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Effect of temperatures and loading rates on direct shear strength of asphaltic concrete using layer-parallel direct shear test

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Abstract. This paper evaluates the influence of temperatures and loading rates on the shear strength of dense asphalt (AC14) prepared based on the Malaysian Public Works Department specification. In this study, different specimen conditioning temperatures, 10°C, 20°C, 30°C, and loading rates of 20.88mm/min, 40.88mm/min, 50.88mm/min, and 60.8mm/min were used to assess the performance of specimens by using Layer-Parallel Direct Shear (LPDS) test. Based on the results, both parameters have significant effects on the shear strength of the asphalt specimens. The results indicate that the loading rate is directly proportional to the shear strength of asphalt specimens. It is because the stiffness of the asphalt mix increases as the loading rate increases. Hence, it enhanced the shear strength of asphalt specimens. On the other hand, the temperature is inversely proportional to the shear strength of asphalt mixes. As the temperature increases, the stiffness of the asphalt mixture reduces due to the lower resilient modulus; therefore, it reduces the shear strength of the specimen.

1. Introduction

The durability and long-term satisfactory pavement performance are greatly affected by asphalt paving materials and the materials' inherent properties. The uppermost layer of a pavement structure is important to support traffic load or stress alleviation and protect the structure. It is conceived as layers of superior quality materials in the structure and constructed accordingly. In bituminous pavements, bituminous binders and aggregates are the key ingredients. Hence it is desiring that the materials are in good quality, making the selection of materials an important task, which is often given less attention due to certain limitations. Asphalt pavement cannot be constructed in a single lift if the thickness of the pavement is higher than 2.5 to 3 inches. It is due to the compaction difficulties offered by thicker lifts. Hence, asphalt pavements are built in layers instead, making the construction of interfaces between layers inevitable. Being a layered structure, the life span of asphalt pavement is dependent on its bond strength and stiffness between individual layers. Similarly, the bond quality and strength between the layers depend on the construction technique, the texture, and placement procedure [1]. Poor bonding between pavement layers can lead to various types of distresses. One of the most common distress is slippage failure. Slippage failure usually occurs at the intersections or sharp curves where heavy vehicles are often accelerating, decelerating, or turning. Vehicle load are applied in both horizontal and vertical direction, which creates dynamic normal and tangential stresses. The interface between the asphalt pavement layers is vital to the pavement's integrity when vehicle loads are being transferred to each underlying layer of asphalt. Slippage failure develops when pavement layers begin to slide on one another, whereas the top layer separated from the lower layer. It is caused by the lack of bonding and due to high horizontal forces that cause two layers to separate [2]. These problems does not only reduce the pavement serviceability, but also adversely affect the short-term and long-term performance of pavements. Therefore, high shear resistance and adequate interlayer bonding are vital in maintaining the pavement's structural and functional integrity.

In the past, many studies have been carried out to evaluate pavement interlayer bonding strength. Raab and Partl [3] evaluated the influence of tack coats on interlayer adhesion of gyratory specimens by using nearly 20 different types of tack coat. The tests were conducted by using the Layer-Parallel Direct Shear (LPDS) test device, and the behavior of specimens with and without tack coat on a rough and a smooth surface were compared. The influences of compaction, surface condition, moisture, heat, and water on interlayer shear behavior, were also evaluated. The study revealed that the application of tack coats did not necessarily result in better interlayer shear strength, and this supported the outcome of a study performed by Molenaar et al. [4] at Delft University of Technology (TUDelft) using a simple shear test. Raab and Partl [3] further mentioned that by using a certain type of tack coat, it was possible to improve the shear adhesion potential for top layer compaction of 204 gyrations up to 5 kN or 10%, while such improvement was not observed for specimens compacted at 50 gyrations. Apart from that, the test also showed that all specimens with smooth surfaces sustained higher shear forces than specimens with rough surfaces. Hu et al. [5] evaluated the effect of tack coat dosage and temperature on the interface shear properties bonded with emulsified asphalt binders. The tests were conducted using a self-designed device with the aid of the Universal Testing Machine (UTM). The results showed that the shear strength at the asphalt interface decreases gradually with an increase in temperature. Additionally, the results designated that the brittleness at low temperatures, the flowability at intermediate temperatures, and the viscosity at high temperatures of tack binder have the most substantial effects on the shear property of the asphalt pavement interface. Collop et al. [6] assessed the pavement bond conditions using the Leutner Shear test. The study investigated the bond between two interfaces in a typical flexible pavement structure. The result showed that there was an approximately linear relationship between interface shear strength and the corresponding shear displacement for a particular combination of materials, which was independent of the bonding condition. Furthermore, the highest average shear strengths were obtained when a normal amount of tack coat was applied at the interface. While, it occurred to have the lowest average shear strength when the interface is dirty and additional tack coats were added. Canestrari et al. [7] used Ancona Shear Testing Research and Analysis (ASTRA) equipment to evaluate the interlayer pavement shear resistance when subjected to various influence parameters such as tack coat type, temperature and applied normal load. The results revealed that the shear strength of asphalt interface increased with an increment of normal stress at a given temperature. Meanwhile, the strength of the sample also increased with a decrease in temperature. In addition, Yao et al. [8] used the direct shear method to investigate the shear characteristics of steel asphalt interface under the influence of temperature, normal stress level and tack coat. The findings showed that the shear strength and shear reaction modulus increase with decreasing temperature and increasing normal stress levels.

