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Developing and validating HMA Workability Prediction Model for Determining the best Paddle as a Machine Component for Workability Device

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Abstract - In extending the previous work in which the authors develop a workability measuring device, this paper presents a laboratory assessment which looks into the relationship between Temperature (T), speed (S), torque (Tq), power (P) and Energy E, under different types of asphaltic concrete mixes using transducer recording devices. Seven types of mix and 210 samples at six different mixing temperatures were used and at five different RPMs on three types of Paddle configurations (A, B & C) to determine the Paddle which produces the highest R^2 and P- values. Statistical analyses by the MINITAB software was used to develop and validate the model for Energy (workability) for the HMA and the selection of the best Paddle for inclusion, as the component for the workability measuring device. It was found that paddle B was the most suitable and the model was therefore developed using this paddle, as a result of the significant P-value and the highest coefficient of domination (R^2) for mixing Temperature, Speed, Power, Energy and Torque. The results of the sensitivity analyses demonstrate that Energy exhibits the highest increase when Speed is kept at minimum, mean and maximum values.

Keywords: Workability Model, Paddle, Development, Validation, sensitivity analysis.

I. INTRODUCTION

The increasing Traffic volumes and loading in recent times has placed more pressure on engineered roads. Hence, the pavement industry has been stressing the need to achieve reliability in measuring the value of workability in a rational and convenient manner.

Literature search has shown that little attention has been directed towards the influence of the mixing temperature on the workability value of the HMA [1, 2 & 3].

The property development of recent has resulted in the need for improvement in the research relating to the workability of Hot Mix. As a result, a number of researches have focused on measuring the workability of the HMA, in which a number of scholars have evaluated the workability of asphalt concrete by torque or a number of indicators obtained from the gyration compactor and porosity.

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While extensive researches have been conducted on measuring workability by torque [examples 4, 5, & 6]; and evaluating workability by some indicators from the gyration compactor and porosity [examples, 1, 7, 8, 9, 10 &11] not much can be said about the development and validation of prediction models that integrate Energy, Speed, Torque, Power and Temperature of the HMA all in a single research.

This paper extends the work of [12,13] who developed a workability measuring device which uses a transducer to capture the values of torque. To address this research gap, this research has been conducted to achieve the following objectives.

II. OBJECTIVE

The objectives of this research are:

1. To select the best paddle that provides a wide range of Torque values using the statistics.
2. To develop and validate a prediction workability model in terms of Energy using the statistical analysis.

III. EXPERIMENTAL PROCEDURE

3.1 Materials

This research uses locally available granite aggregates provided by the Kajang Rock Quarry in the state of Selangor, Malaysia. Three gradations of granite aggregate were selected based on the Malaysian Public Works Department (PWD) [14] and the Malaysian Specification AC14, namely the highest point, midpoint and lowest point of percentage by passing, used to produce hot asphalt concrete with specific gravities of 2.606, 2.607 and 2.608 gm/cm3 respectively. There are two reasons for the closeness of the gravity values: Firstly, the total percentage of combined aggregates (coarse and fine) is 100%. Secondly, the proportion of coarse and fine aggregates between upper, center and lower limits is the same.

Table 1. Proportion of Coarse and fine Aggregates

Aggregate combination	Highest point %	Midpoint %	Lowest point %
Coarse	46	53	60
Fine	53	47	40

The combined aggregates include coarse aggregates, fine aggregates and mineral filler according to the PWD requirements. All samples produced are the combination of the aggregates proportioned with bitumen of 60/70 and 80/100 penetrations, having specific gravities of 1.02 and 1.03 gm/cm3 respectively.

It should also be added that the Reclaimed Asphalt Pavement (RAP) material was obtained from the Public Works Institute Malaysia (Institut Kerja Raya Malaysia: IKRAM) along the Kajang road in Kuala Lumpur, of which 100% of the materials was used for the research.

The basic properties of the aggregates and bitumen are within specifications in accordance with the PWD requirements, , as shown in Tables 2 and 3.

