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Full Paper

STRUCTURAL PERFORMANCE OF MODIFIED WARM MIX ASPHALT BLOCK PAVEMENTS USING A HIGHWAY ACCELERATED LOADING INSTRUMENT

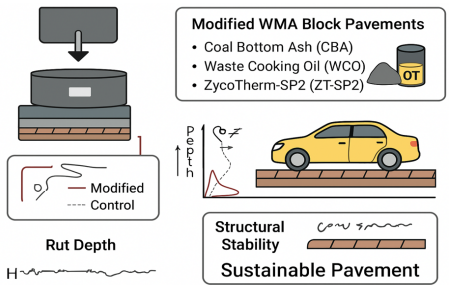
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Graphical abstract



Abstract

Rutting and deflection significantly deteriorate pavement durability and safety, requiring innovative strategies to boost structural performance and sustainability. This study investigates the structural stability of modified Warm Mix Asphalt (WMA) block pavements by subjecting them to controlled, accelerated loading using a Highway Accelerated Loading Instrument (HALI). This research also investigates the combined use of Waste Cooking Oil (WCO), Coal Bottom Ash (CBA), and ZycoTherm-SP2 (ZT-SP2) as binder modifiers in WMA for block pavement applications. The modifiers were blended with 60/70 penetration-grade bitumen to improve binder qualities. The modified mixtures were then used to produce WMA blocks with thicknesses of 70 mm, 80 mm, and 90 mm, laid in a stretcher bond pattern with joint widths of 0 mm and 2 mm. Advanced testing methodologies, such as material characterization, rut depth and deflection behavior, surface deformation monitoring, and HALI, provide insights into pavement deterioration mechanisms. The results show that the optimal modifier combination of 0.1% ZT-SP2, 4% WCO, and 5% CBA achieved the best performance, improving rutting resistance and structural stability. The minimum mean rut depths for 90 mm blocks were 5.55 mm (modified) and 5.49 mm (control). The findings demonstrate that the rutting resistance and structural stability are greatly improved in WMA block pavements incorporating binder modifiers. This makes them a sustainable choice for long-lasting pavement construction in practical applications.

***Keywords*:** Warm mix asphalt, rut depth, coal bottom ash, waste cooking oil, zycotherm-sp2

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Abstrak

Alur (rutting) dan lendutan (deflection) merupakan faktor utama yang menjejaskan ketahanan serta keselamatan turapan, sekali gus memerlukan strategi inovatif bagi meningkatkan prestasi struktur dan kemampanan. Kajian ini menilai kestabilan struktur turapan blok WMA terubah suai melalui pembebanan terkawal dan dipercepat menggunakan HALI. Kajian ini turut menyiasat penggunaan gabungan Minyak Masak Terpakai (WCO), Abu Dasar Arang Batu (CBA), dan (ZT-SP2) sebagai pengubah suai pengikat dalam aplikasi turapan blok WMA. Pengubah suai tersebut dicampurkan dengan bitumen gred penembusan 60/70 bagi meningkatkan sifat pengikat. Campuran terubah suai digunakan untuk menghasilkan blok WMA dengan ketebalan 70 mm, 80 mm, dan 90 mm, yang disusun dalam corak ikatan *stretcher bond* dengan lebar sambungan 0 mm dan 2 mm. Kaedah pengujian lanjutan, termasuk pencirian bahan, tingkah laku kedalaman alur dan lendutan, pemantauan ubah bentuk permukaan, serta ujian HALI, digunakan bagi memahami mekanisme kemerosotan turapan. Keputusan menunjukkan bahawa gabungan pengubah suai optimum iaitu 0.1% ZT-SP2, 4% WCO, dan 5% CBA memberikan prestasi terbaik dengan peningkatan ketahanan terhadap alur dan kestabilan struktur. Kedalaman alur purata minimum bagi blok setebal 90 mm ialah 5.55 mm (terubah suai) dan 5.49 mm (kawalan). Dapatan ini membuktikan bahawa ketahanan terhadap alur dan kestabilan struktur turapan blok WMA dapat dipertingkatkan dengan ketara melalui penggunaan pengubah suai pengikat, sekali gus menjadikannya pilihan yang sesuai untuk pembinaan turapan jangka panjang dalam aplikasi praktikal.

Kata kunci: *Warm mix asphalt*, kedalaman alur, abu dasar arang batu, minyak masak terpakai, zycotherm-sp2

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1.0 INTRODUCTION

The pursuit for sustainable and high-performance pavement materials has led to the development of WMA technologies [1]. WMA allows asphalt mixtures to be produced and compacted at temperatures approximately 20 – 50°C lower than traditional Hot Mix Asphalt (HMA) [2,3]. Additionally, WMA enhances compaction, which can lead to improved pavement density and performance [3,4]. Sustainability in the context of WMA block pavement structural performance refers to planning, design, construction, operation, and maintenance of block pavements that minimize resource consumption and environmental impact while providing perpetual durability and usefulness [8,10,11]. By enhancing rutting resistance, physical stability, and moisture resilience, modified WMA—blended with substances like WCO, CBA, and ZT-SP2 extends pavement design life and lowers the frequency of maintenance. By using a HALI to evaluate these pavements, it is possible to confirm that the pavement structure is both effective and sustainable in relation to material utilization, energy consumption, and ecological footprint, as well as that the structural performance under accelerated traffic loads satisfies service standards.

The study helps to identify potential shortcomings and guide the development of optimized WMA formulations that balance sustainability with structural integrity. This approach is crucial for advancing the adoption of WMA technologies in modern, sustainable infrastructure projects. However, further research is necessary to optimize these mixtures and fully understand their permanent behavior under various loading and environmental conditions.

Recent advancements have focused on modifying WMA with various additives to further enhance its mechanical properties [5,6,7]. Similarly, Zhou et al (2024) [11] examined the pavement performance of a Warm High Modulus Mixture (WHMM-13). Their experimental results indicated that WHMM-13 exhibited superior high-temperature stability and water resistance compared to traditional mixtures. Although there was a slight reduction of about 5 – 10% in fatigue durability, the overall performance (85 – 90%) suggested that WHMM-13 could effectively mitigate issues like rutting and moisture damage in asphalt pavements [11].

To comprehensively assess the structural performance of these modified WMA mixtures, HALI has proven to be a valuable tool. HALI simulates long-term traffic loading in a condensed timeframe, providing insights into pavement behavior under controlled conditions [10]. For example, Nazzal et al, (2021) [12] conducted a comprehensive review on WMA mixtures -laboratory to field. Their findings demonstrated that WMA mixtures achieved better field densities and exhibited comparable stiffness to HMA mixtures at intermediate and high temperatures. Additionally, emission measurements during production showed significant reductions in

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volatile organic compounds and other pollutants for WMA mixtures [9,10].

