Evaluate the Rutting Performance of Sustainable Gap-Graded Asphalt Mixes Subjected to Moisture Conditioning

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Abstract

Rutting is one of the common pavement distresses which led to lower riding comfort for road users and high maintenance costs. The aim of this study is to enhance the properties of Gap-Graded Asphalt Mixes (GGAM) by using Calcium Carbonate ($CaCo_3$) with new by-product material Treated Palm Oil Fuel Ash (TPOFA) used as a filler. The dynamic modulus (E*) Simple Performance test (SPT) was conducted at 4°C, 21°C, and 37.8°C, and used 10 Hz and 0.5 Hz loading frequencies. The same samples were used for the flow number test (F_N) at 54. 4°C to evaluate the Rutting Performance of GGAM subjected to acceleration moisture conditioning using a continuous haversine loading. Results from the study indicated that the SPT test was effective and that enhancement in the stiffness and water sensitivity resistance is achieved by adding $CaCO_3$ with TPOFA to the GGAM. Furthermore, to use new by-product material treated palm oil fuel ash in road pavement wherever available to solve the solid waste disposal problem of the environment.

Keywords: Gap-graded asphalt mixes, Rutting, SPT, Flow number, Moisture conditions.

1. Introduction

The development of modern pavement technology is needed to accelerate the significant improvement of the pavement quality of highways. Pavement surface distress such as cracks is prevalent on pavements due to the action of repeated traffic loading and cyclic environmental conditions. The rutting is mainly caused by the denseness of the asphalt mixture, while the unmodified asphalt mixture rutting is caused by the combination of compactness and push. Using new materials may help mitigate the problem by improving the properties of asphalt mixtures. Researchers in the highways have conducted extensive research on the rutting performance of asphalt pavement. In previous laboratory investigations performed by means of wheel tracking tests, the Authors found that in some cases rubberized gap-graded mixtures exhibited poor rutting resistance properties [1]. The Simple Performance Test (SPT) dynamic modulus was conducted to evaluate the rutting potential of GGAM. The SPT test's benefit is that it is repeatable and non-destructive and was conducted at a broad range of temperatures and loading frequencies applied during testing giving a better understanding of the rutting deformation occurring under different conditions. Due to the importance of the dynamic coefficient of asphalt mixtures as a performance parameter, many studies have been initiated to determine the dynamic coefficient of asphalt mixtures using simple tests or prediction models [2]. Sirin et al. (2006) obtained the anti-rutting performance of the asphalt pavement modified by SBS through the accelerated loading test of the road surface [3]. Ziari et al., (2019) proposed an asphalt mixture with waste rubber powder as a modifier and amorphous carbon powder as a filler, which has shown good fatigue and rutting resistance [4]. Walubita et al. (2019) compared and evaluated the anti-rutting performance of asphalt mixture by dynamic modulus, repeated load permanent deformation, simple shearing and Hamburg rutting [5]. Moisture susceptibility is the loss of strength in asphalt concrete mixtures due to the loss of adhesion between asphalt binder and aggregate or the weakening of the asphalt mastic in the presence of moisture and can result in rutting and fatigue distresses developing [6]. Asphalt binder ageing is one of the principal factors causing the deterioration of asphalt mixtures [7]. Many fillers obtained by processing natural or recycled materials can be used for asphalt pavements such as Portland cement, hydrated lime, and ground slag [8]. The choice of materials in road construction greatly impacts road construction technology, maintenance and cost [9]. In tropical climatic conditions, rutting and fatigue are the most common surface distress prone to occur on Malaysian roads [10,11]. This study aims to evaluate the Rutting Performance of GGAM subjected to acceleration moisture conditioning using continuous haversine loading.

2. Materials and Methods

A conventional asphalt binder grade 60/70 supplied by SHELL Company was used and its properties are shown in Table 1 [12].