Table 2. Basic Properties of Aggregate

Property	**Test Result**	**PWD Requirements**	**Designation**
Aggregate Abrasion Value AIV %	22.6	< 25 %	ASTM : C 131-96
Aggregate Impact Value, AIV %	21.64	< 25 %	BS 812: PART 112:1990
Aggregate Crushing Value, ACV	22.5	< 25 %	BS 812: PART 110
Water absorption %	0.65	< 2 %	(BS 812 : PART107:1995)
Specific Gravity each grading gm / cm^3	2.606 2.607 2.608		(BS 812 : PART 107:1995)
Flakiness Index %	13	< 25 %	(BS 812 : PART 105: 1990)
Polish Stone Value , PSV	48	> 40 %	(BS 812 : PART 114: 1989)

Source: BS [15]; ASTM [16]

Table 3. Basic Properties of Bitumen, RAP and Viscosity

Type of test	**Test result 80/100**	**Designation**
Penetration at 25°C, 100g	91	ASTM D 5
Softening point (°C)	47.5	ASTM D 36
Ductility at 25°C (cm)	100	ASTM D 113
Viscosity at 135 °C (cP)	425	ASTM D 4402-02

3.2 Method

The preparation was performed, according to the following procedure. Seven types of mix were designed using the AC14 gradation of three different aggregate fractions. The first three mix designs were of typical density- graded asphalt concrete using bitumen of 80/100 penetration. The other three mixes were similarly graded, using bitumen of 60/70 penetration and the last mix was RAP. The mixtures were identified as mixtures 1 to 7. In this research, 60-70 and 80-100 penetration grades had been used because they are specifically outlined in section 4.11 of the Malaysian standard. In addition, the RAP was used to ensure that the device could be used in testing hard asphalt concrete. The selected new aggregate proportions and RAP aggregate fraction were investigated as are their specification limits. The mixtures were identified as mixtures 1, 2 and 3 as shown in Table 4.

TABLE 4. Job Formula for Blended Mix

Mix Designation	Power ^ 0.45	Wearing Course AC 14							RAP	
		80/100 penetration			60/70 penetration			Specification Passing Limits PWD	Passing Mix7	Specification Limits PWD (Type 1)
B.S Test Sieve		Mix1 Pass	Mix2 Pass	Mix3 Pass	Mix4 Pass	Mix5 Pass	Mix6 Pass			
20.0 mm	3.85	100	100	100	100	100	100	100	100	100
14.0 mm	3.28	100	95	90	100	95	90	90 – 100	95	80 – 95
10.0 mm	2.82	86	81	76	86	81	76	76 – 86	86	68 – 90
5.0 mm	2.06	62	56	50	62	56	50	50 – 62	67	52 – 72
3.35 mm	1.72	54	47	40	54	47	40	40 – 54	56	45 – 62
1.18 mm	1.08	34	26	18	34	26	18	18 - 34	33	30 – 45
425 µm	0.68	24	18	12	24	18	12	12 – 24	20	17 – 30
150 µm	0.43	14	10	6	14	10	6	6 - 14	11	7- 16
75 µm	0.31	8	6	4	8	6	4	4 – 8	6	4 – 10
Filler OPC %		2	2	2	2	2	2	2	-	-
Bitumen Content %		4.92	4.71	4.62	5.08	4.82	4.74	4 - 6	5.6	5 – 7

The asphalt required of the combined aggregates for mix number 7 (RAP) was determined using a formula [17].

The samples were labeled as mix 1 to mix 7. Paddle A was fixed to the device and the motor set at 5 RPM, then the paddle was immersed into mix 1 at 120 °C. The torque was recorded during the paddle revolution at the same temperature, where the RPM was adjusted to 10 then 15, 20, 25 RPM and the torque recorded at each speed using, this time, paddle A, with the temperature increased to 130 °C using the heater attached to the device at RPM 5. The same procedure was repeated at 10, 15, 20 and 25 RPM. Another round of procedures was repeated for temperatures 140 °C, 150 °C, 160 °C and 170 °C respectively for mix 1. The entire procedures were repeated using paddle B and C on mix 1 to complete the tests in stage one. These processes consist of seven stages, and each stage yielded 18 samples, totaling 126 samples and the total weight of each sample was 3600 grams. The data recorded for each sample lasted 60 seconds. Figure 1 below depicts the three paddle configurations used in this research.

