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Saving Energy in the Transportation Sector: An Analysis of Modified Bitumen Application Based on Marshall Test

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Abstract: Energy consumption and material production are two major factors associated with the road construction industry. Worldwide, millions of tons of hot mix asphalt production consume a huge amount of fuel as an energy source in terms of quantity and cost to achieve the standard temperature of up to 170 °C during the mixing process. Modification of bitumen can not only reduce its usage but also the consumption of energy (fuel) during the asphalt mix production process at low temperatures. This study provides a method to save energy by proposing the addition of bitumen modifier in the road construction sector. Furthermore, to make it compatible with the field conditions for road construction, stability analysis is executed on the prepared samples by partially replacing the bitumen with polyurethane foam (PUF) and plastic waste (PW) (at 10%, 20%, 30%, 40%, and 50%). Experimental results demonstrate a reasonable saving in the amount of energy (33%) and material (40% bitumen) used and showed that similar strength of developed asphalt mix can be achieved using PUF. An extensive calculation concludes that these savings could make a huge difference in construction economics of mega road infrastructure projects, especially during an energy crisis.

Keywords: energy; fuel; consumption; stability; transportation; construction

1. Introduction

The significant increase in growth rate and population all over the globe has given rise to significant concerns about meeting the needs of energy supply and usage. The world has observed serious energy crises that tend to deteriorate and damage the infrastructure and economies of many countries across the globe. Making new roads and developing extensive road networks is not feasible during energy crises as the fuel needed to burn the asphalt mixes and bitumen is very costly and scarce to be enough for uninterrupted supply [1]. Researchers have proposed many ways to save energy and develop road networks in a much cheaper way, including experiments conducted on the complete process of asphalt making and processing. It was found that adding sulfur to bitumen in some effective proportions produced great savings in fuel required for heating the mix. Adding sulfur to bitumen causes a significant decrease in the melting point of bitumen, which leads to fuel savings as less amount of energy is required [2]. Many other options have been studied to save energy during the development of warm asphalt, such as synthetic zeolite [3,4]. However, these methods produce energy savings by the indirect method of compaction characteristics improvement. Over the years, many materials have been presented and tested by researchers across the globe that have proven to be effective in modifying the properties of bitumen and reducing energy consumption. This has included researchers employing materials like polymer wastes, crumb rubber tires, plastic bottles, nylon wastes, etc., with the aim of modifying and improvising bitumen properties for road construction [5]. All these researches have proven helpful for the road industry. In this study, we focus on the modification of bitumen in a manner that enables two major outcomes: The first is the energy conservation and fuel saving that is required to process the asphalt and bitumen for road construction and development. The second is the economical and eco-friendly development of roads that helps countries across the globe utilize their own waste materials and produce a cheap, yet highly durable, road network and reduce toxic air and noise pollution in metropolis and urban cities [6–8].

During asphalt mix development, a significant binder—bitumen of required standard grade—is lightly heated to make it flowable and is then pumped into bitumen storage tanks. With gas-charged heaters, bitumen is heated until the melting point is reached and in a form that can be used easily. From here, the bitumen is pumped into the modification processing tanks, where desired proportions of additives are added into it. At a temperature of 160–170 °C, the bitumen is thoroughly blended with the additives, and the temperature is maintained at a constant range to avoid local overheating. After this, aggregates and bitumen are comprehensively mixed to prepare the asphalt mix. Mixing is done at a maintained range of temperature, with continuous heat supplied by gas burners.

