Utilization of Used Tires and High-Density Polyethylene Waste for Environmentally Friendly Porous Asphalt Mixtures with Response Surface Methodology Analysis

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ABSTRACT

The growing impact of environmental pollution caused by used tire waste and High-Density Polyethylene (HDPE) highlights the need to investigate their potential use as alternative building materials. In this study, a porous asphalt mixture was modified with used tire waste (outer and inner tires) and HDPE. Its optimization was conducted employing the Response Surface Methodology (RSM) alongside a Central Composite Design (CCD). The mixture composition was experimentally designed and tested in the laboratory, and performance parameters, including Cantabro Loss (CL), Asphalt Flow Down (AFD), Voids in Mix (VIM), and Marshall stability, were evaluated. The most significant results were achieved by combining a 9-11% outer tire with HDPE; this combination improved the structural stability, decreased the asphalt flow, created ideal voids, and produced excellent wear resistance. Conversely, the mechanical performance degraded due to increased inner tire content owing to unstable viscoelastic properties. The novelty of this research lies in that it integrates two types of solid waste, namely used tires and HDPE, into a single hybrid system in a porous asphalt mixture, which is optimized using a multivariate statistical approach. The research contribution is a predictive model and practical formulation recommendations for sustainable porous asphalt mixtures.

Keywords-component; porous asphalt mixture; used tire waste; HDPE; RSM

I. INTRODUCTION

The growth of the automotive industry and global plastic consumption has resulted in a massive accumulation of used tires and HDPE waste, with similar accumulation observed in Indonesia. Based on data from the Ministry of Environment and Forestry (KLHK), more than 6.8 million tons of plastic waste are produced annually in Indonesia. HDPE has been identified as a primary component of single-use plastic items, including beverage containers and household packaging materials. Meanwhile, as the Indonesian Tire Industry Association (AIBI) reported, more than 80 million vehicle tires have been produced and circulated annually in Indonesia, most of which will transform into used tire waste within 3-5 years of use.

HDPE plastic waste and used tires that are not appropriately handled can pollute the environment, both in the form of macroplastics and microplastics produced through physical and chemical degradation processes in the open environment [1]. In addition, bioaccumulating toxic compounds from plastic and rubber waste can potentially affect the ecological system and human health through the food chain [2].

To address these challenges, incorporating used tire waste and HDPE as a substitute material for pen 60/70 as a binder in porous asphalt mixtures is one of the strategic solutions within a circular economy framework [3]. Adding HDPE can increase viscosity, reduce plastic deformation, and improve resistance to asphalt mixtures [4]. Meanwhile, incorporating used tires in the form of crumb rubber can increase the flexibility value and fatigue resistance of asphalt to heavy traffic loads [5].

Applying porous asphalt mixtures can drain rainwater and direct it to seep directly into the next layer, reducing the rainwater on the surface [6]. However, the porosity level in this mixture can decrease the mechanical stability, so research on the binder used is needed. Incorporating used tire waste in the mixture can increase the flexibility and resistance to cracking due to repeated loads at extreme temperatures [7]. Meanwhile, adding HDPE can increase and strengthen cohesion between the aggregates, plastic deformation resistance, and wear resistance to the mixture in the long term [8].

Incorporating used tires and HDPE as individual modifiers in asphalt mixtures has been widely explored [3]. However, the combination of both wastes in developing porous asphalt is minimal. In addition, the statistical optimization approach in formulating the mixture composition has not been widely studied. Therefore, the present study optimizes the proportion of the combination of used tire waste (outer tires and inner tubes) [9] and HDPE in a porous asphalt mixture using the RSM approach, to improve the mechanical performance of the pavement while reducing the accumulation of used tire waste and plastic waste [10].

II. MATERIALS AND METHODS

This study was designed using RSM with the CCD scheme to determine the optimum composition of used tire waste (used outer tire/used inner tire) and HDPE in a porous asphalt mixture. The RSM approach was chosen as it can model the non-linear relationships between variables with a relatively efficient number of experiments while allowing visualization through response surfaces and three-dimensional contours [11]. The two main independent variables analyzed were the content of used tire waste (outer/inner tire) and HDPE content, each varied at three levels: 5%, 10%, and 15% of the asphalt weight. The materials utilized included Pen 60/70 asphalt in accordance with the specifications in [12], used tire waste shredded to a powder size of ±1 mm to ensure homogeneous dispersion [13, 14], and HDPE obtained from household waste bottles, such as shampoo and detergent, which were shredded, washed, and dried before use. The coarse and fine aggregates were crushed stone in accordance with the porous asphalt gradation of [15].

The studied mixture variations consisted of three compositions: V1 (15% used tire: 5% HDPE), V2 (10% used tire: 10% HDPE), and V3 (5% used tire: 15% HDPE) in proportion to the asphalt weight. The mixing process was carried out deploying the wet mixing method at a temperature of 150–170 °C, where the used tire waste and HDPE were gradually added to the hot asphalt and stirred using a laboratory mixer until a homogeneous mixture was obtained [7]. Next, the modified asphalt was mixed with hot aggregate until it became uniform. It was then compacted using a Marshall Compactor with 50 blows per side and a cylindrical test specimen with a diameter of 101.6 mm and a height of 63.5 mm.