Based on research conducted by Hachiya and Sato [2], the result indicated that the loading rate was a significant influence factor on pavement interlayer bond strength. The results demonstrated that the loading rate of 100 mm/min yielded much higher bond strengths than 1 mm/min. Sholar et al. [9] have evaluated the shear strength of field cores at 25^{o}C with 50.8 mm/min by using Simple Direct Shear test equipment. The findings indicated that the presence of moisture at the material interface had significantly reduced the bond strength of the specimens. Furthermore, the shear strength of specimens was found to be directly proportional to curing time. As for surface texture, it considerably affected the shear strength of the pavement interfaces. Additionally, the HMA coarse graded mixture gives a higher shear strength compared to fine graded mixes. While Mohammad et al. [10] mentioned that the shear strength of the pavement interface yielded at 25ºC was approximately five times the shear strength at 55ºC. Chen and Huang [11], in their study, declared that the usage of a tack coat was more effective for dense-graded mixtures to increase peak shear strength compared to gap-graded and open-graded mixtures. The increase of mean texture depth has resulted in a higher peak shear stress and greater interlayer residual stress. However, thicker asphalt film thickness had caused a reduction in bonding properties. The shear strength reduces when temperature increases due to the reduction of viscosity of asphalt cement that causes greater deformation and lowered the interlayer resistance at elevated temperatures [12, 13]. Raab et al. [14] have postulated that shear strength reduced due to deterioration of pavement as a results of traffic volume exceeds the allowable design limit over a span period of time. The proper bonding within the pavement is not always achieved, and several pavement failures were linked to poor bond conditions. Due to a lack of pavement bonding and shear strength, pavement structural integrity had compromised and hastens the pavement failure. Hence, it results in frequent maintenance and high rehabilitation costs. Based on the previous studies, this study was initiated to investigate the effects of temperatures and loading rate on the direct shear strength of dense asphalt mixture prepared according to Malaysian Public Works Department (PWD) specifications. In this study, different temperatures and loading rates were adopted to assess the performance of AC14 specimens using the LPDS test. The ANOVA and Duncan’s Post Hoc test analyses were adopted to analyze the data.

2. Materials and Methods

2.1 Materials

The aggregates used in this study were crushed granite aggregate supplied by Kuad Quarry Sdn. Bhd. The aggregates were sieved into the selected size range according to PWD specifications on designated sieve sizes, as shown in Table 1. The virgin asphalt binder used was a conventional binder 80/100 penetration grade with 5% optimum binder content (OBC), and Ordinary Portland Cement (OPC) was used as a filler material in this study. The target air void of asphalt mixes is 4 ± 1 %.

Table 1. Gradation limit for asphaltic concrete AC14.