2. Literature Review

All existing roads, even the best made and designed ones, become deteriorated over time, mainly because of traffic loading and severe weather conditions [9,10]. With the major objective of enhancing basic bitumen performance, several blends with a diverse variety of useful modifiers have been prepared and analyzed by researchers [11]. Some previous studies have employed substances as additives, such as sulfur [12], polyphosphoric acid [13], fatty acid amides, etc. [14]. Polymers have also been used by many researchers [15–18]. Among them, the most effective and widely used ones to modify desired properties of bitumen are styrene–butadiene–styrene copolymer (SBS) and styrene–butadiene rubber (SBR). In addition, ethylene vinyl acetate (EVA) and polyethylene (PE) have been used for detailed properties analysis and experiments [15,19]. These efficient modifiers can affect all basic technical properties of normal bitumen. Blending the additives with bitumen will affect the cost of road construction and processing of bitumen. The major cost of the whole process must be considered to get an analysis of economic benefits [20]. Nowadays, there is an existing international consensus regarding the necessity of useful and long-term sustainable development in order to comprehensively manage limited natural resources [21]. The significant employment of major solid waste in asphalt-based pavements have been investigated with a variety of products, such as glass [16], steel waste slag, crumbed rubber tires [22], and finely crushed waste bricks [23]. In all these cases, the recycled materials are an effective substitute for the main aggregates that are part of the asphalt mix. As explained previously, many polymers have been efficiently used to enhance the basic bitumen properties to advanced levels. Known polymers like polystyrene and polypropylene with efficient reclaimed geomembranes are also utilized to induce desired characters in bitumen [24–26]. Natural rubber is also employed to improvise the general trends in properties of bitumen [27]. In regard to the efficiently recycled waste polyurethane foam, researchers have previously developed and analyzed its general employment in mortars [28] and lightweight range plaster [29]. As an efficient substitute for aggregate, it is employed in flexible pavement roads [30]. The ultimate performance of polyurethane foam when used for modified bitumen has been analyzed in depth [31]. However, in this study, the used polymers were completely manufactured and developed at a local level. In addition, back in 2015, studies [32–34] analyzing the efficient use of polyurethane-foam-modified bitumen [35] proposed a completely new approach of developing in situ polymerization of monomers that was derived from PET wastes. In these studies, the materials were replaced by up to 10%. However, in this study, 50% modification has been proposed with the aim of lowering the mixing temperature and achieving savings in fuel consumption during the asphalt mix production process.

3. Materials and Methods

The complete methodology to efficiently perform the entire experiment is illustrated as a flow chart in Figure 1.

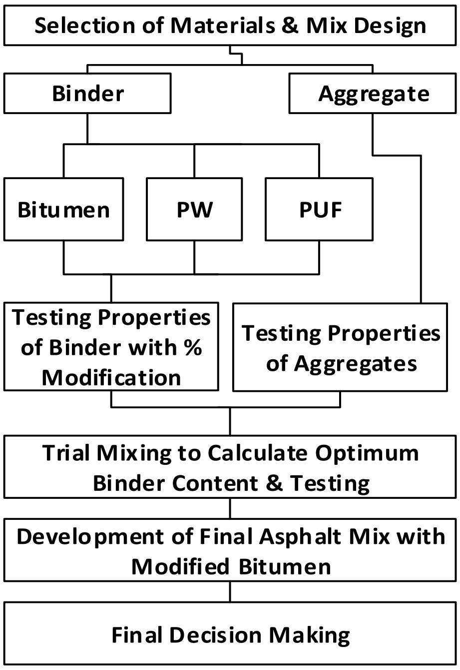


Figure 1. Research framework.

3.1. Basic Materials

Bitumen is a sticky, viscous black and semisolid form of petroleum (Figure 2a). It is generally found in natural reserves underground and is produced while refining crude petroleum. The basic and most primary usage of bitumen is in the road construction industry. It is also actively used as a strong binder, glue, and sealant adhesive compound. Bitumen is composed of structured hydrocarbons and is effectively used as waterproofing products and roofing. The binder, i.e., bitumen, is mixed thoroughly with aggregates and additives to make asphalt that is used in road construction. The massive growth in the world's population has created a demand for good infrastructure development for ease of mobility. However, there is also a need for developments to be based on sustainable use of resources because transportation adds a considerable amount of non biodegradable, solid harmful wastes into the atmosphere and ecosystem. The significantly higher rate of increase in traveling vehicles on roads compared to the rate of development and road construction has resulted in wear and damage to flexible pavements. To cope with these issues, many different binders are presently available in the industry, such as the SBS and atactic polypropylene (APP). However, the main benefits of basic modified asphalt need to be analyzed by keeping all financial aspects clearly in consideration. APP is a type of plastic bitumen and is therefore easier to use than SBS. The resistance of SBS to heating is higher, but the application of APP is more user friendly [36–39]. Bitumen is a complex material formed by extensive hydrocarbons, along with other associated molecules containing small percentages of prominent heteroatoms, such as sulfur, nitrogen, and oxygen [40].

