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ORIGINAL RESEARCH ARTICLE

STRUCTURAL EVALUATION OF CONVENTIONAL AND MODIFIED FLEXIBLE PAVEMENT PERFORMANCE

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ABSTRACT

Experimental studies indicate that using rubber particles (RP) as additives improves hot mix asphalt (HMA) engineering properties when used as a road surface layer. Two critical strains are identified with asphalt pavement: horizontal tensile strain beneath the AC layer and vertical compressive strain on top of the subgrade. However, these strains are difficult to be predicted by experimental simulations. This research aims to conduct a comparative structural performance evaluation of conventional and modified asphalt pavement cross-sections with a particular reference to compute pavement responses (stress, strain, deflection, and stiffness) by utilizing Kenlayer computer code. Each cross-section is modelled as an elastic multilayer system consisting of five (5) layers with assigned material properties. The pavement compositions illustrate a typical highway pavement structure. The elastic modulus for both HMA materials was obtained at the average design temperature of 25°C to reflect tropical and subtropical regions. The standard tandem axle load that causes damage to the pavement having a contact pressure of 673 kPa (0.673 MPa) with a set of dual tires center to center spacing of 33.75 cm was considered. The similarities and differences between the two pavement cross-sections concerning performance responses are compared. The analysis revealed that for both conventional and modified HMA cross-sections, the horizontal tensile strains at the bottom of the surface and binder layers are (2.62E-06 & -172E-04) and (-2.04E-05 & -2.14E-04) με; at the same time, the vertical compressive strains on top of the subgrade are (1.57E-04) and (1.69E-04) με. And finally, the computed surface layer stiffnesses are (833.51 kN/cm) and (734.89 kN/cm). It is appropriate to say that the modified HMA significantly decreases the surface layer's stiffness; as such, it eventually prolongs the rapid encroachment of fatigue cracking and rutting deformation.

1.0 Introduction

The structural design is considered an alternative to experimental study when there is sometimes difficulty conducting experimental modeling. On the other hand, pavement structural performance predictions for construction are initially carried out before a detailed experimental investigation of pavement materials. Besides, the structural modeling of pavement also serves as a control to achieve satisfied material properties due to traffic loading and environmental elements (temperature and precipitation).

In highway pavement design, attention has been given to critical pavement distresses such as fatigue and permanent deformation in flexible pavement. Many research projects and field applications have been investigated and proven that rubber particles in asphalt mixture improve the long-term durability of flexible pavement. RP in HMA at a certain varying percentage contributes to resistance in the rutting deformation (Laily *et al.*, 2019, Hamzani *et al.*, 2019, Mashaan and Karim, 2014). These experimental investigations have been centered on experimental studies.

The study objective is to perform structural modeling considering two asphalt pavement cross-sections (conventional and modified pavement) to evaluate critical performance responses due to160 kN dual wheel load. To distinguish the cross-section, each HMA surface layer elastic modulus was obtained at the design temperature of 25˚C. The Kenlayer is a semi mechanistic program that was used to model the pavement cross-sections analytically.

Pavement design concept

The basic design concept for flexible pavement determines the required thickness based on the traffic level. In addition, pavement performance is associated with environmental conditions such as temperature and precipitation (Aashto-Mepdg, 2015). However, apart from the empirical way of selecting pavement layers and thicknesses, some structural codes for the design of asphalt pavements use the concept of a layered elastic system. The pavement design determines every layer’s thickness, ensuring that the stresses/strains caused by the traffic loads and transmitted through the pavement to the sub grade do not exceed each layer’s supportive capacity (Jiang *et al.*, 2017). The pavement’s primary purpose is to lessen the sub grade stresses to such a level that the sub grade does not deform under traffic.

Because of that, the top layer must be of the best quality to sustain maximum compressive stress and wear and tear (Asadi *et al.*, 2019, Congress, 2018, Alaa and Al-Azzawi, 2012). The pavement layers must be strong enough to tolerate the stresses and strains for each layer exposed, which is the structural design.

Flexible Pavement structure

Asphalt pavement structure supports the traffic loads and transmits them to the sub grade, where there will be potential for stress reduction. The pavement layers are superimposed, with each layer performing a different primary function.

