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EVALUATION OF ASPHALT MIXTURES PERFORMANCE PRODUCED VIA DRUM AND BATCH MIXING PLANTS

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Abstract

This paper evaluates the performance of asphalt mixtures produced via drum and batch mixing plants. Mixtures performance was studied in terms of Marshall Flow, indirect tensile strength, semi-circular bending, resilient modulus, dynamic creep and wheel tracking test results. Statistical analysis was also conducted to evaluate the effects of mixture characteristics on the test results. In general, it was found that the mixtures produced using 60/70 penetration grade binders were more durable as a whole compared to those produced with 80/100 penetration grade binders. In addition, the aggregate gradation and binder content were also found to play crucial roles in mixture behaviour. Statistical analysis revealed that the level of significance may vary with the change of the analysed parameters. For instance, binder type significantly affected creep modulus but showed no significant impacts on the strain rates. The outcomes indicated that the improvement of each mixture was highly associated with the adequacy of its constituents. This research outcome can be utilized as a reliable database for researchers and road authorities to understand the behaviour of plant-produced asphalt mixtures under different conditions. They could also be used as a reference for purpose of quality control, design enhancement, as well as continuous assessment of pavement sections.

Keywords: Asphalt mixing plant, Design enhancement, Mixture constituents, Mixture performance.

1. Introduction

The road construction industry consumes a huge amount of energy and non-renewable materials. According to the literature, the United States followed by China, Canada and Australia annually produced approximately 500, 150, 45 and 8 million tons of asphalt mixtures, respectively [1-3]. Pavement performance varies due to variations in the characteristic of raw materials, pavement design, asphalt mixture production methods and environmental conditions (such as humidity and temperature changes). According to Ding et al. [4], mixing method and duration as well as storage time and additives can influence blending efficiency, which may adversely affect the pavement effectiveness as designed. In addition, the performance of pavement differs based on their exposure to dissimilar environmental conditions. In this conjunction, it is known that aging adversely affects the pavement service life while such effects were found to be more severe in the tropics compared to those in temperate regions [5].Ahmad et al. [6] and Aguiar-Moya et al. [7] found that premature deteriorations due to moisture-induced damage has become one of the main concerns among road and highway authorities in the tropics. According to Luo et al. [8], the concurrent influences of high temperature and heavy rainfall in the tropics accelerate asphalt binder aging and the adhesion loss between aggregate that results in early pavement degradation. Jitsangiam et al. [9] conducted a comparative study to evaluate the asphalt mixture design protocols using Superpave and Marshall methods for pavements in tropical countries. The superiority of the Superpave mix design for implementation under Thailand weather conditions was reported. However, Abdullah et al. [10] and Sirin et al. [11] reported that the current standard cannot precisely simulate the actual aging experience of asphalt binders and mixtures subjected to tropical and harsh environmental conditions. Fwa and Ang [12] simulated Singaporean weather conditions in laboratory and evaluated its effects on mixture properties. They found that the severity of moisture damage depends on the mixture type, duration, and number of treatment cycles. They recommended 150 4-hr cycles of concurrent application of wetting-drying and thermal cycles as a better simulative conditioning parameters.

Pavement deteriorations due to the presence of moisture (like stripping, ravelling, potholes) are the main factors causing road accidents in Malaysia, especially those involving motorcyclists [13]. Malaysia road authorities at the national and state levels have allocated a huge amount of annual fund on road maintenance and rehabilitations. These maintenance costs will keep on escalating due to aging of asphalt pavement, and severe environmental conditions such as continuous heavy rainfall, and vehicle overloading.

This study was initiated to comprehensively evaluate the performance of plant-prepared asphalt mixtures to develop an accurate and reliable database, which is crucial for further investigation and pavement enhancement. This database can be used for additional assessments as well as evaluation of the effects of adopting a new technology, such as incorporating warm mix asphalt to promote energy savings and lowers the carbon footprint. The experimental works began with preliminary tests on collected samples to determine the actual binder content, aggregate grading and the Marshall Flow of the compacted samples. The study continued with the mixture performance evaluation using the indirect tensile strength (ITS), semi-circular bending (SCB), resilient modulus, dynamic creep and Hamburg wheel tracking tests.

2. Materials and Methods

2.1. Materials and sample designation

Asphalt mixture specimens were collected from two asphalt plants. The mixtures were produced with 60/70 and 80/100 binders via both drum and batch mixing plants. The loose mixtures were sampled and immediately placed in an insulated container just after the hot asphalt mixture was loaded onto the truck bed. The loose mixtures were then transported to the Highway Engineering Laboratory at University Sains Malaysia and compacted using a gyratory compactor. The 60/70 and 80/100 penetration grade binders used for the mixture preparations, were also obtained from the corresponding asphalt plants for further evaluations. To simplify labelling of samples, binders 60/70 and 80/100 from source A are designated as A60 and A80, respectively. Meanwhile, binder 80/100 from source B are designated as B80. The basic properties of binders and granite aggregates that were used for the preparation of asphalt mixtures are shown in Table 1 and 2, respectively. All collected samples are designated and summarized in Table 3. For filler materials, 2% hydrated lime was used to produce A60D, A60B and A80D, while a similar percentage of Portland cement was used during production of B80B1 and B80B2.