Two materials that can be used as modifiers to bitumen were considered in this study. The first was polyurethane foam, which was developed from used waste joggers and shoe soles that were thrown away in garbage wastes. The second was mix waste plastic, which was dumped into the garbage. Powdered PUF are shown in Figure 2b. Both of these materials were shredded and converted into usable forms [41]. Polyurethane foam from waste shoe soles was prepared by shredding the jogger soles in a shredder and converting them into a powdered form that is easy to mix in hot bitumen.

Similarly, the plastic waste was shredded and converted into a grain form of about 650 mm in size. Different statistical methods were also used to analyze the properties of produced asphalt mix [42–47].

The basic aim of this research was to study the application of PUF and PW as bitumen modifier, with the main recycled material, polyurethane foam, being produced from waste jogger soles. Less heat energy is required to process PUF- and PW-modified bitumen asphalt mixes. This type of production of cheap yet efficient roads would help in saving energy resources [48]. Saving energy in the production of roads will allow the road industry to prosper, even in situations of an energy crisis or expensive fuels.

(**a**) (**b**) (**c**)

Figure 2. (**a**) Bitumen sample; (**b**) powdered polyurethane foam (PUF); (**c**) shredded grains of plastic waste (PW).

Shredded waste plastic (Figure 2c) with a small particle size and specific gravity of about 1.18 was utilized in the comprehensive binder mix. All properties of bitumen were analyzed [49]. Tests for penetration, ductility, softening point, and main specific gravity were performed to analyze all the basic physicochemical properties of the utilized additives in bitumen.

3.2. Modification of Binders

The shredded waste plastic and polyurethane foam waste from soles of shredded shoes were carefully mixed and blended with bitumen at a constant temperature in predetermined proportions. Plastic waste was replaced in the binder bitumen. Both additives were mixed in the basic order of 10%, 20%, 30%, 40%, and 50%, maintaining all processes and with constant heat supply [50–54]. To measure the fuel amount being utilized to heat the binder and additives together, a measuring gauge was placed on the gas cylinder that measured the total amount of gas required to heat the mix. This was aimed at analyzing energy savings. The results showed that these additives effectively decreased the temperature of the binder in terms of their flash and fire points. New controls with types of e-sensing sensors could be used to highlight the presence of gaseous pollutants that are harmful to human health [55].

3.3. Properties of Binders

The chief physicochemical properties of bitumen were comprehensively tested under American Society for Testing and Materials (ASTM) standards. Penetration test was efficiently carried out to analyze and determine the main consistency of bitumen. The softening point was also analyzed, which clearly determined the actual temperature point at which the binder attained a significant softness. Ductilometer apparatus was used to check the quantitative measurement of bitumen's ductility, which was analyzed for both modified and unmodified ranges. The bitumen used was 60/70 grade. Results of this experiment performed on the unmodified plane bitumen are shown in Table 1.

Table 1. Standards for testing bitumen properties.

Properties/Tests	Units	Limit	Test Method
Density at 25 °C	Kg/m^3	1010–1060	ASTM D70 or D3289
Penetration at 25 °C	Mm/10	60–70	ASTM D5
Softening point	°C	49–56	ASTM D36
Ductility at 25 °C	cm	100 min	ASTM D113
Loss of heating	wt%	0.2 max	ASTM D6
Drop in penetration after heating	%	20 max	ASTM D5
Flash point	°C	232 min	ASTM D92
Solubility in trichloroethylene	wt%	99.0 min	ASTM D2042
Spot test	-	Negative	AASHTO 102
Viscosity at 60 °C	p	2000 ± 400	ASTM D2171
Viscosity at 135 °C	cst	300 min	ASTM D2170
Test on Residue From Thin Film Oven Test (ASTM D1754)			
Retained penetration (TFOT)	%	54 min	ASTM D5
Ductility (25 °C), 5 cm/min, cm after TFOT	cm	50	ASTM D113
Viscosity at 60 °C	p	1000 max	ASTM D2171

3.4. Properties of Aggregate

A complete blend of all aggregates was carefully prepared. Coarse grain (size 20 mm) with a medium grain (size 10 mm) and fine grain (size < 4.75 mm) were used. The fine local soil was employed for the preparation of the basic skeleton of all Marshall samples. Mechanical testing and analysis were performed efficiently on all the aggregates, as shown in Table 2, to analyze their properties. All results were compared with standard allowable values in the range [56–60].