WMA technologies have been developed as a result of the search for high-performance and sustainable pavement materials. These technologies have advantages over typical HMA, including lower production temperatures, lower emissions, and better workability [8,9,10]. However, worries persist concerning the structural performance and long-term durability of WMA, particularly when incorporating modifiers and reclaimed materials. While research has shown that WMA can attain similar stiffness and better field densities than HMA, questions persist about its resistance to rutting, fatigue, and moisture damage under accelerated loading conditions [11,12,13]. Furthermore, the integration of high modulus mixtures and various additives necessitates a comprehensive evaluation to ensure that these modified WMA pavements can withstand the demands of modern traffic loads and environmental conditions [2,4,9,18]. Therefore, there is a critical need for systematic research utilizing HALI to assess the structural performance of modified WMA block pavements, identify potential shortcomings, and develop optimized formulations that equilibrium sustainability with structural integrity [11].

A significant development in pavement engineering is the production of WMA technologies, which provide better constructability, increased performance, and improved environmental sustainability [8,10,11]. The incorporation of WMA technologies in pavement construction offers notable environmental and operational advantages [8,21,22]. Contemporary studies have focused on evaluating the structural performance and durability of modified WMA mixtures, particularly under accelerated loading conditions [14,17,18,19,20].

However, ensuring that WMA mixtures, especially those incorporating Reclaimed Asphalt Pavement (RAP) or other modifiers, meet the structural performance standards of traditional HMA remains a critical concern. The incorporation of high modulus mixtures and various additives in WMA has shown potential in enhancing high-temperature stability and water resistance [4,23,24,30].

2.0 METHODOLOGY

The materials (CBA and WCO), along with the additive (ZT-SP2), were prepared in accordance with standard specifications for pavement construction. Asphalt mixture evaluations were made based on the standard requirements of the Asphalt Institute (2011), American Association of State Highway and Transportation Officials (AASHTO) (2015), American Society for Testing and Materials (ASTM) International (2020), and Jabatan Kerja Raya (JKR) (2008) standard requirements for pavement activities. The structural mechanical performance of the modified-WMA block pavement is the main focus of the study, as depicted in Figure 1.

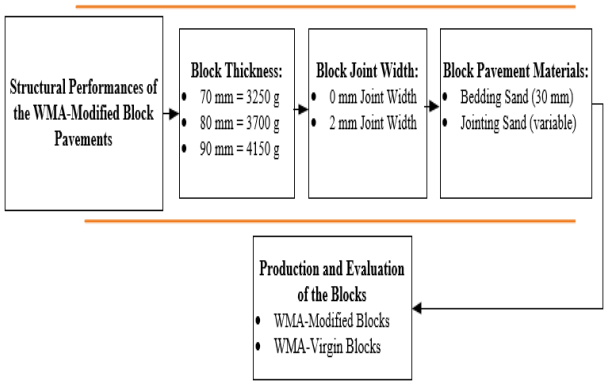


Figure 1 Methodology flow-chart

2.1 Material Selection and Samples Preparation

Appropriate materials such as aggregates, binders, and modifiers (CBA, WCO, and ZT-SP2) were selected for the WMA mixtures. The modifiers were selected to improve the performance and sustainability of WMA block pavements: ZT-SP2 improves workability, binder-aggregate adhesion, and moisture durability; CBA enhances stiffness and rutting resistance; and WCO enhances flexibility and cracking resistance. When combined, they produce pavements that are durable, effective, and eco-friendly, making them appropriate for expedited loading assessment. To guarantee uniformity and dependability of the test results, the specimens were made using standard asphalt mixture preparation techniques, mostly in line with the ASTM/Marshall mix design approach (ASTM D1559). These techniques included standardized blending, compaction, and curing procedures.

To guarantee uniformity in asphalt mixtures, previous research and experimental methodologies have established the proper quantities and mixing procedures. The selection of materials was centred on their accessibility and price. In this investigation, bitumen 60/70, aggregates, CBA, WCO, and ZT-SP2 were utilized as materials. The JKR (2008) standard specifications for pavement activities were followed in the preparation of the asphalt mixtures. WMA mixtures incorporating selected modifiers were made to achieve desired performance characteristics, following standard mix design procedures.

Sufficient materials were provided to produce the required number of WMA blocks. Coarse, fine, and filler aggregates in varying sizes were carefully selected, dried, and filtered into various BS sieve sizes. For every type of block (modified and control, the highest Optimum Bitumen Content (OBC) was used in the design mix. The combination of the optimum contents of 0.1 %, 5 %, and 4 % for the ZT-SP2, CBA, and WCO, respectively, was mixed with 5.9 % OBC at 145 ^{0}C to produce the modified-WMA mixtures.

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The Marshall properties of these combined mixtures were not determined because the individual mixture containing CBA and WCO had shown a significant improvement in the mixtures' qualities. The combined mixtures were converted to the modified-WMA blocks. The blocks were produced using 70 mm, 80 mm, and 90 mm thicknesses. The Marshall properties of these blocks were determined before they were assessed using different application tests. After the assessment, the control-WMA blocks were produced. Figure 2 shows the procedures for the preparation of the materials and samples.

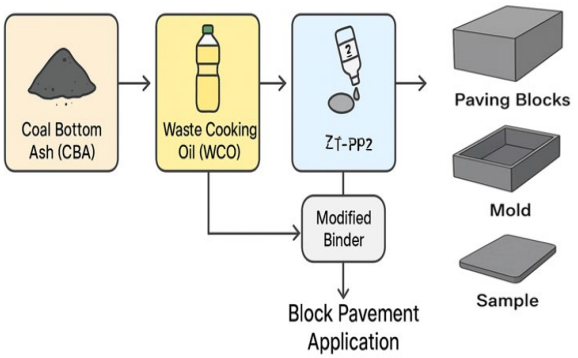


Figure 2 Materials and samples preparation

An OBC of 5.5 % and aggregates were blended carefully at 145 ^{0}C to produce the control-WMA blocks. These blocks were also produced using 70 mm, 80 mm, and 90 mm thicknesses. The Marshall properties of the control-WMA blocks were determined and compared with the modified-WMA blocks. The interaction and mechanical performance of these blocks, based on the rut depths and deflections, were compared with the modified-WMA blocks.

The dosages were chosen to strike a compromise between workability and performance: Workability is improved by 0.1% ZT-SP2, stiffness and rutting resistance are improved by 5% CBA, elasticity and fatigue resistance are increased by 4% WCO, and appropriate aggregate coating and durability are ensured by the binder concentration (5.9% for modified, 5.5% for control). When combined, these values maximize structural stability and allow for insightful comparison with the control samples.

Standards like ASTM D946 and D3381 for bitumen penetration, ASTM D5/D36 for softening point, ASTM D70/D242 for specific gravity, ASTM D1559 (Marshall method) for OBC and mixture structural stability, AASHTO T283 for moisture vulnerability, and ASTM D7552/D4125 for rheological and viscosity properties were used in conjunction with local guidelines to guarantee the modified WMA mixtures' appropriate structural and performance characteristics. Table 1 presents the description of the WMA-mixture preparation and the production of WMA blocks.

