

Article

Mechanical and Volumetric Properties of Hot Mix Asphalt with Rice and Wheat Husk Waste as Alternative Filler

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Abstract

Fillers (<0.075 mm) in hot mix asphalt (HMA) play a pivotal role in optimizing bitumen content, filling voids, and improving mechanical performance. In many agricultural countries, large quantities of rice and wheat husk waste are produced, while the road construction industry faces material shortages of conventional filler materials and related performance challenges. This study evaluates the feasibility of using rice husk (RH) and wheat husk (WH) fillers on HMA performance. Unlike previous studies that primarily focused on ash-derived agricultural residues, this work investigates the direct utilization of raw husk materials, eliminating the need for energy-intensive processing. Few studies directly examine the aggregate gradation and binder concentration with respect to rice and wheat husk ash. As a result, the relative effectiveness of these two agricultural waste fillers in improving the volumetric and Marshall properties of asphalt mixtures is yet unknown. Fifteen mixtures with varying bitumen contents (3.0–5.0%) were tested to determine the optimum bitumen content (OBC). Subsequently, modified mixtures were prepared at the OBC using RH and WH fillers at five replacement levels (5.0–15.0%). The Marshall Mix design method was employed to assess stability, flow, density, and air voids content. The control mixture showed a Marshall stability of 14.86 kN, flow of 3.52 mm, density of 2.342 g/cm³, and air voids of 2.9%. At their optimum filler contents (i.e., 10.33% for RH and 10.43% for WH), the modified mixtures achieved higher Marshall stability (14.96 kN and 15.06 kN, respectively), with flow values of 3.51 mm and 2.83 mm, and densities of 2.335 g/cm³ and 2.330 g/cm³. Statistical analysis using ANOVA at the OBC confirmed that RH and WH fillers can be used as alternative fillers in HMA without adversely affecting Marshall performance, while contributing to agricultural waste valorization and resource conservation.

Keywords: hot mix asphalt; rice husk; wheat husk; filler; alternative materials

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1. Introduction

Solid waste management has become a critical global challenge due to the continuous increase in waste generation and the resulting pressure on landfill capacity [1]. Environmental conservation and resource preservation are increasingly important concerns, prompting researchers and policymakers to develop environmentally sustainable and economically viable recycling strategies [2]. In this context, the asphalt pavement industry has increasingly incorporated waste and by-products as alternative raw resources to reduce environmental impacts and construction costs [3]. Although several studies have considered the use of agricultural waste materials as fillers in asphalt mixes, most of them have either focused on a single waste item or looked at multiple materials under different mix design conditions. Few studies directly examine the aggregate gradation and binder concentration with respect to rice and wheat husk ash. As a result, the relative effectiveness of these two agricultural waste fillers in improving the volumetric and Marshall properties of asphalt mixtures is yet unknown. Mineral fillers play a crucial role in the performance of hot mix asphalt (HMA) [4]. Defined as materials with particle sizes smaller than 0.075 mm, fillers enhance mixture stability under traffic loading [5,6], environmental conditions [7], and long-term distresses [8]. Their physical properties (e.g., particle size distribution, shape, texture, and porosity) and chemical characteristics (e.g., mineral composition and active clay content) significantly influence pavement performance [3,5,9]. Moreover, fillers improve the adhesion between bitumen and aggregates and affect the optimum bitumen content (OBC) required in asphalt mixtures [4]. Extensive research has investigated the use of industrial and agro-industrial waste materials as alternative fillers in HMA [9,10]. Materials such as silica, fly ash, brick dust, and marble dust have demonstrated improvement in mechanical and volumetric properties [11,12]. For instance, marble dust has been reported to enhance Marshall stability and rutting resistance at an optimal content of approximately 4%, although it may reduce fatigue life [13]. Similarly, calcium carbide residue has improved stiffness modulus and resistance to rutting and cracking [14] in HMA. Other waste-derived fillers (i.e., glass, limestone, red mud, rice straw ash, brick, carbide lime, and copper tailings) have exhibited performance comparable to conventional fillers such as ordinary Portland cement [5]. Calcium-rich fillers, such as limestone dust, hydrated lime, and carbide lime, have been effective in improving moisture resistance [15] and adhesion properties [5] at around 4% content [10]. In addition, materials like diatomite, bentonite, and fly ash have been found to enhance mastic performance and high-temperature behavior when used at optimal dosages [16–18]. The incorporation of crumb rubber (5–10%) has also improved Marshall stability, stiffness, and rutting resistance compared to conventional mixes [19,20]. Likewise, glass powder at content levels between 6% and 7.5% yielded mechanical properties comparable or superior to conventional materials [20–23].

Previous studies have also examined the influence of filler characteristics on asphalt mastic behavior. Geometric properties, particularly those of hydrated lime, have been identified as a key factor contributing to stiffening effects, while chemical properties play a less direct role [24,25]. Asphalt mastic viscosity increases nonlinearly with filler content [26], whereas low-temperature creep behavior is primarily governed by filler volume rather than particle characteristics [27]. The combined use of modifiers such as styrene-butadiene-styrene and volcanic ash has demonstrated improvements in thermal stability and mechanical performance [28]. Brick dust as a filler in HMA ensured satisfactory Marshall properties [29,30] compared to reference mixtures containing cement.

In recent years, agricultural waste materials have been explored as sustainable alternatives in HMA. Palm kernel shell ash at the OBC and 1% to 5% replacements had better mechanical properties and moisture resistance than the control mixture [31]. Rice husk ash (RHA) and wheat husk ash (WHA) have shown promising results in enhancing

mechanical properties and moisture resistance in HMA [32]. These materials are typically characterized by high silica content and porous structures that may influence bitumen absorption and interparticle bonding. Bitumen modified with RHA exhibits higher softening point and viscosity, along with lower penetration values compared to conventional bitumen [33]. RHA, waste brick, and waste glass fillers improved fatigue resistance of HMA, and no discernible alteration was observed between them [34]. RHA, in particular, has been associated with increased softening point, higher viscosity, and improved adhesion due to its fine and porous structure [33,35]. However, findings regarding fatigue performance remain inconsistent, indicating the need for further investigation [36,37].

