Optimisation of bitumen using sulphur as a binder and coconut shell charcoal as a filler for sustainable road construction

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Abstract. An attempt has been made to optimise the bituminous concrete mixes by varying bitumen content and mixing 3% coconut shell charcoal powder as a filler and 1% sulphur as a binder using Marshall Stability Mix Design method. The key properties of the mix such as flow value, density, stability, voids in total mix (VTM), total air voids (AIV), and voids in mineral aggregate (VMA) are determined. The findings of the tests reveal that bituminous mix with 4.5% bitumen has shown better performance in terms of the key properties of the mix. This study further emphasizes sustainable use of materials by replacing the waste products such as Coconut shell charcoal. It is a renewable byproduct of agricultural waste that serves as an effective filler and reduces dependence on conventional, non-renewable fillers. Additionally, sulphur is used as a binder which not only enhances the durability and lifespan of the mix but also contributes to lower environmental emissions. The results of the study can be used in developing a bituminous concrete mix, that has good mechanical properties and eco-friendly composition suiting for high-traffic environments. This approach helps in reducing the carbon footprint promoting circular economy and encouraging waste to wealth concept.

1 Introduction

In this world of today, where environmental sensitisation has increased due to its complex scenarios that would create in future, integration of renewable materials like Coconut Shell Charcoal (CSC) has gained relevance for researchers in bituminous mixes [1]. CSC has been used as a filler in bituminous mixes and has proved to be an alternative material that showed a significant improvement in physical and rheological properties [2,3]. These studies align with the sustainable development goals by reducing the usage of non-renewable materials [4]. Marshall stability Mix design assesses the performance of the mix in terms of its load bearing capacity [5] and this study introduces CSC as filler and sulphur as binder in this design framework. Though many studies have done research on bio-based fillers, limited research has been done in this combination. Molvi and Singh found that CSC has improved the Marshall parameters [6]. Girish et al. has partially replaced stone dust with CSC ash and has found an improvement in the mix properties [7]. Sulphur has also been used a modifier

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in many studies. Study on sulphur usage has enhanced the rheological properties and allowed lower mixing temperatures [8]. Emmanuel and Etuk have seen improvement in durability of the mix with 15% CSC [9]. Gladkikh et al. has found an improvement in mechanical properties by usage of sulphur [10]. Abdullah et al. has found that CSC has improved softening point and aging properties [11]. Azahar et al. stressed controlled permeability for structural integrity [12]. Some studies have emphasised the use of CSC in improvement of engineering properties with a limitation on ingredient segregation [13,14,15].

2 Materials used

The materials used in this study included coconut shell charcoal, sulphur, VG30 grade bitumen, and coarse and fine aggregates. Materials have been selected to suit the requirements of the bituminous pavement preparation. VG30 is a binder classified as per viscosity grading and is considered suitable for hot and humid climates as it has high-temperature resistance and durability. It gives good coating for aggregates and improves the pavement performance over various ranges of temperature. Sulphur has been used in molten form as a partial substitution for bitumen as it improves bituminous stiffness and durability properties. Sulphur-modified mixes resist aging, moisture damage, and deformation, offering a more sustainable pavement solution. CSC serves as a sustainable filler due to its high carbon content and porous structure. It has the property of improving bitumen adhesion, temperature stability, and durability, and its usage also leads to waste reduction. It is light in weight and has high surface area that enhances void structure and mix performance. Crushed stone aggregates with proper gradation as per MORTH specifications have been used that can make a well graded mix with both coarse and fine aggregates. All aggregates have been tested for the requirements of the dense graded bituminous macadam to meet the standards of construction and testing. The percentages of CSC and sulphur in the mix have been selected based on the previous research studies.

2.1 Determination of CSC Percentage

Previous research done by Nur et al., and Girish has demonstrated that addition of CSC has improved stability of the mix and reduced air voids [2,7]. Based on this, CSC of 1–3% by mix weight has been added.

2.2 Sulphur Percentage Determination

Based on prior studies, sulphur was added to bitumen at 1–5% levels to improve the properties of the bitumen.

Aggregate samples were prepared as per MORTH specifications for DBM Grade 1, with calculated proportions to total 1200 grams and sieved accordingly to meet the required gradation for bituminous pavement. Table 1 shows the composition of DBM as per MORTH.

