

Review

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Review

Application of Plastic Waste as a Sustainable Bitumen Mixture – A Review

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Abstract

Plastic trash is one of the world’s fastest growing environmental issues, with millions of tons ending up in landfills and natural ecosystems each year. At the same time, the road construction industry is facing escalating costs and sustainability problems as a result of its strong reliance on petroleum-based bitumen. Integrating recycled plastic into asphalt provides a twofold benefit, it reduces waste accumulation while also increasing pavement performance. This review compiles data from 51 papers and 251 experimental records to investigate the impacts of plastic alteration on bitumen properties, with an emphasis on penetration, softening point, and viscosity. Consistent trends suggest that adding plastic stiffens the binder, as evidenced by reduced penetration and increased softening point and viscosity. These enhancements improve rutting resistance, but they may make mixing and handling more difficult. This paper uses machine learning (ML) methodologies such as Random Forest and XGBoost to improve predictive understanding by outperforming linear models in capturing nonlinear relationships between dosage, plastic type, and processing conditions. The review identifies knowledge gaps, such as variability across studies, a lack of standardized test methodologies, and insufficient consideration of long-term environmental and economic repercussions. This study provides a synthesis of experimental findings as well as a data-driven methodology for developing long-lasting, high-performance asphalt binders supplemented with plastic waste.

Keywords: plastic waste; sustainable pavement; mean absolute error (MAE); XGBoost; dosage; Root means square error (RMSE); coefficient of determination(r^2); modified bitumen; temperature

1. Introduction

Plastic production has increased worldwide in recent decades, creating a substantial waste management problem. Landfilling and incineration are traditional disposal methods that pose significant environmental risks, such as soil damage, greenhouse gas emissions, and ocean contamination. Since its inception, an estimated 8,300 million tons of plastic have been produced [1]. By 2015, around 6,300 million tons of garbage had been generated. Only 9% was recycled, 12% was burned, and the rest 79% wound up in landfills or the environment. If current trends continue, by 2050, approximately 12,000 million tons of plastic waste will have accumulated in landfills and natural places [1]. Natural resources are used extensively in road construction. Bitumen, the major binder in asphalt, is derived from petroleum, hence its price and availability fluctuate with the market. There is currently a critical need to increase the quality of asphalt mixes while simultaneously making them more sustainable.

The use of recycled plastic trash in bitumen has emerged as a viable road construction solution. This strategy not only reduces the quantity of plastic that ends up in landfills, but it also reduces reliance on virgin bitumen, which is expensive and restricted. By combining these advantages, the strategy promotes a more sustainable and circular economy, benefiting both waste management and the building industries [2]. Over the last 20 years, research has shown that plastics can operate as efficient modifiers, altering the rheological properties of bitumen to increase the performance of

asphalt concrete in terms of rutting resistance, fatigue life, and durability. The findings revealed that the penetration values of the plastic-modified bitumen dropped as the amount of plastic increased. According to [3] the penetration values for 5%, 10%, and 20% plastic were 7.7 mm, 7.3 mm, and 2.0 mm, respectively. In contrast, as the plastic percentage increased, so did the softening point and ductility.

Another experiment was conducted where the dose of plastic used were 2,4,6,8 & 10% and it was concluded that replacing bitumen with plastic waste significantly improves tensing point, ductility, and penetration in flexible pavement construction, making it a cost-effective alternative to bitumen [4]. Also with the same amount of dose, researcher [5] conducts test on different quantities of 80/100 bitumen which showed, qualities such as elastic modulus, tensile strength, durability, resistance to permanent deformation, heat susceptibility, and fatigue resistance improved. Experiment conducted by [6], where he used 2,3,6,8 and 10% of PET, showed a result as by adding 3 % PET waste improves the properties of modified bitumen, reducing penetration by 12 units and increasing softening point by 5°C.

This review paper assembles over 250 data points from 51 distinct investigations to provide a thorough understanding of plastic-modified bitumen. The study looks at how different plastics, such as PET, LDPE, HDPE, PP, hybrid and PVC, as well as dose levels, mixing temperature and mixing rate, affect essential bitumen qualities like penetration, softening point, and viscosity. Machine learning models are applied to the combined dataset to improve the analysis by predicting material behavior and providing fresh insights into the complicated interactions between processing conditions and performance outcomes. The review aims to integrate existing knowledge, identify consistent trends and gaps, recommend optimal parameters, and discuss future difficulties and opportunities for the wider use of plastic-modified bitumen in road building.

2. Materials and Methods

To describe and analyze the behavior of plastic-modified bitumen, this project took a data-driven method. A tabular dataset of 251 records (Table 1) was generated from published studies, including three important bitumen target properties: softening point, penetration, and viscosity. Each row represents one experimental condition, and each row is labeled with a “study id” to indicate the original study for grouping validation. Modeling and analysis were done in the help of Python as well as Google Colab to facilitate sharing and repeatability.

Table 1. Data set and reference.

