IJCRT.ORG ISSN : 2320-2882

INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)

An International Open Access, Peer-reviewed, Refereed Journal

A Critical Review On Performance Of Flexible Pavement Using Co-Polymers And Tyre Waste

Visvdeep Verma and Devender Kumar

Department of Civil Engineering, OSGU, Hisar- 125001

Abstract

India is a developing nation. With the evolution of urbanization, plenteous amount of disposed waste products like scrap rubber tires, polythene carry bags, plastic bottles, etc are generating day by day. Total waste plastic generation in India is 5.6 million tons per year, which is 70% of total plastic consumption. Being a non-biodegradable product it could not be dumped in landfills because through the erosion caused by wind and water, it will come back to the surrounding environment, which cause risk to human health. Similarly accumulation of scrap tyres which are stacking up at a rate of 20% per year due to rapid increase in number of vehicles worldwide has become the major waste management problem. The main aim of the work is to make partial replacement of bituminous binder by recycled tyre waste and recycled High density polyethylene (co-polymer) to improvise the various characteristics of Bituminous Concrete (BC) mix and to use discarded waste in an effective manner. This review details about the properties, advances, effects in bitumen concrete. It also states the background and deep study on pavement design with crumb rubber and HDPE.

Keywords: *Tyre waste; HDPE; bituminous concrete; scrap tyres; plastic.*

Introduction

India is an emerging country. India's population accounts for 17.74% of the world's total, which is 1.37 billion, with a growth rate of 1.08%. The population density is 460 per km2 with 33.6 per cent of the local population. The massive population count needs not only subsistence services as well as the need for strong infrastructure growth. Since transport infrastructure plays a fundamental role in country social and economic growth. It encourages the growth of the market, seamless exchange of both individuals and commodities. It has always found itself superior to any other means of transport because of its durability, versatility of activities, ease of access, door-to - door facility. Subsequently, in India, the flow

of freight and passengers has increasingly moved to the highways, rather than other forms of transport, over the past few decades.

According to the Government of India's "National Highways Development Project' report, over the 60-year period from 1951 to 2011, the complete road length in India expanded by more than 11 times. The network services expanded from 3.99 lakh km to 46.90 lakh km from 31 March 1951 until 2011. Translationally, the breadth of the paved path extended in absolute as well as proportional words. As of 31 March 2011, the number of paved highways, that was 1.57 lakh km (39.35 percent with all road lengths) as at 31 March 1951, grew to 25.25 lakh km (53.83 percent with all road lengths). In India, nearly 60 percent of the overall commodities and 85 percent of total people are carried with the usage of transport infrastructure systems. In India, too, automobile numbers are rising at an annualized rate of 12 percent, although the highway network's rate of growth has been 4 percent per annum from 1951. Because of this rise in the number of vehicles compared to road expansion, the growth of potholes, longitudinal and lateral cracks and permanent deformations in flexible pavement has been accounted for [1].

Paving plays an essential function on every road initiative. The design of each road must be conducted in such a manner that this can survive the traffic load without even any degradation and harm during its design life.

Paved essentially are categorized into two kinds:

1. Flexible pavement
2. Rigid pavement

Flexible pavement is built with different layers of granular materials with the bituminous binder coating at the center. The flexible pavement can be functionally evaluated during its design life, regarding the traffic load and climatic conditions, whenever needed. The defective pavement surface could be used for the approach of 'milling and recycling' that also helps to obtain the high salvage value of the substance regressed. Rigid pavement consists of a cement concrete pavement slab of paving quality concrete (PQC) which utilizes both as worn surface and even an effective base layer. The pavement slab also isn't settled immediately over subgrade to the soil. There is indeed a sub-base path that sits under the asphalt paving layer of cement. There is indeed a sub-base level that sits under the asphalt paving layer of cement. There is also no necessity for major repairs in cement concrete pavement compared with the bituminous pavement, except for the servicing of joints and drainage system.

