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Investigation of the Fatigue Performance of Sustainable Asphalt Pavement

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ABSTRACT

Selecting suitable materials for sustainable asphalt pavement construction can be a challenging task, particularly due to the significant issue of fatigue damage in flexible pavement. The fatigue performance of gap-graded asphalt mixes (GGCP) was assessed through four-point bending beam fatigue testing, examining the impact of incorporating 6% Calcium carbonate (CaCO3) and 2% treated palm oil fuel ash (TPOFA) on fatigue cracking. The testing was conducted at various stress levels (800, 1000, and 1200 kPa) and a temperature of 5°C. Additionally, the asphalt mixtures underwent acceleration ageing and moisture conditions, which varied during the study. The experimental findings indicated that higher stress levels resulted in a decrease in the fatigue life of asphalt mixtures due to ageing effects. Moreover, moisture conditioning was found to diminish the fatigue life of the asphalt mixture. Comparatively, the fatigue model incorporating a plateau value and fatigue life demonstrated greater accuracy when compared to previous regression models.

دراسة أداء الكلال للرصف الأسفلتي المستدام

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الكلمات المفتاحية:
الاستدامة.
التقادم.
الكلال
رماد الوقود.
ظروف الرطوبة.

الملخص

يمكن أن يكون اختيار المواد المناسبة لبناء الرصف الإسفلتي المستدام مهمة صعبة، خاصة بسبب المشكلة الكبيرة المتمثلة في فشل الكلال في الرصف المرن. تم تقييم أداء الكلال لخلطة الأسفلت ذات الفجوة المتدرجة (GGCP) من خلال اختبار كلال شعاع الانحناء رباعي النقاط، وفحص تأثير دمج 6% من كربونات الكالسيوم (CaCO3) و2% من رماد وقود زيت النخيل المعالج (TPOFA) على فشل الكلال. تم إجراء الاختبار عند مستويات إجهاد مختلفة (800، 1000، 1200 كيلو باسكال) ودرجة حرارة 5 درجات مئوية. بالإضافة إلى ذلك، خضعت الخلطات الإسفلتية لظروف شيخوخة ورطوبة متسارعة، والتي تباينت خلال الدراسة. أشارت النتائج التجريبية إلى أن ارتفاع مستويات الإجهاد أدى إلى انخفاض في عمر الكلال للخلطات الإسفلتية بسبب تأثيرات التقادم. علاوة على ذلك، وجد أن ظروف الرطوبة تقلل من عمر الكلال للخلطة الإسفلتي. نسبيا، أظهر نموذج الكلال المعتمد على قيمة الهضبة وعمر الكلال أكثر دقة من نماذج الانحدار الأخرى.

Introduction

TheFatigue cracking poses a significant challenge in maintaining the longevity of flexible pavements. The fatigue life of an asphalt pavement is greatly influenced by environmental factors and the increasing number of repetitions from heavy axle loads. To mitigate premature cracking and ensure optimal pavement performance, several factors must be carefully considered during pavement planning and material selection. These factors include temperature variations, loading rates, pavement age, and the specific type of testing conducted [1, 2]. Fatigue failure in flexible pavement occurs when the asphalt-bound layer undergoes flexing and develops cracks. In recent years, nanotechnology has played a significant role in improving the thermomechanical properties of bitumen and enhancing its resistance to fatigue cracking and rutting in flexible pavement [3]. Additionally, substantial research efforts have been devoted to developing models for predicting fatigue failure in bitumen materials [4]. These models utilize three distinct criteria: stiffness reduction (Nf50), dissipated