Fig. 1. Photograph of Three Types of Paddle Used in Research

IV. RESULT AND DISCUSSION

The workability prediction model relies on the statistical output. Data was obtained from outputs generated by the transducer, where 30 samples of each type of mixture totaling 210 samples were prepared and examined under different temperatures and speeds, and this goes for each of the three types of paddles. The values for Torque, power and energy for each sample was obtained. Based on DanielSoper, [18], Paddle C was dropped before further experiment because it produced a low range of Torque as shown in Table 5 below. As shown in the table, 2.06 KN was produced by paddle A at speed 5RPM (TA5); 8.98 KN was produced by paddle B at speed 5RPM (TB5) and 1.5 KN was produced by paddle C at speed 5RPM (TC5). The test was repeated for 10 RPM, 15RPM, 20RPM and 25RPM to produce torque ranging from 1 to 7.

Table 5. Range of Torque

TORQUE	TA@5	TB@5	TC@5	TA@10	TB@10	TC@10	TA@15	TB@15	TC@15	TA@20	TB@20	TC@20	TA@25	TB@25	TC@25
Range 1	2.06	8.98	1.5	2.05	7.19	1.39	2.95	8.5	0.81	1.93	6.81	1.31	3.54	5.38	1.2
Range2	0.99	3.36	0.96	1.9	2.13	1.13	0.98	4.78	1.73	2.01	1.87	1.75	2.54	3.35	1.77
Range3	8	8.01	1.7	10.89	19.73	1.06	6.34	16.69	0.54	14.94	15.02	1.27	19.27	17	1.48
Range4	1.95	2.35	1.15	0.93	3.14	2.06	0.99	1.25	1.7	2.12	5.49	2	0.7	4.1	2.81
Range5	9.42	14.19	8.35	8.35	15.71	4.02	5.84	19.69	5.18	7.73	11.82	3.95	7.71	10.52	5.13
Range6	5.73	2.82	1.22	6.56	2.13	0.66	5.47	4.04	1.8	4.77	8.47	2.28	5.76	2.19	3.05
Range7	7.32	5.3	2.2	7.13	4.63	2.35	6.44	5.02	2.58	4.18	4.27	2.4	7.58	5.06	2.35

To address the effect of outliers on our data, outliers were first removed. Outlier samples can occur in datasets for a number of reasons. The reasons are usually categorised as either technical in this project. This could be termed a technical outlier because the sample was taken from the wrong place (during data recording, the aggregate crashed between the blades and bowl) The outlier was then removed from the dataset to provide conditions of skewness and kurtosis; the skewness for a normal distribution is zero, and any symmetric data should have a skewness near zero.

Table 6. Selection of Paddle using the statistics

Regression Analysis	Paddle A			Paddle B		
	P	R^2 %	Remark	P	R^2 %	Remark
TEM versus SPEED	0.849	0.0		0.604	0.1	✓
TEM versus TORQUE	0.0**	13.3	✓	0.0**	6.7	
TEM versus POWER	0.327	0.5	✓	0.750	0.1	
TEM versus ENERGY	0.259	0.7		0.126	1.2	✓
SPEED versus TORQUE	0.643	0.1		0.463	0.3	✓
SPEED versus POWER	0.0**	60		0.0**	62.4	✓
SPEED versus ENERGY	0.0**	58.8		0.0**	68.1	✓
TORQUE versus POWER	0.0**	19.9	✓	0.0**	10.2	
TORQUE versus ENERGY	0.007**	3.8	✓	0.006**	3.7	✓
POWER versus ENERGY	0.0**	59.6		0.0**	65.9	✓

NOTE: Paddle B chosen based on $P < 0.05$ & high R^2, ** Significant at 0.05

The coefficients of determination of the R^2 and P-values were used as the bases for comparing between A and B because literature has shown that R^2 is a useful descriptive statistics. Additionally, high R^2 indicates a good fit between the data and the equation [19].

4.1 Model Development

Following Soper's [18] statistical guide on the sample, 210 sample size is adequate for this study at 95 percent confidence level. Outliers were removed from the dataset to provide conditions of skewness and kurtosis , whereby the skewness for a normal distribution is zero, and any symmetric data should have a skewness near zero. Two normality tests using Anderson darling and Kolmogorov Smirnov were performed. However, both tests were rejected because of the fact that the P-values are below 0.150 P-value thresholds. Following Ryan [20], the data were transformed to meet the requirements of data normality and also to improve interpretability.

