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**RESEARCH ARTICLE**

## Highway Engineering

# Use of carbonised wood particles as filler replacement in hot mix asphalt

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**Abstract:** This study investigated the feasibility of using carbonised wood particles (CWP) as a sustainable filler replacement in hot mix asphalt (HMA), addressing both environmental concerns and construction material performance. Despite considerable research, the moisture susceptibility of HMA modified with CWP, possessing a wider particle size distribution, remains unestablished. Twenty five HMA mixes with varying CWP content (0 to 40 g, equivalent to 0 – 24% filler replacement by mass) and asphalt content (4 – 6%) were evaluated against ASTM standards for their Marshall stability and indirect tensile strength, moisture susceptibility, and water absorption. The results indicate a clear trade-off: incorporating CWP improved physical properties like void structure but significantly reduced the mechanical strength and moisture resistance. Marshall stability and indirect tensile strength decreased by up to 79% and 75%, respectively, with higher CWP contents. The study conclusively identified 12% CWP replacement (20 g) as the optimal dosage. This proportion maintains acceptable performance for medium-traffic highways while delivering significant sustainability benefits by reducing reliance on quarried mineral filler and repurposing industrial waste. This optimal balance offers a viable pathway for more eco-friendly pavement construction without compromising critical performance criteria for specific applications.

**Keywords:** Carbonised wood particles, hot mix asphalt, mineral filler, indirect tensile strength, Marshall properties.

## INTRODUCTION

Hot mix asphalt (HMA) is the primary material used in the construction of flexible pavements. Typically, HMA consists of variously sized aggregates bonded together by asphalt. Aggregates constitute roughly 95% of HMA by weight (Ahmedzade & Sengoz, 2009; Sargın et al., 2013; Sapkota et al., 2023). The need for greater quantities of aggregates in HMA production has led to increased demand for quarrying (Akbulut & Gürer, 2007; Huang et al., 2007). However, the depletion of natural resources has raised serious concerns regarding the sustainability of pavement construction (Jegatheesan et al., 2020; Rengarasu et al., 2020). Escalating prices resulting from diminishing availability of natural resources have become a pressing issue in the global highway construction industry, particularly in countries where construction costs are a significant concern. Consequently, the pursuit of low-cost alternative materials to natural aggregates in HMA holds substantial priority in numerous countries.

The use of waste or industrial by-products, after some preprocessing, as an alternative to natural aggregates in highway construction (Jegatheesan et al., 2017; Jegatheesan et al., 2020; Rahman et al., 2020; Jegatheesan et al., 2021; Hoy et al., 2024), has gained global traction. Sawdust emerges as a potential alternative material, although it has received less attention in previous studies compared to other industrial byproducts, similar to fly ash or slag. In Sri Lanka, and indeed globally, significant quantities of sawdust are generated as waste from timber processing, with much of it being disposed of through landfilling or open burning, raising environmental concerns (Perera et al., 2005; Shyamalee et al.,

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2015). With nearly 4,000 sawmills and 680 furniture manufacturers producing 112,000 MT of sawdust annually as waste in Sri Lanka alone (Shyamalee et al., 2015), the viability of using wood sawdust as a substitute for HMA material has been the subject of numerous previous investigations (Xue et al., 2014; Jegatheesan et al., 2017; Osuya & Mohammed, 2017; Yasanthi et al., 2017; Guesmi et al., 2024; Karati & Kumar Roy, 2024).

Mineral filler, which consists of the portion of aggregate passing through the ASTM No.200 sieve, plays a crucial role in packing the mix to regulate air voids in HMA samples (Huang et al., 2007; Osuya & Mohammed, 2017). The body of research exploring sawdust in HMA primarily focuses on its use in two forms: as processed ash or as carbonised particles. Early work by Marteano et al., (2002) investigated partial replacement with raw sawdust, finding that a 50% replacement blend approached the characteristics of control samples (Marteano et al., 2002). However, the study lacked a comprehensive analysis of potential negative effects, such as binder drainage or long-term durability.

Subsequent research has largely focused on sawdust ash (SDA), obtained by combusting sawdust. Studies have shown that SDA, rich in Calcium Oxide (CaO), can improve the viscosity and rutting resistance of the asphalt binder (Adlinge et al., 2013; Xue et al., 2014; Hämäläinenet et al., 2025). Osuya & Mohammed (2017) reported enhanced bulk and strength properties with a 15% SDA replacement, while Yasanthi et al. (2017) observed a decrease in Marshall stability, indicating a potential compromise in medium-temperature stability. More recent investigations have explored optimal blend ratios; Boura & Hesami (2020) determined that a combination of limestone with 25% SDA could yield higher tensile strength than control mixes. However, a critical limitation of these SDA studies is the assumption that only the fraction passing through the 0.075 mm sieve (traditional filler size) is valuable, potentially overlooking the utility of larger particulate fractions.

An alternative approach involves using CWP, Jegatheesan et al. (2020) demonstrated that when processed sawdust was utilised as filler with polymer-modified bitumen, the strength properties of the HMA were enhanced. This suggests that the carbon structure of CWP may interact differently with the asphalt binder compared to the ash form. Furthermore, controlled carbonisation yields a residue with a wide particle size distribution, offering the potential to replace a broader range of aggregate particles, not just the fine filler fraction. This presents a significant opportunity to increase the volume of waste material utilised per ton of HMA produced.

Despite these advancements, two critical research gaps remain unaddressed. First, the moisture susceptibility of HMA modified with CWP has not been thoroughly established or mechanistically explained in prior literature. The highly porous nature of CWP raises valid concerns about water absorption and its impact on adhesive failure, which are critical for long-term pavement performance. Second, a small number of characteristics have been the subject of numerous earlier studies. A comprehensive evaluation encompassing volumetric properties, strength, moisture sensitivity and water absorption is necessary to fully understand the viability of CWP.

This study, therefore, aims to fill these gaps by conducting a systematic investigation into the feasibility of replacing the filler portion of HMA with CWP. The feasibility is comprehensively assessed based on a holistic suite of tests, including physical properties, Marshall strength properties, Indirect tensile strength, and critically, moisture susceptibility through tensile strength ratio, retained Marshall stability, and water absorption kinetics. The study explicitly determines the optimal replacement level that balances performance with sustainability goals.

## MATERIALS AND METHODS

Broken stones and stone dust were used as the conventional materials in this study. For detailed descriptions of the conventional materials used in this study, please refer to Jegatheesan et al., 2020 and Jegatheesan et al., 2021. Carbonised wood particles were used as an alternative material to the filler of HMA. Wood sawdust undergoes a process of losing free and hygroscopic water as the temperature increases, with carbonisation commencing when the temperature exceeds 270 °C (Fung et al., 2006; Dias et al., 2016). To prevent the entire sawdust sample from turning into ash, the sample was heated only to its minimum ignition temperature of 400 °C (Fung et al., 2006). The wood sawdust sample, sourced from Albizia (*Albizia julibrissin*), was carbonised in the laboratory under air-tight conditions. The resulting CWP, characterised by an apparent specific gravity of 0.61 and absorption of 5.8%, were then dry sieved through a 1.18 mm sieve (No.16, ASTM C136), and the portion passing through was utilised. The gradation of CWP is depicted in Figure 1.