Sl.no.	Data			Reference
	Softening	Penetration	Viscosity	
St_01	49.5	547	0.81	[7]
St_01	83.7	403	1.46	[7]
St_01	119.3	253	3.52	[7]
St_01	122.3	143	5.75	[7]
St_02	70	490	0.35	[8]
St_02	72	400	0.34	[8]
St_02	80	320	0.8	[8]
St_02	85	250	0.9	[8]
St_02	90	200	1.4	[8]
St_03	43	550	NA	[9]
St_03	51	450	NA	[9]
St_03	62	400	NA	[9]
St_04	47.5	820	6.5	[10]
St_04	48.5	810	7.1	[10]
St_04	50	780	7.55	[10]
St_04	51.25	740	7.8	[10]

St_04	53	710	7.9	[10]
St_04	55	670	8.1	[10]
St_05	NA	NA	NA	St_05
St_05	NA	NA	NA	St_05
St_05	NA	NA	NA	St_05
St_05	NA	NA	NA	St_05
St_06	80	250	NA	[11]
St_06	75	250	NA	[11]
St_06	90	240	NA	[11]
St_07	43	730	NA	[4]
St_07	48	580	NA	[4]
St_07	57	550	NA	[4]
St_07	61	530	NA	[4]
St_07	63	500	NA	[4]
St_07	66	460	NA	[4]
St_08	NA	420	NA	[12]
St_08	NA	400	NA	[12]
St_08	NA	400	NA	[12]
St_08	NA	420	NA	[12]
St_09	NA	NA	NA	[13]
St_09	NA	NA	NA	[13]
St_09	NA	NA	NA	[13]
St_09	NA	NA	NA	[13]
St_09	NA	NA	NA	[13]
St_10	NA	NA	2.4	[14]
St_10	NA	NA	0.9	[14]
St_10	NA	NA	0.5	[14]
St_10	NA	NA	1.2	[14]
St_11	42	97	NA	[15]
St_11	43	91	NA	[15]
St_11	43.55	84	NA	[15]
St_12	67.33	29	NA	[16]
St_12	83.33	59	NA	[16]
St_12	73	56	NA	[16]
St_12	73	53	NA	[16]
St_12	115	47	NA	[16]
St_13	40.5	165	0.245	[15]
St_13	41.3	157	0.282	[15]
St_13	42	150	0.298	[15]
St_14	55	760	NA	[17]
St_14	59	710	NA	[17]
St_14	61	660	NA	[17]
St_14	66	590	NA	[17]
St_14	71	530	NA	[17]
St_14	78	490	NA	[17]
St_14	81	450	NA	[17]
St_14	83	390	NA	[17]
St_15	6	463	NA	[15]
St_15	5.3	490	NA	[15]
St_15	3.833	540	NA	[15]
St_16	44.1	593	0.62	[7]
St_16	49.5	547	0.81	[7]
St_16	83.7	403	1.46	[7]

St_16	119.3	253	3.52	[7]
St_16	122.3	143	5.57	[7]
St_17	45	81	NA	[15]
St_17	46.25	73	NA	[15]
St_17	51	83	NA	[15]
St_18	10	NA	NA	[18]
St_18	5	NA	NA	[18]
St_18	29	NA	NA	[18]
St_18	130	NA	NA	[18]
St_18	131	NA	NA	[18]
St_19	41.05	135	0.25	[15]
St_19	41.85	122	0.3	[15]
St_19	42.25	106	0.39	[15]
St_20	NA	450	NA	[19]
St_20	NA	420	NA	[19]
St_20	NA	390	NA	[19]
St_20	NA	350	NA	[19]
St_20	NA	300	NA	[19]
St_20	NA	450	NA	[19]
St_20	NA	440	NA	[19]
St_20	NA	430	NA	[19]
St_20	NA	460	NA	[19]
St_20	NA	470	NA	[19]
St_20	NA	460	NA	[19]
St_20	NA	450	NA	[19]
St_20	NA	410	NA	[19]
St_20	NA	415	NA	[19]
St_20	NA	450	NA	[19]
St_21	46.9	80	0.38	[20]
St_21	48.4	73	0.44	[20]
St_21	48.8	65	0.41	[20]
St_21	50.1	60	0.45	[20]
St_22	NA	101.5	0.65	[5]
St_22	44.5	102.75	0.73	[5]
St_22	44.8	103.5	0.79	[5]
St_22	45.2	104.75	0.86	[5]
St_22	47	110	0.91	[5]
St_22	47.5	112	0.95	[5]
St_23	55.7	47	NA	[21]
St_23	54.4	49	NA	[21]
St_23	53.9	53	NA	[21]
St_24	NA	NA	NA	[22]
St_24	NA	NA	NA	[22]
St_24	NA	NA	NA	[22]
St_24	NA	NA	NA	[22]
St_24	NA	NA	NA	[22]
St_24	NA	NA	NA	[22]
St_25	52	730	NA	[6]
St_25	54	650	NA	[6]
St_25	57	610	NA	[6]
St_25	56	620	NA	[6]
St_25	55	640	NA	[6]