Table 1: *Properties of base binder [12]*

Ageing condition	Property	values
Unaged	Penetration [1/10 mm]	63
	Softening Point [ºC]	48
	Ductility @ 25 ºC [cm]	115
	Relative Density @ 25ºC	1.03
	G*/sinδ @ 64ºC [Pa]	1621.40
Short term aged	G*/sinδ @ 64ºC [Pa]	3584.20
Long term aged	G* sinδ @ 25ºC [MPa]	4.51

The crushed granite geometrically cubical aggregate (GCA) supplied by Kuad Quarry Sdn. Bhd., Penang was used. The basic properties of the aggregate as well as the gradation used which was developed by OPUS International are shown in Tables 2–3 respectively [12].

Table 2: *Engineering Properties of GCA [12]*

Property	Test result	Test method
Coarse Aggregates Bulk Specific Gravity (g/cm3)	2.624	AASHTO T85
Absorption (%)	0.53	AASHTO T85
Fine Aggregates Bulk Specific Gravity (g/cm3)	2.575	AASHTO T84
Polished Stone Values	51.10	ASTM D3319
Flat and Elongated (%)	13.56	BS 812
Los Angeles Abrasion (%)	8.0	ASTM C131
Aggregate Crushing Value (%)	16.77	BS 812-110

Table 3: *Aggregate Gradation Developed by OPUS International [12]*

Sieve Size (mm)	Lower and Upper Limit of Percentage of Passing by Weight (%)	Gradation Used (%)
20	100	100
14	100 - 90	94
10	65-50	63
6.3	45-30	42
4.75	32-21	29
2.36	25-16	23
0.6	18-11	16
0.075	12-8	8

Combinations of 6% $CaCO_3$ with 2% (TPOFA) were used as fillers to enhance the bond between the cubical aggregate particles and asphalt binder and improve the performance of the mixture. Moreover, using TPOFA, which is the by-product of the palm oil industry, can reduce the cost of total road construction. Several procedures were conducted in Concrete Lab in USM to obtain the TPOFA as shown in Plate 1.

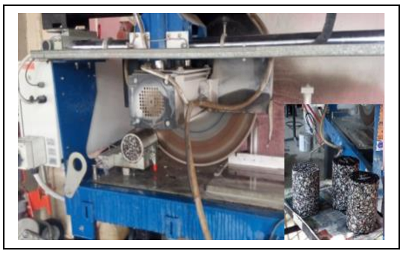
(a) Raw POFA *(b) Grind POFA* *(c) TPOFA*

Plate 1: *Obtain the TPOFA*

1. Sample Preparation and Test Methods

The SPT was used to determine the strains and displacements of layered pavement under different temperatures and loading conditions according to AASHTO TP79 (AASHTO, 2013) procedures [13]. The test is a fully integrated device that is comprised of an environmental chamber, hydraulic actuator and pump, refrigeration and heating unit and data acquisition system as presented in Plate 2(a). Approximately 6350 g of batch weight was needed to prepare cylindrical samples 150 mm in diameter and 165 mm in height that was compacted by the Superpave Gyratory Compactor (SGC) with 7% air voids. After compaction and cooling at room temperature for 24 hours, the specimens were cored and trimmed from the centre of the gyratory compacted specimen as shown in Plate 2(b). Both ends of the specimen were sawed by approximately 5 mm to achieve the final dimensions of the specimen of 100 mm in diameter and 150 mm in height. The LVDT sensors were then fixed to measure the deformation when the sample had been subjected to stress as shown in Plate 2(c).


