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SUSTAINABLE PAVEMENT DESIGN USING WASTE TYRE CRUMB RUBBER AS BITUMEN MODIFIER

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Abstract: Conventional bituminous surface courses in pavements are getting damaged easily. They suffer from deformation, fatigue cracking and thermal distress. This happens because of increasing traffic loads and extreme weather conditions in places like Maharashtra, India. At the time disposing of old tyres is a big environmental problem. This study checks if waste tyre crumb rubber (CRM) can be used to improve concrete surface course mixes. CRM is used to replace VG-30 bitumen in the mixes. The mixes are prepared using the process of modification. The base VG-30 bitumen was first tested as per IS 73:2013. It was found to be within all limits. The Optimum Bitumen Content (OBC) was found to be 5.4% by weight of mix. This was done using Marshall mix design. CRM-modified specimens were then made at four levels: 10% , 12.5% , 15% , 17.5% These levels are based on the weight of bitumen. The specimens were tested for Marshall Stability, Flow Value and Bulk Density as per IS 17127:2019. The results show that as CRM content increases: Penetration reduces , Softening point and flash point increase This means that the binder becomes stiffer. It also becomes more thermally stable and safer to handle. Among all tested levels 17.5% CRM content gave the performance. It achieved a Marshall Stability of 15.45 kN. This is a 32% improvement over the mix at 11.7 kN. The average Flow Value was 3.58 mm. Both results meet IS 17127:2019 requirements. The 12.5% and 15% CRM mixes had flow values, above the permissible limit of 4.0 mm. The study confirms that waste tyre crumb rubber can be used to improve bitumen. It can be used for surface course applications. This can lead to pavement performance and sustainable waste tyre management.

***Index Terms* -** Crumb Rubber Modifier (CRM); VG-30 Bitumen; Marshall Stability; Flexible Pavement; Sustainable Pavement; Waste Tyre Recycling; IS 17127:2019; Bituminous Concrete Surface Course

I. INTRODUCTION

Bituminous pavement is the backbone of road infrastructure. It is valued for being durable and cost-effective to build and maintain. As cities grow and more people drive road networks face increasing stress. This demands innovation in pavement materials and design. Some pressing challenges include managing end-of-life tyres, a waste stream and the need for sustainable construction. This reduces dependence on materials. Bituminous pavement construction involves layering materials. This creates a flexible road surface that can withstand heavy traffic and varying weather. The process starts with preparing the subgrade. This establishes a foundation. A sub-base and base course of aggregates provide support. The binder course bonds aggregates with bitumen. The wearing course provides a wear-resistant surface. Waste tyre rubber, when turned into crumb rubber is a modifier for bituminous mixes. Adding it to pavements improves performance. This includes being more flexible and resistant to rutting. It also improves fatigue life. At the time it addresses environmental concerns associated with tyre disposal. The recycling of end-of-life tyres through crumb rubber integration is a pathway. This leads to sustainable infrastructure solutions. Despite these advantages significant gaps remain in the literature. These are regarding the long-term field performance of crumb rubber-modified pavements. This is under climatic and traffic conditions. There is also a need for standardisation of mix design procedures. The present study aims to investigate the use of waste tyre rubber. This is as a modifier in bituminous pavement mixes. It evaluates its effect on pavement performance. It assesses its potential as an environmentally responsible solution. The significance of this research lies in its contribution. This advances knowledge of modified pavement behaviour. It supports the goals of circular economy and sustainable construction. By demonstrating the viability of crumb rubber as a pavement modifier this study contributes. It reduces tyre waste. Lowers the environmental footprint of road construction. It informs policy and engineering standards, in this domain.

II. RESEARCH METHODOLOGY

A. Materials Used

We used three materials for this study: VG-30 bitumen, waste tyre crumb rubber and well-graded aggregates like 6 mm and 10 mm stones and crushed sand with stone dust filler. The VG-30 bitumen came from a certified petroleum refinery. We checked it according to IS 73:2013 before using it. We got the crumb rubber from tyres that were recycled and we used it without doing anything to it first. We dried the aggregates sorted them by size and mixed them together according to the rules for Bituminous Concrete surface course in IS 17127:2019.