The different pavement layers are shown in Figure 1 and are composed of surface, binder, base, sub base, and sub grade.

Surface Course is the top layer directly in contact with the traffic load, sometimes referred to as wearing course. It provides the riding surface of HMA for road users. Binder Course is a premixed asphalt surfacing at times laid in two layers of different materials. It is sometimes referred to as an asphalt base course below the surface course. The base course is the main load-spreading layer. It is constructed immediately beneath the surface or the binder course. It extends some distance beyond the edge of the top layers to ensure that underlying layers will support the loads applied at the edge of the pavement. Base course may consist of asphalt concrete, cement concrete, graded granular gravel, crushed stones, and other treated or stabilized materials. Sub-Base Course is a secondary load-spreading layer. It separates the sub grade and the base and provides a platform for constructing the pavement’s upper layer. The provision for a sub-base optionally provides the strength of the sub grade. Sub-grade is the soil acting as a foundation for the pavement prepared to receive the stresses of the above layers. The earthwork’s sub grade results may consist of undisturbed, local soil or material excavated elsewhere and placed as a fill. The surface of the sub grade creates the platform for the upper layers (Aashto-Mepdg, 2015, Congress, 2018, Huang, 2004a).

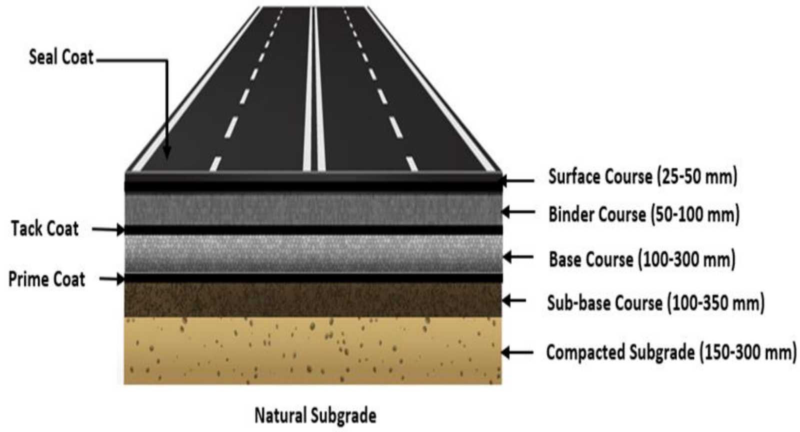

Figure 1: A Typical Flexible Pavement Structure (Note, 1993)

Structural analysis

To characterize the behavior of a flexible pavement under wheel loads, it is considered as a homogeneous half-space (Huang *et al.*, 2003). A half-space has an infinitely large area and an infinite depth with a top plane on which the loads are applied (Jamshidi and White, 2019, Guo and Lu, 2019). The structural analysis of flexible pavement systems has been computed using verities of computing codes. The finite element analysis through ANSYS and ABAQUS computer software to predict pavement responses have been used by some researchers (Yan *et al.*, 2020, Liu *et al.*, 2017, Dong and Ma, 2017). (Gupta and Kumar, 2013) studied the role of variables in lowering the vertical surface deflections, critical tensile strains at the bottom of the bitumen layer, and the critical compressive strains on the top of the sub-grade. The study used the finite element approach and Kenlayer to compare the performance of flexible pavements

Furthermore, some researchers investigated flexible pavement response subjected to cyclic loading and simulated three levels of truckloads at four different tire inflations pressures. The results were in good agreement with the measured in-situ-scale test data. They concluded that the finite element method could efficiently estimate the fatigue life of flexible pavement with thin bituminous surfacing layers (Mulungye *et al.*, 2005).

Conventional asphalt pavement

Conventional flexible pavement is mainly affected by environmental exposure such as low and high-temperature, precipitations, traffic loading, and other phenomena.

Road pavement distress has to be restricted as it directly or indirectly affects the overall long-term performance (Patel and Patel, 2020). Distresses in the conventional pavement are either load-related, environmental-related and asphalt mix design-related. Therefore, the conventional asphalt pavement should be designed to provide a durable, skid resistance surface under in-service conditions.