(a) SPT Device


(b) Cored and Trimmed


(c) Fixed the LVDT

Plate 2: *Simple Performance Test*

The stress versus strain relationship of an asphalt mixture under a continuous haversine loading is defined by its complex dynamic modulus (E*). The E* test was conducted under a series of temperatures (4.4, 21.1, 37.8 and 54.4 °C) and loading frequencies (0.1, 1, 5, 10 and 25 Hz). Before testing, samples were conditioned for 4 hours in a temperature-controlled chamber at the test temperature. The test began with the highest loading frequency of 200 cycles at 25 Hz with the lowest test temperature 4.4°C. A 60 seconds rest period was applied between each frequency to allow specimen recovery before applying the next lower-frequency loading. The test was conducted under a stress mode with a uniaxially applied haversine load, and the parameters employed in this test are shown in Table 4. This test is categorised as a non-destructive test. Whereby, the same samples were used for the flow number test to quantify the rutting potential of asphalt mixture at 54.4°C. The flow number is defined as the number of load pulses where the minimum rate of change in permanent strain occurs during the repeated load test. To simplify the identification of the GGAM, the samples are designated first by their mix type, followed by the main filler and secondary filler as GGCP.

Table 4: *Parameters for the Simple Performance Test*

Parameters	Values					
Test Temperature	4.4°C, 21.1°C, 37.8°C and 54.4°C					
Test Condition	Dry and Wet					
Loading Frequencies (Hz)	25	10	5	1.0	0.5	0.1
No. of Cycle	200	200	100	20	15	15
Sample Diameter	100 mm					
Sample Height	150 mm					

2. Samples Conditioning

After mixing, the trays were kept in a draft oven at 135°C for 4 hours to simulate short-term ageing (STA) according to AASHTO R30 (AASHTO, 2006) procedures [14]. The samples were then subjected to ultraviolet radiation (UV) at 85°C for five days to simulate long-term ageing (LTA) that represents 7 to 10 years of the service life [15]. Likewise, samples were subjected to moisture conditioning parameters to simulate field conditions in the laboratory. Each sample was partially saturated in distilled water using a desiccator under a 635mm-Hg vacuum for 30 minutes at room temperature to achieve 50% to 70% saturation. Different methods of moisture conditioning were applied to the samples as presented:

(a) Unconditioned or controlled sample (dry) was kept at room temperature.

(b) Vacuum saturation in distilled water for 30 minutes at room temperature and then submerged in distilled water for 48 hours at 25°C.

(c) Vacuum saturation in distilled water for 30 minutes at room temperature and then freeze in a deep freezer for 24 hours at -6°C.

(d) Vacuum saturation in distilled water for 30 minutes at room temperature and then soaked in distilled water for 24 hours at 60°C.

(e) Vacuum saturation in distilled water for 30 minutes at room temperature and then freezing in a deep freezer for 24 hours at -6°C and then thawing in distilled water for 24 hours at 60°C (freezing-thawing).