St_26	50	55	0.8	[7]
St_26	80	40	1.5	[7]
St_26	118	25	3.5	[7]
St_26	120	15	6.7	[7]
St_27	62.2	323	0.54	[23]
St_27	68.6	285	0.78	[23]
St_27	73.5	218	1.28	[23]
St_27	75.7	199	1.42	[23]
St_27	74	213	1.54	[23]
St_28	56	422	NA	[24]
St_28	59.4	400	NA	[24]
St_28	60.1	383	NA	[24]
St_28	61	361	NA	[24]
St_29	66	NA	1.5	[25]
St_29	90	NA	2.7	[25]
St_30	65.1	470	0.618	[26]
St_30	61.9	473	0.609	[26]
St_30	63.6	464	0.626	[26]
St_30	63.3	475	0.606	[26]
St_30	62.9	473	0.612	[26]
St_30	62.6	484	0.6	[26]
St_30	62.5	473	0.617	[26]
St_31	45	666	0.196	[27]
St_31	46.5	649	0.238	[27]
St_31	48	638	0.293	[27]
St_31	50.5	612	0.341	[27]
St_31	53	594	0.407	[27]
St_31	55.5	573	0.459	[27]
St_31	56	569	0.537	[27]
St_32	52.5	55	0.54	[28]
St_32	52.7	49	0.72	[28]
St_32	61.8	38	0.84	[28]
St_33	NA	NA	NA	[29]
St_33	NA	NA	NA	[29]
St_33	NA	NA	NA	[29]
St_33	NA	NA	NA	[29]
St_33	NA	NA	NA	[29]
St_33	NA	NA	NA	[29]
St_33	NA	NA	NA	[29]
St_33	NA	NA	NA	[29]
St_34	45	55	NA	[9]
St_34	47.5	53	NA	[9]
St_34	53	43	NA	[9]
St_35	NA	NA	NA	[30]
St_35	NA	NA	NA	[30]
St_35	NA	NA	NA	[30]
St_36	51.6	45	0.2	[31]
St_36	50.3	50	0.18	[31]
St_36	50.1	54	0.175	[31]
St_36	50	57	0.17	[31]
St_36	49.8	60	0.16	[31]
St_37	63	320	0.7	[32]
St_37	61	270	0.578	[32]

St_37	59	210	0.38	[32]
St_37	63	240	0.6	[32]
St_37	57	500	0.98	[32]
St_37	58	560	0.94	[32]
St_38	75	730	NA	[33]
St_38	78	710	NA	[33]
St_38	85	670	NA	[33]
St_38	98	560	NA	[33]
St_38	99	530	NA	[33]
St_38	100	500	NA	[33]
St_39	77	300	NA	[34]
St_39	77	300	NA	[34]
St_39	77	300	NA	[34]
St_39	77	300	NA	[34]
St_39	87	255	NA	[34]
St_39	87	255	NA	[34]
St_39	87	255	NA	[34]
St_39	87	255	NA	[34]
St_40	47	650	NA	[35]
St_40	47.5	620	NA	[35]
St_40	48.5	600	NA	[35]
St_41	80.7	670	NA	[36]
St_41	81.2	490	NA	[36]
St_42	50	138	2	[37]
St_42	55	100	4	[37]
St_42	54	90	4.1	[37]
St_42	54	85	4.9	[37]
St_42	55	85	3.5	[37]
St_42	59	80	5.8	[37]
St_43	55	550	4.3	[38]
St_43	58	440	5	[38]
St_44	NA	NA	NA	[39]
St_44	NA	NA	NA	[39]
St_44	NA	NA	NA	[39]
St_44	NA	NA	NA	[39]
St_45	52	49	NA	[40]
St_45	53	35	NA	[40]
St_45	57	29	NA	[40]
St_46	46.5	649	3.73	[41]
St_46	48	638	3.93	[41]
St_46	50.5	612	4.02	[41]
St_46	53	594	4.13	[41]
St_46	55.5	573	4.59	[41]
St_46	56	569	4.88	[41]
St_46	56.7	550	4.93	[41]
St_47	54	643	0.99	[42]
St_47	55	114.33	1.14	[42]
St_47	66.7	123.33	1.46	[42]
St_47	74.5	113.33	1.86	[42]
St_47	85	313	2.01	[42]
St_48	48.5	70	NA	[43]
St_48	45	59	NA	[43]
St_48	47.5	68	NA	[43]

St_48	42	54	NA	[43]
St_49	NA	NA	5.3	[44]
St_49	NA	NA	5.05	[44]
St_50	54	140	NA	[37]
St_50	56	89	NA	[37]
St_50	57	90	NA	[37]
St_50	58	81	NA	[37]
St_50	61	80	NA	[37]
St_50	64	75	NA	[37]
St_50	70	70	NA	[37]
St_50	54	140	NA	[37]
St_50	50	138	NA	[37]
St_50	55	103	NA	[37]
St_50	53	90	NA	[37]
St_50	54	86	NA	[37]
St_50	53	85	NA	[37]
St_50	59	80	NA	[37]
St_51	45	75	4	[45]
St_51	46.5	50	4.5	[45]
St_51	47	40	6	[45]
St_51	51	38	8.5	[45]
St_51	52	25	10	[45]

Categorical fields (such as plastic types) were saved as categories, whereas numerical variables were saved as floats. To maintain traceability, values reported in different units in source studies were preserved as reported and their units indicated in the data dictionary. To prevent information leakage across studies, all evaluations employed grouped K-fold splits with ‘study id’ as the grouping key—that is, the same study was never included in both the training and validation folds. This design more properly assesses generalization to previously unseen investigations. We created three different regression tasks to predict (i) softening point, (ii) penetration, and (iii) viscosity, so that each attribute could be modeled and assessed independently. This ensures that metrics for each engineering property are understandable.