Despite the growing body of research on industrial waste fillers, relatively limited attention has been paid to untreated agricultural residues such as rice husk (RH) and wheat husk (WH). Large quantities of these materials are generated annually, particularly in agricultural economies, while the depletion of natural filler resources and increasing material costs pose challenges for the asphalt industry. The main objective of this study was to find out how substituting mineral fillers with rice husk ash (RHA) and wheat husk ash (WHA) influenced the mechanical and volumetric performance of asphalt mixes under the same binder conditions. Consequently, all modified blends were purposely retained at the same optimum bitumen content (OBC) as the control mixture. This experimental approach was utilized to separate the effects of filler type and dose by removing a variable (binder content) that would mask the impact of the filler itself. The incorporation of RH and WH as fillers in HMA can reduce environmental impacts, lower material consumption, and promote sustainable pavement construction. In this context, the novelty of this study lies in: (i) the direct utilization of untreated RH and WH as filler materials, avoiding energy-intensive pre-processing; (ii) the evaluation of mechanical and volumetric properties using the Marshall mix design approach; and (iii) the application of statistical analysis (ANOVA) [38] to rigorously assess the significance of filler type on HMA performance. By comparing modified mixtures with a conventional control mix, this research seeks to assess the feasibility of these agro-wastes as sustainable filler substitutes in HMA applications.

2. Materials and Methods

2.1. Materials

In this study, the HMA mixtures were prepared using crushed granite as virgin aggregates, a conventional asphalt binder, and RH and WH powders as alternative fillers. The blended gradation met the requirements of ASTM D6926 [39] (Table 1).

Table 1. Blended gradation of control and modified mixes.

Sieve Size (mm)	Control Blend	RH-Modified Blend	WH-Modified Blend	Specification Limits
38.1	100	100	100	100
25.4	100	100	100	100
19.1	94.3	94.3	94.3	90–100
9.52	66.2	66.2	66.2	56–70
4.76	47.1	46.0	42.0	35–50
2.4	27.5	32.0	28.0	23–35
0.3	6.3	7.5	9.0	5–12
0.075	2.4	4.0	4.0	2–8

Table 2 provides the physical properties of the aggregates.

Table 2. Physical properties of the aggregates.

Property	Standard	Test Results	Specification Limits
Los Angeles abrasion value	ASTM C131/C131M [40]	20	≤40%
Aggregate impact value	BS 812-112 [41]	22.25	≤30%
Crushing strength	ASTM C131/131M [40]	19.10	≤30%
Specific gravity coarse aggregate	ASTM C127 [42]	2.57	2.5–2.9 g/cm ³
Specific gravity fine aggregate	ASTM C128 [43]	2.68	2.4–2.8 g/cm ³
Aggregates water absorption %	ASTM C127 [42]	1.21	≤2%

A bitumen binder, penetration-grade 60/70, was used in this study; its properties are listed in Table 3.

Table 3. Properties of bitumen.

Property	Standard	Test Results	Limit/Reference Value According to Bitumen Grade
Penetration at 25 °C (0.1 mm)	ASTM D-5 [44]	67 mm	60/70
Softening point	ASTM D-36 [45]	47.8 °C	48–56 °C
Flash point	ASTM D-92 [46]	322 °C	>232 °C
Fire Point	ASTM D-92 [46]	364 °C	>260 °C
Ductility at 27 °C	ASTM D-113 [47]	147.30 cm	≥100 m
Specific gravity	ASTM D-70 [48]	1.006 g/cm ³	0.97–1.02 g/cm ³

The specific gravity of fillers used in this study was 2.66, 2.10, and 2.11 g/cm³ for the conventional mineral filler, RH, and WH, respectively.

2.2. Methods

The Marshall mix design method was employed to evaluate the effect of RH and WH fillers on the performance of HMAs. Initially, control mixtures were prepared using conventional filler at five bitumen contents ranging from 3.0% to 5.0% (0.5% increments, three samples for each percentage content) to determine Marshall stability, flow, and volumetric properties. The stability and flow Marshall results were then used to determine the OBC according to Equation (1).

$$\text{OBC} = \frac{B1 + B2 + B3}{3} \quad (1)$$

where B1, B2, and B3 is the bitumen content for the maximum stability, the maximum density, and the 4% air voids in compacted samples, respectively.

Once the OBC of the control mixture was established, modified HMA mixtures incorporating RH and WH as partial replacements for the conventional filler were prepared at this fixed bitumen content. The effects of RH and WH on the mechanical performance of HMA and the optimum replacement level of rice husk and wheat husk that might be utilized were investigated using five different replacement levels (5%, 7.5%, 10%, 12.5%, and 15%, three samples for each percentage content). The optimal bitumen content discovered for the control mixture was used for all changed combinations. This approach isolated the effect of filler replacement on the engineering properties of asphalt mixtures by maintaining constant binder concentration. If the OBC were to be recalculated for each filler type and replacement amount, it would be interesting to identify each filler material's distinct contribution to the observed performance [49,50]. Table 4 lists the tested recipes. In this study, each recipe at OBC has an ID code TxRyWz that details the percentage content of conventional mineral (i.e., x%), WH (i.e., y%), and RH filler (i.e., z%), respectively. Therefore, the mixture T36R0W0 has 36% of conventional mineral filler,

0% of RH filler, and 0% of WH filler, while mixture T31R5W0 has 31% of conventional mineral filler, and 5% of RH and 0% WH filler; likewise, T28.5R0W7.5 has 28.5% of conventional mineral filler, and 0% of RH and 7.5% WH filler.

Table 4. HMA recipes.