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energy ratio (DER), and the ratio of dissipated energy change (RDEC) to calculate the fatigue life. Statistical analysis indicates that these methods yield comparable results for fatigue and healing tests [5]. Various testing methods can be developed using the same analysis technique, such as the ASTM D7460 cyclic haversine test. AASHTO T-321 specifies that the specimen should be returned to its initial position after each load pulse through continuous sinusoidal loading within a frequency range of 5 to 10 Hz [6]. When nanomaterials like fly ash and silica fumes are added to asphalt binder, they can reduce the stiffness modulus, with the reduction being more pronounced at higher quantities of fly ash [7]. Stone mastic asphalt, on the other hand, has shown potential for enhancing fatigue life by mitigating structural distress caused by increased traffic loading. It strengthens the resistance to cracking and permanent deformation, particularly at higher stress levels [8]. In Malaysia, the use of unconventional filler materials in Gap-graded Asphalt Mixtures (GGAM) is still in the experimental phase. Palm Oil Fuel Ash (POFA) has shown promising potential as a filler material in asphalt mixtures, although its usage has been predominantly explored in concrete materials rather than pavement materials [9]. Previous studies have demonstrated that incorporating 5% POFA as a filler in asphalt mixes can enhance their properties [10]. It has been observed that a strong linear relationship exists between the fatigue life of asphalt mixtures and the requirement for 50% stiffness reduction, as reported by Cheng et al. (2022) [11]. However, for the dissipated energy criterion, fatigue failure occurs with a stiffness reduction of only 30% instead of 50%. The choice of fatigue failure criteria is also influenced by the type of asphalt mixture. Polymer-modified asphalt mixtures, for instance, may not meet the 50% stiffness reduction criterion due to difficulties in achieving such a level of reduction even with high loading cycles, as highlighted by Huang et al. (2016) [12]. In a study by Ameri et al. (2017), a strong correlation was found between the fatigue lives of different asphalt mixtures using the dissipated energy technique [13]. The primary objectives of this study are to investigate the impact of incorporating 6% CaCO3 and 2% TPOFA on the fatigue life of GGCP, as well as to assess the combined effects of stress levels, long-term ageing, and moisture conditioning on the fatigue response of GGCP.

Materials and Methods

Asphalt Binder

Table 1 summaries properties of the base binder [13].

Table 1: Properties of Base Binder [13].

Ageing Condition	Property	Values
Un-aged	Penetration	63
	Softening Point (ºC)	48
	Ductility at 25ºC (cm)	115
	Relative Density at 25ºC	1.03
	G*/sinδ at 64ºC (Pa)	1621.40
Short-Term Aged	G*/sinδ at 64ºC (Pa)	3584.20
Long-Term Aged	G* sinδ at 25ºC (MPa)	4.51

Coarse and Fine Aggregates

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 [14].

Table 2: Engineering Properties of GCA [14].

Property	Test result	Test method
Bulk Specific Gravity (g/cm3)	2.624	AASHTO T85
Absorption (%)	0.53	AASHTO T85
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 [14]

	Lower and Upper Limit 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

Filler

Two filler combinations, 6% $CaCO_3$ and 2% TPOFA, were utilized in the study. The specific gravity of these fillers was determined following the guidelines outlined in AASHTO T 133, and the corresponding results are presented in Table 4. To acquire the TPOFA, various procedures were carried out in the Concrete Lab at USM, as illustrated in Figure 1.

Table 4: Specific Gravity of Fillers [14]

Filler Type	Result (g/cm^3)
$CaCO_3$	2.85
TPOFA	2.56
OPC	3.14

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

Figure 1: Obtain the TPOFA [12]

Methodology of Study

Asphalt Mixture Preparation

The Shear Box Compactor (SBC) was developed in order to simulate real construction compaction in the field. As shown in Figure 2, a uniform block of asphaltic concrete was produced utilizing the SBC for the flexural beam fatigue test (4PBT). The compaction parameters are shown in Table 5.

Figure 2: Shear Box Compactor Device

Table 5: Compaction Parameters for Beam Fatigue Test

Test	Weight (kg)	Dimensions (mm)			No. of Gyration	Air Voids (%)
		Length	Width	Height		
4PBT	26.6	450	150	170	40	7±0.5

The autosaw was also used for accurate cutting of beams for the four-point bending beam test. As shown in Figure 3(a), the block samples were trimmed from all sides to achieve a smooth outer surface. Then, the block was cut into six beams. The final specimen geometry (50W*57H*400L) mm is shown in Figure 3(b).

a) Block Samples Were Trimmed b) Specimens Geometry

Figure 3: Beam Samples were Cut and Trimmed

Ageing Procedures

Following the AASHTO R30 guidelines, the trays containing the samples were mixed and placed in a draft oven at 135°C for 4 hours to simulate short-term ageing (STA) [15].

Subsequently, the samples underwent exposure to UV light (UV) at 85°C for five days to simulate long-term ageing (LTA), which is equivalent to approximately 7 to 10 years of service life [14].