Laboratory tests were conducted to evaluate the mixture's performance parameters, namely CL to assess the wear resistance [15], AFD to measure the asphalt drainage stability [15], VIM to determine the air void content [15], and Marshall Stability testing in accordance with SNI 06-2489-1991 to evaluate the strength and structural stiffness of the mixture. All test data were analyzed using Design-Expert v13 software with CCD-based quadratic modeling. Statistical analysis was performed using ANOVA, while model suitability was assessed utilizing the coefficient of determination (R^2), adjusted R^2, and a lack-of-fit test. The visualization of the interactions between variables was displayed as response surfaces and 3D contours to identify the optimum combination [16]. Multi-response optimization was performed employing a functional equation approach to obtain the best combination that balances the CL, AFD, VIM, and Marshall stability values. The results were validated by comparing the model predictions with actual experimental data to ensure prediction accuracy [16].

III. RESULTS AND DISCUSSION

A. *Test Results*

The results of the independent variable parameters and response values are presented in Tables I and II. For the independent variables, Table I shows the outer tire (A) and HDPE (B), and Table II depicts the inner tube (A) and HDPE (B), with the same response for both tests: CL, AFD, VIM, and Marshall stability.

Figure 1 demonstrates that the optimal combination of used outer tires and HDPE in the 9–11% range resulted in the lowest CL value, indicating the best wear resistance in porous asphalt mixtures.

TABLE I. USED OUTER TIRE TEST RESULTS: HDPE

No.	Independent variables		Response			
	A: used outer tire	B: HDPE	CL	AFD	VIM	Stability
	(%)	(%)	(%)	(%)	(%)	(kg)
1	15	15	26.89	0.044	18.64	597.44
2	10	10	23.65	0.023	18.37	630.70
3	10	10	22.84	0.020	18.31	639.86
4	10	10	22.47	0.018	18.28	645.76
5	10	10	23.29	0.021	18.33	635.72
6	10	5	24.33	0.027	18.43	624.93
7	10	10	23.96	0.025	18.41	628.37
8	5	15	28.56	0.047	19.91	581.58
9	10	15	25.85	0.035	18.52	620.96
10	15	5	25.58	0.032	18.45	618.73
11	5	5	27.36	0.039	18.70	590.47
12	15	10	24.84	0.022	18.39	626.60
13	5	10	26.73	0.028	18.59	610.58

TABLE II. USED INNER TUBE TEST RESULTS: HDPE

No.	Independent variables		Response			
	A: used inner tube	B: HDPE	CL	AFD	VIM	Stability
	(%)	(%)	(%)	(%)	(%)	(kg)
1	5	15	22.95	0.014	20.07	513.92
2	10	15	26.42	0.003	23.72	543.34
3	15	5	28.14	0.059	23.53	643.55
4	15	15	25.54	0.032	15.75	678.45
5	10	10	21.59	0.033	17.95	558.18
6	5	15	19.90	0.017	23.78	565.86
7	10	10	23.30	0.027	19.61	574.70
8	10	5.0	35.10	0.011	22.74	552.67
9	10	10	23.22	0.026	17.70	541.23
10	5	10	26.42	0.025	14.52	548.18
11	10	10	23.52	0.025	18.89	542.65
12	10	10	23.48	0.035	19.78	574.70
13	15	5.0	25.54	0.051	23.24	644.70

B. Statistical Analysis and Discussion

1) Cantabro Loss

This is due to the elastomeric properties of the outer tires and HDPE thermoplastic, which increase the cohesion between aggregates. [17]. On the other hand, using inner tubes above 10% increases the CL value significantly due to the soft nature of the high carbon content, which can weaken the bonds of the particles in the mixture. HDPE has been proven effective in reducing CL if combined with inner and outer tires in the right proportions, while inner tires must be limited in content [18]. When using tire and plastic waste in porous asphalt mixtures, each material's characteristics must be considered to obtain an environmentally friendly and wear-resistant mixture.

The quadratic regressions in (1) and (2) represent the CL value model based on variations in the content of the outer tires or inner tires (A) and HDPE (B) as modified materials in the porous asphalt mixture. Based on this model, the equation of Y_1 is:

$$Y_1 = 23.32 - 0.8883A + 0.6717B + 0.0275AB + 2.29A^2 + 1.59B^2 \qquad (1)$$

Equation (1) shows that the quadratic effect of A^2 and B^2 is positive and dominant, demonstrating a simultaneous increase in A and B levels beyond the optimum point when increasing the CL value. The linear effect of A is adverse, indicating that the simultaneous increase in the outer tire level tends to decrease the CL value [18]. The asphalt mixtures with rubber and plastic exhibit increased wear resistance at optimum concentrations, but decrease when the composition exceeds the optimum limit [19]. Furthermore, the Y_2 model is given as:

$$Y_2 = 23.23 - 3.05A - 5.37B + 5.10AB - 0.8815A^2 + 7.02B^2 \qquad (2)$$

Equation (2) shows that the interaction effect between (AB) is very large and positive, indicating that the high inner tube and HDPE combination can increase the CL value. In addition, the negative coefficients and A^2 indicate that increasing the content of used inner tubes tends to decrease the wear performance significantly.