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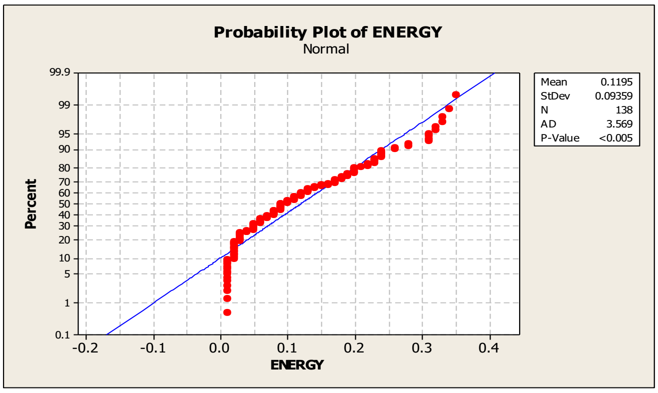

Fig. 2. Anderson Darling's normality graph

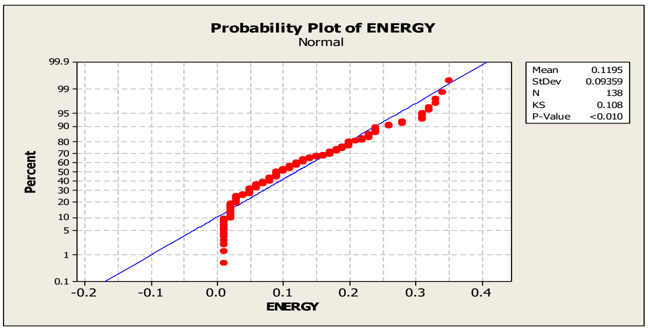

Fig. 3. Kolmogorov Smirnov's normality graph

Figure 2 above depicts a graphical presentation of the probability plot for Energy against Torque, speed, power and temperature. The graph shows that the data are not uniformly distributed using the Anderson Darling test and that the P-value is below the threshold of 0.150. This is also the same for Kolmogorov Smirnov having P-value of 0.01 as shown in figure 3. The logarithm transformation of the data was therefore performed, in which data were transformed into Log and were tested for normality using Anderson Darling and Kolmogorov Smirnov. Both tests yielded a normal distribution as shown in figure 4 & 5 and P-values of 0.150 and 0.303, respectively. Based on the trial-and-error technique, the results show a Regression Analysis: E versus S, Tq, log-P*T

Table 7. Regression Analysis: E versus S, Tq, log-P*T

Predictor	**Coef**	**SE Coef**	**T**	**P**
Constant	-0.28535	0.06855	-4.16	0.000
S	0.0093151	0.0009695	9.61	0.000
Tq	0.004797	0.001013	4.74	0.000
log-P*T	0.05921	0.02549	2.32	0.022
R-Sq	79.1%			

Table 8. Analysis of Variance

Source	DF	SS	MS	F	P
Regression	3	0.88903	0.29634	162.73	0.000
Residual Error	129	0.23492	0.00182		
Total	138	1.12394			

Table 7 above presents the output of the regression model. The R2 is 79.1 %, implying that independent variables can explain 94% changes in the value of Torque. Hence, there is statistical evidence that the independent variables (Temperature (T), speed (S), torque (Tq) and power (P)), can be used to predict the values of mixing energy. The result of the analysis of variance (ANOVA) in table 8 provides evidence that the model is statistically significant-indicating that the model is fit. The regression equation obtained is presented below.

The regression equation is

E= - 0.285 + (0.00932 * 'SPEED') + (0.00480 * 'TORQUE') + (0.0592 * Log T ('POWER' * 'TEM'))

