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Sustainable Silicon Waste Material Utilization for Road Construction: An Application of Modified Binder for Marshall Stability Analysis

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Abstract: Across the globe, sustainable infrastructure development—in context of road networks, and recycling waste material and production—are the two predominant factors associated with the construction industry in making roads and developing transportation networks. Globally, millions of tons of basic hot mix asphalt are produced, which are being utilized to generate large volumes of the finished road material. This study deals with the method of modifying bitumen by adding a silicon mobile cover waste material in a cost-effective manner, that can yield improved characteristic properties to bitumen, in a sustainable way to save material, improve quality/performance and reduce costs. In this investigation, globally produced and used mobile silicon cover accessories were utilized as a partial replacement (at 10%, 20%, 30%, 40%, and 50%) with bitumen. A large quantity of used silicon phone covers are thrown in the garbage and dumped in grounds as a waste material worldwide. Modifying bitumen with up to 40% silicon, using a potentially viable waste available in large quantities, was proven to be stabilized according to ASTM Marshall Test criteria of stability (>9) and flow(within range 2–4) in road construction. The results of the investigation are promising, and the use of silicon waste could mark a significant impact on the economics of road construction industry for sustainable infrastructure development by saving bitumen, which is a costly resource.

Keywords: waste materials; construction; Silicon; infrastructure

1. Introduction

It has been observed that with rapid growth across the globe, the availability of materials required for development is declining. This shortfall of essential construction and developmental materials has induced a crisis, which has tended to prominently deteriorate and adversely affect the development infrastructure of many countries around the world. Roads and highways are, indeed, the means of cheap and convenient transportation for the efficient conveyance of goods in developing countries. Constructing new road networks seems unfeasible in scenarios when materials required for the construction of roads are either highly expensive or are short in supply. The commonly used and major material utilized as a binder in the road construction industry is bitumen. Previously, many ideas have been experimented with, and researchers have efficiently employed many waste materials such as polymer waste, crumb rubber tires of vehicles, ordinary plastic bottles and nylon wastes. All these studies were aimed at successfully enhancing the major bituminous properties that are essential for road construction [1,2].

In the present study, we utilized the basic idea of modifying the binder by replacing bitumen with a selected waste material (silicon mobile cover waste, as shown in Figure 1) to yield a new material with useful properties and efficient outcomes. According to mobile industry studies, in 2007, there were nearly 700 million cell phones (old and used ones) only in America, of which 36.8% were stored in shelves and drawers, 10.2% were thrown away and only 9.4% mobile phones were recycled. There are companies working in the recycling process industry, who opt for an eco-friendly mechanism to recycle and reuse mobile phone accessories, one of which is silicone covers. Being experts in silicone recycling, companies recycle silicone products effectively but also collect the disposed parts from their respective clients [3]. As cellphones have become global, making cases for them has become big business. According to the research, around 75% of people put a case on their smartphone. With around 1 billion smartphones sold in 2014, this corresponds to 750 million phone cases sold, making the assumption that the buyers purchased only one case each. U.S. retail sales were $81.2 million last year, which translates to $2.6 billion, where locations like marketplace stalls and mall shops were not included [4]. According to reuse analysis in research, silicon waste powder works under higher loading. Furthermore, the changes in hardness, hysteresis loss, tension set, and stress relaxation are marginal. The percent changes in the modulus and tensile strength of silicone rubber on aging at 200 °C for 48 h remained almost the same [5].

