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Synergic Effect of Diethylenetriamine (DETA) and Stearic Acid on Improved Storage Stability of Crumb Rubber Modified Bitumen

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***Abstract* - Crumb rubber is most commonly used for bitumen modification due to its elastic nature. However, crumb rubber modified bitumen has storage stability issue at high temperature. Thus, this study focused on improvement of storage stability of the crumb rubber modified bitumen (CRMB) using seven different ratios of DETA and stearic acid, i.e. 1:0, 0:1, 1:1, 1:2, 1:3, 2:1 and 3:1 to visualize the synergic effect in combination. We have found that storage stability of CRMB was enhanced synergically using 1:1 ratio of DETA and stearic acid in CRMB (separation value decreased from 8 to 2.4 °C) with improved rheological and performance properties as compare to conventional CRMB. With that we have also found that high temperature rutting resistance (G*/Sinδ) has increased from 0.75 to 1.19 kPa for unaged binder and 1.45 to 2.35 kPa for aged binder at 82 °C. Meanwhile, the low temperature creep rate (m-value) has increased from 0.28 to 0.33 at -18 °C.**

Key words:* *Bitumen, Crumb Rubber, Diethylenetriamine, Stearic Acid, Synergic Effect, Storage Stability

1. INTRODUCTION

The increasing number of vehicles on the road generates billions of used tires every year in world. Being non-biodegradable and production in large volume, these tires are most problematic sources of waste. Therefore, environment awareness has led us to seek alternative usage of waste tires. One of the usages of these waste tires is to ground in to crumb rubber and used for the modification of bitumen. Due to high elastic properties of crumb rubber, it has been used for bitumen modification purpose for past several decades. The utilization of scrap tires for bitumen modification can not only help in the conservation of natural resources but also enable the creation of high-performing asphalt pavements in comparison with conventional paving grade bitumen.

Crumb rubber is the term widely used for recycled tire rubber produced from scrap tires. Rubber from discarded tire is grinded to crumb and is mixed with bitumen to form crumb rubber modified bitumen (CRMB). The utilization of scrap tires in crumb rubber-modified bitumen (CRMB) can not only help in the safe disposal of rubberized waste but also enable the creation of high-performing bitumen pavements in comparison with conventional paving grade bitumen.[1] It has been shown by some research that the incorporation of crumb rubber into bitumen is a proper method of enhancing the performance grade (PG) of the bitumen which improves the high temperature rutting resistance and low temperature cracking.[2-6]

There are two processes for the production of crumb rubber modified bitumen one is wet process and another is dry process, but generally wet process is more used.[7] Bitumen-Rubber pavements have also been depicted to have lower maintenance costs,[8] lower noise generation,[9-11] higher skid resistance with better night-time visibility due to contrast in the pavement.[12] The disadvantage of using wet process is there is a chance of formation of a non-homogeneous blend.

During the storage or transportation of crumb rubber modified bitumen without agitation, phase separation occurs between the crumb rubber particles and the binder. Due to this phase separation most of the crumb rubber particles are settled down at the bottom of the container. So, there is a formation of unstable condition in a rubberized bitumen blend with different properties after the storage.[13-17] The variation in storage stability between different modified binders is due to the variation in crumb rubber modifier compositions.[18-20] Therefore, researchers modified the chemical bonds between the modifying agent and bituminous compound.[21-23] The storage stability of CRMB mainly depends on various parameters such as bitumen composition, swelling of rubber,[24] digestion of rubber,[25] particle size [13] and concentration of crumb rubber. [26]

Yadollahi and Mollahosseini (2011)[27] used polyphosphoric acid and an additive known as vestanamer were used to achieve cross linking between the sulphur elements in the asphaltenes and maltenes in the bitumen to produce macropolymer network. This produces a CRMB that has good elastic properties at high temperatures and lower creep stiffness at low temperatures. Storage stability of CRMB can be highly improved with the addition of furfural as an activation agent in the bituminous mix[17]. Cheng, Shen et al. (2011)[28] used polymeric compatibilizer containing conjugated diene was used that reacts as a cross-linking agent to produce an improved permanent deformation and thermal cracking resistance with improved storage stability of CRMB.

However, studies on the synergic effects of polyamine and fatty acid on anchoring of crumb rubber in bitumen binder are relatively limited. Therefore, the objective of current research is to enhance the storage stability of CRMB with addition of diethylenetriamine (DETA) and stearic acid in seven combinations, i.e.1:0, 0:1,

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1:1, 1:2, 1:3, 2:1 and 3:1 to visualize the synergic effect over storage stability. With that, we have also carried out the rheological and performance properties of storage stable CRMB blends to support our findings.

2. MATERIALS AND METHODS

2.1 Materials

VG-10 grade (viscosity grade) bitumen was obtained from Mathura Refinery, Indian Oil Corporation Ltd., India was used for all experimental activities. Physiochemical properties of neat bitumen were given in Table 1.

Crumb rubber (CR) powder of 30 mesh size, was collected from local market. Physiochemical properties neat bitumen was given in Table 2.

Chemicals like diethylenetriamine (DETA) (purity >99.0 %) obtained from Spectrochem and Stearic acid (purity >99.5%) were obtained from sigma Aldrich (India). All chemicals were used without any further purification.

