Journal Homepage: - www.journalijar.com

INTERNATIONAL JOURNAL OF ADVANCED RESEARCH (IJAR)

ISSN NO. 2320-5407

Article DOI: 10.21474/IJAR01/15026
DOI URL: http://dx.doi.org/10.21474/IJAR01/15026

RESEARCH ARTICLE

EFFECT OF LDPE/CR ADMIXTURE ON THE PROPERTIES OF BITUMINOUS BINDER USED IN PAVING APPLICATIONS

Lokesh Kumar
Department of Chemistry, J. V. Jain College, Saharanpur-247001, India.

Manuscript Info

Manuscript History
Received: 15 May 2022
Final Accepted: 18 June 2022
Published: July 2022

Key words:-
LDPE, Crumb Rubber, Bitumen, Viscosity, Thermoplast-Elastomer

Abstract

A plastic-elastomer admixture was prepared by blending the recycled low density polyethylene (LDPE) and crumb rubber (CR) recycled from wasted tyres in the presence of tall oil. They are blended in two ratios 1:2 and 1:3, LDPE/CR respectively. In this study two wasted materials, LDPE and CR were taken to improve the properties of base bitumen binder. The CR in the form of powder having particle size less than 0.7 mm, was used blended with melted bitumen at 160-170^{0}C with the help of high speed shear mixer for 1 hour. In the same manner the different compositions were made 3, 5, 8 and 12 percent by weight of LDPE, CR and LDPE/CR combination in both ratios 1:2 & 1:3. These modified blends are characterized in terms of penetration, softening point and viscosity, which found better as compared to base bitumen. The most suitable results are obtained when LDPE, CR and LDPE/CR were used below 8% by weight. The elastic recovery test of 8% by weight of LDPE/CR in the ratio 1:3 meets the requirement of specification and this composition is best suited to be for road constructions.

Introduction:-

The performances of bituminous pavement such as resistance to rutting, cracking, fatigue, temperature susceptibility and visco-elastic characteristics can be achieved by using several approaches which includes alteration in type and source of bitumen, uses of extenders/ flexibilizers, fillers, minerals, polymers and their recycled wastes and chemicals , known as bitumen modifiers. The bitumen used for the production of pavement asphalt (mix of bitumen, aggregate and fillers) is generally characterized by poor thermal susceptibility, poor adhesion to the surface and inadequate visco-elastic properties, which results poor performances of pavements, while modified binders have improved flexibility, durability and improved temperature susceptibility[1-5]. However, to get specified properties of durable and cost effective bituminous pavement, the modifications of bitumen with either virgin polymers or with their recycled wastes were most studied. Earlier, virgin polymers are used for the modification of bitumen binders, but because of their high cost, the virgin polymers are replaced with their recycled form.

Mainly three types of polymers, thermoplastic elastomers, plastomers and reactive polymers are used for the modification of bitumen[6]. All these three types of polymers can enhance the performances of pavement in respect of improved temperature susceptibility and durability, but each polymer has a specific effect on the properties of bituminous binder. Thermoplasts or reactive polymers increase the stiffness and resistance to permanent deformation over a lomg period of loading, while elastomers increases the elastic response which in turn increases

Corresponding Author:- Lokesh Kumar
Address:- Department of Chemistry, J. V. Jain College, Saharanpur-247001, India.

the fatigue resistance of pavement[7]. The estimated global production capacity of polyethylene will reach 157 million tons[8] per year in 2023. Economically, the global polyethylene market size is expected to reach from $107.43 billion in 2019 to $130.26 billion by 2027[9]. These data shows that polyethylene is the most consumed polymer globally and used to produce a variety of daily used products.

Table1:- Estimated global production capacity of Polyethylene per year in 2023.

Continent	Production capacity (Million tons/year)	Growth (%)
Asia	57.1	7.2
North America	33.82	7.6
Middle east	28.52	6.3
Russia	9.16	22.6
Africa	4.7	16.6

On the basis of density and polymer chain, polyethylenes (PE) are classified into three categories; low density polyethylene (LDPE, density , 0.910 and 0.940 g/cm^3), linear low-density polyethylene (LLDPE, density 0.910 to 0.920 g/cm^3) and high-density polyethylene (HDPE, density 0.941 to 0.967 g/cm^3)[10]. The melting point ranges of polyethylenes; 110-120^{0}C for LDPE[11-13], about 125^{0}C for LLDPE[14] and 139-149^{0}C for HDPE[15-17], makes suitable for incorporation of them into bitumen for production of hot mix asphalt. The melting points of mostly plastomers are below the processing temperature of bituminous mixtures, which ensures the homogeneity by the physical and chemical interaction between polymers and bitumen[18-20].