Three models were constructed and assessed to establish a performance baseline and examine different algorithmic techniques such as Baseline Model, Linear Regression Model and Tree-Based Model. We used three popular regression measures to assess the model’s performance.

- Mean absolute error (MAE)
It tells how far a model’s predictions are from the actual values on average, without regard for whether they were too high or too low. A high MAE could indicate that the model should be retrained or modified. A lower MAE increases confidence that the model generates useful estimates [46]. According to the research [47] equation to find the mean absolute error is

$$MAE = \frac{1}{n} \sum_{i=1}^n (Y_1 + Y_i)^2$$

- Root means square error (RMSE)
The difference between predicted and actual values in a regression model is measured, and the standard deviation of the residuals (errors) is used to determine its accuracy. A lower RMSE suggests that the model fits the data better, with 0 indicating a perfect model [48]. The root mean square error is determined as follows:

$$\sqrt{\frac{1}{n} \sum_{i=0}^n (O_{iexp} - \frac{O_{irep}}{pred})^2}$$

- Coefficient of Determination (R²)

The coefficient of determination is a summary statistic that shows how well the independent variable in the regression explains the variation in the dependent variable [49]. The coefficient of determination R2 is the following ratio:

$$R^2 = \frac{\text{Explained Variation}}{\text{Total Variation}} = \frac{RSS}{TSS}$$

To supplement these measurements, diagnostic charts such as Predicted vs. Observed charts and Feature Importance Plot were created.

Table 2. Data Dictionary.

Column Name	Data Type	Data Category	Sample Value	Null Count	Completeness (%)	Unique Value	Value Range	Mean
Study_id	object	Text	St_01, St_01, St_01	0	100	51	NA	NA
Type of plastic	object	Text	R-LLDPE, R-LLDPE, R-	0	100	28	NA	NA
Dose of plastic	float64	Numeric	LLDPE	0	100	25	0-36	5.43
(%)	float64	Numeric	3.0, 3.0, 3.0	15	94	17	120-250	170
Mixing Temp.	float64	Numeric	170.0, 170.0, 170.0	85	66	16	20-13000	211
Mixing Rate	float64	Numeric	3500.0, 3500.0, 3500.0	42	83	17	2-180	0
Mixing Time	object	Text	90.0, 90.0, 90.0	11	95	39	NA	49
Type of Bitumen	object	Text	C320, C320, C320	231	7.6	2	NA	NA
Age/unage	float64	Numeric	Unaged, Unaged, Unaged	57	77.2	102	3.83-131	NA
Softening point	float64	Numeric	49.5, 83.7, 119.3	44	82.4	120	15-820	61
Penetration	float64	Numeric	547.0, 403.0, 253.0	144	42.4	94	0.16-10	320
Viscosity			0.81, 1.46, 3.52					2.2

The table above shows data dictionary that provides a comprehensive overview of the variables associated with plastic-modified bitumen. The dataset includes both categorical variables and essential numerical values. An initial data quality check, which is reported in the dictionary, indicated different levels of completeness. While most of the parameters are well-populated. This understanding is vital for maintaining the dependability of subsequent analysis and model construction.

3. Results and Discussion

The combined data shows that experimental parameters are highly variable. Plastic incorporation rates were primarily between 0.5% and 12%, with a subset of research looking at concentrations as high as 36%. The mixing temperature was primarily kept between 160 and 180°C. The most evaluated plastic modifiers were polyethylene variations (LDPE, HDPE, LLDPE) and PET.

A continuous tendency across multiple tests is an increase in softening point and a decrease in penetration value with the addition of plastic waste, showing that the binder stiffens. For example, adding 8% LDPE improved the softening temperature from 43°C to 63°C [50]. Similarly, at 12% dose, R-LLDPE enhanced the softening point from 44.1°C to 122.3°C [7]. This stiffening effect is ideal for boosting asphalt rutting resistance in hot areas. Viscosity often rises with plastic content, improving binder cohesion but boosting mixing and compaction temperatures, which is an important concern in plant manufacturing.