Table 1. Binder properties.

Binder Type	Test Parameters	Test Results	Standard
A60	Penetration at 25°C (dmm)	62	[14]
	Softening point (°C)	50	[15]
	Ductility at 25°C (cm)	>100	[16]
A80	Penetration at 25°C (dmm)	81	[14]
	Softening point (°C)	47	[15]
	Ductility at 25°C (cm)	>100	[16]
B80	Penetration at 25°C (dmm)	80	[14]
	Softening point (°C)	46	[15]
	Ductility at 25°C (cm)	>100	[16]

Table 2. Aggregate properties.

Tests	Plant A	Plant B	Specification limits
Coarse aggregate bulk specific gravity	2.601	2.622	N/A
Fine aggregate bulk specific gravity	2.600	2.640	N/A
Coarse aggregate water absorption (%)	0.62	0.46	N/A
Fine aggregate water absorption (%)	0.67	0.52	N/A
Aggregate crushing value (%)	N/A	20.97	<25
Los Angeles abrasion value (%)	20.92	23.86	<25
Soundness test (%)	0.30	1.82	<18
Flakiness index (%)	23.10	17.27	<25
Polished stone value (%)	51.90	51.92	>40

Table 3. Samples designation.

Loose Mixture Source	Mixing Type	Binder Type	Binder Source	Designation
A	Drum	60/70	A	A60D
	Batch	60/70	A	A60B
	Drum	80/100	A	A80D
B	Batch	80/100	B	B80B1
	Batch	80/100	B	B80B2

2.2. Test methods and study plan

In the preliminary stage, a sieve analysis was carried out to determine the aggregate gradation. Marshall flow was also determined from the Marshall testing machine in this stage. The NCAT ignition oven was used to determine the actual binder content of each sample. The asphalt mixture with aggregate gradation within the upper and lower limits of grading curve in accordance with the Malaysian Public Works Department (PWD) specifications [17] for the aggregate grading AC14 as well as flow value satisfied the PWD specification were adopted for further evaluation. Further evaluation was performed in terms of ITS, SCB, resilient modulus, dynamic creep, and wheel tracking tests results. The related parameters and descriptions of all tests are summarized in Table 4.

Table 4. Description of tests.

Test	Standard	Testing Machine	Sample and Test Descriptions
ITS	[18]	Marshall Testing Apparatus	Marshall cylindrical sample with 4% air voids was used. The test conducted at a constant rate of 5 mm/min at 15 ˚C.
SCB	[19]	SHIMADZU AG-X	Semi-circular sample with a notch (150 mm diameter sample) and 4% air voids was used. The test conducted at a constant rate of 5 mm/min at 10 ˚C.
Resilient Modulus	[18]	Universal Testing Machine-25 (UTM-25)	Marshall cylindrical sample with 4% air voids was used. The test was conducted at pulse width 100 ms with 1200 N, Haversine load, rest period 3000 ms with 100 N, Poisson’s ratio 0.35 at 25 ˚C.
Dynamic Creep	[20]	Universal Testing Machine (MATTA)	Marshall cylindrical sample with 4% air voids was used. The test was carried out using Haversine load, pulse width 100 ms with 207 kPa, rest period 900 ms with 9 kPa, up to 3600 cycles at 40 ˚C.
Wheel Tracking	[21]	Hamburg Wheel Tracking	Cylindrical sample with 7% air voids was used. The test was carried out on sample placed in a confined mold, submerged in water, sample loads using solid rubber tire, at 710 N, up to 10000 cycles at 50 ˚C.

3. Results and Discussion

3.1. Experimental evaluation

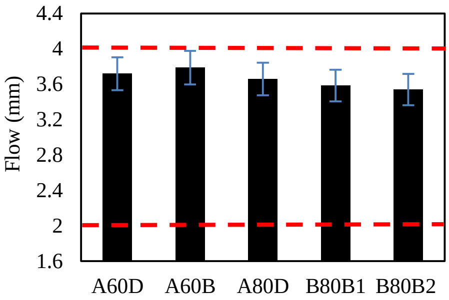
The actual binder contents and aggregate gradations of all samples obtained from the ignition oven and sieve analysis are summarized in Table 5 and 6, respectively. Since, excessive or shortage in binder content may cause several distresses in pavements, the actual binder content was determined using NCAT ignition oven to double check the quality of produced mixtures. Table 5 shows that the actual binder contents are approximately equal to the optimum binder content (OBC) which was designed for the asphalt mixing plants. From Table 6, gradations of A60D, A60B and A80D are within the standard PWD [17] aggregate grading limits for AC14. The gradations of B80B1 and B80B2 are out of the limit. However, they were still evaluated for flow because the deviations from the gradation limits are not significant.

Table 5. Binder content of collected samples.

Sample	**Binder Content (%)**	
	Based on the Test Conducted at USM	Specified by the Asphalt Mixture Producers
A60D	4.70	4.8
A60B	4.83	4.8
A80D	4.65	4.8
B80B1	4.90	5.02
B80B2	4.99	5.02

Table 6. Aggregate gradation of collected samples.