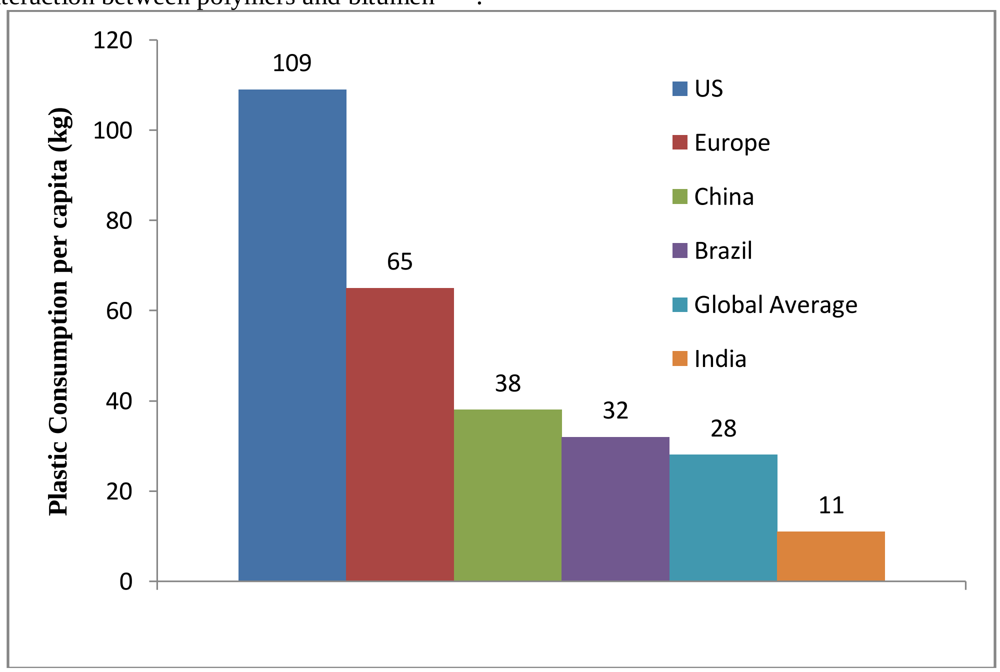

Figure 1:- Plastic waste consumption per capita (kgs) worldwide (Source: FICCI).

The utilization of recycled tyre rubbers (Crumb rubber) for the modification of bitumen may be carried out by two processes: wet or dry process. In wet process, the polymers are added first into bitumen and then it is mixed with aggregate to produce asphalt mixture. In this process the mixing of polymers and bitumen at high temperature led to physical and chemical interactions between them. While in dry process, there are two ways of adding polymer into asphalt mix: bitumen and polymer either can be added into aggregate or the polymers can be added to the aggregate first[21, 22]. Mostly researchers have recommended the wet process for the modification of asphalt mixtures, because the higher processing temperature promotes the better physical and chemical bonding between the constituents of asphalt mixtures[20, 23, and 24]. However, asphalt mixture made from wet process shows a degree of separation over long storage[25, 26]. The crumb rubber is preferred over the virgin polymers to minimize the cost as well as to obtain desired properties of modified bitumen for a particular application, because by using crumb rubber in modification of bitumen, better performances of pavement can be achieved at minimal cost with ease of availability[26]. The number of vehicles is increasing every year due urbanization and globalization, which generates wasted tyres. To overcome the problems of their disposal and other environmental aspects associated with waste tyre, many industries have been established to produce crumb rubber from these waste tyres. Many researchers found crumb rubber suitable for modification of bitumen for paving applications[27-32]. The crumb particles absorbs oil fraction of bitumen, which results into swelling and softening of crumb particles. This phenomenon makes the some physical and chemical bonding between swell rubber and constituents of bitumen. However, the overall performance of bitumen binder depends upon various factors including crumb rubber dosages, mixing time and temperature, size, shape and constituents of crumb rubbers[33-35]. 12% to 37% reduction in penetration value was observed by using 10% of ground tyre rubber. The conventional and rheological studies revealed that extended service life pavement can be achieved by enhancing resistance to rutting of asphalt mix at high temperatures and reduction in low temperature cracking of the pavements by using these elastomers in the modification of base bitumen[36]. However, due to high molecular weight of crumb rubber and less compatibility with bitumen, some authors find out phase separation and non-homogeneity in the bituminous mixtures over long hot storage[37, 38] although the separation can be reduced by using crumb particle size lower than 0.35 mm along with high shear blending[39].

It was observed from the vast literature that none of modifier can improve the overall performance of pavements. Many researchers have focused on the use of combination of plastomers and elastomers as bitumen modifiers and this combination evaluated on the basis that the combination of plastomers and elastomers leads to better performances of pavements than the case in which each of them was used separately[19, 40, 41, 45]. In the previous literature, many combinations are reported like GTR and PE[41, 42], SBS and PE, GTR and EVA[43], GTR and PET[44].

In the present study, a combination of crumb rubber (CR) and recycled low density polyethylene (LDPE) were used for the modification of base bitumen and the modified binders are evaluated in terms softening point, penetration and viscosity test to optimize the enhanced performances of bituminous binders such as increased stiffness i.e. resistance to rutting, low and high temperature behaviour and visco-elastic properties of bituminous binders. Thermoplast-elastomeric characteristics can be achieved by using the admixture of crumb rubber and LDPE for modification of bitumen binders and it also solve the problems associated with hazards of environment and cost of modifiers as recycled LDPE and waste tyres rubbers are used to produce admixture of crumb rubber and LDPE.

In India, per capita consumption of plastic is about 11 kg and the expected consumption of plastic would be 20 kg per capita in 2022. Only 60% of this plastic waste is recycled. The major plastic wastes are come from house hold materials like water and soft drink bottles, milk pouch, etc[46]. Figure 1 shows the per capita consumption of plastic waste worldwide in 2014-15.

In India, the waste plastic generation has more than doubled from 15.89 lakh tons in 2015-16 to 30.59 lakh tons in 2018-19 and 34 lakh tons in 2019-20[47]. In India, around 43% of manufactured plastics are used for packaging purpose and most are of single use. Different uses of plastic wastes are shown in figure 2.