Sieve Size (mm)	Percentage Passing (%)
20	100
14	90-100
10	76-86
5	50-62
3.35	40-54
1.18	18-34
0.425	12-24
0.150	6-14
0.075	4-8

2.2 Experimental works

During the specimen’s preparation, the aggregate and asphalt binder were mixed and compacted at 160^{o}C and 150^{o}C, respectively. Before the sample compaction, the loose asphalt mixture was conditioned at the compaction temperature of 150^{o}C for 2 hours to provide a realistic simulation of short-term aging and to allow binder absorption which occurs during construction. The mixes were subjected to compaction in a 100 mm diameter mold using a Servopac gyratory compactor. The specimens were then allowed to cool overnight after compaction had ceased. Before performing the test, the dimensions of the specimen were measured to the nearest mm. Based on the volumetric properties evaluation, the theoretical maximum specific gravity and the bulk specific gravity of the asphalt mixes obtained are 2.421 and 2.323, respectively. Based on those values, the calculated average air void is equal to 4.16 %, which has fulfilled the required air voids limit specified by

Malaysian PWD (4 ± 1%). Then, the specimens were conditioned at the designated temperature; 10°C, 20°C, and 30°C for a minimum of five hours. After setting up the apparatus, the specimen was placed on the U-bearing, and the interface are aligned between the lower and upper shear rings. The sample support are tightened, and the jig are placed into the loading frame. The upper shear ring was adjusted until it nearly touched the specimen. The loading rate was adjusted to the required rates, which were 20.8mm/min, 40.8mm/min, 50.8mm/min and 60.8mm/min. The shear strength of the mix are recorded once it reached its maximum shear strength.

2.3 Testing device

The LPDS test device (Figure 1) is a Swiss Federal Laboratories for Materials Science and Technology (EMPA) modified version of similar equipment developed in Germany by Leutner [15]. The LPDS is incorporated into the Swiss Standard SN 671961 (Schweizer Norm SN 671961, 2000) since the year 2000. This test device fits into an ordinary servo-hydraulic Marshall testing machine and allows the testing of cores with a diameter of about 150 mm [3]. One part of the core is laid on a circular u-bearing and held with a well-defined pressure by a semi-circular pneumatic clamp. The other part, the core head, remain unsuspended. The shear load was induced to the core head by a semi-circular sheer yoke with a specified deformation rate, thus producing fracture within the pre-defined shear plane. The specimens were conditioned in a climate chamber for a minimum of five hours before testing, and the tests was performed at the room temperatures. Figure 2 shows the Servopac gyratory compactor and the LPDS equipment that was used in this study.

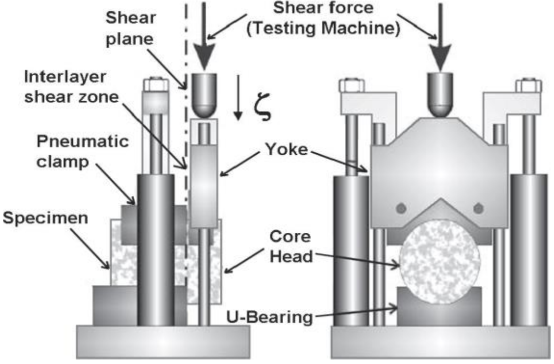

Figure 1. Schematic diagram of the LPDS test device [3]

(a) (b)

Figure 2. (a) Servopac gyratory compactor, and (b) LPDS equipment used in this study

2.4 Statistical analysis

One-way analysis of variance (ANOVA) is used to compare the means of two or more samples by using the F distribution. The ANOVA tests the null hypothesis that samples in two or more groups are drawn from the same population at a 95 % confidence level ($\alpha = 0.05$). The parameters used in the ANOVA analysis are presented in Table 2.

Table 2. Parameters in one-way ANOVA analysis.

Variable	Parameters				Hypothesis
	μ_1	μ_2	μ_3	μ_4	
Temperature (°C)	10	20	30	-	$Ho{:}\mu_1=\mu_2=\mu_3$ $Ho{:}\mu_1\neq\mu_2\neq\mu_3$
Loading rate (mm/min)	20.8	40.8	50.8	60.8	$Ho{:}\mu_1=\mu_2=\mu_3=\mu_4$ $Ho{:}\mu_1\neq\mu_2\neq\mu_3\neq\mu_4$

Duncan’s Post Hoc test was carried out to provide specific information on which parameters it significantly different from each other. The mean shear strengths which do not show a significant difference from each other will be grouped together. The two-way ANOVA is also used for further statistical analysis. This analysis measures the effect of two factors simultaneously. From this analysis, it does not only assess the effect of temperature and loading rate on the shear strength separately but also evaluates the interaction between these two parameters.

