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Investigating the suitability of used heavy, medium, and light automobile tyres for bituminous mix pavement applications

T. B. Vishnu[1] · Kh. Lakshman Singh[1] · Paul Thomas[2] · Nelson Pynadathu Rumjit[2]

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Abstract

This article studies the enhancement of bitumen properties by the addition of crumb rubber obtained from different scrap tyres. Crumb rubber extracted from scrap tyres through shedding and other traditional process has smaller size, which has the ability to enrich the various relevant characteristics of bitumen. An extensive study of different scrap tyres obtained from different automobiles (heavy, medium, and light) was conducted and also analysed its effects on bitumen properties. Different dosages of the crumb rubber added to bitumen evaluate its physical properties, Marshall stability, and indirect tensile strength to identify the optimum dosage. And retained Marshall stability test is used to assess the resistance against moisture susceptibility. The result obtained proved that modified crumb rubber bitumen is more effective and can be utilized for wide applications such as road constructions. A comparative analysis is executed between the CRMB samplings and bituminous mixes utilizing waste tyres of different automobiles and recommended the best automobile waste tyre for the purpose of bitumen modification and to acquire best outcomes.

Keywords Shredding · Marshall · Dosage · Optimum · Bitumen · Scrap · CRMB

Abbreviation

ASTM	American Society for testing and materials
TSR	Tensile strength ratio
AASHTO	American Association of state highway and transportation officials
AC	Asphalt concrete
VMA	Void in mineral aggregate
VFB	Voids filled with bitumen
CRMB	Crumb rubber-modified bitumen
ITS	Indirect tensile strength
CR	Crumb rubber

✉ Paul Thomas
thanikkalvishnu91@gmail.com

[1] Department of Civil Engineering, National Institute of Technology, Silchar, Assam 788010, India

[2] Department of Environmental and Water Resources Engineering, VIT University, Vellore, Tamil Nadu 632014, India

1 Introduction

Waste management is always an issue for Nations; it has been estimated that the automobile industry contributes 60% of total waste in the form of tyres (Van Beukering and Janssen 2001). There lies a technological gap in the proper management of scrap tyres which demands an attention. The life cycle assessment of tyre consists of five phases starting from extraction followed by production, usage, collection, and ends with waste management (Nicoletti and Notarnicola 1999). In the worldwide scenario, it is evaluated that 285 million tyres were scrapped out, and studies revealed that only half of them were disposed of properly. Various studies projected that more than 700 million tyres were disposed in every year (Greene et al. 2015). If the current trends continue, there will be an increasing trend in the growth by 2% in production per year (EEA 1995).

Traditional waste management approaches such as landfill disposal and utilization of fuel are mostly practised in the worldwide, with potentiality of reusing and recycling being least considered past. Scrap tyre constitutes 75% of rubber, and it could act as a suitable supplement in the assemblage for materials like bitumen which have voluminous applications such as road construction (Hu et al. 2014). Usage of scrap tyre considered as a sustainable approach proved to be more eco-friendly compared to other bitumen materials and flexible pavements.

Two main technologies, namely wet and dry processes, are commonly employed in the production of hot-mix asphalt. In the dry process, scrap tyre particles are added with aggregates to a hot-mix central plant and finally mixed with bitumen (Mturi et al. 2014). However, in the wet process, rubber is added with bitumen in its initial stage followed by mixing with the aggregates. The binder produced from the wet process is recognized as asphalt rubber. As per ASTM D 6114: Standard Specification for Asphalt-Rubber Binder, this mixture is a combination of scrap tyre and asphalt cement which has a broad range of applications. Several studies are being carried out in this field to improve and enhance the various properties associated within. Depending on the dosage, temperature and time, process has an influence on the chemical and physical characteristics of both rubber and bitumen.

The preliminary stage focused on the recovery or extraction of rubber from scrap tyre with the help of size reduction techniques. Some of the generally utilized techniques are wet grinding, mechanical extrusion, mechanical grinding, cryogenic grinding and hydro-jet processing. Depending on these technologies, the size and properties of the rubber particles differ, which also have an influence on the bitumen (Lo 2013). The above-mentioned wet process is a novel approach to obtain liquid rubber-modified bitumen by adding crumb rubber particles at medium temperature (180–210 °C) to enhance bitumen characteristics (Yan et al. 2015). Various enhancement properties make this modified bitumen an appropriate and suitable option for constructing road pavements.

Kebaïli et al. (2015) investigated the properties of bitumen modified with crumb rubber powder of various sizes. They showed the changes in the bitumen behaviour with the addition of 5–15% of rubber powder. And they concluded that with the increase in the addition of rubber powder content the penetration value decreases considerably. They also determined that the bitumen properties are enhanced with increase in the fineness of the crumb rubber powder. Many laboratory studies are conducted on modified bitumen performance with the addition of crumb rubber of four various particle sizes, to determine the most appropriate size for bitumen modification, and they concluded that the modification with crumb rubber enhances the physical properties of bitumen, and also they found out crumb rubber size (0.3–0.15 mm) as the best suitable size for modification (Magar 2014). The outcome of the investigation organized by Mashaan et al. (2011) stated that bituminous mixture made using crumb rubber-modified bitumen shows better rutting resistance and durability for the pavement and that proper adoption of crumb rubber in the modification provides a secured and uneven pavements with a pollution-free environment. Some other experimentation were focused on the bituminous binder properties like storage and loss modulus, viscosity, and softening point with the addition of crumb rubber to bitumen, proving that the binder properties are enhanced by this addition. Moreover, he also explained that the performance efficiency of the asphalt concrete mixture depends upon the features such as mixing duration, temperature, waste tyre source, bitumen grade (Ibrahim et al. 2013). The utilization of scrap tyre-modified bitumen in the asphalt concrete mixture raised the Marshall stability by approximately 18% for the ultimate value (Kumar et al. 2013). Zolfaghari et al. (2014) investigated the changes obtained in the coarse-graded aggregate by bitumen modification with the addition of different quantity of crumb rubber and also determined that the resistance to temperature sensitivity, resistance to impact of the asphalt concrete mixture, etc., are enhanced with the addition of crumb rubber powder. Furthermore, the cost-effectiveness of asphalt mixtures using unmodified, polymer, and asphalt rubber-modified binder on the basis of fatigue efficiency was also studies. It is mentioned that the cost-effectiveness of polymer and asphalt rubber mixture were 2.6 times and 4.1 times higher as compared to unmodified mixture. The asphalt concrete pavement of 20 cm thickness is found to be more cost-effective than the asphalt concrete pavement of 10 cm thickness for the same materials and vehicle having same speed (Souliman et al. 2015).

Regarding the above-mentioned context, the key objectives of this study are to assess the characteristics of the modified asphalt rubber bitumen and to distinguish various physical properties and to investigate its performance. To accomplish these objectives, physical strength, tensile strength, and resistance to permanent deformation characteristics tests were carried out, and the results were compared with those of normal bitumen. Various properties of bituminous mixes obtained from different automobiles were compared and evaluated to identify suitable optimizer for pavement applications.