Aggregate Gradation	**Sieve Size (mm)**								
	28-20	20-14	14-10	10-5	5-3.35	3.35-1.18	1.18-0.425	0.425-0.150	0.150-0.075
	Percentage Passing (%)								
AC 14 Lower Limit	100	90	76	50	40	18	12	6	4
AC 14 Upper Limit	100	100	86	62	54	34	24	14	8
A60D	100	98	86	55	41	22	14	8	4
A60B	100	98	86	62	54	35	21	8	4
A80D	100	95	84	62	52	30	17	9	5
B80B1	100	98	88	65	51	28	15	8	4
B80B2	100	97	87	63	49	25	16	9	4



The flow test results is shown in

Fig. **1**. According to the PWD specifications [17], the acceptable flow ranges between 2 to 4 mm when tested at 60˚C to make sure that the mixtures are flexible enough to withstand deflection and bending without cracking. The results show that the flow of all five chosen mixtures falls within the acceptable range.

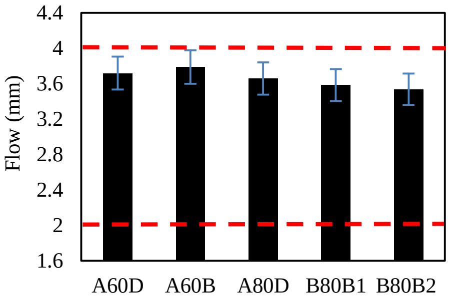


Fig. 1. Mixture flow results.

Further evaluations were then carried out on the samples and the results are presented in

Fig. **2** to 6 for ITS, SCB, resilient modulus, dynamic creep and wheel tracking tests.

The tensile strength of asphalt mixtures is commonly used to assess the crack propagation potential. The outcomes from both tests (

Fig. **2** and 3) indicate that mixtures produced using 60/70 binders are stiffer compared to those produced with 80/100 binders. The ITS of samples produced using 60/70 binders are approximately 11% higher compared to those produced using 80/100 binders. A60B sustains the highest load before cracking, while B80B2 exhibits the lowest strength among all samples. This trend is similar to the test results reported by Huang et al. [22]. The results of ITS and SCB test follow the same trend. According to Bassett and Bassett [23], mixture produced using coarser aggregate grading is generally stronger compared to those prepared using finer aggregate grading. The higher ITS and SCB of A80D can be attributed to its higher proportion of coarse aggregate compared to B80B1 and B80B2. It can also be inferred that different mixing plants, filler types, and binder contents of A80D, B80B1 and B80B2 might be another cause for variations in their results.

In

Fig. **2**, A60B exhibits higher ITS compared to A60D. While, A80D exhibits higher ITS compared to B80B1 and B80B2. Even though A60B and A80D were produced via batch and drum mixing plants, respectively, the possibility of mixing plant effects on mixture performance is slightly vague due to the contradictory results. Therefore, statistical analysis is conducted to assess the effects of mixing production method on mixture performance in the subsequent section. Hydrated lime was used as filler to produce A60D, A60B and A80D. While, Portland cement was used as filler for the preparation of B80B1 and B80B2. A60D, A60B and A80D exhibit higher tensile strength compared to B80B1 and B80B2. This indicates that incorporation of hydrated lime can potentially increase the stability of asphalt mixtures.

From the ITS results, the effect of binder content on asphalt mixture's performance is difficult to conclude. Therefore, statistical analysis is carried out in the following section to identify the significance level of binder content effects on mixture performance. Comparison between B80B1 and B80B2 that were collected from the same mixing plant (with the same binder and filler type), shows that the results of B80B1 is comparable to B80B2. The slight discrepancy in the results can be attributed to the small variations in their aggregate gradations and binder contents. As all tests approximately provides consistent results, these explanations could be used to interpret the outcomes from other tests (SCB, resilient modulus, dynamic creep and wheel tracking) as well.

Fig. **3** shows the ultimate bearing capacity of samples from the SCB test. Samples produced using 60/70 binders exhibit approximately 3.5% and 18.5% higher resistance to fracture compared to the corresponding values of mixtures produced using 80/100 binders from source A and B, respectively. Although A60B exhibits the highest maximum force (F_{max}) to reach fracture point and the highest fracture toughness (K), yet it is apparently comparable to A60D. Therefore, it can be verified that asphalt mixtures produced using different types of mixing plants may not have much effect on pavement service life. Referring to the test results of specimens prepared using 80/100 binder, the fracture toughness of A80D is approximately 16 % higher compared to B80B1 and B80B2. This clarifies that even when using a similar binder grade for mixture preparations, their behaviour may vary due to the difference in binder source, aggregate grading and source and filler type.

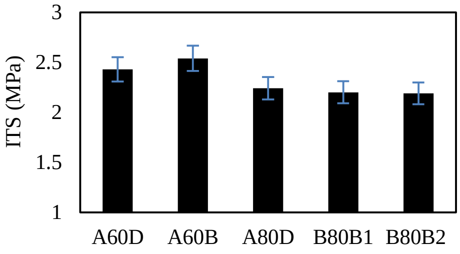


Fig. 2. ITS test results.

