Buton asphalt is an alternative material for road surfacing from Indonesia. Cold paving hot mix asbuton (CPHMA) is one of the buton asphalt technologies that has great potential as an alternative to conventional asphalt pavement; however, it still possesses several limitations that remain the focus of ongoing scientific research.

The problem solved by this study is the improvement in CPHMA performance as the storage duration of the mixture increases, which is a controlling factor in conventional CPHMA products.

The results show that the use of candlenut oil modifier improves the CPHMA performance. The study is focused on the CPHMA performance with variations in the storage duration of the ready-mix.

This study shows that the highest resistance from fatigue and creep tests was obtained at a storage duration of 21 days. There was an anomaly in the stiffness modulus test, where the highest resistance was obtained from the 7-day sample. However, this value is somewhat questionable because the two samples used yielded a high standard deviation. Therefore, if to disregard the results from this sample, the sample with the highest resistance is the same as in the fatigue and creep tests.

The most distinctive feature of these results is the discovery of increased CPHMA resistance to dynamic loads that increases with storage duration. This contradicts the CPHMA product manufactured by the factory.

Regarding the scope of practical use, the results obtained in this study indicate that CPHMA modified with candlenut oil is very suitable for low-volume pavement applications, especially in areas that do not have an Asphalt Mixing Plant. Certain conditions of use, field application is ideally carried out during dry weather to effectively facilitate the evaporation of volatile bio-modifiers, ensuring the mixture reaches the desired stiffness as shown in the laboratory results

Keywords: fatigue, stiffness modulus, creep, lawele granular asphalt, CPHMA, dynamic loads

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IDENTIFICATION OF THE IMPACT OF CANDLENUT OIL MODIFIERS ON LGA DYNAMIC RESILIENCE

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1. Introduction

In the modern era, the shift towards sustainable infrastructure has intensified the demand for cold-mix asphalt technologies that minimize carbon emissions. Furthermore, achieving resource sovereignty by optimizing indigenous materials, such as Lawele granular asbuton (LGA), is critical to reducing dependence on imported bitumen. These studies are necessary to bridge the gap between material availability and performance requirements; specifically, by utilizing bio-based modifiers like Candlenut Oil to overcome the logistical and mechanical limitations of traditional cold mixes. Understanding the dynamic resilience of this mixture is essential for developing road surfaces that can withstand modern traffic loads while offering the flexibility needed for long-distance distribution in remote regions.

A common operational challenge in conventional CPHMA is the degradation of mechanical properties during prolonged storage or slow curing phases.

Therefore, studies that are devoted this problem are scientific relevance, by demonstrating that candlenut oil modifiers trigger a time-dependent strengthening mechanism, where extended storage durations actually enhance the mixture's dynamic resilience. Practically, this allows contractors and practitioners to store and transport the material over longer periods without quality loss, providing a logistical advantage for road projects in remote areas. This could become a technical basis for a more flexible and reliable supply chain in cold-mix pavement construction.

2. Literature review and problem statement

One of these problems is getting a modifier that can improve the quality of LGA on CPHMA. Studies have been conducted on modifiers [1, 2], but there has been no real follow-up on the application of these modifiers to the asbuton industry. From the previous research results, a method for making laboratory-scale CPHMA test objects was formulated [3]. Also, a conducted study on the potential of 13 vegetable oils as LGA's modifiers [4] showed that candlenut oil has the potential as an alternative to LGA's modifiers. Research has also been published on the optimal composition of CPHMA mixtures with candlenut oil modifiers [5].

Following this, the application of the modifier to CPHMA was then tested by mechanical testing in order to determine the quality of the pavement modifier in terms of resisting damage in the form of cracks and permanent deformation due to traffic loads [6]. The highway research (SHRP) suggested that the main causes of damage to flexible pavements are rutting, creep stiffness, and fatigue [7]. In the same vein, rutting resistance testing has been carried out in previous research [8]. Pavement comprises stiff materials (not flexible), hence, if given repeated loads, it will experience permanent deformation. A flexible material if subjected to repeated loads will also experience deformation but not permanently, and this is because of the material's ability to stretch and return to its original shape (elastic) [9]. Resistance to elastic and permanent deformation can be determined by testing the material's stiffness and creep modulus.

Fatigue testing is carried out to determine the maximum path that a pavement can withstand before collapsing. This type of damage occurs when the load on the pavement due to traffic volume exceeds a certain limit. This will cause the bond between the binder and aggregate to deteriorate, hence, causing crack propagation from the surface layer [10].

