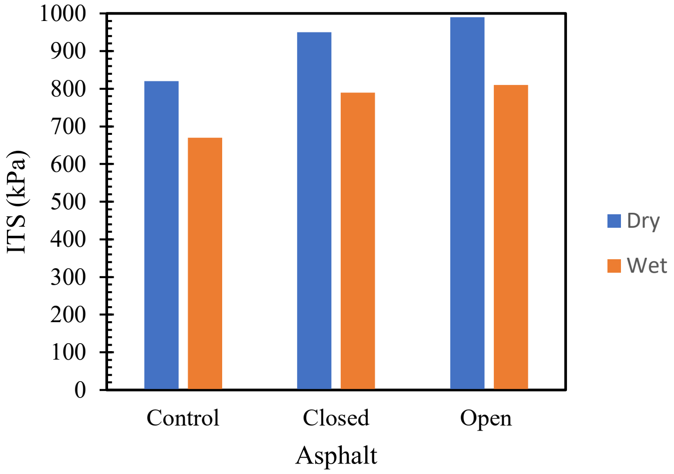


Figure 8: ITS of control and reheated asphalts

3.4. Dynamic modulus

Table 3 shows the dynamic modulus of the asphalts at various temperatures and frequencies. Three different trends can be found based on the test temperature. Firstly, the difference between the E* of the control and the reheated samples varies from 2.0 to 7.2% at 5°C, which is not significant. The reason for this is that the E* of all the samples, at low temperatures, is relatively high. Therefore, the elastic component of bitumen plays a dominant role in this temperature range. In addition, there is only a slight difference between E* of the open and closed samples, implying that the reheating method had no significant effect on E* at low temperatures.

Secondly, the difference between the control and the reheated samples increased at 15°C. In other words, the effect of the reheating process on E* appears at 15°C. The reason for this is the higher temperature range results in softer bitumen. Consequently, stiffer bitumen due to reheating has a higher E* compared with control samples. At this temperature, the difference between the samples varied from 7.9% to 21.4%, which is greater than the range of difference observed at 5°C.

Finally, the maximum difference between the control and reheated samples occurs at 25, 30 and 40°C (or beyond 15°C). This is likely a result of stiffness due to the higher elastic component of reheated samples i.e. E* increases which leads to the greater difference between the samples. As highlighted in red in Table 3, the differences between the control and some of the open samples at the specific frequency is 50%. It should be noted that the higher E* of open samples can be misleading for the evaluation of pavement response to vehicle loads. With the exception of an open sample tested at 10 Hz and 40°C, the rest of the results showed the highest difference when the control asphalt was tested at the low frequencies. This indicates that the effect of reheating is noticeable at the frequencies where the sample is subjected to a longer loading time.

The maximum difference between the control and closed asphalt sample results is 44.6%. Therefore, the reheating method for the evaluation of E* at higher temperatures and lower frequencies needs to be focused on, as the samples are more viscous.

Figure 9 illustrates the master curves of E* based on the time–temperature superposition principle. As shown, the calculated master curve using the sigmoid function shows a close match to measured values obtained from the complex modulus test for the control and reheated samples. The good fit of the experimental data to the master curve indicates that the time–temperature superposition principle is applicable to reheated samples. In other words, the reheating has no effect on the general trend of the master curves, i.e., the master curves are relatively smooth and appears to follow the expected trend with respect to temperature and frequency sweeps. The upper part of the dynamic modulus master curve approaches asymptotically to a maximum value of E*. At higher temperatures and lower frequencies, the dynamic modulus approaches a limiting value, which depends on changes in the rheological bitumen properties due to reheating.