2 Characterization of crumb rubber and bitumen modification

The initial section of this study focused on characterization of the crumb rubber and on the design methodology for bitumen modification. Afterward, the properties of modified bitumen of different automobile crumb rubber were compared to those with virgin bitumen.

2.1 Crumb rubber material and Virgin bitumen

The virgin bitumen considered in this initial study of penetration grade was 60/70 (1/10 mm) asphalt bitumen. In detail, the softening point was 45 °C, the penetration of the bitumen was 70 (1/10 mm), the specific gravity was 1.02, the ductility was 100 cm, and the elastic recovery was 50%.

Crumb rubber is a general terminology adapted for the recycled rubber tyres from different vehicles. Steel and fluff are eliminated at the time of recycling stage, leaving automobile tyre rubber in a coarse-grained texture. These rubber particles are processed further with the help of granulator or cracker mill, with the intention to decrease the rubber

Table 1 Automobile types and vehicles

Type of the automobile	Vehicles
Heavy automobiles	Bus, Truck, Lorry, etc.
Medium automobiles	Car, Jeep, Auto rickshaw, etc.
Light automobiles	Bike, Bicycle, etc.

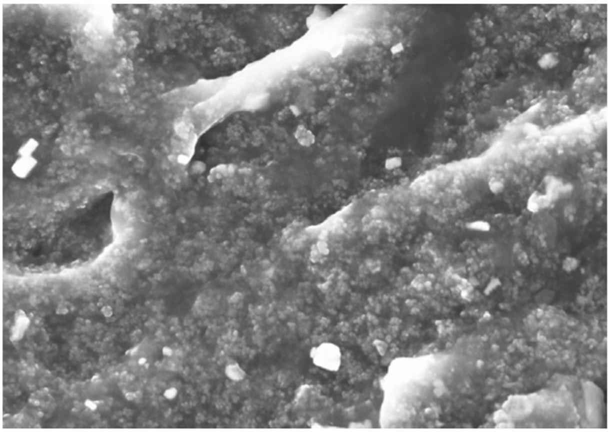


Fig. 1 Scanning electron microscopy image of crumb rubber (2 μm)

particle size by cryogenics or mechanical process (Zolfaghari et al. 2014).We have considered the weight of the vehicle as a parameter for classifying different tyres, and some vehicles and their corresponding automobile type are given in Table 1.

Figure 1 exhibits result of scanning electron microscope of crumb rubber. The image helps to distinguish the physical differences of internal structures of rubber materials. Crumb rubber material was observed to be more homogeneous particles with a smaller diameter. Crumb rubber is obtained from three various categories of automobile waste tyres of sizes 600–300 μm.

2.2 Chemical composition of crumb rubber

Crumb rubber obtained from waste tyres of different automobiles consists of various compounds like natural rubber and synthetic rubber contents, carbon black, total rubber hydrocarbons, acetone extract, ash. This heterogeneity in the chemical composition between waste tyres of heavy, medium, and light automobiles is due to the proportional dissimilarity of synthetic rubber, natural rubber, and some other components. Waste tyres of heavy automobiles consists higher natural rubber content than synthetic rubber content, and this affects the interaction among the bitumen and tyre rubber particles. The chemical composition of crumb rubber of different automobiles is determined and given in Table 2. From Table 2 it is clear that the rubber hydrocarbon content, carbon black content and ash content are higher for heavy automobile tyres and least for light automobile tyres, whereas the acetone extract is least for tyres obtained from heavy automobiles and higher for light automobile tyres.

Table 2 Chemical composition of different automobile tyres

Chemical composition	Light automobile tyre (%)	Medium automobile tyre (%)	Heavy automobile tyre (%)
Rubber hydrocarbon	43.5	45.3	47.5
Carbon black	32	32.6	33
Acetone extract	17.3	14.9	11.8
Ash	6.4	7.1	7.6

2.3 Bitumen modification

Bitumen modification was carried out for crumb rubber material using a wet process. The procedure consists of main three stages. At the initial stage, the virgin bitumen is preheated to a specified temperature of 160 °C. After reaching specified temperature, crumb rubber added manually to the virgin bitumen. Finally, the blend is mixed using mechanical stirrer at 1440 rpm for 50 min to promote homogenization and blending. Proper care and attention are maintained to keep the operating temperature between 160 °C to 170 °C, and later the modified bitumen was cooled to room temperature.

Figure 2a, b presents the homogeneity of both virgin and modified bitumen. There noticed the presence of small particles in the modified bitumen. According to the literature, most of the crumb rubber particles were dissolved during the blending process, and the remaining particles had smaller diameter (Ghavibazoo et al. 2013). As per the modification, there was a decline in rubber particle size which makes this approach more suitable for blending conditions.

2.4 Mechanism

The interaction process between bitumen and crumb rubber is not absolutely defined. Interaction between bitumen and crumb rubber is conventionally announced as not chemical in character (Heitzman 1999). The bitumen crumb rubber reaction consist of two instantaneous mechanisms: first one is a partial fusion of crumb rubber powder into bitumen, and the second mechanism is the adsorption of aromatic oils that are present in the bitumen inside the polymeric chain of rubber. The absorption of aromatic oil existing in the bitumen into the polymeric chain of rubber leads the rubber to attain swelling and softening nature (Cheovits et al. 1982).

The absorption in the oily stage at greater temperature (160–220 °C) leads to the formation of gelly material. Along with this process, there is a significant decrease in the oil atmosphere and expansion in the rubber grains sizes together with considerable decrease in the inter particle gap. Viscosity enhances because of the production of the gel composition.

Time and temperature are the two important factors affecting the reaction between bitumen and rubber powder. When the temperature is extreme and time duration is also very lengthy, the swelling will sustain until reaching a certain stage where, because of the lengthy contact with extreme temperature, swelling is substituted by depolymerization/devulcanization which leads to the dispersion of rubber particles into bitumen. Depolymerization begins to discharge rubber modules returns to the liquid state leading to the reduction in the material's stiffness property and the material's elastic nature, remain to change.

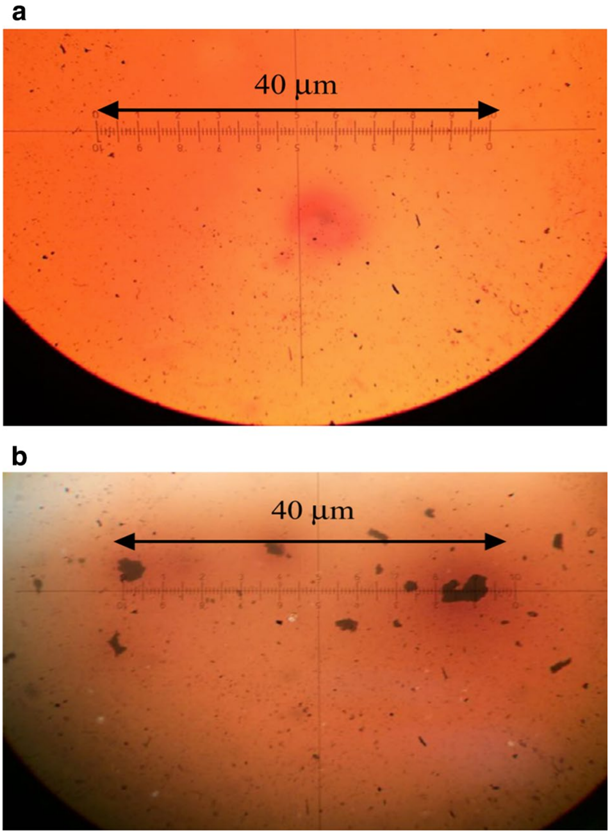


Fig. 2 **a** Microscopy image of virgin bitumen. **b** Microscopy image of crumb modified bitumen

If the temperature is extreme and time duration is lengthy, depolymerization will progress leading to excess damage of the binder interlinking and thus phase angle modification is wasted (Abdelrahman and Carpenter 1999).

