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Application of Crumb Rubber Modified Bitumen in the Asphalt Concrete Mix

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Abstract

Nepal has significant potential for road development projects, which require substantial financial resources for construction, maintenance, and operation over time. Bitumen is widely used to construct durable road pavements. However, increasing vehicles and deteriorating road conditions necessitate effective pavement management. The rise in vehicles also leads to a gradual increase in waste tyres, which, along with other carbon-based products, contribute to environmental pollution. The durability and quality of road pavements depend heavily on the type and properties of bitumen used. Alternative technologies involving modifications to bitumen are being explored to improve pavement performance. One such approach is crumb rubber-modified bitumen, which requires experimental analysis to assess its feasibility for road pavement. This study investigates the application of Crumb Rubber Modified Bitumen (CRMB) in asphalt concrete mixes as a solution to environmental issues caused by waste tires. The experimental tests were conducted to compare the properties of CRMB with conventional VG30 bitumen. CRMB was prepared by blending VG30 bitumen with crumb rubber (CR) at varying percentages (6%, 8%, 10%, 12%, and 14%). The results indicated that 8% CR provided the best performance, increasing Marshall stability by 17.16% and reducing bitumen content by 15.66%. This study highlights the potential of CRMB in enhancing pavement stability while addressing environmental concerns related to waste tires.

Keywords: Waste Tire; Crumb Rubber (CR); Crumb Rubber Modified Bitumen (CRMB); Viscosity Grade Bitumen (VG30); Marshall Test

1. Introduction

The development of road transportation is considered one of the important indicators for the socio-economic growth of the nation with its expansion, improvement, and new construction of highway transportation (Ng et al., 2019). Nepal has a large scope of the road project and involves considerable amounts of financial resources for its construction, maintenance, and operation which were prioritized in the 15th Periodic Plan of Nepal and most of the roads are constructed in Nepal is flexible pavement among them strategic bituminous roads are 6,979 km (National Planning Commission (NPC, 2020). The use of bitumen in pavement road has done as per the standard specification for Road and Bridge works (DOR, 2011). The quality of pavement road relies in use of bitumen type. The vehicle increment and road condition are simultaneously sustained. The vehicle increment has increase waste tyre (DOTM, 2019). According to Nagabhushana (2009), bitumen is used in the majority of road construction projects to create long-lasting pavements. The American Society for Testing and Materials (ASTM) Committee D04 on road and paving materials established the penetration grading system as the first standard method in 1918, according to Kandhal (2007). According to (Mampearachchi et al. 2012), the viscosity grading system was first used in 1960. Both approaches are empirical and are based on observations and prior experiences. Zumrawi (2013) claims that the most recent grading scheme, the Super Pave grading scheme, was initially implemented in 1998.

According to the Department of Transport Management (DOTM), the number of registered vehicles in Nepal has been increasing annually. Between FY 1989 and 2019, vehicle registrations grew at a cumulative rate of 14% per year. On the other hand, In FY 2019/20, the Government of Nepal allocated approximately 10% of the national budget to the land transportation sector, prioritizing road development annually (NPC, 2020)). Though government has working with a huge amount of investment in the road sector giving them higher priorities. However, expected longevity life of pavement found to be short and it could not meet target as expected. Also, there is increasing

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maintenance works which may be due to one may be reason of adverse climatic conditions and another might be increasing number of repetitions of wheel load beyond design. Thus, surface course of pavement deterioration could be improved for greater stability by various means.

Pavement performance capacity is put under more strain by increased traffic factors such as heavier loads, more traffic, and higher tyre pressures. Styrene-butadiene-styrene (SBS), styrene-butadiene rubber (SBR), ethylene-vinyl acetate (EVA), and crumb rubber modifier (CRM) are a few of the numerous modification techniques and additives that are currently used in bitumen modifications, according to Kazi (2017). It is demonstrated that the sample made with crumb rubber that is between 600 and 300 μm in size yields the highest stability value, the lowest air voids, the lowest flow value, the highest unit weight, and the lowest VMA and VFB percentage values. According to Kazi (2017), the ideal size for crumb rubber modifications is between 600 and 300 μm, which is the size used for commercial crumb rubber manufacturing.

According to Vasudevan et al. (2006), there is an urgent need to improve pavement properties due to increasing wheel loads, tyre pressure, climatic variations, and daily wear and tear, all of which significantly impact the performance of bituminous pavements. Prusty (2012) found that, the amount of plastic waste materials is mixed with Municipal solid waste or dumped in an open area leading to an increase in the area covered under wasteland. Based on previous studies, Crumb Rubber Modified Bitumen (CRMB) emerges as an environmentally friendly alternative for modifying base bitumen. CRMB can play a crucial role in utilizing non-biodegradable waste tyres from motor vehicles, reducing environmental pollution caused by landfill disposal.