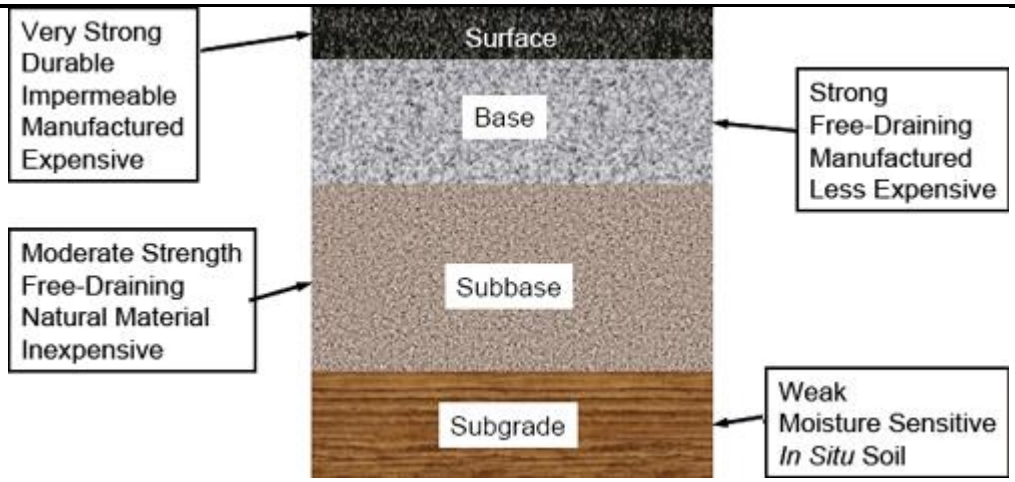

Fig. 1 Flexible Pavement Structure

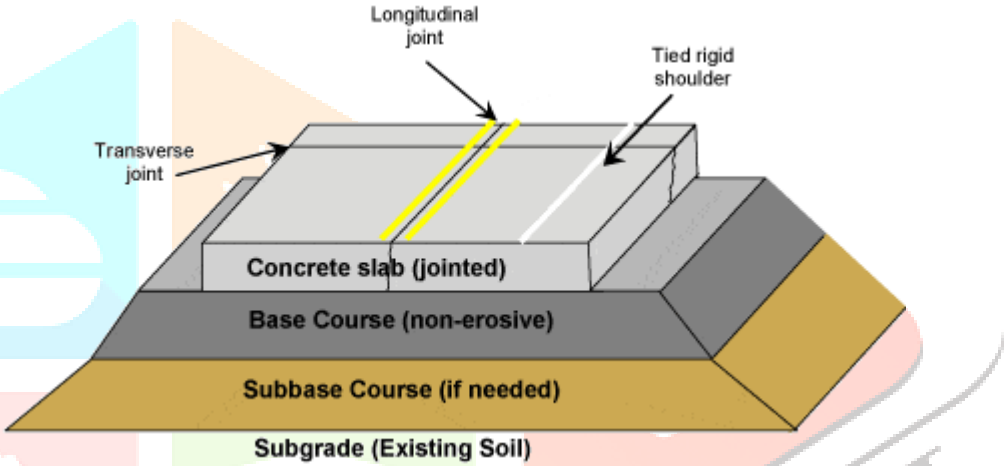

Fig. 2 Rigid Pavement Structure

For its low operating cost, the flexible pavement is recommended over cement concrete pavement, and it could be enhanced or reinforced in able to be collected on traffic growth during its useful life. Paved choice depends both on expense of the life cycle and initial expense. The expense of the cement concrete pavement's life cycle seems to be lesser than the flexible pavement, that also varies on initial cost, recovery, and servicing costs throughout pavement life span. Due to the sharp increases in the cost of bituminous paving, now a day engineers are paying increasingly interest in the development of concrete block pavements.