2.5 Bitumen characterization

An initial comparison study on physical properties (i.e. softening, penetration, ductility, elastic recovery and specific gravity) was performed on virgin bitumen and modified bitumen of different automobiles tyres. However, different authors have chosen 5% crumb rubber as their initial percentage (Kebaïli et al. 2015; Zolfaghari et al. 2014; Parmar et al. 2014; Bilema et al. 2018). From various studies, it is observed that the optimum percentage of crumb rubber is used within a range of 9–15% of crumb rubber content (Kök and Çolak 2011; Siddharth 2012; Kebaïli et al. 2015; Kumar et al. 2013; Zolfaghari et al. 2014; Parmar et al. 2014; Bilema et al. 2018). It seems less than 5% CR is not much effective as compared to optimum. The present study is mainly focusing on the optimum percentage of crumb rubber content. Hence, 5% of crumb rubber is taken as initial percentage of modification which can enhance the properties of binder. Thus, four distinctive dosages with reference to the weight of the normal bitumen (5, 7, 9 and 11%) were preferred. Table 3 gives properties and experimental results of crumb rubber obtained from heavy vehicles (trucks,

Table 3 Physical properties of waste tyre-modified bitumen for different blend (heavy, medium and light automobile tyres)

Type of automobiles tyres	Properties						
	Blend	Crumb rubber (%)	Penetration (0.1 mm)	Softening point (°C)	Ductility (cm)	Sp. gravity	Elastic recovery (%)
	Only bitumen	0	70	45	100	1.02	50
Heavy automobile tyres	Bitumen + 5% CR	5	63	56	29	0.99	69
	Bitumen + 7% CR	7	60	58	23	0.98	72
	Bitumen + 9% CR	9	57	59	20	0.98	75
	Bitumen + 11% CR	11	54	62	19	0.97	77
Medium automobile tyres	Bitumen + 5% CR	5	64	54	29	0.98	67
	Bitumen + 7% CR	7	62	57.5	25	0.98	69
	Bitumen + 9% CR	9	59	58.75	21	0.97	72
	Bitumen + 11% CR	11	55	61	20	0.97	74
Light automobile tyres	Bitumen + 5% CR	5	65	53	30	0.98	64
	Bitumen + 7% CR	7	63	57	26	0.98	66
	Bitumen + 9% CR	9	60	58	22	0.97	70
	Bitumen + 11% CR	11	56	60	21	0.97	72

buses), medium vehicles (car, van, etc.) and light automobiles (bike, cycles etc.). For better understanding and interpreting, differences in the experimental outcomes of different scrap tyres are illustrated in Fig. 3a–d.

The experiment finding showed a decreasing trend in penetration and ductility; however, an increasing trend in softening point and elastic recovery with respect to enhancement dosages was noticed. Compared to various automobile tyres, the heavy vehicles tyres witnessed better outcomes in comparison with other categories of automobiles tyres. The decreasing trend of penetration in heavy vehicles with maximum ranges up to 23%, medium vehicles range up to 22%, and for a light vehicle, it is 20%. After all, both the penetration and softening point outcomes proved that the modified bitumen is more resistive toward temperature variations. Indeed, ductility also observed similar trends of decrease for heavy vehicles, i.e. 81%, while for medium and light vehicles, they are 80% and 79%. On the other hand, softening point noticed an increasing trend in softening point for different automobiles; heavy vehicles ranged to a maximum of 38%, medium vehicles ranged to 36%, and light vehicles to 33%. Furthermore, it was also detected a boost in the elastic recovery, in which heavy vehicles observed highest of 54%, medium vehicles 48%, and light vehicles noticed 44%.

3 Properties and performance of modified bituminous mix

Sieve analysis and mix composition of the aggregate used in this study are shown in Fig. 4 and Table 4.

3.1 Indirect tensile strength analysis

Figure 5a–f demonstrates the indirect tensile strength (ITS) and the corresponding divergences of testing specimens (60 mm height by 100 mm in diameter) for various samples, at standard room temperature of 25 °C. The outline of test composed of applying compressive load adjacent towards the direction of the cylinder axis. The test concludes when the particular sample fails as an outcome of the increase in tensile strain. The indirect tensile strength (ITS) of the material is characterized by calculating maximum tensile stress at peak load to the sample at failure.

The results proved that tensile strength of modified bitumen were superior compared with normal bitumen. It is seen that tensile strength both conditioned and unconditioned of asphalt concrete (AC) mix with crumb rubber additive shows increasing up to 9% and then it decreases at 11% crumb rubber content. And it is observed that the indirect tensile strength (ITS) of the mix is increasing in the order of light automobiles tyre, medium tyre, and heavy tyre, respectively. The sample prepared by using heavy automobile tyre-modified bitumen gives more indirect tensile strength (ITS) than sample prepared with a medium automobile tyre and light automobile tyre in both conditioned and unconditioned cases. The sample prepared by using heavy automobile tyre-modified bitumen increases indirect tensile strength (ITS) by 10, 17, and 36% compared with a sample prepared with a medium automobile modified mix and a conventional bituminous mix of the unconditioned case. The sample prepared by using heavy automobile tyre-modified bitumen increases indirect tensile strength (ITS) by 16% and 23% compared with a sample prepared with the medium tyre and tyre-modified mix of the conditioned case.