2. Materials and method

The crumb rubber materials used in this study were obtained from the local market of Chabel, Kathmandu, Nepal tyre shredding area. The locally sourced crumb rubber did not follow a specific gradation; however, it was used in laboratory experiments as there are no crumb rubber production plants in Nepal.. In this study, the following binder tests have been performed on five samples of crumb rubber modified bitumen with different percentages of crumb rubber; 6%, 8%, 10%, 12% and 14%, of 0.3-0.15 mm size in addition to a viscosity grade bitumen VG-30 to evaluate their performance through application of CRMB in Asphalt concrete mix and identify the optimal mixture.

2.1 Preparation of Crumb Rubber Modified Bitumen (CRMB)

First, 1500 g of VG-30 viscosity grade bitumen was heated to a temperature within the fluidity range of 150–160°C. While crumb rubber was achieved through sieving and gradation by utilizing a size range of 0.3-0.15 mm which was also mentioned by Magar (2014). At hot bitumen 6% of crumb rubber i.e 90 gm mixing and blending was done. The mixture of crumb rubber modifier and VG-30 bitumen was manually stirred for 3-4 minutes and then placed in a hot air oven at 160-170°C for 30 minutes.

2.2 Test on Crumb Rubber Modified Bitumen

In the penetration test, a standard needle weighing 100 g is pressed against the surface of the binder for 5 seconds at 25°C. This test procedure is based on the Standard specification for roads and bridge works 2017 with amendment 2019 (NS221:2047 (Part III)/ IS: 1203).

The softening point test was carried out with a ring and ball apparatus, with the ring containing the binder suspended in water at 5°C. The binder sample was then placed on a steel ball, and water was heated at a rate of 5°C per minute. When the softened binder made contact with the apparatus plate, the temperature was measured which was mentioned in Mathew and Krishna Rao (2006).

The ductility test is performed by pulling the briquette mold containing the binder sample at a temperature of 25°C with a speed of 5 cm/min This test procedure is based on the Standard specification for roads and bridge works 2017 with amendment 2019 (ASTMD113).

2.3 Marshall Mix Design

According to standard specification for road and bridge works 2017 with amendment 2019 Nepal, (DoR, 2019), aggregates grading that satisfied the requirement of the specification for gradation for Grading-1 of bituminous concrete of 50 mm thick where selected. Also, adaptation ratio for marshal mix design were obtain through trial-and-error method, 28% of 19 mm down aggregates, 12% of 16 mm down aggregate, 25% of 10mm down aggregate and 35% of crushed stone dust as a filler material were used. This was achieved by performing sieve analysis. The adopted values of different size of aggregates were fall in between given specific limits. Figure. 1 shows the grain size distribution curves of adopted aggregates.

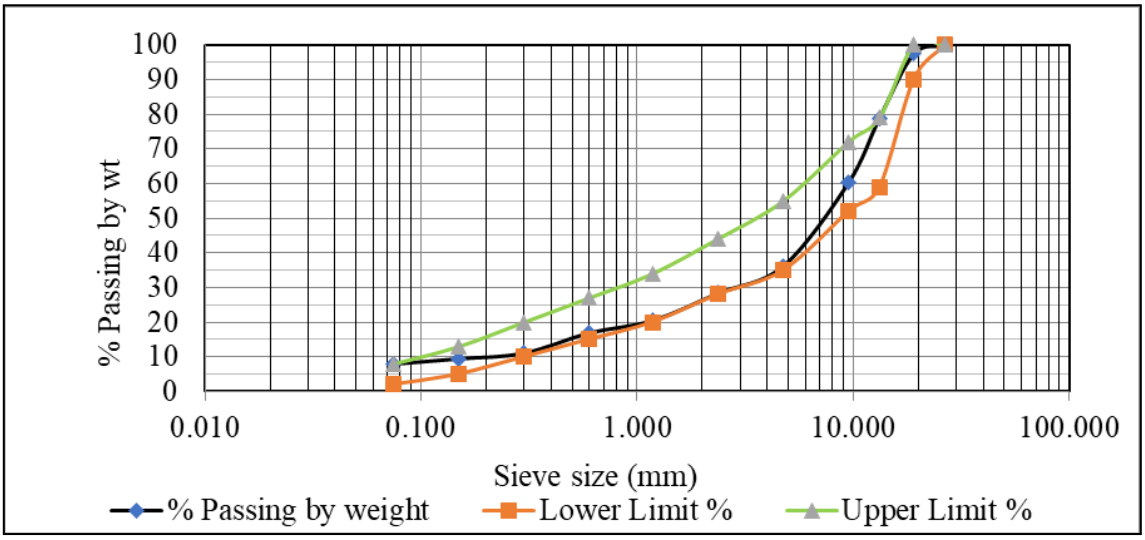

Figure 1. Gradation of Aggregate

In this study, the binder content ranges from 4.5% to 6.5% by total weight of the mix with 0.5% increments. The main steps of preparing Marshall specimens DoR (2019), which is as per mentioned in Asphalt Institute Manual MS-2 and is followed by DoR 2019.

