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Waste polyethylene effect on asphalt binder and mixture properties: State of the art

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ABSTRACT

A detailed review evaluating performance of asphalt binder and mixture after adding waste polyethylene (WPE) is presented in this paper. Searching for the most suitable ratio of WPE to be added and looking for which properties of asphalt binder and mixture are affected by WPE addition are addressed. There is an assent among many researchers that adding WPE to asphalt mixture has resulted in better properties shown by increasing softening point, viscosity and specific gravity, decreasing penetration, enhancing complex shear modulus values and decreasing phase angle values in addition to improving thermal stability, permanent deformation resistance, moisture resistance and creep modulus, while modified mixture bulk density and creep rate have decreased. The most suitable ratio of WPE is recommended between 4% and 12% by binder weight. Using WPE in its different forms has recently become very common in different regions worldwide because it helps in saving environment and country's economy.

Keywords: asphalt binder, asphalt mixture, waste polyethylene, rheological properties, Marshall test.

INTRODUCTION

Use of waste plastic (WP) dates to beginnings of 1990s [1]. Plastic material in general is non-biodegradable and durable. Strong chemical bonds make it durable and highly resistant to nature. Plastic is a non-biodegradable material, which means that it stays in environment and causes pollution and some diseases like cancer [2]. WP material is accumulated widely causing environmental damage. A suitable easy solution is to convert it into useful new material [3]. Since middle of last century, billion tons of plastic is dropped away. Thousands of WPs mixed with water that cannot be decomposed led to kill of water creatures. For best resources utilization, we can utilize it by adding it to asphalt mixture.

WP includes different shapes that result from different origins, such as polyethylene (PE), polypropylene (PP), polyurethane (PU), ethylene-vinyl acetate (EVA), and many other fibers that could be used with asphalt binder to improve its characteristics [4, 5]. Since PE is considered as one of the most important waste sources, it will be considered in detail. Reuse of WP including PE is advantageous. Replacing some of ordinary used asphalt binder by PE reduces pavement construction and repairing cost in addition, to some extent, it helps in reducing pavement distresses especially rutting and potholes and makes roads more durable.

When WP material is used in asphalt pavement, wet and dry processes can be used [6, 7]. During wet process, asphalt is modified with WP by adding melting plastic to asphalt mixture to act as binder polymer additive. However, dry process includes a direct addition of WP to asphalt mixture in a form of aggregate or modifier material – WP is used as portion of aggregate particles in asphalt mixture. Using WP as part of aggregate needs to ensure that plastic particles are similar to aggregate particles. During mixing process, WP will soften at high temperatures [8].

In high-populated countries, number of serviced populations is dramatically huge, so fuel consumption, congestion, delay time, and accidents are challenges. Therefore, need to upgrade utilized resources becomes an important issue. Because road networks reflect economical level of countries, we can utilize waste material to save economy, upgrade road pavement characteristics and save environment [3].

Resource utilization of waste materials varies from country to another; some countries utilize 100% of waste materials but other countries utilize less. Recycling and addition of waste materials to any other raw materials are considered so effective in resource utilization. Roads are considered as one of the most important infrastructure facilities that constitute considerable cost and consume huge amounts of asphalt mixture [1].

Economic productivity and competitiveness have been met by developed countries, recently. When talking about competitiveness it does not mean only increasing production percentage or amount, but it deals with developing efficiency and safety of utilized issues. As population number increases, need for goods and transport vehicles also increases. Need for extra axle loads and much tire pressure also increases. Therefore, need for roads that accept all these changes became a necessity. Pavement road design should be developed in many suitable ways and use of some waste materials with asphalt binder/mixture to enhance its strength and durability is considered a great job [9].

Asphalt mixture is used widely worldwide. For effective utilization of available resources, it can be used with some waste material to overcome some environmental problems while enhancing economical side [10]. A great utilization of resources will be accomplished if we take environmental side into consideration. If there is a chance to utilize and use some waste material in improving pavement characteristics, it can be said that we optimize benefit and win. Recently, environmental pollution is enormous. Since waste polyethylene (WPE) is not a biodegradable material, its reuse is a great beneficial purpose. Circular economy is accomplished by reducing waste that is generated from normal use and using it in enhancing other product properties in addition to saving raw materials while using secondary one. Waste material utilization in asphalt roads is used only if it is environmentally superior to other alternatives.