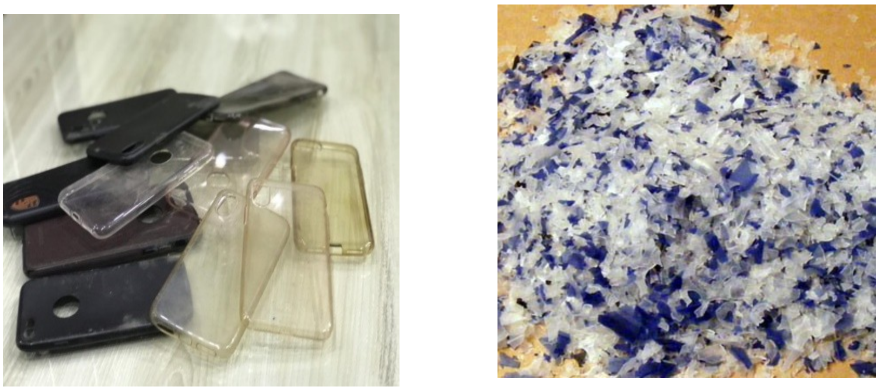

Figure 1. Silicon mobile cover waste.

These are either soft silicon covers or hard rigid fitting covers. With the passage of time and prolonged usage, these covers get faded and scratched due to continuous abrasion against rough surface contacts of cell phones. These accessories are useful in saving and protecting the cell phones from the sudden shock, scratches on the body and any damage to the casing of the phone. Once they have completed their useful life, these covers and cases are discarded and thrown away in the garbage, where they remain untreated as solid waste in dumps. It is estimated that if even 10% of the mobile users used silicon mobile cases every year, then 500 million cases would be wasted annually (i.e., so we can clearly estimate hundreds of tons of waste covers and cases remain untreated, either requiring recycling or safe disposal). These are basically synthetic material-based products and are harmful to the environment. In developing countries, these covers, and cases are mostly either burnt along with the waste or dumped into landfills. However, in developed countries like the U.S., different companies are collecting and treating mobile cover wastes [3]. In the case of open burning, harmful gases are released in the air, thereby causing air pollution. In landfills, hazardous chemicals are released from these materials in the form of leachate, contaminating soil and groundwater. During the development of asphalt mix (as shown in Figure 2), a significant binder—that is bitumen of a required standard grade—is lightly heated to make it flowable and then pumped into bitumen storage tanks. With gas charged heaters, bitumen is heated until the melting point is reached, and it is in a form to be used easily.

From here, the bitumen is pumped into the modification processing tanks where desired proportions of additives are added into it.

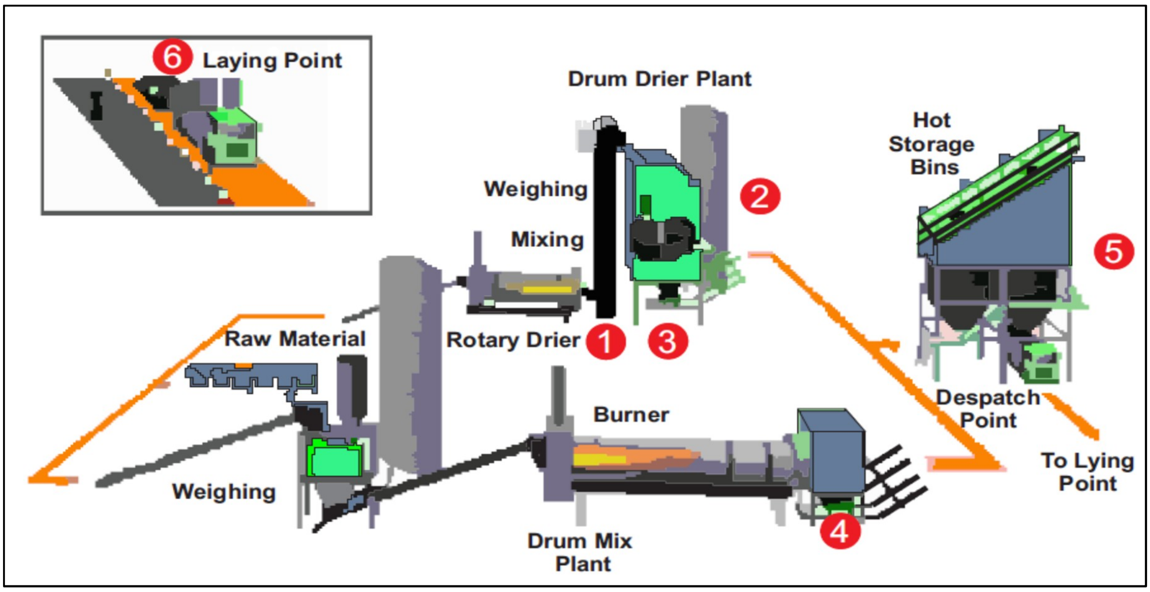

Figure 2. Hot mix asphalt production and laying process for road construction.