Some plastics can be recycled but they became more poisonous to a natural atmosphere after processing due to adding fire retardants, stabilizers, chemicals and shades etc. Plastic can also be reused only three or four times, as the thermal recycling process tends to cause the composite material to deteriorate owing to those whose life is decreased. As such recycling can never be the even dependent alternative for secure treatment and disposal of plastic material.

In general, plastic materials are of two kinds:

- Thermoplastic (Reusable)
- Thermosetting (Non-Reusable)

Thermoplastics

Carving of thermoplastic substances can be done in any form underneath the impact of heat and pressure, and then they become hard on freezing. Individuals could be sculpted under another much of the same circumstances when needed. Several of the components used in thermoplastics are poly ethylene (low density & high density), poly vinyl chloride, poly propylene, poly ethylene terephthalate, poly vinyl alcohol etc.

Thermosetting

Remolding or restructuring for thermosetting substances could not be achieved by force and heat impact; their form can be provided once and only. Suggestions are epoxy resins, vinyl esters, polyesters, melamine, alkyd resins, urea-Formaldehyde and Bakelite. Likewise, the abundance of waste tires, that are trying to stack at a rate of 20 percent annually owing to the sudden automobile growth worldwide, has now become the big issue of waste disposal[4]. Nevertheless, there is not a particular solution besides about their dumping from these strategies. Accidental fires triggered in accrued routes can cause harmful exhausts for just a significant length of time. Opposite to natural order. Whenever a significant heap can get flames, cessation of the flames is difficult, if totally plausible. In some cases it is possible to be seen from the kilometers the soot generated by ongoing fires of the heap of tyres for days.

Due to the extreme creation of smoke and heat, firemen encounter significant problems with traditional techniques of extinguishing such fires. Furthermore, usage of water or foams for extinguishing fires would worsen the contamination extent of air as well as soil. With this purpose, waste tires flames are permitted to blow out periodically in a fairly much regulated fashion until the entire heap is exhausted.
Through recent decades, various researches have been carried out on the use of reused waste material to modify bitumen rather than virgin polymers, where both pavement construction and environmental protection would then reduce costs. This would also boost the pavement's structural behavior which helps reduce the maintenance and repairs even during pavement 's service outcomes and cause the versatile pavement's life-cycle expense. Thus, issues linked to the lightweight pavements could be operated with in a safer and more efficient way by adding reused waste products to binder.

Throughout its fractional extraction, bitumen is usually produced as synthetic oil by product. The bitumen binder consists of a colloid multiphase structure. There are generally three groups with substances within it that are oils, resins, as well as asphalt. The separation of maltene shapes the

petroleum and resin. Distinctive dimensions of these mixtures can prompt different types of bitumen micro structure [5]. Bitumen was used to build versatile roads for such a long period of time thanks towards its water insulation and linking abilities. The mechanical performance of bitumen depends primarily on the chemical makeup of maltenes as well as the quantity of asphalt that consequently reduces the binder's temperature and stress-strain behavior [6].

Paving level bitumen especially used to build surface and binder courses. Bitumen continues to remain semi-solid, moist and venomous at standard surface temperatures however its viscosity reduces and reaches fluid uniformity with temperature rises. The bitumen is heated to temperature range of 135 to 180 ° C based mostly on bitumen grade being used and method of design adopted for the development of the durable pavement. Bituminous mixture is produced by combining in the hot combining plant preset amounts of "fine and coarse aggregates, filler including bitumen binder". The efficiency of bituminous blends depends on the bitumen's rheological and physical characteristics [7, 8]. Rutting tolerance of the versatile pavement relies on the properties of a bitumen binder for 40 per cent [9].

Need for Asphalt Mix Modification

The bitumen viscosity varies substantially per degree because about which the surface is much more heat reactive. Under high weather events, the resilient worn surface of the pavement is too elastic for the likelihood of irreversible deformation across the rim line of the automobiles and is too steep under lower temperature conditions, resulting in fractures developing under the repeated movement of loads [10].