Table 2. Standards of testing aggregate properties.

Type of Test	Test Method	Results	Specifications
Aggregate impact test	BS812: Part 3	20.47%	Less than 27%
Los Angeles abrasion test	ASTM: C131	31%	Less than 35%
Aggregate crushing test	BS812: Part 3	26.59%	Less than 30%
Water absorption test	ASTM: C127	1.50%	Less than 2%
Specific gravity (aggregate)	ASTM:C127	2.37	2–3

3.5. Marshall Test Specimen Preparation and Testing

All Marshall specimens were cast with the modified and unmodified types of binders. The properties of aggregates and bitumen used during the development of asphalt mix are shown in Table 3. About 1200 g of total aggregate were carefully taken from the basic prepared blend. They were efficiently dried by heating in a heated oven at a constant temperature of about 150–175 °C. Bitumen was carefully heated at a safe temperature range of about 160–170 °C. To avoid any local overheating, the temperature was kept in the mentioned range in the ATSM standards [26,61]. Both the binder and all aggregates were thoroughly mixed homogeneously using an asphalt mixer jacket. The advantage of asphalt mixing equipment is that it provides variation in temperature during the mixing process. The mixing of asphalt was conducted at the temperature of about 165 °C for 60/70 grade of bitumen. When the binder layer fully covered the whole aggregate in the mixer, the prepared mix was carefully laid in the preheated metal molds at a temperature of 100–140 °C for mechanical compaction. The effective impact loading was applied on all specimens using a standard compactor hammer of 75 blows on both sides of samples. After the specimens cooled down, they were extracted from the metallic molds with the help of hydraulic sample extractor in the lab [61]. After completion of demolding and cooling processes, all samples were kept submerged in water using a complete, thermostatically controlled efficient water bath that was maintained at approximately 60 °C for about

30–40 min prior to the testing process. All prepared specimens were then carefully tested with accurate calibration of Marshall's testing machine (Figure 3) for the main analysis of stability and flow values.

Table 3. Gradation of aggregates for bituminous mixes.

Passing Sieve Designation	Retained on Sieve Designation	Percent by Weight *
$\frac{3}{4}$ in. (19.0 mm)	$\frac{1}{2}$ in. (12.5 mm)	5
$\frac{1}{2}$ in. (12.5 mm)	3/8 in. (9.5 mm)	20
3/8 in. (9.5 mm)	No. 4 (4.75 mm)	25
No. 4 (4.75 mm)	No. 10 (2.00 mm)	15
Total coarse aggregate	-	65
No. 10 (2.00 mm)	No. 40 (0.475 mm)	10
No. 40 (0.475 mm)	No. 80 (0.177 mm)	10
No. 80 (0.177 mm)	No. 200 (0.75 mm)	8
No. 200 (0.75 mm)	-	7
Total fine aggregate and filler	-	35
Total mineral aggregate	-	100
Bituminous mix	-	-
Total mineral aggregate	-	93
Bitumen content	-	7
Total mix	-	100

* Note: Our gradation (percent by weight of specimen, i.e., 1200 g).

Figure 3. Marshall testing machine with asphalt specimen and compactor apparatus.

4. Results and Discussion

All tests and basic properties analyses were made efficiently to get an in-depth analysis of the effective modifications and changes that were induced in bitumen by additives.

4.1. Analysis of Modified Bitumen

The first phase was to analyze the properties of bitumen and the impact of modification. Two different modifiers were added up to 50% as a replacement of bitumen to reduce the consumption of fuel as well as material. The properties of the modified bitumen are given in Table 4. The basic properties of bitumen before and after modification of different percentages were tested to analyze the behavior of modified bitumen. Although bitumen is famous for its elastic-plastic and plastic-elastic behavior, it was necessary to analyze the basic properties of bitumen as a binder during the research process. Ranges of modified bitumen (PUF and PW) samples for penetration (>60), ductility (>75), and softening points (40–55) are compared and discussed in Table 4.

Table 4. Physical properties of binders.