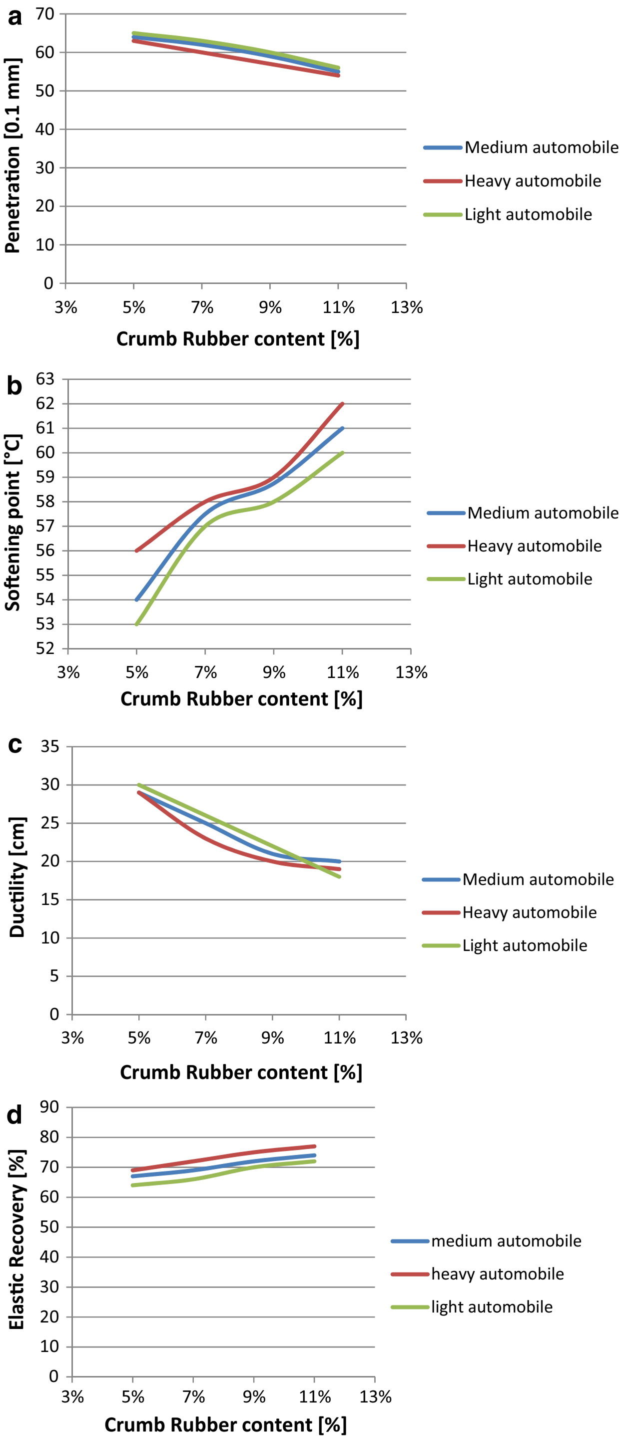


Fig. 3 **a** Effect of CR content on penetration of CRMB. **b** Effect of CR content on softening point of CRMB. **c** Effect of CR content on ductility of CRMB. **d** Effect of CR content on elastic recovery of CRMB

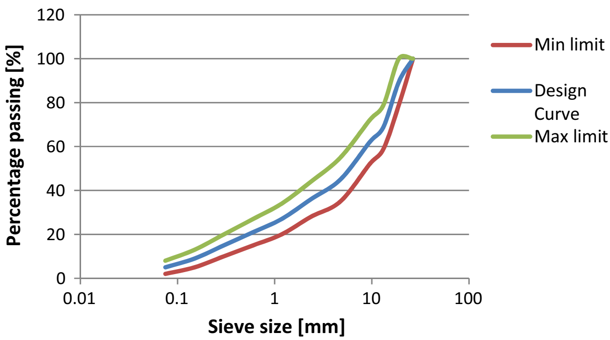


Fig. 4 Gradation Curve of aggregate

Table 4 Composition of asphalt concrete mix (MORTH gradation)

Nominal aggregate size	19 mm	19 mm
Layer thickness	50–65 mm	50–65 mm
Sieve size (mm)	Percentage passing by weight	Percentage passing by weight
26.5	100	100
19	89.5	79–100
13.2	69	59–79
9.5	62	52–72
4.75	45	35–55
2.36	36	28–44
1.18	27	20–34
0.6	21	15–27
0.3	15	10–20
0.15	9	5–13
0.075	5	2–8
Bitumen content,% by weight of total mix	5.0–6.5	5.0–6.0
Bitumen grade	VG 30	VG 30

3.2 Variation of indirect tensile strength ratio of asphalt concrete (AC) mix

The indirect tensile strength (ITS) ratio is used to evaluate the moisture susceptibility of an asphalt mixture. A higher indirect tensile strength ratio values typically indicate that the mixture will perform well with a good resistance to moisture damage. From Table 5, it was observed that the tensile strength ratio (TSR) value of the conventional bituminous mixture is nearly 58.51% which is less than 70% a minimum TSR (tensile strength ratio) value set forth by AASHTO T 283. The tensile strength ratio (TSR) for the mixes containing the additives is greater than the specification limits. From these results, it can be concluded that the presence of additives significantly reduces the moisture-induced damage of the asphalt concrete (AC) mixture.

The results indicate that the tensile strength ratio (TSR) which represents the moisture susceptibility increased up to a certain percentage of additives and, after that, it found to be decreasing. In heavy automobile tyre-stabilized mixture, the tensile strength ratio (TSR) value is high compared to other type tyre-stabilized mixture. From Table 5 it is evident that the crumb rubber-stabilized AC mixture with medium automobile tyre gives slightly higher tensile strength ratio (TSR) than the normal AC mixture with crumb rubber of light automobile tyre. From Table 5 it is clear that all stabilized mixture gives higher tensile strength ratio (TSR) than normal AC mixture indicating its less water-induced damage. Also AC stabilized with crumb rubber of bus tyre gives a slightly higher tensile strength ratio (TSR) compared to AC mixture with other type of tyres as shown in Fig. 6.

3.3 Marshall stability analysis

The Marshall stability is a measure of strength of bituminous mix. The Marshall stability test method is very simple and rapid method for designing bituminous mixes scientifically. The stability values obtained in this test procedure indirectly represent the strength of a paving mix at a zero vertical stress level which is critical. Marshall sample for various tests is presented in Fig. 7. The variation of Marshall properties with different binder contents and with different waste rubber tyre modifiers is given in Tables 6, 7 and 8.

3.3.1 Unit weight

The unit weight increases as the additive content increases, reaches a maximum value and then declines. With the addition of crumb rubber, unit weight increases up to a certain limit and further addition of crumb rubber unit weight starts decreasing as shown in Fig. 8. It is observed that unit weight of the mix increases in the order of light automobile tyre, medium tyre, and heavy automobile tyre, respectively, and samples prepared from heavy automobile tyre give more unit weight and increases by 1.01 and 1.009 times compared of sample prepared by medium tyre and light automobile tyre, respectively. Samples prepared by heavy automobiles tyre give more unit weight, and it increases by 1.004 times compared with the normal bitumen mix.

3.3.2 Air voids

Air voids are small airspaces or pockets of air that occur between the coated aggregate particles in the final compacted mix. A certain percentage of air voids is necessary in all dense-graded highway mixes to allow for some additional pavement compaction under traffic and to provide spaces into which small amounts of asphalt can flow during this subsequent compaction. The air void percentage decreases with increase in the binder content. It is noticed that air void of the mixes increase with increase in CR content in the binder and, with further addition of crumb rubber, air void starts decreasing. The air voids of sample prepared with bus tyre-stabilized mixture has increased by 1.06 times as compared to conventional bituminous mix. The air void of sample prepared with heavy automobile tyre-stabilized mixture has increased by 1.02 and 1.42 times as compared to medium tyre- and light automobile tyre-stabilized mixture.