Table 1. Composition of Dense bitumen macadam

Grading	1	2
Nominal aggregate size	37.5 mm	26.5mm
Layer thickness	75-100 mm	50-75 mm
IS Sieve (mm)	Cumulative % by weight of total aggregate passing	Cumulative % by weight of total aggregate passing
45	100	-

37.5	95-100	100
26.5	63-93	90-100
19	-	71-95
13.2	55-75	56-80
4.75	38-54	38-54
2.36	28-42	28-42
0.3	7-21	7-21
0.075	2-8	2-8
Bitumen content % by mass of total mix	Min 4.0	Min 4.5

Upon conducting various experiments on the aggregates, the following specifications and observations were recorded as shown in table 2.

Table 2. Specifications and observation on aggregates

Property	Test	Specification for DBM	Obtained values	According to IS codes
Particle shape	Flakiness Index	Max 15%	9.84%	IS 2386 (Part-1) 1963
	Elongation Index	Max 35%	19.81%	
Hardness	Los Angeles Abrasion test	Max 35%	31.4%	IS 2386 (Part-4) -1963
Toughness	Aggregate Impact test	Max 30%	29.19%	IS 2386(Part-4)-1963
Crushing Strength	Crushing test	Max 35%	28.08%	IS 2386(Part-4)-1963
Specific Gravity	Specific gravity	Coarse aggregate	2.62	IS 2386(Part-3)-1963
		Fine aggregate	2.64	

3 Procedure

Marshall Mix design method has been adopted for optimising the bituminous mix. Four fundamental properties of the mix are evaluated with the test procedure – Stability, Density, Voids in Mineral Aggregate (VMA), and Voids Filled with bitumen (VFB). Marshall Stability measures the ability of the bituminous mixture to withstand shear stress under load, ensuring that the mix can support traffic loads without deformation. Density refers to the mass per unit volume of the bituminous mixture, which is crucial for determining the mix's overall strength and durability. Voids in Mineral Aggregate (VMA) measures the volume of voids in the aggregate mix, which is essential for ensuring proper binder content and avoiding excessive air voids. Voids Filled with bitumen (VFB) indicates the percentage of the VMA that is filled with binder, which affects the mixture's performance and durability. The specific cases analysed in this study are described in terms of the percentages of these materials used, highlighting the influence of coconut shell charcoal and sulphur on the overall mix performance. The various mixes for coconut shell and binder are given in table 3 to 8.

Table 3. Percentage retained and cumulative percentage of aggregates

Sieve No. (mm)	Percentage retained aggregates on each sieve (%)	Cumulative percentage of aggregates	Weight of aggregates on each Sieve for total mix of 1200grams (grams)
37.5	2.5	2.5	30
26.5	19.5	22	234
13.2	13	35	156
4.75	19	54	228
2.36	21	75	252
0.3	11	86	132
0.75	9	95	108
Pan	5	100	60

The prepared aggregate sample is shown in figure 1.

Fig. 1. Aggregate sample

Table 4. Various percentages of sulphur in bitumen

Bitumen (%)	Sulphur Binder content (%)	Stability (KN)	Flow Value (mm)
4	0.5	25	2.5
3.5	1	36	3.5
3	1.5	34	2.5
2.5	2	32	2.75

Table 5. Various percentage of coconut shell charcoal in Asphalt mix.

Coconut shell Charcoal %	Stability (KN)	Flow value (mm)
1	24	2.50
1.5	25	2.65
2	25	3.45

2.5	26	3.25
3	30	4.25
3.5	24	3.95
4	20	2.65
4.5	20	2.75
5	22	2.50

Table 6. Properties of Mix of an Asphalt mix with 0 % Sulphur and 0 % charcoal

S.L NO.	Bitumen (%)	Wt. In air	Wt. In water	S.S.D	Bulk Volume	Bulk Density	Max. Specific gravity	Air Voids (%)	V.M.A	V.F.B
1	4	1248	736	1260	524	2.38	2.475	3.8	14.69	74.13
2	4	1246	742	1262	520	2.39	2.475	3.4	13.61	75.01
3	4	1250	742	1254	526	2.41	2.475	3.4	12.89	73.62
4	4.5	1249	742	1264	522	2.39	2.475	3.4	14.06	78.10
5	4.5	1251	746	1266	520	2.4	2.475	3.0	13.70	78.10
6	4.5	1253	749	1272	523	2.39	2.475	3.4	14.06	75.81
7	5	1260	751	1280	529	2.38	2.475	3.8	14.87	74.44
8	5	1259	742	1278	536	2.34	2.475	5.4	16.30	66.84
9	5	1263	746	1279	533	2.36	2.475	4.6	15.58	70.74
10	5.5	1266	749	1281	532	2.37	2.475	4.2	15.67	73.19
11	5.5	1269	750	1283	533	2.38	2.475	3.8	15.32	75.19
12	5.5	1271	746	1289	535	2.37	2.475	4.2	15.67	73.19
13	6	1272	754	1275	539	2.39	2.475	3.4	15.41	77.93
14	6	1273	742	1276	534	2.38	2.475	3.8	15.76	75.88
15	6	1275	749	1280	531	2.1	2.475	3.0	13.29	77.42