The mix proportions of combined aggregates and CWP were determined according to the ASTM D3515-01 design specifications, specifically adhering to the gradation requirements of the dense mix designation of 'D-4'. These gradation limits are outlined in Table 1.

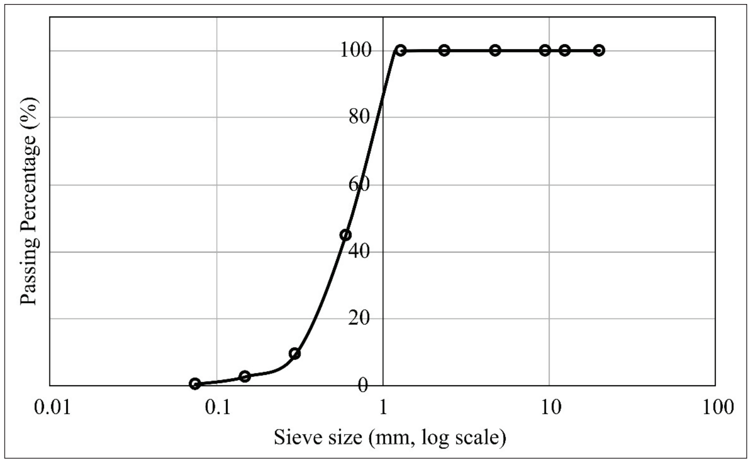


**Figure 1:** Particle size distribution of CWP (carbonised wood particles)

**Table 1:** The gradation limit for dense mix designation of 'D-4' given in ASTM

| Sieve size (mm) | 20 | 9.5 | 4.75 | 2.36 | 0.3 | 0.075 |
|---|---|---|---|---|---|---|
| Lower limit (%) | 90 | 56.0 | 35.0 | 23.0 | 5.0 | 2.0 |
| Passing (%) | 100 | 65.9 | 44.7 | 32.5 | 11.3 | 2.4 |
| Upper limit (%) | 100 | 80 | 65 | 49 | 19 | 8 |

The determination of particle size distribution of aggregates of different sizes is crucial in establishing the mix proportions of the aggregates in HMA (Kandhal & Mallick, 2001).

In this study, Marshall specimens with and without CWP were prepared according to ASTM D6926 specifications. Twenty five different HMA mixes were investigated, with CWP contents ranging from 0 to 40 g at 10 g intervals and asphalt contents ranging from 4% to 6% at 0.5% intervals. Here, 0 g CWP denotes the control sample. The CWP replacement levels were selected on a weight basis as 0 g, 10 g, 20 g, 30 g, and 40 g. This corresponds to a replacement of 0%, 6%, 12%, 18%, and 24% of the mass of the conventional mineral filler, respectively. This range was chosen for the following four reasons:

1. Incremental progression: The 10 g increments (approximately 6% mass replacement intervals) provide a systematic and sufficiently wide range to clearly observe trends and potential threshold effects. A finer increment would significantly increase the number of samples and laboratory workload without necessarily providing proportionally greater insight, while a coarser increment might miss critical performance changes.
2. Capturing a performance spectrum: The range from 0% to 24% replacement was designed to capture the full spectrum of behaviour, from performance nearly equivalent to the control to a significant degradation of properties. This allows for the clear identification of an "optimal" range where benefits are maximised, and drawbacks are minimised, as well as a "failure" point where the mixture becomes unacceptable.
3. Bridging past research: The selected range encompasses and extends beyond the replacement levels found in previous literature. For instance, studies on sawdust ash often focused on replacements up to 15-25% (Osuya & Mohammed, 2017; Boura & Hesami, 2020). By testing up to 24%, this study investigates the upper practical limit of CWP incorporation.

4. Practicality and statistical significance: Testing five distinct CWP levels, each at five asphalt contents and with three replicates, resulted in a total of 75 specimens. This provided a robust data set for statistical analysis while remaining a logistically feasible number of samples to produce and test under controlled conditions.

A volume-by-volume replacement approach was employed in this study. Because, replacing the filler on a weight basis would result in an increase in specimen volume (Mahmoud et al., 2013; Kuity et al., 2014), given a significant disparity between the specific gravity of CWP (0.61) and the conventional filler of HMA (2.71).

To elaborate, 10 g, 20 g, 30 g, and 40 g of CWP were utilised to substitute 6%, 12%, 18%, and 24% of the mass of filler in HMA, respectively. During the batching process, CWP and aggregates were preheated to a mixing temperature of 165 °C before being mixed with the asphalt binder. Compaction was promptly carried out using a Marshall hammer following ASTM D6926 at 135 °C immediately after the completion of mixing.

Initially, the physical properties of HMA were assessed, including bulk specific gravity (ASTM D2726), voids filled with binder, voids in mineral aggregate, and voids in the mix. Subsequently, specimens underwent the Marshall test to determine stability and flow values (ASTM D6927).

For each CWP modification, the optimal rates of conventional aggregates, CWP, and asphalt content were determined, considering the properties and standards utilised in the Marshall mix design.

The durability of HMA specimens, fabricated with optimal asphalt content for each CWP content, was further examined. Moisture within the HMA can cause adhesive or cohesive failure between asphalt and aggregate (Do et al., 2019), a longstanding concern recognised as a primary cause of pavement distress.

Consequently, the moisture sensitivity of optimum CWP-modified HMAs was assessed, taking into account the tensile strength ratio (ASTM D4867), retained Marshall strength, and water absorption. Two groups of optimum CWP-modified specimens, one moisture-conditioned and the other unconditioned, were analysed to evaluate the tensile strength ratio.

The first group of specimens was immersed in water at 60 ± 1 °C for 24 hours, while the second group was left to stabilise at room temperature. Indirect tensile strength values were calculated using Equation (1), and the tensile strength ratio was determined utilising the indirect tensile strength values obtained from the moisture-conditioned and unconditioned specimens, using Equation (2).

$$ITS = \frac{2P_{Max}}{\pi t d} \qquad ...(01)$$

Where, *ITS* is indirect tensile strength (MPa), $P_{max}$ is peak load (N), $t$ is the height of the specimen (mm), and $d$ is the diameter of the specimen (mm).

$$TSR = \frac{T_1}{T_2} \times 100 \qquad ...(02)$$

Where, $T_1$ is the average indirect tensile strength of moisture-conditioned HMA (MPa), and $T_2$ is the average indirect tensile strength of unconditioned HMA.