Desired Properties of the Asphalt Mix

The asphalt blend will have the following characteristics for building the levels of durable pavement:

- Bituminous mix will have ample flexibility to withstand the permanent deformation & stresses that evolve as a consequence of repeated wheel loading condition. The desired stiffness of the blend may be achieved by careful selection of aggregates uniformity, bitumen binder and its ratio.
- Throughout the pavement's construction period, the bituminous blend will stay stable to tolerate the creation of cracking and wear impact. Adequate combining of binding material and aggregates may accomplish this.
- The mix will also have the up nearly of air voids because more redevelopment of a mix with both the bleeding of bitumen mix will occur underneath the traffic flow, so that will allow the reducing of resistance to skid on the slippery roads.
- The bituminous top surface will have ample resistance to skid right just after start of traffic movement and during pavement's maintenance window. To fulfill this criterion, coarse aggregates included in the paving will has a highly reflective appearance of marble.

Day after day weather shifts and intensified strain on tires, axle weights, automobiles rely on requests to improve the characteristics of the bituminous blend. Alteration of a bituminous blend has been the main approach to enhance the multiple properties. Some of the best solutions is to adjust polymers that boost the temperature sensitivity of its binding material, which implies that they improve the rigidity of the mixture at extreme temps and minimize its rigidity under lowered conditions of temperature [11, 12].

Asphalt Mix modification using polymers

Normally, the fusion of polymer compounds in bitumen mix by chemical change or mechanical mixing will greatly enhance the properties of the traditional binder [13]. There really are different polymers used during bitumen modification that would generally be divided into two categories: thermoplastic plastomers and elastomers [14]. Table 1 describes the description of the different types of polymers according to IRC: SP: 53-2010, used to adjust asphalt blend.

Thermoplastic elastomers which are the form of copolymers exhibit each elastomeric and thermoplastic characteristic. Bituminous blend that is produced by adjusted elastic polymer bitumen exhibits considerably high durability which has less density modulus than traditional blends. While the blend formulated by improved bitumen from plastomeric polymer does have the same or stronger stiffness modulus than the traditional mix with no noticeable improvement in durability. But elastomeric style polymers could be used in less temperature areas whereby larger versatility is necessary [15].

Table 1 Polymer Modifier Classification

	Polymers	**Examples**
Thermoplastic	Elastomeric	Ethylene Ter Polymer (ETP) SBR, SBS block copolymer ,Styrene Isoprene Styrene (SIS) etc.
	Plastomeric	Ethylene-Methyl-Acrylate copolymers (EMA), PE, Ethylene Butyl Acrylate (EBA)etc.
Rubber	Crumb Rubber/ Treated Crumb Rubber	Powdered scrap Rubber
	Natural Rubber	Rubber Powder or Latex
	Synthetic Rubber Latex	SBR latex and any other suitable synthetic rubber

Uses of modified plastic waste

As per the CPCB report, gross plastic waste production in the country is 5.6 million tons each year, which constitutes 70 per cent of the overall plastic use. Because of the non - recyclable existence of plastic, they will create significant environmental concerns if they spill in an unjustified manner. Plastic waste materials are combusted to create poisonous gases like HCL, CO and N3 - etc. Inappropriate waste disposal plastics such as HDPE, LDPE and PP may contribute to surface water pollution due to contamination of the radioactive materials such as cadmium and lead. Use new polymers to change the binder contributes to expensive concrete development owing to their significantly higher costs relative to the traditional binding material. Many experiments have also been produced today using the reused polymers to adjust the bitumen blend to address these problems. Basically, reused plastic wastes are grouped into seven groups, as seen in table 2.