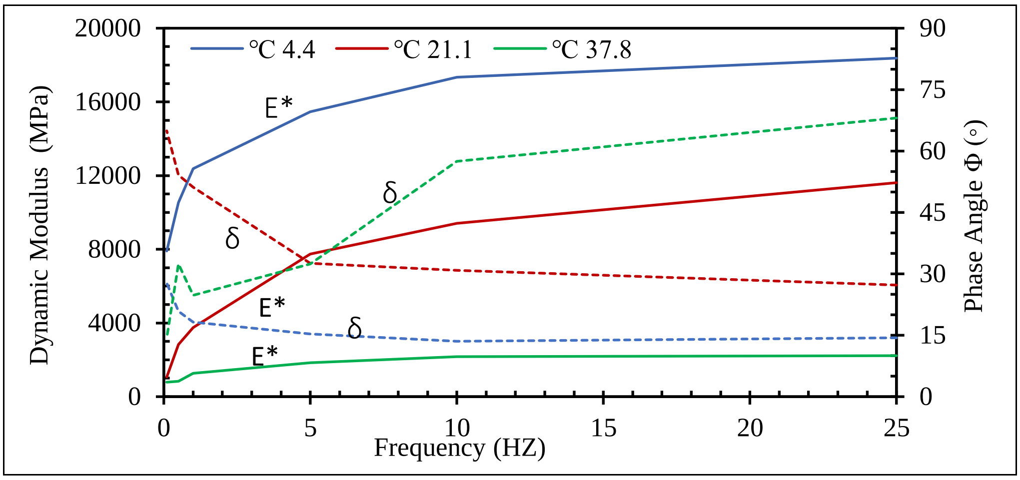
3. Results and Discussion

1. Combined Effects of Ageing and Moisture on Rutting Using SPT

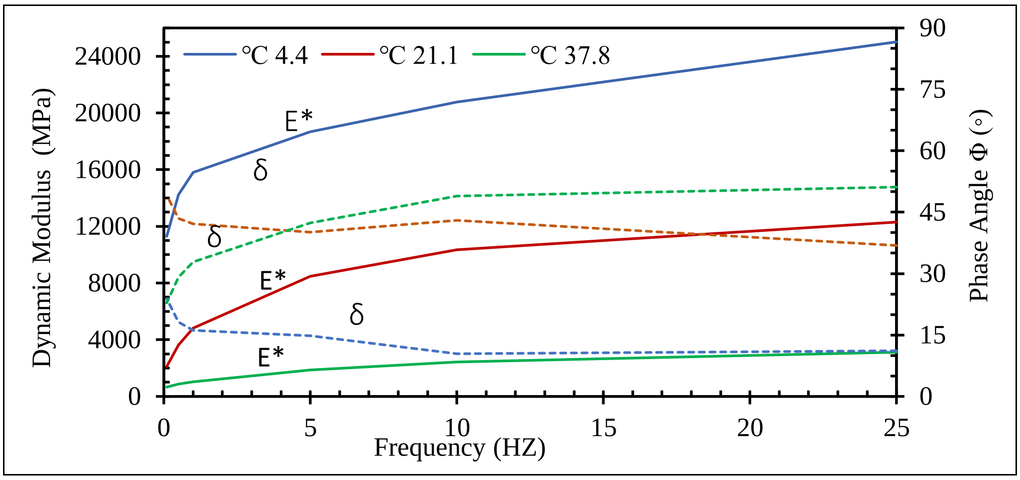
Figure 1 presents the mean dynamic modulus (E*) and phase angle (δ◦) GGCP subjected to different ageing conditions. Referring to the results, the mixture exhibits higher moduli values at lower temperatures (4.4 °C), while the trend is reversed at elevated temperatures (21.1 and 37.8 °C). Furthermore, the increase in dynamic modulus (E*) when subjecting the mixture to different ageing conditions are desirable for better resistance to permanent deformation. Also, lower E* at low temperatures are desirable for the better resistance to thermal cracking. The ageing has a significant effect on the GGCP as indicated by the higher calculated modulus ratio as shown in Table 5.

Table 5: *Dynamic Modulus Ratios of GGCP*

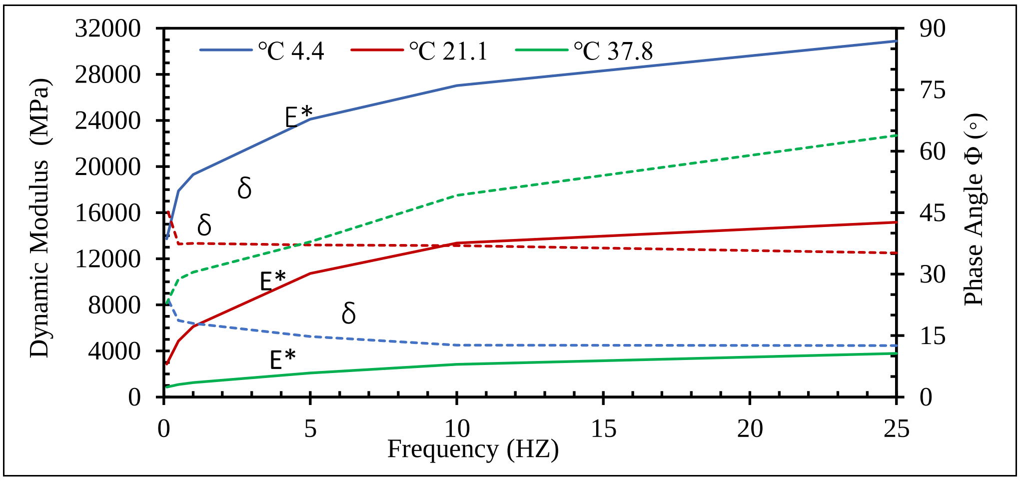
Freq. (HZ)	Ratio = E* (STA) / E* (Un-aged)		Ratio = E* (LTA) / E* (Un-aged)	
	4°C	37.8°C	4°C	37.8°C
10	1.20	1.12	1.56	1.31
0.5	1.35	1.03	1.70	1.29