Sample	Composition	Penetration	Ductility	Flash Point	Softening Point
		(25 °C, 100 g, 5 s)	25 °C	1 °C	°C
Test Method		ASTM: D5-97	ASTM: D113	ASTM: D92-16b	ASTM: D36
Units		0.1 mm	1 cm	1 °C	1 °C
PUF 1	100% B + 0% PUF	66.0	99	266	55
PUF2	90% B + 10% PUF	65.1	98	238	58
PUF3	80% B + 20% PUF	64.7	98	230	60
PUF4	70% B + 30% PUF	64.0	96	225	63
PUF5	60% B + 40% PUF	63.3	94	213	66
PUF6	50% B + 50% PUF	61.0	91	203	68
PW1	100% B +0% PW	66.0	99	266	55
PW2	90% B+ 10% PW	61.0	86	231	60
PW3	80% B + 20% PW	54.0	75	219	64
PW4	70% B + 30% PW	43.0	69	208	67
PW5	60% B + 40% PW	27.0	63	200	71
PW6	50% B + 50% PW	23.0	57	187	73
Standard	Pure bitumen	60–70	>75	232 min	40–55
Remarks	-	>60 are ok	>75 are ok	>232 min are ok	higher than level

Although the softening point was higher, the mixing temperature of modified bitumen decreased at the later stage during mixing and helped in developing the asphalt mix. Further investigation depicted that the flash and fire points were decreasing. Overall analysis of both materials showed that PUF was a somewhat better replacement than PW because its basic properties were within the range of the ATSM standards. Even higher melting point is sometimes helpful during hot climatic conditions as it resists bleeding of bitumen.

4.2. Marshall Stability Analysis

Marshall stability analysis was comprehensively done on both types of bitumen, i.e., the unmodified and additive-added, modified mixes. Three samples were prepared for each of the different percentage of additives added to bitumen. The average stability value of all three samples for each tested proportion was considered for detailed analysis with reference to previously followed procedures [2,10,15,25,34,62,63], as shown in Table 5. The testing of the modified bitumen samples showed that stability and flow value, along with mixing temperatures, were within ranges of up to 40% modification, i.e., PUF 5 and PW 5. Beyond that, they crossed the flow value limit.

Table 5. Stability and flow analysis of asphalt mix samples with modified and unmodified bitumen.

Sample	Composition	Marshall Stability (60 °C)	Marshall Flow (60 °C)	Mixing Temp (°C)
Test Method		ASTM: D1559	ASTM: D1559	
Units		KN	mm	
		Polyurethane Foam (PUF)		
PUF 1	100% B + 0% PUF	9.65	2.23	160
PUF 2	90% B + 10% PUF	10.05	2.84	150
PUF 3	80% B + 20% PUF	10.34	3.01	150
PUF 4	70% B + 30% PUF	11.63	3.35	145
PUF 5	60% B + 40% PUF	11.97	3.97	135
PUF 6	50% B + 50% PUF	13.92	4.16	130
		Plastic Waste (PW)		
PW 1	100% B + 0% PW	9.65	2.23	160
PW 2	90% B + 10% PW	10.09	2.79	150
PW 3	80% B + 20% PW	10.36	3.01	150
PW 4	70% B + 30% PW	11.12	3.51	145
PW 5	60% B + 40% PW	11.54	3.78	135
PW 6	50% B + 50% PW	12.04	4.03	130
Standard	With pure bitumen	>9	2–4	100–170
Remarks	-	ok: criteria fulfilled	ok: within range	ok: within range

The stability value indicated that with the application of PUF up to 50% and PW up to 30%, a satisfactory performance of asphalt mix could be achieved. Another advantage was a reduction in mixing temperature from 160 to 130 °C, which would help in energy consumption.

