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Rheological properties of crumb rubber modified bitumen-A lab study

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In this paper, bitumen is modified with crumb rubber (CR). Changes in rheological properties of 60/70 and 80/100 grades bitumen modified with CR have been studied for rheological properties using Dynamic Shear Rheometer (SR5 Ashphalt Rheometer). CR improves complex modulus and elastic response of bitumen at high temperatures.

Keywords: Bitumen, Crumb rubber, Rheological properties

Introduction

Significant variations in daily and seasonal temperature of pavement induce early development of distress conditions (raveling, undulation, rutting, cracking, bleeding, shoving and potholing) of bituminous pavement. Another major concern for distress of road surface is overloading of commercial vehicles and increase in traffic density. Rheological properties of bitumen needs to be enhanced with use of chemical additives and modifiers in order to provide more durability to pavements under extreme climatic conditions and increased traffic density[1-3].

In present study, crumb rubber (CR) was used as a modifier to bituminous materials, dynamic mechanical analysis (DMA) was applied to characterize CR modified bitumen (CRMB), and rheological properties (complex modulus, resistance to deformation, storage modulus, binder elasticity, loss modulus, viscous behaviour with phase angle and visco-elastic) have been studied.

Experimental

Materials

Two grades of bitumen (60/70 and 80/100) were supplied by Mathura Refinery. CR was obtained from crushing of discarded truck tyres supplied by local market. Material passing through 1.18 mm IS sieve and retained on 200 μ IS sieve was used.

Dynamic Shear Rheometer (DSR)

SR 5 Asphalt Rheometer was used for measuring dynamic rheological properties. Test was conducted as per guidelines in AASTHO TP5-1994, and a sinusoidal shear stress [frequency, 10 rad/s (1.6 hz)] was applied to a sample of bitumen sandwiched between two parallel plates (25 mm). Resulting sinusoidal shear stress was monitored as a function of temperature and frequency. Based on stress and stain measurements, stiffness and viscosity can be obtained at different temperatures, frequencies and strain levels for bitumen samples. Measurements were taken between 46-82°C with an increment of 6°C. All binders were tested (frequency, 10 rad/s) to determine performance of binder formulations.

Under DSR operation, bitumen is sandwiched between two parallel plates; one of which is fixed and another is oscillating type. Bituminous binders are viscoelastic and response of bitumen to stress depends on loading rate and temperature. Between stress and induced strain, no time gap is applied in short duration of load applied to loading material, whereas long time gap is applied in case of viscous material. Therefore, perfectly elastic material exhibits a phase angle (δ) equal to zero, while a viscous material exhibits an angle of 90°. Asphalt tends to be elastic (δ= 0) at cold temperatures and viscous (δ = 90°) at very high temperatures.

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Results and Discussion

Physical Properties of Crumb Rubber Modified Bitumen (CRMB)

Physical properties of bitumen (Table 1) and that of CRMB were determined (Table 2). Ageing changes physical properties of binders. Penetration and softening point values before and after short-term ageing were also determined (Table 3).

Table 1-Physical properties of bitumen

Properties	60/70 grade	80/100 grade	Permissible limits
Penetration at 25°C, 100g, 5s, dmm	63	94	80-100
Softening Point, °C	49.5	47	35-50
Ductility at 27°C, cm	100+	100+	75 (min.)
Specific gravity at 27°C, gm/cc	1.01	1.02	0.99 (min)
Flash Point, °C	285	310	175 (min)

Table 2—Physical properties of crumb rubber modified bitumen

Binder type	Modifier content, %	Penetration at 25°C, dmm	Softening point, °C	Elastic recovery at 15°C, %	CRMB grade as per IS 15462:2004
80/100	-	94	47	16	-
CR	3	67	48	47	50
	5	58	52	57	50
	7	55	53	60	50
	9	54	54	71	50
60/70	-	63	49.5	21	-
CR	3	57	54.25	57.5	50
	5	55	55	62	55
	7	54	57	64.5	55
	9	51	59.75	77	55

Table 3—Changes in penetration and softening point values after ageing

Binder	Penetration value		Softening Point value	
	Before ageing dmm	After ageing dmm	Before ageing °C	After ageing °C
80/100 bitumen	94	82	47	48.5
80/100 + 3%CR	67	47	48	52
80/100 + 5%CR	58	45	52	55
80/100 + 7%CR	55	44	53	55.5
80/100 + 9%CR	54	43	54	56
60/70 bitumen	63	58	49.5	51
60/70 + 3%CR	57	40	54.3	56.5
60/70 + 5%CR	55	36	55	58
60/70 + 7%CR	54	34	57	58.5
60/70 + 9%CR	51	33	59.8	61

Penetration Index

Penetration index (PI) is given as

$$\text{P.I.} = \frac{20 - 500\,A}{1 + 50\,A} \qquad \ldots(1)$$

where, $A = \dfrac{\log 800 - \log \text{pen}\,(25^{o}\text{C})}{\text{Temp}_{(R\,\&\,B)} - 25^{o}\text{C}}$. A and PI can be derived at two temperatures.