In the meantime, aggregates were prepared by following gradations, adaptation ratio by trial-and-error method, and batching of aggregates were dried at 110°C. Approximately 1200 gm of aggregates and filler were utilized for each specimen test. After that, mixtures were prepared by dried aggregates of 1200 gm mixed with CRMB binder at 150-165°C thoroughly using a mechanical mixer, i.e., weight of CRMB binder for 4.5% = 5.4 gm. The sample was transferred to the pre-heated mold then specimen was compacted by applying 75 blows in each side of specimen using automatic marshal compaction hammer (DoR, 2019). Marshall specimens were extracted from the mold by means of extraction jack. Sample were allowed to cool overnight. Thickness of each specimen were measured and were weighted for volumetric analysis. Immersed specimen in water batch at 60°C for 40 minutes before testing.

2.3.1 Marshall Test

Marshall tests were performed as per the process defined in ASTM-D6927 by Asphalt Institute (2014), which is the standard test method for Marshall Stability and Flow of bituminous mixtures. The Marshall test is one of the most important tests for asphalt concrete mixtures prepared with modified and conventional bitumen. It was used in this study to determine the maximum load supported by compacted test specimens as well as the plastic flow caused by loading. This test was carried out on 90 specimens. One asphalt rubber and another was conventional asphalt to compare their capacity resistance to deformation as shown in Figure 2.

2.3.2 Optimum bitumen content

The integrated results of Marshall stability, flow, and void analysis have been used to determine the optimum binder contents of asphalt rubber and regular asphalt. Depending on traffic, climate, and prior experience with specific substances, engineering judgment is needed to determine the optimum bitumen content. The compacted specimen with 4% air spaces reached the optimum bitumen content. Five alternative bitumen contents with a 0.5% incremental were chosen for the optimum bitumen content; at least two of these contents were higher than the estimated design value, and the other two were lower.

Given 4% air voids is the mean value of the air voids range, it was determined that this was the optimum binder content. It is also frequently utilized in the design of asphalt mixes. In order to ascertain whether the selected mix satisfies MS-2 requirements, the properties at the optimum binder content have been ascertained and contrasted with Marshall design standards (Asphalt Institute, 2014).