Considering the performance gaps identified in previous studies, particularly the low fatigue life and stiffness of cold-compacted CPHMA as reported by [11], finding a sustainable method to enhance these mechanical properties at ambient temperatures is expedient.

Paper [11] presents the results of the study on the fatigue resistance, stiffness modulus, and creep of CPHMA compacted both cold and hot. It is shown that hot compaction results in higher fatigue resistance and stiffness modulus. However, there are unresolved issues related to compaction temperature because CPHMA compaction is carried out at a maximum temperature of 50°C, while in this study, the highest resistance to fatigue and stiffness increased with increasing temperature up to 150°C. Additionally, creep samples with cold compaction could not be tested. The reason is that high temperatures (60, 90, 120, 150°C) improve performance because the mixture becomes denser, while at low temperatures (30°C), the mixture is stiffer and therefore difficult to compact. As for the creep sample, it could not be tested because it had already broken before 3600 passes. This is because the sample was unable to withstand the test temperature (40°C), resulting in increased viscoelastic deformation and accelerated creep [12]. The way to overcome this difficulty is by choosing a fine aggregate-filler combination that improves interlocking and rutting resistance, and controlling the influence of temperature thru appropriate aggregate selection because aggregate shape/geology and temperature affect mixture performance. This approach is used in [11]. This source provides a fundamental comparison between cold and hot compaction, concluding that cold-compacted CPHMA requires additional measures to match the mechanical performance of hot-mix variants.

Paper [13] presents the results of fatigue resistance research on BRAM (buton rock asphalt modified). It shows that the fatigue resistance of BRAM is higher than that of ACM (asphalt concrete modified). However, there are unresolved issues regarding the lower long-term moisture durability of BRAM. The reasons for this may be the weakening of aggregate-binder bonds and repeated environmental degradation. Ways to overcome these difficulties include strengthening interfacial adhesion, improving resistance to aging that damages the interface, and controlling water/freeze-thaw susceptibility thru mix design, additives, and construction control. This approach is used in [13, 14]. All of this suggests that research on the dynamic resistance of buton asphalt-based pavements is recommended. The paper [13] presents the results of research on BRAM, showing that its fatigue resistance is higher than that of ACM.

The paper [15] presents the results of a study on the stiffness modulus testing of modified asbuton, showing that the stiffness modulus of asphalt (E^*) increases with the addition of asbuton in Pen 80/100 asphalt by [15]. At the same time, they also showed that the higher the test temperature, the lower the E^*. Based on the minimum stiffness modulus criteria, the study concluded that the optimum asbuton content is 30% (30% asbuton in Pen 80/100 asphalt). However, there is an unresolved issue related to the operational contradiction where the addition of asbuton increases E^*, but the increase in test temperature decreases E^*. In other words, although asbuton can strengthen asphalt under one condition, the increase in temperature can reduce stiffness, leading to the need for optimization of asbuton content against the minimum modulus criteria. The reason is that asbuton has a viscoelastic behavior (rheological parameter) and that the temperature effect is inversely proportional to the modulus: higher test temperatures decrease E^*. Thus, the reason for the emergence of the "modulus decreases at high temperatures" issue in the study is the fundamental character of asphalt material being viscoelastic and temperature-sensitive, so the increase in temperature enhances the dominance of the viscoelastic response, which reduces the measured stiffness (E^*) [15]. One way to address this difficulty is thru the activation of BRA/asbuton (grinding + heating) to increase viscosity/softening point and improve micro-modulus, making it more stable against temperature [16], or curing/conditioning and compaction control to tackle the high viscosity of asbuton and enhance uniform coating, resulting in more consistent performance [17]. These approaches are used in [16, 17]. The findings in paper [15] regarding the inverse relationship between test temperature and stiffness modulus underscore the necessity of our research to evaluate how candlenut oil, as a bio-modifier, can stabilize the stiffness of CPHMA under varying thermal conditions.

Paper [18] presents the results of creep testing research on cold mix asphalt (CMA). It was shown that CMA has low resistance to the accumulation of permanent deformation (rutting) in the early stages after laying. However, there were unresolved issues related to the long delay required for natural curing to achieve acceptable stability. The reason for this may be the slow evaporation of volatiles and the low initial viscosity of the binder. The way to address this issue is by extending the curing duration [18], using rejuvenating agents [11] to tackle the high viscosity problem in buton asphalt (asbuton) that hinders aggregate coating. This approach is used in [11, 18]. This paper [18] is very strong in supporting the Creep test with variations in storage duration because [18] emphasizes that CMA is weakest at the beginning and improves over curing.