Bitumen normally used for road construction has a PI between +1 and -1. Bitumen (PI, < -2) is substantially Newtonian and usually characterized by brittleness at low temperatures. Coal tar pitches also fall within this group. Bitumen (PI, > +2) is usually less brittle. Blown bitumen usually fall within this group. PI at different percentage modifier for 60/70 and 80/100 grades of bitumen (Table 4) indicate that with increase in percentage of modifier, PI also increased. PI of CR binder and that of different percentage of CR is found < +2.

Rheological Properties of Modified Binders

Complex modulus (G*) and phase angle (δ) define resistance to deformation of binder in viscoelastic region. Shear modulus (G*/ sin δ) is an indicator of binder stiffness to deformation under load at specified temperature. G* is determined at 10 rad/s and at 58°C and 70°C respectively for polymer modified bitumen 60/70 and 80/100 grades. With increase in temperature, G* decreases but δ increases (Table 5). Neat bitumen has lost elasticity at 70°C as δ is > 90°. However, modified binders still display considerable elasticity at 70°C.

Relationship between Shear Modulus and Test Temperature

Superpave Performance Grade (PG) bitumen is based on climate. Performance based SHRP specifications have suggested different grades of bituminous binders on the basis of shear modulus. Temperature at which this parameter attains a value of 1.0 kPa before ageing of binder and 2.2 kPa after ageing (short term) is termed as PG of binder. Bitumen (80/100), modified with optimum CR (5%), meet PG 64 requirements.

Relationship between Complex Modulus and Phase Angle with Temperature

Modified binders has higher G* than neat bitumen. With increase in temperature, δ increases but decreases with increase in modifier contents (%). For modified binder, δ is lower than that of neat bitumen, indicating higher elastic behaviour of binder.

Table 4—Penetration Index values at different percentage of modifier

Modifier (CR) %	60/70	80/100
0	-0.76	-0.36
3	0.063	-1.038
5	0.159	-0.115
7	0.65	-0.248
9	1.003	-0.061

Table 5—Rheological properties of CRMB

Bituminous binder	Temperature °C	Complex modulus (G*) kPa	Shear modulus (G*/sin´) kPa	Loss modulus (G* sin´) kPa	Phase angle (δ), °
60/70 Bitumen	58	3.78	3.79	3.77	86.2
	70	0.80	0.81	0.80	93.2
60/70 + 3%CR	58	5.21	5.29	5.13	79.9
	70	1.33	1.34	1.31	81.8
60/70 + 5%CR	58	6.01	6.17	5.86	77.1
	70	1.56	1.58	1.54	80.0
60/70 + 7%CR	58	6.31	6.47	6.15	77.2
	70	1.53	1.55	1.52	82.1
60/70 + 9%CR	58	9.21	9.97	8.51	67.5
	70	2.93	3.14	2.74	68.9
80/100 Bitumen	58	1.91	1.92	1.91	89.8
	70	0.47	0.47	0.46	98.2
80/100 + 3%CR	58	3.14	3.17	3.12	82.9
	70	0.753	0.753	0.753	89.7
80/100+ 5%CR	58	3.48	3.51	3.44	82.1
	70	0.881	0.882	0.881	88.2
80/100 + 7%CR	58	4.51	4.63	4.4	77.1
	70	1.17	1.19	1.16	80.2
80/100 + 9%CR	58	6.47	6.86	6.11	70.7
	70	1.86	1.93	1.79	74.5

Table 6—Changes in rheological properties of CRMB modification at different temperatures and 10 rad/s

Binder	G*CRMB/G* bitumen		G'CRMB/G' bitumen		G"CRMB/G" bitumen	
	46°C	58°C	46°C	58°C	46°C	58°C
60/70 Bitumen	1.0	1.0	1.0	1.0	1.0	1.0
60/70+3%CR	1.2	1.4	1.7	3.6	1.2	1.3
60/70+5%CR	1.3	1.6	2.4	5.3	1.3	1.5
60/80+7%CR	1.4	1.7	2.5	5.5	1.3	1.6
60/70+9%CR	1.5	2.4	4.1	14.0	3.6	1.9
80/100 Bitumen	1.0	1.0	1.0	1.0	1.0	1.0
80/100+3%CR	1.7	1.6	1.6	1.6	4.0	58.2
80/100+5%CR	1.9	1.8	1.8	1.8	4.6	71.8
80/100+7%CR	2.0	2.3	1.9	2.3	6.3	151.2
80/100+9%CR	2.6	3.4	2.4	3.2	11.9	321.1