In addition to the tensile strength ratio, another moisture sensitivity test examined in this study was the retained Marshall stability. The Marshall stability ratio of moisture-conditioned and unconditioned specimens was utilised to calculate retained Marshall stability.

Specimens were moisture-conditioned by submerging them in water at 60 ± 1 °C. Subsequently, Marshall stability values for unconditioned and moisture-conditioned specimens were assessed in accordance with ASTM D6926. The retained Marshall stability was then determined using Equation (3).

$$RMS = \left(\frac{MS_1}{MS_2}\right) \times 100 \qquad ...(03)$$

Where, retained Marshall stability the index of retained Marshall stability (%), $MS_1$ is the average Marshall stability of moisture-conditioned specimens (kN), and $MS_2$, is the average Marshall stability of unconditioned specimens (kN).

For the final test, specimens were immersed water in room temperature water. The variation in moisture content of the specimens over time was monitored according to ASTM D2726. Subsequently, the statistical significance of laboratory results was assessed using the R software environment (R Core Team, 2023). To evaluate the significant effect of each factor at a 95% confidence level ($\alpha$ = 0.05), a two-factor analysis of variance (ANOVA) was employed.

The two-factor ANOVA was specifically chosen to test the null hypothesis that the means of the measured properties (e.g., Marshall stability, bulk specific gravity) are equal across different levels of the two independent factors, asphalt content and CWP content. The factors were considered fixed effects. The model determined whether the variation in the data caused by these factors was significantly greater than the variation within the groups (error variance).

A significance level of 0.05 was selected for all tests, meaning there was a less than 5% probability that the observed results occurred by chance alone. For each dependent variable, the ANOVA produced an F-statistic and a corresponding p-value. An F-value greater than the critical F-value ($F_{critical}$) and a p-value less than 0.05 led to the rejection of the null hypothesis, confirming that the factor (either asphalt content or CWP) had a statistically significant effect on the property.

Following a significant result in the ANOVA, post-hoc analyses (e.g., Tukey's honest significant difference test) would typically be conducted to identify which specific levels of the factors (e.g., 20 g vs. 30 g CWP) differed from each other. The highly significant p-values (p = 0.000) and large F-values reported in Table 2 overwhelmingly confirm that both asphalt content and CWP content are major drivers of change in all measured HMA properties.

Additionally, a paired t-test was used to compare the means of moisture-conditioned and unconditioned samples for the tensile strength ratio and retained Marshall stability analyses. The paired t-test was the appropriate choice for these comparisons because the moisture-conditioned and unconditioned specimens were not independent; each conditioned specimen was intrinsically linked to an unconditioned specimen from the same optimum mix design. The test assessed the null hypothesis that the mean difference between the paired observations was zero. A p-value less than 0.05 (as reported for the decrease in stability, P-value=0.00) indicated a statistically significant effect of moisture conditioning on the strength of the HMA specimens.

## RESULTS AND DISCUSSION

### Physical properties

#### *Bulk specific gravity*

Variation of the bulk specific gravity with the dosage of asphalt content and CWP is shown in Figure 2. As shown in Table 2, the bulk specific gravity of modified HMA decreased significantly with increasing asphalt content and CWP. Because CWP have a lower specific gravity than conventional fillers in HMA, the bulk specific gravity of CWP-modified HMA is lower than the control. It was observed that the BSG of modified HMA decreased as the asphalt content increased, and this variation was like that of the control HMA. A similar reduction of bulk specific gravity with asphalt content was presented in past studies too (Hassan, 2005; Gashi et al., 2017). A maximum reduction of 4.6%, 6.6%, 8.8%, and 10.9% in bulk specific gravity for control HMA was observed at 10 g, 20 g, 30 g, and 40 g of CWP, respectively.

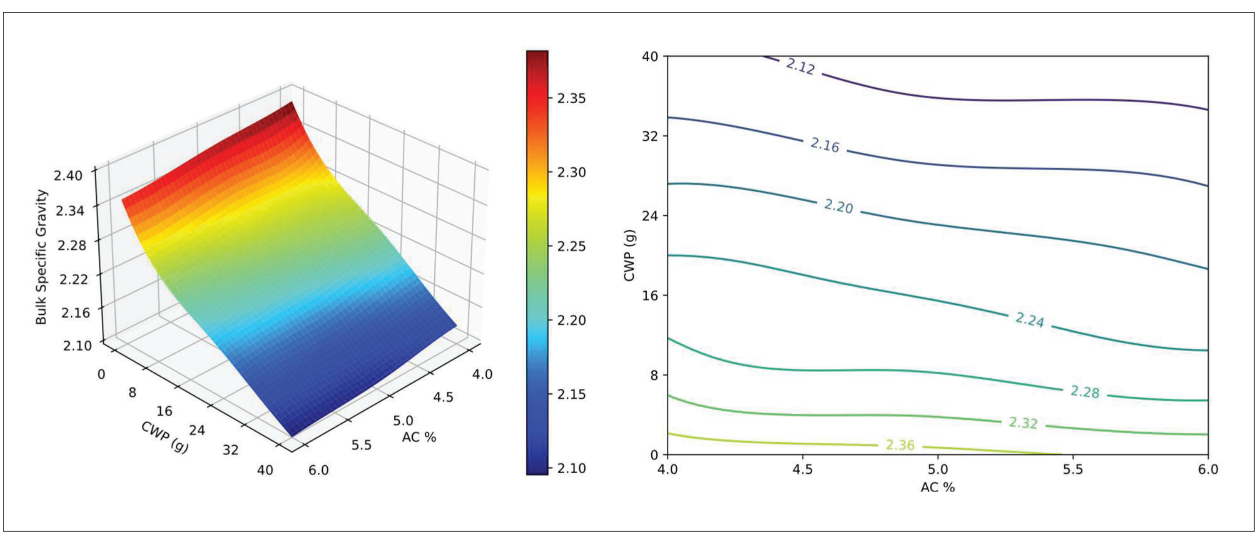


**Figure 2:** Bulk specific gravity of HMA (Hot mix asphalt) mixtures as a function of AC (asphalt content) and CWP (carbonised wood particles)

The significant reduction in bulk specific gravity observed is a direct consequence of the fundamental property difference between CWP and conventional mineral fillers. The apparent specific gravity of CWP (0.61) is substantially lower than that of the stone dust (2.71) it replaces. This introduces a larger volume of lighter material into the mix for the same weight replacement, effectively reducing the overall density of the compacted specimen. The trend is systematic: the greater the proportion of low-density CWP, the greater the reduction in bulk specific gravity. This correlation is strongly supported by the exceptionally high F-value (3639.3) for the CWP factor in the ANOVA (Table 2), indicating that CWP content is the dominant variable controlling bulk specific gravity. This reduction, while expected, is critical as it directly influences other volumetric properties and the structural mass of the pavement layer.