At a temperature of 160–170 °C, the bitumen is thoroughly blended with the additives and the temperature is maintained in a constant range to avoid local overheating. These aggregates and bitumen are comprehensively mixed to prepare the asphalt mix. The mixing is done at a maintained range of temperatures, where continuous heat is supplied by gas burners.

This study, for the first time, investigated the use of untreated silicon mobile cover waste in bitumen as a replacement material to yield a modified binder that could be used in asphalt mix concrete for road construction. The proportion of waste covers and case material (percentage) was increased gradually to an optimum level, to determine an efficient replacement source for both saving the material (bitumen) costs for road construction and the eco-friendly development of the road infrastructure. This intends to help, in particular, developing countries to efficiently utilize all their own waste cell phone covers and cases, and efficiently develop cheaper yet durable roads. This will also aid in providing the solution for the disposal of waste (mobile covers and cases) to a considerable extent, significantly reducing the associated pollution due to the elimination of the waste [6]. The only treatment required by phone covers and cases is shredding to small grains in a crushed form of waste. These crushed grains of phone covers and cases are then heated to melt, added to hot bitumen, and mixed to develop homogenous modified bitumen.

By employing such synthetic wastes in roads, we can easily modify the binder content of asphalt in roads. This leads to producing an eco-friendly road network for the growing urbanizations across the globe. By replacing the bitumen binder content at different proportions of 10%, 20%, 30%, 40% and 50% with the shredded mobile phone silicon cover and case waste material, a detailed analysis was done for the behavior of the asphalt by the Marshall test and all physical properties of the bitumen were analyzed.

2. Materials and Methods

The comprehensive and effective methodology, which was employed to perform all the associated major experimentations is discussed. For the asphalt mixing and developmental process (as shown in Figure 2), bitumen of standard grade 60/70, or any desired grade, was lightly heated in heat burner drums to make it soft in form and flow for ease of bonding. This was then pumped into large bitumen-specified storage tanks [7–13]. From these storage tanks, the heated bitumen was mechanically pumped into modifier tanks for the modification phase, where all desired proportions of the additives were mixed in it. At a constant range of temperatures of 160–170 °C, the binder was homogeneously blended with the additives, while keeping the heat constant to avoid the unwanted process of local overheating for the mix [14–17]. After this, the aggregates and filler were added to the mix and a well-prepared asphalt mix was ready to be laid on the road surface.

The experimental procedure is explained in the stepwise methodology as:

Step 1: Selection of basic materials and mix design.
Step 2: Characterization of the bitumen and aggregates.
Step 3: Selection of new modifiers for the bitumen.
Step 4: Testing of the properties with references to modification.
Step 5: Trial mixing of the asphalt mixing for cake formation.
Step 6: Development of samples with pure and modified bitumen.
Step 7: Application of the Marshall test mechanism.
Step 8: Calculation of fuel consumption and saving during the sample formation.
Step 9: Comparative performance analysis with reference to standards.
Step 10: Statistical analysis for the impact analysis of factors.
Step 11: Final decision making.

2.1. Basic Materials

Bitumen is a sticky, black viscous and semi-solid textured material that comes from petroleum. It is mostly found in natural reserves underground and is globally produced by the efficient refining processes of dense crude petroleum for purification [18]. The sole primary effective usage of bitumen all around the world is in the road industry, where it is employed to serve as a binder material. It is also being used as a strong durable binder, effective glue, and a quality sealant adhesive compound. It has structured hydrocarbons in composition and also acts as a waterproofing agent for leakages, walls, foundations, and roofing.