Table 2 Categorization of Waste Plastics

Plastics	**Use**
PS	Loading with gel, ice cream cups, tea cups, etc.
LDPE	Bear Boxes, films
HDPE	Detergent-milk bottles, pots etc.
PET	PET flasks, water cups, etc.
PVC	Pipes, wires, flooring etc.
PP	Container films, drug tubes, snack liners, etc.
Others	Multilayer and varnished fabrics, fabrics of thermoset, acrylic Bakelite, melamine, polycarbonate etc.

As per the analysis performed by **Murphy et al. (2001**) [16], polypropylenes really aren't effective in changing the bituminous mix since they exhibit functional problems during processing and combining, resulting in low bitumen cohesion. It was also observed that there was not sufficient stiffness of the adjusted blend throughout the Indirect Tensile Stiffness Modulus check as LDPE used as a replacement for SBS.

Garćıa-Morales et al. (2004) [17] performed an examination using Low Density Polyethylene (LDPE) & Ethylene Vinyl Acetate recycled as modifications as well as the findings showed the mechanical characteristics of bitumen could be strengthened by using reused polymers while the adjusted binder is used as a layer cover. Bitumen alteration by waste materials increases the thermophysical, thermal and physical characteristics of bitumen, but impact strength relies on the polymer quality in the changed binding agent [18]. The key issue for reused waste polymers is the isolation between phases owing to the inadequate chemical reaction of binding material and polymers. The physical and thermal characteristics of a changed binding material could be improved by applying a irradiation method to reused polymers, that allows to achieve stronger contact among binding material and polymer thanks to the gradual chain cross-linking [19, 20] .

High Density Polyethylene (HDPE)

High density polyethylene, officially shortened as HDPE or PEHD, is a synthetic polymer that has a broad variety of applications due to its versatile characteristics. While as the title indicates, HDPE's absolute gravity is higher to LDPE, but the disparity isn't really that much. Because of its limited spreading, the HDPE has variation in its physical characteristics, irrespective to which it has greater tensile strength than the LDPE. HDPE exhibits strong intermolecular forces rendering it a regular polymer. Since with its favorable properties it can also be used in the production of different products. The HDPE 's real gravity varies from 0.93 to 0.97. Being rigid and immune to a motion of effects, this can withstand the temp up to One hundred twenty ° C without even being affected. Like PP this is not autoclavable, goods should be sterilized with the usage of high temperature and pressure through the use of autoclave circumstances. HDPE holds a transparent or opaque feel. It is usually used to produce engine oils cans, chlorine jars, water bottle, or dairy pots.

Recycling of High-Density Polyethylene

HDPE is among the polymers that could be used more quickly. The garbage materials are obtained also by recycling firms whereby their sorting is carried out. At first there was plastic washing, to remove any unused garbage. The plastic is then homogenized, with both the intention of recycling only HDPE, so if there are certain plastic polymers in such a collection, these can kill the finished version after reusing. The specific gravity of HDPE is far weaker than those of PET (1.430-1.450) which means that such plastic polymers may be separated by using the "Sink-Float Separation" technique. Yet HDPE does have a particular gravity close to PP's, meaning that such a product cannot be utilized. NIR devices should be used for such case, even when the plastic becomes extremely dark and unifies that infrared waves. Before that the HDPE is shredded and melted to enable further processing. Then the plastic is chilled in the shape of flakes which can be used again during the manufacture of plastic goods.

Asphalt mix Modification using Recycled HDPE

Hınıslıoğlu et al. (2004) [21], a research on the alteration including its bituminous concrete blend was carried out utilizing various HDPE amounts, i.e. 4, 6 and 8%. It was observed from the tests also that 4 percent HDPE was the optimal material and for alteration with mixing time of 30 min and mix temperature of 165 ° C. Tests show also that HDPE adjustment dramatically improves the mix's Marshall Stability and Marshall Quotient performance that can provide improved tolerance to irreversible deformation. So, although changed BC mix flow value was expected to be comparable to those of standard mix.