B. Bitumen Characterisation Tests

We did four tests on the VG-30 bitumen to make sure it was good enough to use: Penetration Test. We used a needle that weighed 100 g and let it go into the bitumen for 5 seconds. The bitumen was, at room temperature which's 25°C. We measured how far the needle went into the bitumen. Softening Point Test. We put the bitumen in a ring and heated it up slowly in water. We stopped when the bitumen got soft and sank 25.4 mm. This temperature is called the softening point of the VG-30 bitumen. Ductility Test. We made blocks of VG-30 bitumen and pulled them apart slowly at room temperature. We wanted to see how far they would stretch before breaking. Flash Point Test. We heated the VG-30 bitumen slowly. Used a small flame to check when it would catch fire. The temperature at which it first caught fire is called the flash point of the VG-30 bitumen.

C. Preparation of Crumb Rubber Modified Bitumen. Wet Process

To make Crumb Rubber bitumen we used a process. This process involved mixing Crumb Rubber into the bitumen before adding things. The process had four steps.

Step 1. Heating: We heated the bitumen, which was VG-30 to a temperature between 150°C and 160°C. We stirred the bitumen all the time to make sure it heated evenly. We made sure the temperature did not go above 165°C because that could damage the bitumen. We had to be careful with the temperature of the bitumen.

Step 2. Addition of Crumb Rubber: We slowly added Crumb Rubber to the bitumen at 150°C. We added the Crumb Rubber at levels: 10% of the bitumen weight 12.5% of the bitumen weight 15% of the bitumen weight and 17.5% of the bitumen weight. We did this to see how Crumb Rubber Modified bitumen would behave with amounts of Crumb Rubber. We wanted to know how the Crumb Rubber would affect the bitumen.

Step 3. Blending: We stirred the Crumb Rubber Modified bitumen mix by hand for one minute at a temperature, between 150°C and 160°C. This helped spread the Crumb Rubber throughout the bitumen. As we did this the Crumb Rubber absorbed some of the bitumen. Swelled up which changed the properties of the bitumen. The Crumb Rubber Modified bitumen started to look different.

Step 4. Immediate Use: We used the Crumb Rubber Modified bitumen away. This was necessary to prevent it from becoming solid and to keep its properties consistent. The Crumb Rubber Modified bitumen was then used for mixing with materials to make something new. We used the Crumb Rubber Modified bitumen to make something useful.

D. Mix Design. Determination of Optimum Bitumen Content

The Optimum Bitumen Content was first found out using the VG-30 bitumen. This was done by making Marshall specimens with bitumen contents of 3.5%, 4.0%, 4.5%, 5.0%, 5.5%, 6.0% and 6.5% by weight of the mix. For each bitumen content one specimen was. Tested for Marshall Stability, Flow Value and Bulk Density. Graphs were made to show the relationship between bitumen content and each parameter. The Optimum Bitumen Content was identified as the bitumen content that gave the Marshall Stability and maximum Bulk Density. The Optimum Bitumen Content was fixed at 5.4% by weight of the mix. Kept constant for all subsequent CRM-modified specimens. This was done to ensure an consistent comparison.

E. Mix Design Proportions for CRM-Modified Specimens

Table 1 shows the mix design proportions used for preparing CRM-modified specimens at each replacement level. The total mix weight was fixed at 1200 g per specimen for all batches.

Table 1: mix design proportions for CRM-modified bituminous specimens

Aggregate (gm)		Crush sand (gm)	Filler (gm)	OBC (gm)	Crumb Rubber (%)	Crumb rubber (gm)	Net Bitumen (gm)	Total Mix Weight (gm)
6 mm	10 mm							
318	204	590	23.2	64.8	10	6.48	58.32	1200
318	204	590	23.2	64.8	12.5	8.1	56.7	1200
318	204	590	23.2	64.8	15	9.67	55.13	1200
318	204	590	23.2	64.8	17.5	11.34	53.46	1200

F. Marshall Specimen Preparation and Testing

The aggregates were heated in a hot air oven at a temperature of 160°C to 165°C for 2 hours. The prepared CRMB binder at the fixed Optimum Bitumen Content was added to the aggregates at a temperature of 160°C to 165°C. The Optimum Bitumen Content was mixed with the aggregates until they were completely and uniformly coated. Each specimen was cast in a Marshall mould with a diameter of 101.6 mm. The specimen was compacted with 75 blows per face using a Marshall Compaction Hammer. The specimens were left to cool down and then conditioned at room temperature for 24 hours before testing. For testing each specimen was put in a water bath at a temperature of 60°C for 60 minutes. The specimen was then tested in the Marshall Stability Testing Machine. The maximum load, at failure was recorded as Marshall Stability. The corresponding deformation was recorded as Flow Value. The Bulk Density was measured using saturated surface dry and submerged weights. For each CRM replacement level three specimens were. Tested. The average values were reported for the Optimum Bitumen Content.