The modifier used here was the waste material available worldwide and remaining untreated prior to disposal. The selected waste, comprising of silicone covers and cases of mobiles, require treatment and hence, were shredded using a mechanical shredder. This shredded waste was then directly heated along with the bitumen to melt on burners and was added and mixed as a replacement of bitumen in percentages, varying from 10, 20, 30, 40, 50% of the total weight of bitumen, and then subsequently added to the asphalt mix.

The phase of preparation for silicon waste to be added into binder started when the silicone covers were firstly brought to shredders. These were finely shredded to smaller homogenous particles. Before shredding, the unwanted materials such as threads and plastic pieces, etc., were carefully removed and the pure waste was brought for shredding. The shredding was done in order to ease the melting and mixing process of the silicone waste into hot bitumen. The shredded waste was then carried to the burners, where it was melted down into hot bitumen. Mechanical shredders powered by electric motors aided in this process of shredding. The shredding of the waste reduced the particle size to smaller grains and thus became easy to melt, which was economical, as less energy was required. After a careful preparatory phase, a homogenous mix was prepared by the addition of waste grains into the binder (bitumen).

2.2. Modified Binders

Earlier investigations suggested the use of shredded plastic waste and polyurethane foam waste from the soles of shoes, which were carefully mixed and blended with bitumen at a constant heat in the pre-determined proportions. The waste was replaced in the binder bitumen. Both the additives were mixed in the basic order of 10%, 20%, 30%, 40% and 50%, maintaining all processes and a constant supply of heat [7–10,19,20]. To measure the fuel amount being utilized to heat the binder and additives together, a measuring gauge was placed on the gas cylinder, which measured the total amount of gas required to heat the mix. Hence an analysis of the saving of energy, based on fuel consumption, was carefully made. It was found that these additives significantly decreased the temperatures of the binder in terms of flash and fire point.

2.3. Properties of Binders

All associated physicochemical properties for the binder (bitumen) were very comprehensively tested and analyzed under the ASTM test standards and prescribed conditions. Some of the basic tests were utilized in the experimentation. Penetration analysis was carried out by the standard Penetrometer to efficiently analyze and fully determine the current consistency of the binder, in both normal and modified states. The analysis was done on the softening point of the binder in modified and unmodified states by the test, which showed the real temperatures or points at which the bitumen (unmodified and modified) significantly attained softness [13,20–24].

A Ductilometer was used to evaluate the ductility factors for both the modified and unmodified types of bitumen. This test gave a good measurement for the ductility characteristics of the binder [19,22,23].

The bitumen used was of 60/70 grade. The specifications and properties of the unmodified plain bitumen selected for the comparative evaluation and analysis are listed in Table 1.

Table 1. Standards for testing bitumen properties.

Analyzed Properties	Units	Limit	Test Method
Density@25 °C	Kg/m^3	1010–1060	ASTM D70 or D3289
Penetration @25 °C	Mm/10	60–70	ASTM D5
Softening point	°C	49–56	ASTM D36
Ductility@25 °C	cm	100min	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@60 °C	p	2000+/−400	ASTM D2171
Viscosity @135 °C	cst	300min	ASTM D2170
Test on Residue from Thin Film Oven Test (ASTM D1754)			
Retained Penetration (T.F.O.T),%	%	54 min	ASTM D5
Ductility, (25 °C), 5 cm/min, cm after TFOT	cm	50	ASTM D113
Viscosity@60 °C	p	1000 max	ASTM D2171

2.4. Properties of the Aggregate

Coarse grain aggregates of size 20 mm, with a medium aggregate grain of size 10 mm, were used and fine grains of size <4.75 mm were utilized for the asphalt mix preparation. Comprehensive mechanical evaluation and testing were carried out on all of the selected aggregates [11–15]. The results are shown in Table 2.