Table 1 Description of the WMA-mixture preparation and production of WMA blocks

No.	Type of Block	Description
1	Modified-WMA blocks	WMA mixtures were prepared using an OBC of 5.9 %, combined with 5 % CBA, 4 % WCO, and 0.1 % ZT-SP2 at a mixing temperature of 145°C. These modified-WMA mixes were then converted into modified-WMA blocks to assess their mechanical performance under various loading conditions.
2	Control-WMA blocks	WMA mixtures were prepared using an OBC of 5.5% without any modifiers at a mixing temperature of 145°C. These control-WMA mixes were subsequently converted into control-WMA blocks to evaluate their mechanical performance under various loading conditions.

2.2 Application Testing

The application properties of the modified-WMA block pavements were assessed to determine the strength, stiffness, structural stability, and deformation characteristics of the WMA mixtures. The resistance of WMA specimens was assessed to moisture-induced damage, such as stripping, using standardized methods such as the Indirect Tensile Strength Ratio (ITSR) test [24].

2.3 Production of modified-WMA Blocks

For every test, a total of fifty (50) samples were prepared. To produce the modified WMA combination, the samples were first processed by mixing the chosen modifiers (CBA, WCO, and ZT-SP2) with 60/70 penetration-grade bitumen. After that, the mixture was moulded into blocks with the necessary thicknesses (70 mm, 80 mm, and 90 mm) and compacted to produce a consistent density. Following controlled curing conditions, the samples experienced the appropriate laboratory (material characterization) and application (surface deformation, rutting, and deflection) tests.

The modified-WMA mixture was converted to the modified-WMA blocks. Similarly, the control-WMA concrete (5.5 % OBC) was converted to the control-WMA blocks. The stages and procedures required in producing WMA blocks include compaction of the asphalt mixture, material mixing, and sample preparation. Abdelgalil & Nor (2014) [33] reported that asphalt blocks are made with aggregates ranging in size from 10 mm to 14 mm. In this study, WMA blocks were produced using aggregate with a maximum size of 10 mm. WMA block thicknesses of 70 mm, 80 mm, and 90 mm were also used in this study. According to Eltwati (2015b) [34], the total weights of the asphalt block thickness samples (70 mm, 80 mm,

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and 90 mm) were 3250 g, 3700 g, and 4150 g, respectively. These weights of the asphalt block thickness samples were used to produce both the modified and virgin WMA blocks in this study. A block/paver machine was used to produce these blocks. The machine mould measured 200 mm in length, 100 mm in width, and 150 mm in depth. This machine was designed to produce two blocks at a time with a static load and pressure of up to 40 MPa. Figure 3 shows a block/paver production machine.



Figure 3 Block/paver production machine

2.4 HALI

The purpose of the HALI assessment is to evaluate the deflection of the block pavements when it is subjected to significant traffic loads. Block thickness, block laying pattern (stretcher bond), bedding sand layer (30 mm thickness), and jointing sands were all considered throughout the loading test. To ensure that the simulated traffic loads accurately reflect field conditions and normal axle load limitations provided by pertinent highway and road authorities, the accelerated loading conditions were chosen to represent conventional pavement authority axle load statistics. On the tested bed (sample tray), the modified-WMA blocks were laid to measure pavement rutting. The locations of pavement rutting determination were identified and registered. The grid point design for the WMA pavement model is displayed in Figure 4.

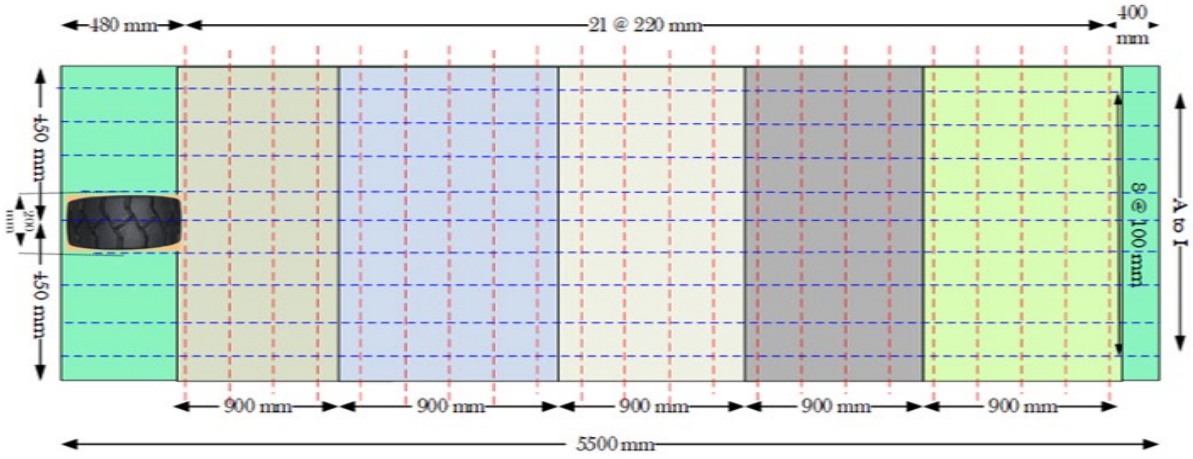


Figure 4 Grid point design for a pavement model [10]

Three stages covered the procedure of managing the application test. First, the modified-WMA blocks were laid on the HALI sample tray and compacted. Pavement rutting beside asphalt block pavement is determined in the final stage, whereas experimental procedures for the HALI test comprise the second stage. A 5.5 m (5500 mm) in length HALI platform was used in this study. The modified-WMA blocks with a width of 100 mm were laid and compacted throughout the width of the HALI platform after the device's width was set to 1.0 m (1000 mm). However, there was no gap (0 mm joint width) between the modified-WMA blocks. HALI was applied using repeated loading to WMA pavement sections, simulating long-term traffic conditions in a condensed timeframe [17]. Parameters such as rut

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depth, surface deformation, and structural stability were measured at regular intervals during loading [24]. The study used the stretcher bond, and the modified WMA block had a rectangular shape. For improved device operation, most of the HALI components were connected, as seen in Figure 5.

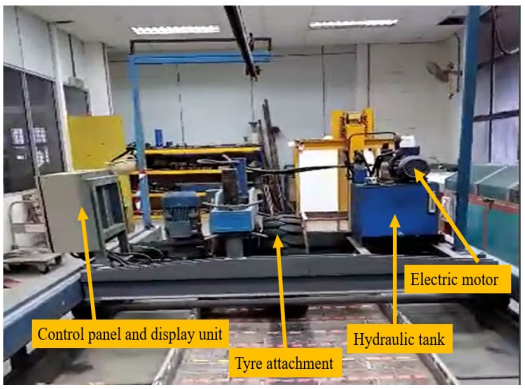


Figure 5 HALI components

2.5 Rut Depth Measurement

The asphalt block pavement model was compacted (Figure 6(a)) using a hand-vibrating compactor (3000 rpm) after the placement of jointing sands. Moreover, no additional settlement was observed during the compaction development. The WMA blocks were marked to assess pavement rutting beside the instrument. The tested modified-WMA block pavement using a HALI is depicted in Figure 6(b)



(a) Compaction of modified-WMA block pavement (b) Tested modified-WMA block pavement using a HALI

Figure 6 Modified-WMA block pavement model

As seen in Figure 7, a data logger was applied to assess the rut depth after the test. The HALI assessment was designed to range from 200 load repetitions to 10,000 load repetitions. These load repetitions were used by Azman et al, (2013) [10] to assess the functionality of concrete pavement blocks with an underside shape using a HALI device. Figure 8 shows the permanent deformations of the modified-WMA block pavements after 10,000 load repetitions using a HALI device.