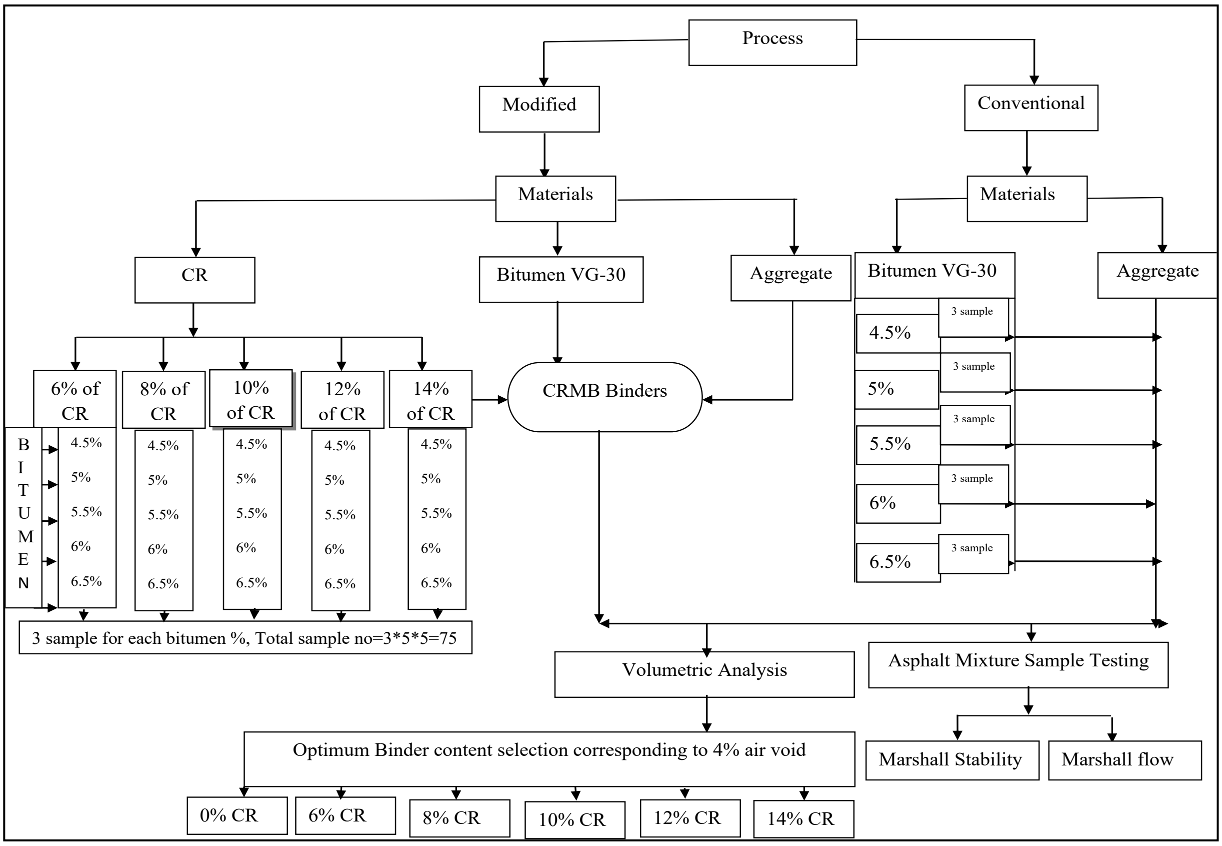

Figure 2. Methodological Framework

3. Result and discussion

3.1 Crumb Rubber Modified Bitumen (CRMB) Test

The modified asphalt concrete mixture was prepared as crumb rubber modified bitumen. The softening point, penetration, ductility and specific gravity tests were performed according to IRC: SP (2010) and the results are shown in Figure. 3