**Table 2:** ANOVA test results for physical and Marshall properties

| Dependent variable | Independent variable | F-value | $F_{cri}$ | α value |
|---|---|---|---|---|
| Marshall stability | asphalt content | 21.1 | 3 | 0 |
| | CWP | 213.5 | 3 | 0 |
| Marshall flow | asphalt content | 33.2 | 3 | 0 |
| | CWP | 106.4 | 3 | 0 |
| Bulk specific gravity | asphalt content | 90.8 | 3 | 0 |
| | CWP | 3639.3 | 3 | 0 |
| Voids in the mix | asphalt content | 11.4 | 3 | 0 |
| | CWP | 9.2 | 3 | 0 |
| Voids in mineral aggregates | asphalt content | 460.4 | 3 | 0 |
| | CWP | 82.9 | 3 | 0 |
| Voids filled by binder | asphalt content | 229.2 | 3 | 0 |
| | CWP | 19.7 | 3 | 0 |

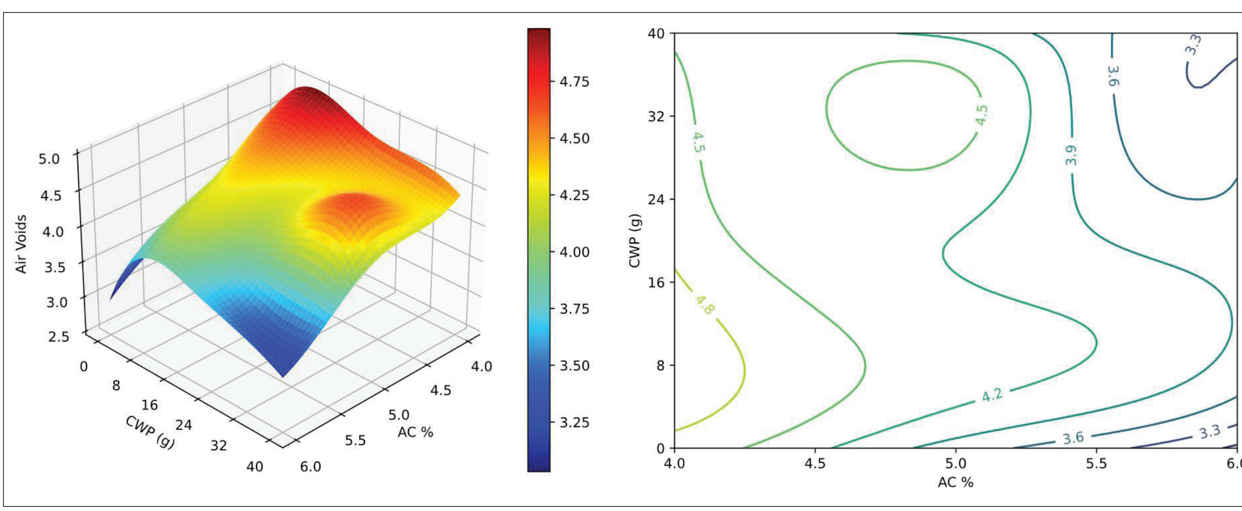


**Figure 3:** Voids in the mix response to asphalt content (AC) and CWP (carbonised wood particles) replacement

### *Voids in the mix*

Variation in the voids in the mix of HMA with asphalt content and CWP content is shown in Figure 3. Initially, voids in the modified HMA mix increased, reached a maximum value, and further increased. The presence of CWP decreased voids in the mix. These observations could be attributed to the fact that air voids were increasingly filled by the fine component of CWP as it increased in the mix, which led to a decrease in the voids in the mix beyond 20 g of CWP replacement in the Marshall specimens. The increasing trend in voids in mix of HMA was due to inadequacy in the amount of fine content at low CWP content (from 0 g to 20 g) to pack the air voids in the HMA.

**Table 3:** Properties of optimum Hot mix asphalt

| | Asphalt content | | | | |
|---|---|---|---|---|---|
| Property | 0 g | 10 g | 20 g | 30 g | 40 g |
| Bulk specific gravity | 2.4 | 2.3 | 2.2 | 2.2 | 2.1 |
| Voids in mix (%) | 3.8 | 4.3 | 4.7 | 4.6 | 4.1 |
| Voids in mineral aggregates (%) | 16.4 | 16.4 | 16.0 | 16.0 | 15.3 |
| Voids filled with binder (%) | 77.1 | 73.5 | 73.8 | 71.5 | 73.1 |
| Marshall stability (kN) | 13.2 | 11.9 | 10.8 | 6.4 | 2.8 |
| Marshall flow (0.25 mm) | 13.5 | 13.6 | 15.5 | 16.8 | 18.2 |
| Retained Marshall stability (%) | 95.5 | 90.4 | 87.4 | 83.7 | 72.2 |
| Indirect tensile strength (kPa) | 843.8 | 682.8 | 557.0 | 308.3 | 200.9 |
| Tensile strength ratio (%) | 91.3 | 86.4 | 82.5 | 76.9 | 68.8 |
| Water absorption (%) | 0.86 | 1.38 | 1.90 | 3.53 | 6.70 |
| Suitable traffic highway | High | High | Medium | Low | Failed |

The voids in mix value decreased significantly with increasing asphalt content (see Table 3). Modified HMA had higher voids in mix values compared to the control at varying asphalt content levels, ranging from 4% to 6%. This indicated that the absorption of asphalt binder in modified HMA by the highly porous CWP at higher temperatures was significant, which tended to increase the voids in mix compared to control HMA. In all modifications tested in this study, the voids in mix values complied with the specifications for medium-traffic highways (Asphalt-Institute, 2014).

The non-linear response of voids in mix to CWP addition reveals a complex interaction between particle packing and binder absorption. The initial increase in voids in mix (from 0 g to 20 g CWP) is likely due to the introduction of rigid, porous CWP particles that disrupt the optimal packing achieved by the well-graded mineral aggregates, creating new, unfilled voids. However, beyond the 20 g threshold, the finer portion of the CWP begins to act as a filler, effectively occupying the voids between larger aggregate particles, leading to a decrease in voids in the mix. Concurrently, the pronounced decrease in voids in mix with increasing asphalt content is attributed to the dual role of the asphalt binder coating aggregates to reduce inter-particle voids, and being absorbed into the porous CWP, causing them to swell and further occupy space within the mix matrix.