Moisture Conditioning

In the flexural beam fatigue test, each beam specimen underwent additional partial saturation in distilled water using an accelerated laboratory vacuum saturator. This process lasted for 30 minutes at room temperature. To facilitate this procedure, a specially designed vacuum chamber was constructed at the School of Materials and Mineral Resources Engineering, USM, as depicted in Figure 4(a). The vacuum chamber allowed for the treatment of two samples simultaneously, as shown in Figure 4(b). It was constructed from stainless steel and had dimensions of 120 x 100 x 420 mm. The apparatus consisted of a vacuum pump, gauge, valve, and six anchors to securely seal the lid. Various moisture conditioning techniques were employed,

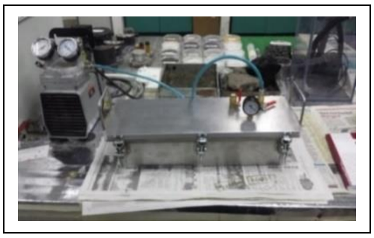
(a) A dry, controlled sample was left at room temperature.

(b) Immersion in distilled water for 48 hours at 25°C after 30 minutes of vacuum saturation in distilled water at ambient temperature.

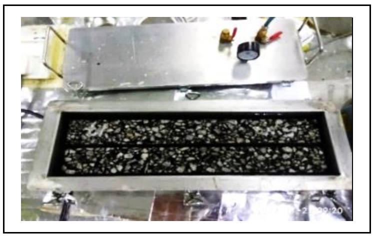
(c) Vacuum saturation in distilled water for 30 minutes at ambient temperature, followed by 24 hours of freezing at -6°C in a deep freezer.

(d) Soaking in distilled water for 24 hours at 60°C after vacuum saturation in distilled water for 30 minutes at room temperature.

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



(a) Fabricated Vacuum Device



(b) Placement of Beam Samples

Figure 4: Fabricated Vacuum Device for Beam Conditioning

Flexural Beam Fatigue

The flexural beam fatigue testing is also known as four-point bending test (4PBT) as shown in Figure 5. The test was carried out according to the AASHTO T-321 (AASHTO, 2010) procedures [16].

a) Test Setup b) Sample Fixed with LVDT

Figure 5: Four-Point Bending Test

The beam specimen was subjected to two symmetrical stresses on the testing apparatus employed in this study. For 4PBT, the specimen's dimensions were 50 x 57 x 400 mm. Table 6 lists the testing schedule. The dissipated energy of the outcomes was examined.

Table 6: Test Program of 4PB Fatigue Test

Type of Mixture	Temp. (ºC)	Tensile Stress levels (kPa)	Frequency (Hz)	Conditions	Number of Samples
GGCP	5	800 1000 1200	10	Unaged	6
				LTA	30

Results and Discussion

Impact of Stress Level on Dissipated Energy

Table 7 illustrates the typical response of the GGCP dissipated energy under various ageing and moisture techniques. Regardless of the training techniques, the amount of energy lost rises as the level of stress increases. It might be explained by the possibility that increased loading accumulation will cause early cracking or discomfort.

Table 7: Impact of Stress Level on Dissipated Energy

Mixture	Conditions	Dissipated energy MJ/m^3		
		800*****	1000*****	1200*****
GGCP	Un-Aged	0.091	0.139	0.196
	LTA (Dry)	0.095	0.142	0.215
	LTA (Submerged)	0.091	0.137	0.201
	LTA (Freezing)	0.086	0.135	0.184
	LTA (Soaked in water 60°C/24h)	0.089	0.136	0.212
	LTA (Freezing Thawing)	0.092	0.138	0.220

(*****): Stress Level

On the other side, such behaviour can result from the asphalt binder's increased viscosity and stiffness at a low testing temperature (5°C).

Low temperatures have little of an impact on the mixture's robust quality, and the viscous-elastic reaction of the asphalt is negligible. Lower fatigue life and higher dissipated energy have been the results of the mixture being damaged by moisture.

Figure 1 summarises the effects of different stress levels on the dissipated energy; it demonstrates that for the GGCP subjected to LTA at implemented testing temperatures of 5°C, as the stress level increases, the fatigue life reduces and the dissipated energy increases.