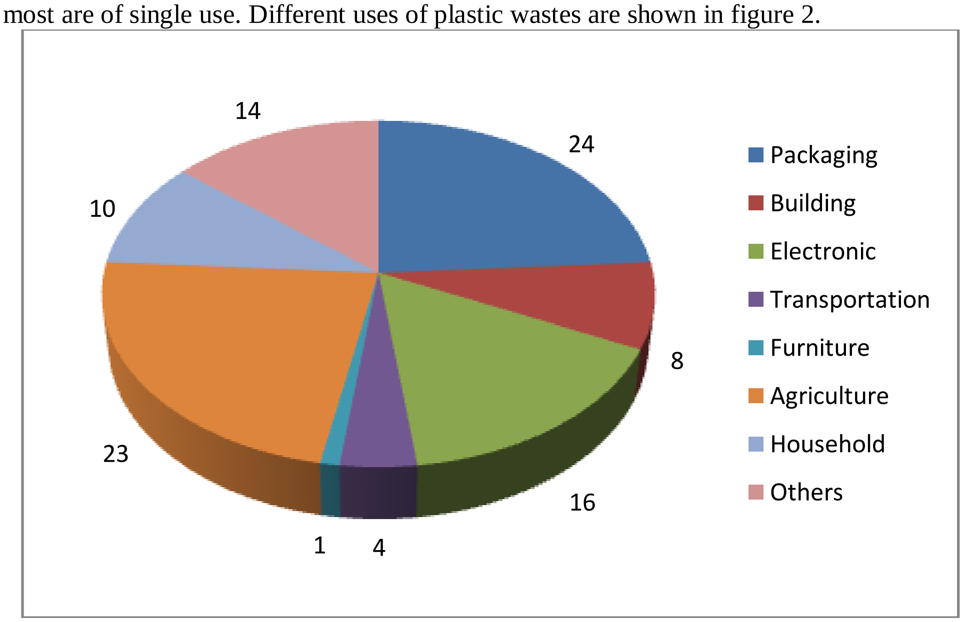

Figure 2:- Area of utilization of recycled plastic waste.

Experimental

Materials:-

The penetration grade (80/100) bitumen was obtained from an Indian industry (table 2). Recycled LDPE, crumb rubber and tall oil were procured from local industrial area. The size of particles recycled wastes was below 0.7 mm.

Table 2:- Specification of Bitumen.

Bitumen grade	**80/100**
Penetration (dmm)	89
Softening Point (^{0}C)	47.9
Specific gravity @ 25^{0}C	1.03
Saturates (wt%)	8.3
Monoaromatic / maphthanics/ aliphatics (wt%)	16.5
Polyaromatics (wt%)	31.8
Resins (wt%)	21.6
Asphaltenes (wt%)	20.5

Preparation of blends of CR and LDPE

For the preparation of admixture of CR and LDPE, the crumb rubber was dissolved in adequate amount of Tall oil and then stirred in steel vessel at 160-170^{0}C for 1 hour, and then LDPE was added into it and stir well at the same temperature in two ratios for LDPE: CR; 1:2 and 1:3.

The 500 gm bitumen is preheated in a double jacketed steel vessel at 180^{0}C with high speed stirring. The concentrate of admixtures of LDPE and CR was added gradually into it and temperature was maintained 160^{0}C while blending it. The base bitumen was also processed in the same manner. The cooled modified bituminous blends were stored in sealed containers for various investigations.

Test Methods

The softening point of specimen was measured by ring and ball method according to ASTM D 36-09. In this test, disks of specimen were cast in shouldered ring. After that, the disks are heated at a constant rate 5^{0}C/ minute in a glycerine bath with continuous stirring with the help of magnetic bead and fitted with thermometer.

The penetration test of bituminous specimen was performed according to the ASTM D 5-06. In this test, the specimens of base bitumen and modified bitumen were casted in specified size of cup and then penetration of standard size needle under a 100 g load into each specimen was measured and reported in tenths of milimeters.

The viscosity of bitumen specimen was measured by Brookfield viscometer. This test determines the adequate workable fluidity of the modified bitumen.

Elastic recovery of the bituminous sample was measured according to IS: 1208-1978. In this experiment, the specimen was elongated upto 10 cm at a specified speed of 5 cm/ min at 15^{0}C in Ductilometer. The stretched specimen is cut into two halves. After 1 hour, length of the recombined specimen was measured by placing elongated cut half of the piece back into such a position just touching the fixed half of test specimen.

Results and Discussion:-

In this study, the modifiers CR and LDPE are utilized in the form of particle of size less than 0.7 mm for the modification of base bitumen while the admixture of LDPE/CR was used in the form of concentrate in order to improve mechanical and rheological properties of base bitumen. By using such modified bituminous binders in pavement, it is expected that these produce a durable pavement surface, as aggregates/ gravel are best coated by these modified binders in comparison to base bitumen. The pavement made by these modified binders could serve for a long time[48].

Softening point test is carried to know about the stiffness of the bituminous sample. It is temperature at which a material attains a particular degree of softness[49]. It is evident from the table 3 that upto 5 wt% dosages of modifiers have no considerable effect on the softening point value of any specimen. But a noticeable increase in softening point of each blend was observed after 8 wt% dosages of modifiers. These results are also represented in figure 3 and 4 which shows that there is less difference in the softening point value of modified bitumen upto 3% dosages of all modifiers. It can be seen that softening point values of modified bitumen increases considerably after the 5% dosages of modifiers in all cases. The increase in softening point of LDPE modified bitumen (12 wt%) is due to the somehow physical and chemical interaction between the polymer chain and constituents of bitumen, because LDPE particles absorbs oily fraction and swelled. Theses swollen particle are easily mixed within the bituminous matrix. This bituminous mixture can deliver good resistance to permanent deformation of pavement[49].