Table 7. Properties of Mix of an Asphalt with 4.5% and 5% sulphur modified bitumen

S.L NO.	Bitumen (%)	Sulphur (%)	Wt. In air	Wt. In water	S.S.D	Bulk Volume	Bulk Density	Max. Specific gravity	Air Voids (%)	V.M.A	V.F.B
4.5% Sulphur modified Bitumen											
1	4.0	0.5	1230	710	1237	527	2.33	2.475	4.90	16.2	69.1
2	3.5	1.0	1235	712	1239	527	2.34	2.475	5.01	15.3	68.4
3	3.0	1.5	1245	720	1249	529	2.35	2.475	4.80	15.0	66.7
4	2.5	2	1252	728	1254	526	2.38	2.475	3.80	14.4	83.4
5.0% Sulphur modified Bitumen											
5	4.5	0.5	1234	714	1238	524	2.35	2.475	5.0	15.94	68.6
6	4.0	1.0	1237	715	1239	523	2.36	2.475	4.6	15.58	70.4

7	3.5	1.5	1238	714	1241	526	2.39	2.475	5.0	15.94	68.6
8	3.0	2	1236	715	1239	523	2.32	2.475	4.7	15.58	70.4

Table 8. Properties of Mix of an Asphalt fine aggregates replaced with Coconut shell charcoal

S.L NO.	Coconut Shell charcoal (%)	Wt. In air	Wt. In water	S.S.D	Bulk Volume	Bulk Density	Max. Specific gravity	Air Voids (%)	V.M.A	V.F.B
1	1.0	1251	739	1263	524	2.38	2.475	3.8	14.42	73.6
2	1.5	1252	742	1265	523	2.39	2.475	3.4	14.06	75.8
3	2.0	1255	749	1270	521	2.40	2.475	3.4	13.70	75.01
4	2.5	1258	750	1272	527	2.29	2.475	3.0	13.07	78.01
5	3.0	1253	734	1256	543	2.43	2.475	3.2	13.08	78.01
6	3.5	1257	754	1262	524	2.38	2.475	3.3	14.21	74.02
7	4.0	1256	738	1265	523	2.36	2.475	4.0	12.08	72.90
8	4.5	1260	748	1267	529	2.39	2.475	3.9	15.0	80.01
9	5.0	1258	749	1272	524	2.38	2.475	3.8	13.70	78.03

4 Results and Discussion

Graphs have been plotted with bitumen and sulphur-modified binder content on the x-axis, and the following parameters on the y-axis: (i) Marshall Stability, (ii) Flow value, (iii) VMA (%), (iv) VFB (%), and (v) Air Voids (Vv %).

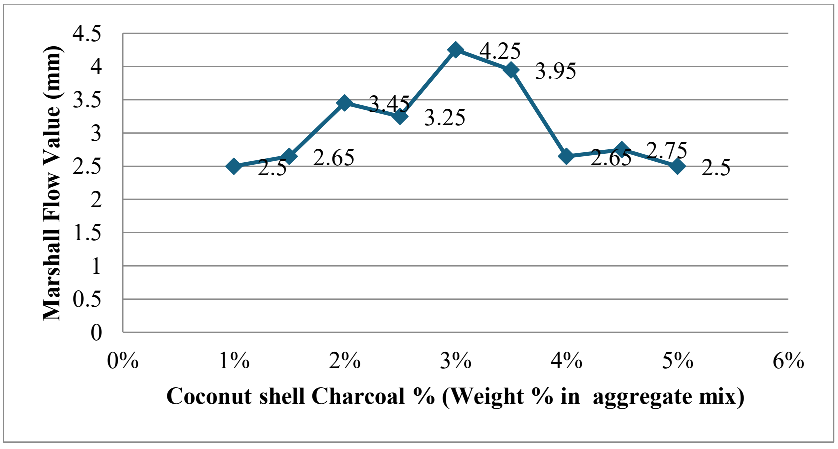

Fig. 2. Graph showing variation of Percentage of coconut shell charcoal and Marshall Flow value

Maximum stability was observed at 5% binder content, indicating the optimal level for peak performance. Flow value increased with CSC content up to 3%, enhancing flexibility due to CSC's porous structure. Beyond 3%, flow declined, likely due to excess filler disrupting binder-aggregate interaction. Hence, 3% CSC offers the best balance of flexibility and deformation resistance as shown in figure 2.