3.3.3 Void in mineral aggregate (VMA)

Voids in mineral aggregate (VMA) are the void spaces between the aggregate particles of the compacted mix. This void space includes the air voids and the effective asphalt content.

Fig. 5 **a** Effect of CR content on ITS without soaking (heavy automobile tyre). **b** Effect of CR content on ITS with soaking (heavy automobile tyre). **c** Effect of CR content on ITS without soaking (medium automobile tyre). **d** Effect of CR content on ITS with soaking (medium automobile tyre). **e** Effect of CR content on ITS without soaking (light automobile tyre). **f** Effect of CR content on ITS with soaking (light automobile tyre) ▶

It is observed that first void in mineral aggregate (VMA) is decreases and then increases. VMA represents the space that is available to accommodate the asphalt and the volume of air voids necessary in the mixture. The more VMA in the dry aggregate, the more space is available for the film of asphalt. The variation of VMA with different binder content with different waste tyre is shown in Fig. 9. The voids in mineral aggregate (VMA) of AC mix with heavy tyre is decreased by 1% and 1.04% with AC mixes with medium and light automobile tyre, respectively.

3.3.4 Voids filled with bitumen (VFB)

Voids filled with bitumen (VFB) value first increases at sharp rate. Variation of VFB with different binder content and with different waste tyres is given in Fig. 10. It is observed that VFB decreases with the addition of crumb rubber and, with further addition of crumb rubber, VFB starts increasing. The sample prepared by using heavy automobile tyre gives less VFB value and is decreased by 1%, 1.08%, 1.13% as compared with medium, light automobile tyre, and conventional bituminous mix, respectively.

3.3.5 Stability

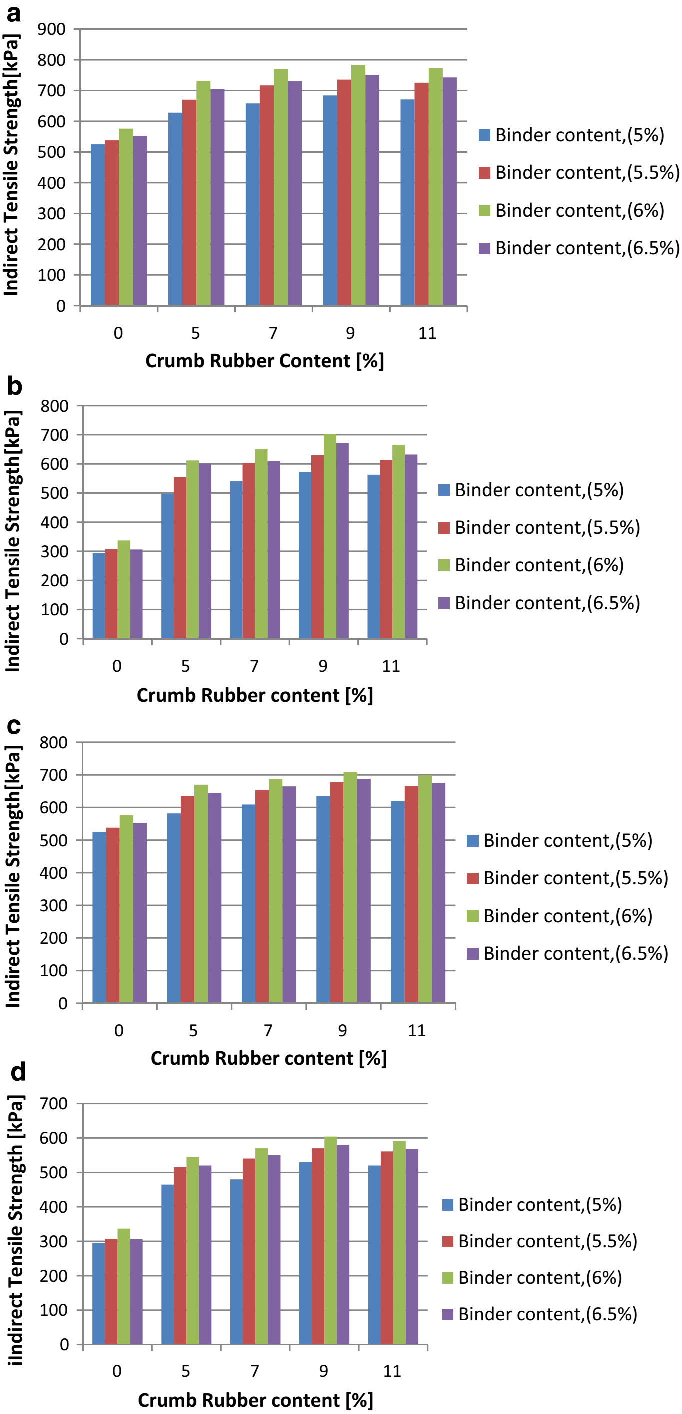
With increase in binder content, stability value increases up to a certain binder content and, thereafter, it decreases. Similarly, with the addition, CR stability value also increases up to a certain limit and with further addition it starts decreasing. In the test, the stability value of the mix is increasing in the order light , medium and heavy automobile tyre-modified bitumen, respectively. The sample prepared by using heavy automobile tyre gives the highest stability value and increased by 69% compared with the conventional bituminous mix. The sample prepared by using heavy tyre increases stability value by 1.4% and 1.5% compared with the sample prepared with medium and light automobile tyre, respectively, as shown in Fig. 11.

3.3.6 Flow value

The variation of flow value for mixes with different waste tyres and different binder content is presented in Fig. 12. Addition of crumb rubber flow value decreases and then, again with further addition of crumb rubber, flow value increases. The flow value of heavy automobile tyre-stabilized mixtures has decreased by 16% compared to conventional bituminous mix. The flow value of the heavy tyre-stabilized mixture has decreased by 3.2% and 6% as compared with medium and light automobile tyre-stabilized mixtures, respectively.

3.4 Retained Marshall stability analysis

The retained Marshall stability of a mix is checked to get an idea of water susceptibility of the bituminous mix. Retained Marshall stability for mixes with the different blend is measured,


a
Indirect Tensile Strength[kPa]
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Crumb Rubber Content [%]
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Binder content,(6.5%)
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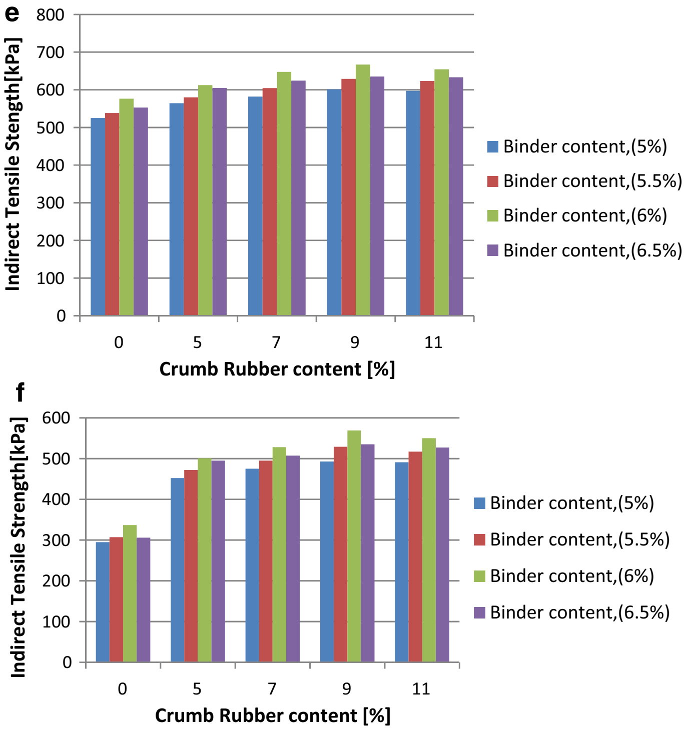