Table 3:- Softening point values of Bituminous blends.

Modifiers	**Softening point (^{0}C)**			
			LDPE : CR 1 : 2	**LDPE : CR** 1 : 3
Wt%	LDPE	CR		
3	52.8	50.1	49.5	49.4
5	56.4	51.8	52.3	52.4
8	71	56	65	58
12	101	62	71.2	64

However, crumb rubber modified bitumen also gives better result in respect of softening point; the reason maybe the similarity of structure of constituents (hydrocarbons) of CR and bitumen both resulting an intermixed composition. Another factor which contributes to the better composition includes; small particle size and softness of crumb rubber particles, this provides a better coating on the gravel.

Figure 3:- Softening point Vs content of LDPE and CR.

Therefore, the resulting pavement made from crumb rubber modified binder could provide improved resistance to fatigue, rutting and cracking in pavement[50]. The softening point of composition containing LDPE/CR in ratio of 1:2 was reached upto 71.2^{0}C at 12% dose as compared to 64^{0}C softening point of in case of admixture LDPE/CR ratio of 1:3 showing that least amount of LDPE is favourable.

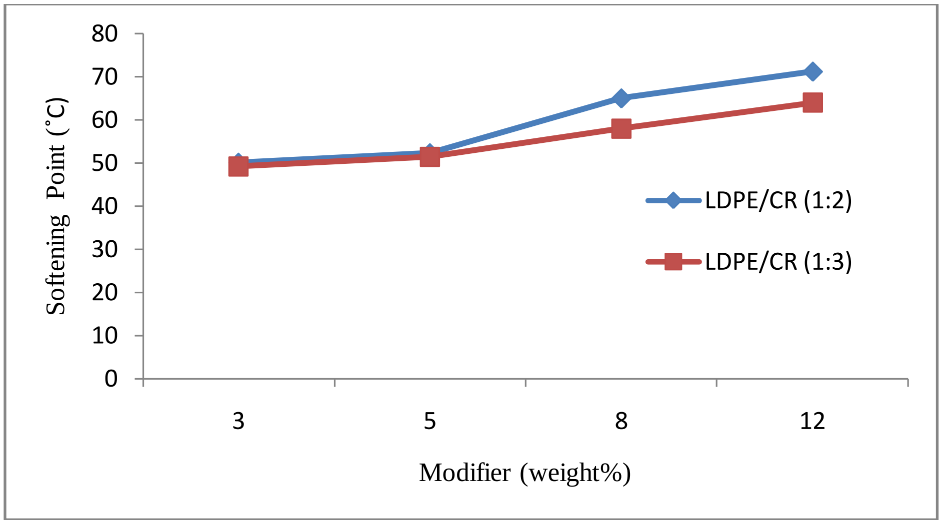

Figure 4 Softening point Vs content of LDPE/CR admixture

Table 4 shows that penetration was decreased to 29 dmm for 12 wt% of LDPE loading as compared to 89 dmm for base bitumen. The same observations were found in case admixture of LDPE/CR. As shown in figure 5 a sharp decrease in penetration was observed, when the amount of modifiers were increased more than 5 wt%.

Table 4:- Penetration value of modified bitumen

Modifiers (%)	**Penetration (dmm)**			
	LDPE	**CR**	**LDPE : CR**	**LDPE : CR**
			1:2	1:3
3	42	49	57	61
5	39	47	42	52
8	34	42	40	47
12	29	40	35	45

From the table 4 and figure 5 it is evident a sharp decline in penetration in case of LDPE/CR ratio of 1:2 (12 wt%) as compared to the base bitumen. While in case of LDPE/CR ratio of 1:3, the decrease in penetration value is not so sharp, which making it more favourable. The decreasing values of penetration with increasing content of CR in bitumen indicate improved stiffness and viscosity of modified bitumen binders[51].

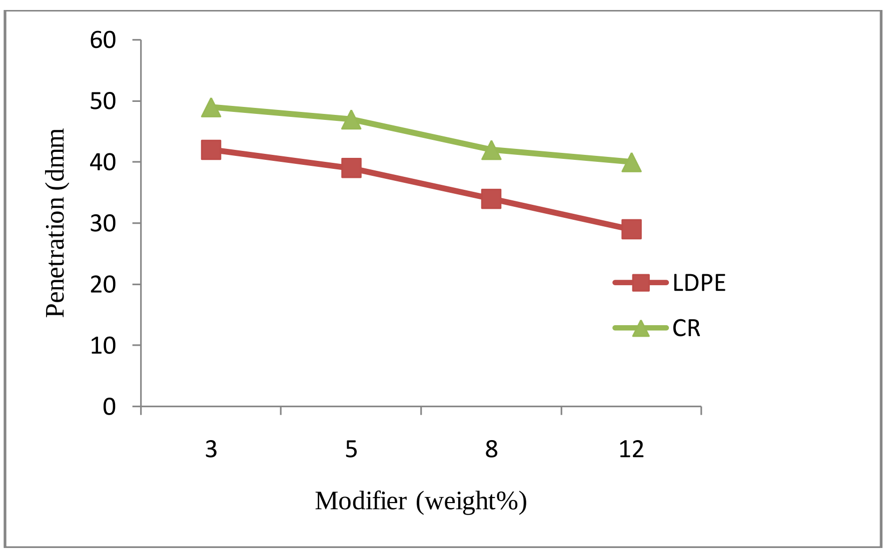

Figure 5:- Penetration Vs content of LDPE and CR.