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

2.5. Marshall Test Specimen Preparation and Testing

The Marshall test specimens were prepared for the experimentation and detailed evaluations of asphalt mix properties. Both modified and unmodified bitumen samples were prepared for comparative analyses of the results. The aggregates were taken and mixed thoroughly, then kept for oven drying at a constant range of temperatures, set around 150–170 °C. The bitumen (binder) was given heat to become flowable. The bitumen was heated at a safe range of temperatures of 160–170 °C to avoid any local overheating issues [25,26]. The binder and aggregates were then homogeneously mixed in a mechanical mixer available in the laboratory. The mixing was done at a temperature of 165°C for efficient mixing. The temperatures were noted, and the mixing was done to achieve a homogenous mix.

The prepared mix was then placed in pre-heated metal molds for making Marshall's specimens at and around temperatures of 100–140 °C for the mechanical compaction and set in molds. The standard compaction was done for all molds by the standard hammer compactor, by 75 blows on both sides of these samples. By using the hydraulic sample extractor, the samples are taken out after cooling in the laboratory [16]. After the samples were demolded and cooled, all samples were placed in a thermostatically controlled water bath at approximately 60 °C, for a specified time of 30–40 min before the testing process began. The samples were then tested in a Marshall testing machine for the detailed comparative analysis of effective stability and the flow values for the asphalt samples made by modified and unmodified bitumen.

3. Results and Discussion

All the essential tests were performed, and the basic properties were analyzed to highlight the effects of the physicochemical behavior due to the addition of a modifier (silicone waste) in the virgin bitumen. Hence, for identification purposes, in the results "M" denotes the modified bitumen, which contained the mixed waste covers and cases of mobiles that were used in this investigation.

3.1. Analysis of Modified Bitumen

The first phase of the experiments comprised a thorough analysis of the critical properties in the standard and modified forms of bitumen to highlight the effects of the modification of the material. The introduction of shredded waste silicon covers into bitumen by heat mixing was limited up to 50% by the weight content on a partial replacement basis. The properties of the modified bitumen are given in Table 3. According to the observations, the bitumen, upon addition of the modifier, showed similar characteristics in the physical properties when compared to the initial (i.e., before adding).

Table 3. 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		0.1mm	0.1cm	1°C	1°C
M 1	100%B + 0%M	67.0	99	266	55
M 2	90%B + 10% M	66.1	99	259	56
M 3	80%B + 20% M	66.7	97	255	56
M 4	70%B + 30% M	66.0	96	250	56
M 5	60%B + 40% M	65.3	94	250	57
M 6	50%B + 50% M	65.0	90	249	58
Standard	**Pure Bitumen**	**60–70**	**>75**	**232 min**	**40–55**

3.2. Marshall Stability Analysis

Marshall stability analysis was extensively carried out on both types of bitumen (plain and modified) for comparative evaluation. For each percentage of the proportions of modified bitumen, there were three sets of samples prepared. The average stability value of all three samples for each tested proportion was taken for detailed analysis, with reference to the previously followed procedures [17,24,27–31] listed in Table 4. These results showed that modified bitumen fell in the better range of stability in comparison to the conventional bituminous mixes.

Table 4. 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: 1559**	
Units		KN	mm	
M 1	100%B + 0%M	9.64	2.24	160
M 2	90%B + 10%M	10.13	2.71	160
M 3	80%B + 20%M	10.21	3.08	160
M 4	70%B + 30%M	11.70	3.42	160
M 5	60%B + 40%M	11.91	3.90	160
M 6	50%B + 50%M	12.1	4.03	160
Standard	**With pure bitumen**	**>9**	**2–4**	**100–170**

Usually, decision-making can be done based on the stability value, which indicated that with the application of silicon waste up to 40%, satisfactory performance of asphalt mix can be achieved. Figure 3 shows the progressive pattern of the relationship of stability and flow, where up to a 40% modification was suitable. However, after the top point, the flow ranges crossed the standard limit.