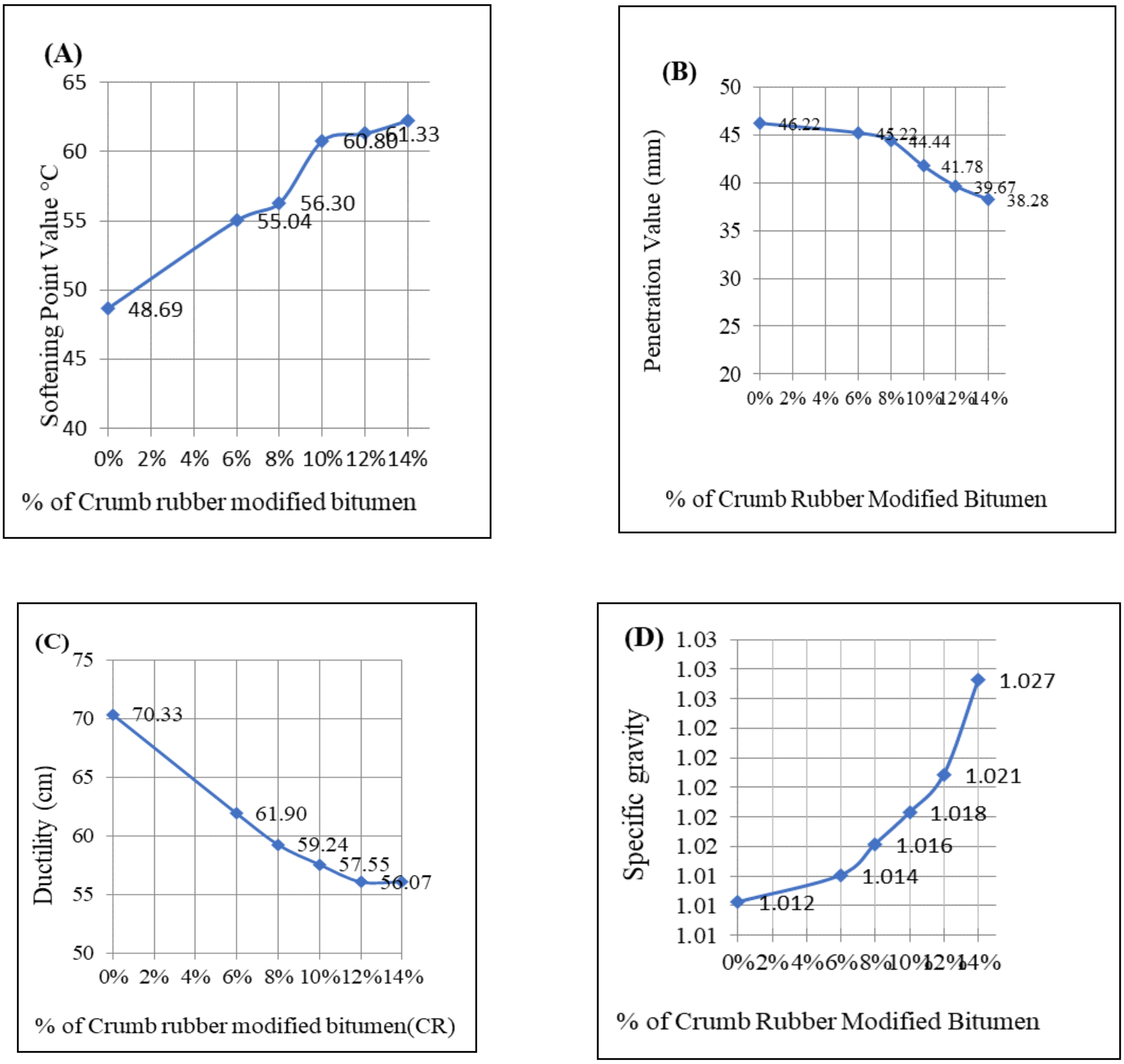

Figure 3. Crumb Rubber Modified Bitumen Test Result

Figure 3. A illustrates that as the percentage of crumb rubber increases, the softening point of crumb rubber-modified bitumen also rises. This indicates that the bitumen becomes less sensitive to temperature variations with higher crumb rubber content. Similar findings were reported by Hanumantharao et al. (2019), who observed an increase in the softening point with higher crumb rubber percentages in CRMB..

Figure 3.B demonstrates that a higher crumb rubber content leads to a reduction in the penetration value of crumb rubber-modified bitumen. Research by Liu et al. (2009) and Mashaan et al. (2011) also found that the decrease in penetration is due to the increased viscosity of bitumen when rubber is added. The rise in rubber content enhances the particle size as the rubber swells upon contact with bitumen during blending, thereby reducing penetration and increasing the rubber mass.

Similarly, Figure 3. C shows that an increase in crumb rubber content results in a decrease in the ductility value of crumb rubber-modified bitumen. Additionally, Figure 3.D indicates that as the percentage of crumb rubber increases, the specific gravity of crumb rubber-modified bitumen also rises.

3.2 Volumetric Analysis

3.2.1 Air voids (Vv)

The longevity of asphalt pavement depends on the air void content within the in-place asphalt concrete. A specific amount of air voids is essential to accommodate additional compaction from traffic loads and minor asphalt expansion due to temperature fluctuations. According to the Asphalt Institute (2019), the optimal mix design should have an aggregate structure and binder content that, when compacted to the designated number of blows, results in 4% air voids. As shown in Table 1, an increase in bitumen content leads to a reduction in air void percentage. Similarly, it was observed that the volume of voids (Vv) slightly decreases as the percentage of crumb rubber-modified bitumen increases, reaching up to 8% CRMB.

Table 1. Percentage of air voids for different combination

Percentage of air voids for different combination						
% Bitumen	0% Crumb Rubber	6% Crumb Rubber	8% Crumb Rubber	10% Crumb Rubber	12% Crumb Rubber	14% Crumb Rubber
4.5	6.67	6.05	4.71	5.66	5.81	7.58
5	4.77	5.41	3.50	5.62	6.52	6.19
5.5	4.07	4.09	3.60	4.06	4.10	5.92
6	3.58	3.72	1.48	3.16	4.26	4.16
6.5	3.61	2.78	1.27	1.38	1.94	2.74

3.2.2 Void in mineral aggregate (VMA)

The Voids in mineral aggregate (VMA) refer to the intergranular void spaces between aggregate particles in a compacted asphalt mixture, encompassing both air voids and effective asphalt content, expressed as a percentage of the total volume. Maintaining a minimum VMA value ensures sufficient space for the binder to properly adhere to aggregate particles without causing bleeding when temperatures rise and the binder expands. Table 2 presents the variation of VMA values with different binder contents and percentages of waste tire (crumb rubber). The VMA analysis results corresponding to 4% air voids are illustrated in Figure 4. The findings indicate that VMA values slightly increase with a higher percentage of crumb rubber-modified bitumen, along with a corresponding rise in VMA as bitumen content increases.

Table 2. Percentage VMA for different combination

Voids in mineral aggregate (VMA) versus Bitumen content						
% Bitumen	0% Crumb Rubber	6% Crumb Rubber	8% Crumb Rubber	10% Crumb Rubber	12% Crumb Rubber	14% Crumb Rubber
4.5	11.95	12.54	13.61	15.77	15.79	16.79
5	11.36	13.11	13.65	16.81	17.49	16.61
5.5	12.91	13.07	14.86	16.50	16.43	17.43
6	13.5	13.89	14.10	16.79	17.62	16.95
6.5	13.85	14.20	15.02	16.33	16.69	16.79