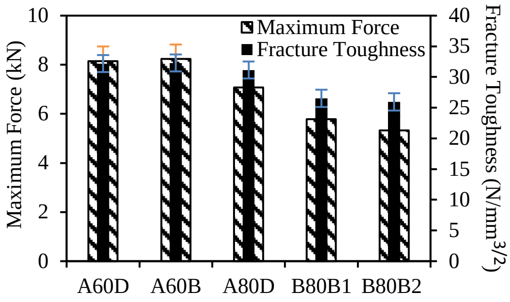


Fig. 3. SCB test results.

The resilient modulus test result is shown in

Fig. **4**. The trend is similar to the ITS and SCB test results. A60B exhibits the highest resilient modulus (M_r), followed by A60D, A80D, B80B1 and B80B2. According to Huang [24], the specimen dimension, applied load waveforms and pulse durations, aggregates gradation, stress magnitude and compaction mode are among factors that influence the resilient modulus of asphalt mixtures. Therefore, it could be inferred that the higher resilient modulus of A80D compared to B80B1 and B80B2 can be attributed to the differences in their aggregate gradations. The results of A80D, B80B1 and B80B2 shows that samples with higher binder content exhibit lower resilient modulus due to ease of aggregate displacement. This finding is consistent with the results reported by Hamzah and Teoh [25]. Hamzah and Teoh [25] also reported that asphalt mixtures that were subjected to aging showed higher resilient modulus compared to unaged sample due to increase in binder stiffness. The results discrepancy points out that the aging rate in the batch plant might be different with the aging rate of samples produced via drum plant. However, statistical analysis should be conducted to illuminate such effects on pavement performance.

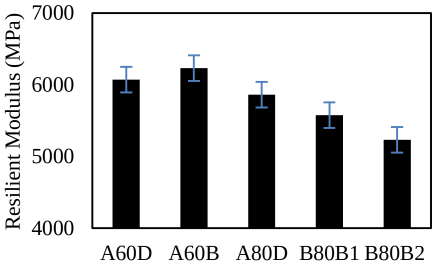


Fig. 4. Resilient Modulus test results.

The results of the dynamic creep and wheel tracking tests are shown in

Fig. **5** and 6, respectively. The results showed that samples prepared using 80/100 binders are more prone to rutting compared to samples produced using 60/70 binders. The creep modulus (M_c) was determined from the ratio of applied stress over the cumulative axial strain [26] except the corresponding value obtained at the 3600 loading cycles. In

Fig. **5**, A60B exhibits the highest creep modulus, while, B80B2 exhibits the lowest creep modulus among all samples. This indicates A60B's superiority and strength to resist rutting compared to other samples which is in agreement with ITS, SCB and resilient modulus test results. The slight difference between creep modulus of A60B and A60D can be attributed to the small variations in their aggregate gradation, binder content and type of mixing plant. Such variables effects on creep modulus is distinguished using statistical analysis in the following section. As suggested by Gardete et al. [27], the strain rate was calculated from the loading cycles 2000 to 3600, where the over compaction stage has ceased. Therefore, the changes in mixture's air voids in the early stage due to over compaction are eliminated.

From

Fig. **5**, A60D exhibits lower strain rate compared to the corresponding value of A60B. This can be attributed to the lower actual binder content obtained in the laboratory for A60D which reduce the aggregate movement as well as pavement further densification. Similar conclusion can be drawn for the strain rate of A80D, B80B1 and B80B2. Gardete et al. [27] found out that samples with higher binder content exhibited less rut resistant. This finding is in line with the results present in this study (Note: The comparison has made between mixtures with the same binder type).

Fig. **5** also shows that A60D exhibits comparable accumulated micro-strain with A60B. While, the accumulated micro-strain of A80D is significantly lower than the corresponding values of B80B1 and B80B2. It is known that the aggregate matrix acts as the vital component in the mixture to resist permanent deformation.

According to a previous study [28], the resistance to rutting of asphalt pavement at high temperatures is generally influenced by the properties of the aggregates. The higher creep modulus and lower accumulated micro strain of A80D compared to B80B1 and B80B2 indicates that the coarser aggregate and lower binder content in the mixtures significantly promote their ability to resist rutting. This finding implies that with adequate aggregate grading as well as mix design, the resistance to permanent deformation can be improved. For instance, mixtures resistance to rutting can be improved through the improvement of aggregate frictional resistance and interlocking. This finding indicates the importance of implementation of rutting evaluation during the mix design procedure.

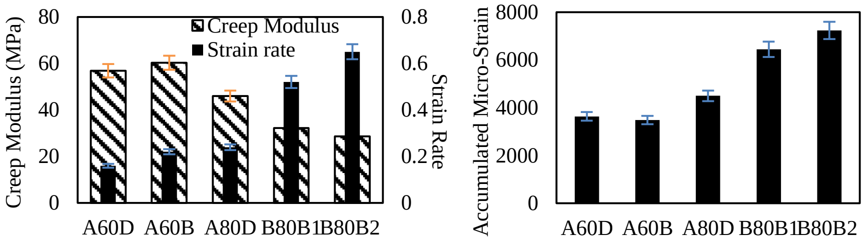


Fig. 5. Dynamic Creep test results.