Mixture	Control Blend	RH-Modified Blend	WH-Modified Blend
OBC (%)	3.83	3.83	3.83
Hot Bin 20–25 mm	10	10	10
Hot Bin 12–20 mm (%)	27	27	27
Hot Bin 5–12 mm (%)	27	27	27
Conventional mineral Filler (%)	36	31, 28.5, 26, 23.5, 21	31, 28.5, 26, 23.5, 21
WH Filler (%)	0	5, 7.5, 10, 12.5, 15	–
RH Filler (%)	0	–	5, 7.5, 10, 12.5, 15

Equations (2) and (3) allowed calculating of the Optimum RH and WH content (ORC and OWC, respectively):

$$\text{ORC} = \frac{R1 + R2 + R3}{3} \quad (2)$$

$$\text{OWC} = \frac{W1 + W2 + W3}{3} \quad (3)$$

where R1 and W1 are the RH and WH content at the maximum Marshall stability, R2 and W2 are the RH and WH content at the maximum value of bulk density, and R3 and W3 are the RH and WH content at 4% of air voids.

Finally, ANOVA allowed for comparison of the obtained means of Marshall stability, flow, and volumetric properties at OBC using the F-distribution at the 95 percent confidence. A matrix (Equation (4)) collected the experimental values for each property: each element $r_{i,j}$ was the experimental result obtained from the i -th mixture in the j -th test. The maximum value of i and j are a and b , respectively.

$$R = \begin{matrix} & r_{1,1} & r_{1,j} & r_{1,b} \\ r_{i,1} & r_{i,j} & r_{i,b} \\ r_{a,1} & r_{a,j} & r_{a,b} \end{matrix} \quad (4)$$

The means of the values in i -th row and j -th column were calculated according to Equations (5) and (6), respectively:

$$\bar{r}_j = \frac{1}{a} \sum_{i=1}^a r_{i,j} \quad (5)$$

$$\bar{r}_i = \frac{1}{b} \sum_{j=1}^b r_{i,j} \quad (6)$$

Equations (7) and (8) allowed calculating the variation between rows (or fillers) (v_m) and residual variation (v_e):

$$v_m = b \sum_{i=1}^b (\bar{r}_i - \bar{r})^2 \quad (7)$$

$$v_e = \sum_{i,j} (r_{i,j} - r_j - r_i + \bar{r})^2 \quad (8)$$

The tested null hypothesis was that the filler type does not affect the mechanical and volumetric properties. The independent variables were the type of filler added at the OBC

and the repeated test results. Particularly, 3 mixtures (*a*) and 7 levels (*b*) of results were considered for each performance variable under the hypotheses: the population is close to a normal distribution; the results are independent. The degrees of freedom between filler (df_m) and the error degrees of freedom (df_e) were obtained according to Equations (9) and (10):

$$df_m = a - 1 = 3 - 1 \quad (9)$$

$$df_e = (a - 1)(b - 1) = (3 - 1)(7 - 1) \quad (10)$$

Therefore, the mean squares are obtained for each source of variation dividing its variation by their degrees of freedom: s_m^2 and s_e^2 refer to mean squares of fillers and error, respectively (Equations (11) and (12)):

$$s_m^2 = \frac{v_m}{df_m} \quad (11)$$

$$s_e^2 = \frac{v_e}{df_e} \quad (12)$$

The F-statistic for the tested hypothesis (F_m) was compared to the F critical value to support or reject the null hypothesis (Equation (13)).

$$F_m = \frac{v_m}{s_e^2} < F_{0.05} \quad (13)$$

3. Results

3.1. Control Mixture

Table 5 lists the average Marshall properties of the control mixture. The relationship between bitumen content and Marshall stability indicates that stability reaches a maximum with 4.0% bitumen content and then decreases with further bitumen additions. With regard to the flow values, they increase with the bitumen content, reaching a maximum flow value of 3.83 mm at 4.5% bitumen content. The analysis of the relationships between bitumen content, voids in mineral aggregates (VMA) and voids in total mineral aggregates (VTM) reveal the sharp drop at 4% bitumen. Voids filled with asphalt (VFA) have their highest value at 4.5% bitumen content.

Table 5. Marshall properties of the control mix.

Property	Bitumen Content (%)				
	3.0	3.5	4.0	4.5	5.0
Stability (kN)	13.028	14.470	14.872	13.636	12.959
Density (g/cm ³)	2.32	2.33	2.35	2.34	2.30
Flow (mm)	2.72	3.30	3.80	3.83	3.58
VTM (%)	5.3	4.0	2.5	2.6	2.6
VMA (%)	12.4	12.5	12.2	13.1	15.0
VFA (%)	57.3	68.0	79.5	80.9	77.3

Figure 1 (a) to (f) present the control mixture properties by varying the bitumen content between 3 and 5%. In these graphs and in the similar ones shown in the following figures, the blue squares represent the experimental data, and the dashed red lines indicate the second-order regression curves.