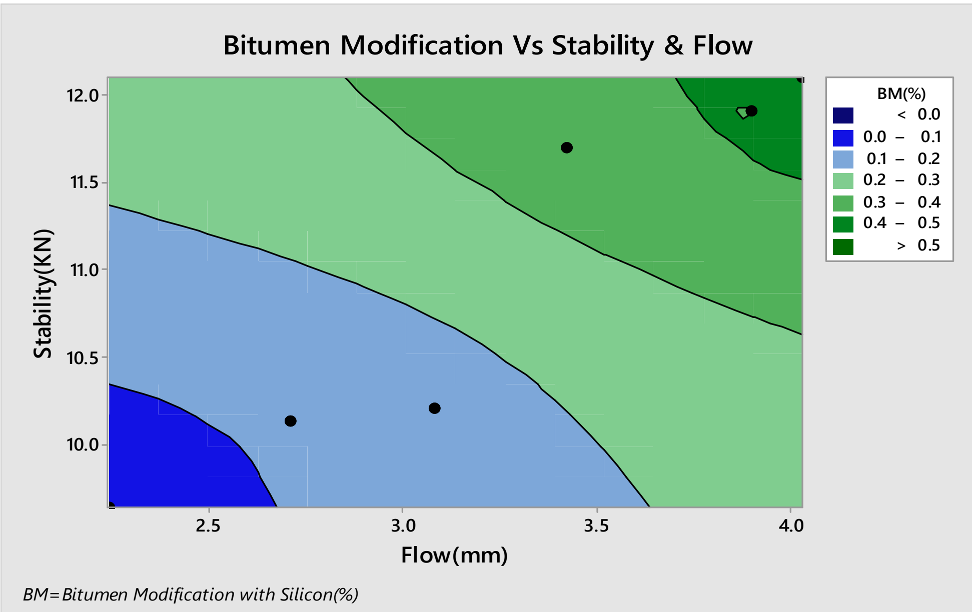

Figure 3. Comparative performance analysis of bitumen modification vs stability (KN) and flow (mm).

3.3. Economical Quantity Analysis

Cost analysis and quantity calculations were done for a full four-lane highway and estimation was calculated for a 1 km long patch of such highway, with 50 mm surface course thickness and additive was added in all respective proportions. Table 5 shows the saving, in terms of cost and quantity of material, per m^3 of asphalt mix. The eco-friendly and cheaper road could be developed from this study design. The calculation is provided in Tables 5 and 6.

Table 5. Description of road section and bitumen saving.

S.No	Design Parameter	Values
1	length of Pavement Section	1 km
2	No of Lanes	1
3	Width of pavement section	3.5 m
4	Bitumen Percentage	7%
5	Surface Course thickness	50 mm

Note: Volume of asphalt mix = length * width * thickness = 1000 m * 3.5 m * 0.05 m = 175 m^3 and density = 2400 kg/m^3. Quantity of asphalt mix = length * width * thickness * density = 1000 * 3.5 * 0.05 * 2400 = 420,000 kg.total quantity of bitumen at 7% = 420,000 kg * 0.07 = 29,400 kg / 1000 = 29.4 tons.

Table 6. Description of bitumen saving per m^3 of asphalt mix.

	Composition	Qty of Bitumen/m^3	% Qty Saving (Bitumen)/m^3	Saving Cost/m^3
Units		Tonnes	%	$
MB1	100% + 0% addt	0.168	0	0
MB2	90% + 10% addt	0.166	1.19	0.84
MB3	80% + 20% addt	0.165	1.78	1.68
MB4	70% + 30% addt	0.163	2.97	2.52
MB5	60% + 40% addt	0.161	4.16	3.36
MB6	50% + 50% addt	0.160	4.76	4.2

Note: Quantity of bitumen/m^3 of asphalt mix = total quantity of bitumen / total volume of asphalt mix = 29.4 / 175 = 0.168 tons and rate used for bitumen = 0.50 $/kg = 500 $/ton, saving cost/$m^3$ = (0.168–0.166) * 500 = 0.84$.

Economic analysis is one of the important aspects of the sustainable production process, which shows how economical a certain intervention is. An increasing trend in cost saving could be seen during the analysis, as shown in Figure 4.