2.2 Bitumen Modification Method

For this, we have initially optimized the bitumen modification using various combinations of bitumen, DETA and stearic acid (0.1, 0.3 and 0.5 wt. % of bitumen) with 10% of crumb rubber as a base material. After optimization of additives at 0.3 wt. %, bitumen was blended with 10% crumb rubber at 160-170 ˚C for 1 h to prepare CRDS-1. Similarly, different blends were prepared by consecutive addition of 0.3% DETA to prepared CRDS-2, CRDS-3, CRDS-4 CRDS-5 CRDS-6 CRDS-7 and CRDS-8, in which the ratio of DETA and stearic acid was, i.e.1:0, 0:1, 1:1, 1:2, 1:3, 2:1 and 3:1 respectively.

2.2.1 Physical Properties Test Methods

The physical properties of CRMB like penetration at 25 °C, softening point and elastic recovery at 15 °C and viscosity at 150 °C were characterized according to ASTM D5, ASTM D36, ASTM D6084 and ASTM D4402 respectively.

2.2.1.1 Storage Stability Test

The Storage stability test is a method to check the separation of CRMB's under storage. It is characterized according to ASTM D7173. In this test samples are put in aluminum tube and heated at 163 °C for 48 hours without disturbance. After that, sample was placed in the freezer for 4 hours to solidify CRMB. Then the tube was removed from freezer and cut into three equal parts by spatula and hammer. The softening points of top and bottom part of the sample were tested separately. Then the difference in softening points between the top and the bottom part of the tube were measured. According to BIS 15462:2004, if the softening point differences between the top and the bottom part are less than 4 °C, then sample could be considered with good storage stability. Which represent lower the separation value between top and bottom portion, higher the storage stability of CRMB.

2.2.2 Rheological Properties Test Methods

2.2.2.1 Dynamic Shear Rheometer (DSR) Test

Rheological properties were characterized with the help of dynamic shear rheometer (DSR, MCR102, Anton Paar Co. Ltd. of Austria). This test includes parallel plate configuration with a gap width of 1 mm and is used to determine the viscosity and elastic behavior of a material at different temperatures for Performance Grade (PG Grade) specification of bitumen binder. In this test, a thin layer of bitumen sample is placed between two circular plates of DSR. The lower plate of DSR is fixed whereas the upper plate oscillates back and forth across the sample for the creation of a shearing action. DSR tests are conducted on unaged, RTFO (Rolling Thin Film Oven) aged and PAV (Pressure Aging Vessel) aged bitumen binder samples. All the DSR testing was performed by using the method AASHTO T315-10. This method is used to evaluate complex shear modulus (G*) and phage angle (δ) at 10 rad/s which correlate the rut resistance of the sample. According to this method, the minimum requirement of rutting factor (G*/Sinδ) value is 1 kPa for unaged sample and 2.2 kPa for RTFO aged sample to pass at a particular temperature.

2.2.2.2 Bending Beam Rheometer (BBR) Test

The bending beam rheometer (BBR, Canon Instrument Company) was used to determine low temperature creep tests. In this test, 100 gm load is applied on PAV aged bitumen beam for 240 seconds and the creep stiffness (S) with rate of change of creep stiffness (m- value) are measured at a particular temperature. These parameters showed the ability of bitumen binder to resist low temperature cracking. The test was performed by using AASHTO T313-10 test method. According to this method sample of bitumen binder is molded into a beam having (6.25 x 12.5 x 127 mm) size. Then sample is immersed in a low temperature liquid bath supported at two points (102 mm) apart. After that load is given at the midpoint of bitumen beam and measured the stiffness and m-value at that particular temperature. The criteria of maximum stiffness of binder are 300MPa and criteria for minimum m-value are 0.30 required as per AASHTO T313-10.

2.2.2.3 Multiple Stress Creep Recovery (MSCR) Test

The multiple stress creep recovery (MSCR) test is the latest and more accurate test for Performance Graded (PG) specification of bitumen binder. This test is conducted by using AASHTO TP70-07 and AASHTO MP19-10 methods which indicates the rutting performance of the bitumen binder more accurately at high temperature. The MSCR test deals with creep and recovery test concept to determine the binder's potential for permanent deformation. This test is characterized by using the dynamic shear rheometer (DSR), the same equipment which is used for PG specification. In this test, a creep load (0.1 kPa) is applied to the bitumen binder sample for one second, then load is removed, and the sample can recover for 9 seconds. It is repeated up to 10 cycles. Similarly, test is conducted at 3.2 kPa stress level and repeated for an additional 10 cycles.

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2.2.3 Performance Properties Test Methods

2.2.3.1 Marshall Stability Test

In this test, Marshall Stability with flow values of the pavement are measured by using Marshall Apparatus (Controls Company). The Marshall Stability and flow value represent the maximum load which is required for the failure of the specimen and the total amount of deformation respectively. The compacted bituminous mix specimens of diameter (100 mm) and thickness (63.5 ± 0.5mm) were prepared as per ASTM D6926 and ASTM D6927 methods. The specimen is immersed in a water bath having temperature of 60 ± 1°C for a period of 30 minutes called (before conditioning, S_1) and when the same is for 24 hours then it is called (after conditioning, S_2). Accordingly, several test specimens were prepared, tested and finally Marshall Strength and flow values and retained Marshall Stability was calculated.

