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Modeling workability of asphalt concrete performance at different temperatures using a statistical model

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Abstract

In this study, a workability model is used to predict the values of Torque in relation to mix and compaction by Temperature, Gyration, Resilient Modulus, Stability and Flow. The data are obtained from workability-measuring devices developed by the authors. The value of R2 implies that about 95 % variation in the values of Torque can be explained by the variation in mixing and compaction according to Temperature, Gyration, and Resilient Modulus. The regression model as a whole shows that while the value of Torque is largely influenced by Compaction, Mixing Temperature and Gyration; Resilient Modulus, Stability and Flow are not significant determinants of workability. The paper recommends that the effect of workability on the performance of Asphalt concrete should be taken very seriously during the design.

Keywords: *Hot mix asphalt; Torque; Workability Model; Sensitivity analysis.*

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1 Introduction

Increasing traffic volumes in recent time has resulted in more pressure on roads and has placed more pressure on engineered roads. Technically, a well-designed and constructed road will not only support regional and national developments of a country, but also assist in sustaining the life span of the infrastructure. To achieve this, an adequate mix design is essential. Additionally, the pavement industry has stressed on the importance of achieving reliable and accurate measurement of the workability values in an efficient and convenient manner. In the meantime, the demand for durable and quality products has resulted in the need for improvement in research relating to the workability of Hot Mix. Literature search has suggested that little attention has been directed towards the influence of the mixing temperature on the workability value of the HMA [1, 2 &3]. While few previous researches have focused on measuring the workability of the HMA, 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. Although some scholars measure workability by torque [4, 5 & 6], others evaluate workability by some indicators from the gyration compactor and porosity [1, 7, 8, 9 &10]. Measuring workability by a number of indicators from the gyration compactor and porosity to produce the desirable pavement could be achieved by developing an asphalt concrete mixer which uses an electric transducer, at the same time it measures the workability value by means of torque within a period of time. In this study, the theory of mixing is considered as a theoretical and underpinning theory. This paper extends the work of Khalil, et al. [11] who developed a workability measuring device which uses a transducer to capture the values of torque.

2 Objective

The main objective of this study is to develop a workability model for evaluating mixing and compaction temperatures, Gyration, Resilient Modulus, Stability and Flow using statistical analyses in relation to the value of Torque. This study extends earlier work on developing workability measuring devices which rely on the accuracy, reliability and efficiency. Thus, this paper focuses on establishing a statistical relationship between the torque (as the dependent variable) and mixing temperature, compaction temperature, gyration, resilient modulus, stability and flow using both the regression and sensitivity analyses (as independent variables).

3 Materials and experimental procedure

3.1 Materials

Aggregates used in this study were sourced locally from the Kajang Rock Quarry in the state of Selangor, Malaysia. Three gradations of granite aggregate were selected based on the Malaysian Public Works Department [12] and Malaysian Specification AC14, namely the highest point, midpoint and lowest point of percentage by passing; all of which were used to produce hot asphalt concrete with specific gravity of 2.606, 2.607 and 2.608 gm/cm3 respectively. There are some reasons for the closeness of the values for specific gravity. First of all, the total percentage of the combined aggregates (coarse and fine) is 100%. Secondly, the proportion of coarse and fine aggregates between upper, centre and lower limits is the same, which is shown in Table 1.

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. This study complies with section 4.3.3.2 (b) of the PWD Malaysia [12], the standard specification for road works on flexible pavements and mineral filler used for the asphalt pavement. The hydrated lime has been used extensively as the mineral filler in HMA mixtures for many years in Malaysia, because of its ability to maintain a good adhesion between the aggregate and the asphalt cement. The Portland cement was used as filler as its effectiveness was tested in this study.

All samples produced are the combination of the aggregates proportioned with bitumen of 80/100 penetrations, having specific gravity of 1.03 gm/cm3, respectively. The basic properties of the aggregates and bitumen are within the specification in accordance with 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 British Standard [13, 14 & 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

Asphalt mixtures were prepared in accordance Malaysian standard. The preparation was performed, according to the following procedure. Three types of mix were designed using the AC14 gradation of three different aggregate fractions. Mix designs were the typical dense-graded asphalt concrete using bitumen of 80/100 penetration. The mixtures were identified as mixtures 1, 2 and 3 as shown in Table 4. In this research, 80-100 penetration grades had been used because these are specifically outlined in section 4.11 of the Malaysian standard.