However, fatigue and rutting deformation are two main pavement distresses in flexible pavement. These are mainly due to increased load repetitions, variance in temperature, deficiency in construction and design faults, and delay in maintenance intervention. It is essential to reduce fatigue cracking and rutting in asphalt pavement layers (Moghaddam *et al.*, 2011).

The increase or decrease in the fatigue life of the conventional asphalt pavement is also attributed to neglecting the structural design as well as the absence of attention to identify or consider the pavement parameters such as the material properties of each layer, traffic loading, and other factors (Ebrahim and El-Maaty, 2012, Portillo and Cebon, 2013, Jamshidi, 2021). Fatigue occurs in the form of alligator cracking associated with the repetition of loading and pavement layer thickness. It is initiated in micro-cracks at the top and bottom; these cracks sometimes grow due to shear and tensile stresses in conventional road pavement. The initiation of fatigue cracking is also affected by different factors and properties of the mixture, temperature, and air voids in the mix. Structurally, the fatigue behavior in road pavement can be simulated by using computer codes to determine stresses and horizontal strains in the asphalt concrete layers. And experimentally, the behavior of fatigue in bitumen mixtures can be characterized by Beam Fatigue Test or indirect Tensile Fatigue Test to control stress and strain modes (MoghaddamKarim *et al.*, 2011, Sohn and Han, 2020, Chandak *et al.*, 2018).

At the same time, rutting in the form of permanent deformation occurs in either of the pavement layers is also the most common distresses in asphalt pavements. It is defined as the longitudinal surface deflection occurring along the wheel paths of roadways due to load repetitions. This type of failure is permanent at road sections where there is sometimes static traffic or traffic moving at a creep speed, thereby delaying the dynamic movement on the pavement. However, the failure is also load and asphalt mix design related and is eventually escalates to include other defects such as cracking, potholes, and deformations (Chilukwa and Lungu, 2019).

Asphalt concrete is a time, temperature, and stress-dependent material that exhibit elastic or plastic, or visco-elastic responses when subjected to repeated loading. The elastic characteristics can be obtained by its elastic modulus and Poison ratio property, meaning they do not contribute to permanent deformation. In exhibiting plasticity, it contributes to permanent deformation, which is attributed to repeated loading. However, rutting can be influenced due to many factors such as vehicle speed/time, vehicle contact pressure depending on the force, and contact area directly in the creep rate model (Khana *et al.*, 2013). The correct application of additives has been recognized by highway agencies as one of the most effective strategies for improving pavement performance by decreasing or preventing related distresses.

Modified asphalt pavement

The primary focus of using rubber asphalt as a modifier is to reduce reflective cracking in hot mix asphalt (HMA). Also, for rehabilitations, overlays, and maintenance purposes, rubber asphalt has performed well in snow and ice locations, thus providing smooth-riding and a good skid-resistant surface. Rubber asphalt has been used in many countries worldwide with promising engineering outcomes (Mashaan *et al.*, 2014, Cetin, 2013).

The improvement in conventional road pavement life span contributes to sustainability as an effort to economic advantages. Waste rubber particles from tires have been suggested as an alternative additive in asphalt binder and asphalt concrete mixture (Picado-Santos *et al.*, 2020).

The contribution of crumb rubber in terms of the value of resilient modulus also resists deformation. Crumb rubber was added to the base asphalt at various rates at a temperature of 177 °C, and the levels of crumb rubber on the asphalt lowered penetration rate, increased bitumen softening point, and enhanced permanent deformation resistance.

The crumb rubber in HMA included increased recoverable deformation and decreased resilient modulus (1500 MPa) (Ariyapijati *et al.*, 2017a). The improvement in road pavements' service life leads to sustainability and a significant economic benefit. Rubber particles have been suggested as a modifier for asphalt and asphalt mixtures to increase flexible pavement performance characteristics, according to various scholars (Nguyen and Tran, 2017, Zumrawi, 2017, Hamzani *et al.*, 2019, Mashaan and Karim, 2014).