Viscosity
Bitumen is behaves as a visco-elastic materials, which is directly affected by the temperature and rate of load application. At low temperature it acts as elastic material while at high temperature it shows viscous behaviour. The viscosity data reported in table 5 shows that the viscosity of the modified bitumen with individual LDPE and CR and with admixture of LDPE in both ratio; 1:2 and 1:3 increases with increase of their content as compared to base bitumen.

Figure 7 exhibited most variation in the viscisity of bitumen modified either with LDPE or CR as found in previous literature[51, 52]. The viscosity difference is more pronounced at the addition of even 3 wt% of LDPE and CR as modifier into the base bitumen. While in case of admixtures of LDPE/CR in both the ratio 1:2 and 1:3, the variation in viscosity is not so high, which was apparent after 5 wt% dosages of modifiers. As the dosages of modifiers increased upto10%, both the admixtures given equal viscosity (6.1dPa.S). Figure 8 shows that upon increasing the dosages of both the admixtures into the base bitumen have led to variation with a lower rate particularly by the admixture of LDPE/CR in a ratio of 1:2. It is thought that the lowering in viscosity is probably due to the increased CR quantity in admixture and this pattern can be seen in figure 8. Due to the lower melting point of LDPE (122^{0}C) than the processing temperature of modified bitumen binder, LDPE particles absorbs some oil fraction from melted bitumen and thus releases low molecular weight fraction into the bitumen, which causes an increased in viscosity values of modified bitumen[53].

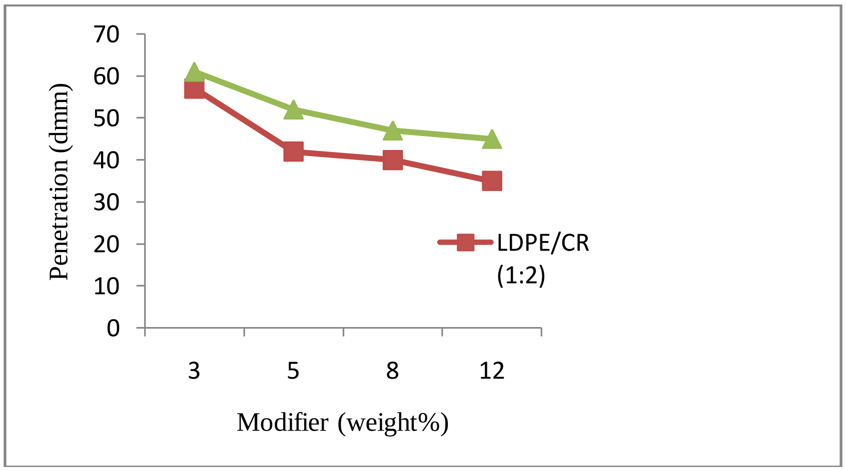

Figure 6:- Penetration Vs content of LDPE/CR admixture.

Optimization of amount of modifier
From the above discussion, it was observed that the unfavourable variation in penetration value, softening point temperature and viscosity is mainly resulted due to the presence of LDPE, as compared to CR and admixture of LDPE/CR, when the concentration of LDPE is 8% or more.

Table 5:- Viscosity value of modified bitumen.

Viscosity (dPa.S)				
			LDPE : CR 1:2	**LDPE : CR** 1:3
Modifiers (%)	**LDPE**	**CR**		
3	3.8	1	0.08	0.51
5	5.1	1.8	4.2	2.9
8	9.8	6.1	6.1	6.1
12	15	10.3	9.3	8.2

This increased viscosity is useful as it increases the stiffness of the binder, but also can lead to cracking[54]. The LDPE modified bitumen with 5% weight of LDPE was showed least phase separation and under specified properties of bitumen binder. To meet the required specification 8% by weight LDPE/CR admixture in the ratio of 1:3 was optimized to produce pavement and also evaluated as per Indian standard specification.

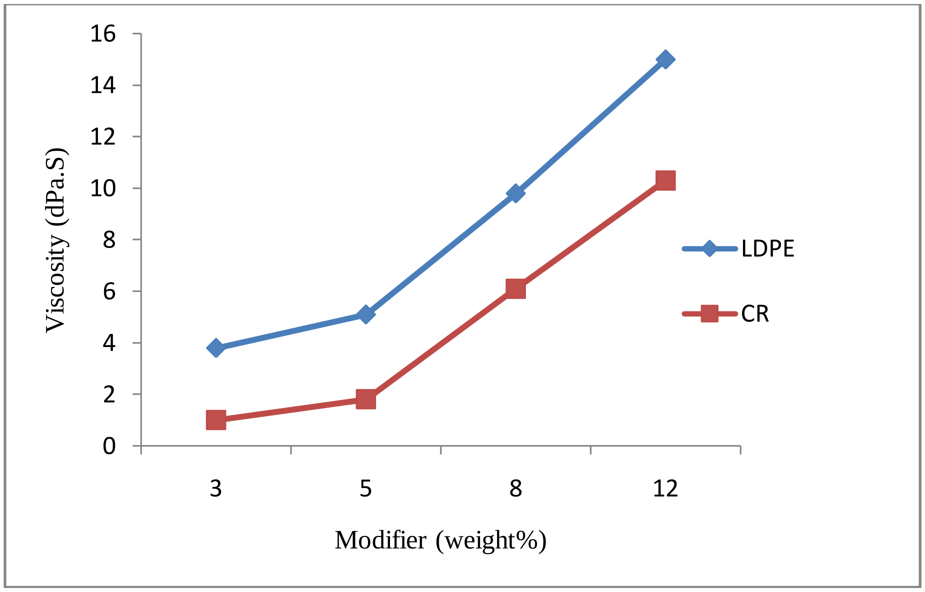

Figure 7:- Viscosity Vs content of LDPE and CR.