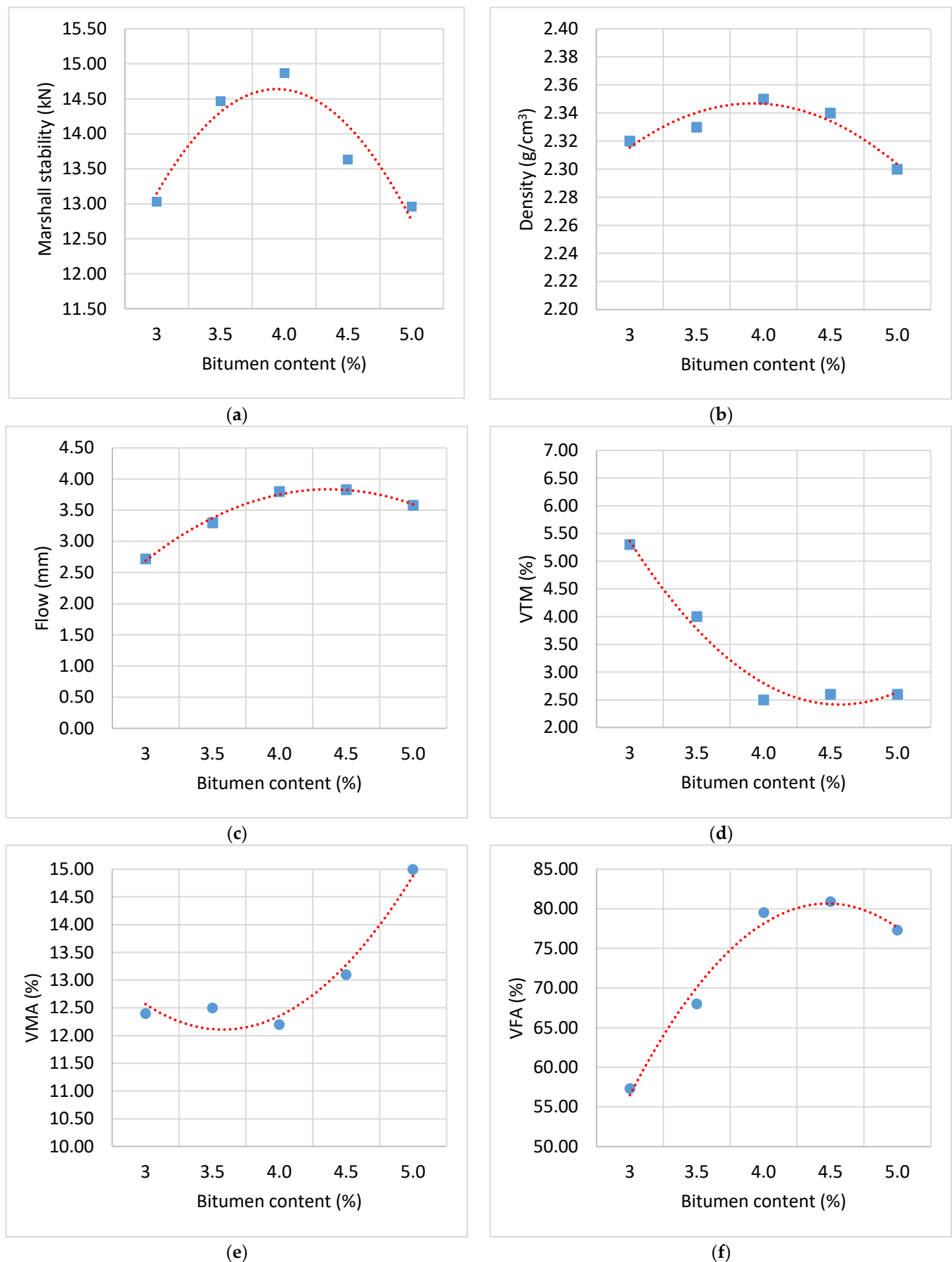


Figure 1. Control mixture properties: (a) Marshall stability; (b) density; (c) flow; (d) VTM; (e) VMA; and (f) VFA.

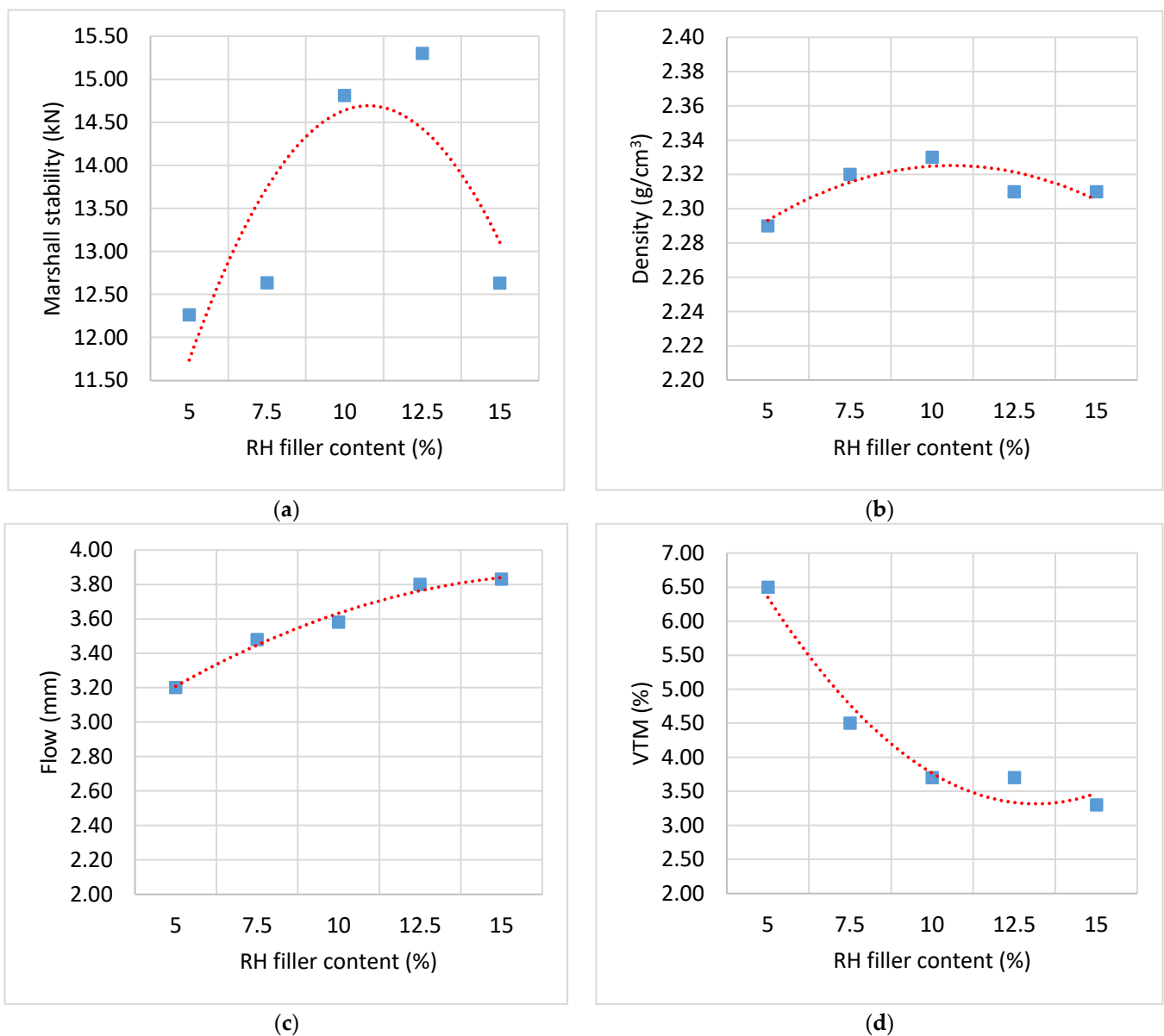
Therefore, according to Equation (1), the OBC is 3.83% for the control mixture. Under such conditions, it is possible to determine graphically the Marshall properties of the control mixture at OBC (Table 6).