2.2.3.2 Rutting Resistance Test

The rutting resistance test was carried out by using wheel tracking apparatus (Cooper Company) as per EN12697–22:2003+A1. A mix slab with dimension (300 × 300 × 40) mm was prepared for testing. The mixes were compacted by a roller compactor at 150–160 °C by maintaining percentage of air void 4-6%. Then the prepared slab could cure at room temperature for 48 hours. After that slab was put into an oven at 60 °C for 5 hours for conditioning before testing. Then a wheel is moved with a frequency of 53 passes per minute on the slab up to 10000 cycles. During test period, rut depth was measured at different cycles.

3. RESULTS AND DISCUSSION

3.1 Physical Properties

The neat bitumen and prepared blends viz: CRDS-1, CRDS-2, CRDS-3, CRDS-4, CRDS-5, CRDS-6, CRDS-7 and CRDS-8 blends were subjected to penetration, softening point, elastic recovery and viscosity and separation test as per ASTM test method. The results of above tests are summarized in Table 3.

We have found that penetration depth ranged from 44 to 86 dmm, CRDS-4 has lowest penetration, i.e. 44 dmm, which was decreased from CRDS-1, i.e. 86 dmm respectively. However, penetration of other crumb rubber modified blends was found to comparable with CRDS-1. Similarly, softening point of modified crumb rubber modified have increased from neat bitumen and ranged from 46 to 57 ºC. Softening points of all CRMB blends are improved compare to CRDS-1. However, the separation value of CRDS-4 was found to be the lowest one, i.e. 2.4 ºC compares to all CRMB blends. Elastic recovery (ER) of all modified bitumen blends were found to be increased from CRDS-1. It is cleared from Table 3, that the rotational viscosities of all modified bitumen at 150 °C decreases in comparison to CRDS-1. Incorporation of DETA and Stearic acid play an important role to decrease the viscosity of modified bitumen which may further helps to improve rheological properties of crumb rubber modified bitumen.

3.1.1 Storage Stability

The test results indicated that increase in the percentage of stearic acid and DETA increases the separation value of the modified blend (Figure 1). It is cleared that the 1:1 combination of DETA and stearic acid (CRDS-4) gives lowest separation value i.e. 2.4 °C. As increase the concentration of Stearic acid i.e. 1:2 and 1:3 combination of DETA and Stearic acid (CRDS-5 and CRDS-6), the separation value increases from 2.4 (CRDS-4) to 3.0 and 3.5 °C. Again, when the concentration of DETA increased i.e. 2:1 and 3:1 combination of DETA and Stearic acid (CRDS-7 and CRDS-8), the separation value increases from 2.4 (CRDS-4) to 6.7 and 7.4 °C. It is known that lower the separation value, higher the storage stability. So CRDS-4 has better storage stability compared to others.

In 1:1 combination of DETA and stearic acid both these additives may react with each other and forms long chain amide molecules. The crumb rubber particles may be entangled within this long chain amide structure inside the body of bitumen. This leads to increase in storage stability of CRMB. As we further increase DETA or Stearic acid, storage stability of CRMB was again found to decreases. This may be attributed due to complete reaction of DETA with doped stearic acid molecules then excess unreacted DETA molecules may separates from bitumen because of its lower density (0.95 g/cm^3) than bitumen (1.03 g/cm^3).

3.2 Rheological Properties

3.2.1 Dynamic Shear Rheometer (DSR)

This test is used to determine the viscosity and elastic behavior of a material at different temperatures for Performance Grade (PG Grade) specification of bitumen binder. The behavior of all unaged modified bitumen was shown in Figure 2 and the RTFO aged modified bitumen were shown in Figure 3. All the DETA and stearic acid doped crumb rubber modified bitumen showed an increase in G*/Sinδ as compared to the neat bitumen and CRDS-1 binder.

We have studied the rheological properties of neat, CRDS-1, CRDS-2, CRDS-3, and CRDS-4. Among all the prepared unaged CRMB samples (CRDS-1, CRDS-2, CRDS-3, and CRDS-4) were found to possess acceptable value for G*/Sinδ, except CRDS-1, which is less than 1 kPa. G*/Sinδ for unaged samples of CRDS-1, CRDS-2, CRDS-3, and CRDS-4 were found to have 0.75, 1.01, 1.11 and 1.19 kPa respectively at 82 °C. The acceptable value for unaged binder as per AASHTO T315-10 standard is the value should be ≥ 1 kPa.

G*/Sinδ for RTFO aged samples of CRDS-1, CRDS-2, CRDS-3, and CRDS-4 were found to have 1.45, 2.23, 2.26 and 2.35 kPa respectively at 82 °C. Among all the prepared RTFO aged CRMB samples (CRDS-1, CRDS-2, CRDS-3, and CRDS-4) were found to possess acceptable value for G*/Sinδ, except CRDS-1, which is less than 2.2 kPa. The acceptable value for RTFO aged binder as per AASHTO T315-10 test method is the value should be ≥ 2.2 kPa.