Table 3. Summary of E* at temperature and frequency sweeps

Temperature (°C)	Frequency (HZ)	Control	Open	Difference (between open and control) (%)	Closed	Difference (between closed and control) (%)	Difference (between open and closed) (%)
5	0.1	10717.0	11025.0	-2.8	10927.5	-1.9	0.8
5	0.2	11872.7	12348.2	-4.0	12163.0	-2.4	1.5
5	0.5	13010.2	13945.2	-7.18	13953.2	-7.2	-0.1
5	1	14636.5	15057.0	-2.8	15123.2	-3.3	-0.4
5	10	17949.0	18825.5	-4.8	18626.7	-3.7	1.0
15	0.1	4268.0	5182.7	-21.4	4804.2	-12.5	7.3
15	0.2	5365.5	6101.0	-13.7	5800.5	-8.1	4.9
15	0.5	6732.5	7617.5	-13.1	7263.75	-7.8	4.6
15	1	7680.2	8956.2	-16.6	8573.0	-11.6	4.2
15	10	11656.7	12868.7	-10.3	12682.5	-8.7	1.4
25	0.1	1126.5	1690.5	-50.0	1530.0	-35.8	9.4
25	0.2	1372.7	2150.5	-56.6	1945.5	-41.7	9.5
25	0.5	1915.5	2818.2	-47.1	2680.0	-39.9	4.9
25	1	2560.7	3545.7	-38.4	3475.7	-35.7	1.9
25	10	5759.25	7277.7	-26.3	7026.2	-21.9	3.4
30	0.1	607.7	958.2	-57.6	849.0	-39.6	11.4
30	0.2	776.7	1184.7	-52.5	1123.7	-44.6	5.1
30	0.5	1062.7	1638.0	-54.1	1524.7	-43.4	6.9
30	1	1455.2	2095.0	-43.9	2059.7	-41.5	1.6
30	10	3910.7	5079.2	-29.8	4894.0	-25.1	3.6
40	0.1	265.7	332.0	-24.9	323.7	-21.82	2.4
40	0.2	307.7	396.0	-28.6	382.0	-24.1	3.5
40	0.5	384.0	486.7	-26.7	494.0	-28.6	-1.4
40	1	482.0	654.2	-35.7	651.2	-35.1	0.4
40	10	1225.5	1870.5	-52.6	1730.5	-41.2	7.4

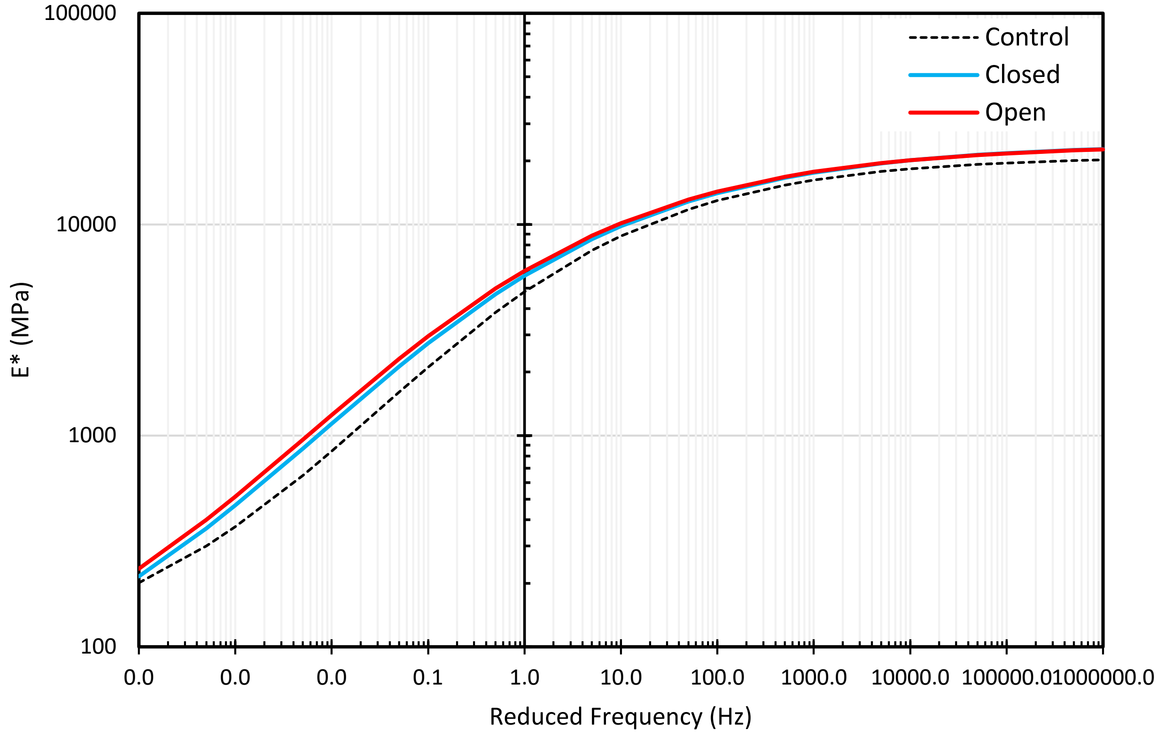


Figure 9: Master curves of asphalt samples

3.5. Wheel tracking

Tracking depth is a criterion for evaluating the resistance of asphalt mixes to rut formation. The development of ruts depends on aggregate gradation, binder stiffness and traffic loading. Higher temperatures decrease binder stiffness which can lead to rutting and stiffer binders generally reduce rutting potential.