3. Result and discussion

3.1 Effects of temperature on shear strength of asphalt mixes

The interface shear strength test of asphalt mixture was carried out at a designated temperature of 10˚C, 20˚C, and 30˚C. The resistance of the asphalt mixture towards shear is among the factors that are affected by changes in temperature. Figure 3 shows the effects of temperature on the shear strength of dense asphalt specimens. The figure indicates that temperature has a significant effect on the shear strength of the asphalt mix, where the specimen shear strength is inversely proportional to the temperature. It is due to the rheological behavior of the bitumen. The bitumen becomes less stiff as the temperature rises, and this phenomenon causes the binder to lose its ability to hold the aggregates together at high temperatures and hence results in lower resilient modulus. As the temperature increases, the stiffness of the asphalt mix reduces due to the lower resilient modulus; therefore, it reduces the shear strength of the mixes. There is only a small fluctuation of shear strength at the temperature of 20˚C and 30˚C. Rapid changes of shear strength was recorded at the testing temperature of 10˚C. Variation of shear strength at different temperatures validates that the bond strength of asphalt mixture is a temperature-dependent component.

The One-way ANOVA result is as shown in Table 3. The analysis shows that the temperature has a significant effect on the shear strength of asphalt mixtures, which is indicated by a p-value less than 0.05. Duncan’s Post Hoc test results is presented in Table 4. Generally, there is no substantial difference in the results of the specimens tested at 20^{o}C and 30^{o}C, which is designated as Group 1 with the p-value equal to 0.194. Noticeable improvement of the asphalt mixture shear strength is recorded in the results when the specimen was tested at 10^{o}C (Group 2) with the shear strength value of 4824 N.

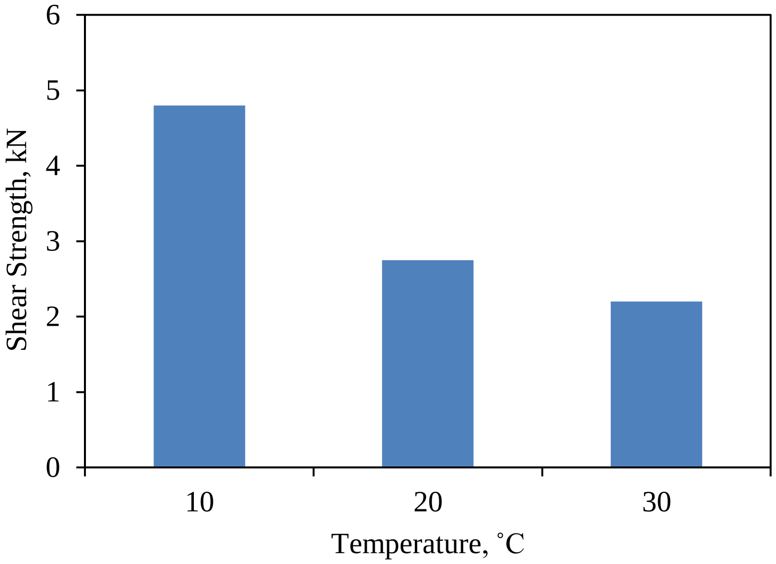

Figure 3. Relationship between shear strength and temperature.

Table 3. One-way ANOVA of temperature and shear strength.

Variable		Sum of Squares	Df	Mean Square	F	p-value
Temperature	Between Groups	4.614E7	2	2.307E7	21.324	<0.001
	Within Groups	3.571E7	33	1081990.455		
	Total	8.158E7	35			

Table 4. Duncan's Post Hoc test analysis for effects of temperature on shear strength.

Temperature	N	Subset for alpha = 0.05	
		1	2
30	12	2191.0000	
20	12	2753.5000	
10	12		4824.0000
p-value		0.194	1.000

3.2 Effects of loading rate on shear strength of asphalt mixes

The effects of strain rate on the shear strength of the asphalt mixture were also studied. The direct shear test by using LPDS seems to be the most commonly used laboratory test method to investigate the interface properties. This test incorporates the application of a normal force in addition to a constant rate of shear loading until the interface failure occurs. Four different strain rates were adapted in this study, namely 20.80 mm/min, 40.80 mm/min, 50.80 mm/min and 60.80 mm/min. Figure 4 shows the effect of strain rates on the shear strength of asphalt mixtures. The result shows that the different strain rate has a significant effect on the shear strength of the asphalt specimens, which is presented by the p-value in Table 5. Figure 4 shows that shear strength is directly proportional to the strain rate. It is due to the fact that the stiffness of asphalt mixes increases as the strain rate increases, hence enhancing the shear strength of asphalt mixes, as presented by Duncan's Post Hoc test result in Table 6. At the strain rate of 20.80 mm/min, the lowest mean bond strength associated to shear strength was recorded which is 1813.33 N. While the highest mean shear strength was recorded at the strain rate of 60.80 mm/min which is 4393.33 N. The difference in shear strength under different strain rate is closely related to the visco-elastic response of asphalt mixture. However, there is no significant difference between groups based on the p-value higher than 0.05.