Furthermore, testing the strength of the crumb rubber asphalt mixture is one crucial way to determine its performance. Pavement engineers have suggested a need for more effective approaches to resolving crumb rubber asphalt's aging and thermal stability problems. Simultaneously, (Liang *et al.*, 2017) investigated various crumb rubber modified asphalt using microwave irradiated and the trans-polycteamer (TOR). In the study, samples were subjected to a thin-film oven test, pressure aging vessels, and high-temperature storage tests and evaluated the effect of the microwave and TOR. The results showed that the microwave-activated crumb rubber increases the risk of fatigue cracking caused by the hardening effect of aging but endows the aged residue with more robust resistance to thermal cracking. The TOR improves the compatibility and storage stability of the crumb rubber-modified asphalt. (Wang *et al.*, 2019) evaluated the durability of crumb rubber-asphalt pavement using the indirect tensile strength test under freeze-thaw boiling cycle and the Cantabria abrasion test underwater immersion and an auxiliary method. On the other hand, the durability test suggested in the study was utterly unsatisfactory underwater immersion. The durability evaluation method proposed should be more effectively evaluated to understand the long-term moisture stability of the crumb rubber asphalt pavement.

2. Materials and methods

2.1 Materials

2.1.1 Pavement cross-section

A single pavement cross-section was considered for the structural analysis to study conventional and modified flexible pavement system responses. The pavement composition consists of five (5) layers as the wearing course (conventional & modified HMA), binder course (HMA), base course (aggregates), sub-base course (granular), and sub-grade. Figure 2 illustrates a typical flexible pavement system, while Table 1 shows the selected material properties obtained from research investigated by Ariyapijati (2017). The study uses 3000 MPa and 1500 MPa to simulate the design temperature of conventional and modified rubber asphalt mixtures at 25°C, respectively (Ariyapijati *et al.*, 2017b)to reflect tropical and subtropical regions.

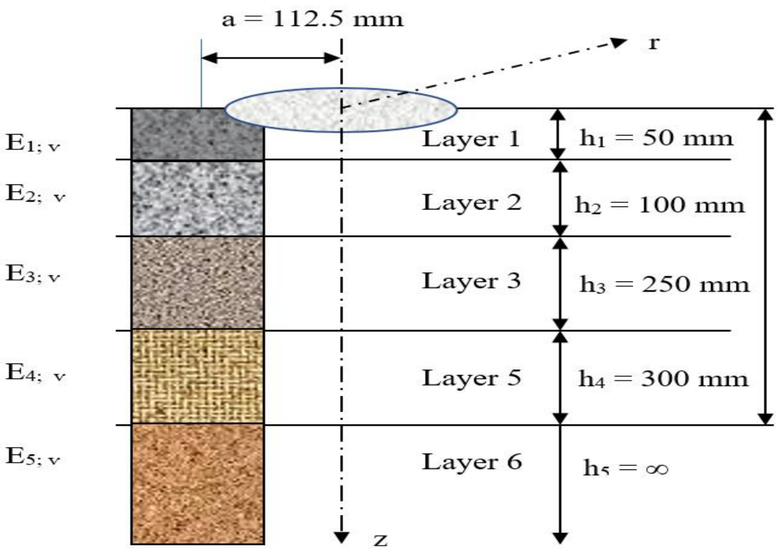

Figure 2: A Typical Pavement System for Analysis (Note, 1993)

Table 1: Material Properties of Conventional and RP Asphalt Concrete (Congress, 2018, Aashto-Mepdg, 2015)

Layer	Layer thickness (cm)	$M_{.R.}$ (MPa)	$M_{.R.}$ (MPa)	Poisson's ratio (*v*)	Unit weight (K.N/m)
Surface layer (HMA.)	5	3000	1500	0.30	22.8
Binder layer (HMA.)	10	2250	1125	0.35	22.8
Aggregate Baselayer	25	450	450	0.40	21.2
Granular Sub-base layer	30	350	350	0.45	21.2
Soil sub-grade	infinite	100	100	0.45	19.6

2.1.2 Traffic Loading

The assumptions foe the loading conditions as a direct input in the model analysis as vehicle load acting on a circular shape. The study considered the following loading characteristics:

i. Axle Configuration: The tandem axle considers having a Centre-to-Centre distance of 121cm between the axles and Centre to Centre spacing between dual-wheel as 33.75 cm.

ii. Loading: A standard Tandem axle load as 160 kN consider respectively. Figure 3 shows the shape of the input loading group.

iii. Contact Pressure: In this study, the contact pressure of 673 kPa for a standard Tandem axle of two dual tires in a parallel direction.

iv. Contact Area: the contact area is an important parameter to be determined to distribute loading under each tire uniformly. Therefore, 11.25 cm (H. Huang, 2019, Huang, 2004a) was adopted in the study.