Fig. **6** shows that mixtures fabricated using 60/70 binder show comparable results, while small discrepancies can be seen in the results of mixtures produced using 80/100 binders. The initial rates of rutting is relatively high due to mixture densification. In this study, the wheel tracking slope, which represents the mixtures deformation rate, was computed based on the values at the last 5000 cycles when the mixture has stabilized to eliminate mixture's air voids and initial densification effects on their performance. Similar to dynamic creep test results,

Fig. **6** shows the decisive influence of binder content on mixtures' deformation rate. The mixtures with higher binder content exhibit greater wheel tracking slope (it should be noted that the comparison has been made between mixtures with the same binder type). As an example, A80D, which contains lower amount of binder content, exhibits lower wheel tracking slope compared to B80B1 and B80B2. This result is consistent with the findings reported by Gardete et al. [27].

Fig. **6** shows that the discrepancy of wheel tracking test results in terms of mean rut depth (R_d) is very small. The maximum mean rut depth difference (between A60B and B80B2) is 0.27mm, which is not significant in a large scale. These findings imply that the asphalt binder as a binding agent (regardless of its type) is only a matter of decelerating the degree of deformation or rutting. Subsequently, the proportional rut depth indicates that the results of A60D and A60B are approximately consistent, while B80B2 exhibits higher corresponding value compared to A80D and B80B1. The main cause of this discrepancy is difficult to distinguish from the experimental analysis. Hence, statistical analysis is carried out in the following section to clarify significance level of mixtures variables impacts on their rutting behaviour.

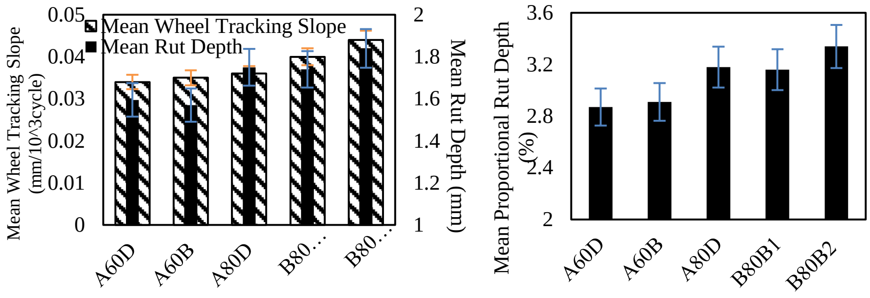


Fig. 6. Wheel tracking test results.

Throughout the findings, error bars were used to represent the relative potential of error or uncertainties in the presented results. It can be seen that A60D and A60B lie in the same range for all tests, as well as B80B1 and B80B2. It indicates that there is no noticeable dissimilarity between these samples. Despite the use of different mixing plants to produce A60D and A60B, the results show that the mixing method exhibited no perceptible difference in the mixture's performance. However, the inconsistencies of the outcomes can be caused by either small variation in binder content or aggregate gradation. Comparison between the results of A80D, B80B1 and B80B2 shows that binder source (despite having identical properties), type of mixing plant, aggregate gradation and filler type can distinctly change the mixture's behaviour. However, in the case of A60D and A60B, it seems that aggregate gradation and binder content played a greater role compared to mixing method. A80D consists of lower binder content and coarser aggregate grading compared to B80B1 and B80B2, which result in higher stiffness and stability. Moreover, the aging rate of drum mixing plant could affect the behaviour of A80D compared to B80B1 and B80B2, which were produced via batch mixing plant. These findings bring up the real necessity for an integrated system to control the quality of produced mixtures. Several aspects should be taken into consideration, which includes binder grade, binder content, aggregate gradation, filler type and method of production.

3.2. Statistical analysis

A One-way Analysis of Variance (ANOVA) was conducted to statistically evaluate the significant effects of variables on asphalt mixture's performance. The analysis was performed using Minitab software at a 95% confidence level ($\alpha = 0.05$). Table 7 presents the variables incorporated in the analysis

Table 7. Test variables involved in the statistical analysis.

Sample	**Binder**		**Aggregate Grading Sieve Size (mm)**									Filler Type	Asphalt Mixing Plant
	Type	Binder Content	28-20	20-14	14-10	10-5	5-3.35	3.35-1.18	1.18-0.425	0.425-0.150	0.150-0.075		
			Percentage Retained (%)										
A60D	60/70	4.80	0	2	12	31	14	19	8	6	4	Hydrated lime	Drum
A60B	60/70	4.80	0	2	12	24	8	19	14	13	4	Hydrated lime	Batch
A80D	80/100	4.80	0	5	11	22	10	23	13	9	4	Hydrated lime	Drum
B80B1	80/100	5.02	0	2	10	24	14	23	13	7	4	Portland Cement	Batch
B80B2	80/100	5.02	0	3	10	24	14	23	9	7	5	Portland Cement	Batch

Table 8 presents the results of the statistical analysis. Factors that significantly affect mixtures' performance are determined based on the p-value (less than 0.05), which are highlighted in the table. The nature of each laboratory test and independent variables have their unique influence that contributed to the complexity of asphalt mixture's behaviour. For instance, the binder type exhibits significant effects on the creep modulus, ITS, maximum force, mean rut depth and mean proportional rut depth (PR_d). However, it has no significant impact on other outcomes.