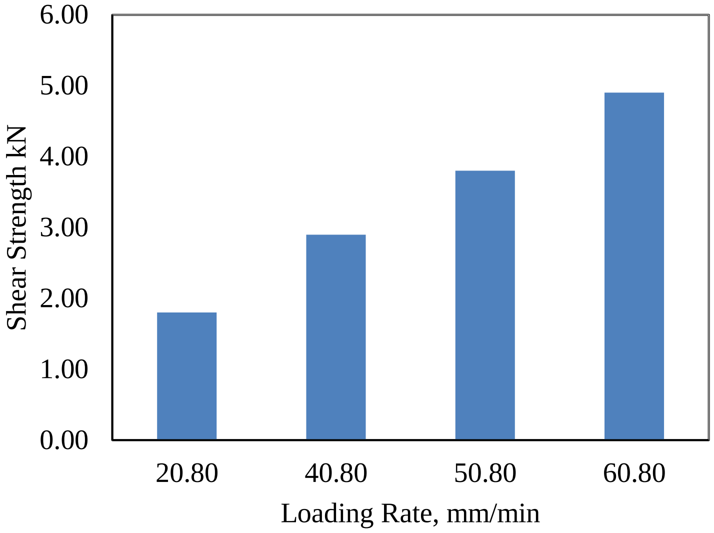

Figure 4. Relationship between shear strength and loading rate.

Table 5. One-way ANOVA of loading rate and shear strength.

Variable		Sum of Squares	Df	Mean Square	F	p-value
Loading Rate	Between Groups	3.430E7	3	1.143E7	7.693	<0.001
	Within Groups	4.755E7	32	1486081.250		
	Total	8.185E7	35			

Table 6. Duncan's Post Hoc test analysis for effects of loading rate on shear strength.

Loading Rate (mm/min)	N	Subset for alpha = 0.05		
		1	2	3
20.80	9	1813.3333		
40.80	9	2968.0000	2968.0000	
50.80	9		3850.0000	3850.0000
60.80	9			4393.3333
p-value		0.053	0.135	0.351

3.3 Interaction factor and correlation between factors

The two-way ANOVA result is as presented in Table 7. It shows that the significance level of temperature and loading rate effects upon the shear strength of the asphalt specimens. The results indicate that the temperature and loading rate have a p-value of less than 0.05. Thus, both parameters should be taken into account as factors that will affect the shear strength of the asphalt specimen. Apart from that, there was also significant effect on the interaction between the temperature and loading rate as the p-value is less than 0.05 (confidence level 95%). Figure 5 presents the relationship between temperature and loading rate to the shear strength of asphalt mixtures. It shows that shear strength is increasing due to the increment of loading rate and decrease of temperature, which complies with Song et al. [16] study.

Table 7. Two-way ANOVA of temperature and loading rate on shear strength.

Source	SS	Df	MS	F	p-value
Corrected Model	8.185E7	11	7440601.000	53529.504	<0.001
Intercept	3.817E7	1	3.817E8	2746002.655	<0.001
Temperature	4.614E7	2	2.307E7	165986.554	<0.001
Loading Rate	3.430E7	3	1.143E7	82243.038	<0.001
Temperature * Loading Rate	1407002.00	6	234500.333	1687.053	<0.001
Error	3336.000	24	139.000		
Total	4.635E8	36			
Corrected Total	8.185E7	35			