Fig. 5 (continued)

after immersing them in a water bath for 24 h at 60 °C. The retained Marshall stability is thus given detailed in Table 9. Retained Marshall stability increases with increase in binder content up to a certain binder content then, with further increase in binder content, retained Marshall stability decreases. The retained Marshall stability of bus tyre-stabilized mixture has increased by 19% compared to the conventional bituminous mix as shown in Fig. 13a–c. The sample prepared by using medium automobile tyre observed to be more stable compared to a light automobile tyre. It is observed that the sample prepared with heavy automobile tyre gives maximum retained stability value among other type of tyres by using 9% of tyre powder with the bituminous mix. The retained Marshall stability is increased by 2%, 4% and 19% compared to bituminous mixes with medium automobile tyre, light automobile tyre, and conventional bituminous mix, respectively. Hence the low water susceptibility occurs in bituminous mixes when heavy automobile tyre is used. Therefore, the mixes with modified blends have very low water susceptibility in comparison with the conventional bituminous mix as clearly indicated by retained Marshall stability value.

4 Conclusions

The experimental investigation proved that the addition of crumb rubber to the bitumen enhanced basic properties like softening point, penetration and elastic recovery. Finally, it is essential to highlight observations:

Table 5 Indirect tensile strength of AC mix with CRMB using (heavy, medium, light automobile) tyres

Type of automobile		Heavy automobile tyres			Medium automobile tyres			Light automobile tyres		
Blend	Binder content (%)	ITS, unconditioned (kPa)	ITS conditioned (kPa)	Percentage TSR (%)	ITS, unconditioned (kPa)	ITS conditioned (kPa)	Percentage TSR (%)	ITS, unconditioned (kPa)	ITS conditioned (kPa)	Percentage TSR (%)
Only bitumen	5	525	295	56.19	525	295	56.19	525	295	56.19
	5.50	538.2	307	57.04	538.2	307	57.04	538.2	307	57.04
	6.00	576	337	58.51	576	337	58.51	576	337	58.51
	6.50	552.7	306	55.36	552.7	306	55.36	552.7	306	55.36
Bitumen + 5% CR	5.00	628	498	79.30	582	465	79.90	564.4	452	80.09
	5.50	670	555	82.84	635	515	81.10	580	472	81.38
	6.00	730	612	83.84	670	545	81.34	612.4	501	81.81
	6.50	705.1	601	85.24	645.2	520	80.60	604.5	495	81.86
Bitumen + 7% CR	5.00	658	540	82.07	609	480	78.82	582	475	81.62
	5.50	717	603	84.10	653	540	82.70	604.5	495	81.89
	6.00	770	650	84.42	687	570	82.97	647.6	528	81.53
	6.50	730.7	610	83.48	664.4	550	82.73	624.4	507	81.20
Bitumen + 9% CR	5.00	684	572	83.63	634.4	530	83.54	601.3	493	81.99
	5.50	735.4	630	85.67	677.8	570	84.10	628.9	529	84.12
	6.00	783.53	702	89.59	708.9	604	85.20	667	569	85.31
	6.50	750.6	672	89.53	687.5	580	84.36	635	535	84.31
Bitumen + 11% CR	5.00	670.9	563	83.92	619.4	520	83.95	597	491	82.24
	5.50	725.5	613	84.49	665.2	561	84.34	623	517	82.99
	6.00	772	665	86.14	698.5	591	84.61	654.4	550	84.05
	6.50	742.3	632	85.14	674.9	568	84.16	633.1	527	83.24

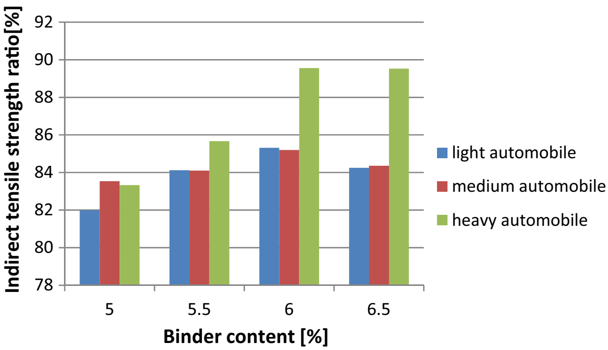

Fig. 6 Comparison of Indirect tensile strength ratio of AC mixes by using different automobile tyres

Fig. 7 Marshall specimen sampling for testing

- The penetration values decreases in regard to the addition of crumb rubber. The heavy automobile tyre-modified bitumen samples proved to be higher effective in reducing the penetration value compared to other samples. Similarly, the softening point and elastic recovery of CRMB noticed increasing corresponding to the addition of crumb rubber. In both these cases, heavy automobile tyre-modified samples demonstrated to be a more suitable option.
- With increase in percentage of crumb rubber content, stability value surges up to 9% and thereafter it starts decreasing. The surging value rises up to 9% only, and the sample prepared using crumb rubber of heavy automobile tyre gives the higher stability value of the 20.57 kN maximum unit weight, maximum air voids, flow values among the other tyres. The stability is increased by 1.69 times when compared to conventional bituminous mixes. Hence the most suitable option for modification of bitumen can be suggested as heavy automobile tyre from the current study. The retained Marshall stability values also follow a similar trend of upsurge compared to conventional bituminous mixes. Retained stability increased by 15.9% as compared to conventional bituminous mix. The sample prepared by crumb rubber using heavy automobile tyre samples has the highest retained Marshall stability value when compared to crumb rubber of other tyres.