Table 6. Marshall and volumetric results of the control mixture at OBC.

Property	Unit	Value
Marshall stability	kN	14.862
Density	g/cm ³	2.342
Flow	mm	3.52
VTM	%	2.90
VMA	%	12.50
VFA	%	78.1

3.2. RH-Modified Mixtures

The Marshall and volumetric results of the RH-modified mixtures by varying the RH filler content at OBC (i.e., 3.83%) are shown in Table 7 and Figure 2.



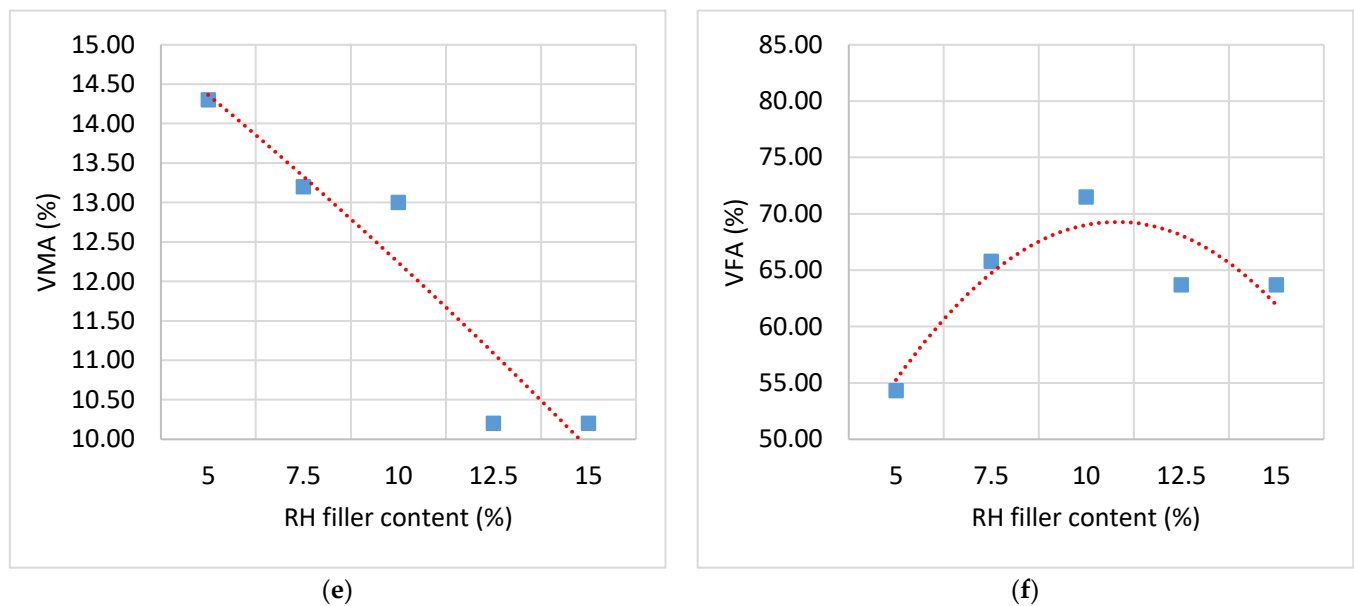


Figure 2. RH-modified mixtures properties: (a) Marshall stability; (b) density; (c) flow; (d) VTM; (e) VMA; and (f) VFA.

Table 7. Marshall and volumetric properties of the RH-mixtures at OBC.

Property	RH Filler Content (%)				
	5	7.5	10	12.5	15
Stability (kN)	12.263	12.636	14.813	15.304	12.631
Density (g/cm ³)	2.29	2.32	2.33	2.31	2.31
Flow (mm)	3.20	3.48	3.58	3.80	3.83
VTM (%)	6.5	4.5	3.7	3.7	3.3
VMA (%)	14.3	13.2	13.0	10.2	10.2
VFA (%)	54.3	65.8	71.5	63.7	63.7

Figure 2a presents the relationship between RH filler content and Marshall stability of the modified mixtures at the OBC. The results show a significant increase in stability, reaching a maximum value of 15.304 kN at 12.5% RH content, slightly higher than that of the control mixture (Table 1). Figure 2c shows that as RH content increases, the flow value also rises. The maximum flow value of the modified mixes was 3.83 mm for T21R15W0, higher than the control mix at OBC. Figure 2b shows that the density of the RH-modified mixes increased from 2.29 to 2.33 g/cm³ at 10% filler, then decreased with further RH filler additions. In contrast, the control mix attains a slightly higher maximum density of 2.342 g/cm³ (Figure 1b). With increasing RH content (from 5.0% to 15.0%), VTM in the modified mixtures decreases, reaching 3.7% for T26R10W0 and T23.5R12.5W0 (Figure 2d), higher than the control mix (Figure 1d). Nevertheless, the air voids in all modified mixtures remain within acceptable limits. VMA decreases as the mineral filler content increases: the highest value (i.e., 14.3%) is for T31R5W0, while the lowest one (i.e., 10.2%) occurs at 12.5% and 15.0% RH filler contents (Figure 2e). Finally, VFA increases with higher RH content up to 12.5%, after which VFA decreases with further filler addition. The peak VFA value of 71.5% is achieved for T23.5R12.5W0 (Figure 2f).