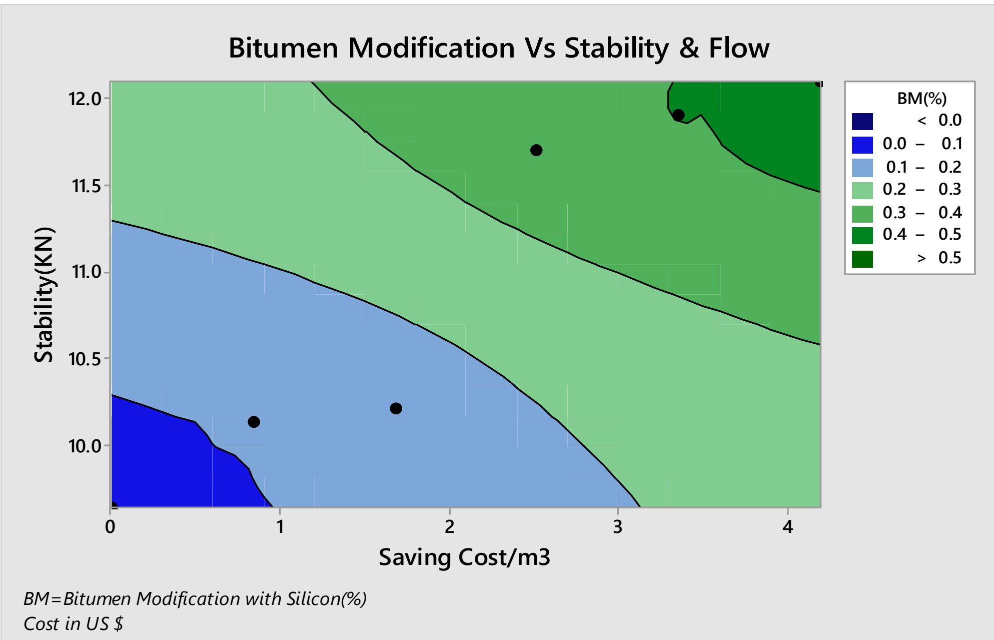

Figure 4. Comparative performance analysis of bitumen modification vs stability (KN) and saving ($).

4. Limitations of the Study

This study was focused on the first phase of testing, which included silicon waste as a modifier to a basic binding ingredient (i.e., bitumen). The range of testing for utilization of silicon waste in the asphalt mix started from the Marshall stability test. After an encouraging response from this stability testing, other tests such as rutting, will also be conducted. Furthermore, during the cost economic analysis, the cost for cutting and transportation of silicon waste to the mixing plant was considered negligible as a cross-cancellation. This was because a similar type of cost would be reduced, which would be paid for formation and transportation of bitumen from factories (i.e., with an increase in the supply cost of the waste, the bitumen transportation cost will be reduced, so can be cross-cancelled).

5. Conclusions

It may be concluded that utilization of such synthetic solid wastes in the road construction industry of developing countries shall not only provide an eco-friendly and cheaper road network, but a solution for disposal of this specific waste in a sustainable manner. It has been shown that the typical material properties of bitumen as a binder remain within the applied normal range as per ASTM standards. The Marshall test results showed favorable results with improved stability and flow values for asphalt mixes made with the modified bitumen. We envisaged that implementation of this idea into practice would enable the construction of roads with a sustainable, cost-effective and eco-friendly mode of urbanization. An increasing trend of mobile phone users will lead to the production of millions of tons of waste cell phone covers and cases. Thus, providing a continuous and significant source of material for use in the road construction industry. The cost of bitumen production would be cut due to the minimization of the requirement of the material, as a substitute/replacement binder material would be available in the preparation of the asphalt mix in the construction of roads. This study also provides a direction for a collection mechanism and usage of silicon mobile cover waste for road construction procedures and waste management as well. In the future, two major aspects of studies about the application of silicon can also be focused upon: First, the application of silicon waste-modified bitumen and its impact on properties like rutting, and second, the impact of its utilization on the environment and on worker's health.

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