Table 4: Blended Mix of Asphaltic concrete

Mix Designation	Power ^ 0.45	Wearing Course AC 14 80/100 Penetration			Specification Passing Limits PWD
B.S Test Sieve		Mix1Pass	Mix2 Pass	Mix3 pass	
20.0 mm	3.85	100	100	100	100
14.0 mm	3.28	100	95	90	90 – 100
10.0 mm	2.82	86	81	76	76 – 86
5.0 mm	2.06	62	56	50	50 – 62
3.35 mm	1.72	54	47	40	40 – 54
1.18 mm	1.08	34	26	18	18 - 34
425 µm	0.68	24	18	12	12 – 24
150 µm	0.43	14	10	6	6 - 14
75 µm	0.31	8	6	4	4 – 8
Filler OPC %		2	2	2	2
Bitumen Content %		4.92	4.71	4.62	4 - 6

The compactability of the designed asphalt mixtures was evaluated using results from the Superpave gyratory compactor (SGC). The compactability of HMA mixtures is often used to describe how easy or difficult it is to compact a mixture on a roadway. Compaction was achieved by the application of a vertical stress 600 via the end platens to a known mass of asphaltic mixture within a 100 mm internal Ø mould, with the angle of 1.25°. The first stage of the experiment involves the preparation of three mixes labeled mix 1, 2 and 3 as shown in table 3 above. In the first step, mixture 1 was mixed at 140 °C. The temperature was regulated to 135 °C and mixed again; simultaneously, the torque at this temperature was recorded. The mix was compacted at the same 135 °C to reach air voids 4 and density, shear stress and gyrations were recorded , and the performance test of Resilient Modulus ASTM 4123, Marshall Stability ASTM D 1559) were conducted. The temperature of the same mix 1 was noted at 140 °C and regulated to 120 °C. The torque was recorded and later compacted at the same 120 °C to reach air voids 4, and density, shear stress and gyrations were recorded , and the performance test Resilient Modulus ASTM 4123, Marshall Stability ASTM D 1559 were again, conducted. The temperature of the same mix 1 was set at 140 °C. The temperature was regulated to the compaction temperature of 105 °C and 90 °C and the same procedure was conducted. The second step involves mixing mix 1 at 155 °C and, the temperature was regulated to the compaction temperature of 150 C. The torque was recorded and then compacted at this temperature until it reached air voids by 4 percent. Simultaneously, the density, shear stress and gyrations were recorded and the performance tests of Resilient Modulus ASTM 4123, Marshall Stability ASTM D 1559) were carried out. This process was repeated at the compaction temperatures of 135 °C, 120 °C, 105 °C and 90 °C, and the density, shear stress and gyrations were recorded and the performance tests Resilient Modulus ASTM 4123, Marshall Stability ASTM D 1559 were carried out. Step one and two were repeated for mix 2 and mix 3, respectively. Also, the total weight of each sample was 3600 grams. The data recorded for each sample lasted 300 seconds in the period of mixing.

4 Method of analyses

Prior to the main analysis, normality tests were conducted in order to check the outliers that could negatively influence the findings. The regression analysis was performed to produce a statistical model for the workability value. Finally, a sensitivity analysis was performed to examine the relationship between the torque and compaction temperature.

4.1 Model development

Following Soper's [17] statistical guide on his sample, 54 subjects are adequate for this study at 95 percent confidence level. Outliers were removed from the dataset to provide the condition of skewness and kurtosis- the skewness for a normal distribution is zero, and any symmetric data should have skewness near zero. Two normality tests using

Anderson darling and Kolmogorov Smirnov had been performed. Both tests yielded a normal distribution as shown in Figures 1 and 2 below.