Table 6 Marshall parameter of AC mix with CRMB using heavy automobiles tyre

Blend	Binder content (%)	Unit weight (g/cm^3)	Air voids (%)	VMA (%)	VFB (%)	Marshall stability (kN)	Flow (mm)
Only bitumen	5	2.27	5.6	16.33	65.7	10.51	3
	5.50	2.28	5	16	72.97	11.60	3.3
	6.00	2.29	4.7	15.8	74.97	12.14	3.6
	6.50	2.28	4	17.7	77.4	11.42	4
Bitumen + 5% CR	5.00	2.28	5.5	16.85	66.5	15.98	2.7
	5.50	2.29	5.2	16.68	67.5	17.17	3.1
	6.00	2.3	4.3	16.5	69.4	18.04	3.4
	6.50	2.28	3.5	17	69.6	15.70	3.7
Bitumen + 7% CR	5.00	2.28	5.7	16.85	65.4	17.35	2.6
	5.50	2.31	5.4	16.54	66.4	17.81	3
	6.00	2.32	4.7	16.45	67.5	18.14	3.3
	6.50	2.29	3.5	16.8	68	17.15	3.6
Bitumen + 9% CR	5.00	2.28	5.8	16.55	64.5	18.33	2.4
	5.50	2.29	5.6	16.44	65	18.53	2.8
	6.00	2.33	5	16.3	66.5	20.57	3.1
	6.50	2.29	3.9	16.7	67	16.08	3.4
Bitumen + 11% CR	5.00	2.27	5.8	16.65	65	17.77	2.6
	5.50	2.28	5.5	16.53	66.5	17.88	2.8
	6.00	2.29	4.6	16.35	67	18.22	3.4
	6.50	2.27	3.5	16.7	67.5	13.87	3.5

- The AC mixtures stabilized with crumb rubber of heavy automobile tyre give maximum indirect tensile strength (ITS) value. The ITS value was stepped up to 26.5% and 52% with respect to the bituminous mixture for both unconditioned and conditioned, respectively. From these observations AC mixes, it could be concluded that crumb rubber of heavy automobile tyre indicates a more cracking resistance as competing with other automobile tyres. All stabilized mixes satisfy the minimum required tensile strength ratio of 70% exhibiting their better moisture resistance than the conventional bituminous mixes. The crumb rubber of heavy automobile stabilized specimen has a slightly higher tensile strength ratio (TSR) than other stabilized mixtures. The AC mixture with crumb rubber of heavy automobile indicates higher resistance to moisture damage.
- The optimum mix for heavy, medium and light automobile modified mixes is at 9% crumb rubber content and at 6% binder content by considering various parameters like stability, unit weight.
- For optimum mix, the quantity of crumb rubber that can be used in 1-km single-lane road is 4.72 tons (3.75 m width, 100 mm thick).
- From an environmental and economic standpoint, the use of crumb rubber of waste tyres ground at ambient temperatures as a bitumen-modifying agent may contrib-

Table 7 Marshall parameter of AC mix with CRMB using medium automobiles tyre

Blend	Binder content (%)	Unit weight (g/cm^3)	Air voids (%)	VMA (%)	VFB (%)	Marshall stability (kN)	Flow (mm)
Only bitumen	5	2.27	5.6	16.33	65.7	10.51	3
	5.50	2.28	5	16	72.97	11.60	3.3
	6.00	2.29	4.7	15.8	74.97	12.14	3.6
	6.50	2.28	4	17.7	77.4	11.42	4
Bitumen + 5% CR	5.00	2.2	5.4	17	66	14.76	2.8
	5.50	2.22	5.3	16.7	67.5	16.18	3.1
	6.00	2.25	4.2	16.5	69.3	16.96	3.5
	6.50	2.24	3.5	17.2	69.7	15.29	3.8
Bitumen + 7% CR	5.00	2.2	5.8	16.9	65.7	16.37	2.7
	5.50	2.25	5.3	16.7	66.4	17.45	3.1
	6.00	2.26	4.8	16.5	67.6	17.63	3.4
	6.50	2.24	3.6	16.9	68	17.15	3.7
Bitumen + 9% CR	5.00	2.22	5.9	16.7	64	18.13	2.6
	5.50	2.26	5.6	16.5	65.5	18.33	2.9
	6.00	2.27	4.9	16.4	66.3	20.30	3.2
	6.50	2.26	3.7	16.8	67.5	15.69	3.5
Bitumen + 11% CR	5.00	2.19	5.8	16.7	65.2	17.05	2.6
	5.50	2.25	5.4	16.5	66.3	17.27	3.1
	6.00	2.26	4.8	16.4	67.4	17.66	3.3
	6.50	2.25	3.7	16.8	67.9	12.91	3.6

ute to solving a waste disposal problem and to improving the quality of road pavements.

5 Future scope

The bitumen modified with crumb rubber of heavy automobile tyre is more effective among crumb rubber of other automobile tyres. Thus further study/modification can be conducted using crumb rubber of many other vehicle tyres separately and along with certain polymers.

Many properties of AC mix such as Marshall properties, retained Marshall stability characteristics tensile strength have been examined in the current study. Only 60/70 penetration grade bitumen and a modified crumb rubber of different tyres have been used in this study. Finally, it is essential to highlight that it is suitable for infrastructure and road projects. It is crucial to complement this study using some other grade bitumen with rheological analysis and modification dosages and with an extended life cycle analysis.

Table 8 Marshall parameter of AC mix with CRMB using light automobiles tyre

Blend	Binder content (%)	Unit weight (g/cm^3)	Air voids (%)	VMA (%)	VFB (%)	Marshall stability (kN)	Flow (mm)
Only bitumen	5	2.27	5.6	16.33	65.7	10.51	3
	5.50	2.28	5	16	72.97	11.60	3.3
	6.00	2.29	4.7	15.8	74.97	12.14	3.6
	6.50	2.28	4	17.7	77.4	11.42	4
Bitumen + 5% CR	5.00	2.2	6.1	17.07	65	14.55	2.7
	5.50	2.24	4.3	16.49	73.93	16.07	3.2
	6.00	2.25	4	16	75	16.66	3.6
	6.50	2.24	3.4	17.59	80	14.25	3.8
Bitumen + 7% CR	5.00	2.21	6	16.72	64.2	15.89	2.7
	5.50	2.24	4	16.3	75.4	17.02	3.2
	6.00	2.27	3.1	16.2	81	16.89	3.5
	6.50	2.26	3	17.2	82.5	15.25	3.7
Bitumen + 9% CR	5.00	2.22	6.02	17.36	65.72	17.84	2.5
	5.50	2.25	5	17	70.5	18.07	2.8
	6.00	2.28	3.5	16.9	72.13	20.27	3.3
	6.50	2.27	3.3	17.73	81	15.49	3.5
Bitumen + 11% CR	5.00	2.2	6.5	17.65	64	16.79	2.7
	5.50	2.24	5.3	17.6	70	16.90	3.1
	6.00	2.27	4.2	17.4	75.8	17.60	3.5
	6.50	2.26	4	18.3	78.1	12.66	3.6

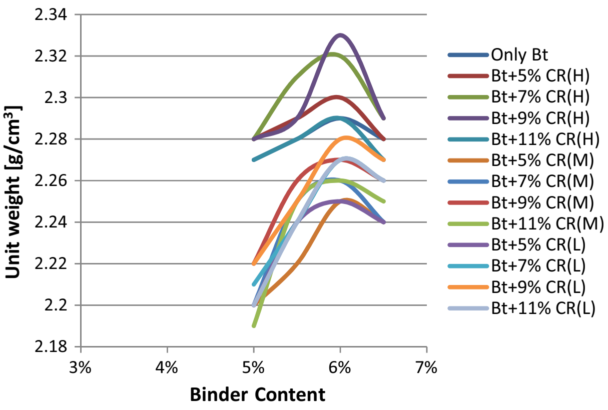

Fig. 8 Variation of unit weight with different binder content [heavy (H), medium (M), light (L) automobile tyre]