Kok and Kuloglu [29] also reported that the mixtures containing different binder types exhibited contrarily when studied using different tests. For example, binder content also plays a crucial role on mixture's performance. Binder content has significant effects on the creep modulus, strain rate, micro strain, flow, resilient modulus, maximum force, fracture toughness and mean wheel tracking slope (WT_s). However, it shows no significant effects on ITS, mean rut depth, and the mean proportional rut depth. Determination of optimum binder content is one of the most important steps in a mix design. Considering all collected samples went through the mix design procedure prior to mixture production, it can be drawn that the slight variation of binder content is only associated with certain mixture characteristics. The following examples clarify this statement. From the ANOVA analysis, binder type shows no significant effects on mixture flow while binder content affects the corresponding value significantly. On the contrary, binder content shows no significant effects on ITS, while binder type influences ITS significantly.

The flow test was carried out at 60 °C, which exceeds the softening point of both binder types (refer to Table 1). It shows that at high temperatures, binder stiffness exhibits less impact on the mixture performance compared to the binder content. The ITS test was performed at 15 °C, where mixtures are stiffer and more fragile compared to higher temperatures. It shows that the binder stiffness, which directly relates to the binder type exhibits more impact on the mixture performance at low temperatures compared to the binder content. The statistical analysis result also reveals that the binder content influences the resilient modulus significantly even when the binder type exhibits no significant effects on the corresponding values. Table 8 indicates that asphalt mixing plant has no significant impacts on the outcomes since the p-value is higher than 0.05. This proves that both drum and batch mixing plants produce mixtures with approximately similar quality and aging rate. Hence, none of the plants exhibit superiority over the others.

In Table 8, percentage of aggregate retained on sieve size 10 mm and 1.18 mm, and filler type also affect mixtures' performance significantly. While, mixing plant type, aggregate retained on sieve size 14 mm, 5 mm, 3.35 mm, and 0.075 mm exhibit no significant effects on asphalt mixtures' behaviour. It was expected that a larger aggregate size exhibits greater impact on the mixture performance compared to smaller aggregates. However, the outcomes show contradiction between the effects of aggregate retain on sieve size 14 mm and 10 mm. Table 7 shows that the percentage of aggregate retained on sieve size 10 mm is much higher compared to the percentage of aggregate retained on sieve size 14 mm. It indicates that the aggregate proportion also exhibits substantial impacts on mixture's performance. Similar conclusion can be implied for aggregate retained on the sieve size 1.18 mm that consist approximately 19% (for A60D and A60B) and 23% (for A80D, B80B1 and B80B2) of the total aggregate mass.

The coefficient of determination (R-square) obtained from the statistical analysis (Table 8) are divided into four groups and further discussed to validate the presented results. R-square is a statistical measure of how well the regression line fits the real data points. Group 1 is highlighted with greycolour to represent the R-square values greater than 75%, which indicates a great accuracy and robustness of the statistical analysis results. Group 2 is highlighted with blue colour to cluster the R-square within 50 to 75%. Although the reliability of the results categorized in group 2 is lower than group 1, they are still acceptable. Groups 3 and 4 indicate the R-square between 25 to 50% and below 25%, respectively, which are not truly acceptable. Groups 3 and 4 are highlighted with green and orange, respectively. Overall, the results indicate that most of the data lie within the most acceptable analysis range. Further evaluation reveals that all factors that significantly affect the mixture's performance have R-square greater than 75%. This finding testifies that the presented results are substantially accurate and reliable.

Table 8. Results of One-Way ANOVA.