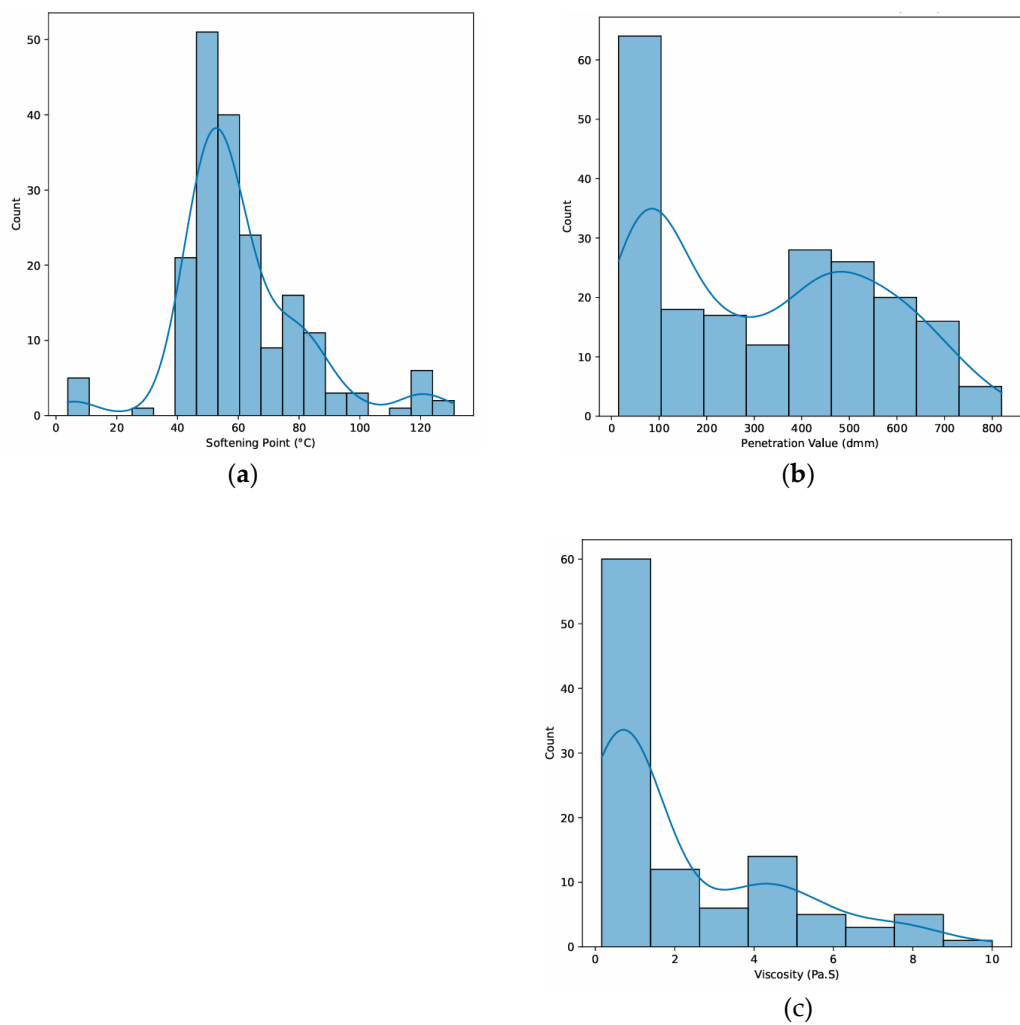


Figure 1. The graph shows key target distribution variables. (a) Distribution of Softening point; (b) Distribution of Penetration values and (c) Distribution of viscosity.

As shown in Table 3 above, tree-based models (Random Forest and XGBoost) outperformed linear and baseline models in terms of predicting Softening Point and Viscosity. XGBoost ($R^2 = 0.39$, $MAE = 11.1^{\circ}C$) and Random Forest ($R^2 = -0.87$, $MAE = 1.76$ Pa.S) were the most effective models for Softening Point and Viscosity, respectively. Some models have negative R^2 values for Penetration and Viscosity, indicating poor performance compared to a baseline model. This highlights the complexity and noise in the data for these targets. The good Softening Point prediction performance shows a more consistent link between inputs and outputs.

Table 3. Summary of Model performance results.

Model	Target	Avg. mae	Avg. rsme	Avg_ R^2	samples
Median Baseline	Softening Point ($^{\circ}C$)	14.154	21.4906	-0.0682	193
Linear Model (Ridge)	Softening Point ($^{\circ}C$)	14.4171	18.6615	0.1014	193
Random Forest	Softening Point ($^{\circ}C$)	11.3263	16.1304	0.3674	193
XGBoost	Softening Point ($^{\circ}C$)	11.0965	15.9136	0.3894	193
Median Baseline	Penetration (dmm)	206.7258	231.3153	-0.0081	206
Linear Model (Ridge)	Penetration (dmm)	235.4897	275.0583	-0.9856	206
Random Forest	Penetration (dmm)	238.3021	275.3899	-0.9717	206
XGBoost	Penetration (dmm)	230.3848	272.7678	-0.9346	206
Median Baseline	Viscosity (Pa.S)	1.7106	2.7141	-0.3008	106
Linear Model (Ridge)	Viscosity (Pa.S)	2.557	3.0389	-4.0487	106
Random Forest	Viscosity (Pa.S)	1.7616	2.1424	-0.8741	106

XGBoost	Viscosity (Pa.S)	1.7879	2.2275	-1.3455	106
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Figure 2 compares model performance using MAE, RMSE, and R², revealing significant variances between tested methodologies. The tree-based model outperforms the baseline and linear models in capturing complicated relationships in the dataset, with lower MAE and RMSE values and a higher R². This suggests that nonlinear models are more suited to predicting binder behavior when numerous interacting variables are involved.