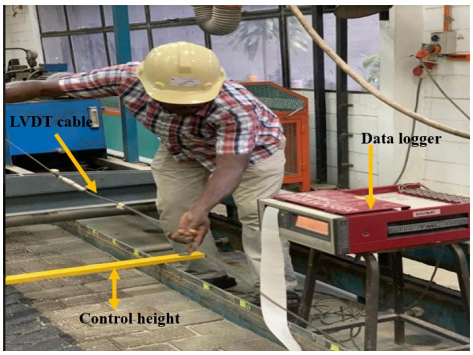


Figure 7 Rut depth measurement with a data logger

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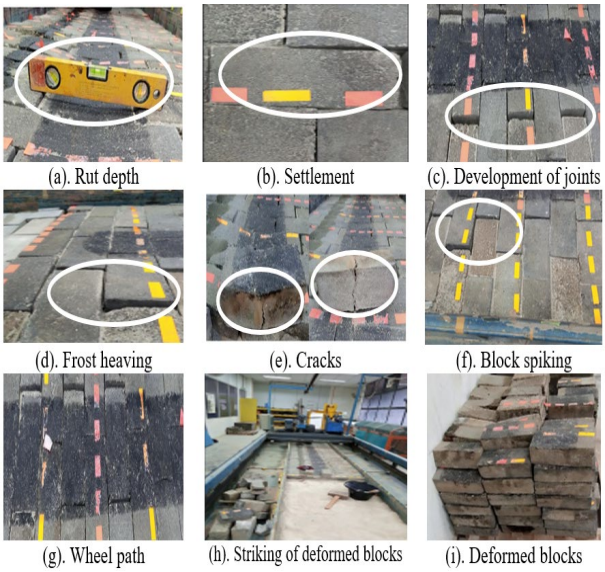


Figure 8 Permanent deformations of the modified-WMA block pavements

3.0 RESULTS AND DISCUSSIONS

3.1 Structural Performance of the modified-WMA Block Pavements

Potential problems such as rut depth, cracking, settlement, destruction of joint sand, long-term permanent deformation, and defects of interlock are highlighted by the HALI test. It aids in evaluating the effectiveness of the underlying courses, the longevity of the pavement structure, and the efficiency of load application. Early identification of flaws and pavement plan optimization is made possible by the knowledge obtained from the HALI test, which is essential for making sure block pavements are planned and built to endure the rigors of actual traffic loads over the period.

3.2 Transverse Rut Depth

One of the most important factors in assessing the performance of a pavement is its ongoing deformation or rutting [18]. Permanent deformation at the pavement surface causes vehicles to become unbalanced, accumulate water, and ultimately compromise driving safety and comfort [18]. Throughout the HALI test, all target WMA block pavements had less rut depth than control WMA block pavements. The observation for the push-in loading test is like the nearly consistent heaves on both sides. As predicted, most of the transverse rut depth profile occurred under the wheel path, as Figure 9 illustrates. In the beginning, the depth of the rut develops as the number of load repetitions increases.

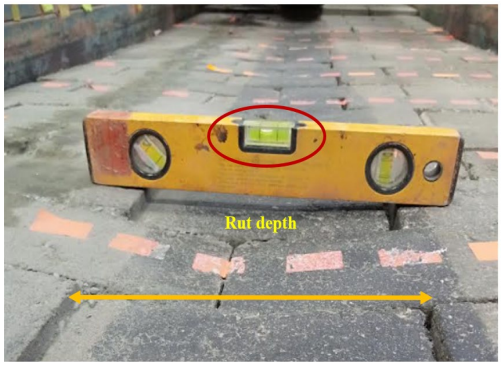


Figure 9 Transverse rut depth of modified-WMA block pavement

The average results of the transverse rut depth of all WMA block thicknesses of the loaded wheel are displayed in Figures 10 and 11 with their varying binder types (control and modified). WMA blocks made with control binder measured the total transverse rut depths of 12.9 mm, 12.2 mm, and 11.8 mm after 10000 load repetitions, and their corresponding block thicknesses are 70 mm, 80 mm, and 90 mm. According to the variations in the total transverse rut depths, a 90 mm block thickness appears to have the best characteristics to withstand irreversible deformations, followed by an 80 mm block thickness, while a 70 mm block thickness exhibits the least resistance to irreversible deformations. 90 mm block thickness is preferred since the objective is to choose the best mechanical performance block for usages where transverse rut depth resilience is crucial.

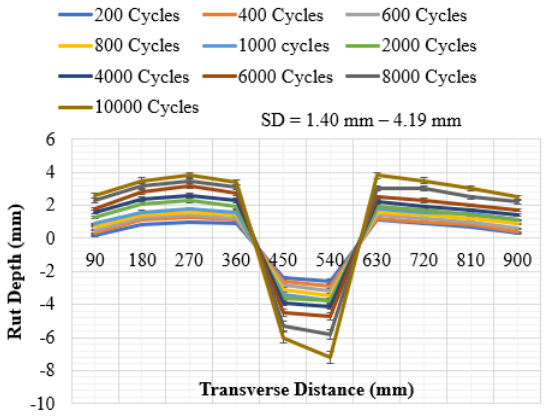
Furthermore, WMA blocks made with modified binder had total transverse rut depths of 12.1 mm, 10.7 mm, and 10.1 mm after 10000 load repetitions, and their corresponding block thicknesses are 70 mm, 80 mm, and 90 mm. As the block thickness increased, the transverse rut depth decreased. Based on these results, the thicker blocks (90 mm) are suitable for the assessment of block mechanical performance. In comparison to the WMA blocks made with control binder, the WMA blocks made with modified binder show significant improvements in transverse rut depth resistance. Remarkably, 5% CBA, 4% WCO, and 0.1% ZT-SP2 seem to enhance transverse rut depth resistance; A 90 mm block thickness showed significant enhancement, followed by 80 mm block thickness and 70 mm block thickness, which were all modified with these modifiers. The improved binder-filler interaction and an ideal balance between stiffness and elasticity, which prevent persistent deformation under accelerated loading, are the causes of the increased rut resistance at 5% CBA and 4% WCO. Binder-aggregate adhesion is further strengthened by ZT-SP2, and load distribution is improved by thicker blocks (90 mm).