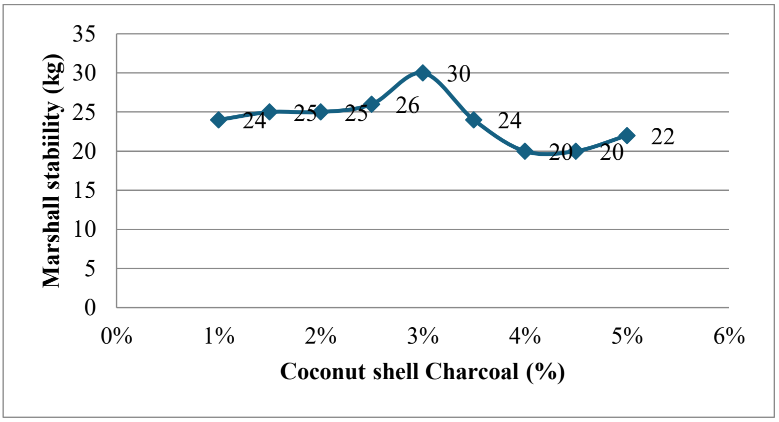

Fig. 3. Graph showing variation of Percentage of coconut shell charcoal and Marshall stability number.

The graph shows that stability increases with CSC content due to improved interlocking and binder bonding, but declines beyond a threshold as excess CSC disrupts mix cohesion. Similarly, flow values rise up to 3% CSC, then decrease, confirming that 3% CSC offers the optimal balance of strength and flexibility as shown in figure 3.

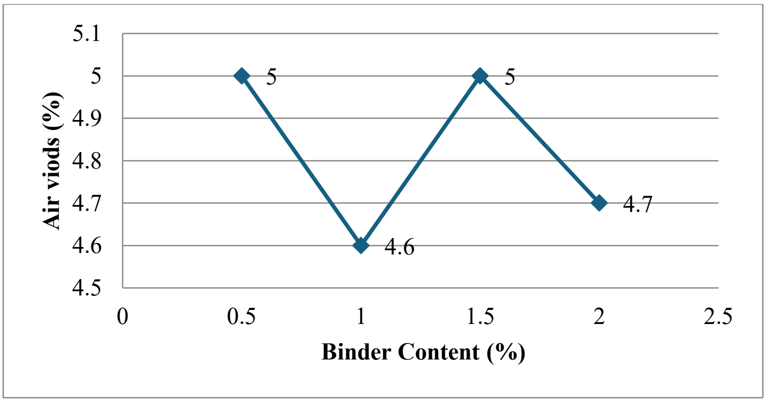

Fig. 4. Graph illustrating the relationship between binder content and air voids for a 5% sulphur replacement in bitumen.

The graph shows a decreasing trend in air voids with increasing sulphur-modified binder content up to 5%, as the binder fills aggregate gaps, leading to a denser mix. This reduction enhances mix density and suggests improved durability as shown in figure 4.

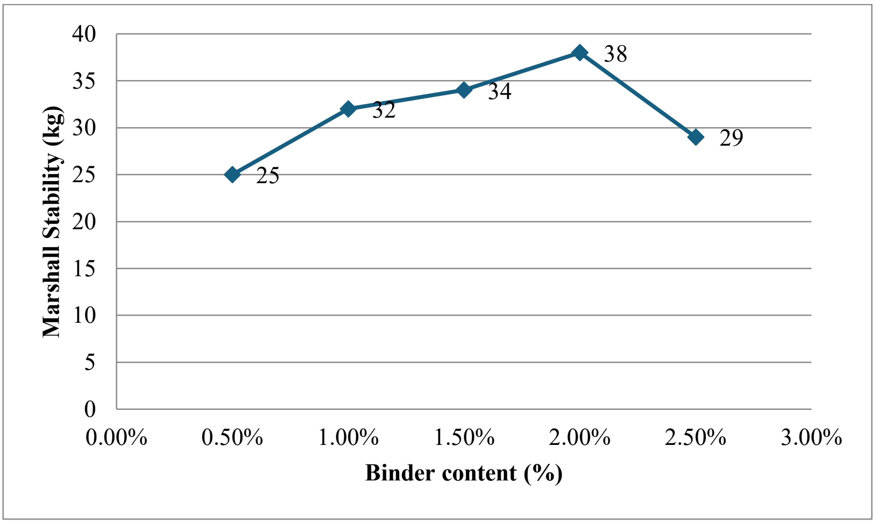

Fig. 5. Graph illustrating the relationship between binder content and Marshall stability for a 5% sulphur replacement in bitumen.