Out of the six prepared CRMB blends in the present work, CRMB-4 was found to have highest value for G*/Sinδ 1.19 for unaged and 2.35 kPa for aged binder as compared to

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others as well as neat bitumen. The test data showed that CRDS-4, CRDS-5 and CRDS-6 blends were found to have better rutting resistance of binder as compared to rest others. Prepared CRDS-4 blend was found to have best rutting factor and hence possess highest rutting resistance of binder.

3.2.2 Bending Beam Rheometer (BBR) Test

This test method is used to determine the low temperature stiffness and rate of relaxation properties of bitumen binders which indicates the ability towards resistance of low temperature cracking. The stiffness value mentioned in Figure 4 for CRDS-1, CRDS -2, CRDS -3 and CRDS -4 blends were comes out to be 243, 169, 175 and 173 at -18 °C, which is less than 300 to be required for passing the sample as per AASHTO T313-10 test method.

The m-value in Figure 5 showed that CRDS-1, CRDS -2, CRDS-3 and CRDS-4 blends were coming out to be 0.281, 0.289, 0.317 and 0.331 at -18 °C. The m-value should be more than 0.3 to be required for passing the sample as per AASHTO T313-10 test method. Thus CRDS-3 and CRDS-4 blends are passed at -18 °C.

CRDS-4 was found to have best stiffness values and m-values at different temperature as compared to rest other blends as well as neat bitumen which showed that CRDS-4 will have good low temperature thermal cracking resistance as compared to others.

3.2.3 Multiple Stress Creep Recovery (MSCR) Test

The MSCR test deals with creep and recovery test concept to determine the binder's potential for permanent deformation. In this work, the MSCR test was used to characterize the resistance of the crumb rubber modified bitumen binder. The test was conducted on conventional CRMB and diethylenetriamine with stearic acid modified CRMB to identify the elastic response and non-recoverable creep compliance (Jnr) at two stress levels, 0.1 kPa^{-1} and 3.2 kPa^{-1}. As shown in (Figure 6). The percent of recovery exhibited by diethylenetriamine with stearic acid modified CRMB binders was significantly greater than that conventional CRMB at the test temperature 64 °C.

Non-recoverable creep compliance (Jnr) values in Figure 7, showed that at 3.2 kPa^{-1} for CRDS-1, CRDS-2, CRDS-3 and CRDS-4 blends were coming out to be 0.52, 0.41, 0.48, and 0.39 kPa^{-1} which are less than 0.5 kPa^{-1} required for extremely heavy traffic road as per AASHTO MP19-10 specification. Average percentage recovery values were also found to be greater than neat bitumen at both 0.1, 3.2 kPa^{-1} (Figure 7). All the test data obtained (Jnr-difference and % Recovery) after multiple stress creep recovery test showed that the prepared CRDS-4 blend will have best for extremely heavy traffic road condition.

3.3 Performance Properties

3.3.1 Marshall Stability Test

Marshall Stability and flow value represent the maximum load that causes the failure of the specimen and the total amount of deformation, respectively. CRDS-4 was the best sample because of its better storage stability, highest G*/Sinδ value, good rutting resistance, better creep stiffness and low temperature thermal cracking resistance characteristics as compared to rest of the other prepared CRMB blends. Therefore CRDS-4 sample was investigated for Marshall Stability test and test data was compared with CRDS-1 and neat bitumen.

Marshall Strength before and after conditioning of the sample was found to be 14.84, 19.76, 22.92 kN and 10.16, 15.13, 19.85 kN respectively. Flow value before and after conditioning of sample was found to be 3.29, 3.35, 3.40 and 3.66 mm, 3.30, 3.34 mm respectively (Table 4). After observing Marshall Strength and flow value before and after conditioning of the samples, Retained Marshall Stability percentage was calculated. It has been found that Retained Marshall Stability percentage for CRMB-4 was better (86 %) than CRMB-1 (76 %) and neat bitumen (68 %).

3.3.2 Rutting Resistance Test

The rutting resistance test was performed according to EN12697–22:2003+A1. The Rutting depth was found to be 6.18, 2.92 and 2.24 mm for neat bitumen, CRDS-1 and CRDS-4 respectively (Figure 8). The rut depth values at different cycles were given in Figure 9. These data indicate that the higher rutting resistance of CRDS-4 and hence better performance over CRDS-1 and neat bitumen.

4. CONCLUSION

These studies have demonstrated a safer way of crumb rubber disposal by bituminous road pavement. Thus, seven different ratios of DETA and stearic acid, i.e. 1:0, 0:1, 1:1, 1:2, 1:3, 2:1 and 3:1 were prepared for bitumen modification to improve the stability of crumb rubber modified bitumen. The result showed that addition of DETA and stearic acid additives in combination were found to promote anchoring of crumb rubber modified bitumen. We have found that, CRDS-4 blend with 1:1 ratio of DETA and stearic acid, was much more pronounced to enhance the storage stability (2.4 °C) as compare to other prepared blends. The results from the above study were concluded below:

1. Storage stability of CRDS-4 (Bitumen + CR + DETA 0.3% + stearic acid 0.3%) was highest as compared to rest other prepared CRMB blends.
2. The result showed that the rotational viscosity of prepared CRMB blends were decreased gradually with addition of DETA and stearic acid as comparison to CRDS-1 (reference sample) without hampering in the penetration and softening point of all the prepared blends.
3. Out of the all prepared CRMB blends in the present work, CRDS-4 blend was found to have better rutting resistance of binder as compared to rest others. CRDS-4 was found to have highest value for G*/Sinδ 1.19 kPa for unaged and 2.35 kPa for aged binder as compared to others and neat bitumen. Prepared CRDS-4 blend was found to have best rutting factor and hence possess highest rutting resistance.
4. CRDS-4 was found to have significant stiffness values (173 MPa) and m-values (0.331) at 331 at -18 °C compared CRDS-1, i.e. 243 MPa, 0.281 respectively, which resulted that CRDS-4 meet the creep stiffness

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specification up to -18 °C, thereby meet the performance for -28 °C in term of creep stiffness.