According to Equation (2), ORC is 10.33%; the Marshall and volumetric properties of the modified-RH mixture at ORC are shown in Table 8.

Table 8. Marshall and volumetric results of the RH-modified mixture at ORC.

Property	Unit	Value
Marshall stability	kN	14.960
Density	g/cm ³	2.335
Flow	mm	3.51
VTM	%	3.43
VMA	%	12.70
VFA	%	73.0

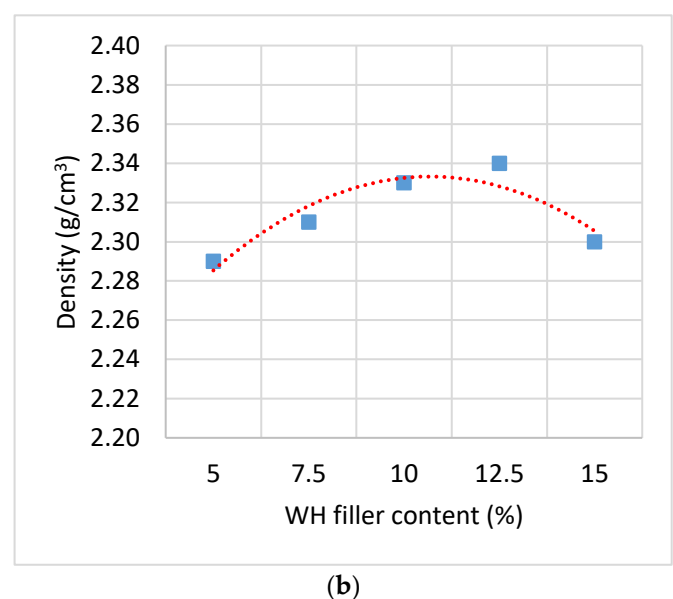
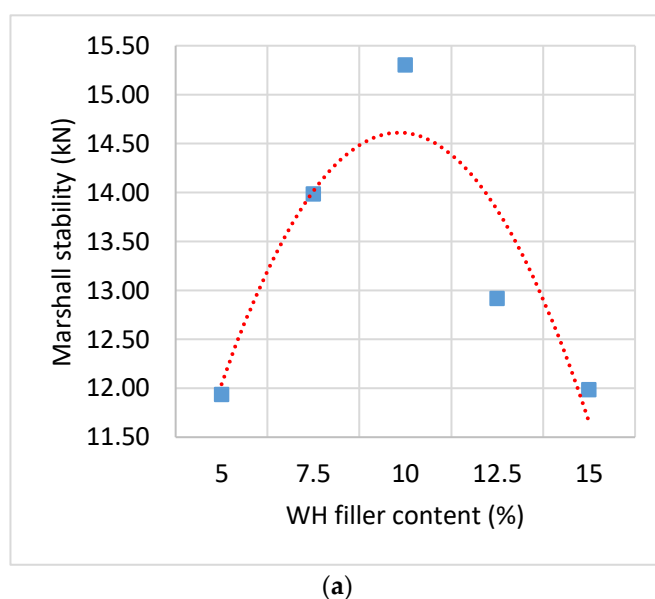
3.3. WH-Modified Mixtures

Table 9 and Figure 3 summarize the Marshall and volumetric properties.

Table 9. Marshall and volumetric properties of the WH-mixtures at OBC.

Property	WH Filler Content (%)				
	5	7.5	10	12.5	15
Stability (kN)	11.939	13.989	15.304	12.920	11.988
Density (g/cm ³)	2.29	2.31	2.33	2.34	2.30
Flow (mm)	2.05	2.67	2.78	2.88	3.08
VTM (%)	6.5	4.5	3.7	3.3	4.1
VMA (%)	14.3	13.2	13.0	13.5	13.5
VFA (%)	54.3	65.8	70.0	72.3	69.4

The Marshall stability increased with increasing WH content up to 10%, where the maximum value of 15.304 kN was obtained for T26R0W10. Further increases in WH filler content resulted in a reduction in stability. The density of the mixtures followed a similar trend, increasing from 2.29 g/cm³ at 5% WH to 2.34 g/cm³ at 12.5% WH before decreasing at 15% replacement (Figure 3b). Flow values increased progressively with increasing WH content, ranging from 2.05 mm at 5% WH to 3.08 mm at 15% WH (Figure 3c). All measured values satisfied the Marshall specification limits. The volumetric properties also varied with filler replacement. VTM decreased from 6.5% to 3.3% as the WH content increased to 12.5%, while VMA generally decreased from 14.3% to approximately 13.0% (Figure 3d,e). Conversely, VFA increased with filler content, reaching a maximum value of 72.3% at 12.5% WH before slightly decreasing at higher replacement levels (Figure 3f).