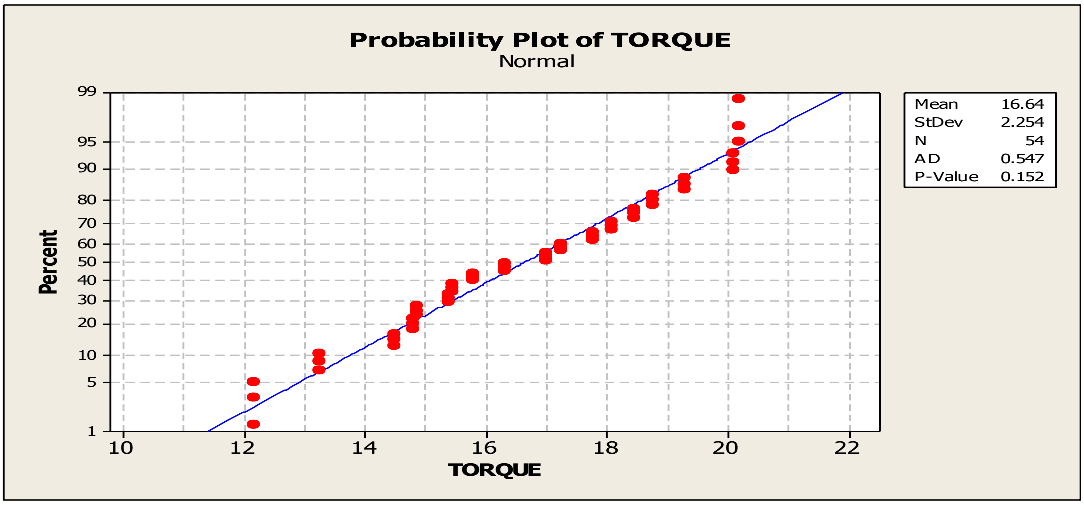

Figure 1: Anderson Darling normality graph

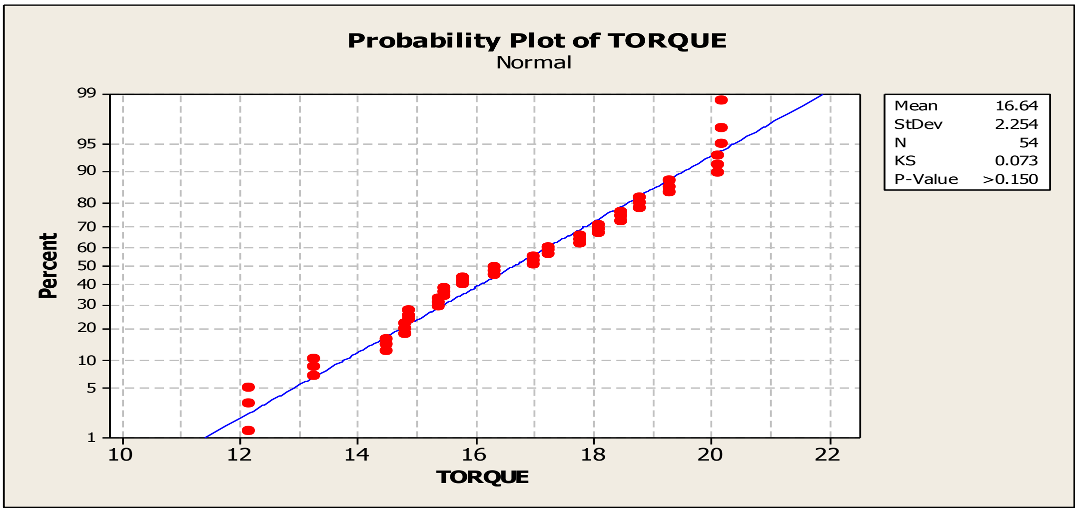

Figure 2: Kolmogorov Smirnov normality graph

4.2 Sensitivity analysis

The sensitivity analysis provides a general qualitative understanding of the trends of the material behaviour in relation to the variation in parameters. The purpose of a sensitivity analysis is to correlate various features of the output of the mathematical model to the different input factors and parameters of the model. The following are the controlled experiments performed for this sensitivity analysis

- Test A: varying the mixing temperature (MT) parameter, and the other five parameters namely compaction temperature (CT), gyration (G), resilient modulus (RM), stability (St) and flow (F) are fixed under five cases.
- Test B: varying the compaction temperature (MT) parameter, and the other five parameters namely mixing temperature (CT), gyration (G), resilient modulus (RM), stability (St) and flow (F) are fixed under five cases.
- Test C: varying the gyration (G) parameter and the other five parameters namely mixing temperature (CT), compaction temperatures (MT), resilient modulus (RM), stability (St) and flow (F) are fixed under five cases.
- Test D: varying the Resilient Modulus (RM) parameter and the other five parameters namely mixing temperature (CT), compaction temperatures (MT), gyration (G), stability (St) and flow (F) are fixed under five cases.
- Test E: varying the stability (St) parameter and the other five parameters namely mixing temperature (CT), compaction temperatures (MT), gyration (G), Resilient Modulus (RM) and flow (F) are fixed under five cases.