III. RESULTS AND DISCUSSION

4.1 Physical Properties of Base VG-30 Bitumen

Table 4.1 shows the test results for the VG-30 bitumen. All values are within the limits set by IS 73:2013 which means this bitumen is good for surface course pavement construction.

Table 4.1: Physical Property Test Results. Base VG-30 Bitumen

Sr. No.	Name Of Test	Result		Specified limit as per IS 73
		Value	Unit	
1	Penetration test	51	0.1mm	Min 45
2	Softening point test	58	℃	Min. 47
3	Ductility	90	cm	Min. 40
4	Flash Point	222.5	℃	Min. 220

The penetration value of 51 shows that VG-30 bitumen is medium-hard which is suitable for high-traffic surface courses in Indian weather. The softening point of 58°C is more, than the required minimum, which means VG-30 bitumen has thermal stability. The ductility of 90 cm shows that VG-30 bitumen is flexible enough. The flash point of 222.5°C meets the safety requirement of least 220°C for handling and laying operations. VG-30 bitumen has the required properties. VG-30 bitumen results are good.

4.2 Effect of Crumb Rubber Modifier on Physical Properties of Modified Bitumen

Table 4.2 presents the results of property tests on VG-30 bitumen that has been modified with crumb rubber modifier. The crumb rubber modifier was added at levels: 10%, 12.5%, 15%, 17.5% and 20% by weight of the bitumen.

Table 4.2: Physical Property Test Results. Crumb Rubber Modifier-Modified Bitumen

Sr no	Name of test	Bitumen %				
		10 %	12.5 %	15%	17.5 %	20 %
1	Penetration test	50	49	49	48	40
2	Softening point test	58.5	59	60	63	60
3	Ductility	88	86	83	75	80
4	Flash Point	255	263	271	282	280

The penetration of the bitumen decreases as the crumb rubber modifier content increases. It went from 50 at 10% crumb rubber modifier to 48 at 17.5% crumb rubber modifier. This shows that the bitumen becomes stiffer and more resistant to deformation at temperatures. This is because the rubber particles absorb the parts of the bitumen making it stiffer. The crumb rubber modifier is really good at making the bitumen stronger.

The softening point of the bitumen increases with crumb rubber modifier content. It went from 58.5°C to 63°C at 17.5% crumb rubber modifier. This means that the bitumen can withstand temperatures without getting soft. This is very important for roads in places like Maharashtra. The crumb rubber modifier is very useful for roads that are used a lot.

The ductility of the bitumen decreases with crumb rubber modifier content. It is still high enough to prevent cracks. It went from 88 cm to 75 cm. The bitumen is still very flexible with the crumb rubber modifier.

The flash point of the bitumen increases significantly with crumb rubber modifier content. It went from 255°C to 282°C. This makes it safer to handle and use. The crumb rubber modifier makes the bitumen much safer.

4.3 Marshall Performance of Conventional Bituminous Mix. Optimum Bitumen Content Determination

Table 4.3 presents the results of Marshall tests on VG-30 mixes with different bitumen contents. These results help determine the Optimum Bitumen Content.

Table 4: Marshall Test Results. Conventional VG-30 Bituminous Mix

Sample	% Of Bitumen	Marshall Stability (KN)	Flow Value (mm)	GB (gm/cc)
1	3.5	9.2	1.9	2.27
2	4	9.5	2.15	2.29
3	4.5	10.1	2.20	2.35
4	5	10.8	2.25	2.39
5	5.5	11.7	2.8	2.34
6	6	11	3.5	2.29
7	6.5	10.5	4.2	2.23

The Marshall Stability of the mix increases with bitumen content up to a point. It peaks at 11.7 kN at 5.5% bitumen content. The bulk density of the mix also increases with bitumen content. Then it decreases. This is because much bitumen fills the voids in the mix. The bitumen content is very important for the mix.

The flow value of the mix increases with bitumen content. The Optimum Bitumen Content is determined to be 5.4%–5.5% by weight of the mix. This is the average of the bitumen contents at stability and maximum density. The Optimum Bitumen Content value of 5.4% is used for all Crumb Rubber Modifier-modified specimens. The Crumb Rubber Modifier-modified specimens are very important, for the research.

4.4 Marshall Performance of CRM-Modified Bituminous Mixes

Table 5 presents the results of the Marshall test for mixes that have been modified with CRM. The test was done at four replacement levels: 10%, 12.5%, 15% and 17.5%. For each level three specimens were tested. The optimum binder content or OBC was fixed at 5.4%.