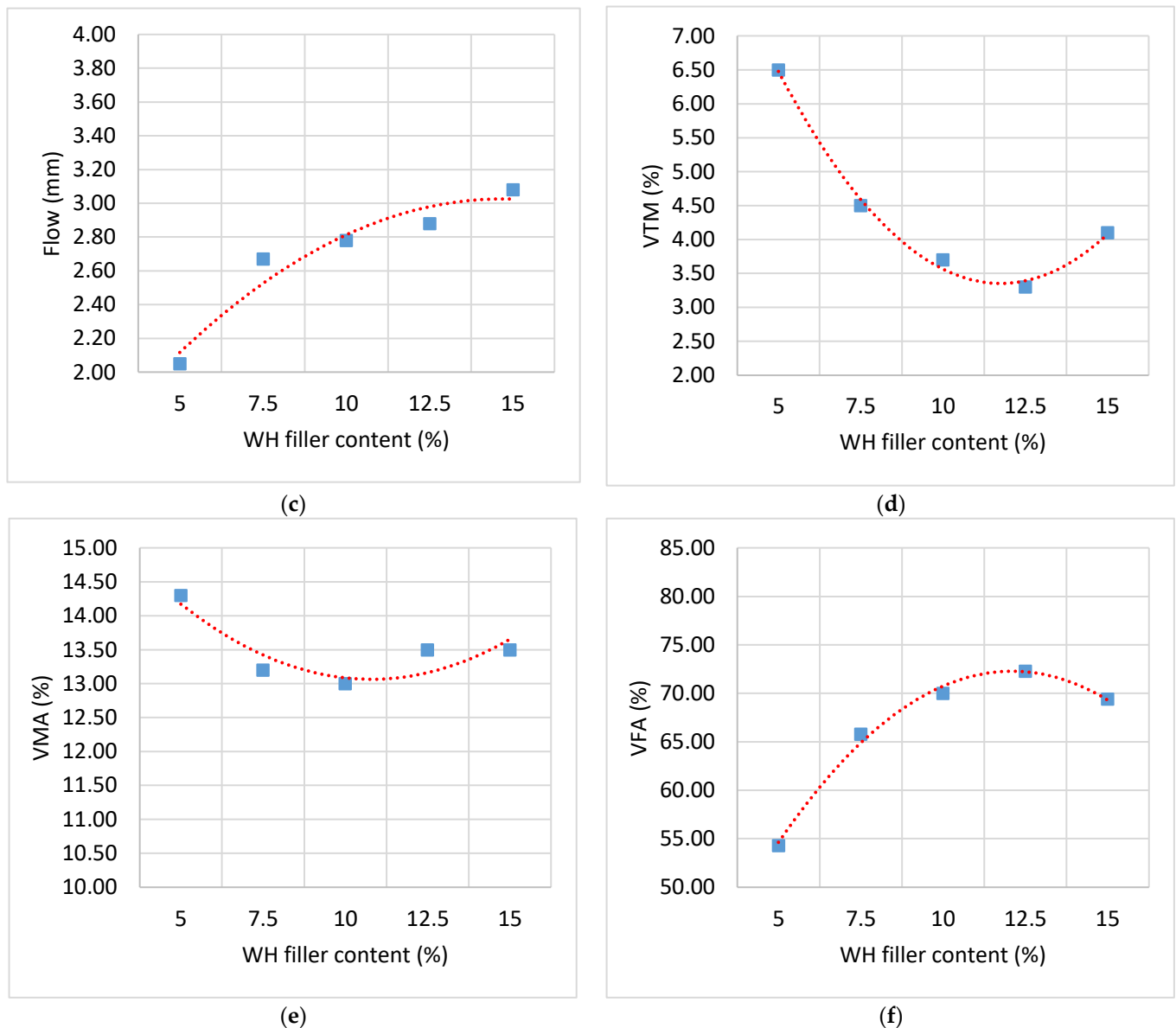


Figure 3. WH-modified mixtures properties: (a) Marshall stability; (b) Density; (c) Flow; (d) VTM; (e) VMA; (f) VFA.

According to Equation (3), the optimum OWC was determined to be 10.43%; the Marshall and volumetric properties of the modified-WH mixture at OWC are summarized in Table 10.

Table 10. Marshall and volumetric properties of the WH mixture at OWC.

Property	Unit	Value
Marshall stability	kN	15.058
Density	g/cm ³	2.330
Flow	mm	2.83
VTM	%	3.70
VMA	%	13.00
VFA	%	72.0

3.4. Statistical Analysis with ANOVA

The analysis of variance (ANOVA) was performed at a 95% confidence level to evaluate whether the type of filler (traditional, RH, and WH) significantly affects the

mechanical and volumetric properties of HMA at the OBC. The null hypothesis assumed that there were no statistically significant differences among the mean values of the mixtures. The hypothesis was tested using the F-statistic, where the null hypothesis is rejected when $F > F_{crit}$ and $p\text{-value} < 0.05$. Table 11 summarizes the ANOVA results for the tested properties of T36R0W0, T25.57R10.43W0, and T25.67R0W10.33. Seven HMA specimens at OBC have been tested for each investigated property.

Table 11. ANOVA results for filler type.

Property	Degree of Freedom	s_e^2	s_r^2	F	F-Critical
Marshall stability	2, 12	0.784	0.302	0.385	<
Marshall flow		0.417	1.111	2.661	<
VTM		0.177	0.965	5.445	> 3.89
VMA		0.357	0.445	1.245	<
VFA		0.031	73.27	2392	>

The ANOVA results in Table 11 reveal different levels of sensitivity of the measured properties to filler type, which provides important insights into the role of RH and WH in asphalt mixture behavior. Most mechanical and volumetric properties (i.e., Marshall stability, flow, VTM, and VMA) are not significantly affected by filler type at the 95% confidence level. On the other hand, VFA is significantly influenced, highlighting the role of filler in bitumen interaction and mastic formation. This behavior is attributed to the greater porosity of RH and WH than that of the conventional mineral filler.

RH and WH fillers can be considered statistically equivalent alternatives to conventional filler in terms of structural performance, while their influence on binder–void interaction (i.e., VTM and VFA) should be carefully considered to optimize HMA mixtures.