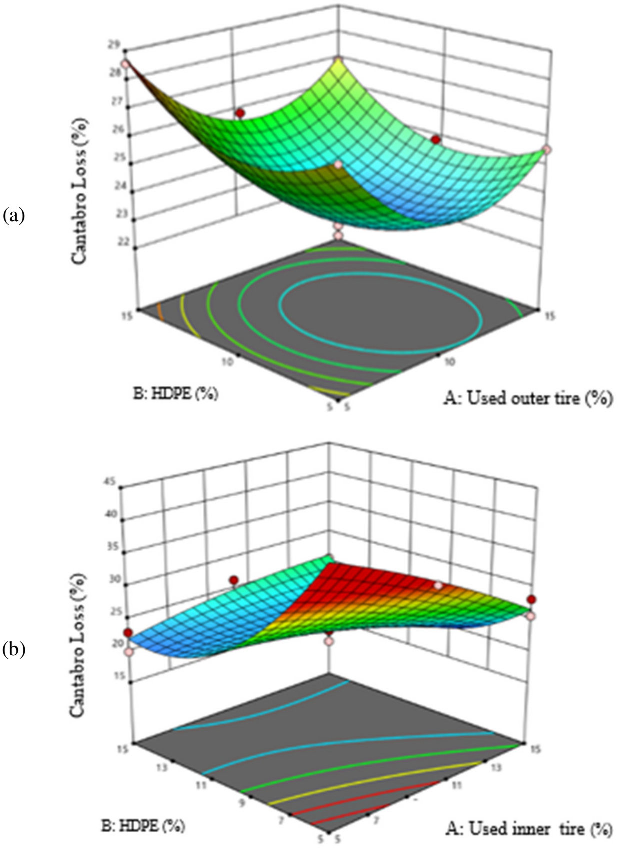

Fig. 1. 3D surface plot between CL: (a) used outer tire, (b) used inner tire.

These findings suggest that the quadratic model proves to be effective within the system, and thus it is highly advisable to employ the RSM statistical approach for optimizing waste material formulations in porous asphalt materials.

2) *Asphalt Flow Down*

Figure 2 illustrates the relationship of AFD with the HDPE content and used tires (outer and inner tubes). In Figure 3(a), the combination of used outer tires and HDPE forms a concave surface contour with a minimum AFD value in the range of HDPE content of 9-11% and used outer tires of 7-9%. This indicates that the composition provides optimal thermal stability by reducing the risk of excessive asphalt flow. In addition, used outer tires can increase the mixture's viscosity and hold the asphalt flow rate down during compaction [20]. Tire rubber can improve the thermal stability in plastic-modified porous asphalt mixtures [4].

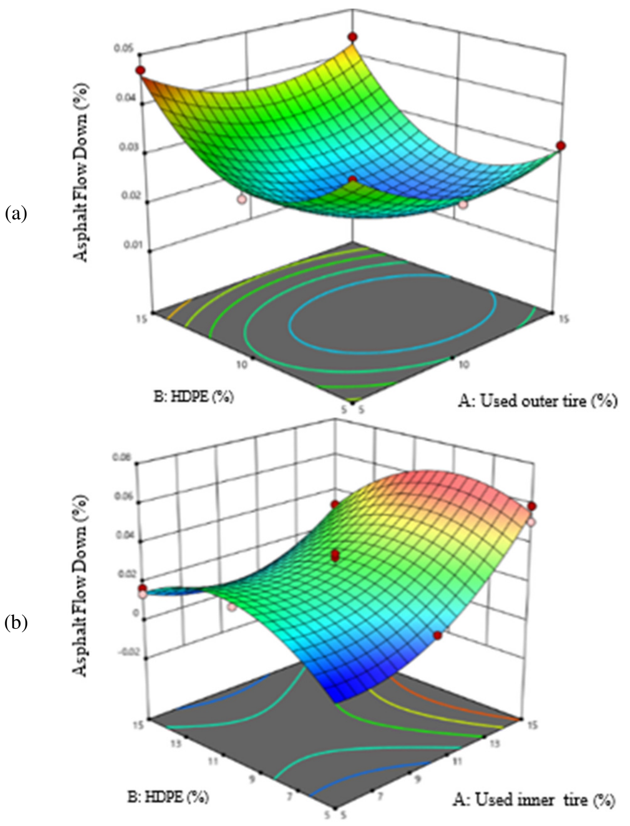

Fig. 2. 3D surface plot between AFD: (a) used outer tire, (b) used inner tire.