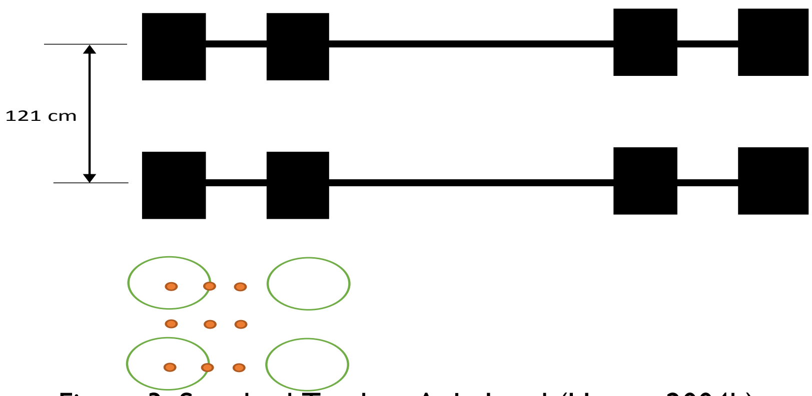

Figure 3: Standard Tandem Axle Load (Huang, 2004b)

2.1.3 Resilience Modulus

The resilience modulus is an essential performance indicator for asphalt mixtures, especially the surface and binder courses. It measures the material strength to withstand and spread the loading over an area. The asphalt mixture with high resilience spreads the load over a wider area, reducing the level of strain experienced at the bottom of the pavement structure, considering the temperature variance and load repetitions. The calculated modulus is the ratio between the maximum stress and the maximum strain in the following equation.

$$E = \frac{\sigma}{\varepsilon} \qquad (1)$$

Where:

E = Resilience Modulus

σ = apply stress in MPa/kPa

є = Apply strain in μm

2.2 Methodology

2.2.1 Analytical Approach

To evaluate the performance of both flexible pavement structures (conventional and modified) HMA, the tandem axle load that causes damage to the pavement of 673 kPa contact pressure was used to predict various pavement responses. The study was carried out to compare with a specific reference to change the elastic modulus of the surface layer material properties to indicate the performance difference of both pavement scenarios. Furthermore, each pavement cross-section was treated as a linear elastic system with assigned elastic modulus and poison's ratio to each pavement layer. The pavement structure was analyzed in five (5) layers using KENLAYER computer code; Yang H. Huang developed the program derived from KENPAVE. The program focuses on a flexible multilayer system solution under a circularly loaded area as the Burmaster layer theory (1943). The program is significantly different from other computer programs as more material list models like linear-elastic, no-linear elastic, viscoelastic, and the combinations of all models are available.

The computations are investigated due to design inputs, the vertical pavement deflections, strains, stress, and stiffness. The obtained results are shown through tables and figures.

3. Results and Discussion

3.1 Vertical Deflection

Surface deflection on pavement indicates a sign of failure, which occurred due to traffic loading. It is a strong indicator that highlights how durable the pavement will perform during the expected design period. Table 2 shows the deflections of each pavement composition decreased uniformly from the top of the surface course to the sub-grade. The deflection in the conventional pavement cross decreased about 12% compared to the rubber asphalt pavement composition because of the high resilient modulus value of the conventional cross-section.

Table 2: Deflections in Each Cross-Section

Layer	Layer thickness (cm)	Conventional Pavement (cm)	Modified Pavement (cm)
Surface layer (HMA)	0	0.048	0.054
Binder layer (HMA)	5	0.046	0.051
Aggregate Base layer	15	0.044	0.048
Granular Sub-base layer	40	0.038	0.040
Soil sub-grade	70	0.034	0.035

3.2 Horizontal Tensile Strain

The analysis determined one of the crucial parameters that guarantee the pavement over the design period is the permissible horizontal tensile stain presented in Figure 4, which showed a significant difference. The fatigue cracking tensile strain was calculated at the bottom of the pavement composition's two asphalt layers (surface and binder layers). In the pavement cross-sections, the computed horizontal strains under the surface and the binder layers of the conventional AC decreased dramatically by 20% (2.6E-06 & -1.7E-04) compared to the modified AC (-2E-05 & 2E-04). This is also due to the increase in the elastic modulus of the asphalt concrete layer.