### *Voids in mineral aggregates and voids filled with binder*

A significant monotonic reduction in voids in mineral aggregates of modified HMA was observed as CWP content increased from 0 g to 40 g. This could be due to the fine portion of CWP, which tended to decrease the voids in mineral aggregates (Osuya & Mohammed, 2017). The Asphalt content voids in mineral aggregates of modified HMA increased significantly, and this increase in variation was similar to that of the control HMA. This could be attributed to the highly porous nature of CWP absorbing higher portions of asphalt in modified HMA at high mixing temperatures (Lesueur et al., 2012; Osuya & Mohammed, 2017; Bennert et al., 2018), which tended to increase in voids in mineral aggregates as the asphalt content increased. All voids in mineral aggregates values of modified HMA satisfied specifications for medium traffic highways (Asphalt-Institute, 2014). Variation in the voids in mineral aggregates of HMA with asphalt content and CWP content is shown in Figure 4.

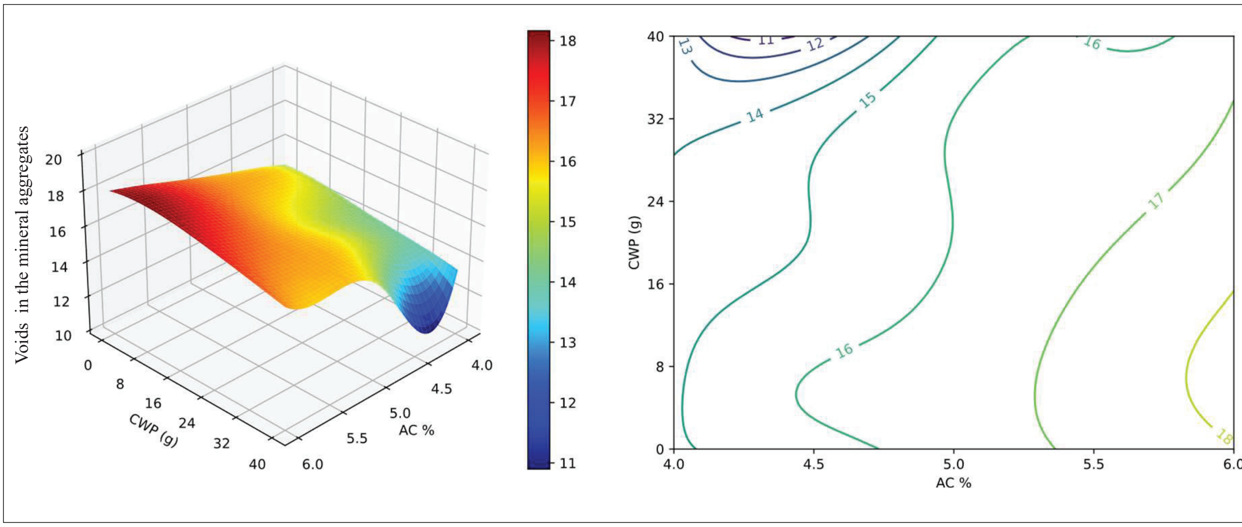


**Figure 4:** Variation of voids in mineral aggregates with asphalt content (AC) and CWP (carbonised wood particles) content

The voids filled with binder values of modified HMA ranged from 66% to 81%, with the highest voids filled with binder values observed at high asphalt content in each modification. Voids filled with binder in modified HMA initially decreased, reached a minimum, and then increased with increasing CWP content. However, as the asphalt content increased, the voids filled with binder of modified HMA (see Table 3) increased significantly. All voids filled with binder values for CWP-modified HMA met the medium-traffic highway specification (Asphalt-Institute, 2014). The variation in the voids filled with binder of modified HMA with CWP content and asphalt content is shown in Figure 5.

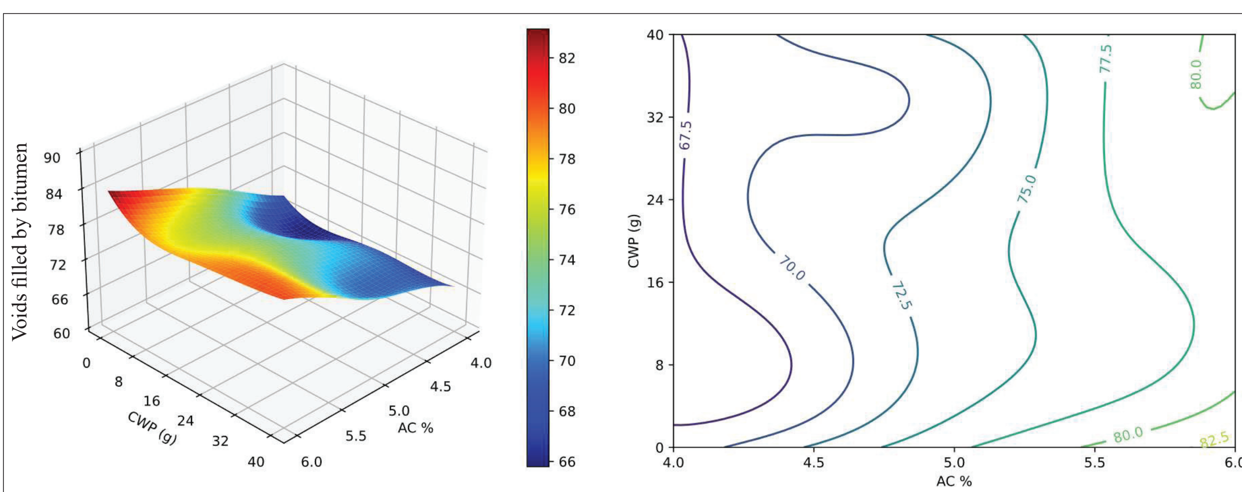


**Figure 5:** Variation of voids filled by binder with asphalt content (AC) and carbonised wood particles (CWP) content.

## Marshall properties

### *Marshall stability*

Marshall stability decreased monotonically as the CWP dosage increased. The presence of tiny particles in CWP reduced the contact between the aggregates (Osuya & Mohammed, 2017), leading to a reduction in the stiffness and Marshall stability of modified HMA. At lower CWP content, modified HMA showed desirable performance. When the asphalt content was set to 4.96% (which is the optimum asphalt content of the control sample), the percentages decreased in Marshall stability of modified HMA specimens compared to control HMA for 10 g, 20 g, 30 g, and 40 g of CWP contents were 10%, 16% 55%, and 79%, respectively.

Marshall stability of control HMA and modified HMA increased initially, reaching peak values of 11.9 kN, 10.8 kN, 6.4 kN, and 2.8 kN for CWP contents of 10 g, 20 g, 30 g, and 40 g, respectively. Marshall stability values at 10 g and 20 g of CWP satisfied specifications for heavy-traffic highways. However, the modified HMA made with 30 g CWP satisfied the specification for medium-traffic highways for asphalt content from 4.8% to 5.2%. Modified HMA with 40 g CWP content did not meet the Marshall stability specifications of medium-traffic highways (Asphalt-Institute, 2014). The Marshall stability variation with CWP content and asphalt content is shown in Figure 6.