In contrast, Figure 3(b) shows a significant upward surface trend at high inner tube and HDPE content, indicating that this combination increases the AFD value. It can increase the risk of bleeding. This is due to the softer, viscous-plastic properties of inner tubes, which are insufficient to withstand the movement of liquid asphalt during heating and compaction. Thus, it can be concluded that the combination of used outer tires and HDPE is more effective in controlling the AFD value compared to used inner tires. Also, the formulation of porous asphalt mixtures must consider the optimum proportions of both materials to ensure that the risk of bleeding remains within the specified technical limits. In contrast, its interaction with used inner tubes is more effective in stabilizing HDPE in the mixture [21]. Additives in porous asphalt mixtures significantly influence the nonlinear characteristics and material synergy, beyond their linear effects [22]. To this end, the AFD optimization strategy should consider the interactions between the materials and the quadratic effects, rather than solely the individual contributions of the components. The model equation for Y_1 is as:

$$Y_1 = 0.0206 - 0.0027A + 0.0047B + 0.0010AB + 0.0064A^2 + 0.0124B^2 \qquad (3)$$

Equation (3) shows that increasing the HDPE content linearly (B) and quadratically (B^2) increases the AFD value, while A decreases AFD linearly but increases AFD at high levels of A^2, indicating an optimum point. The Y_2 model is given as:

$$Y_2 = 0.0288 + 0.0185A - 0.0020B - 0.0103AB + 0.0167A^2 - 0.0208B^2 \qquad (4)$$

Equation (4) demonstrates that A has a significant contribution in increasing AFD both linearly and quadratically. In contrast, HDPE has an adverse effect on AFD, especially at high levels of B^2, which can reduce the risk of bleeding. The AB interaction also exhibits an opposite behavior in both models [23]. Thermoplastic materials, such as HDPE are important in controlling the asphalt viscosity, while waste rubber exhibits complex behavior depending on its type and composition. [24]. Thus, this model not only supports the RSM-based material optimization approach, but also shows the importance of understanding the properties of each material in controlling the thermal performance of porous asphalt mixtures.

3) *Voids in Mix*

VIM indicates that the viscous-plastic characteristics of used inner tires that are soft and less cohesive can reduce the efficiency of void filling, increase excessive porosity, and decrease the stability of the mixture [25]. VIM control is greatly influenced by the balance between the flexibility and adhesiveness of the modified binder, where HDPE is effective in stabilizing the cavity volume to the optimum limit. At the same time, excess elastomeric materials, such as used rubber, cause segregation and irregularity of the internal structure [26]. Thus, managing plastic and rubber waste composition is important to ensure an optimal VIM performance in porous asphalt mix design.

Figure 3 displays the 3D surface plot of the relationship of VIM with variations in HDPE and waste tire content (used outer tires and used inner tires) in porous asphalt mixtures. Figure 3(a) shows that increasing the HDPE content and using outer tires to the optimum point of 9–11% causes a significant decrease in VIM, forming a concave pattern indicating improved mixture density. This implies that the specific combination can effectively fill the voids between aggregates without disturbing the desired open pore structure in porous asphalt. In contrast, Figure 3(b) demonstrates that the combination of used inner tires and HDPE tends to produce more fluctuating VIM values, with high VIM areas especially at extreme HDPE and waste tire content.

Meanwhile, in the used inner tire and HDPE model, only the interactions AB, A^2, and B^2 are significant, while the linear effect of used inner tires and HDPE is not significant. This shows that the stability of VIM in this combination is more determined by the synergy and nonlinear effects than the direct contribution of each material. These results generally indicate that the optimal design of porous asphalt mixtures requires considering the proportions of the materials and understanding the interactive and quadratic relationships between the waste materials used.

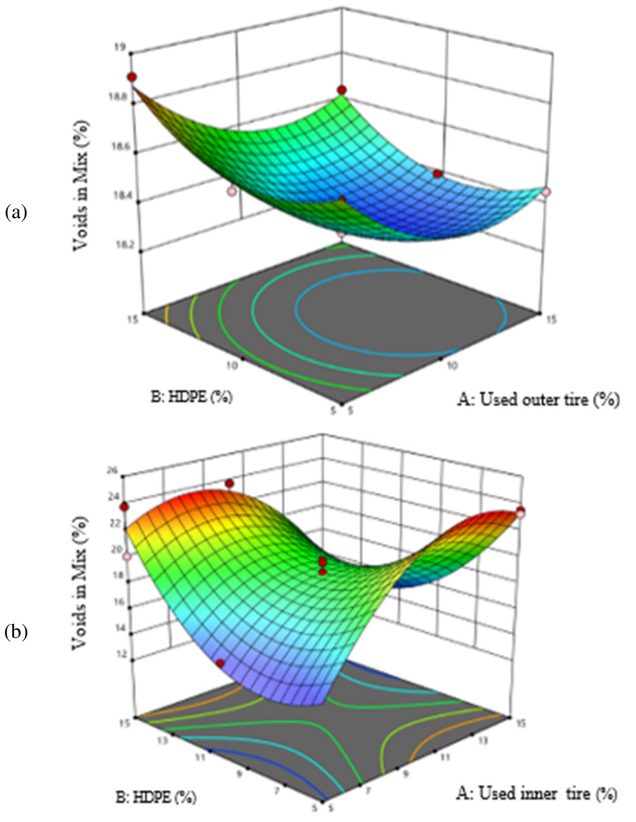

Fig. 3. 3D surface plot between VIM: (a) used outer tire, (b) used inner tire.