Figure 10 shows the wheel tracking depth for the control and the reheated samples. The trends of development of tracking depth of the reheated samples are almost identical. However, the tracking depth of the closed sample is less than that of the open asphalt sample. Furthermore, the tracking depth of the control sample was slightly lower than that of the reheated samples until 1400 passes was reached (Figure 10b). Beyond this number, the tracking depth of the control sample was much higher than the reheated samples. In other words, the difference in the depth of the ruts of the reheated and control samples is significant as the number of passes increase.

The final depth (1.55 mm) observed after 5000 passes was the same for both reheated asphalt samples (Figure 10a). It can therefore be said that the method of reheating samples has no effect on the final tracking depth. However, the final tracking depth of the control samples was 55% greater than those of the reheated samples.

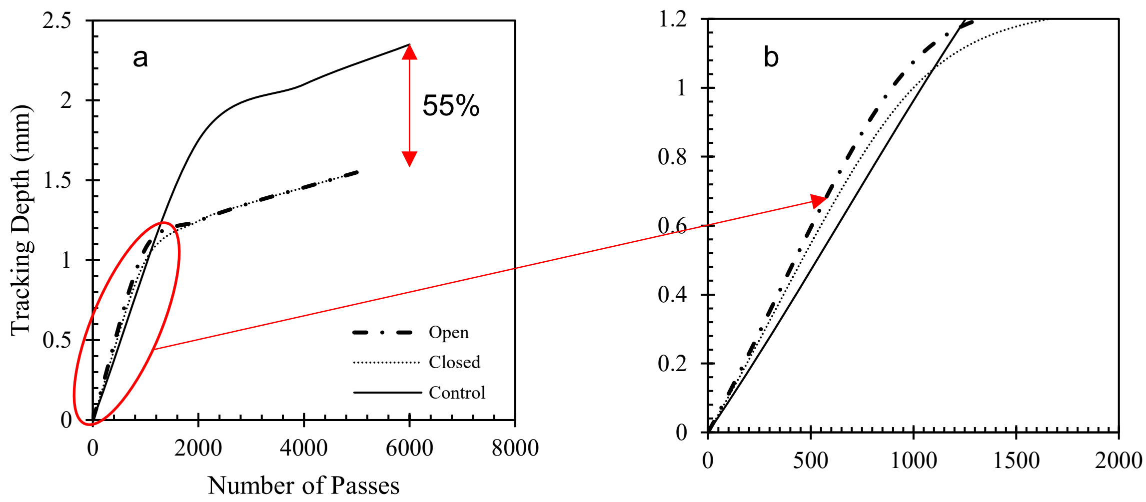


Figure 10: Results of the wheel tracking test

Figure 10 also illustrates that the inflection point of the control sample occurs after 2000 passes, and at around 1600 passes for the reheated samples. Beyond the inflection point, the rate of tracking depth development decreases. The inflection points of the reheated samples took place at around 1.2 mm, which is 40% lower than the control sample. The lower inflection point means that the sample reached the point where the rate of depth development (not the value of the depth) decreases more rapidly. In other words, the greater stiffness due to reheating resulted in the samples reaching their inflection points at a lower number of passes. In the Hamburg wheel tracking test, the inflection point is where the mode of failure from rutting transforms to moisture sensitivity. The asphalt inflection points are therefore key in determining the response of asphalt to wheel track loading.

4. CONCLUSION

Reheating changed the engineering properties of the nominally identical asphalt samples. Reheating increased asphalt ageing, the rate of which was slower for the closed asphalt container than for the open container due to a lower ‘thermal shock’ and limited contact with air and light. The reheating method can therefore be said to influence molecular ageing in the bituminous binder, which resulted in different mechanical responses by the asphalt. The elasticity range of the asphalt changed, for example, at low temperatures and higher loading frequency, the results of the reheated and control samples were comparable for the destructive test. However, the reheating method may cause molecular rearrangement and the formation of long chains of hydrocarbons in the bitumen as a polar material. The greater entropy due to gradual heat loss from the closed container leads to enough time for the generation of stronger covalent chemical bonds that increase the resilient response of the polar molecules in the bitumen. It should be noted that the performance test chosen plays an important role in the analysis of reheating effects. Further evaluation is required for conclusive results.

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