(a) Un-Aged



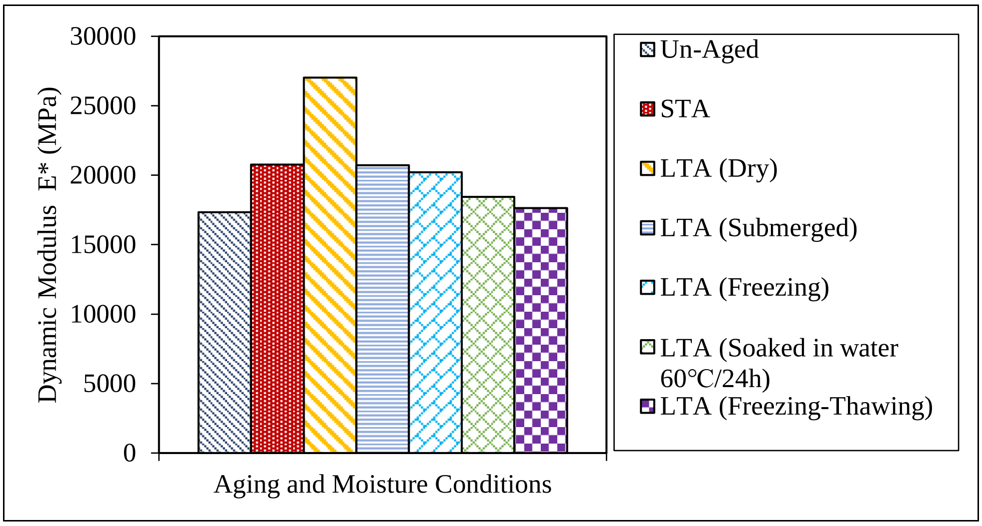
(b) STA



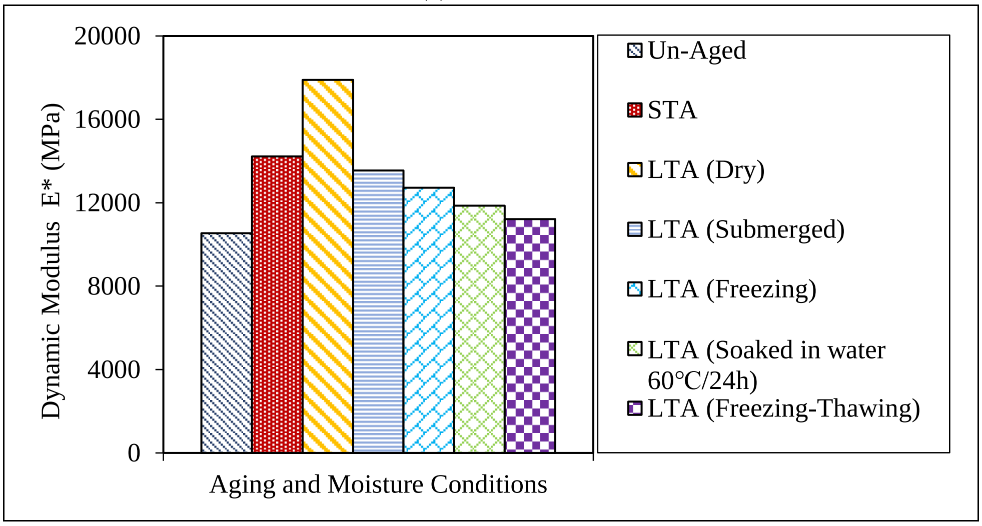
(c) LTA

Figure 1: *Effects of Ageing on E* and (Φ ◦) for GGCP*

The E* ratios of GGCP were greater than 1.0 at the higher temperatures regardless of the test frequencies, a desirable characteristic can be observed especially for the rutting resistance and for all types of loading conditions. The temperature and frequency conditions used for the comparison are 4.4 °C for low temperatures, and 37.8 °C for higher temperatures. The frequency selected is 10 Hz, representing the typical vehicle speed for an arterial street and 0.5 Hz representing much slower vehicle speed for the case of parking lots or at approaches to intersections. On the other hand, the relationship between the dynamic modulus of GGCP subjected to several ageing and moisture conditioning is illustrated in Figures 2 and 3. Each figure presents the summary comparison of E* for selected values of test temperatures (4.4 and 37.8 °C) and loading frequencies (10 Hz and 0.5 Hz).