The quadratic regression equations of Y_1 and Y_2 show the relationship between the levels of tire waste (*A*), HDPE (*B*), and VIM in porous asphalt mixtures. The Y_1 model equation is:

$$Y_1 = 18.33 - 0.1200A + 0.0817B - 0.0050AB + 0.174A^2 + 0.1591B^2 \quad (5)$$

The linear effect on the content of used outer tires (*A*) is negative, indicating that increasing the content of used outer tires tends to decrease VIM. While the content of *B* can slightly increase the VIM value linearly, the nonlinear effects of A^2 and B^2 demonstrate the effect of increasing VIM at high levels. The Y_2 model equation is:

$$Y_2 = 18.87 + 0.6680A + 0.0886B - 3.76AB - 4.08A^2 - 4.16B^2 \quad (6)$$

On the contrary, (6) indicates that the content of the used inner tube (*A*) and HDPE (*B*) quadratically increases VIM, with a vast and adverse *AB* interaction effect, exhibiting that, in specific combinations, both materials can drastically reduce VIM. The high quadratic coefficient also indicates that the VIM value is susceptible to fluctuations in material composition in the experimental range used [27]. The porosity characteristics of modified asphalt mixtures are highly dependent on the quadratic effects and interactions between waste materials, such as plastic and rubber. So, nonlinear models are essential for mix design optimization [28]. Therefore, the formulation of waste materials in porous asphalt must simultaneously consider the individual and combined effects to control VIM effectively.

4) Stability

Figure 4 illustrates the 3D surface plot of the relationship of Marshall stability with variations in the content of HDPE and used tire waste (outer tires and inner tires) in porous asphalt mixtures. Figure 4(a) shows that increasing the content of used outer tires and HDPE simultaneously significantly increases the stability of the mixture, with the maximum area of stability achieved at a level combination of around 11–13%. The raised surface pattern and curve indicate a synergistic effect between the used outer tires that act as elastomers and HDPE, increasing the mixture's stiffness.

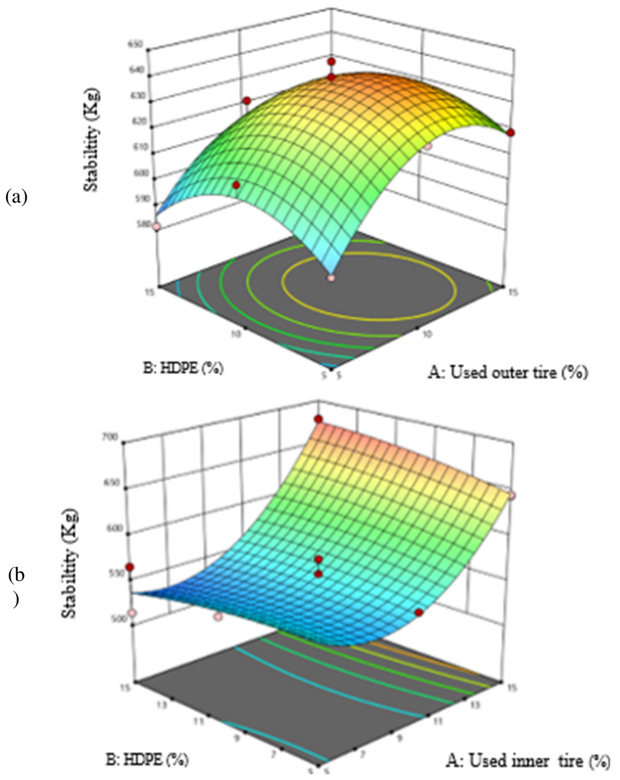

Fig. 4. 3D Surface plot between stability: (a) used outer tire, (b) used inner tire.

In contrast, Figure 4(b) shows that increasing the content of used inner tires can increase stability, but it is more dominant than HDPE, with a steep surface shape. This demonstrates that using inner tires substantially contributes to elasticity and internal bonds, but requires careful control to avoid excessive deformation due to excess soft rubber [29]. Used tire waste can improve the mechanical performance of asphalt, especially in terms of stability and deformation, while thermoplastic materials, such as HDPE, function more as structural reinforcements in the long term [28].