4.3. Fuel Consumption and Saving Analysis

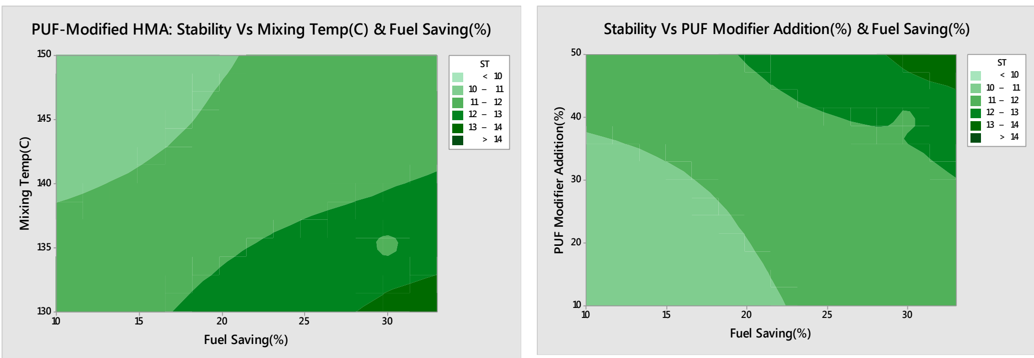
In many earlier studies, it has been shown that mixing and compaction temperatures found through the shear rate concept are about 10 to 30 °C lower (depending on quantity and type of modifier) compared to the one obtained through equiviscous method. Lower mixing and compaction temperatures will have low emissions, less binder aging, and will definitely increase the mix quality and paving duration. Keeping that concept in mind, we used trial-and-error-based mixing and compaction method to find the appropriate, lowest possible mixing temperature by taking four trials for each modified sample and then selecting the lowest mixing temperature with suitable workability. This temperature was maintained in an asphalt mixer until the required level of mixing was achieved. By achieving compact mixing ranging between 130–150 °C instead of 160 °C, energy saving was achieved due to less consumption of fuel. Marshall stability test validated the mixing temperature choice to develop the asphalt mix for road construction. Energy consumed during preparation of standard bitumen (100%)-based asphalt mix sample was 0.20 L of fuel. However, with the increasing proportions of additives in modified bitumen, the amount of gas required to heat the sample of the same mass decreased significantly, e.g., with addition of 10% PUF at 150 °C, fuel saving was 10% of the original volume. However, with addition of 20% PUF, the same mixing temperature was achieved earlier due to higher modifier quantity, resulting in fuel saving of 13% of the original volume. The same procedure was repeated for the addition of PW modifier to analyze the fuel savings. The detailed energy reduction analysis is presented in Table 6. The calculation of fuel was based on the application of fuel during the heating process and ease of mixing for preparation of hot mix asphalt. Although it required higher fuel to melt the material at the start, when it was heated in combination with bitumen, it required only low mixing temperature. This is the reason plastic waste is already applied as modifiers with bitumen for road construction in the Netherlands and other parts of the world [64,65]. Our study showed that PUF waste additive was more efficient and successful than plastic waste. There was a 14% reduction in fuel consumption for PW-modified bitumen, while the PUF additive improved efficiency by 33%. This comparative variation in both reduction percentages was particularly due to the strong cohesive forces present inside the plastic molecules and binder forces that tended to increase the melting points. Nevertheless, it offered an observable reduction in the range of about 14% compared to 0% additive sample. The calculation was done on the basis of preparation of one sample for testing the Marshall test mechanism.

Table 6. Fuel saving analysis of asphalt mix production with modified and unmodified bitumen.

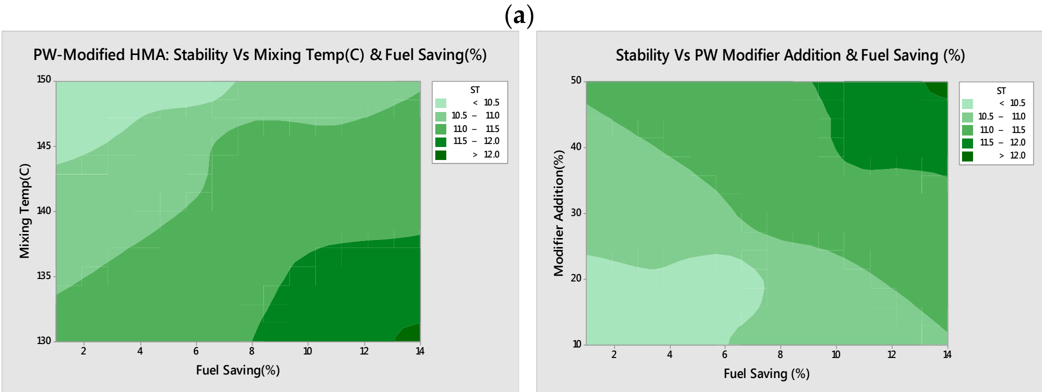
S.N.	Modifier + Bitumen	Mixing Temp (°C)	Used Fuel Vol. (L)	% Fuel Saving (Gas)
1	0% PUF + 100% B	160	0.200	-
2	10% PUF + 90% B	150	0.180	10%
3	20% PUF + 80% B	150	0.174	13%
4	30% PUF + 70% B	145	0.148	26%
5	40% PUF + 60% B	135	0.134	33%
6	50% PUF + 50% B	130	0.134	33%
1	0% PW add + 100% B	160	0.200	-
2	10% PW + 90% B	150	0.198	1%
3	20% PW + 80% B	150	0.187	6.5%
4	30% PW + 70% B	145	0.184	8%
5	40% PW + 60% B	135	0.178	11%
6	50% PW + 50% B	130	0.172	14%