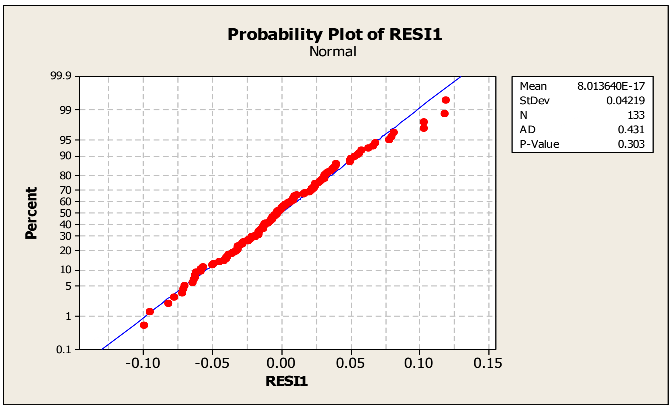

Fig. 4. Anderson Darling's normality graph for transformed data

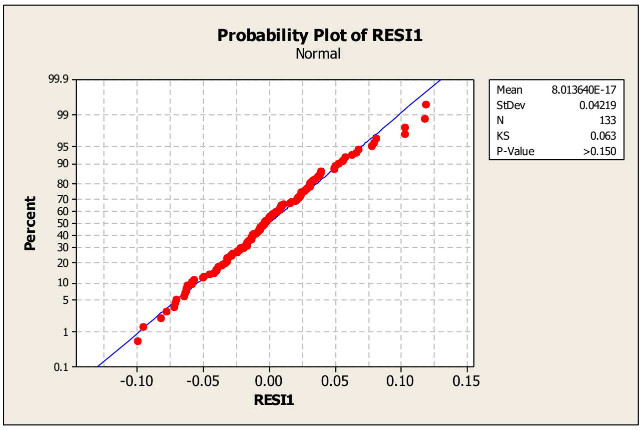

Fig. 5. Kolmogorov Smirnov's normality graph for transformed data

4.2 Model Validation

Fifty nine samples (59) were used to validate the model developed. The validation of model is essential because literature has shown that the value R^2 is not enough to establish a model; instead it requires validation. In this research, the Paired T-Test was performed to validate the model. Statistics literature has demonstrated that model validation is possibly the most important step in the model building sequence, although it is also one of the most overlooked. In addition, a high R2 value does not guarantee that the model fits the data well. The use of a model that does not fit the data well cannot provide good answers to the underlying engineering [21].

The summary of the model validation is presented below. The paired T-test was performed to compare the values of Torque from the model output and laboratory experiments.

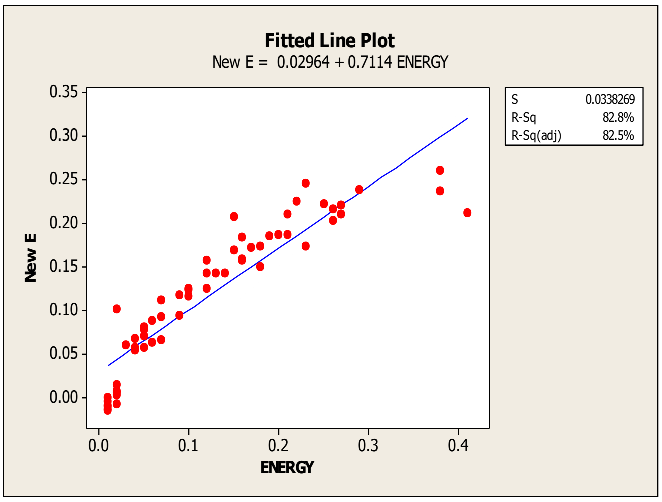

Fig. 6. Model validation

4.3 Sensitivity Analysis (SA)

Table 9 summarizes the sensitivity analysis consisting of 5 group tests from the control experiment. First off, there is Test A, which consists of three conditions namely minimum, average and maximum values. The mixing temperature was varied from 120 °C– 170 °C, while the speed was fixed at 5RPM for minimum, 15 for mean and 25 for the maximum values. Then the Torque was fixed at 6.5 KNm for minimum, 14.2KNm for mean and 26.2KNm for maximum values. Thereafter, the Power was fixed at 3.6KW for minimum, 19.3KW for mean and 51.1KWh for the maximum values.

Second of all, in test B the compacting Speed varied from 5-25RPM while other variables were fixed at minimum, mean and maximum values. Temperature was varied from 120 °C for minimum, 145 °C for mean and 170 °C for maximum values. Then, the Torque was fixed at 6.5 KNm for minimum, 14.2KNm for mean and 26.2KNm for maximum values. Next, the Power was fixed at 3.6KW for minimum, 19.3KW for mean and 51.1KW for the maximum values. In Test C, the Torque was fixed 6.5KNm -26.2 KNm while the other variables were kept at minimum, mean and maximum values. The same procedure was used in Test D in which Power was kept between 3.6KW – 51KW while other variables were kept at minimum, mean and maximum values as shown below.