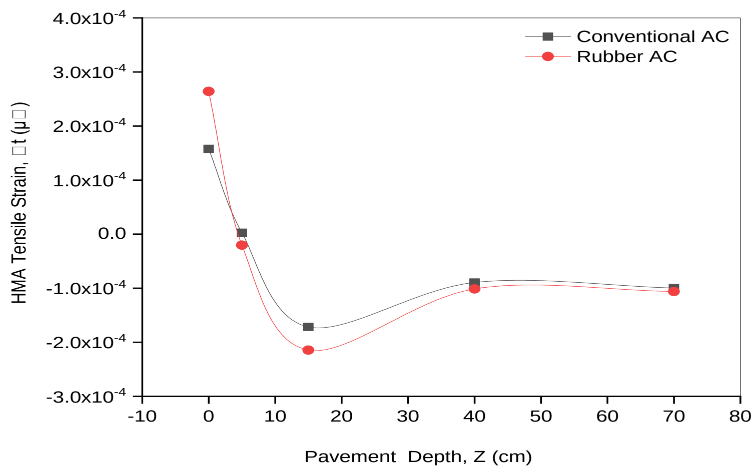

Figure 4: Computed Horizontal Tensile Strain

3.3 Vertical Compressive Strain

Rutting is typically followed by surface failure in the form of fatigue cracking in asphalt pavement. The computed vertical compressive strain for permanent deformation on the top of the sub-grade is identified in Figure 5. The compressive strain in the conventional AC decreased by 8% (1.57E-04) compared to the modified AC (1.69E-04). Unlike the vertical strains in other layers, the result of the vertical strain above the sub-grade is not significantly different from the computed fatigue strain in the binder layer.

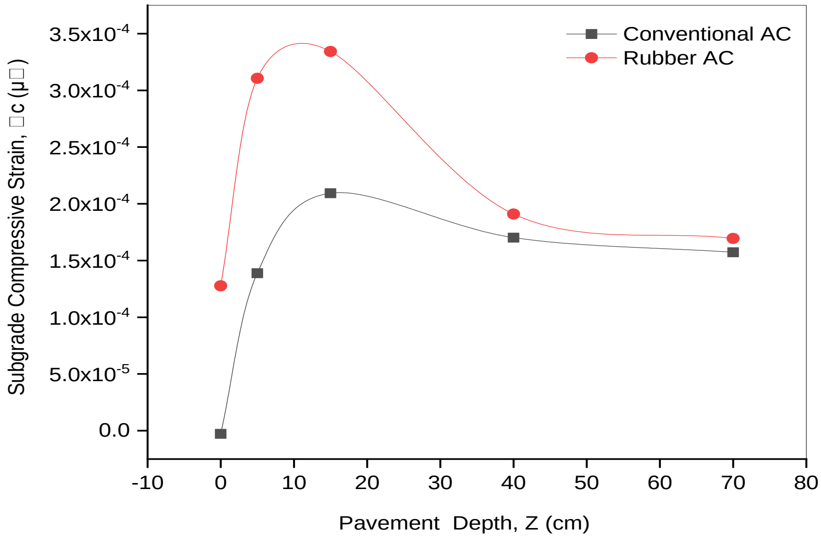

Figure 5: Computed Vertical Strain

3.4 Vertical Compressive Stress

In the pavement cross-sections, the vertical stress for both cases uniformly decreased from top to bottom for the conventional AC are (673.0 kPa, 579.2, 198.7, 58.9 and 22.3 kPa) and for the modified AC are (673.0, 599, 256.5, 68.3 and 24.4 kPa) respectively. Figure 6 illustrates the diagram of the vertical stress as it changes in pavement depth. It can be observed that the uniformed decrease in the vertical stresses demonstrates a satisfactory pavement composition.