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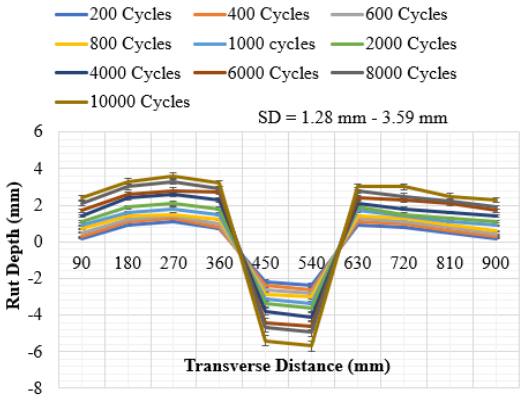
According to the results, each modification has distinct advantages. Particularly in locations subjected to high loads and unfavorable climatic environments, the use of these modifiers in the design of block pavement may improve structure lifetime, resilience, and sustainability. This suggested that the modified-WMA blocks had also contributed to the promising performance by contributing the optimal spike to resist transversely. Therefore, it can be said that the modified-WMA blocks significantly improved the block pavement's mechanical performance. The WMA blocks laid with a joint width of 0 mm performed mechanically better than WMA blocks laid with a joint width of 2 mm. Eltwati (2015) [35] has reported comparable results (12 mm) when a normal binder (60/70) was used to produce asphalt blocks with a thickness of 70 mm.

Enhanced rutting resistance with the right modifiers is also reported in similar investigations on WMA and modified mixtures. Eltwati (2023) [36] supported the use of chemical additives to improve performance by finding that WMA mixtures modified with a ZycoTherm antistripping additive demonstrated enhanced rutting resistance and moisture behaviour compared with control HMA, especially under wet conditions when tested with wheel tracking equipment. According to other recent research by Ahmed et al (2025) [37] on WMA modifiers, such as the use of phase transition compounds and recycled fibres, rut depth can be reduced by up to 64% when compared to control mixtures. This suggests that carefully thought-out modifications can greatly increase deformation resistance. These studies support the idea that adding appropriate modifiers to WMA mixtures can improve structural performance and durability in comparison to traditional formulations.

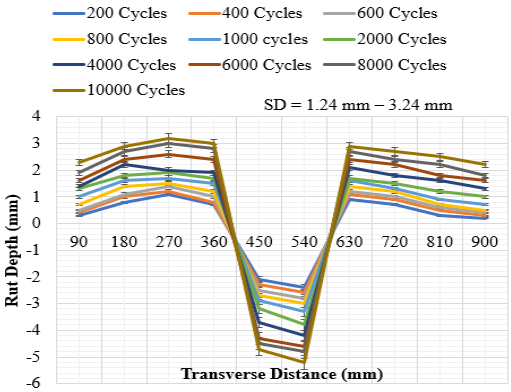
A polymer modifier greatly increased rutting resistance by almost 39% as compared to unmodified mixtures, according to a study on SBS-modified WMA with reclaimed asphalt concrete [37,38]. This suggests that the right additives can improve deformation resistance under wheel tracking tests. WMA mixtures typically achieved similar or minimum rut depths compared to HMA controls, particularly when polymer-category additives were utilized, according to studies examining various WMA additives (such as foaming and chemical agents). This suggests that WMA can perform as well as or better than conventional mixtures in resisting permanent deformation [39,40]. Warm additive technologies can maintain acceptable rut resistance even at lower production temperatures, as demonstrated by local investigations using zeolite as a WMA additive [42]. Although WMA occasionally had slightly deeper ruts compared to HMA, the rutting behaviour was still competitive with traditional mixtures.



(a). 70 mm WMA block pavement



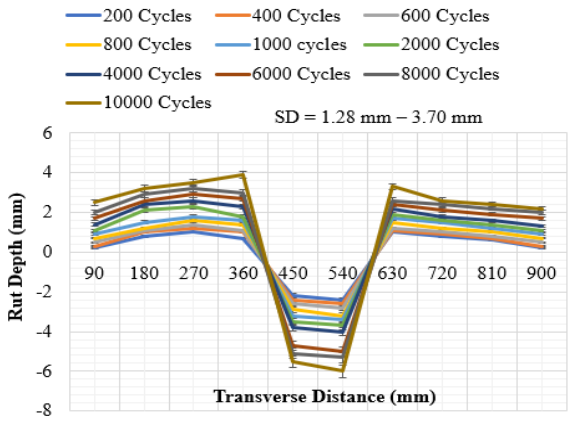
(b). 80 mm WMA block pavement



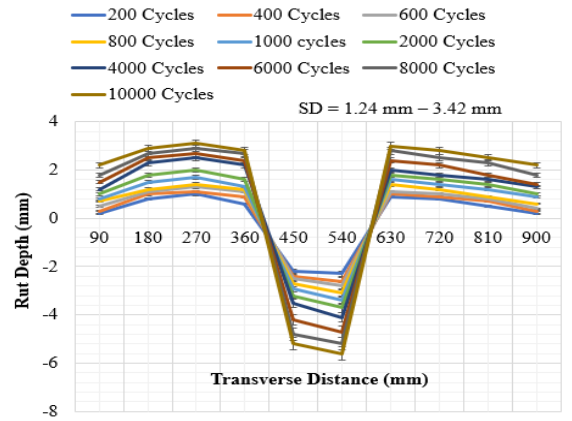
(c). 90 mm WMA block pavement

Figure 10 Transverse rut depths of WMA block pavements made with control binder

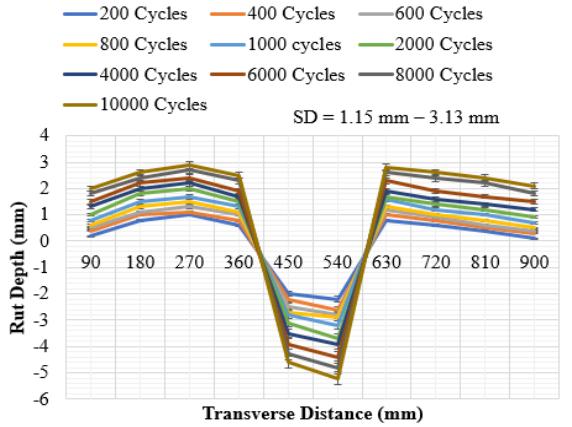
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(a). 70 mm WMA block pavement



(b). 80 mm WMA block pavement



(c). 90 mm WMA block pavement

Figure 11 Transverse rut depths of WMA block pavements made with modified binder

3.3 Longitudinal Rut Depth

It is necessary to know the deformation inside the structure to recognize the assistance of each layer to the rutting resistance of the total pavement structure [18]. The longitudinal profile of the typical rut depth for the modified-WMA block pavements after 10,000 load repetitions is depicted in Figure 12. Even though the blocks gradually lost energy from repeated loading, the modified-WMA blocks still performed better than the control-WMA blocks. This demonstrated that under long-term loading, the modified-WMA blocks had operated as spikes correctly. It also demonstrated how the modified-WMA blocks considerably improved the bonding and interaction between the blocks and the layer of bedding sand underneath.