Thus, the proportional combination of HDPE and used outer tires can effectively increase the stability of the mixture but it must be controlled so as not to exceed the optimum threshold, which could potentially reduce other performances, such as flexibility or crack resistance.

Equations (7) and (8) represent the predictive model for the Marshall stability (kg) of porous asphalt mixtures modified with a combination of waste tires and HDPE:

$$Y_1 = 637.24 + 10.02A - 5.69B - 3.10AB - 21.55A^2 - 17.19B^2 \quad (7)$$

The values of the linear coefficient A indicate that increasing the content of used tires can increase stability, while HDPE has a negative linear and quadratic coefficient. The negative values in A^2 and B^2 indicate that exceeding the optimum content of used tires and HDPE reduces stability due to the potential for over-coating and weakening of aggregate cohesion. The Y_2 model equation is:

$$Y_2 = 557.05 + 56.01A + 1.56B + 13.27AB + 53.38A^2 - 5.93B^2 \quad (8)$$

In contrast, the Y_2 model indicates that inner used tubes (A) make a substantial quadratic contribution to enhancing stability, with a significant AB interaction. The adverse quadratic effect of HDPE (B^2) still indicates that there is an optimum limit for the use of plastic [30]. Utilizing inner tube rubber can significantly strengthen the structure of the asphalt mixture by increasing the elasticity and bonding power between particles. While using recycled plastics, such as HDPE, provides structural benefits up to a specific dose, it reduces performance when overdosage occurs [31]. Therefore, these two models show the importance of optimizing the waste material content in the mixture to obtain maximum statistical and structural stability performance.

The test results and statistical analysis indicate that the mechanical performance of porous asphalt mixtures can be substantially enhanced by incorporating a blend of recycled outer tire waste and HDPE at an optimal concentration of 9–11%. Reducing the CL, AFD, VIM, and Marshall stability values signifies this enhancement. The quadratic regression model developed through the RSM approach has been validated with an R^2 value above 0.90 with an insignificant lack of fit, so it can be used to predict mixture behavior accurately. HDPE significantly contributes to the mixture's plastic deformation resistance and cohesion, while adding used outer tires improves elasticity and fatigue resistance. Including used inner tires at high levels reduces the combination's performance due to their viscoelastic properties. The optimization of eco-friendly porous asphalt has been achieved using the integration of waste material, enhancing structural performance, and aiding in the reduction of the contamination of the environment within a circular economy framework.

IV. CONCLUSION

This study demonstrates that utilizing used tire waste (outer and inner tubes) with High-Density Polyethylene (HDPE) as a modifying material in porous asphalt mixtures can significantly improve the mechanical performance at an optimum asphalt content. Deploying the Response Surface Methodology-Central Composite Design (RSM-CCD) approach, the optimum asphalt content obtained with a combination of used outer tires and HDPE in the range of 9–11% yields the best results, characterized by low Cantabro Loss (CL) values, decreased Asphalt Flow Down (AFD) values, controlled Voids in Mix (VIM) values, and increased Marshall stability values. The elastomeric properties of used outer tires increase flexibility and wear resistance, while HDPE contributes significantly to the stiffness and cohesion of the mixture. In contrast, incorporating used inner tubes at high asphalt content reduces performance due to less stable viscoelastic properties.

The novelty of this study lies in the integration of two different solid wastes: used tires (outer and inner tubes) and recycled HDPE plastic, which had previously been studied separately. Furthermore, this study employed a multivariate optimization approach based on RSM-CCD to reveal nonlinear interactions between variables. This resulted in a quadratic model with an R^2 value > 0.90 and an insignificant lack of fit. This demonstrates the reliability of the predictive model in formulating waste-based porous asphalt mixture compositions.

The primary contribution of this study is two-fold: technical and ecological. From a technical perspective, the optimal formulation provides an alternative pavement material with superior mechanical performance, meeting the porous asphalt mixture standards. From an ecological perspective, this study supports the concept of a circular economy by utilizing waste tires and HDPE plastic waste, which are abundant in Indonesia, thereby reducing environmental pollution and providing added value. Therefore, this study makes both a scientific contribution by developing a waste-based material optimization methodology and a practical contribution by proposing a mixture formulation ready for implementation to support sustainable road infrastructure development.

REFERENCES

[1] S. Wagner, T. Hüffer, P. Klöckner, M. Wehrhahn, T. Hofmann, and T. Reemtsma, "Tire Wear Particles in the Aquatic Environment - A Review on Generation, Analysis, Occurrence, Fate and Effects," *Water Research*, vol. 139, pp. 83–100, Aug. 2018, https://doi.org/10.1016/j.watres.2018.03.051.

[2] M. A. Carvajalino-Fernández, P. N. Sævik, I. A. Johnsen, J. Albretsen, and N. B. Keeley, "Simulating Particle Organic Matter Dispersal Beneath Atlantic Salmon Fish Farms using Different Resuspension Approaches," *Marine Pollution Bulletin*, vol. 161, Dec. 2020, Art. no.111685, https://doi.org/10.1016/j.marpolbul.2020.111685.