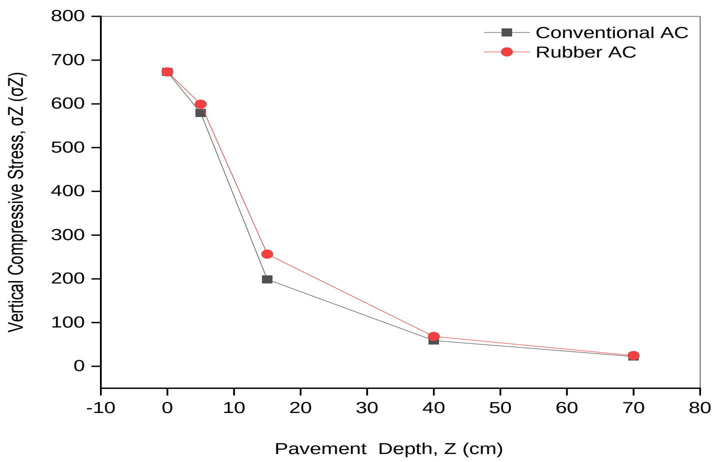

Figure 6: Computed Vertical Stress

3.5 Stiffness

Material stiffness is an essential factor that affects the performance of asphalt pavements. Experimentally, it can be determined by conducting the triaxial test. Additionally, it can also be achieved by measuring the deflection in response to load. A simple stiffness parameter was calculated by applying a standard wheel load that causes a deflection in the pavement. The stiffness for each layer was calculated and compared. Figure 7 presents the stiffness responses of both conventional and rubber AC. As can be observed, there was a general increase in stiffness with increasing pavement depth. Rubber AC also exhibited lower stiffness compared to conventional AC when the pavement depth was the same. In this scenario, the stiffness modulus of the lower layers is higher than that of the upper layers. Hence, it is appropriate to say that the rubber AC significantly decreases the surface layer's stiffness; as such, it eventually prolongs the rapid encroachment of fatigue cracking and rutting deformation.

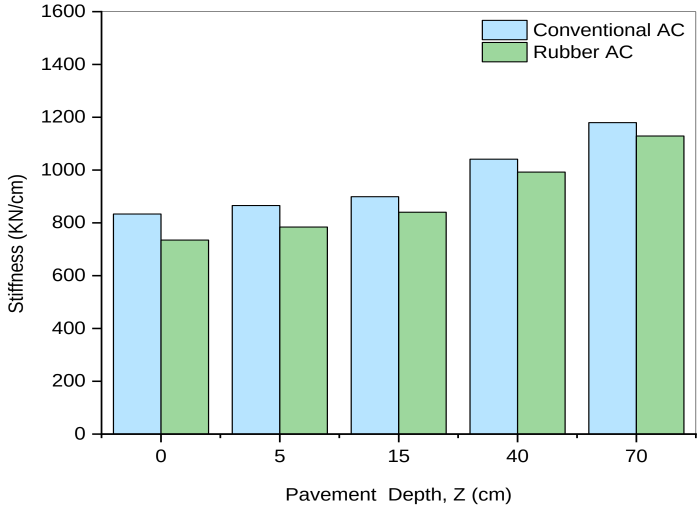

Figure 7: Computed stiffness

4. Conclusion

The evaluation of asphalt pavement cross-sections considered in this study under Tandem axle load of dual wheels using Kenlayer program to predict critical pavement responses was investigated and the following findings were drawn:

1. The computed top deflection in the conventional AC layer decreased by 11% compared to the modified HMA layer.
2. The predicted horizontal strains breath the conventional HMA surface layer decreased substantially compared to the modified HMA cross-section. Whereas, the vertical compressive strains on the top of the sub-grade reduced by 8% compared to the modified cross-section. The reduction in the strain values of the conventional cross-section was due to the increase in the material property of the HMA surface layer. Meanwhile, the computed strains at the critical points (bottom of AC and top of sub-grade) in each cross-section could be considered to check against the allowable strains in achieving the permissible number of load repetitions.
3. Due to material properties and layer thickness variances, the vertical stress level gradually decreased from the top to the sub-grade layer.

Finally, the modified HMA surface layer responded very well in reducing the pavement stiffness compared to the conventional HMA surface layer. The modified asphalt again contributed to the reduction of the material's stiffness modulus despite reducing its elastic modulus. It would also increase the pavement's endurance for fatigue life without further compromising deformation resistance, which is the pavement's overall benefit.

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