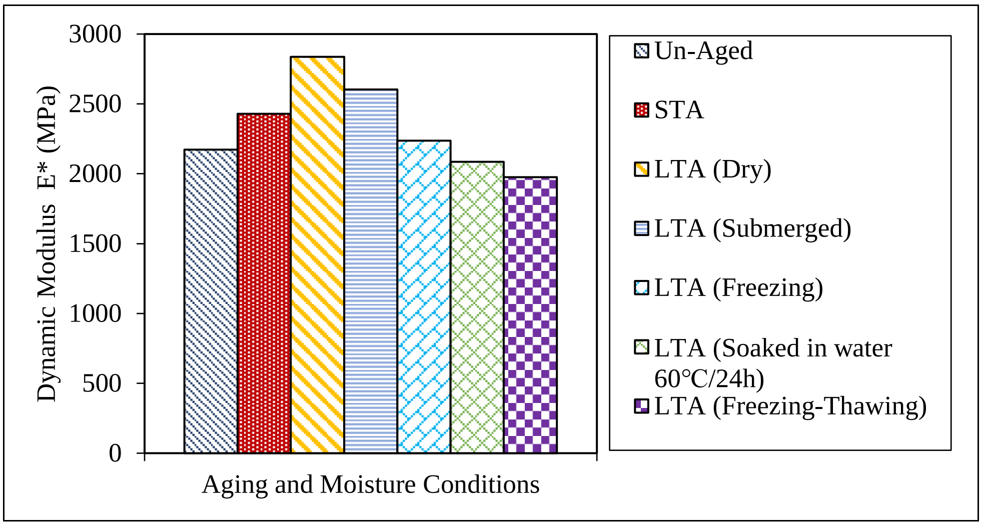


(a) At 10 Hz

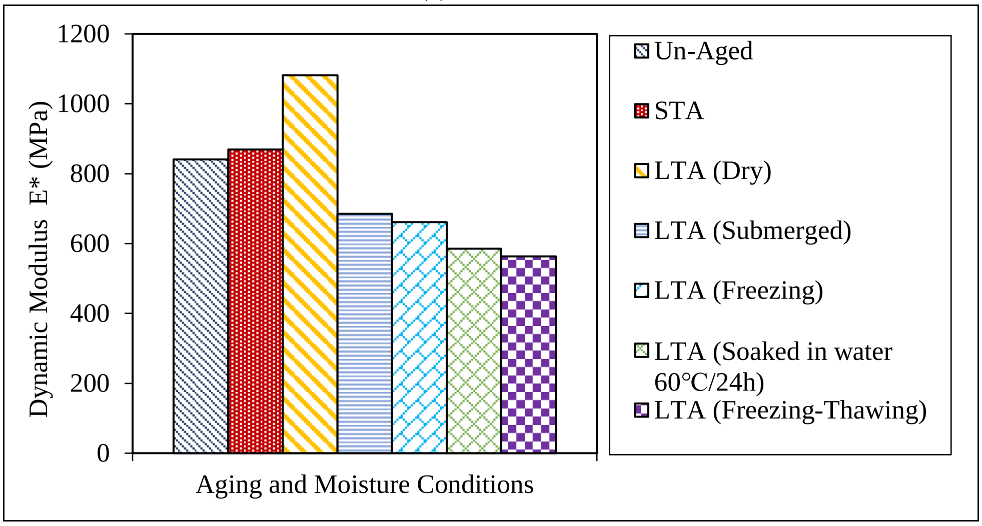


(b) At 0.5 Hz

Figure 2: ***Comparison of Measured Dynamic Modulus at 4.4 °C for GGCP***



(a) At 10 Hz



(b) At 0.5 Hz

Figure 3: ***Comparison of Measured Dynamic Modulus at 37.8 °C for GGCP***

The effects of the test temperature on E* show that the stiffness of the mixture responds to variations in temperature. At constant frequency, E* values are higher at a lower test temperature and start to decrease as the test temperature increases. The variations in E* results are also observed to be less at a higher temperature. As the asphalt binder softens, the stiffness of the mixture reduces, and the mixture performance is largely dictated by the aggregate matrix within the mixture. The rutting characteristics of GGCP subjected to ageing and various moisture conditioning methods were assessed from the dynamic modulus test performed at elevated temperatures. A relationship has been established with a hypothesis that the stiffness of the mixture from the dynamic modulus test can be used to evaluate rutting. The temperature chosen was at 37.8°C and loading frequencies were at 10 Hz and 0.5 Hz because rutting is expected to occur at higher temperatures and lower loading times. Figures 4 show the correlation plots for the rut stiffness factor at 37.8 °C against the rut depth for GGCP mixtures. In general, there exists a strong correlation is observed for GGCP tested between rut stiffness factor and rut depth at a higher loading frequency.