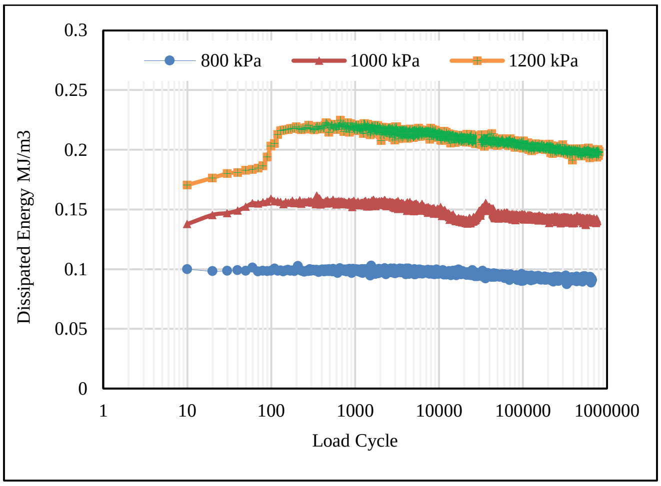


Fig 1: Impact of Stress Level on Dissipated Energy of GGCP

During the initial stage of loading, the relationship between logarithmic load cycles and dissipated energy exhibits a straight-line trend, with minimal variation in the dissipated energy. However, after approximately 10 to 100 loading cycles, nonlinearity becomes apparent in the trend line. This nonlinearity indicates a change in behavior and is associated with the initiation of possible fatigue cracks in the binder [16]. This point is often referred to as the crack initiation point. Beyond this point, the variation in dissipated energy becomes more significant, and this variation is influenced by the three stress levels considered in the analysis.

Impact of Stress Level on Cumulative Dissipated Energy

The concept of the ratio of dissipated energy change is developed to characterize fatigue damage in asphalt mixtures. The cumulative dissipated energy (CDE) initially exhibits an unstable period but eventually reaches a plateau, followed by a sharp increase, indicating a significant fatigue failure. This behavior is often represented by the cumulative dissipated energy versus loading cycles damage curve. The consistent value of CDE during the plateau stage is crucial for assessing the fatigue behavior of Hot Mix Asphalt (HMA) because it represents the period when a relatively constant proportion of input energy is converted to damage.

To determine the best-fit equation for the data, including the failure point and cumulative dissipated energy (CDE), a modified curve-fitting approach is employed. Typically, a power law relationship is used to achieve a strong curve fit, characterized by a high R2 value and an accurate curve trend [17].

Equation 1 describes the relationship between the total energy lost and the fatigue life [18].

$$W_f = A(N_f)^z \qquad (1)$$

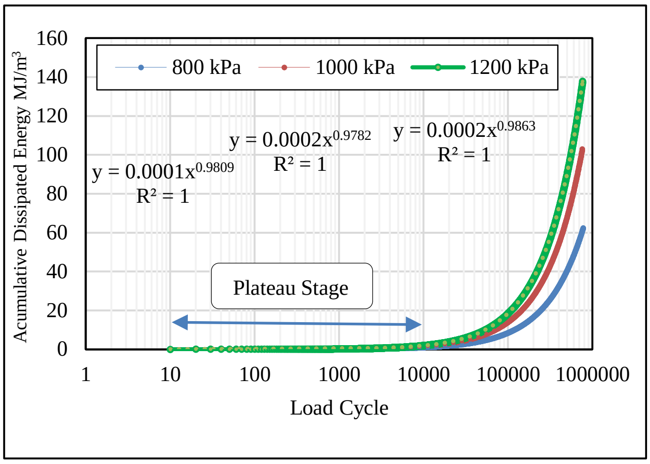
Where:

W_f = The cumulative dissipated energy

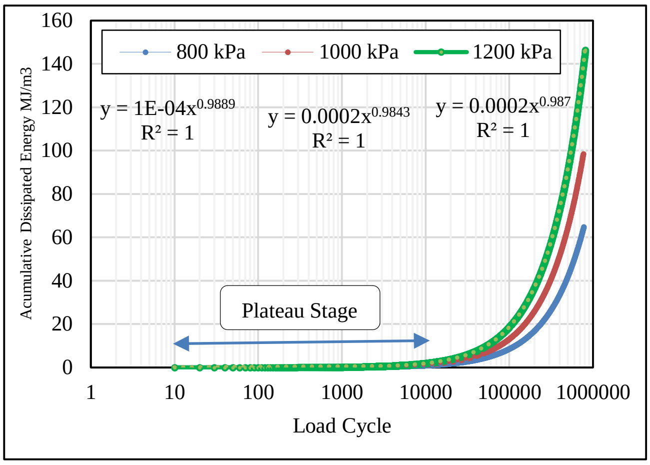
N_f = The load cycle index when fatigue failure

A, Z = The obtained test model parameters

Figures 2 illustrate the behaviour of GGCP subjected to LTA at testing temperature, approximately 5°C. The impact of stress level on the fatigue life and accumulative dissipated energy is very well pronounced.



a) un-aged



b) Long-Term Ageing

Fig 2: Impact of Stress Level on CDE of GGCP

After 10,000 load repetitions, the relationship's trend shifted from being linear to non-linear, and the variety in cumulative lost energy became more noticeable. The fatigue life of a dense mixture is determined by the number of cycles required to dissipate a cumulative energy equivalent to 1x108 J/m^3.