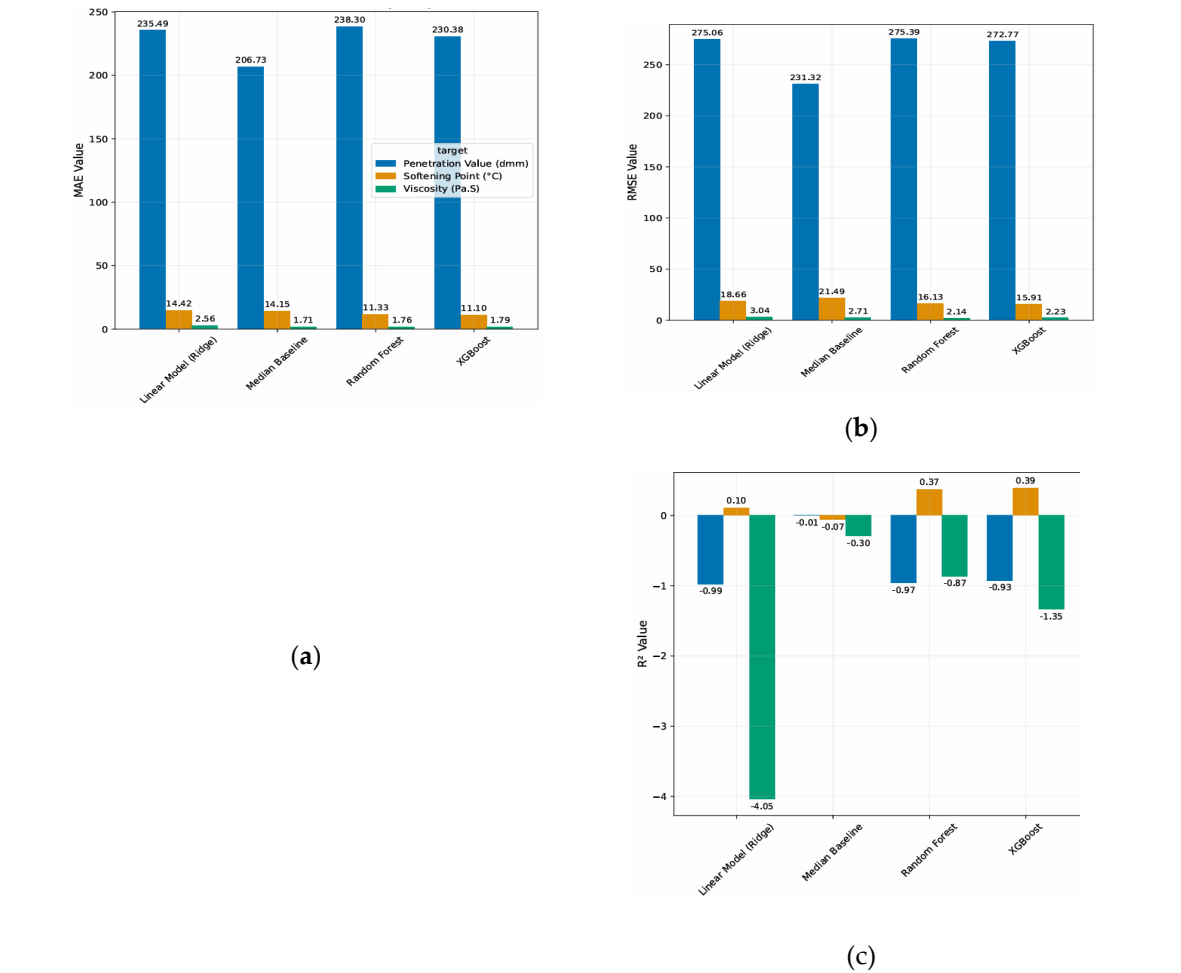


Figure 2. Figure showing the Model Comparison as (a) Mean Absolute Error [MAE], (b) Root Mean Square Error [RMAE] and (c) R² Score.

In a Figure 3(a), the graph successfully explained about 79% of the variation in Softening Point, as seen by the predicted versus real plot ($R^2 = 0.791$). The mean absolute error (MAE) of 0.834 means that the average difference between projected and actual values is less than one unit, indicating high predictive accuracy. Most of the points are closely aligned with the red 1:1 line, suggesting that the model can accurately capture the trend between actual and anticipated values. However, at higher Softening Point values, there is visible scattering, indicating that the model underestimates actual performance. This shows that, while the model is generally useful, it may have limitations when dealing with extreme values, or that additional contributing elements, such as polymer type, dosage, or dispersion quality, are not adequately accounted for in the existing features.