All of those previous study suggests that research on the dynamic resistance of buton asphalt-based pavements is recommended since the global pavement industry is increasingly shifting toward sustainable technologies to reduce energy consumption and carbon emissions. In this context, CPHMA as a variant of cold-mix technology utilizing natural rock asphalt presents a significant opportunity for greener road construction. Ideally, cold-mix technologies should provide a structural performance and service life equivalent to traditional hot-mix asphalt (HMA) to be considered a viable large-scale alternative. However, a major barrier to the global adoption of cold-mixed natural asphalt is the inherent uncertainty regarding its mechanical durability under dynamic loading conditions. Specifically, the material's ability to withstand repetitive traffic stresses without succumbing to premature fatigue cracking or excessive permanent deformation remains a critical technical challenge. Despite various studies on cold-mix stability, there is a lack of comprehensive evidence regarding the fundamental dynamic response of CPHMA. The absence of detailed data on its fatigue life, stiffness modulus, and creep behavior prevents engineers from confidently predicting its long-term performance in high-volume traffic environments. Consequently, research into these dynamic properties is essential to validate CPHMA as a robust and durable material for the global transition toward sustainable infrastructure.

All this allows to assert that it is expedient to conduct a study on investigates the impact of adding candlenut oil-based modifiers to the cold paving hot mix asbuton (CPHMA) surface layer on dynamic loads such as indirect tensile fatigue test (ITFT), indirect tensile stiffness modulus (ITSM), and creep.

3. The aim and objectives of the study

The aim of this study is to identify the impact of candlenut oil modifiers on the dynamic resilience of LGA-based mixtures by evaluating their fatigue life, stiffness modulus, and creep behavior under various loading conditions, thereby validating its potential as a sustainable alternative to conventional hot-mix asphalt.

To achieve this aim, the following objectives were accomplished:

– to determine the fatigue life of CPHMA by analyzing its resistance to repetitive dynamic stresses and identifying its cracking initiation and propagation characteristics;

– to measure the stiffness modulus of the mixture across various frequencies and temperatures to understand its structural response to high-volume traffic loads;

– to analyze the creep behavior of CPHMA to assess its resistance to permanent deformation under sustained and cyclic loading.

4. Materials and methods

4. 1. The object and hypothesis of the study

This study investigates the impact of adding candlenut oil-based modifiers to the cold paving hot mix asbuton (CPHMA) surface layer on dynamic loads such as indirect tensile fatigue test (ITFT), indirect tensile stiffness modulus (ITSM), and creep.

The main hypothesis of the study:

1. H1 (fatigue). The addition of candlenut oil to CPHMA enhances its flexibility, thereby extending its fatigue life and delaying crack initiation compared to conventional cold mixes.

2. H2 (stiffness). The modified CPHMA exhibits a stable stiffness modulus that remains resilient under high-volume traffic loads, showing an optimal balance between stiffness (to support loads) and elasticity (to prevent brittle failure).

3. H3 (Creep). The incorporation of the modifier improves the visco-elastic recovery of the CPHMA, resulting in a higher resistance to permanent deformation (rutting) under cyclic and sustained loading.

Assumptions made in the study are:

– it is assumed that the candlenut oil is uniformly distributed throughout the bitumen and that the diffusion process within the CPHMA is completed during the specified curing period;

– the air void content and aggregate gradation are assumed to be consistent across all laboratory specimens, representing an idealized pavement structure;

– for the purpose of stiffness and fatigue analysis at 20°C, the material is assumed to operate within a linear viscoelastic range where strain is proportional to stress;

– the laboratory testing environment is assumed to be stable, where the target temperatures (20°C and 40°C) are maintained without interference from external humidity or fluctuating thermal gradients.

To facilitate a controlled mechanistic evaluation of the CPHMA modified with candlenut oil, several simplifications were adopted regarding material behavior and testing conditions. In the stiffness modulus and fatigue tests conducted at 20°C, the material was assumed to behave within a linear viscoelastic range, with the stiffness analysis specifically adopting a constant Poisson's ratio of 0.35 and a fixed deformation of 5 μm to simplify the stress-dependent lateral expansion. The complex nature of traffic loading was simplified into standardized pulse cycles (100 ms to 250 ms load widths), effectively disregarding long-term healing effects. Furthermore, the creep test at 40°C utilized a constant haversine load function with a 600-second pre-loading time to assume a stabilized initial contact state, while neglecting potential internal temperature rises during the 3,600 completion cycles. Across all tests, the diffusion of candlenut oil was assumed to be instantaneous and homogeneous, treating the CPHMA as an isotropic structure and disregarding microscopic variability in air void distribution.