Table 6 shows that Properties of bituminous binder modified with LDPE/CR in the ratio of 1:3 with the dosages of 8 wt% meets the requirement of IRC SP 53-2010, Guideline on the use of modified bitumen in road construction[55], with little difference in penetration value. It is suggested that pavement made by using this modified bituminous binder can achieve better performances in terms of resistance to fatigue, rutting and cracking, temperature susceptibility and also in terms of durability.

Table 6:- Properties of bituminous binder modified with LDPE/CR in the ratio of 1:3.

Property	IRC SP 53-2010	Modified bitumen with LDPE/CR in the ratio of 1:3 (8 wt%)
Penetration @ 25^0C, 100g, dmm	50	47
Softening point R&B method	55	58
Elastic recovery @ 15^0C, %	60	62
ViscosityPa.S	3-6	6.1

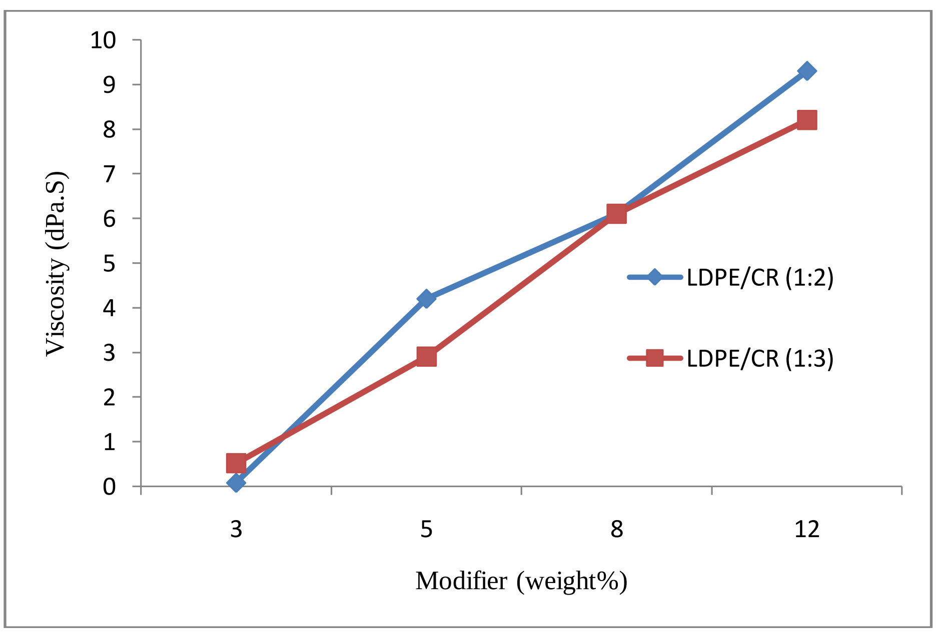

Figure 8:- Viscisity Vs content of LDPE/CR admixture.

Conclusions:-

In this study both modifiers CR and LDPE are recycled material, by using such wasted materials we can save environment and also we can minimize the cost of road construction as the virgin polymers are very costly. From the above results it is revealed that LDPE is the main factor for hardening of the bitumen binder and show unfavourable results of penetration, softening point and viscosity, when its dosages increased above 8 wt%. Addition of CR in the amount of 8 wt% delivers a better performance. The bituminous binder modified with LDPE/CR in the ratio of 1:3 with the dosages of 8 wt% meets the requirement of standard specifications.