[3] K. Dewi, W. W. Raharjo, and B. Kusharjanta, "Mechanical Strength Optimization of HDPE Biocomposite with Water Hyacinth Fiber Reinforcement using a Dispersing Agent," *Engineering, Technology & Applied Science Research*, vol. 15, no. 1, pp. 20388–20394, Feb. 2025, https://doi.org/10.48084/etasr.9509.

[4] Y. Gao, T. Yue, W. Sun, D. He, C. Lu, and X. Fu, "Acid Recovering and Iron Recycling from Pickling Waste Acid by Extraction and Spray Pyrolysis Techniques," *Journal of Cleaner Production*, vol. 312, Aug. 2021, Art. no. 127747, https://doi.org/10.1016/j.jclepro.2021.127747.

[5] L. N. Assi, Y. A. J. Al-Hamadani, E. (Eddie) Deaver, V. Soltangharaei, P. Ziehl, and Y. Yoon, "Effect of Sonicated Deionized Water on The Early Age Behavior of Portland Cement-Based Concrete and Paste," *Construction and Building Materials*, vol. 247, June 2020, Art. no. 118571, https://doi.org/10.1016/j.conbuildmat.2020.118571.

[6] S. Hille, S. Weber, and T. Brosch, "Consumers' Preferences for Electricity-Saving Programs: Evidence from a Choice-Based Conjoint Study," *Journal of Cleaner Production*, vol. 220, pp. 800–815, May 2019, https://doi.org/10.1016/j.jclepro.2019.02.142.

[7] Y. Sun, X. Zhu, Y. Han, Y. Li, and P. Gao, "Iron Recovery from Refractory Limonite Ore Using Suspension Magnetization Roasting: A Pilot-Scale Study," *Journal of Cleaner Production*, vol. 261, July 2020, Art. no. 121221, https://doi.org/10.1016/j.jclepro.2020.121221.

[8] A. S. Leão, S. A. Sipert, D. L. Medeiros, and E. B. Cohim, "Water Footprint of Drinking Water: The Consumptive and Degradative Use," *Journal of Cleaner Production*, vol. 355, June 2022, Art. no. 131731, https://doi.org/10.1016/j.jclepro.2022.131731.

[9] S. Sarkar, S. K. Biswas, and S. Chakraborty, "Deflection and Elastic Modulus Assessment of Subgrade in Flexible Pavement mixed with Waste Tire Scrap Material," *Engineering, Technology & Applied Science Research*, vol. 14, no. 2, pp. 13208–13215, Apr. 2024, https://doi.org/10.48084/etasr.6858.

[10] T.-B. Huynh, T.-A.-S. Do, T.-K.-A. Tran, and T. Dang-Bao, "Optimization of Microwave-Assisted Extraction of Polyphenolics from Rambutan (Nephelium Lappaceum L.) Peels using Response Surface Methodology and Central Composite Design," *Engineering, Technology & Applied Science Research*, vol. 15, no. 3, pp. 22431–22436, June 2025, https://doi.org/10.48084/etasr.10570.

[11] S. A. Ahmed, S. A. Tayh, and N. A. Jasim, "Assessing the Mechanical Properties of Open-Graded Asphalt Mixtures," *Engineering, Technology & Applied Science Research*, vol. 15, no. 1, pp. 20056–20063, Feb. 2025, https://doi.org/10.48084/etasr.9673.

[12] *General specifications: 2018*, South Jakarta, Indonesia: Directorate General of Highways, Ministry of Public Works. Umum, 2018.

[13] D. Nasr, R. Babagoli, and M. Mazrouei, "Evaluation of Rheological Behaviour of Asphalt Binder Modified by Recycled Polyethylene Wax and Crumb Rubber," *Construction and Building Materials*, vol. 328, Apr. 2022, Art. no. 127069, https://doi.org/10.1016/j.conbuildmat.2022.127069.

[14] R. A. Rahman, A. R. Radzi, M. S. H. Saad, and S. I. Doh, "Factors Affecting the Success of Highway Construction Projects: The Case of Malaysia," *IOP Conference Series: Materials Science and Engineering*, vol. 712, no. 1, Jan. 2020, Art. no. 012030, https://doi.org/10.1088/1757-899X/712/1/012030.

[15] *Open Graded Asphalt Design Guide*, Victoria, Australia: Asphalt Pavement Association, 2004.

[16] D. Liu, X. Zhu, and Y. Wang, "China's Agricultural Green Total Factor Productivity Based on Carbon Emission: An Analysis of Evolution Trend and Influencing Factors," *Journal of Cleaner Production*, vol. 278, Jan. 2021, Art. no. 123692, https://doi.org/10.1016/j.jclepro.2020.123692.

[17] G. Hao *et al.*, "Long-Term Performance of Porous Asphalt Pavement Incorporating Recycled Plastics," *Resources, Conservation and Recycling*, vol. 212, Jan. 2025, Art. no. 107979, https://doi.org/10.1016/j.resconrec.2024.107979.