Fig. 9 Variation of VMA% with different binder content [heavy (H), medium (M), light (L) automobile tyre]

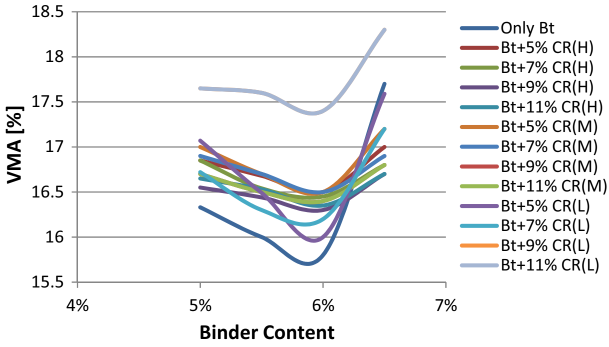

Fig. 10 Variation of VFB% with different binder content [heavy (H), medium (M), light (L) automobile tyre]

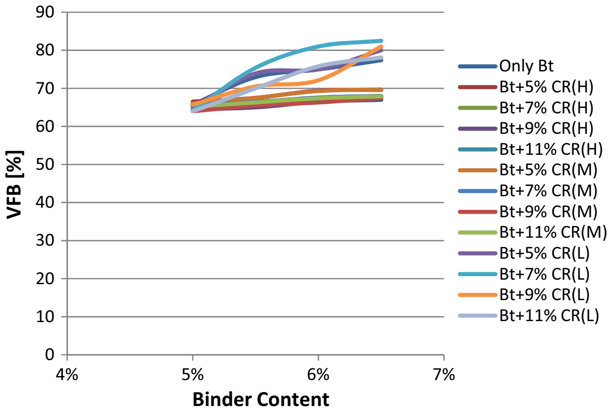

Fig. 11 Variation of stability with different binder content [heavy (H), medium (M), light (L) automobile tyre]

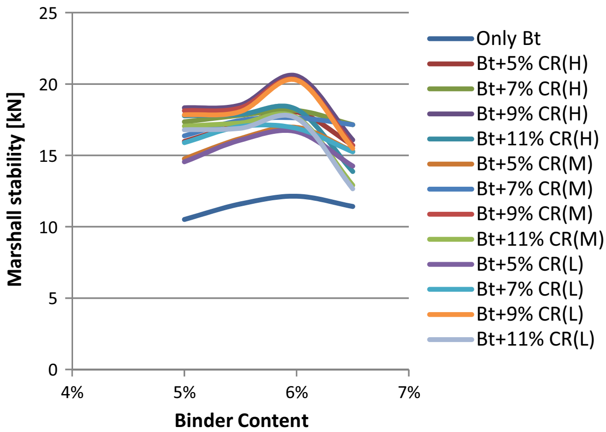

Fig. 12 Variation of flow with different binder content (heavy (H), medium (M), light (L) automobile tyre)

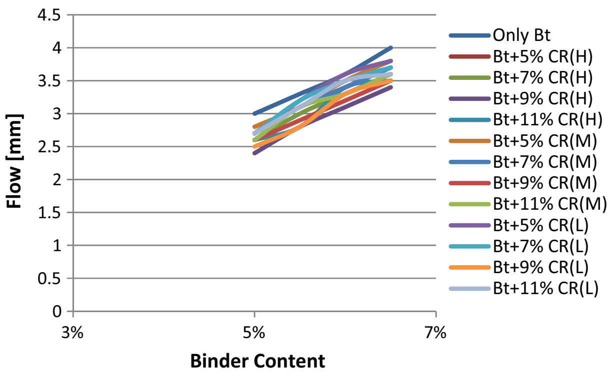

Table 9 Retained Marshall stability of AC mix with CRMB using (heavy, medium, light automobiles) tyres after 24 h

Type of automobile		Heavy automobile tyres	Medium automobile tyres	Light automobile tyres
Blend	Binder content (%)	Retained Marshall stability after 24 h (%)	Retained Marshall stability after 24 h (%)	Retained Marshall stability after 24 h (%)
Only bitumen	5	67	67	67
	5.50	70	70	70
	6.00	74	74	74
	6.50	73	73	73
Bitumen + 5% CR	5.00	78	78	75
	5.50	82	81	78
	6.00	86	84	82
	6.50	77	77	75
Bitumen + 7% CR	5.00	82	79	79
	5.50	83	82	80
	6.00	86	85	83
	6.50	81	79	78
Bitumen + 9% CR	5.00	85	82	82
	5.50	86	84	84
	6.00	88	87	85
	6.50	84	81	80
Bitumen + 11% CR	5.00	80	78	76
	5.50	83	82	83
	6.00	86	84	84
	6.50	83	77	77

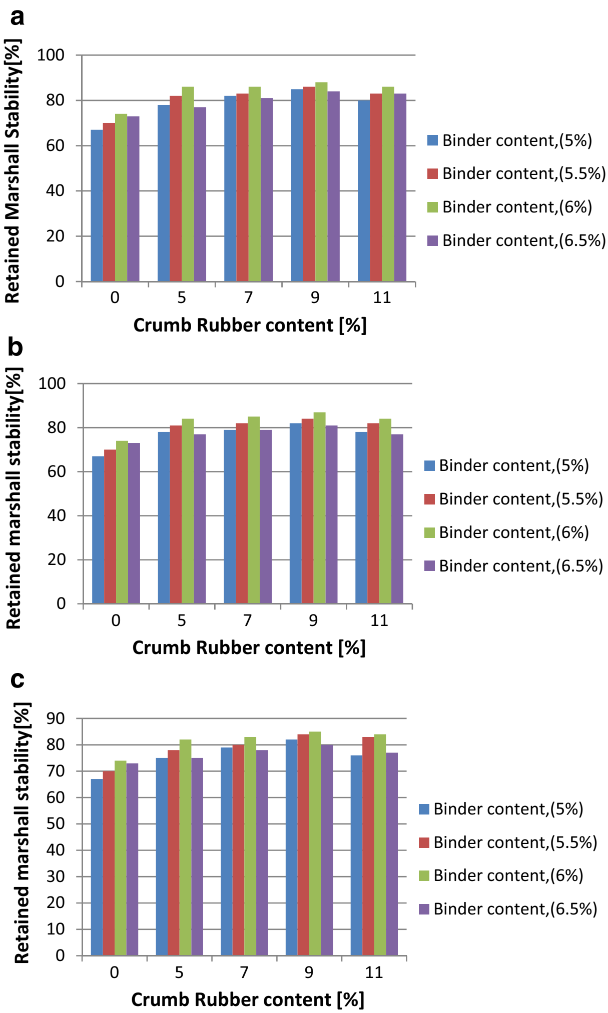

Fig. 13 **a** Retained Marshall stability values using different blends of (heavy automobiles tyre) crumb rubber. **b** Retained Marshall stability values using different blends of (medium automobiles tyre) crumb rubber. c Retained Marshall stability values using different blends of (light automobiles tyre) crumb rubber

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