5. The MSCR test data obtained (Jnr difference and % Recovery) after multiple stress creep recovery test showed that the prepared CRDS-4 blend sample will be good even for extremely heavy traffic road condition.
6. Retained Marshall Stability percentage of CRDS-4 (86%) mix was better than CRDS-1 (76%) and neat bitumen (68%).
7. Rutting depth was found to be 6.18, 2.92 and 2.24 mm for neat bitumen, CRDS-1 mix and CRDS-4 mix respectively. These data indicate that the higher rutting resistance of CRDS-4 and hence its better performance over CRDS-1 and neat bitumen.

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List of Tables

Table 1. Properties of neat bitumen

Properties	Neat Bitumen	Reference Specification
Penetration at 25 ˚C (100 g, 5 s) 0.1mm	86	IS:1203-1978
Softening Point, ˚C	46	IS:1205-1978
Absolute Viscosity (60 ˚C), Poise	1333	IS:1206 (PART-2)
Kinematic Viscosity (135 ˚C), cst	367	IS:1206 (PART-3)
Viscosity at 150 ˚C, Poise	1.63	ASTM:D4402
Ductility at 25˚C (5 cm/min), cm	100+	IS:1208-1978
Ductility after TFOT at 25 ˚C, cm	100+	IS:1208-1978
Flash point open cup (COC), ˚C	245	IS:1209
Compositional analysis (%)		
Saturates	3.4	
Aromatics	42.9	
Resins	32.9	
Asphaltene	20.8	

Table 2. properties of crumb rubber

Properties	Crumb rubber	Reference Specification
Ash content	5.7%	ASTM D5667-95
Moisture content	0.54%	ASTM D5668-99
Toluene Insoluble	58.2%	-
Type of Rubber	Isoprene	IS 5650
Particle size passing through 600 µm	100%	ASTM D5667-95

Table 3. Physical properties of modified bitumen

Sample code	% of VG-10	% of CR	% of DETA	% of Stearic acid	Penetration in dmm	Softening Point in ˚C	ER@ 15˚C in %	Viscosity@ 150˚C in Poise	Separation Value in ˚C
Neat Bitumen	100	-	-	-	86	46	15	1.63	-
CRDS-1	90	10	-	-	47	56	70	6.28	8.0
CRDS-2	89.7	10	0.3	-	46	57	75	6.00	5.6
CRDS-3	86.7	10	-	0.3	46	57	73	5.60	7.0
CRDS-4	89.4	10	0.3	0.3	44	57	76	5.50	2.4
CRDS-5	89.1	10	0.3	0.6	45	57	75	5.45	3.0
CRDS-6	88.8	10	0.3	0.9	45	57	75	5.30	3.5
CRDS-7	89.1	10	0.6	0.3	46	57	75	4.51	6.7
CRDS-8	88.2	10	0.9	0.3	46	57	75	4.57	7.4

Table 4: Retained Marshall Stability of bituminous mixes

Sample code	Marshall Strength (kN) before conditioning (S_1)	Flow value (cm) before conditioning	Marshall Strength (kN) after conditioning (S_2)	Flow value (cm) after conditioning	Retained Marshall Stability (%) = (S_2/ S_1)×100
Neat Bitumen	14.84	3.29	10.16	3.66	68.46
CRDS-1	19.76	3.35	15.13	3.30	76.56
CRDS-4	22.92	3.41	19.85	3.34	86.60