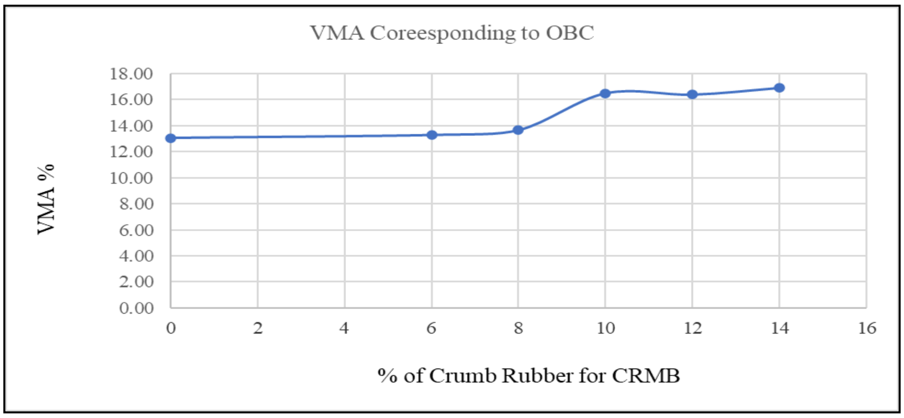

Figure 4. Variation of Percentage VMA value for different combinations

3.2.3 Voids filled with bitumen (VFB)

The voids filled with bitumen (VFB), voids in mineral aggregate (VMA), and air voids are closely interconnected, meaning that knowing any two of these values allows for calculating the third. The VFB criteria play a crucial role in preventing the design of asphalt mixtures with marginally acceptable VMA. The primary goal of VFB analysis is to regulate the maximum permissible levels of VMA and binder content while also limiting the allowable air void content in compacted mixtures. According to the findings, increased bitumen content leads to a rise in VFB values. Additionally, the VFB value shows a slight increase with the addition of crumb rubber-modified bitumen (CRMB) up to 8%, after which it begins to decline. Table 3 presents the variation in VFB values corresponding to different binder contents and CRMB percentages.

Table 3. Percentage VFB for different combinations

Percent void filled with Bitumen (VFB) versus Bitumen content						
% Bitumen	0%Crumb Rubber	6%Crumb Rubber	8% Crumb Rubber	10% Crumb Rubber	12% Crumb Rubber	14% Crumb Rubber
4.5	44.15	51.72	65.41	64.10	63.23	54.85
5	58.04	58.73	74.35	66.56	62.71	62.73
5.5	68.5	68.72	75.74	75.41	75.03	66.05
6	73.51	73.24	89.53	81.16	75.82	75.47
6.5	73.95	80.40	91.54	91.56	88.35	83.66

3.2.4 Bulk density

Density plays a crucial role in the construction of asphalt concrete mixtures. A well-designed and properly compacted mixture should have sufficient air voids to prevent rutting caused by plastic flow while maintaining a low enough air void content to minimize air and water permeability. It represents the actual density of the compacted mix. The bulk density of the mixture depends on the air voids; as a result, bulk density of mix decreases with an increase in waste crumb rubber content up to certain percentage as shown in Table 4 shows the bulk density of mix with 0%, 6%, 8%, 10%, 12% and 14% crumb rubber content at corresponding optimum bitumen content.

Table 4. Bulk density for different combination

Unit weight (Density) versus Bitumen content						
% Bitumen	0% Crumb Rubber	6% Crumb Rubber	8% Crumb Rubber	10% Crumb Rubber	12% Crumb Rubber	14% Crumb Rubber
4.5	2.46	2.44	2.41	2.35	2.35	2.32
5	2.49	2.44	2.42	2.33	2.32	2.34
5.5	2.49	2.45	2.40	2.36	2.36	2.33
6	2.48	2.44	2.44	2.36	2.34	2.36
6.5	2.46	2.45	2.42	2.39	2.38	2.37

3.2.5 Flow value

Marshall flow quantifies the deformation (both elastic and plastic) of a specimen during the stability test. A higher Marshall flow value in bituminous pavement signifies reduced rigidity. Table 5 illustrates the variation in Marshall flow values with different bitumen contents and varying percentages of crumb rubber. Overall, the flow values exhibit a slight increase as crumb rubber content rises, reaching up to 8%.

Table 5. Flow value for different combination

Flow versus Bitumen content						
% Bitumen	0% Crumb Rubber	6% Crumb Rubber	8% Crumb Rubber	10% Crumb Rubber	12% Crumb Rubber	14% Crumb Rubber
4.5	3.94	4.21	5.29	3.18	3.06	2.75
5	3.30	4.14	3.86	3.55	2.73	3.66
5.5	4.56	4.88	4.21	3.14	2.78	3.98
6	4.57	5.01	2.79	3.13	2.72	3.46
6.5	4.30	5.58	3.99	4.29	3.53	4.00

3.3 Marshall Stability Value

Table 6 presents results of the Marshall Stability test for various mix combinations. The stability of all mixes increases with binder content up to an optimal percentage. It was observed that Marshall stability values improved as the crumb rubber percentage increased, reaching a high of 8%. The highest stability recorded was 14.55 kN at an 8% crumb rubber mix with an optimum bitumen content of 4.79%.