The drastic reduction in Marshall stability (up to 79%) and increase in flow are the most critical mechanical findings. This behaviour can be mechanistically explained by two primary factors: (1) The introduction of fine, often plate-like CWP particles acts to lubricate the aggregate skeleton, reducing the internal friction and interlock between the coarse aggregates, which are the primary contributors to the mix's shear strength and stability. The increased Marshall flow values provide direct evidence of this reduced internal friction, indicating a more ductile but less resilient mixture. (2) The highly porous CWP absorbs a significant portion of the asphalt binder, meaning that for a given asphalt content, the amount of effective binder available to coat aggregates and provide cohesion is reduced. This creates a weaker matrix, making the mix more prone to deformation under load. The stability loss is therefore not just a function of the CWP itself but also of a consequential reduction in effective binder content.

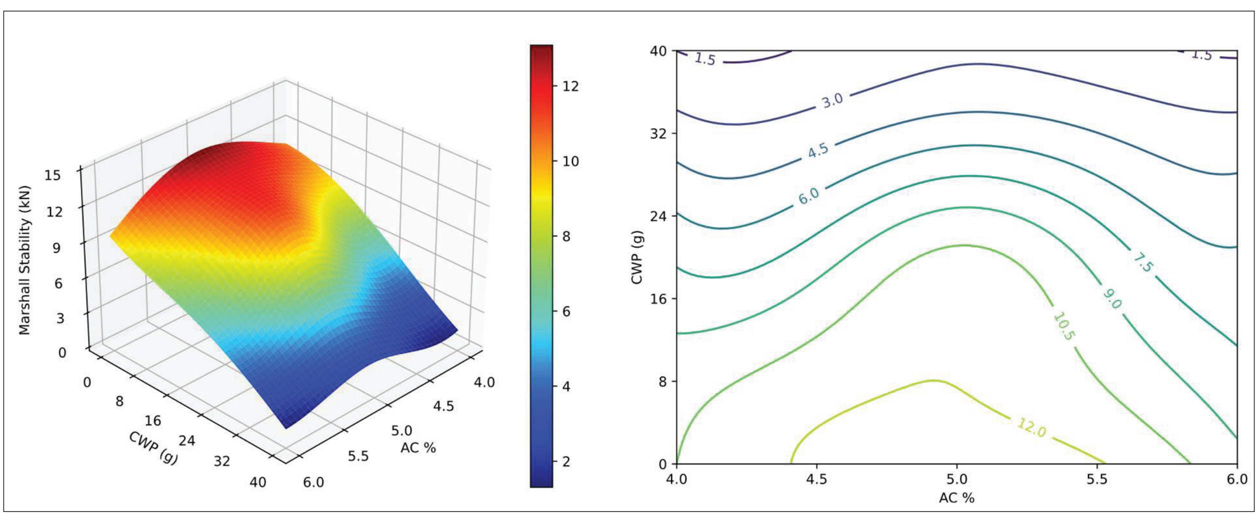


**Figure 6:** Variation of Marshall stability with asphalt content (AC) and carbonised wood particles (CWP) content.

The results indicate that at low doses (10 g to 20 g), the filler effect and potential slight stiffening of the binder (from absorbed light oils) can partially compensate for these negatives. However, beyond 20 g, the lubrication and absorption effects become dominant, leading to a precipitous drop in performance.

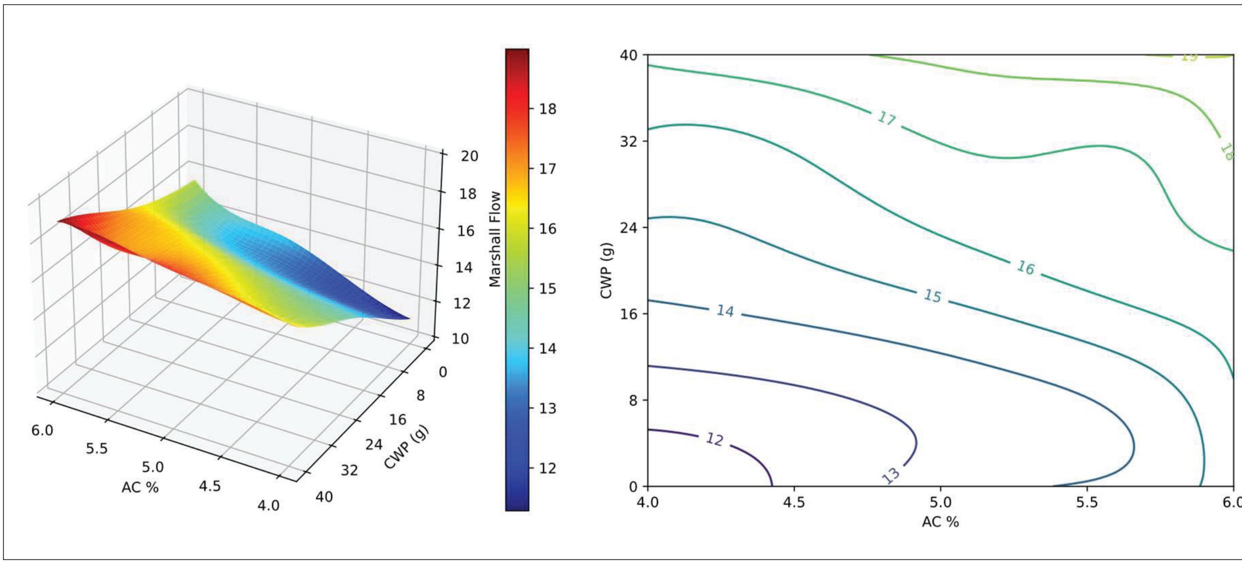


**Figure 7:** Variation of Marshall flow with asphalt content (AC) and carbonised wood particles (CWP) content.

***Marshall flow***

Marshall flow significantly increased as the dosage of CWP increased (Table 3). This indicates that the friction between the aggregates decreased with increasing CWP content in the HMA. The addition of 10 g, 20 g, 30 g, and 40 g of CWP resulted in 1%, 15%, 25%, and 35% increases in Marshall flow, respectively, compared to the control HMA made with 4.96%.

Similarly, in each modification tested in this study, an increase in asphalt content raised the Marshall flow in the modified HMA. A similar trend in Marshall flow was observed in the control HMA samples. Marshall flow was not within the specified range of the Asphalt Institute MS-2 specification for medium traffic highways at 40 g CWP content. However, the modified HMA mixes with 10 g and 20 g of CWP content satisfied specifications for medium-traffic highways. The Marshall flow specifications for light-traffic highways were met by HMA with 30 g of CWP. The variation in Marshall flow of modified HMA with Asphalt content and CWP content is shown in Figure 7.