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List of Figures

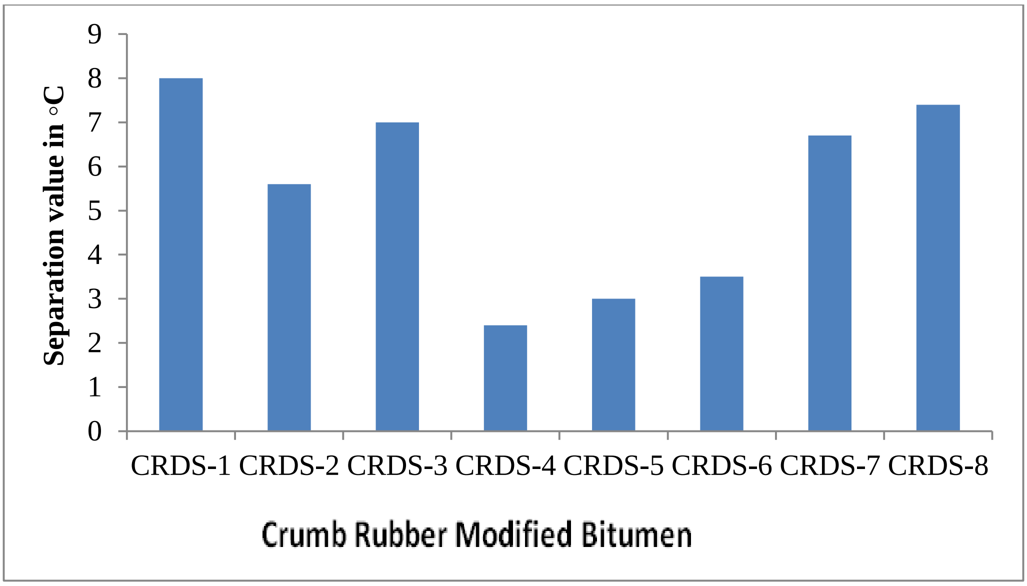

Figure 1: Storage stability of modified Bitumen

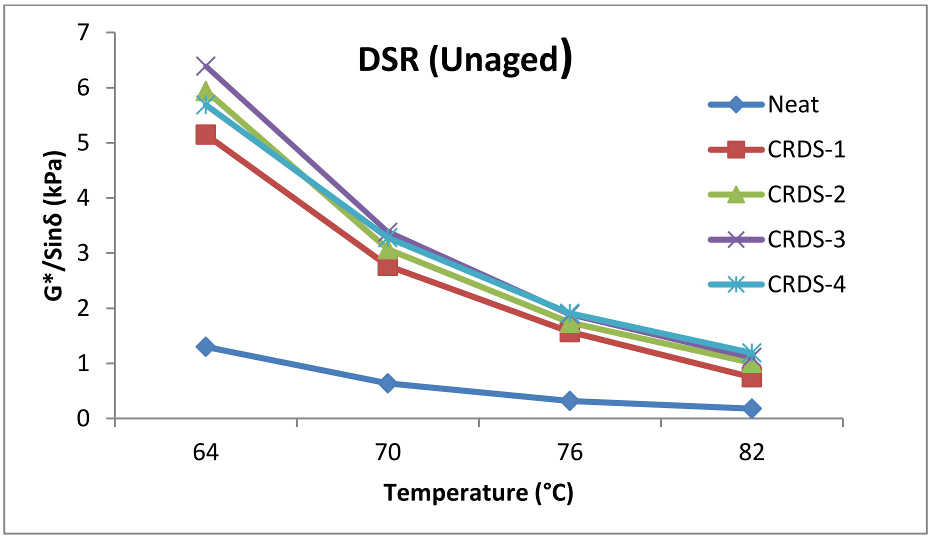

Figure 2: G*/Sinδ (kPa) Measured as a function of temperature of Unaged Binder

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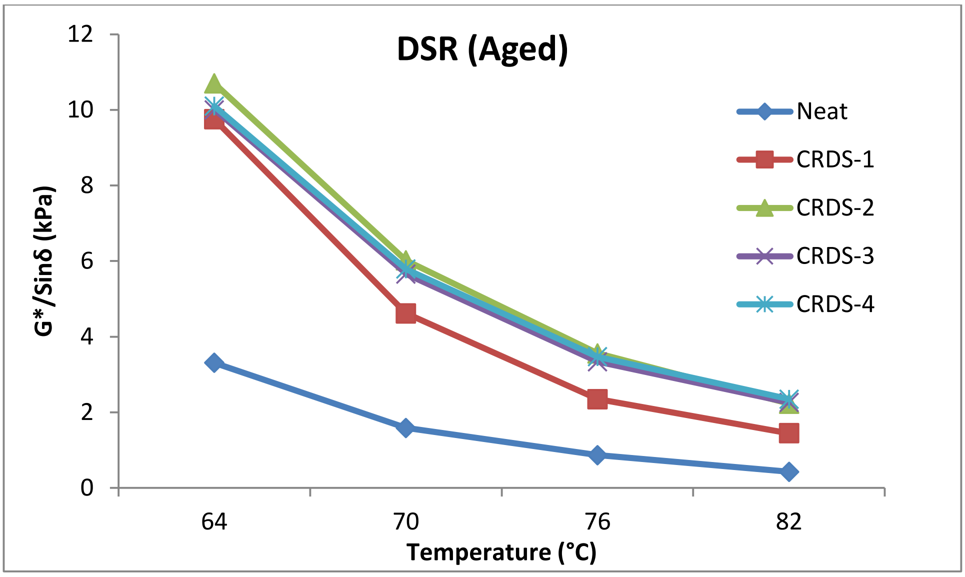

Figure 3: G*/Sinδ (kPa) Measured as a function of temperature of RTFO Aged Binder