The test (types A-D) of four predictors involved in the prediction of the response variable Energy (E) is as follows:

i. **Type A**: Varying the temperature (T) parameter and the other three parameters- speed (S), torque (Tq) and power (P)- are fixed under three cases.
ii. **Type B**: Varying the speed (S) parameter and the other three parameters namely temperatures (T), torque (Tq) and power (P) are fixed under three cases.
iii. **Type C**: Varying the torque (Tq) parameter and the other three parameters namely temperatures (T), speed (S) and power (P) are fixed under three cases.
iv. **Type D**: Varying the power (P) parameter and the other three parameters which are temperatures (T), speed (S) and torque (Tq) are fixed under three cases.

Table 9. Summary of sensitivity analysis in types A, B, C and D

Model:		**E= - 0.285 + (0.00932 * 'SPEED') + (0.00480 * 'TORQUE') + (0.0592 * Log T ('POWER' * 'TEM'))**			
Type:	Condition	T	S	Tq	P
A	1	Value increased [120 to 170]	Fixed at: 5.0	Fixed at: 6.5	Fixed at: 3.6
	2		Fixed at: 15.0	Fixed at: 14.2	Fixed at: 19.3
	3		Fixed at: 25.0	Fixed at: 26.2	Fixed at: 51.1
B	1	Fixed at: 120	Value increased [5 to 25]	Fixed at: 6.5	Fixed at: 3.6
	2	Fixed at: 145		Fixed at: 14.2	Fixed at: 19.3
	3	Fixed at: 170		Fixed at: 26.2	Fixed at: 51.1
C	1	Fixed at: 120	Fixed at: 5.0	Value increased [6.5 to 26.2]	Fixed at: 3.6
	2	Fixed at: 145	Fixed at: 15.0		Fixed at: 19.3
	3	Fixed at: 170	Fixed at: 25.0		Fixed at: 51.1
D	1	Fixed at: 120	Fixed at: 5.0	Fixed at: 6.5	Value increased [3.6 to 51.1]
	2	Fixed at: 145	Fixed at: 15.0	Fixed at: 14.2	
	3	Fixed at: 170	Fixed at: 25.0	Fixed at: 26.2	

Condition or situation 1: based on the minimum parameter value, condition or situation 2: based on the mean parameter value and condition or situation 3: based on the maximum parameter value.

Figures 7-10 depict the result of the five tests in a control experiment. The graph presents the influence of the control experiment under varying conditions of the values of the Energy. Figure 1 depicts the result of test A, consisting of three conditions namely minimum, average and maximum values. The mixing temperature was varied from 120 ° C– 170 °C, while the speed was fixed at minimum, mid and maximum values in which the value of energy increased slightly for situations 1, 2 &3. Figure 8 presents the result of test B in which the Speed was kept at 5- 25 RPM, while other variables were kept at the minimum, mean and maximum values. As shown in the graph, there is a significant increase in the values of energy for all the three situations but the highest in situation 3 with an increase observed from 1KWh to 6.5KWh. Similarly, figure 9 presents the result of test C in which the Torque was kept at 6- 26KNm while other variables were kept at the minimum, mean and maximum values. The graph shows that there is a moderate increase in the values of energy for situation 1 but it proves to be higher in situations 2 & 3 with an increase from 0.5 – 1.5 KWh, and from 2.5 – 5.4 KWh. In test D, the Power was fixed at 3.6 KW – 51.1KW while other variables were kept at minimum, mean and maximum values. Figure 10 shows that the value of energy had initially increased and becoming slightly stable, exhibiting a curve for situations 1, 2 & 3.