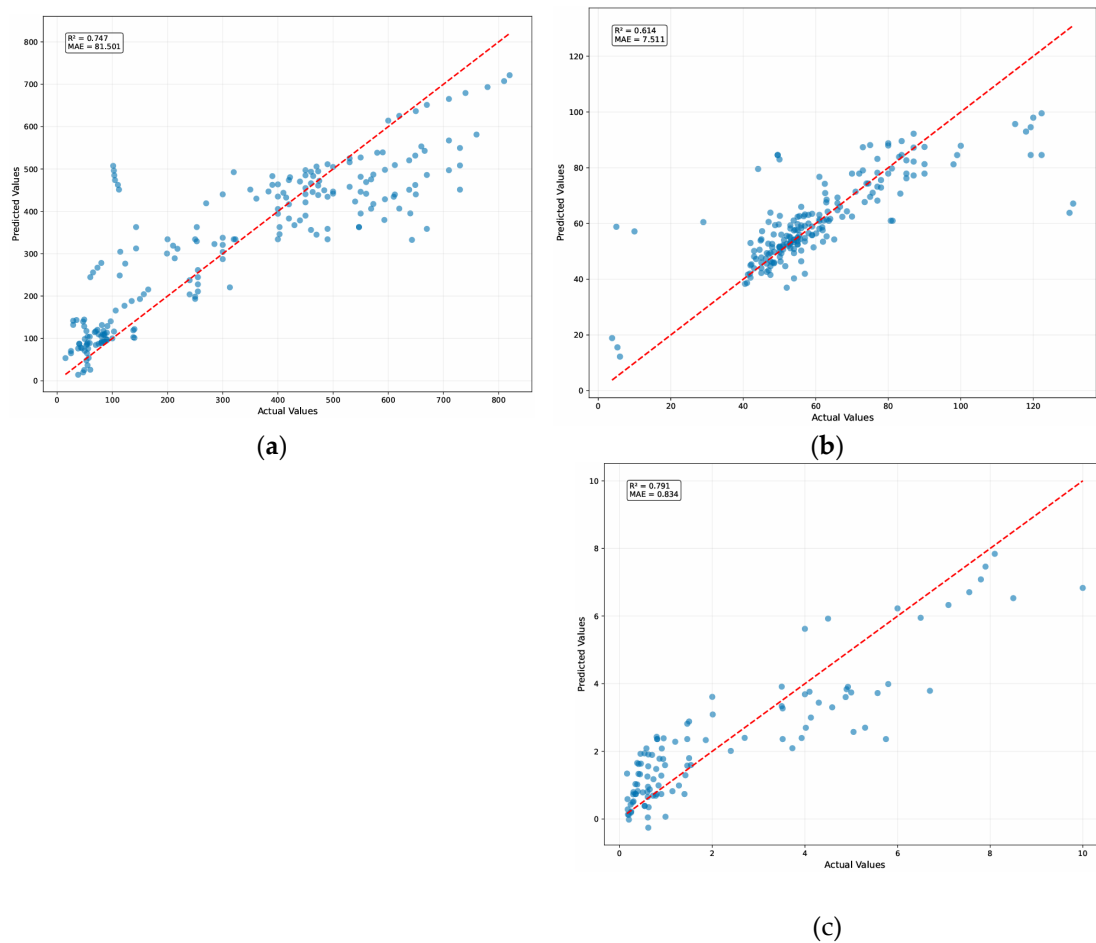


Figure 3. Showing Predicted vs. Actual values for best-performing models: (a) Softening Point (°C) predicted by XGBoost ($R^2 = 0.61$), (b) Penetration Value (dmm), and (c) Viscosity (Pa.S) predicted by Random Forest ($R^2 = 0.79$).

The Penetration test as shown in Figure 3(b) has moderate accuracy, with a R^2 value of 0.614, as seen in the anticipated versus actual plot. This shows that the model can explain around 61% of the variation in penetration values. The mean absolute error (MAE) of 7.511 is a larger average difference between anticipated and actual values than the softening point model, implying that penetration is more difficult to predict effectively. While many points match the 1:1 line, the scatter pattern indicates significant variance, particularly at lower and higher penetration rates. This dispersion suggests that additional parameters, such as plastic waste type, particle size, and mixing homogeneity, may have a significant impact on penetration.

Furthermore, in Figure 3(c), the model effectively gives about 79% of the variability in viscosity, as shown in the predicted versus real graphic ($R^2 = 0.791$). The mean absolute error (MAE) of 0.834 demonstrates that the average forecast error is quite tiny, indicating great accuracy. The scatter points are closely aligned with the 1:1 line, particularly for lower and mid-range viscosity values, indicating that the model accurately predicts these ranges. Some variance can be seen at higher actual viscosity levels, when the model tends to slightly underestimate performance, but the overall trend good.

Similar findings were discovered in plastic-waste modification research, Such as by adding waste polyethylene reliably boosts the softening point, increases viscosity, and decreases the penetration [51]. Experiments demonstrate that as plastic content increases, viscosity increases, and penetration decreases, often with nonlinear behaviour that complicates straightforward modelling [52]. PET-modified bitumen performs similarly, increasing hardness and improving high-temperature responsiveness at the expense of ductility, which adds scatter to Softening Point or Penetration modelling [53]. Furthermore, ML-based studies on polymers or modified binders underscore the importance of nonlinear approaches in capturing complicated interactions, explaining

why viscosity (which is more directly related to polymer content) is more predictable than penetration or softening point [54]. Finally, morphological investigations of polymer dispersion show that microstructure and compatibility play a role in variability, particularly in softening point and penetration predictions [55].