References:-

1. Galdina V.:Modifitsirovanye Bitumy. SibADI, Omsk 2009.
2. Kishchynskiy S.:Vestnik HNFDU, 2008, **40**, 28.
3. Zhu J., Birgisson B. and Kringos N.: Eur. Polym. J., 2014, **54**, 18.
4. Tarasov R., Makarova L. and Kadomtseva A.: Mod. Sci. Res. Innovat., 2014, **5**, 56.
5. Polacco, G.; Stastna, J.; Biondi, D.; Zanzotto, L. Relation between polymer architecture and nonlinear viscoelastic behavior of modified asphalts. Curr. Opin. Colloid Interface Sci. **2006**, 11, 230–245.
6. García-Travé, G.; Tauste, R.; Moreno-Navarro, F.; Sol-Sánchez, M.; Rubio-Gámez, M.C. Use of Reclaimed Geomembranes for Modification of Mechanical Performance of Bituminous Binders. J. Mater. Civ. Eng. **2016**, 28, 04016021
7. Polacco, G.; Stastna, J.; Biondi, D.; Antonelli, F.; Vlachovicova, Z.; Zanzotto, L. Rheology of asphalts modified with glycidylmethacrylate functionalized polymers. J. Colloid Interface Sci. **2004**, 280, 366–373.
8. https://www.echemi.com/cms/487375.html
9. https://www.fortunebusinessinsights.com/industry-reports/polyethylene-pe-market-101584.
10. Williams K. Kupolati and Julius M. Ndambuki, The use of polyolefins in geotextiles and engineering applications in Polyolefin Fibres (Second Edition), 2017.
11. Jun, L.; Yuxia, Z. and Yuzhen, Z. The research of GMA-g-LDPE modified Qinhuangdao bitumen. Constr. Build. Mater. **2018**, 22, 1067–1073.
12. 24. Al-Hadidy, A.I. and Yi-Qiu, T. Effect of polyethylene on life of flexible pavements. Constr. Build. Mater. **2009**, 23, 1456–1464
13. Vargas, M.A., Sánchez-Sólis, A. and Manero, O. Asphalt/polyethylene blends: Rheological properties, microstructure and viscosity modeling. Constr. Build. Mater. **2013**, 45, 243–250.
14. Roman, C.; Cuadri, A.A.; Liashenko, I.; García-Morales and M.; Partal, P. Linear and non-linear viscoelastic behavior of SBS and LDPE modified bituminous mastics. Constr. Build. Mater. **2016**, 123, 464–472.
15. Lastra-González, P., Calzada-Pérez, M.A., Castro-Fresno, D., Vega-Zamanillo Á., and Indacoechea-Vega, I. Comparative analysis of the performance of asphalt concretes modified by dry way with polymeric waste. Constr. Build. Mater. **2016**, 112, 1133–1140.
16. Attaelmanan, M., Feng, C.P. and Al-Hadidy, A.I. Laboratory evaluation of HMA with high density polyethylene as a modifier. Constr. Build. Mater. **2011**, 25, 2764–2770.
17. Fernandes, S., Costa, L., Silva, H. and Oliveira, J. Effect of incorporating different waste materials in bitumen. Ciência Tecnol. Mater. **2017**, 29, e204–e209.
18. Nuñez, J.Y.M.; Domingos, M.D.I.; Faxina, A.L. Susceptibility of low-density polyethylene and polyphosphoric acid-modified asphalt binders to rutting and fatigue cracking. Constr. Build. Mater. **2014**, 73, 509–514.
19. Yan, K.; Xu, H.; You, L. Rheological properties of asphalts modified by waste tire rubber and reclaimed low density polyethylene. Constr. Build. Mater. **2015**, 83, 143–149.
20. Wong, S.F.; Htwe, A.A.; Oh, S.H.; Leo, T.Y.; Cheng, J.; Tay, B.K. Utilization of Waste Plastics in Stone Mastic Asphalt for Infrastructural Applications. Mater. Sci. Forum **2017**, 902, 55–59. Modarres, A.; Hamedi, H. Effect of Waste Plastic Bottles on the Stiffness and Fatigue Properties of Modified Asphalt Mixes. Mater. Des. **2014**, 61, 8–15.
21. Earnest, M.D. Performance Characteristics of Polyethylene Terephthalate (PET) Modified Asphalt. Electronic Dissertations M.S. Thesis, Georgia Southern University, Statesboro, GA, USA, 2015; p. 1260. Available online: https://digitalcommons.georgiasouthern.edu/cgi/viewcontent.cgi?article=2328&context=etd (accessed on 25 January 2019).
22. Kalantar, Z.N., Karim, M.R. and Mahrez, A., A review of using waste and virgin polymer in pavement. Constr. Build. Mater, **2012**, 33, 55–62.
23. González, E., Costa, L.M.B., Silva, H.M.R.D. and Hilliou, L., Rheological characterization of EVA and HDPE polymer modified bitumen's under large deformation at 20^0C, Constr. Build. Mater, **2016**, 112, 756–764.