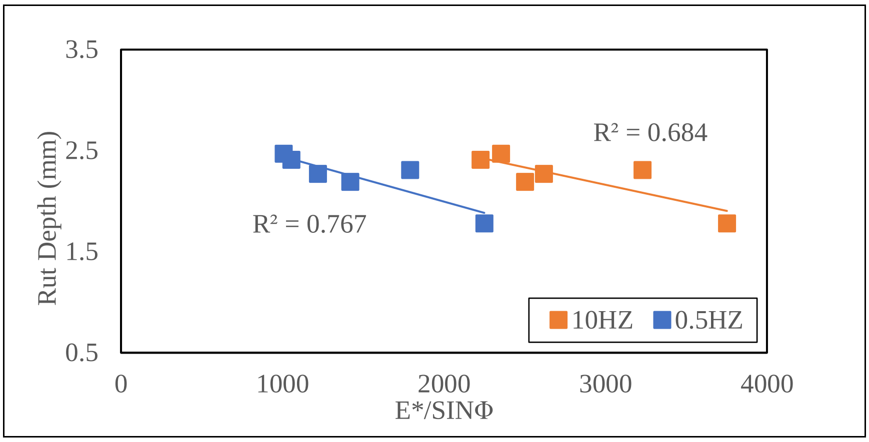


Figure 4: Rut Depth Versus Rutting Factor at 37.8°C for GGCP

The Flow Number test (F_N) was conducted for GGCP mixes. All tests were carried out on 100 mm in diameter and 150 mm in height cylindrical specimens. Plate 3 shows the actual specimen setup for the F_N test. Both specimen ends were lubricated to warranty frictionless surface conditions. All tests were conducted within an environmentally controlled chamber throughout the testing sequence.

(a) Specimen Before Test (b) Specimen After Test

Plate 3: Actual Specimen Set-Up for F_N Test

Figure 5 presents the results of the unconfined F_N test. Flow numbers are varied significantly depending on their ageing and moisture conditioning methods. The results show that the GGCP has higher F_N indicated to less susceptibility to permanent deformation. The LTA sample with a dry moisture conditioning method exhibited a higher flow number than others moisture conditioning methods. Tables 6 show the results of the statistical analysis of dynamic modulus test results at a 95% confidence level (α = 0.05) indicating that a higher test temperature and the combined effects of ageing and moisture condition had a significant influence on mixture stiffness properties.