	Analysed Test Variables

		Binder Type	**Binder Content**	**Mixing Plant**	**Sieve Size 14 mm**	**Sieve Size 10 mm**	**Sieve Size 5 mm**	**Sieve Size 3.35 mm**	**Sieve Size 1.18 mm**	**Sieve Size 0.425 mm**	**Sieve Size 0.150 mm**	**Sieve Size 0.075 mm**	**Filler**
Creep Modulus	p-value	0.046	0.025	0.475	0.581	0.016	0.746	0.585	0.046	0.427	0.115	0.248	0.025
	R-square	78.43	85.35	18.09	41.92	98.44	25.40	41.52	78.43	88.28	99.19	40.57	85.35
Strain Rate	p-value	0.174	0.007	0.213	0.405	0.056	0.530	0.702	0.174	0.057	0.271	0.135	0.007
	R-square	51.22	93.51	45.30	59.49	94.42	47.05	29.84	51.22	78.66	95.40	58.02	93.51
Micro Strain	p-value	0.098	0.010	0.354	0.484	0.028	0.682	0.623	0.098	0.502	0.210	0.172	0.010
	R-square	65.32	92.04	28.55	51.61	97.15	31.78	37.70	65.32	83.53	97.26	51.61	92.04
ITS	p-value	0.009	0.163	0.889	0.613	0.062	0.809	0.375	0.009	0.115	0.029	0.431	0.163
	R-square	92.41	53.04	0.76	38.70	93.79	19.14	62.46	92.41	99.19	99.95	21.51	53.04
Flow	p-value	0.055	0.049	0.647	0.536	0.085	0.877	0.433	0.055	0.332	0.200	0.225	0.049
	R-square	75.81	76.61	7.91	46.41	91.45	12.35	56.69	75.81	93.06	97.50	43.69	76.61
Resilient Modulus	p-value	0.091	0.040	0.513	0.370	0.112	0.811	0.557	0.091	0.321	0.379	0.114	0.040
	R-square	66.81	80.02	15.45	62.98	88.81	18.87	44.28	66.81	93.49	90.88	61.87	80.02
Maximum Force	p-value	0.048	0.021	0.414	0.545	0.015	0.688	0.649	0.048	0.427	0.155	0.219	0.021
	R-square	76.81	86.71	22.97	45.50	98.47	31.17	35.13	76.81	88.30	98.51	44.44	86.71
Fracture Toughness	p-value	0.132	0.002	0.288	0.557	0.004	0.630	0.607	0.132	0.634	0.082	0.230	0.002
	R-square	58.54	97.51	35.63	44.26	99.57	37.02	39.27	58.54	72.71	99.58	43.00	97.51
Mean Wheel Tracking Slope	p-value	0.165	0.025	0.268	0.300	0.124	0.591	0.736	0.165	0.426	0.426	0.078	0.025
	R-square	52.76	85.47	37.98	69.96	87.65	40.89	26.36	52.76	88.37	88.37	69.84	85.47
Mean Rut Depth	p-value	0.019	0.160	0.731	0.326	0.103	0.722	0.588	0.019	0.040	0.390	0.194	0.160
	R-square	87.64	53.47	4.53	67.36	89.71	27.81	41.20	87.64	99.90	90.31	48.14	53.47
Mean Proportional Rut Depth	p-value	0.021	0.162	0.612	0.316	0.109	0.597	0.720	0.021	0.046	0.403	0.187	0.162
	R-square	87.03	53.25	9.57	68.39	89.12	40.32	28.04	87.03	99.87	89.63	49.19	53.25

Note: Gray cells show the parameters significantly affect test results (p-value < 0.05), Gray cells indicate the R-square greater than 75%, Blue cells specify the R-square between 50 to 75%, Green cells denote the R-square between 25 to 50% and Orange cells represent the R-square lower than 25%.

For better understanding, the main effects of the variables that have the highest significant effects on the pavement performance were also determined. As shown in

Fig. **7** and 8, there are two consistent trends presented by the main effects plot of the experimental test results. The main effects plots for creep modulus, ITS, flow, resilient modulus, maximum force and fracture toughness follow the same trend presented in

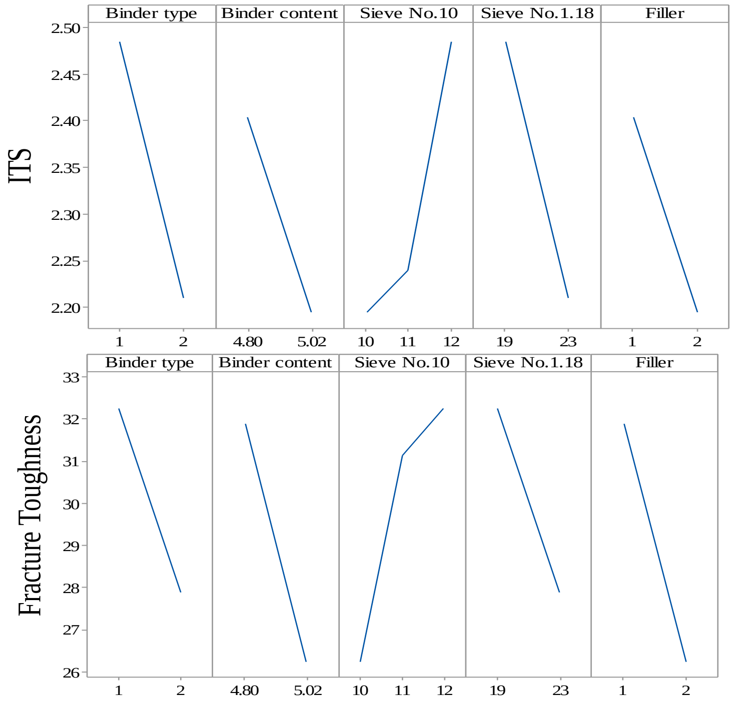
Fig. **7**. While strain rate, micro strain, mean wheel tracking slope, mean rut depth and mean proportional rut depth follow the trend presented in

Fig. **8**.