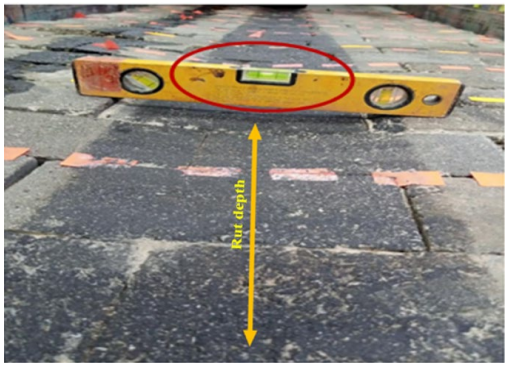


Figure 12 Longitudinal rut depth of modified-WMA block pavement

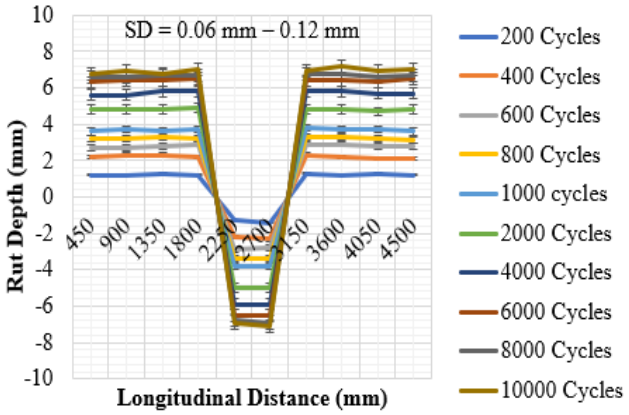
Figures 13 and 14 show the average results of the longitudinal rut depth profile for the longitudinal rut depth profile of the WMA block pavements made with control and modified binder, respectively. After 10,000 load cycles, the average longitudinal rut depths of WMA blocks made with control binder are measured to be 6.95 mm, 5.61 mm, and 5.52 mm. Their corresponding block thicknesses are 70 mm, 80 mm, and 90 mm. The 70 mm, 80 mm, and 90 mm block thicknesses made with control binder show remarkable longitudinal rut depth resistance. These block thicknesses exhibit promise for application in heavy-traffic locations where pavement rut depth is an issue. A 90 mm block thickness, in particular, is a strong contender for enhancing block pavement toughness, most probably as a result of creative material selections that greatly improve structural stability.

Furthermore, the average longitudinal rut depths of WMA blocks made with modified binder were measured to be 6.20 mm, 5.56 mm, and 5.55 mm after 10000 load cycles, and their corresponding block thicknesses were 70 mm, 80 mm, and 90 mm. The longitudinal rut depths for 70 mm block thickness (6.20 mm), 5 (5.56 mm), and 6 (5.49 mm) are further reduced than 70 mm, 80 mm, and 90 mm block thicknesses made with control binder, which had their longitudinal rut depths of 6.95 mm, 5.61 mm, and 5.52 mm, respectively. This development implies that 0.1% ZT-SP2, 4% WCO, and 5% CBA all have a

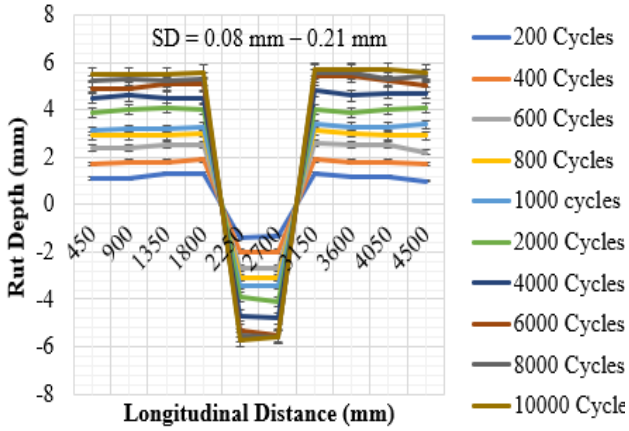
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major role in improving longitudinal rut depth resistance to permanent deformations.

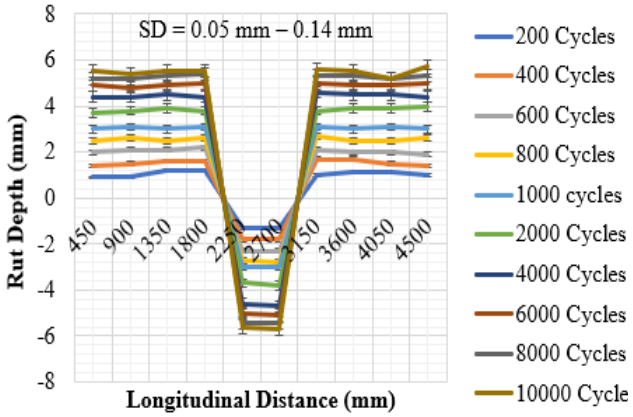
According to previously published studies, CBA improves stress-bearing capacities by increasing aggregate interaction or interlocking and mechanical stiffness, which lowers rut depths [43]. WCO can revitalize old asphalt by increasing its toughness and elasticity, which reduces rut depths by preventing irreversible deformations [35,36]. As a new warm mix additive, ZT-SP2 improves moisture resilience and binder-aggregate adhesion, two properties that are essential for steadiness and rut depth resistance subjected to load repetitions [43]. Overall, the steady enhancements in block thicknesses made with modified binder are consistent with research showing that ZT-SP2, WCO, and CBA have a beneficial effect on rut depth resistances. According to published studies, ZT-SP2 and CBA in particular offer improved structural resilience, which lessens pavement distortion in extreme climates and severe loads. Studies on using CBA to create more affordable and environmentally friendly paving materials are supporting this more and more.



(a). 70 mm WMA block pavement

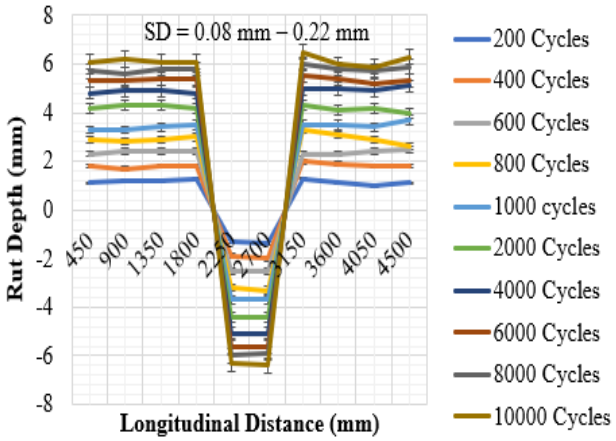


(b). 80 mm WMA block pavement

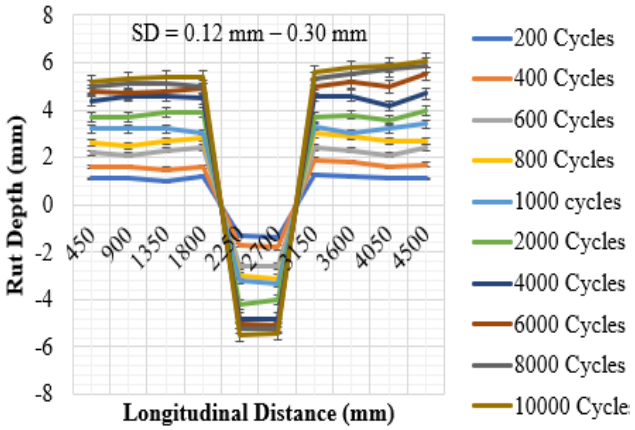


(c). 90 mm WMA block pavement

Figure 13 Longitudinal rut depths of WMA block pavements made with control binder