However, when comparing different stress levels, it is observed that the effect of stress level on fatigue life under 1200 kPa shows an extreme value of cumulative dissipated energy at 1.3x108 J/m^3 [19]. The data presented in Table 8 indicates that an increase in stress levels has a significant impact on fatigue. It is evident that regardless of the stress level, fatigue life decreases as the cumulative dissipated energy increases. Furthermore, when comparing the fatigue life of GGCP under maximum tensile stress levels (800, 1000, and 1200 kPa) to unaged samples evaluated at 5°C, a reduction of 26.9%, 15.5%, and 26.2% is observed, respectively. This reduction in fatigue life can be attributed to the combination of hardening and fracturing, although the specimen did not show signs of failure until the very end of the test.

Table 8: The Relationship between CDE and Fatigue Life

Condition	Stress Level (kPa)	GGCP			
		N_f	A	z	W_f (MJ/m^3)
Un-aged	800	78000	0.0001	0.981	6.29
	1000	58000	0.0002	0.978	6.85
	1200	42000	0.0002	0.986	7.26
LTA (Dry)	800	57000	0.0001	0.989	5.05
	1000	49000	0.0001	0.984	5.17
	1200	31000	0.0002	0.987	5.42

Figure 3 depicts the impact of stress levels on the fatigue life of unaged GGCP. It is evident that as the maximum tensile stress level increases, the fatigue life significantly decreases. Notably, GGCP exhibits a 31% longer fatigue life at 1200 kPa compared to lower stress levels. When considering prolonged ageing, the fatigue levels decrease with higher stress levels. These findings align with the conclusions of Sarsam's study from 2016 [20].

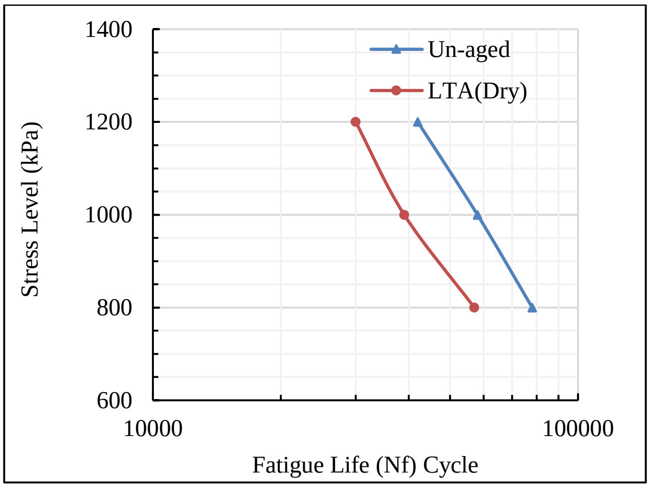


Fig 3: The Relationship Between Stress Level and Fatigue Life for GGCP

Conclusion

The study findings demonstrate that incorporating a combination of 6% CaCO3 and 2% TPOFA as green filler enhances the performance of GGCP. The mixture exhibits excellent performance in the fatigue resistance test, as indicated by the results from all samples. A power model proved to be the most suitable in describing the relationship between applied stress and the number of fatigue load cycles before failure. Additionally, it was observed that GGCP beams subjected to long-term ageing (LTA) have a shorter fatigue life compared to unaged beams. A lower rigidity modulus is associated with a longer fatigue life. Moisture damage also affects the stiffness of the mix, as samples subjected to ageing and various moisture conditioning experienced rapid stiffness loss during initial load repetitions. The utilization of CaCO3 and TPOFA, whenever available, is recommended as a solution to the environmental issue of solid waste disposal. In future studies, the cumulative dissipated energy approach is likely to be employed to enhance the mechanistic-empirical (ME) pavement design process. By incorporating these advantages, they can be fully integrated into the design of pavement construction.

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