Table 4.4: Marshall Test Results. CRM-Modified Bituminous Mix, at Fixed OBC

CR Content (%)	Sample NO	Marshall Stability (KN)	Average Marshall Stability (KN)	Flow Value (mm)	Average Flow Value (mm)	Bulk Density (gm/cc)
10	1	13.73	18.06	3.18	2.15	2.46
	2	16.55		1.88		2.43
	3	23.90		1.41		2.39
12.5	1	10.31	10.54	4.14	4.10	2.41
	2	12.11		3.61		2.33
	3	9.21		4.56		2.39
15	1	9.93	11.26	4.21	4.14	2.40
	2	12.10		4.40		2.40
	3	11.76		3.83		2.41
17.5	1	16.269	15.45	3.05	3.58	2.41
	2	12.89		3.85		2.44
	3	17.22		3.86		2.44

4.5 Comparative Analysis. Conventional vs. CRM-Modified Mix

Table 4.5 presents a comparison of Marshall performance between the VG-30 bituminous mix at OBC and the CRM-modified mixes at all four replacement levels alongside the IS 17127:2019 minimum requirements.

Table 4.5: Comparison of Marshall Performance. Conventional vs. CRM-Modified Mix

Parameter	Conventional Bitumen	CRMB — CR Content (%)				IS 17127 : 2019 Requirement
		10%	12.5%	15%	17.5%	
Bitumen content (%)	OBC (5.4%)	OBC	OBC	OBC	OBC	-
Avg. Marshall stability (kN)	11.7	18.06	10.54	11.26	15.45	Min. 9 kN
Avg. flow value (mm)	2.8	2.15	4.10	4.14	3.58	2 – 4 mm
Avg. bulk density (gm/cc)	2.39	2.43	2.38	2.40	2.43	Higher = better

The CRM-modified mixes were compared to the mix. The CRM-modified mixes did well in general. All four CRM replacement levels were better than the Marshall Stability requirement of 9 kN under IS 17127:2019.

The 12.5% and 15% CRM mixes had Flow Values that were a little too high they were 4.10 mm and 4.14 mm, which is higher than the limit of 4.0 mm. This means that the CRM-modified mixes at these levels might be too soft.

The 10% CRM mix was very strong it had a stability of 18.06 kN but it was not very consistent the stability varied a lot it was between 13.73 kN and 23.90 kN. This means that the rubber particles were not mixed in well at this CRM-modified mix level.

The 17.5% CRM mix was very good it had a Marshall Stability of 15.45 kN, which's 32% better than the conventional mix. The average Flow Value was 3.58 mm, which's within the allowed range. The bulk density was also very high at 2.43 gm/cc. This means that the CRM-modified mix was compacted well and performed consistently. The CRM-modified mix at this level was very good the CRM-modified mix, at this level is a choice. The CRM-modified mix performed well at this level.

4.6 Discussion

The results show that using waste tyre crumb rubber to replace some of the VG-30 bitumen at the amounts makes the Marshall Stability better without affecting the flow behaviour. The stability goes up from 11.7 kN in the mix to 18.06 kN in the mix with 10% crumb rubber. This happens because the rubber particles absorb some of the parts of the bitumen, which makes the bitumen stronger like Wang and his team said and Ren and his team also found this out. The rubber particles are also elastic which means they can stretch and then go back to their shape so they help the bitumen resist deformation when it is under heavy loads.

When we add crumb rubber at 12.5% and 15% the stability goes down but then it goes back up at 17.5%. This means that something is changing in the way the crumb rubber is affecting the bitumen. When we add much crumb rubber the rubber particles can get in the way of the aggregate particles sticking together and the bitumen flowing properly which makes the stability go down.. When we add 17.5% crumb rubber the rubber particles and the bitumen start working together again and the stability goes back up. This is similar to what Badri and his team found and AlJaberi and his team also saw this happen.

The Flow Value goes up from 2.15 mm at 10% crumb rubber to 4.14 mm at 15% crumb rubber because the rubber particles make the bitumen more elastic.. Then the Flow Value goes down to 3.58 mm at 17.5% crumb rubber because the bitumen gets stiffer at this point which means it does not deform as much. The density of the bitumen is the same for all the mixes, which means they are all compacted properly. However the rubber particles can bounce back a bit when they are compacted which can affect the density measurement as Zakerzadeh and his team pointed out.

Using crumb rubber from waste tyres to replace some of the bitumen is good for the environment because it uses recycled material to make roads, which helps to reduce waste and supports development like the idea of a circular economy that some people talk about. When we use 17.5% crumb rubber we are using a lot of tyre material, which is good, for the environment and helps to make roads that are more sustainable.

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