4. 2. Materials

The composition of the materials for ITFT and ITSM used in this research are shown in Table 1. Following this, the material for creep's sample with a height of 10 cm was converted by testing to obtain the required sample height.

Table 1

Material composition

Testing	LGA (gram)	Modifier (gram)	Aggregate (sieve retained) (gram)					
		Candlenut oil	1/2"	No. 4	No. 8	No. 50	No. 200	Pan
ITFT	238.9	47.8	47	352.5	149.5	186.3	13.7	12.1
ITSM	238.9	47.8	47	352.5	149.5	186.3	13.7	12.1
Creep	398.2	79.7	78.3	587.5	249.2	310.5	22.8	20.2

The size of the aggregate sieve used is based on the material specifications for CPHMA, with a minimum LGA particle size of 12 mm.

4. 3. Fatigue test

The fatigue test was based on BS EN 12697-24:2012 [19] using the ITFT method. The test has been implemented with setup parameters, namely seating force 10 N, load cycle width 100 ms, cycle repeat time 500 ms, and target temperature 20°C. Furthermore, the horizontal strain was measured using LVDT and the lowest load employed for the test was 25 kPa, hence, the cycle repetitions can be read.

The data obtained from the test were then visualized on a graph in the form of load repetition cycles, strains, and forces. In accordance, the resistance to fatigue or fatigue life was indicated by the load repetition value until it collapsed (Nf) [20]. The installation of samples and fatigue testing instruments on UTM are shown in Fig. 1.

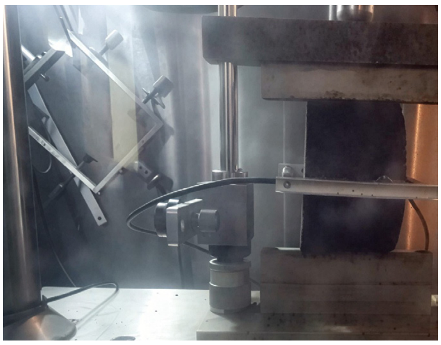


Fig. 1. Indirect tensile fatigue test method

Circular-shaped samples can be made in the laboratory or obtained from core drilling. The load will be applied repeatedly with a haversine load signal thru the vertical side of the sample. This load will create a relatively uniform tensile stress perpendicular to the loading direction and along the vertical side of the sample, causing the sample to split along its vertical side. The horizontal displacement of the sample will be measured so that the tensile stress can then be calculated using the Poisson's Ratio assumption.

4. 4. Stiffness test

The stiffness test was conducted according to BS EN 12697-26:2012 [21] using the ITSM method. This was done by configuration parameters, namely width of load pulse 250 ms, time of pulse repeat 3000 ms, count of conditioning pulse 5, temperature 20°C, deformation 5 μm, and Poisson's ratio estimation 0.35. The data obtained was in the form of stiffness modulus and horizontal deformation. Accordingly, the installation of samples and instruments for testing stiffness in UTM is shown in Fig. 2.

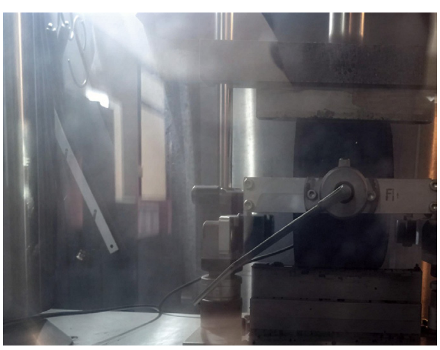


Fig. 2. Indirect tensile stiffness modulus method

The cylindrical test specimen will be deformed under repeated loading or controlled strain loading, and then the waves and phase difference between stress and strain will be measured.

4. 5. Creep test

This test was based on BS EN 12697-25:2005 (2005) using the creep method for uniaxial cyclic compression (Method A) with various restraints. During this test, the specimen was undergone to axial stresses and in order to reach a determined limit, the plate for loading was assumed to be smaller than that of the sample in diameter. Fig. 3 shows the installation process of samples and creep testing instruments on UTM.

Fig. 3. Creep test

Furthermore, the examination was using the following setup parameters namely load function haversine, cyclic pressure and confining stress each 100 kPa, seating pressure 5 kPa, load cycle width and repeat time each 1000 ms, preload stress 20 kPa, pre-loading time 600 s, no constrain control pivot, completion cycle count 3600, termination tension 100 με, and target temperature 40°C.