- Test F: varying the flow (F) parameter, and the other five parameters namely mixing temperature (CT), compaction temperatures (MT), gyration (G), Resilient Modulus (RM) and stability (St) are fixed under five cases.

5 Result and discussion

5.1 Regression analyses

Table 5 presents the result of the regression analyses between the variables to determine if there is any significant relationship among them. The results show that Torque has a significant relationship with the mixing temperature, compaction temperature, stability and flow. Stability has a significant relationship with the compaction temperature and Gyration. Furthermore, Gyration and Flow are significantly related. It is on this basis that Torque (a dependent variable) was regressed against the independent variables (Mixing and compaction temperature, Gyration, Resilient Modulus and Flow).

Table 5: Summary of Regression Analysis among variables

NO	Regression analysis	Regression equation	R-sq	p- value
1	Mixing temperature versus compaction temperature	mixing temperature = 140.0 + 0.07143 compaction temperature	3.6%	0.171
2	Mixing temperature versus torque	mixing temperature = 164.8 - 0.9921 torque	8.8%	0.029**
3	mixing temperature versus gyration	mixing temperature = 148.9 - 0.002318 gyration	0.3%	0.682
4	Mixing temperature versus resilient modulus	mixing temperature = 141.7 + 0.002596 resilient modulus	1.8%	0.332
5	Mixing temperature versus stability	mixing temperature = 153.1 - 0.4768 stability	0.7%	0.555
6	Mixing temperature versus flow	mixing temperature = 150.2 - 0.426 flow	0.1%	0.858
7	Compaction temperature versus Torque	compaction temperature = 248.4 - 7.917 torque	80.4%	0.000**
8	Compaction temperature versus gyration	compaction temperature = 120.2 - 0.01392 gyration	1.7%	0.350
9	Compaction temperature versus resilient modulus	compaction temperature = 109.5 + 0.002831 resilient modulus	0.3%	0.690
10	Compaction temperature versus Stability	compaction temperature = 47.32 + 6.870 stability	20.0%	0.001**
11	Compaction temperature versus flow	compaction temperature = 141.1 - 5.529 flow	1.5%	0.379
12	Torque versus gyration	torque = 17.34 - 0.002761 gyration	5.1%	0.099
13	Torque versus resilient modulus	torque = 18.14 - 0.000591 resilient modulus	1.0%	0.462
14	Torque versus stability	torque = 22.68 - 0.5991 stability	11.8%	0.011**
15	Torque versus flow	torque = 8.941 + 1.740 flow	11.5%	0.012**
16	Gyration versus resilient modulus	gyration = 157.8 + 0.03859 resilient modulus	0.7%	0.559
17	Gyration versus stability	gyration = 654.2 - 39.44 stability	7.6%	0.044**
18	Gyration versus flow	gyration = 1373 - 252.5 flow	35.9%	0.000**
19	Resilient modulus versus stability	resilient modulus = 2487 + 5.95 stability	0.0%	0.887
20	Resilient modulus versus flow	resilient modulus = 3585 - 234.6 flow	7.0%	0.053
21	Stability versus flow	stability = 6.645 + 0.7799 flow	7.0%	0.053

** Significant at 0.05

Table 6 below presents the output of the regression model. The R^2 is 94%, which implies that independent variables can explain 94% changes in the value of the Torque. Hence there is statistical evidence that the independent variables (Mixing and compaction temperature, Gyration, Resilient Modulus and Flow) can be used to predict the values of the torque. The result of the analysis of variance (ANOVA) in table 7 proves that the model is statistically significant, which implies that the model is fit. The regression equation obtained is presented below.