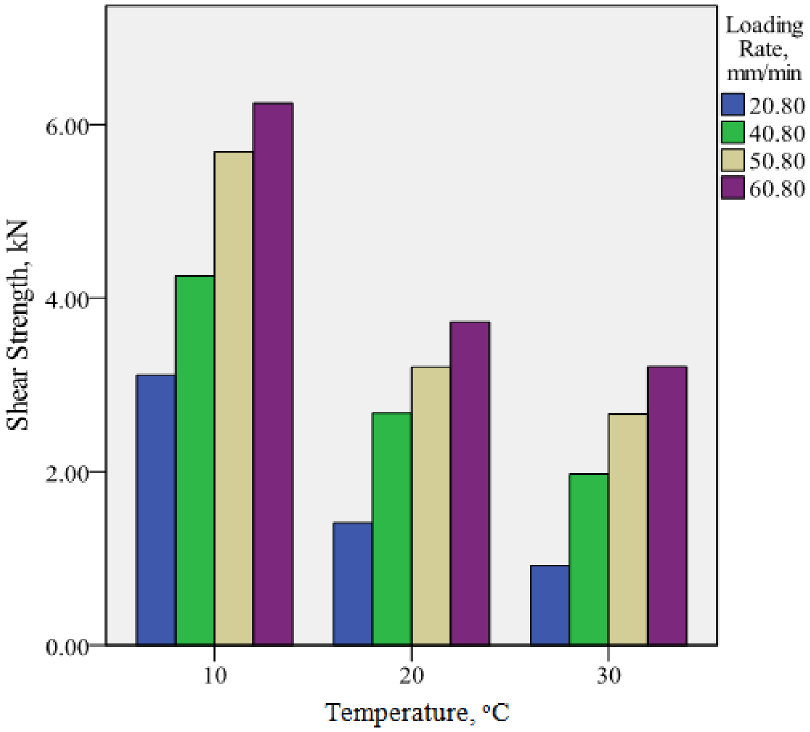

Figure 5. Relationship between shear strength with temperature and loading rate

The relationships between the factors and the pavement shear strength have been analyzed using the Pearson correlation analysis. The Pearson correlation analysis result is typically presented by the correlation coefficient and p-values as shown in Table 8. The correlation coefficient (*r*) is a numerical summary of a bivariate relationship that ranges from -1.00 to 1.00. A positive value indicates a positive relationship between two variables while a negative value indicates an inverse relationship between variables. The *r*-value typically divides into various scales depending on the level of correlation ranging from very weak to very strong.

Table 8 presents the Pearson correlation between temperature and loading rate to the shear strength of asphalt specimens. The result shows a strong inverse correlation between temperature and shear strength based on the *r*-value equal to -0.713. Meanwhile, the shear strength increases as the loading rate increases, as shown by the strong and positive correlation coefficient ($r = 0.645$). Theoretically, the Pearson correlation values obtained from this study are valid to use based on two-tailed p-values less than 0.05 (95% confidence interval).

Table 8. Correlation between shear strength with temperature and loading rate.

Variable		Temperature	Loading Rate	Shear Strength
Temperature	Pearson Correlation	1	0.000	-0.713
	p-value (2-tailed)		1.000	<0.001
	N	36	36	36
Loading Rate	Pearson Correlation	0.000	1	0.645
	p-value (2-tailed)	1.000		<0.001
	N	36	36	36
Shear Strength	Pearson Correlation	-0.713	0.645	
	p-value (2-tailed)	<0.001	<0.001	
	N	36	36	

4. Conclusion

High shear strength and strong interlayer bonding are important in designing asphalt pavement. It is also vital in maintaining the pavement's structural and functional integrity. Thus, this study is carried out to assess the performance of the asphalt concrete specimen by using the Layer-Parallel Direct Shear test. The study investigates the influence of temperature and loading rate on the shear strength of the specimen. In the experimental works, the dense mixes type AC14 was prepared according to Malaysian Public Works Department specifications and tested under different temperatures and loading rates.

Based on the experimental works and statistical analyses, the results indicate that the temperature and loading rate significantly influences the shear strength of conventional dense asphalt due to the rheological behavior of the binder. Where the shear strength is inversely proportional to the test temperature, in contrast, shear strength positively correlated to the loading rate. The increases in loading rate enhance the stiffness of asphalt specimens, hence increasing the shear strength of the asphalt specimens. The finding from this study can be related to the slippage failure distress that commonly occurs at the intersections or sharp curves where heavy vehicles are often accelerating, decelerating, or turning. Plastic deformation of asphalt pavement typically occurs under loading at high ambient temperatures and sudden action of heavy vehicles. However, a test method that incorporates cyclic loading in both the vertical and shear directions should be considered in order to have a better result (e.g., Superpave Shear Tester).

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