Table 6. Marshall Stability value for a different combination

Marshall Stability (KN)						
% Bitumen	0% Crumb Rubber	6% Crumb Rubber	8% Crumb Rubber	10% Crumb Rubber	12% Crumb Rubber	14% Crumb Rubber
4.5	10.81	15.88	14.33	13.16	13.30	13.53
5	11.68	13.98	14.71	13.52	11.36	11.81
5.5	12.34	14.87	9.28	12.30	12.44	12.11

Marshall Stability (KN)						
% Bitumen	0% Crumb Rubber	6% Crumb Rubber	8% Crumb Rubber	10% Crumb Rubber	12% Crumb Rubber	14% Crumb Rubber
6	8.81	11.26	12.50	13.16	11.40	13.62
6.5	8.47	10.53	9.52	10.51	11.11	12.41

Similar studies conducted by Wulandari and Tjandra (2017); Wiranata and Malik (2021) which concluded that, increase in Marshall Stability can be explained better chemical and swelling mechanism of crumb rubber with bitumen for the formation of strong intermolecular bonding. The excellent high-temperature performance and fatigue resistance of crumb rubber modified bitumen (CRMB) make it a popular choice for asphalt pavement, according to Zhu et al. (2022), which handles the increasing traffic axle load and changing climate.

Since the nature of this study is also similar to the above-mentioned studies though this study has many limitations, the higher value of Marshall stability achieved in this study may be due to strong chemical and intermolecular bonding. Therefore, these intermolecular interactions may have increased the strength of asphalt concrete mix improving the overall stability of the mixture.

3.4 Optimum Bitumen Content (OBC)

The bitumen content was modified at 4.5%, 5%, 5.5%, 6%, and 6.6% by weight of bituminous mixture in order to figure out the optimum bitumen content (OBC). For each bitumen content variation, three samples were tested; the optimum bitumen content was established by combining the Marshall test results that matched the requirement criteria. The optimum bitumen contents are 0% CR, 6% CR, 8% CR, 10% CR, 12% CR, and 14% CR, as shown in Figure 5. It was shown that the optimal bitumen content is least in 8% CR, approximately 4.79%.

Table 7. Marshall Mix Design Test Result of CRMB by using varying % of CR

Marshall Parameters	Unit	0% (CR)	6% (CR)	8% (CR)	10% (CR)	12% (CR)	14% (CR)
Optimum Bitumen Content	%	5.54%	5.61%	4.79%	5.51%	5.52%	6.04%
Stability	KN	12.05	14.07	14.55	12.28	12.48	13.74
Density	gm/cc	2.48	2.45	2.42	2.36	2.36	2.36
Air Voids	%	4.00	4.00	4.00	4.00	4.00	4.00
VMA	%	13.03	13.26	13.63	16.49	16.38	16.91
VFB	%	68.9	69.78	70.66	75.74	75.55	76.31
Flow	Mm	4.56	4.90	4.46	3.13	2.78	3.42
% Stability (increase/Decrease) wrt 0%CR	%		14.35	17.16	1.81	3.40	12.29
% Of OBC Bitumen Increase/Decrease wrt 0%CR	%		1.25	-15.66	-0.54	-0.36	8.28