Table 7 —Temperature susceptibility of modified binder with CR at 1 and 10 rad/s

Binder	GTS* at 1 rad/s	VTS* at 1 rad/s	GTS* at 10 rad/s	VTS* at 10 rad/s
60/70 Bitumen	7.30	7.30	5.46	7.63
60/70+3%CR	6.98	6.98	4.76	6.54
60/70+5%CR	6.15	6.15	4.59	6.27
60/70+7%CR	6.56	6.56	4.64	6.34
60/70+9%CR	5.07	5.07	3.73	5.0
80/100 Bitumen	8.86	8.86	5.53	8.0
80/100+3%CR	5.50	5.50	5.29	7.46
80/100+5%CR	7.14	7.14	5.13	7.18
80/100+7%CR	7.19	7.19	4.65	6.44
80/100+9%CR	5.14	5.14	4.14	5.63

Relationship between Loss Modulus And Storage Modulus With Temperature

Binder should have a large value of storage modulus (G') at high temperatures for deformation resistance, because G' measures binder elasticity. Decrease in elasticity of binder at low temperatures facilitates in avoiding cracking, as absorbed energy is more easily dissipated. Loss modulus (G") and G' of modified binder are higher than that of neat bitumen. With increase in temperature, both G' and G" decrease. Variation in G' and G" is more at lower temperature than at higher temperature. Above 58°C, G' and G" are found with least value for neat bitumen but these properties are improved by adding polymer. Thus, CR modified binder shows a predominantly viscous behaviour (G">G') in whole temperature range (46 - 70°C).

Relationship between Dynamic Viscosity and Temperature

Dynamic viscosity varies more at lower temperature than at higher temperature. Dynamic viscosity at specified temperatures increases with increase in modifier content.

Variation in Rheological Properties of Modified Binders

In superpave specification purposes, frequency (10 rad/s) is related to a traffic speed (100 km/h). For slow moving traffic, a low frequency is used. A very low frequency (1 rad/s) is appropriated for standing traffic (SHRP–A-410). In general, a binder should have high values of G* and G' at high temperatures for deformation resistance. Modified binders have higher G* than neat bitumen at same temperature (Table 6). Deformation resistance ($G^*_{PMB}/G^*_{Bitumen}$) and elasticity ($G'_{PMB}/G^*_{Bitumen}$) of modified binders improved at high temperature (Table 6). Value of G* at 46°C has increased 1.7 times by adding 3%CR to 80/100 bitumen.

Temperature Susceptibility of Binders

Temperature susceptibility changes in binder properties as a function of temperature. In Dynamic Mechanical

Table 8 — Temperature susceptibility of modified binders after ageing at 10 rad/s

Binder	GTS at 10 rad/s	VTS at 10 rad/s	Binder	GTS at 10 rad/s	VTS at 10 rad/s
60/70+3%CR	5.00	6.80	80/100+3%CR	5.46	7.52
60/70+5%CR	4.63	6.24	80/100+5%CR	4.94	6.76
60/70+7%CR	4.34	6.33	80/100+7%CR	4.90	6.69
60/70+9%CR	4.43	5.92	80/100+9%CR	4.90	6.82

Analysis (DMA), temperature susceptibility of bitumen may be evaluated by measurements of various viscous and elastic parameters (storage and loss moduli, dynamic and complex viscosities) at different temperatures and frequencies. Asphalt mixtures containing binders with lower temperature susceptibility should be more resistant to cracking and rutting at low and high temperatures, respectively. Temperature susceptibility, determined at 1 rad/s and 10 rad/s between 46-70°C (Table 7), decreases as modifier content increases.

Influence of Ageing on Modified Binders

Ageing of binders is performed using Thin Film Test (TFOT). As temperature increases, G* decreases and difference is more pronounced at temperature < 58°C (Table 8). There is increase in G* over temperature domain after ageing however, a slight reduction in G* at temperature higher than 58°C for CR modified binders is observed.

Conclusions

Changes in physical properties of bitumen (penetration, softening point and penetration index) are improved with addition of crumb rubber. Complex modulus increases with increase in modifier and decreases with increase in temperature. However, phase angle decreases with increase in modifier and increases with increase in temperature. Increase in complex modulus and decrease in phase angle of modified binder indicate higher resistance to deformation as compared to neat bitumen. Neat bitumen has lost elasticity at 70°C, as phase angle is > 90°. However, modified binders still display considerable elasticity at 70°C. Complex modulus at 46°C increased 1.2 and 1.7 times by adding 3% CR to 60/70 and 80/100 bitumen respectively. Temperature susceptibility of modified binder is lower than neat bitumen and increase in modifier content decreases temperature susceptibility. Improvement of rheological properties (stiffness and binder elasticity) increases with increase in temperature and modifier contents.

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