The creep stiffness value was an additional indicator of resistance to deformation [22]. The pavement strength in receiving traffic loads related to creep based on the minimum slope (a) obtained from the equation of the linear trend line, namely $y = ax + b$ in the secondary curve area base on BS EN 12697-25:2005 is shown in Table 2.

Table 2

Minimum slope dynamic creep

Annual average pavement temperature (°C)	Big traffic load ($>10^6$ ESA)	Middle traffic load (5×10^5–10^6 ESA)	Small traffic load ($<5\times10^5$ ESA)
more than 30	less than 0.5	between 0.5 to 3	more than 3 to 6
between 20 to 30	less than 1	between 1 to 6	more than 6 to 10
between 10 to 20	less than 2	between 2 to 10	not applicable

Source: [23].

The data obtained were visually represented on a graph in the form of strain (ε) and load repetition cycles (n) obtained from testing, as well as creep stiffness obtained from the formula, also permanent strain can also be calculated if the deformation is known as shown below:

$$En = \sigma / \varepsilon n, \tag{1}$$

$$\varepsilon n = \text{deformation} / ho, \tag{2}$$

where En – creep stiffness;

σ – pressure exerted on the sample;

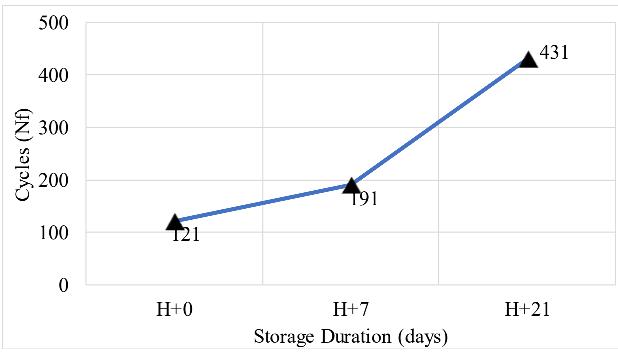
εn – permanent strain;

ho – initial height of the sample.

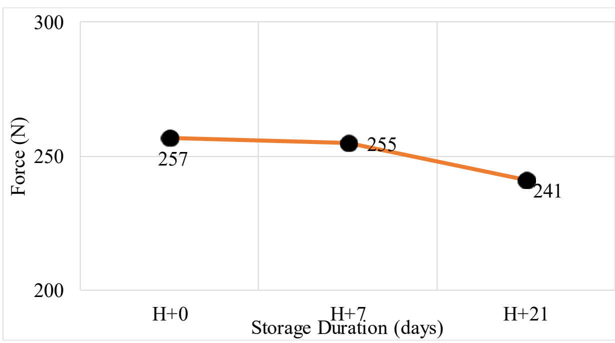
5. Results of mechanical resilience of cold paving hot mix asbuton (CPHMA) under dynamic loading conditions

5. 1. Fatigue life and cracking resistance of candlenut oil-modified CPHMA

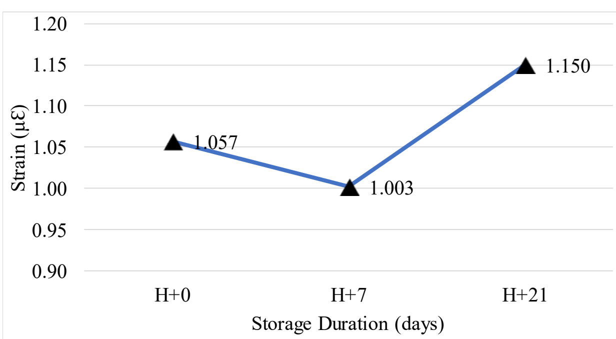
This section details the experimental findings from the fatigue life assessment, highlighting the material's capacity to withstand repeated loading before failure occurs. The results of the fatigue test for the CPHMA mixture across different storage durations are illustrated in Fig. 4.



a



b



c

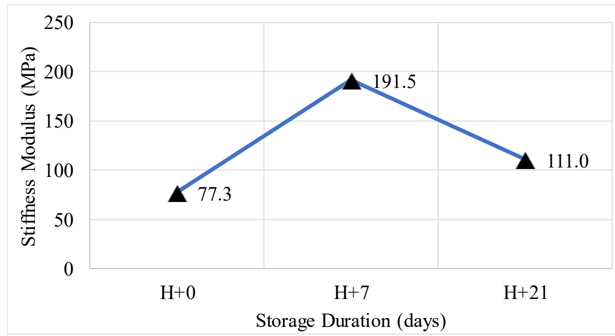
Fig. 4. Indirect tensile fatigue test result:
a – fatigue life; *b* – force; *c* – strain

Fatigue resistance is expressed by the fatigue life value. Fig. 4, *a* shows that fatigue life increases with increasing storage duration, and the highest endurance (431 cycles) was found on the 21st day.