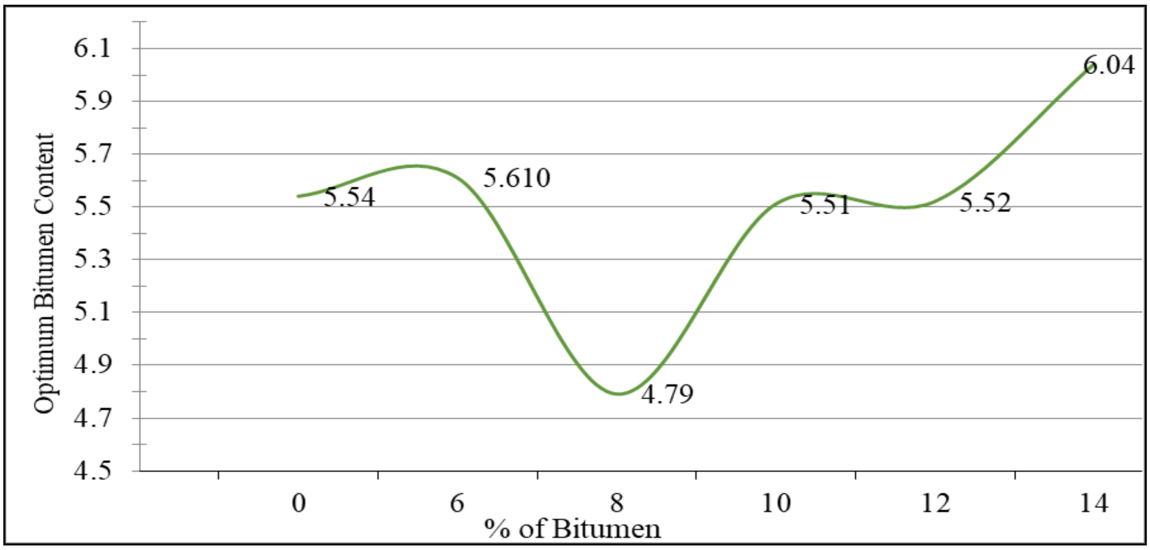

Figure 5. Variation of Optimum Bitumen Content in Varying % of Crumb Rubber

3.5 Optimum Crumb Rubber Content

For 0% CR, 6% CR, 8% CR, 10% CR 12% CR and 14% CR from which by using excel forecast tool optimum bitumen content (OBC) of respective crumb rubber content corresponds to 4% air void was determined. It was found that, 6% CR had optimum bitumen content 5.61%, 8% CR has 4.79 optimum bitumen content, 10% CR has 5.51% optimum bitumen content, 12% CR has 5.52% optimum bitumen content and 14% CR has 6.04% optimum bitumen content. Figure 5. indicates that the value of OBC decreases sharply up at 8 % of crumb rubber content. After 8% crumb rubber, it starts to increase. In overall, it was found that, at 8% crumb rubber content leads to minimal OBC that was 4.79% for asphalt concrete pavement.

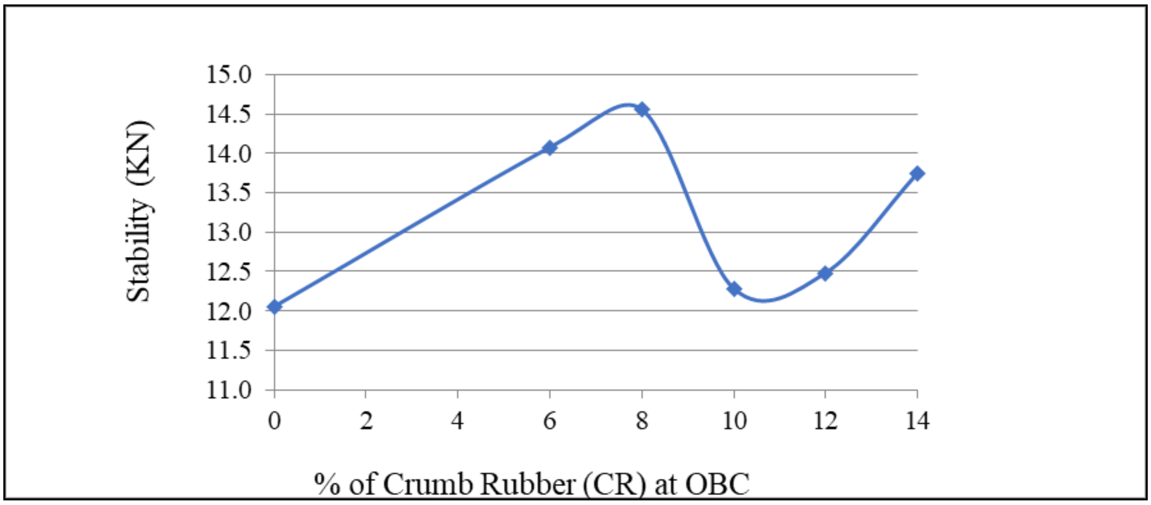

Figure 6.Variation of Stability Value at varying Optimum Bitumen Content in varying % of Crumb Rubber

For 0% CR, 6% CR, 8% CR, 10% CR 12% CR and 14% CR from which by using excel forecast tool, optimum bitumen content of respective crumb rubber content corresponds to 4% air void was determined. It shows that the Marshall stability values corresponding to different crumb rubber (CR) percentages were as follows: 6% CR with respect to OBC resulted in a stability value of 14.07 kN, while 8%, 10%, 12%, and 14% CR yielded values of 14.55 kN, 12.28 kN, 12.48 kN, and 13.74 kN, respectively. As illustrated in Figure 6, the Marshall stability value increased significantly up to 8% crumb rubber content. Beyond 8%, the stability began to decline at 10% CR, after which it gradually increased with further increments in CR percentage. Overall, the maximum stability value of 14.55 kN was achieved at 8% crumb rubber content, which corresponded to the minimum optimum bitumen content.

4. Conclusion

The study demonstrates that Crumb Rubber Modified Bitumen (CRMB) significantly improves the performance of asphalt concrete mixes. The addition of 8% CR increased Marshall stability by 17.16% and reduced bitumen content by 15.66%, making it an environmentally and economically viable option for road construction. CRMB not only enhances pavement durability but also addresses the challenge of waste tire disposal, contributing to sustainable development.

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