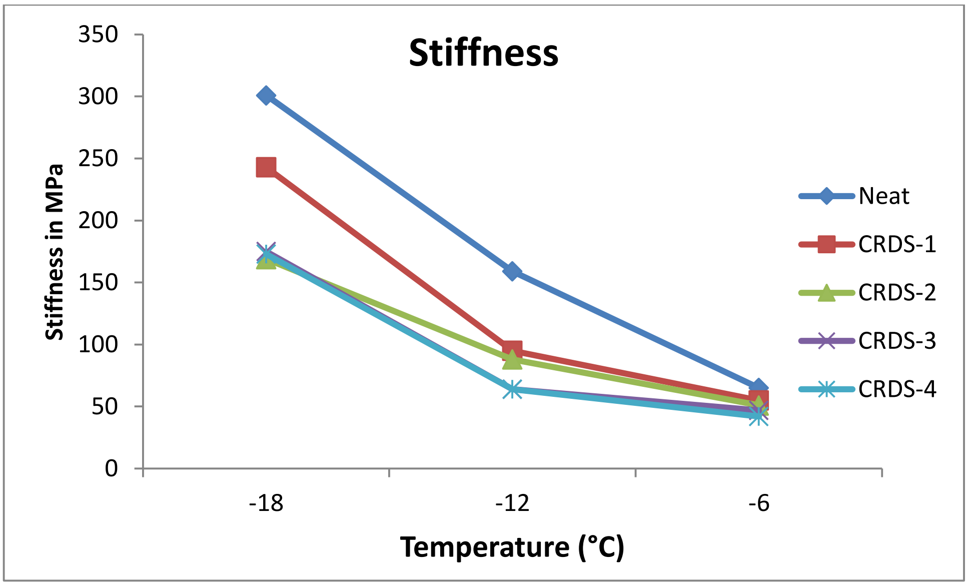

Figure 4: Stiffness of Modified Bitumen

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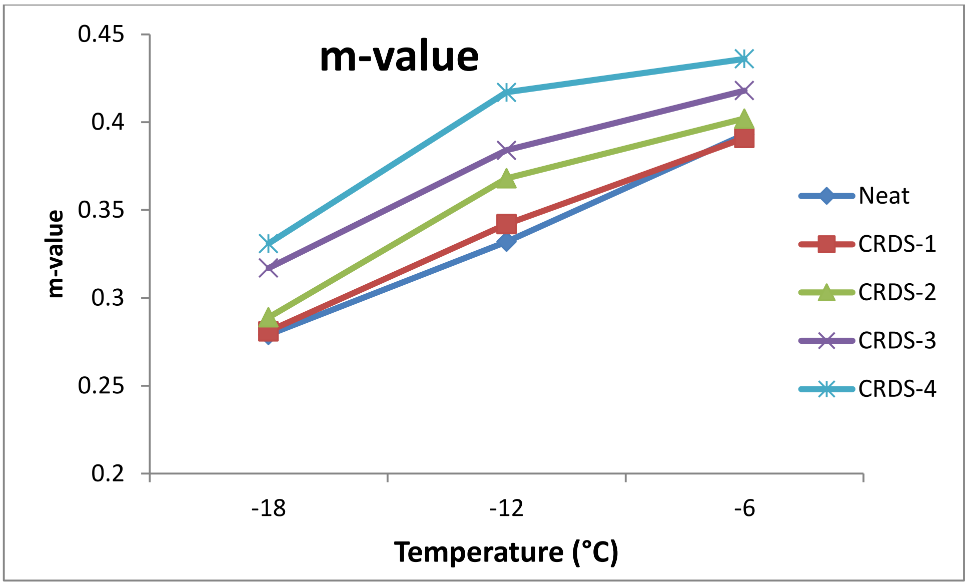