The temperature vulnerability as well as the resistance to moisture of an asphalt blend could be decreased by adding HDPE throughout the asphalt binder. It is attributed to rise of the adjusted mix's tensile strength & rupture modulus. Updated HDPE blends have lower strain values than unmodified blends [22].

As per studies carried out by **Köfteci (2016)** [23], the strongest results were obtained with 4 percent HDPE when various percentages of up to 4 percent were being used to change the asphalt blend. The features of the adjusted blend up to 3 per cent are not much changed. Therefore, the change above 3 per cent could produce the asphalt mix's beneficial benefits.

There seems to be an inappropriate chemical reaction among bitumen and reused HDPE polymer, owing about which phase separation chances occur. To solve this issue recycled HDPE is subjected to irradiation that enhances the chemical exchange between them. Because of its stiffening effect, the thermal sensitivity of bitumen could be reduced by irradiated reused HDPE [24].

Waste Tyres

Tyre waste is a reused rubber that is collected from vehicle waste tyres. The tyres' main components are plastics, fiber, steel, black tar, plant, and vulcanized rubber. Reuse of such products may create certain products with a such a small risk of contamination. When recycled washed out tyres are collected, crumb rubber is produced.

- Cryogenic Grinding
- Ambient Mechanical Grinding

In cryogenic procedure grinding is achieved with the use of industrial refrigerants or liquid nitrogen to cool the tire chips at temperatures below - 80 ° C. In this annealing temperature, rubber begins to lose its strength that becomes porous in nature and it could be damaged or shattered quickly.

Scrap tyres split up at the temperature of the air setting, which is either at or near the usual room temperature. This grinding method has been used where tyres are split into tiny parts by utilizing the granulator strategies and bagel mills.

For each of these methods the magnetic current is used to isolate the steel wires from the tyres and the rubber compounds are removed with the application of vibrating sieves. Cryogenic methods used during crushing are much more costly but result produce tinny and finer crumbs.

Asphalt Mix Modification using tyre waste

As per the analysis undertaken by **Colom et al. (2007) [**25] about one billion tires are regarded as waste per year and this figure could hit 1200 million by 2030. There have been several reports about the usage of crumb rubber to adjust the bitumen blend.

Modified blends of crumb rubber are far less vulnerable to humidity and temperature. We perform flexibly at low temp and at high temperature environments provide greater tensile strength and steadiness. CR-modified blends and traditional mixes has no variation throughout the Marshall properties; however, the CR-modified mixes' exhaustion and rutting activity is considered to be stronger than traditional [26].

Xiao-qing et al. (2009) [27], a research on the usage of mechanically devulcanized field tyre rubber (m-GTR) with SBS for bitumen modification was performed, as well as the findings revealed that both traditional and rheological characteristics of modified SBS / m-GTR binder were stronger than those of updated SBS binder.

If the dry cycle is used to adjust the bituminous blend, the density declines even as amount of CR rises, leading to a change in the number of air voids. Regardless of its robust properties that is attributed to the recovery impact of rubber and that allows the combination less lightweight. Both of these factors, only with introduction of a greater proportion of CR, more bitumen binder is required to ensure good consistency of the blend [28]. The abrasion tolerance, fatigue function, creep resistance & indirect tensile strength are enhanced with the usage of crum rubber in BC mix [29]**.**

Use CR throughout the bitumen blend helps minimize noise pollution throughout traffic flow, while provides travelers with convenience while protection while minimizing break size.

Advantages of tyre waste

- An impermeable wearing course layer.
- Greater cohesion, which makes it possible to obtain structure with more critical granulometries.
- Greater resistance to fatigue, reducing the risk of cracking.
- Greater service durability, since greater resistance to aging is achieved in adverse conditions (Juniad et al., 2014).

Salient features of the polymer-waste-bitumen mix road

- Road strength is twice stronger than normal roads;
- Resistance towards water stagnation i.e. no potholes are formed;
- Less bleeding during summer;

- Burning of plastics waste could be avoided
- It doesn't involve any extra machinery;
- It doesn't increase cost of road construction; and
- It helps to reduce the consumption of bituminous mix vis-à-vis reduce cost.