Torque = 36.4 - 0.0473 Mixing temperature - 0.0989 Compaction temperature - 0.00417 Gyration + 0.000050 Resilient Modulus - 0.128 Stability + 0.231 Flow (1)

Table 6: Regression Model

Predictor	Coef	SE Coef	T	P
Constant	36.403	2.079	17.51	0.000
Mixing temperature	-0.04730	0.01056	-4.48	0.000
Compaction temperature	-0.098894	0.004671	-21.17	0.000
Gyration	-0.0041747	0.0005287	-7.90	0.000
Resilient modulus	0.0000502	0.0002048	0.24	0.808
Stability	-0.12794	0.07186	-1.78	0.081
Flow	0.2306	0.2401	0.96	0.342
R-Sq = 94.7%				

Table 7: Analysis of Variance

Source	DF	SS	MS	F	P
Regression	6	255.132	42.522	141.10	0.000
Residual Error	47	14.163	0.301		
Total	53	269.295			

5.2 Model validation

Twenty seven samples (27) 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, as 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 [18]. 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.

Table 8: Paired T test for New TORQUE - TORQUE

	N	Mean	StDev	SE Mean
new TORQUE	27	16.7109	1.6296	0.3136
TORQUE	27	15.7087	1.9019	0.3660
Difference	27	1.00226	0.48239	0.09284

95% CI for mean difference: (0.81143, 1.19308)

T-Test of mean difference = 0 (vs not = 0): T-Value = 10.80 P-Value = 0.000

5.3 Sensitivity analyses

Table 9 below presents the summary of the sensitivity analysis consisting of six group tests of the controlled experiment. Test A, to begin, consists of three conditions: minimum, average and maximum values. The mixing temperature was varied from 140^{o} C – 155^{o}C, while the compaction temperature was fixed at 90 for minimum, 115 for average and 150 for maximum value. Gyration was fixed at 35 for minimum, 250 for average and 500 for maximum value. Resilient Modulus was fixed at 1900 for minimum, 2500 for average and 2600 for maximum value. Stability was fixed at 7 for minimum, 10 for average and 15 for maximum value. Flow was fixed at 3 for minimum, 4 for average and 5 for maximum value. In test B, the compacting temperature varies from 90-150 while other variables were fixed at minimum, average and maximum value. Gyration varied from 35-500. Resilient Modulus varied in test D, Stability in test E and Flow in test F, as shown below.

Table 9: Summary of the sensitivity analysis

Model: **TORQUE = 36.4 - 0.0473 MT - 0.0989 CT - 0.00417 G + 0.000050 RM - 0.128St+ 0.231 F**

Test	Condition	MT	CT	G	RM	St	F
A	1	Value increased [140 to 155]	Fixed at: 90	Fixed at: 35	Fixed at: 1900	Fixed at: 7	Fixed at: 3
	2		Fixed at: 115	Fixed at: 250	Fixed at: 2500	Fixed at: 10	Fixed at: 4
	3		Fixed at: 150	Fixed at: 500	Fixed at: 2600	Fixed at: 15	Fixed at: 5
B	1	Fixed at: 140	Value increased [90 to 150]	Fixed at: 35	Fixed at: 1900	Fixed at: 7	Fixed at: 3
	2	Fixed at: 150		Fixed at: 250	Fixed at: 2500	Fixed at: 10	Fixed at: 4
	3	Fixed at: 155		Fixed at: 500	Fixed at: 2600	Fixed at: 15	Fixed at: 5
C	1	Fixed at: 140	Fixed at: 90	Value increased [35 to 500]	Fixed at: 1900	Fixed at: 7	Fixed at: 3
	2	Fixed at: 150	Fixed at: 115		Fixed at: 2500	Fixed at: 10	Fixed at: 4
	3	Fixed at: 155	Fixed at: 150		Fixed at: 2600	Fixed at: 15	Fixed at: 5
D	1	Fixed at: 140	Fixed at: 90	Fixed at: 35	Value increased [1900 to 2600]	Fixed at: 7	Fixed at: 3
	2	Fixed at: 150	Fixed at: 115	Fixed at: 250		Fixed at: 10	Fixed at: 4
	3	Fixed at: 155	Fixed at: 150	Fixed at: 500		Fixed at: 15	Fixed at: 5
E	1	Fixed at: 140	Fixed at: 90	Fixed at: 35	Fixed at: 1900	Value increased [7 to 15]	Fixed at: 3
	2	Fixed at: 150	Fixed at: 115	Fixed at: 250	Fixed at: 2500		Fixed at: 4
	3	Fixed at: 155	Fixed at: 150	Fixed at: 500	Fixed at: 2600		Fixed at: 5
F	1	Fixed at: 140	Fixed at: 90	Fixed at: 35	Fixed at: 1900	Fixed at: 7	Value increased [3 to 5]
	2	Fixed at: 150	Fixed at: 115	Fixed at: 250	Fixed at: 2500	Fixed at: 10	
	3	Fixed at: 155	Fixed at: 150	Fixed at: 500	Fixed at: 2600	Fixed at: 15	