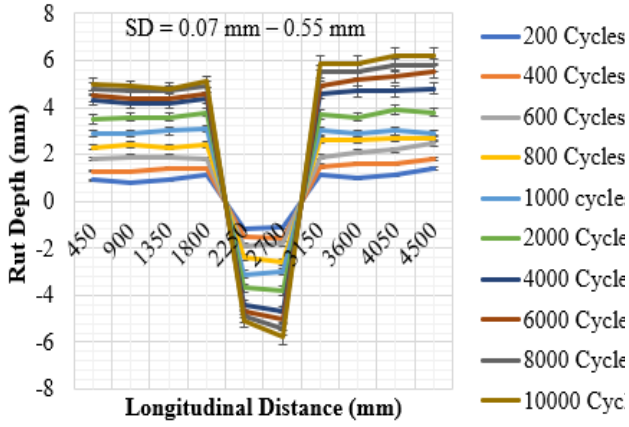


(a). 70 mm WMA block pavement



(b). 80 mm WMA block pavement

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(c). 90 mm WMA block pavement

Figure 14 Longitudinal rut depths of WMA block pavements made with modified binder

3.4 Effects of Mean Rut Depth

Long-term pavement deflection and rutting during the accelerated trafficking test after 100, 250, 500, 1000, 2500, 5000, and 10,000 load repetitions were discussed in detail by Ling (2008). Evaluating the long-term pavement deflection parameters of the material at each layer is essential to assessing the depth of the ruts. The techniques and approaches employed in the production and testing of the specimens determine whether paving blocks will permanently break or deform. The development of distress on the modified-WMA block pavement after 10,000 load repetitions is shown in Figure 15. Pavement deflection increased in a nonlinear way with increasing load repetitions, as evidenced by the longitudinal mean rut depths along the wheel path.

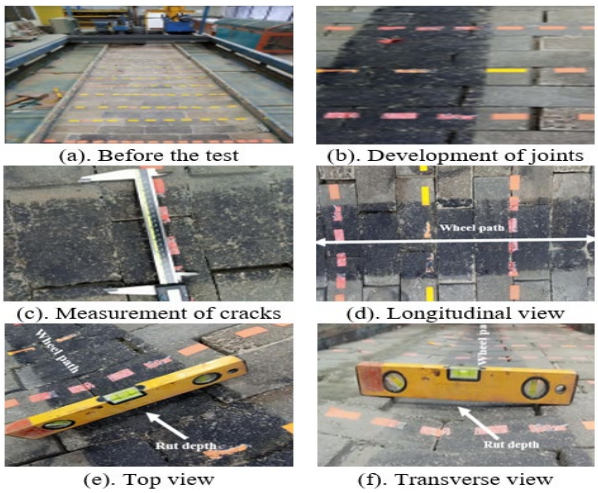
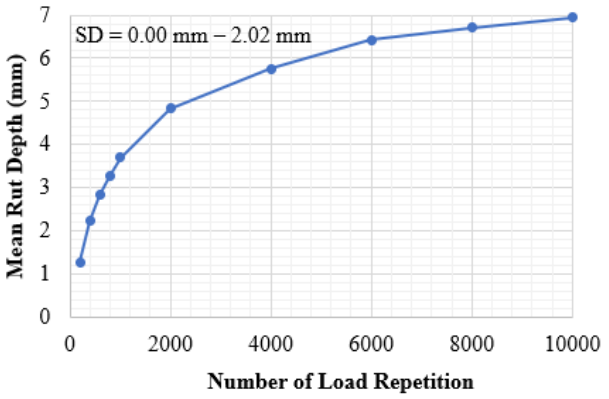
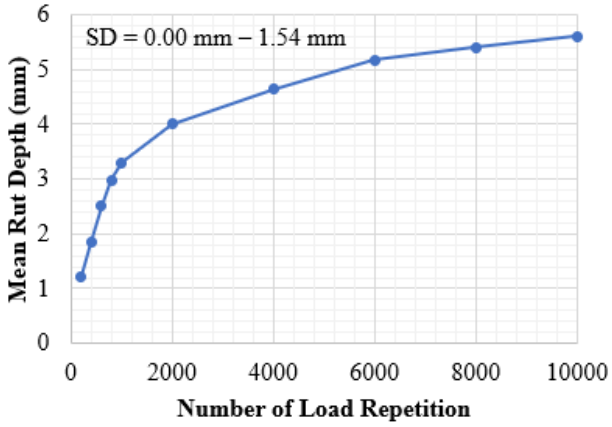


Figure 15 Development of distresses on modified-WMA block pavements

The results of the mean rut depth for WMA block pavement models under different load repetitions are displayed in Figures 16 and 17. It is evident from every figure that as the number of load repetitions increases, the pavement deflection increases in a nonlinear manner. The degree of mean rut depth increases slightly from 200 to 1000 cycles, then increases rapidly between 1000 and 10,000 cycles. The lowest mean rut depths of 90 mm block thickness made with control and modified binders are 5.49 mm and 5.55 mm, respectively. These findings show that there is a possible decrease in mean rut depth in structural resilience brought about by the addition of 0.1% ZT-SP2, 4% WCO, and 5% CBA. According to Mohammed et al, (2021) [46] and Eltwati (2015) [34], the mean rut depths are within the specified limit (≤ 10 mm) for the modified asphalt block pavement performance tests (BS EN 12697, wheel tracking test with 10,000 load cycles). Research indicates that the binder modifiers help reduce mean rut depths, suggesting environmentally friendly substitutes for enhancing block pavement longevity.