Benefits of modified binder

- Improved resistance to surface-initiated cracking due to high binder content.
- Improved ageing and oxidation resistance.
- Improved resistance to fatigue and reflection cracking due to higher binder contents.
- Improved resistance to rutting due to higher viscosity and softening points.
- Increased night time visibility due to contrast between pavement and stripping.
- Reduced tyre noise due to increased binder film thickness and opening texture.
- Reduced construction time on site.
- Lower pavement maintenance costs due to improved quality pavement.
- Help in managing hazardous waste.
- Eco-friendly method of construction, and helps maintaining balance of environment.

Conclusions

Plastic used in road construction is not new. It is already in use as PVC or HDPE pipe mat crossings built by cabling together PVC (polyvinyl chloride) or HDPE (high-density poly-ethylene) pipes to form plastic mats. The plastic roads include transition mats to ease the passage of tyres up to and down from the crossing. Both options help protect wetland haul roads from rutting by distributing the load across the surface. But the use of plastic-waste has been a concern for scientists and engineers for a quite long time. Recent studies in this direction have shown some hope in terms of using plastic-waste in road construction i.e., Plastic roads. Waste plastic is ground and made into powder; 3 to 4 % plastic is mixed with the bitumen. The durability of the roads laid out with shredded plastic waste is much more compared with roads with asphalt with the ordinary mix. The use of the innovative technology not only strengthened the road construction but also increased the road life as well as will help to improve the environment and also creating a source of income.

References

1. Appiah, J. K., Berko-Boateng, V. N., & Tagbor, T. A. (2017). "Use of waste plastic materials for road construction in Ghana". *Case studies in construction materials, 6*,1-7
2. Grand View Research Inc. (2014). "Bitumen Market Analysis and Segment Forecasts to 2020". San Francisco.
3. CPCB (Central Pollution Control Board). (2013). "Overview of plastic waste management". Delhi.

4. Alamo-Nole, L. A., Perales-Perez, O., & Roman-Velazquez, F. R. (2011). "Sorption study of toluene and xylene in aqueous solutions by recycled tires crumb rubber". *Journal of hazardous materials*, *185*(1), 107-111.
5. Partal, P., Martınez-Boza, F., Conde, B., & Gallegos, C. (1999). "Rheological characterisation of synthetic binders and unmodified bitumens". *Fuel*, *78*(1), 1-10.
6. Cheung, C. Y., & Cebon, D. (1997). "Deformation mechanisms of pure bitumen". *Journal of Materials in Civil Engineering*, *9*(3), 117-129.
7. Chen, Z., Wu, S., Xiao, Y., Zeng, W., Yi, M., & Wan, J. (2016). "Effect of hydration and silicone resin on Basic Oxygen Furnace slag and its asphalt mixture". *Journal of cleaner production*, *112*, 392-400.
8. Pan, P., Wu, S., Xiao, Y., & Liu, G. (2015). "A review on hydronic asphalt pavement for energy harvesting and snow melting". *Renewable and Sustainable Energy Reviews*, *48*, 624-634.
9. Sybilski, D., Soenen, H., Gajewski, M., Chailleux, E., & Bankowski, W. (2013). "Binder testing." In *Advances in Interlaboratory Testing and Evaluation of Bituminous Materials*(pp. 15-83). Springer, Dordrecht.
10. Masad, E., Huang, C. W., Airey, G., & Muliana, A. (2008). "Nonlinear viscoelastic analysis of unaged and aged asphalt binders". *Construction and Building Materials*, *22*(11), 2170-2179.
11. King, G. N., & King, H. W. (1986). "POLYMER MODIFIED ASPHALTS: AN OVERVIEW". *Solutions for Pavement Rehabilitation Problems*.
12. Airey, G. D. (2002). "Rheological evaluation of ethylene vinyl acetate polymer modified bitumens". *Construction and Building Materials*, *16*(8), 473-487.
13. Ahmedzade, P. (2013). "The investigation and comparison effects of SBS and SBS with new reactive terpolymer on the rheological properties of bitumen". *Construction and Building Materials*, *38*, 285-291.
14. Zhu, J., Birgisson, B., & Kringos, N. (2014). "Polymer modification of bitumen: Advances and challenges". *European Polymer Journal*, *54*, 18-38.
15. Isacsson, U., & Lu, X. (1995). "Testing and appraisal of polymer modified road bitumens—state of the art". *Materials and Structures*, *28*(3), 139-159.
16. Murphy, M., O'mahony, M., Lycett, C., & Jamieson, I. (2001). "Recycled polymers for use as bitumen modifiers". *Journal of materials in civil engineering*, *13*(4), 306-314.
17. García-Morales, M., Partal, P., Navarro, F. J., Martínez-Boza, F., Gallegos, C., González, N., ... & Muñoz, M. E. (2004). "Viscous properties and microstructure of recycled eva modified bitumen". *Fuel*, *83*(1), 31-38.
18. Naskar, M., Chaki, T. K., & Reddy, K. S. (2010). "Effect of waste plastic as modifier on thermal stability and degradation kinetics of bitumen/waste plastics blend". *Thermochimica Acta*, *509*(1-2), 128-134.