From the test results, changes in the binder grades (from 60/70 to 80/100), applications of a higher binder contents, higher portion of aggregates retained on sieve size 1.18 mm and the variation of hydrated lime to Portland cement have reduced the ITS and fracture toughness (

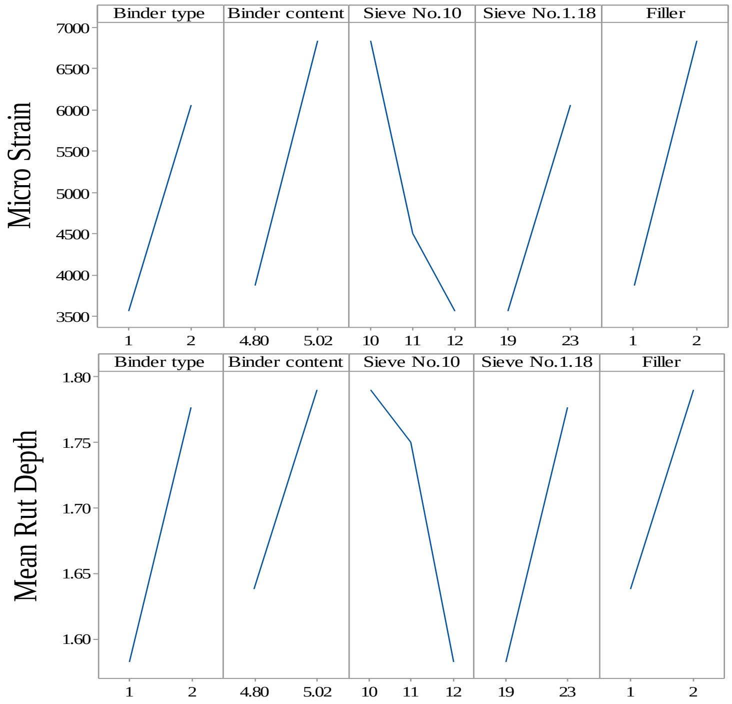
Fig. **7**). As expected, the opposite trend is presented by the same variables on the dynamic creep and wheel tracking tests as depicted in

Fig. **8**. These findings are inline together. For instance, certain parameter variation that results in ITS reduction causes increment in rutting. The significant effects of aggregate gradation on pavement performance can also be seen from these figures. As can be seen, a higher percentage of aggregate retained on sieve size 10 mm has resulted in a higher ITS or fracture toughness and lower micro strain and mean rut depth. This indicates that coarser aggregate gradation results in higher mixture strength or stability. In addition, referring to the ANOVA analysis and main effects plots results, some parameters might not have a significant impact on the asphalt mixture performance. However, it may indirectly affect the pavement performance in some extent during its service life. It also implies that variation in the materials could vary the pavement's performance in different ways.



Note: Binder Type 1 Refers to Binder 60/70, Binder Type 2 Refers to Binder 80/100, Filler Type 1 Represents Hydrated Lime and Filler Type 2 Stands for Cement.

Fig. 7. The Main effects plots of ITS and fracture toughness.



Note: Binder Type 1 Refers to Binder 60/70, Binder Type 2 Refers to Binder 80/100, Filler Type 1 Represents Hydrated Lime and Filler Type 2 Stands for Cement.

Fig. 8. The main effects plots of micro strain and mean rut depth.

4. Conclusions

Based on this study the test results, several conclusions can be drawn as follows:

- Overall, the results indicate that the performance of mixtures is highly associated with the mixture's constituents. Asphalt mixtures produced using stiffer binders exhibited higher flow, ITS, fracture toughness, resilient modulus and creep modulus, while exhibited lower strain rate and accumulated micro strain as well as mean wheel tracking slope, mean rut depth and mean proportional rut depth. This can be correlated to higher stiffness and rutting resistance of stiffer binder compared to softer binders.
- The One-Way ANOVA results revealed that the level of significance may vary with the nature of tests and independent variables. It also shows that enhancement of specific properties, will be highly influenced by certain criteria during mixing process.
- According to the results, changes in aggregate gradation, filler type, and binder content during mixture production can considerably enhance the mixtures behavior. Mixtures with coarser aggregate gradation (as a mixture skeleton) and hydrated lime (as a filler) exhibit better performance. In addition, binder content were among factors that significantly affect the pavement performance in terms of both rutting resistance and stiffness. The differences between the performance of mixtures produced via batch and drum mixing plants were found to be statistically insignificant. The outcomes of this study provide

essential insight towards understanding of mixture performance, which are useful to be used as a reference to enhance pavement performance in future.

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Nomenclatures

ITS	Indirect tensile strength, MPa
F_{max}	Maximum force, kN
K	Fracture toughness, N/mm$^{3/2}$
M_c	Creep modulus, MPa
M_r	Resilient modulus, MPa
PR_d	Mean proportional rut depth, %
R_d	Mean rut depth, mm
WT_s	Mean wheel tracking slope, mm/10^{3}cycle

Greek Symbols

α	Significance level of statistical analysis
ε	Strain

Abbreviations

ANOVA	Analysis of Variance
ERGS	Exploratory Research Grant Scheme
ITS	Indirect Tensile Strength
OBC	Optimum Binder Content
PWD	Malaysian Public Works Department
SCB	Semi-Circular Bending

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