[18] S. A. Hussein, Z. Al-Khafaji, T. J. M. Alfatlawi, and A.-K. N. Abbood, "Improvement of Permeable Asphalt Pavement by Adding Crumb Rubber Waste," *Open Engineering*, vol. 12, no. 1, pp. 1030–1037, Dec. 2022, https://doi.org/10.1515/eng-2022-0345.

[19] X. Yang, A. Hasan, C.-H. Yu, L. Xu, and J. Yi, "Reimagining Medical Sustainability: The Role of Symbolic Visuals Against Plastic Waste," *Journal of Cleaner Production*, vol. 434, Jan. 2024, Art. no. 139982, https://doi.org/10.1016/j.jclepro.2023.139982.

[20] L. Kumar *et al.*, "Opportunities and Constraints for Cleaner Production Policy in the Developing World: A Case Study of Sindh Region, Pakistan," *Environment, Development and Sustainability*, vol. 26, no. 2, pp. 4391–4434, Jan. 2023, https://doi.org/10.1007/s10668-022-02889-0.

[21] Z. Wang *et al.*, "A Review on Indirect Coal Liquefaction Residue Used in Asphalt Pavement," *Construction and Building Materials*, vol. 364, Jan. 2023, Art. no. 129755, https://doi.org/10.1016/j.conbuildmat.2022.129755.

[22] F. B. Santos, A. L. Faxina, and S. D. A. Soares, "Soy-Based Rejuvenated Asphalt Binders: Impact on Rheological Properties and Chemical Aging Indices," *Construction and Building Materials*, vol. 300, Sept. 2021, Art. no. 124220, https://doi.org/10.1016/j.conbuildmat.2021.124220.

[23] W. Zhang, Q. Li, J. Wang, X. Zeng, and B. Yu, "Evaluation of the Effect of Different Preparation Processes on the Road Performance of Thermoplastic Resin Modified Porous Asphalt Mixtures," *Construction and Building Materials*, vol. 428, May 2024, Art. no. 136256, https://doi.org/10.1016/j.conbuildmat.2024.136256.

[24] C. Groening and J. Peloza, "Are We Paying Attention to the Right Metric? The Impact on Firm Value of Consumers' Perceptions Versus Actual Corporate Social Responsibility Actions," *Journal of Cleaner Production*, vol. 417, Sept. 2023, Art. no. 137981, https://doi.org/10.1016/j.jclepro.2023.137981.

[25] W. N. H. Mior Sani, R. P. Jaya, K. A. Masri, K. Saptaji, and A. Dulaimi, "Exploring the Chemical Properties and Microstructural Characterisations of Hybrid Asphalt Binders for Enhanced Performance," *Discover Applied Sciences*, vol. 6, no. 4, Apr. 2024, Art. no. 193, https://doi.org/10.1007/s42452-024-05868-4.

[26] Ş. O. Kalkan, A. Yavaş, S. Güler, M. Torman Kayalar, M. Sütçü, and L. Gündüz, "An Experimental Approach to a Cementitious Lightweight Composite Mortar Using Synthetic Wollastonite," *Construction and Building Materials*, vol. 341, July 2022, Art. no. 127911, https://doi.org/10.1016/j.conbuildmat.2022.127911.

[27] M. F. Chong, K. P. Lee, H. J. Chieng, and I. I. Syazwani Binti Ramli, "Removal of Boron from Ceramic Industry Wastewater by Adsorption–Flocculation Mechanism Using Palm Oil Mill Boiler (POMB) Bottom Ash and Polymer," *Water Research*, vol. 43, no. 13, pp. 3326–3334, July 2009, https://doi.org/10.1016/j.watres.2009.04.044.

[28] T. Brydges, "Closing the Loop on Take, Make, Waste: Investigating Circular Economy Practices in the Swedish Fashion Industry," *Journal of Cleaner Production*, vol. 293, Apr. 2021, Art. no. 126245, https://doi.org/10.1016/j.jclepro.2021.126245.

[29] A. Mohajerani *et al.*, "Recycling Waste Rubber Tyres in Construction Materials and Associated Environmental Considerations: A Review," *Resources, Conservation and Recycling*, vol. 155, Apr. 2020, Art. no. 104679, https://doi.org/10.1016/j.resconrec.2020.104679.

[30] A. M. Odeh and H. T. Battaineh, "Causes of Construction Delay: Traditional Contracts," *International Journal of Project Management*, vol. 20, no. 1, pp. 67–73, Jan. 2002, https://doi.org/10.1016/S0263-7863(00)00037-5.

[31] X. Sun *et al.*, "Biomass Estimation and Physicochemical Characterization of Winter Vine Prunings in the Chinese and Global Grape and Wine Industries," *Waste Management*, vol. 104, pp. 119–129, Mar. 2020, https://doi.org/10.1016/j.wasman.2020.01.018.