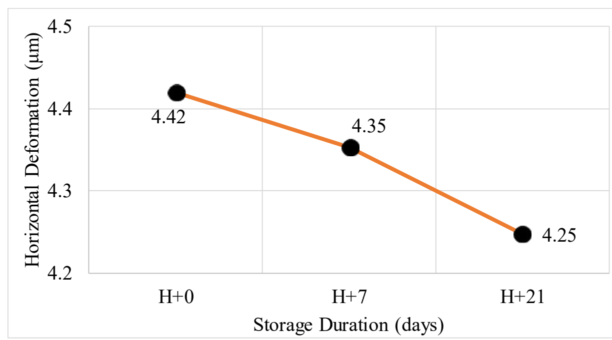
The pressure did not change significantly, as shown in Fig. 4, *a* with the pressure range on 241–257 N. With a standard deviation (SD) = 7.1. The strain due to fatigue, which also indicated no significant difference with the range on 1.003–1.15 με, is shown in Fig. 4, *b*. The obtained SD value of strain was equal to 0.061.

5. 2. Stiffness modulus and structural response of LGA mixtures under pulse loading

The structural rigidity and load-bearing capacity of the CPHMA mixture are characterized by the stiffness test results presented in the following Fig. 5.



a



b

Fig. 5. Indirect tensile stiffness modulus:
a – stiffness modulus; *b* – horizontal deformation

The highest stiffness modulus in this study was 191.5 MPa and obtained from a 7-day storage duration (H+7), as shown in Fig. 5. Out of the 5 samples/variations tested, only 2 or 3 of them had a small standard deviation of combination values. Following this, regardless of the fact that the H+7 sample only has 2 samples with the smallest standard deviation, it was also the largest standard compared to H+0 and H+21. Stiffness values, average stiffness, and SD for each variation of storage were:

a) H+0; 82; 72; 78; average = 77.3; SD = 4.1;

b) H+7; 175; 208; average = 191.5; SD = 16.5;

c) H+21; 108; 118; 107, and average = 111; SD = 5.

Therefore, the stiffness value for H+7 is inconsistent with other samples.

The strain that shown with value of horizontal deformation (4.2–4.4 μm) did not indicate a significant difference as shown in Fig. 5. Also, since the SD value equated to 0.07.

5. 3. Permanent deformation and creep resistance of modified LGA under cyclic haversine loading

The CPHMA susceptibility to permanent deformation is analyzed through the comprehensive data obtained from the creep test. The relationship between storage duration and the mixture's resistance to permanent deformation is illustrated in Fig. 6.