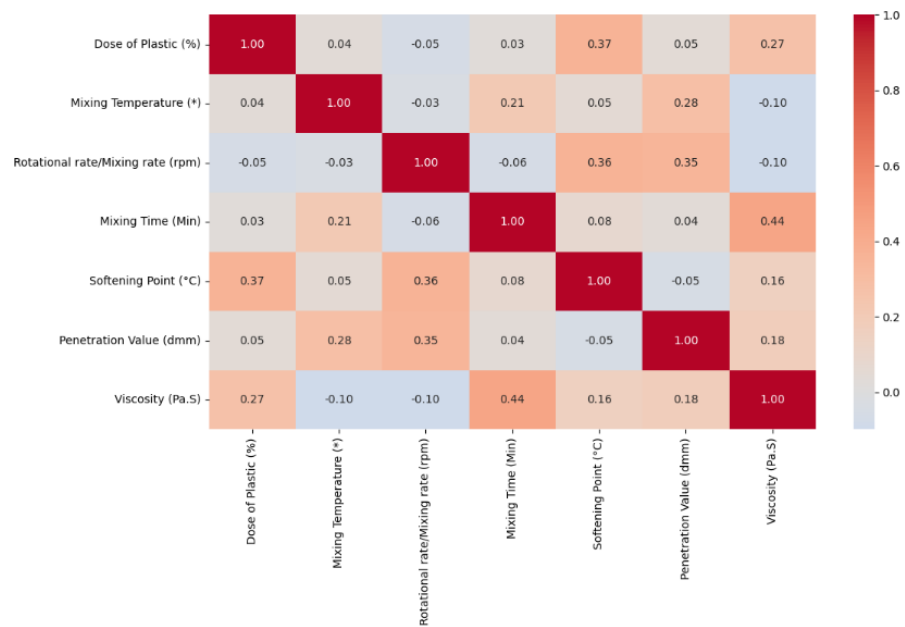


Figure 4. Showing the Correlation Matrix of Numerical variables.

A correlation matrix above containing numerical variables was examined. Plastic dose correlated with softening point (≈ 0.37), viscosity (≈ 0.27), and penetration value (≈ 0.28), indicating a stiffening effect. Temperature and time of mixing revealed very modest relationships with final attributes, implying that within the generally reported ranges, plastic type and volume are more relevant factors.

4. Discussion

- Incorporating plastic waste results in a higher softening point, decreased penetration, and increased viscosity, confirming the stiffening effect that improves rut resistance.
- The Softening Point model has high prediction accuracy ($R^2 = 0.79$) but underestimated at extreme values.
- The Penetration model ($R^2 = 0.61$) had small scale accuracy due to its susceptibility to parameters such as plastic type, particle size, and mixing consistency.
- The Viscosity model ($R^2 = 0.79$) made accurate predictions, notably in the low to mid ranges, demonstrating a greater correlation with observable process parameters.
- Tree-based ML algorithms (Random Forest, XGBoost) outperformed linear models, demonstrating the usefulness of nonlinear techniques in predicting binder characteristics.
- Previous research has shown that PE, PET, and other plastic wastes improve high-temperature stability while decreasing ductility.

For further studies, the researcher should use larger datasets and dosage ranges. Microstructural and compatibility studies with microscopy and spectroscopy could give clear result on how dispersion and bonding affect attributes like penetration and softening point. The environmental and economic viability of large-scale adoption should be evaluated using life cycle assessment (LCA) and cost-benefit analysis.

5. Conclusions

In this report the efficiency of machine learning (ML) techniques for predicting the engineering features of plastic-modified bitumen was explored. Using a dataset of 251 experimental records from the literature, three regression tasks were built to model binders' softening point, penetration, and viscosity. To increase model dependability, data from the same research were excluded using grouped K-fold cross-validation. MAE, RMSE, and R^2 were used to evaluate model performance. Predicted vs. real plots were also reviewed for interpretation. The following is a summary of the conclusions:

- Four models were evaluated: median baseline, linear regression, random forest, and xgboost. Tree-based models (Random Forest and XGBoost) outperformed other models in predicting softening point and viscosity, with R^2 values of 0.79 and 0.61, respectively, demonstrating their ability to capture nonlinear interactions.
- Softening Point predictions were highly accurate ($R^2 = 0.79$, MAE = 0.83), with consistent alignment between anticipated and actual values, but underestimate occurred at greater ranges.
- The penetration predictions demonstrated modest accuracy ($R^2 = 0.61$, MAE = 7.51), showing more sensitivity to uncontrolled parameters such as plastic type, particle size, and mixing homogeneity.
- Viscosity predictions were extremely trustworthy ($R^2 = 0.79$, MAE = 0.83), notably in the low to mid ranges, showing viscosity as a feature closely related to quantifiable processing factors.
- The results are consistent with existing research that show that plastic modification regularly increases softening point and viscosity while decreasing penetration, stiffening the binder and enhancing rutting resistance at high service temperatures.
- The findings demonstrate that nonlinear machine learning techniques outperform baseline or linear models in predicting binder performance, encouraging its usage in sustainable pavement design research.

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