The graph shows that stability increases with sulphur-modified binder content up to 5%, as added binder improves cohesion and structural integrity by effectively binding aggregates, enhancing strength and deformation resistance as shown in figure 5.

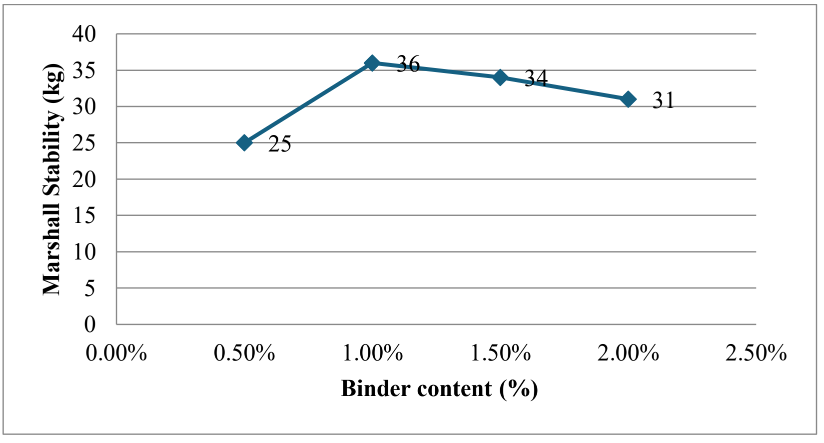

Fig. 6. Graph illustrating the relationship between binder content and Marshall stability for a 4.5% sulphur replacement in bitumen.

Figure 8 shows the relationship between sulphur binder content and asphalt mix stability. Stability peaks at 1% sulphur, indicating the optimal content for maximizing performance, durability, and pavement strength as shown in figure 6.

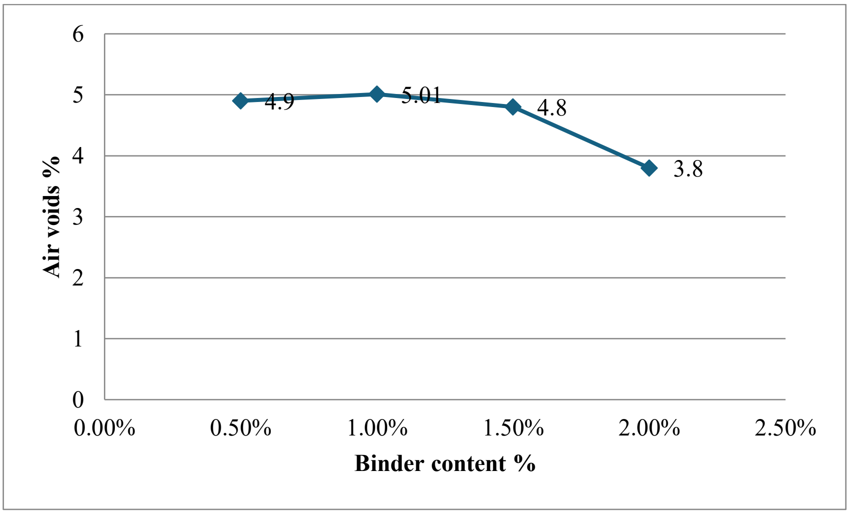

Fig. 7. Graph illustrating the relationship between binder content and air voids for a 4.5% sulphur replacement in bitumen.

The findings from the study and as displayed in figure 7, indicate that 4.5 % sulphur modified bitumen has yielded good results in the performance of the mix in terms of Marshall stability and air voids. A successful balance of the air voids decreasing while stability increase has been observed as the binder content approaches 4.5% Incorporation of 3% CSC and sulphur till 4.5% are consistent with previous studies on coconut shell-based modifications [2].

5 Conclusion

This study has proved that the bituminous mix performance can be enhanced by missing sulphur and CSC. Sulphur can be replaced with bitumen by 4.5% and CSC can replace filler by 3%. Excessive sulphur usage will reduce the stability properties and affects the structural integrity of the pavement. Specifically, an increase in sulphur content by 1.0% enhances mix stability but it decreases when the bitumen content exceeds 5%. Hence moderate levels of sulphur are recommended. The flow value reaches to 3.1 mm maximum which can handle heavy traffic loads. VMA shows a decreasing trend as sulphur content increases. Hence the optimal mix improves the performance of the bitumen and also promotes economy and sustainable construction practices. These insights from the study can leverage on usage of eco friendly alternate materials like CSC in pavement construction which can promote circular economy and waste to wealth concepts.

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