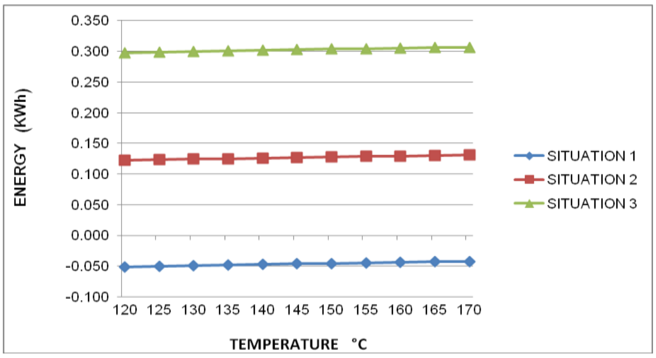

Fig. 7. Sensitivity analysis output for type A

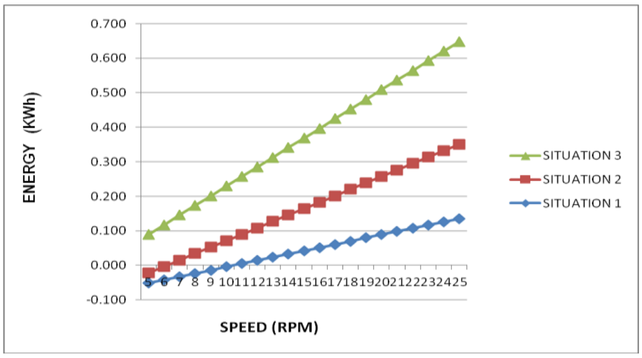

Fig. 8. Sensitivity analysis output for type B

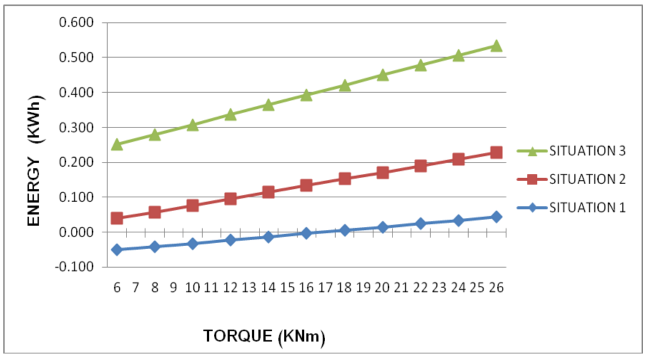

Fig. 9. Sensitivity analysis output for type C

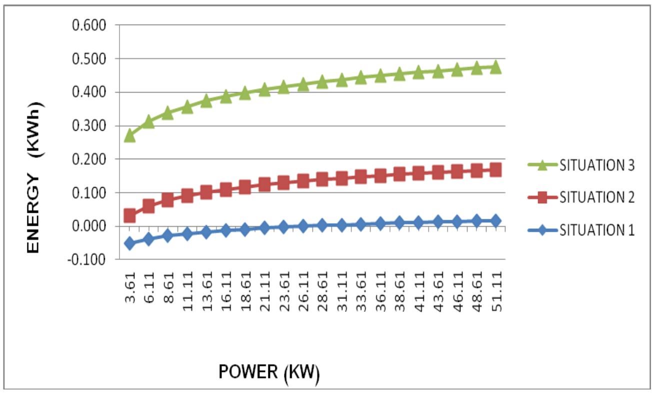

Fig.10. Sensitivity analysis output for type D

V. CONCLUSION

The objectives of this paper are to select the best paddle that provides a wide range of Torque values using statistics, and develop, as well as validate a prediction workability model in terms of Energy using statistical analysis. The paper presents a workability model development and validation for selecting a Paddle for inclusion to a workability device based on the statistical analysis. Three types of paddles- coded as Paddles A, B and C were tested to determine their efficiency based on the value of coefficient of the R^2 and P-value determination. Paddle C was dropped at the initial stage of the research because of the fact that it has the least number of Torque range. Values for Paddle A and B were further subjected to regression analyses towards further developing the model. Paddle B was found to be significant in the regression of mixing temperature, speed, power, energy and torque. The significance of this research paper lies in expanding the previous empirical studies that focus on improvements of workability devices. The paper presents the most suitable paddle for workability device used, measuring workability and the energy of mix Asphalt concrete. The results of the sensitivity analyses are also pursued, to examine the effect of energy on temperature, speed, torque and power and at this point, the results demonstrate that Energy increases insignificantly with temperature that is kept at minimum, mean and maximum values, that it exhibits the highest Energy increase with Speed, moderates the Energy increase when Torque is at the minimum value. The increase in Energy forms a curve when Power is varied from minimum, mean and maximum values. It is anticipated that the model presented in this paper can be used to validate other experiments underway or even become the point of reference for future ones, on device workability under Malaysian conditions.

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