19. Hawryluk, R. J., Hawryluk, A. M., & Smith, H. I. (1974). "Energy dissipation in a thin polymer film by electron beam scattering". *Journal of Applied Physics*, *45*(6), 2551-2566.
20. Berejka, A. J., Montoney, D., Cleland, M. R., & Loiseau, L. (2010). "Radiation curing: Coatings and composites". *Nukleonika*, *55*, 97-106.
21. Hınıslıoğlu, S., & Ağar, E. (2004). "Use of waste high density polyethylene as bitumen modifier in asphalt concrete mix". *Materials letters*, *58*(3-4), 267-271.
22. Attaelmanan, M., Feng, C. P., & Al-Hadidy, A. I. (2011). "Laboratory evaluation of HMA with high density polyethylene as a modifier". *Construction and Building Materials*, *25*(5), 2764-2770.
23. Köfteci, S. (2016). "Effect of HDPE based wastes on the performance of modified asphalt mixtures". *Procedia engineering*, *161*, 1268-1274.
24. Ahmedzade, P., Günay, T., Grigoryeva, O., & Starostenko, O. (2017). "Irradiated recycled high density polyethylene usage as a modifier for bitumen." *Journal of Materials in Civil Engineering*, *29*(3), 04016233.
25. Colom, X., Carrillo, F., & Canavate, J. (2007). "Composites reinforced with reused tyres: surface oxidant treatment to improve the interfacial compatibility". *Composites Part A: Applied Science and Manufacturing*, *38*(1), 44-50.
26. Palit, S. K., Reddy, K. S., & Pandey, B. B. (2004). "Laboratory evaluation of crumb rubber modified asphalt mixes". *Journal of materials in civil engineering*, *16*(1), 45-53.
27. Xiao-qing, Z., Can-hui, L., & Mei, L. (2009). "Rheological property of bitumen modified by the mixture of the mechanochemically devulcanized tire rubber powder and SBS." *Journal of Materials in Civil Engineering*, *21*(11), 699-705
28. Moreno, F., Rubio, M. C., & Martinez-Echevarria, M. J. (2011). "Analysis of digestion time and the crumb rubber percentage in dry-process crumb rubber modified hot bituminous mixes". *Construction and Building Materials*, *25*(5), 2323-2334.
29. Msallam, M., & Asi, I. (2018). "Improvement of local asphalt concrete binders using crumb rubber". *Journal of Materials in Civil Engineering*, *30*(4), 04018048.