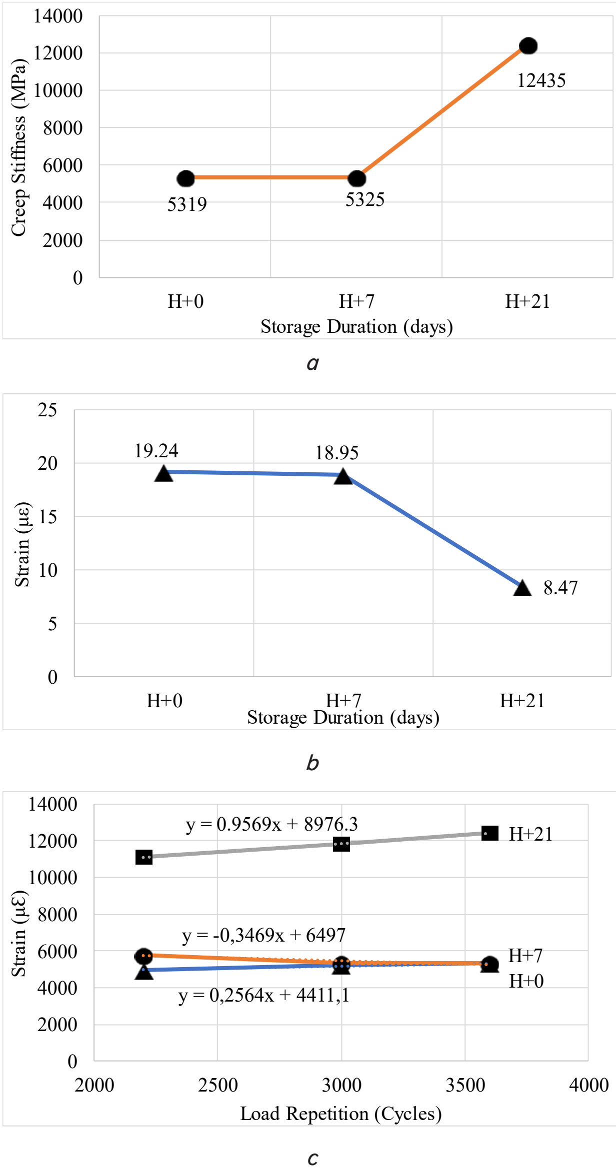


Fig. 6. Creep test result:
a – creep stiffness; *b* – strain; *c* – minimum creep slope

Fig. 6, *b* shows the minimum slope is the coefficient of the trendline strain vs load repetition, which is the secondary area on the creep curve. Regarding creep, this area is a steady state strain rate, where the strain is relatively constant. This area represents the strength of the pavement in receiving traffic loads.

The minimum slope of the loading cycle 2200, 3000, and 3600 pulses where the results obtained for H+0, H+7, and H+21 are 0.2564, 0.3469, and 0.9569 respectively.

Following this, the creep stiffness value was affected by deformation, and both are inversely proportional. The highest creep stiffness value was obtained from the lowest storage duration, which was on the first day at 19.24 MPa with strain at 5319 με as shown in Fig. 6, *a*.

6. Discussion of the mechanical resilience results of CPHMA under dynamic loading

Fatigue resistance is consistent with the results of the previous research [5] in which the Marshall, tensile strength, and rutting were tested. This shows that storage duration has an effect on the fatigue resistance of CPHMA in such a way that whenever the storage duration increases, the resistance also increases. As the tensile strength decreases the fatigue life of the mixture also decreases [24], and this proves that the fatigue life as shown at Fig. 4, *a* is directly proportional to the tensile strength. This condition is usually caused by a loss of stiffness which triggers cracking and stripping [24]. This is in accordance with the results of previous research on tensile strength testing [5] where the highest resistance was also obtained on the 21st day of storage. Following this, the storage duration did not affect the pressure received by the CPHMA at the time of failure as shown at Fig. 4, *b*. The obtained SD value of strain was equal to 0.061, and the strain between duration variations is considered not different as shown at Fig. 4, *c*. This indicates that the fatigue strain experienced by CPHMA is not affected by storage time.

The results of the stiffness test as shown at Fig. 5, *a* were not consistent with the results of previous research [5]. They are also not in accordance with the research where it was indicated that the results of the mixed resistance test against ITSM are consistent with ITFT and creep [11, 22, 23]. Ideally, the stiffness value for the duration of H+7 is linear with respect to H+0 and H+21, regardless of whether or not the value for H+7 is ignored, a graph will be formed showing the increase in strength against the stiffness with the addition of storage duration. Generally, a low stiffness value indicates a high level of saturation occurs due to the presence of remaining water in the void of mineral aggregates (VMA) [21]. As the duration of storage increases, evaporation of the remaining water occurs, resulting in a higher stiffness modulus value. This further reinforces that the test results for H+7 were not valid. When the results of H+7 were ignored, the highest stiffness modulus was obtained from H+21, which is 111 MPa as shown at Fig. 5, *a*. The strain shown that the storage time did not affect the strain due to stiffness in CPHMA as shown at Fig. 5, *b*.

The minimum slope of the loading cycle indicated that the pavement strength decreased on receiving traffic loads as storage duration increased. The lower the value of minimum slope as shown at Fig. 6, *c* the higher the traffic load that can be withstood as shown in Table 2. Furthermore, the strength to withstand the highest load was obtained from H+0 based on the minimum slope. This strength was able to withstand heavy traffic loads. The creep stiffness value as shown at Fig. 6, *a* shows that storage duration affects the CPHMA's creep resistance. As the storage duration increases, the CPHMA creep stiffness value decreases. In contrast, a research came up with creep stiffness values that were consistent with ITSM and ITFT [11, 23]. These values were, however, inconsistent with previous test results for rutting [25, 26], and they are directly proportional to creep resistance. According to a research, a decrease in the creep stiffness indicates the addition of asphaltene which will increase the penetration value, hence, making the asphalt adherence better. The addition of asphaltene can be caused by the evaporation of maltene due to heating which causes the asphalt to age. Furthermore, this will cause the pavement to become susceptible to fatigue [23]. Therefore, it can be deduced that the decrease in stiffness of creep with increasing storage duration was not due to the addition of asphaltene. The strain that occurred, as shown in Fig. 6, *b* was a result of the deformation of the pavement and this was influenced by the storage duration. The lower the strain value, the higher the creep stiffness value. This is because a high creep stiffness value indicates a stiffer pavement. When the pavement experiences a relatively small deformation, the strain that occurs is also usually small [22].