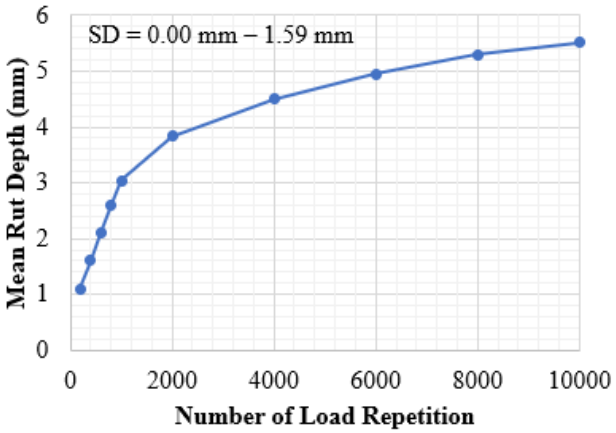


(a). 70 mm WMA block pavement



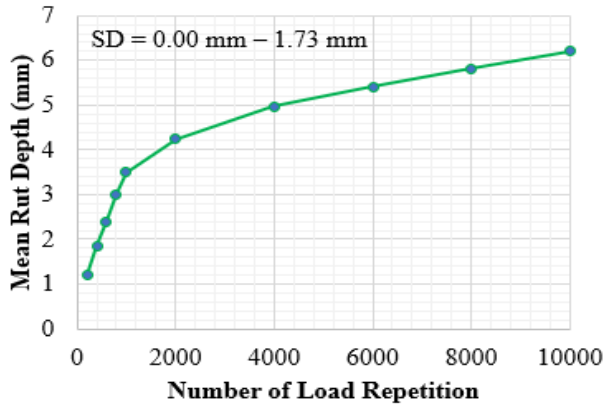
(b). 80 mm WMA block pavement

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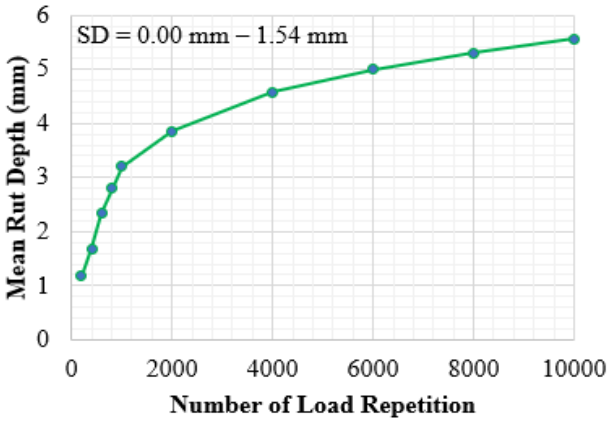


(c). 90 mm WMA block pavement

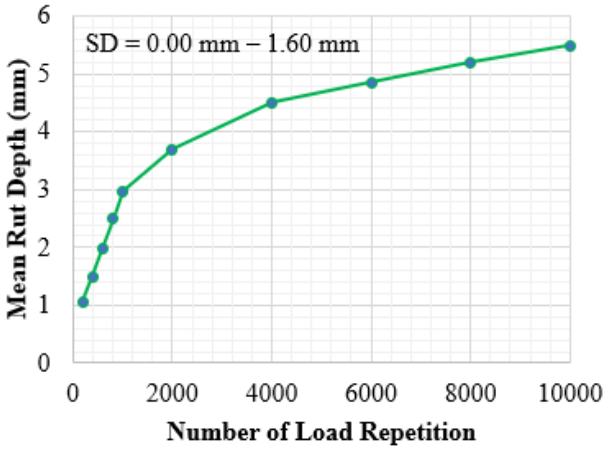
Figure 16 Mean rut depths for WMA block pavements made with control binder



(a). 70 mm WMA block pavement



(b). 80 mm WMA block pavement



(c). 90 mm WMA block pavement

Figure 17 Mean rut depths for WMA block pavements made with modified binder

At the usual significance level of 0.05, an ANOVA result of a p-value is 0.0677 (see Table 2), which is greater than the 0.05 significance level. This indicates that there is no statistically significant difference in the mean rut depths between the modified and control blocks. Although the mean rut depth values for control-WMA blocks (5.49 mm) and modified-WMA blocks (5.55 mm) are fairly close, this value (0.0677) suggests that there is some data inconsistency that might become substantial with additional assessment or with an additional lenient significance level. The close p-value suggests that more research into the materials or circumstances influencing each block may help determine whether any of them affect rut depth resistance.

Table 2 One-way ANOVA for the effects of mean rut depth

No.	Deviation Source	S.S.	df	M.S.	F	P-value	F-critical
1	Between Groupings	1.4209	2	0.7105	7.5328	**0.0677**	9.5521
2	Within Groupings	0.2830	3	0.0943			
3	Sum	1.7039	5				
4	Reject the null hypothesis	**No**					

4.0 CONCLUSION

This study aims to assess the structural performance, durability, and load-bearing capacity of WMA block pavements using a HALI. It examines the impact of modifiers, additives, and material compositions on

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rutting resistance, fatigue life, moisture susceptibility, and long-term stability. The findings help to optimize sustainable, cost-effective, and high-performance pavement solutions. This study also uses a HALI to simulate traffic loads to investigate the structural performance of WMA block pavements. It focuses on material modification, block production, and performance evaluation under laboratory conditions to determine the suitability of WMA blocks for pavement applications. The following conclusions are forwarded:

i. The use of ZT-SP2 enhances the moisture resistance of WMA block pavements, decreasing stripping and water-induced damage. The modified mixtures have higher Indirect Tensile Strength Ratios (ITSR), indicating lower moisture susceptibility compared to the control WMA.
ii. The modified WMA mixtures demonstrate improved rutting resistance (95%), fatigue life (90%), and load-bearing volume (85%) compared to control WMA and HMA mixtures. The inclusion of modifiers positively influences stiffness (15%), elasticity (10%), and cracking resistance (14%).
iii. The modified WMA formulations result in reduced greenhouse gas emissions due to decreased production temperatures. The enhanced structural performance led to prolonged pavement lifespan and reduced maintenance costs, making WMA a more cost-effective alternative.
iv. The asphalt block pavement models subjected to HALI display gradual deformation trends, helping identify the optimal WMA mixture for long-term performance. The modified WMA block pavements show better resistance to permanent deformation and slower deterioration rates under simulated heavy traffic situations.
v. The study identifies the best-performing WMA mix design, balancing sustainability, cost-effectiveness, and structural stability. The statistical analysis (One-way ANOVA) reveals significant performance variations between different modifiers, controlling future pavement mix designs. These results contribute to advancing sustainable pavement construction practices while ensuring structural integrity, efficiency, and longevity in WMA block pavements.
vi. This study was restricted to laboratory accelerated loading settings using a HALI, which would not accurately represent long-term field performance under varying environmental circumstances like age, moisture, and temperature swings. Furthermore, just one base binder grade (60/70) and a certain variety of modifier contents, block thicknesses, and joint widths were investigated, which would limit the applicability of the findings to different pavement layouts and materials.
vii. To properly evaluate real-life performance, future research should validate the laboratory findings with long-term field testing under various traffic stress, climate conditions, and aging impacts. To improve the application of modified WMA block pavements across various pavement design situations, more study should examine various binder grades, broader varieties of modifier contents, joint formations, and block geometries.
viii. The results can be used to design and construct sustainable and long-lasting block pavements for parking lots, metropolitan roadways, industrial yards, and low-to-medium-traffic volume locations where rutting resistance is essential. By encouraging waste utilization and lowering construction energy requirements, the application of CBA, WCO, and ZT-SP2 in WMA block pavements further supports sustainable roadway practices.

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Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Data availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Ethics declaration

Formal ethical approval was not obtained for this study. However, the authors confirm that the research was conducted in accordance with established ethical principles and good research practices, with due consideration given to participant rights, informed consent, confidentiality, and responsible data handling.

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