Note: Fuel saving = (fuel used for heating pure bitumen sample − modified sample)/used pure bitumen sample, e.g., (0.20 − 0.18) × 100/0.20 = 10%. Mixing temperature was achieved earlier due to modification of bitumen. Less fuel was consumed to achieve less mixing temperature along with higher modifier percentage.

The graph shown in Figure 4a shows that with the addition of PUF, the stability of asphalt mix increased, resulting in increased fuel savings due to a lowering of the mixing temperature. On the other hand, Figure 4b shows that although stability is achieved up to the standard with the addition of PW but fuel saving was compromised.



(**a**)



(**b**)

Figure 4. Fuel consumption savings during asphalt mixing: (**a**) PUF and (**b**) PW modified bituminous mix.

Contour graph provides an opportunity to study the changing pattern of factors affecting each other. It can be clearly seen that PUF can be a good replacement up to 50% with reference to bitumen—it can not only attain a standard level of stability but also help in energy saving.

4.4. Statistical Analysis

To study the relationship between variables, many statistical techniques are used to analyze the relationship and impact. Although complex techniques such as artificial neural networks (ANNs) [66] exist, one of the simple and popular methods to study the relationship of one or more than one variable is the ordinary least-square (OLS) regression, which provides a comprehensive approach to studying the impact of multiple variables on one single variable. In this study, fuel saving (%) was considered as the dependent variable, while modifier addition (%), modifier type, stability, and mixing temperature (°C) were taken as independent variables. The accuracy of estimation of a system is measured by the foundation of the root mean squared error (RMSE) reported below in Equation (1) and Equation (2), a difference between the actual and the predicted values, and the various coefficient of determination (R^2) [67].

$$\text{RMSE} = \sqrt{\left(\frac{1}{N}\sum_{n=1}^{N}(\text{actual} - \text{predicted})^2\right)} \quad (1)$$

$$R^2 = 1 - \frac{SSE}{SS_y} \quad (2)$$

where SSE is sum of squared errors of prediction and SS_y is total variation. Mean absolute error is similar to root mean square except that it uses absolute difference instead of squared difference. Performance of a model is usually compared by coefficient of determination (R^2). A classic fit would bring about a R^2 of 1, and poor fit would be almost 0. In this analysis, R^2 was 0.95, which was very good, and RMSE was 2.5, which was also very good, as shown in Table 7.

Table 7. Parameter estimates for the modeled terms.

Parameter	Estimate	Std Error	*t* Ratio	Prob > |*t*|
Intercept	−74.18191	34.68682	−2.14	0.0417 *
Modifier (%)	0.3436028	0.127946	2.69	0.0122 *
Modifier type [BIT]	−2.242923	1.283906	−1.75	0.0920
Modifier type [PUF]	7.3048418	0.768412	9.51	<0.0001 *
Stability (KN)	3.6878587	1.099319	3.35	0.0024 *
Mixing temp (°C)	0.255308	0.198011	1.29	0.2082
R^2	0.954754	Remarks: Near to 1 = V. Good		
RMSE	2.508468	Remarks: V. Low = V. Good		
N	33	Sample Size		

* $p < 0.05$, R^2 = coefficient of determination, RMSE = root mean square error.

4.4.1. Performance Profiler

Fuel saving trend was studied with reference to factors/variables having a strong impact on asphalt mix production. The prediction profile analysis, shown in Figure 5, showed that PUF was a better alternative for modification—it not only improved stability but also contributed to cost savings.