4. Discussion

The experimental results demonstrate that untreated RH and WH can successfully replace part of the conventional mineral filler without adversely affecting the Marshall performance of HMA. Although the modified mixtures exhibited only moderate changes in Marshall properties, the observed trends provide insight into the mechanisms governing the interaction between agricultural fillers, bitumen, and the aggregate skeleton.

Both RH and WH increased Marshall stability at intermediate replacement levels, with optimum contents of approximately 10–12%. This improvement can be attributed to the morphology of the husk particles, which are characterized by irregular shapes, relatively high surface roughness, and internal porosity. These characteristics enhance mechanical interlocking within the asphalt mastic and promote stronger filler–binder interactions. Similar mechanisms have been reported for other porous silica-rich fillers, whose large specific surface area increases mastic stiffness and improves stress transfer under loading [51,52]. When the replacement level exceeded the optimum value, Marshall stability declined. This behavior is consistent with the increased bitumen absorption associated with porous agricultural fillers. Excessive filler contents reduce the amount of effective binder available to coat the aggregates, producing a stiffer but less cohesive mastic and weakening the internal structure of the mixture. Consequently, an optimum filler content exists at which the beneficial stiffening effect is balanced by sufficient effective binder [53].

Flow values remained within acceptable specification limits for all mixtures, while ANOVA confirmed that the observed differences were not statistically significant. This

indicates that replacing conventional filler with RH or WH does not substantially alter the deformation characteristics of the mixtures under Marshall loading. Therefore, from a practical pavement engineering perspective, both agricultural fillers provide mechanical performance comparable to that of conventional mineral fillers.

The volumetric properties exhibited greater sensitivity to filler replacement than the Marshall indices. The reduction in VMA observed with increasing RH and WH content suggests improved particle packing and a more efficient filling of intergranular voids. Conversely, the statistically significant differences observed for VFA indicate that the agricultural fillers influence binder distribution within the mixture. Because RH and WH possess lower specific gravity and higher porosity than conventional mineral filler, they absorb part of the binder and modify the effective asphalt film thickness surrounding the aggregates. These effects primarily influence the asphalt mastic rather than the aggregate skeleton itself.

The ANOVA results support these observations. Marshall stability, flow, density, and VMA were not significantly affected by filler type, demonstrating that untreated RH and WH perform similarly to conventional filler from a structural standpoint. In contrast, the significant variation observed in VFA confirms that the principal effect of the agricultural fillers is associated with filler–binder interaction rather than aggregate rearrangement. This finding agrees with previous studies showing that filler morphology, pore structure, and specific surface area exert a greater influence on asphalt mastics than mineralogical composition alone [54,55].

From a sustainability perspective, the direct use of untreated RH and WH represents an important advantage over ash-based fillers. Previous investigations have generally relied on combustion to produce rice husk ash or wheat husk ash, requiring additional energy consumption and generating associated emissions. The present study demonstrates that untreated agricultural residues can provide comparable Marshall performance while eliminating this processing stage, thereby improving both environmental and economic sustainability. Nevertheless, the conclusions of this work should be interpreted within the scope of the experimental program. The Marshall method primarily evaluates strength and volumetric characteristics and does not directly assess rutting resistance, fatigue cracking, moisture susceptibility, or long-term durability. Consequently, further investigations using performance-based laboratory tests and field validation are required before untreated RH and WH can be recommended for widespread pavement applications.

5. Conclusions

Raw agricultural residues, such as rice husk and wheat husk, have received minimal systematic investigation, despite their abundance, low cost, and physicochemical properties. Unlike conventional mineral fillers, RH and WH have organic composition, low density, and high porosity, which may fundamentally alter bitumen absorption, mastic formation, and interfacial bonding mechanisms. However, previous research has neglected the combined evaluation of mechanical and volumetric properties required for practical mix design. To address these gaps, this study investigated the feasibility of using untreated RH and wheat husk WH as alternative fillers in HMA. Unlike most previous studies, which focused on ash-derived agricultural residues, the present work evaluated the direct incorporation of untreated husk materials while maintaining a constant optimum bitumen content to isolate the influence of filler replacement. Marshall mix design and statistical analysis were employed to evaluate their effects on the mechanical and volumetric properties of asphalt mixtures.

The main findings are as follows:

- The optimum bitumen content of the control mixture was 3.83%.

- Both RH and WH fillers produced Marshall stability values comparable to or slightly higher than those of the conventional mixture. The optimum replacement contents were 10.33% for RH and 10.43% for WH.
- ANOVA results demonstrated that filler type did not significantly affect Marshall stability, flow, density, or VMA at the 95% confidence level. These results indicate that untreated RH and WH can replace conventional mineral filler without compromising the structural performance assessed by the Marshall method.
- Significant differences were observed for VFA, confirming that the agricultural fillers primarily influence the binder–mastic phase through their lower density and greater porosity, which modify bitumen absorption and effective binder distribution.
- The direct use of untreated agricultural residues eliminates the energy-intensive ash production process while providing an effective pathway for agricultural waste valorization and reducing dependence on conventional mineral fillers.

Overall, the results demonstrate that untreated rice husk and wheat husk are technically feasible and environmentally attractive alternative fillers for hot mix asphalt, particularly at replacement levels close to 10%.

Nevertheless, certain limitations remain and require further studies. The current work does not capture long-term behavior under field conditions and environmental and economic benefits of adopting RH and WH fillers on an industrial scale. Moreover, microstructural and chemical analyses are necessary to deepen the filler–binder interaction mechanisms. Future studies should also expand the scope to include different bitumen grades, aggregate sources, and regional waste compositions to assess the generalizability of these results.

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Abbreviations

The following abbreviations are used in this manuscript:

HMA	Hot Mix Asphalt
OBC	Optimum Bitumen Content
RH	Rice Husk
WH	Wheat Husk
ORC	Optimum Rice Husk Content
OWC	Optimum Wheat Husk Content
VMA	Voids in Mineral Aggregates
VFA	Voids Filled with Asphalt
VTM	Voids in Total Mineral Aggregates

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