24. Polacco, G., Berlincioni, S., Biondi, D., Stastna, J. and Zanzotto, L., Asphalt modification with different polyethylene-based polymers, Eur. Polym. J, **2005**, 41, 2831–2844.
25. 19. Yu, R., Fang, C., Liu, P., Liu, X. and Li, Y., Storage stability and rheological properties of asphalt modified with waste packing polyethylene and organic montmorillonite, Appl. Clay Sci., **2015**, 104, 1–7.
26. A.Mahrez, Properties of rubberised bitumen binder and its effect on the bituminous mix [M.S. thesis], Faculty of Engineering, University of Malaya, Kuala Lumpur, Malaysia, 1999.
27. J.R.M. Oliveira, H.M.R.D. Silva, L.P.F. Abreu, S.R.M. Fernandes, Use of a warm mix asphalt additive to reduce the production temperatures and to improve the performance of asphalt rubber mixtures, J. Cleaner Prod. 41 (2013) 15–22.
28. A. Subhy, D. Lo Presti, G. Airey, Rubberised bitumen manufacturing assisted by rheological measurements, Road Mater. Pavement Des. 17 (2) (2016) 290–310.
29. S. Fernandes, H.M.R.D. Silva, Oliveira JRM. Mechanical, surface and environmental evaluation of stone mastic asphalt mixtures with advanced asphalt binders using waste materials, Road Mater. Pavement Des. (2017) 1–18.
30. P. Li, X. Jiang, Z. Ding, J. Zhao, M. Shen, Analysis of viscosity and composition properties for crumb rubber modified asphalt, Constr. Build. Mater. 169 (2018) 638–647.
31. G. Airey, M. Rahman, A.C. Collop, Crumb rubber and bitumen interaction as a function of crude source and bitumen viscosity, Road Mater. Pavement Des. 5 (4) (2004) 453–475.
32. Liliana M.B. Costa, Hugo M.R.D. Silva, Joana Peralta and Joel R.M. Oliveira, Using waste polymers as a reliable alternative for asphalt binder modification – Performance and morphological assessment, Construction and Building Materials, 198 (2019) 237–244.
33. Moreno, F.; Sol, M.; Martín, J.; Pérez, M.; Rubio, M.C. The effect of crumb rubber modifier on the resistance of asphalt mixes to plastic deformation. Mater. Des. **2013**, 47, 274–280. [CrossRef]
34. Moreno-Navarro, F.; Sol-Sánchez, M.; Rubio-Gámez, M.C.; Segarra-Martínez, M. The use of additives for the improvement of the mechanical behavior of high modulus asphalt mixes. Constr. Build. Mater. **2014**, 70, 65–70. [CrossRef]
35. Shen, J.; Li, B.; Xie, Z. Interaction between crumb rubber modifier (CRM) and asphalt binder in dry process. Constr. Build. Mater. **2017**, 149, 202–206. [CrossRef]
36. Luzana Brasileiro, Fernando Moreno-Navarro, Raúl Tauste-Martínez, Jose Matos and Maria del Carmen Rubio-Gámez, Reclaimed Polymers as Asphalt Binder Modifiers for More Sustainable Roads: A Review, Sustainability 2019, 11, 646; doi:10.3390/su11030646.
37. Xu, O.; Rangaraju, P.R.;Wang, S.; Xiao, F. Comparison of rheological properties and hot storage characteristics of asphalt binders modified with devulcanized ground tire rubber and other modifiers. Constr. Build. Mater. **2017**, 154, 841–848.
38. Han, L.; Zheng, M.; Li, J.; Li, Y.; Zhu, Y.; Ma, Q. Effect of nano silica and pretreated rubber on the properties of terminal blend crumb rubber modified asphalt. Constr. Build. Mater. **2017**, 157, 277–291.
39. Navarro, F.J., Partal, P., Martınez-Boza, F. and Gallegos, C., Thermo-rheological behaviour and storage stability of ground tire rubber-modified bitumens, Fuel, **2004**, 83, 2041–2049.
40. Lee, S.J., Akisetty, C.K.and Amirkhanian, S.N., The effect of crumb rubber modifier (CRM) on the performance properties of rubberized binders in HMA pavements, Constr. Build. Mater, **2008**, 22, 1368–1376.
41. Zhang, F.and Hu, C., The research for crumb rubber/waste plastic compound modified asphalt, J. Therm. Anal. Calorim., **2016**, 124, 729–741.
42. Navarro, F.J., Partal, P., Martínez-Boza, F.J. and Gallegos, C. Novel recycled polyethylene/ground tire rubber/bitumen blends for use in roofing applications: Thermo-mechanical properties. Polym. Test. **2010**, 29, 588–595.
43. Yuan, J., Wang, J., Xiao, F., Amirkhanian, S., Wang, J. and Xu, Z., Impacts of multiple-polymer components on high temperature performance characteristics of airfield modified binders, Constr. Build. Mater., **2017**, 134, 694–702.
44. Karahrodi, M.H., Jazani, O.M., Paran, S.M.R., Formela, K. and Saeb, M.R., Modification of thermal and rheological characteristics of bitumen by waste PET/GTR blends, Constr. Build. Mater., **2017**, 134, 157–166.
45. Rean Maharaj, Chris Maharaj and Martina Mahase, The performance and durability of polyethylene terephthalate and crumb rubber–modified road pavement surfaces, Progress in Rubber Plastics and Recycling Technology, Vol. 35(1), 3–22, 2019.
46. https://www.teriin.org/sites/default/files/files/factsheet.pdf
47. https://www.business-standard.com/article/current-affairs/india-s-plastic-waste generation-has-more-than-doubled-in-5-years-govt-121120601297_1.html

48. Hunt EAPE (2002) Crumb Rubber Modified Asphalt Concrete in Oregon.
49. Zainab HN, Ibrahim K, Madzalan N, Isa Mohd T (2011) Rheological Properties of Polyethylene and Polypropylene Modified Bitumen. World Academy of Science, Engineering & Technology 50: 293.
50. Haopeng Wang, Xueyan Liu, Sandra Erkens and Athanasios Skarpas, Experimental characterization of storage stability of crumb rubber modified bitumen with warm-mix additives, Construction and Building Materials 249 (2020) 118840.
51. Mashaan NS, Ali AH, Karim MR and Abdelaziz M, Effect of crumb rubber concentration on the physical and rheological properties of rubberised bitumen binders. Int J Phys Sci 6, 684-690, 2011.
52. Punith VS, Veeraragavan A and Amirkhanian SN, Evaluation of Reclaimed Polyethylene Modified Asphalt Concrete Mixtures. International Journal of Pavement Research & Technology, 4, 1-10, 2011.
53. Awwad MT and Shbeeb L,The Use of Polyethylene in Hot Asphalt Mixtures, American Journal of Applied Sciences 4, 390-396, 2007.
54. Lesueur D, Colloidal Structure of Bitumen: Consequences on the Rheology and Mechanism of Bitumen Modification. Adv Colloid Interfac, 145, 42-82, 2009.
55. IRC SP 53-2010, Guidelines on Use of modified bitumen in road construction, Indian Road Congress, New Delhi-110022.