Previous research references that can be used for comparison with this study are somewhat difficult to find, as this study focuses not only on a specific type of pavement mix, but also on the type of modifier, testing method, and the impact of storage duration. One study [11] used a different type of modifier, the PH-1000, which is a conventional modifier. Fatigue testing at 25 KPa resulted in failure at 800 cycles, while in this study, failure occurred at 431 cycles, as shown in Fig. 4, *a*. Stiffness Modulus testing in that study resulted in sample failure at 152 MPa, whereas in this study, failure occurred at 111 MPa, as shown in Fig. 5, *a*. Furthermore, creep testing could not be performed because the sample failed before 3600 load repetitions, while in this study, the highest failure occurred at 12435 MPa, as shown in Fig. 6, *a*. The highest resistance in this study was observed at a storage duration of 21 days, with the potential to increase further with longer storage duration, which is a significant difference from previous studies.

The limitations of this study are classified as follows:

1) material:

a) the type of asphalt used is LGA 50/30;

b) the modifier used is candlenut oil;

2) testing:

a) samples are compacted using a Marshall compactor;

b) the mixture is heated using an oven;

c) fatigue testing is performed using a dynamic load of 25 KPa;

d) creep testing is conducted at a temperature of 20°C.

The disadvantages of this study are:

1) the mechanical strength at 0 days of storage is relatively low;

2) the sample heating process does not reflect the process used in industry.

Long-term plans include:

1) testing with storage durations exceeding 21 days;

2) field-scale trials;

3) developing standard operating procedures for mass production at the Asphalt Mixing Plant. A potential difficulty with this material application is the relatively high cost of purchasing candlenut oil at the moment.

The development of this study may proceed towards optimizing the early-age performance of the mixture. While candlenut oil significantly enhances dynamic resilience through a maturation process, there is a potential to integrate secondary additives or catalysts to accelerate this strengthening mechanism. Future research should explore the synergistic effects of combining candlenut oil with specific additives to ensure high static and dynamic resistance starting from the early storage duration. Additionally, full-scale field trials are necessary to observe how these optimized mixtures perform under actual traffic loading and climate fluctuations. Finally, a comprehensive life cycle cost analysis (LCCA) will be vital to quantify the economic benefits of reducing the required maturation time for industrial applications.

7. Conclusions

1. Fatigue test results showed the highest resistance was obtained from the 21-day duration sample, with 431 cycles, compared to previous studies which showed resistance at 800 cycles. The uniqueness of these test results is the discovery of increased resistance with increasing storage duration.

2. The results of the stiffness modulus test showed the highest resistance was obtained from the 21-day duration sample at 111 MPa, while previous studies showed 152 MPa. The uniqueness of these test results was the discovery of an anomaly in the 7-day storage duration sample, but this may have occurred due to the lack of samples, unlike the 0 and 21-day duration samples, which had 3 samples, while the 7-day sample only had 2. The SD value is also relatively large, so it can be said that the test results for the 7-day sample are inconsistent with the other samples.

3. The creep test results showed the highest resistance was obtained from the 21-day duration sample, which was 12435 MPa, while previous studies could not be tested because the samples crumbled before the load was repeated 3600 times. The uniqueness of these test results is the finding of increased resistance with increasing storage duration.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this study, whether financial, personal, authorship or otherwise, that could affect the study and its results presented in this paper.

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Data availability

Manuscript has no associated data.

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Use of artificial intelligence

During the preparation of this work, the authors used Gemini Ai and QuillBot Ai in the Introduction and Literature Review sections to enhance the linguistic quality and clarity of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication. The authors emphasize that the AI tool did not influence the experimental data analysis or the final scientific conclusions.

Authors' contributions

Lila Khamelda: Conceptualization, Methodology, Validation, Data Curation, Writing – original draft, Writing – review & editing, Supervision; **Sunik**: Software. Formal analysis, Investigation, Resources, Visualization, Project administration, Funding acquisition.

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