**Statistical analysis of physical and marshall properties**

Statistical significances of physical and Marshall properties were examined at an alpha value of 0.05. Properties of modified and control HMAs were statistically differentiated using a two-factor ANOVA. Table 2 presents variance analyses for physical and Marshall properties. The obtained F-values were greater than the F-critical values, and the P-values were smaller than α of 5%, indicating that the effect of CWP and asphalt content on the characteristic values of modified HMA was significant for each property tested.

**Indirect tensile test**

The indirect tensile strength is commonly used to evaluate the relative field quality of asphalt mixes and the potential for rutting or cracking (Bennert et al., 2018; Jegatheesan et al., 2020). Increasing CWP content in HMA resulted in a significant decrease in the indirect tensile strength value (Figure 8). This is because the CWP tends to absorb the asphalt binder. Therefore, increasing CWP in HMA decreases ITS. The HMA samples modified with CWP of 10 g, 20 g, 30 g, and 40 g caused a 20%, 32%, 60%, and 75% decrease in indirect tensile strength compared to the control HMA, respectively. This suggests that increasing CWP content in the HMA mix can accelerate crack propagation.

**Tensile strength ratio**

The moisture sensitivity of CWP-modified HMA was investigated using tensile strength ratio. The variation in the indirect tensile strength of optimum HMA with CWP content is shown in Figure 8. The indirect tensile strength of modified HMA significantly (*P* = 0.00) decreased as CWP content increased for both moisture-conditioned and unconditioned cases. Compared with the control sample, the indirect tensile strength of moisture-conditioned modified HMA decreased by 23%, 40%, 69%, and 82% at 10 g, 20 g, 30 g, and 40 g of CWP content, respectively. The availability of flat, larger surface particles stimulates the absorption of water by CWP, which could lead to decreased binding between the binder and aggregates. Modified HMA specimens containing 20 g or less CWP content complied with the ASTM specifications limit of 80%. Modified HMA specimens made with 30 g and 40 g had more sensitivity to moisture and would experience ravelling.

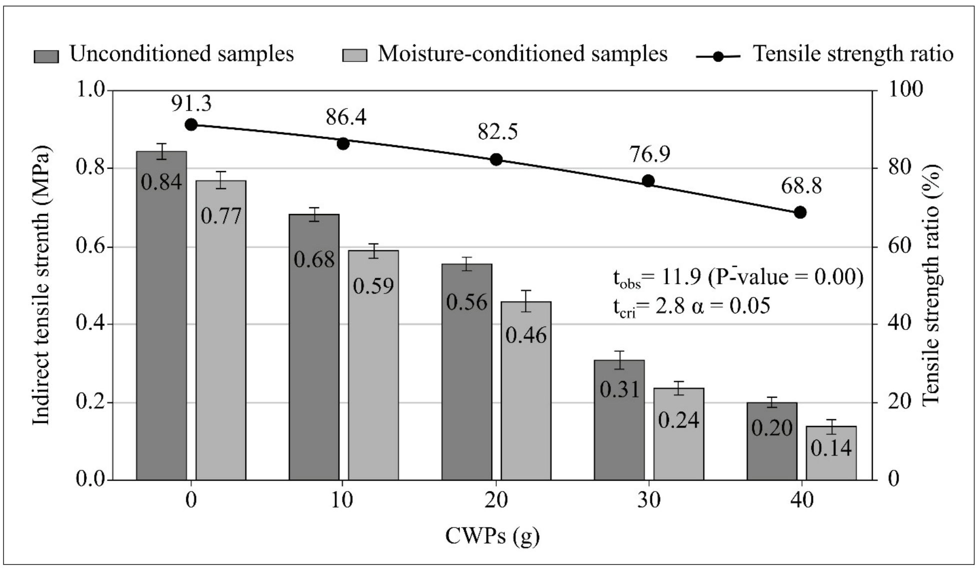


**Figure 8:** Variation of indirect tensile strength and tensile strength ratio of optimum modified HMA (Hot mix asphalt)