Note: Condition or situation 1 is for the minimum parameter value, 2 for average parameter value and 3 for maximum parameter value

Figure 3-8 depict the result of the sensitivity analysis for all the six tests in controlled experiments. The graphs present the influence of the controlled experiments under varying conditions on the values of the Torque. Figure 3 depicts the result of test A, in which the Mixing temperature was increased from140 to 155 at minimum, average and maximum (situation 1, 2, & 3) values and all other variables at fixed values, respectively. The value of Torque slightly dropped from 21 to less than 20 KNm in condition 1; from 17 to 16KNm in condition 2; and 11.8 to 11KNm in condition 3. In test B when the compaction temperature was increased from 90 to 150, the value of Torque dropped from 21 to 15KNm in condition 1; 19 to 13KNm in condition 2 and 17 to 11KNm in condition 3. In test C when Gyration was increased 35 to 500 for minimum, average and maximum values, value of Torques increase from 18 to 21KNm in condition 1; 15 to 17KNm in condition 2 and 12 to 14KNmin condition 3. The findings imply that increase in Gyration will result to increase in the value of Torque. This is due to the low compaction temperature at high Gyration. This finding is consistent with Cardone et al. [19] who also used Gyratory Compactor in their research. Contrary to Bahia & Hanson [20]; Huner & Brown [21] ; and Gudimettla et al. [6], who conclude that Gyratory compactor is not sensitive to temperature; this research finds that Gyratory compactor is sensitive to temperature. This difference can be largely attributed to effect of temperature on viscosity of mixture. Test E which was increased from 7 to 15 illustrated a slight drop in the values of the torque. In condition 1, 21KNm dropped to 19KNm; 17KNm to 14 in condition 2; and 13.5 to

11 in condition 3. Conversely, Test F yielded slight increase in values of Torque when Flow was increased from 3 minimum and 5 maximum. The value of torque rose from 20 to 21KNm; 16 to 18KNm and 11 to 13KNm, respectively.