Figure 5: m-value of Modified Bitumen

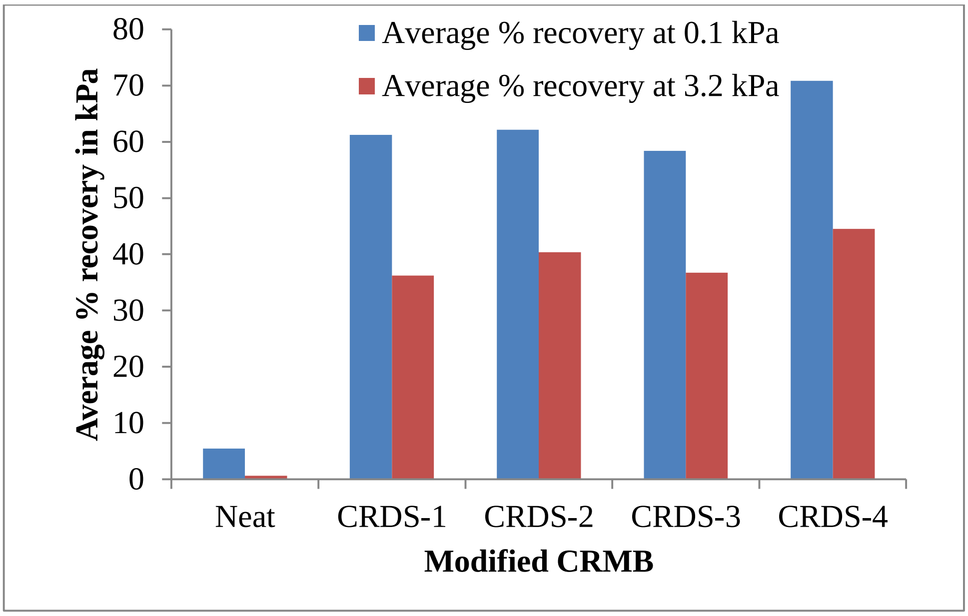

Figure 6: MSCR percentage of average recovery at 64 ºC

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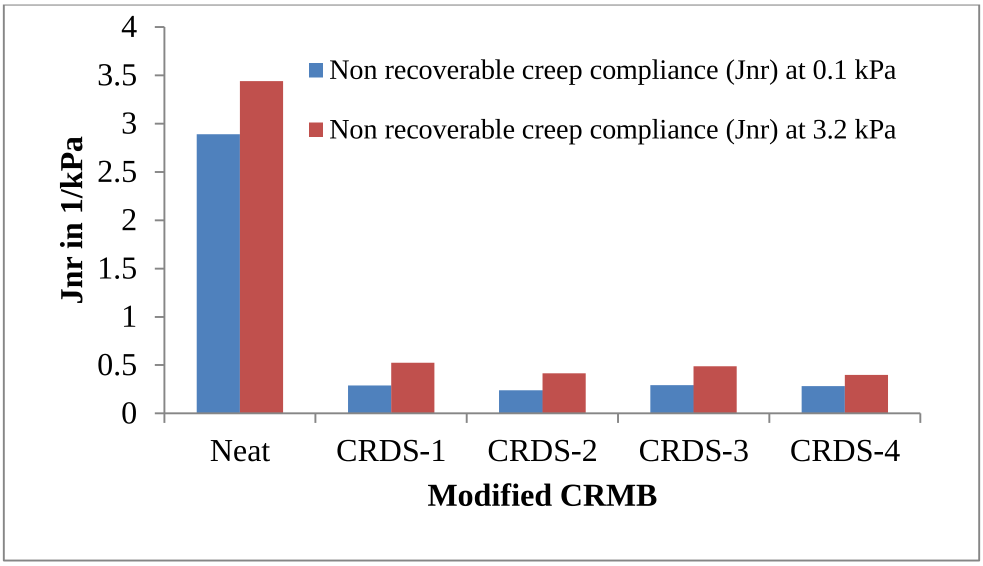

Figure 7: Non-recoverable compliance (Jnr) at 64 ºC

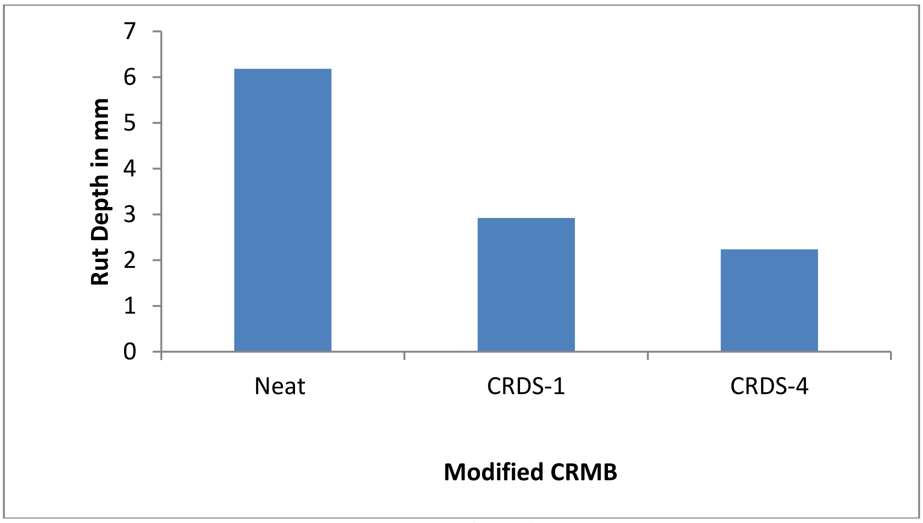

Figure 8: Rut depth of modified Bitumen

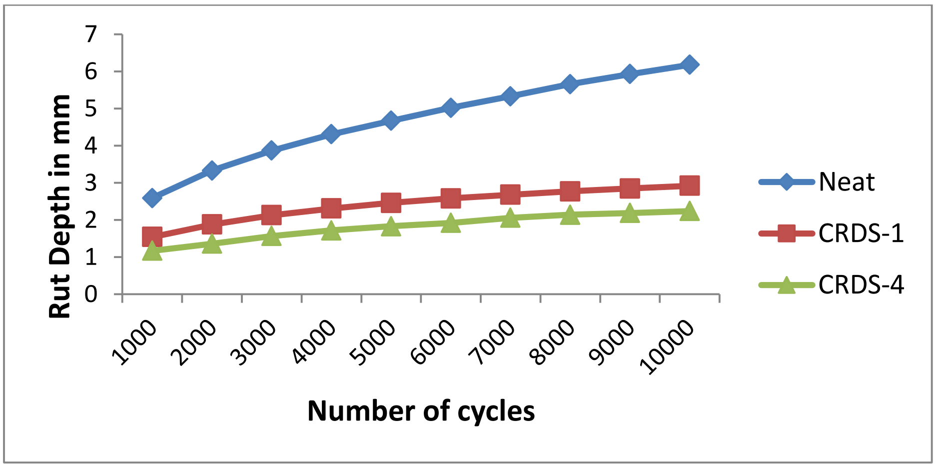

Figure 9: Rutting depth of the modified Bitumen at different cycles

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