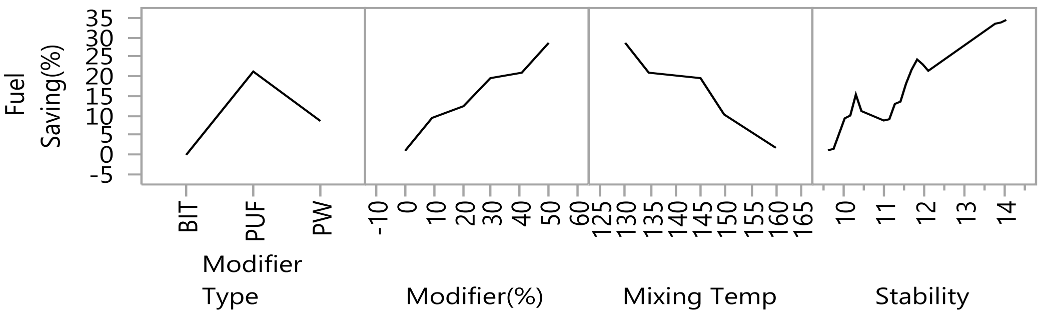


Figure 5. Prediction profile of fuel saving.

4.4.2. Variable Importance

Variable importance gives researchers an opportunity to understand and decide the target variables. In our study, the modifier type was the most important variable, and its replacement percentage was one of the key factors for achieving the best fuel saving results, as shown in Table 8.

Table 8. Variable importance analysis.

Parameter	Main Effect	Total Effect	Graphical Description
Modifier type	0.289	0.416	
Modifier (%)	0.272	0.272	
Mixing temp (°C)	0.253	0.253	
Stability (KN)	0.186	0.186	

5. Limitations of the Study

This study is the first stage of testing the basic properties of PW- and PUF-modified bitumen by measuring it up to the Marshall test mechanism to identify an alternative for bitumen modification. Further extensive studies will be conducted in the future to validate it for commercial purposes by applying rheological and fatigue analysis. Furthermore, this is only the first phase of research and will need to be followed by advanced testing. Therefore, at this stage, this research is not recommended for commercial use, although it can be applied as an open horizon for academic research. Commercial testing by contractors at lower level can help to verify these results by applying it to small segments or farms to market roads for testing purposes. During this research study, PUF was found to be a better option with respect to application as a binder or modifier because of low temperature application, and therefore it can be recommended on a trial basis.

6. Conclusions

The most prominent finding of this study relates to the conservation and saving of fuel, i.e., when gas was utilized to heat the mixes, the mixing temperatures is achieved earlier with the addition of additives resulting in fuel saving. Considerable changes were observed in the flash and fire points of bitumen mix as they decreased significantly after additive modification. Thus, it led to more fuel saving that would help meet the standards of an energy-economical process for road construction. The results effectively showed that the whole process could be improvised in terms of energy savings and reduction in the total cost of road construction. In times of energy crises, this strategy will be especially effective and efficient in terms of fuel savings in road construction processes. A large number of materials that are considered as waste after their utilization and service life, such as old shoes, joggers, and hard plastic materials, may be efficiently utilized and induced as a partial effective replacement in standard bituminous concrete mixes. This strategy enables us to modify the desired characters of bitumen in a positive way. The findings of this study have clearly indicated the fact that PUF and PW can be efficiently used to improve the overall durability of the bituminous concrete mix.

The study also found that these additives tended to increase the overall exhibited performance, both for basic properties of bitumen and for mechanical properties of asphalt mix. The comprehensive application of all these wastes in the considered fixed proportions and percentages up to 40% efficiently targeted the base characters of asphalt mix. The production of bitumen is also associated with crude oil, which is one of the largest sources of energy. Reducing the use of bitumen with alternatives like PUF and PW can therefore help in reducing energy consumption. Furthermore, reduction in mixing temperature can also help in reducing energy consumption during the mixing process. In mega road projects, this can mean savings of millions of dollars. In addition to these benefits, using wastes in bitumen and utilization in road construction process leads to the development of an eco-friendly road network that effectively aids in reducing toxic land and pollution caused by the deposition of gaseous powders and pollutants [68].

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