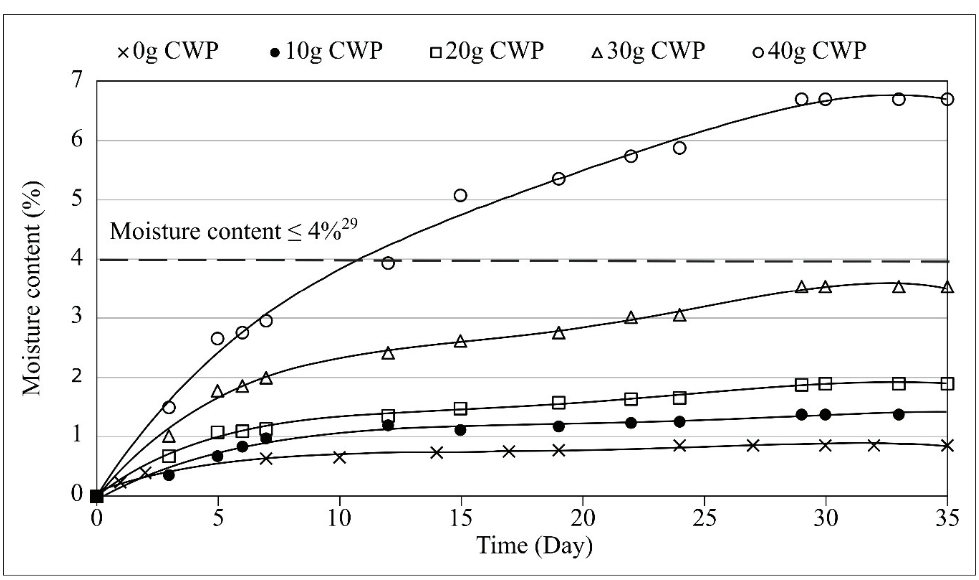


**Figure 9:** Variations in the water absorption of the optimum modified HMA (Hot mix asphalt)

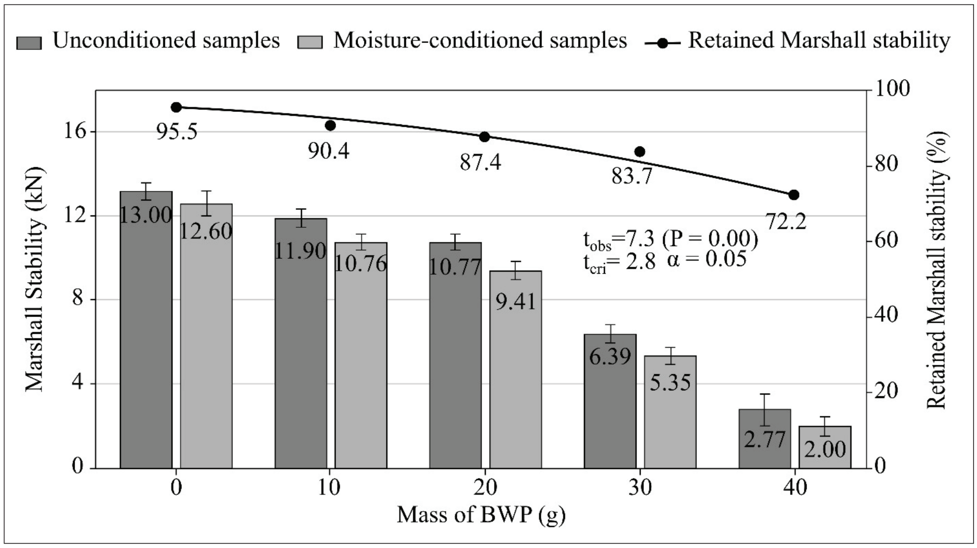


**Figure 10:** Marshall stability and retained Marshall stability of the optimum modified HMA (Hot mix asphalt)

The moisture susceptibility results (tensile strength ratio and RMS) and water absorption data are intrinsically linked and form a central part of the study's contribution. The porous and hydrophilic nature of CWP creates pathways for water to infiltrate the asphalt mixture. As shown in Figure 9, mixes with high CWP content (30 g, 40 g) act almost like a sponge, absorbing water rapidly. This water intrusion directly attacks the adhesive bond between the aggregate and the asphalt binder (stripping) and can also soften the asphalt binder itself.

**Retained Marshall stability**

Retained Marshall stability of modified HMA was also tested to determine its moisture susceptibility. Marshall stability of moisture-conditioned HMA was lower than that of unconditioned samples. With increasing CWP content, the decrease in Marshall stability of modified HMA compared to control HMA increased significantly (P-value=0.00). This increase could be attributed to the presence of more absorbed water between the binder and aggregate in comparison to the control HMA, which reduced the adhesion of the HMA mix (Ahmedzade & Sengoz, 2009).

The observed retained Marshall stability values were 95.5%, 90.4%, 87.4%, 83.7%, and 72.2% for the samples with 0 g, 10 g, 20 g, 30 g and 40 g CWP content, respectively. The observed retained Marshall stability values of HMA samples with 0 g, 10 g, 20 g, and 30 g CWP contents satisfied the retained Marshall stability limit of 80% set by the ASTM specifications. Moisture-conditioned and unconditioned Marshall stability of the optimum HMAs is shown in Figure 10.

The difference in water absorption of control HMA and modified HMA determined every 24 hours is shown in Figure 10. Water absorption at 10 g and 20 g of CWP shares a nearly similar trend with that of the control. The absorption rate of HMA made with 30 g and 40 g of CWP in the first few days was high compared to the mix made with 10 g and 20 g of CWP. From this, it can be concluded that increasing CWP in HMA decreases the water sensitivity resistance. Further, HMA specimens made with CWP less than 30 g complied with the specification requirement for water absorption (APRG, 1998).

**Recommendations for practitioners and policymakers**

Based on the findings of this study, practitioners are advised to strictly limit the replacement of CWP to 12% by mass of the filler in asphalt mixes for medium-traffic applications. To ensure performance, mix designs must account for higher binder demand and prioritise tensile strength ratio (TSR) testing (>80%) to guard against moisture damage. Initial use should target lower-stress applications like local roads or parking lots.

Policymakers can accelerate adoption by revising material specifications to include bio-fillers like CWP and implementing green procurement incentives, such as tax credits or preferential bidding for sustainable practices. Funding pilot projects and supporting wood waste recycling programs will validate long-term performance and formally integrate this technology into sustainable infrastructure strategies.

### Limitations and future directions

While this study demonstrates the feasibility of using CWP in HMA for specific applications, several limitations must be acknowledged to contextualise the findings and guide future research.

The research was conducted under controlled laboratory conditions. The performance of CWP-modified HMA under real-world traffic loading, environmental weathering (UV radiation, etc.,), and long-term ageing has not been validated. The findings are based on CWP derived from a single wood species (*Albizia julibrissin*) carbonised at a specific temperature (400 °C). The properties of CWP can vary significantly with different wood types and pyrolysis conditions. The study utilised a conventional asphalt binder. The interaction of CWP with polymer-modified or other advanced binders could yield different results and remain unexplored. While cost savings are implied, a detailed economic analysis including carbonisation costs and a full lifecycle assessment (LCA) to quantify the environmental benefits was beyond the scope of this study.

The logical next step is the construction and long-term monitoring of pilot test sections on low-to-medium traffic roads to validate laboratory findings against real-world performance. Future work should investigate the impact of key variables such as wood species, particle size distribution of CWP, and carbonisation temperature on HMA performance to optimise the material properties. Research should explore combining CWP with polymer-modified binders or anti-stripping agents to mitigate the loss of moisture resistance and strength observed at higher replacement levels. Comprehensive studies on the long-term ageing characteristics (using methods like rolling thin film oven and pressure ageing vessel) and resistance to fatigue cracking of CWP-modified HMA are essential. Addressing these limitations in future work will be vital for transitioning this promising technology from laboratory validation to practical, widespread implementation in sustainable pavement construction.

## CONCLUSION

This study comprehensively evaluated the feasibility of using CWP as a sustainable filler replacement in HMA.

(1) The findings demonstrate a clear trade-off: while CWP improve certain physical properties related to void structure, they significantly reduce mechanical strength and moisture resistance. The optimal replacement level was identified as 12% by mass of the filler (equivalent to 20 g in this study's mix design).
(2) At this optimum dosage, the modified HMA maintains satisfactory performance, meeting key specifications for medium-traffic highways. Specifically, mixes with 12% CWP replacement exhibited acceptable Marshall stability, flow, and most critically, moisture resistance, as validated by tensile strength ratio and retained Marshall stability values.
(3) The practical application of this finding is significant. It provides a validated formula for highway engineers to utilise a substantial volume of industrial waste (sawdust), reducing reliance on quarried mineral filler by 12%. This translates to direct cost savings on raw materials and contributes to more sustainable construction practices by diverting waste from landfills and reducing the environmental footprint of quarrying. However, replacements exceeding 12% (i.e., 30 g and 40 g CWP) led to a severe deterioration in strength and moisture resistance, rendering the mixes unsuitable for paved highways. Therefore, for the successful implementation of CWP-modified HMA, strict adherence to the 12% replacement limit is essential to balance sustainability goals with the necessary mechanical performance for medium-traffic applications.

While the study shows promise for using wood-derived carbonised waste powder (CWP) in asphalt, its findings are limited to laboratory conditions, a single wood type, and a conventional binder, leaving real-world performance unverified. Future research requires field testing and investigation into different materials, binders, and long-term durability to enable practical application.

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