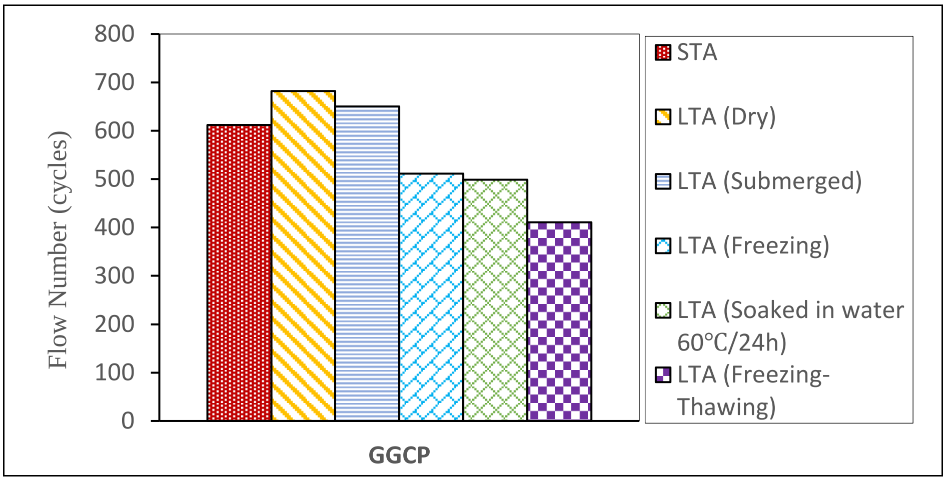


Figure 5: ***Effects of Ageing and Moisture Conditioning Methods on F_N***

Table 6: *ANOVA Analysis of the dynamic modulus (E*)*

Sample	Source	Mean Square	Df	F	p-value	Sig.
Un-Aged	TT[a]	7.1E+07	6	449.572	<0.001	Yes
	CP[b]	1.2E+06	4	7.628	<0.001	Yes
	TT * CP	1.96E+08	24	1246.812	<0.001	Yes
	Error	1.57E+05	70			
	Total		105			
	Corrected Total		104			
		R Squared = 0.999 (Adjusted R Squared = 0.999)				
Sample	Source	Mean Square	Df	F	p-value	Sig.
STA	TT[a]	1.55E+09	6	166.51	<0.001	Yes
	CP[b]	3.40E+08	4	1901.25	<0.001	Yes
	TT * CP	5.85E+05	24	3.26	<0.001	Yes
	Error	8.80E+08	70	4909.16		
	Total		105			
	Corrected Total		104			
		R Squared = 0.999 (Adjusted R Squared = 0.999)				
Sample	Source	Mean Square	Df	F	p-value	Sig.
LTA	TT[a]	9.55E+13	6	94.70	<0.001	Yes
	CP[b]	4.82E+13	4	478.09	<0.001	Yes
	TT * CP	1.3E+13	24	12.88	<0.001	Yes
	Error	1.0E+12	70			
	Total		105			
	Corrected Total		104			
		R Squared =0.980 (Adjusted R Squared = 0.970)				

(a) TT= Test Temperature, (b) Asphalt Mastics Containing CP

Conclusions

The results indicated that the SPT test was adequate and that enhancement in the stiffness and characterized lab-measured water sensitivity resistance for GGAM mixtures. The SPT test was an effective tool for quantifying rutting potential with a better simulation of typical field behavior. The results of this testing can be considering the effects of unconditioned versus conditioned dynamic modulus values and their respective impacts on pavement performance in predicting pavement distresses. Good correlations of unconfined FN, with LTA sample with a dry moisture conditioning method. Furthermore, the results showed that the GGCP exhibited the highest resistance to permanent deformation. This observation was also evident from the statistical analysis. Thus, it can be concluded that there are more advantages to using GGCP in road pavement.

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