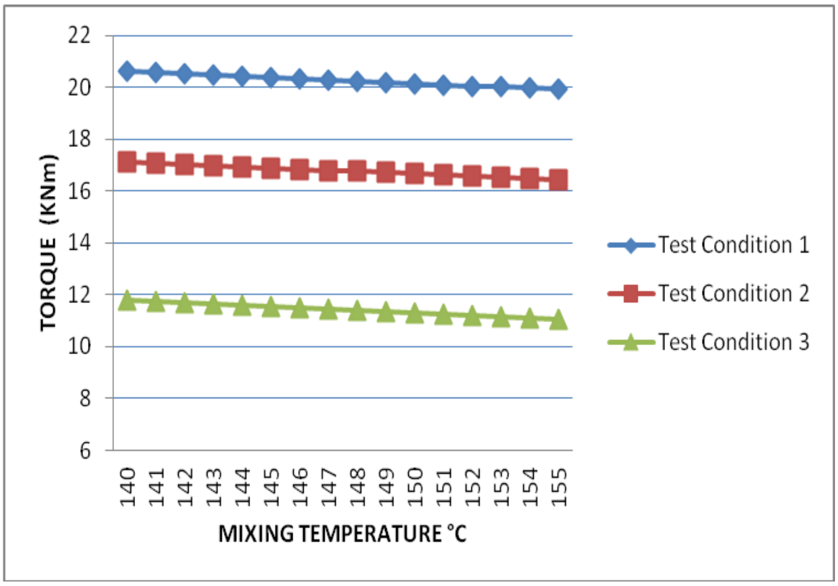

Fig. 3: Test A: effect of mixing temperature on Torque

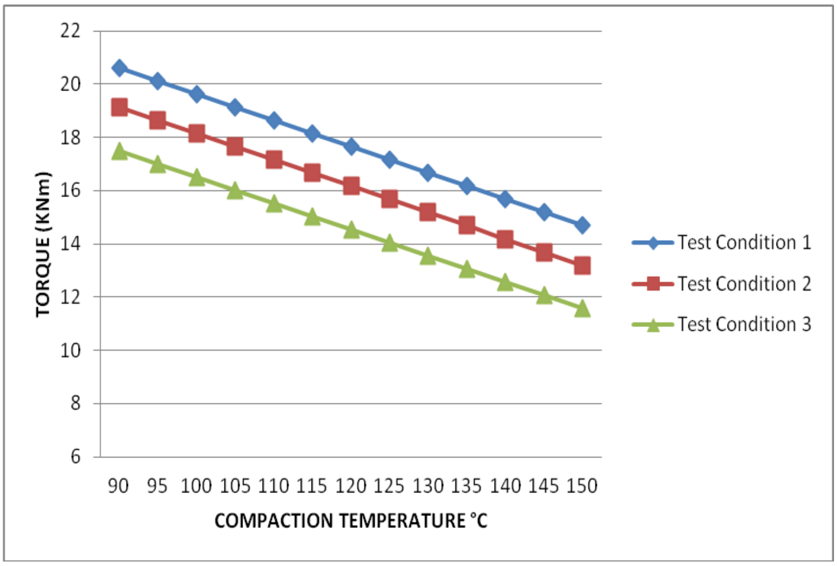

Fig. 4: Test B: effect of compaction temperature on Torque

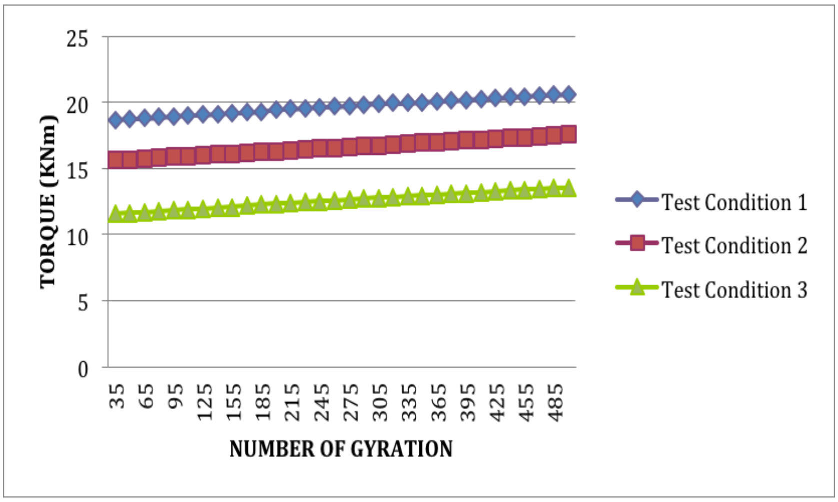

Fig. 5: Test C: effect of Gyration on Torque

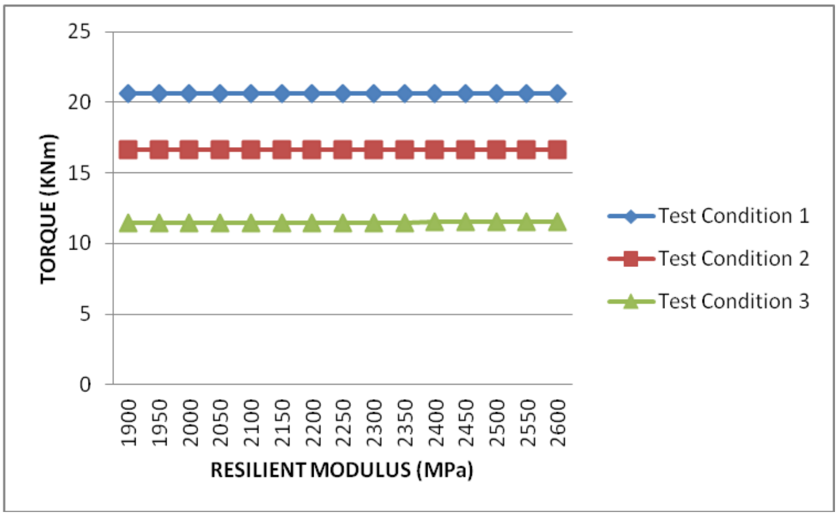

Fig. 6: Test D: effect of Resilient Modulus on Torque

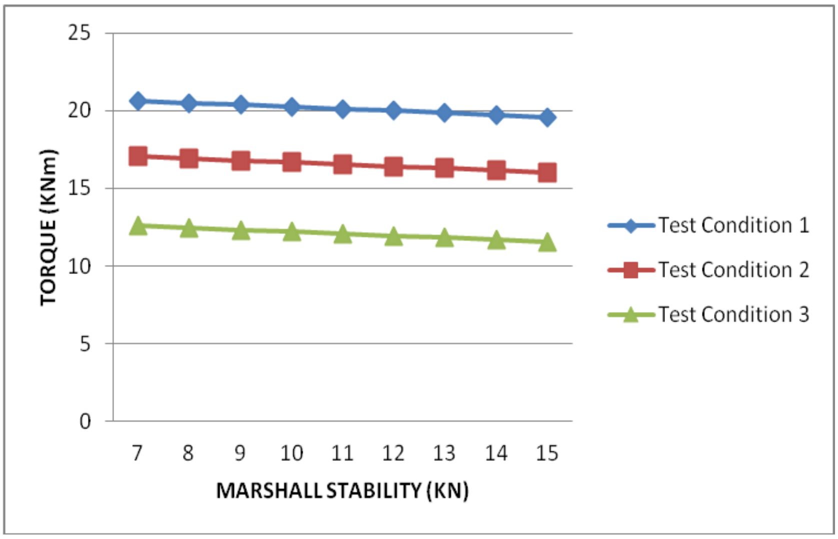

Fig. 7: Test E: effect of Marshall Stability on Torque

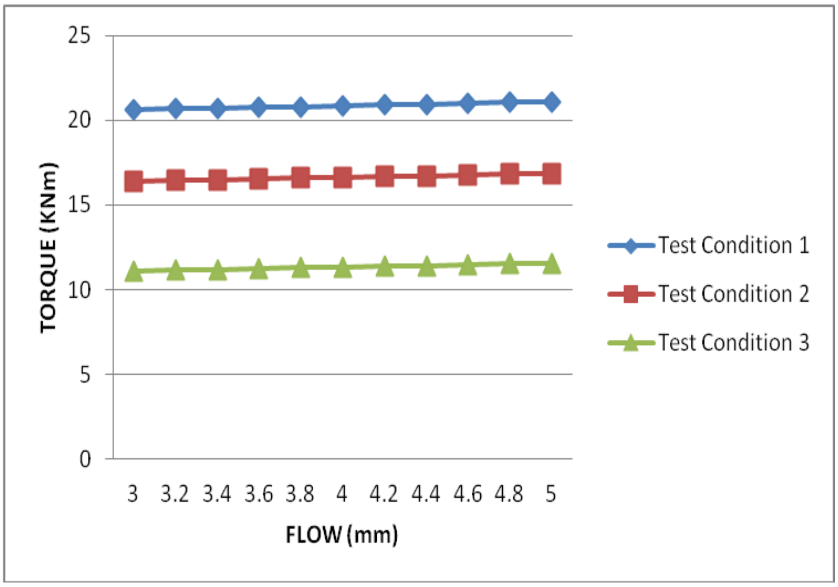

Fig. 8: Test F: effect of Flow on Torque

6 Summary and conclusion

This paper presents the statistical relationships between the Workability in Torque (dependent variable) and mixing temperature, Compaction temperature, Gyration, Resilient Modulus, Stability and Flow (independent variables). To determine the relationship, regression and sensitivity analyses were performed on the data obtained from the tests. Based on the results of the experiments and the analyses, the following conclusion can be drawn.

- As a whole, compaction is the strongest determinant of Torque.
- The value of Torque is influenced by Compaction, Mixing temperature and Gyration.
- There is no significant relationship between Torque; Resilient Modulus, Stability and Flow.
- The value of Torque drops when the mixing temperature increases and Compacting Temperature, Gyration, Resilient Modulus, Stability and Flow are controlled. Similar results are produced for Compacting temperature, Gyration, Resilient Modulus Stability with the exception of Flow, which results in an increase in the value of Torque.

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