WPE pollutes environment easily, natural asphalt is considered as a non-renewable source of energy and asphalt in general is an ultraviolet (UV) radiation material through its service life [11]. Using PE effectively reduces binder content which consists of the most expensive ingredient in asphalt mixture in addition, it enhances asphalt binder performance [12]. Considerable amounts of these secondary materials can be used in asphalt pavement roads. PE is one type of polymer used to enhance asphalt mixture characteristics. Different types of PE could be used with asphalt and many tests were done to decide suitable type for each mixture. Asphalt concrete modified with WPE is a suitable solution used to save environment, reduce thermal cracking, and improve pavement fatigue life. Effect of adding PE to asphalt mixture was noticed and many properties such stability, unit weight, flow, and air voids percent were studied to determine the effectiveness of adding PE.

Asphalt concrete or bituminous concrete is a material used in construction projects such as paving roads/parking lots/airports. Asphalt binder (bitumen) and aggregates are mixed, layered, and compacted. Dramatic increase in traffic volume and rabidly changes in environmental weather create a real need to search for a suitable alternative to improve pavement characteristics and prolong its service life through applying some modifications that satisfy strong pavement and enhance economical side.

Pavements are classified as flexible or rigid. When surface layer of pavement consists of bitumen, it is a flexible pavement that could deflect or bend under traffic loading. Bituminous concrete consists of aggregate and bitumen, and some additives or modifiers can be used. Flexible pavement consists of bitumen or asphalt used as binder material in addition to mineral aggregate that are mixed, laid down to form layers before compaction. Increase in traffic volume and variation in temperature from season to season affect performance of bituminous pavements that need to be improved to go with new changes. A lot of work has been developed on use of additives/ modifiers in bituminous mixtures [13].

Hot mix asphalt (HMA) is composed mainly of asphalt cement binder, which is a black to dark brown material extracted mainly from petroleum refining. It is used primarily in roads construction due to its waterproofing properties and remarkable binding. Asphalt is considered a very complex material with not enough good properties because it contains many aromatic/aliphatic compounds with high carbon numbers [14, 15]. Asphalt consists mainly of carbon and hydrogen that reach 80% and 10% respectively in addition to sulfur/asphaltenes/nitrogen/oxygen [16].

Environmental/thermal conditions accompanied by traffic loading are considered as roots for pavement distresses. Any extreme condition such a very high or low temperature leads to wide pavement cracks and rutting. Considerable efforts are made to overcome this problem and it could be solved or at least reduced by using some additive materials such PE. Increasing asphalt pavement service life and improving its performance by adding WP, especially WPE, are benefits at both economic and environmental sides [9]. Adding polymers in general to asphalt binders improves interfacial cohesiveness bond between binder and aggregate which enhances some properties and strengthens asphalt pavements. These additives or modifiers are used to enhance required properties and reduce economical aspects [13].

This paper summarizes several previous studies that have investigated effect of adding WPE to asphalt binder and mixture, aiming to provide a basis that helps utilize WPE in pavement construction. Material characteristics and environmental/economics aspects of using WPE in road construction are addressed. Impact of WPE on properties of asphalt binder and mixture are discussed. Search for optimum ratio of WPE by weight of binder is conducted. Conclusions and recommendations are provided based on better understanding of impact of WPE on properties of asphalt binder and mixture to enhance pavement performance.

WASTE POLYETHYLENE CHARACTERIZATION

Polyethylene is defined as a plastomer that flows when subjected to high temperature and becomes rigid when temperature decreases. PE melting point varies (110 °C to 120 °C) for low dense PE [17,18], and between 130 °C and 149 °C for high dense PE [19–21], but all these temperatures are still below common ranges used in production of HMA. Thus, it can be easily incorporated into asphalt mixture.

PE, shown as (CH_2-CH_2)n, contains long-chain polymer of ethylene and is produced as high-density polyethylene (HDPE), low-density polyethylene (LDPE), and linear low-density polyethylene (LLDPE). PE material is chemically synthesized by polymerization of ethane and differs widely according to its side chains, which can be changed during manufacturing. PE backbone is composed of C-C single bonds that are non-hydrolyzed. Mechanical properties of PE are not strong enough. It has poor creep resistance and low tensile strength, but it has good impact resistance. Impact effect increases as follows, HDPE < LLDPE < LDPE. As molecular weight (MW) and crystallinity increase, mechanical characteristics are enhanced [22–25].

Different ways could be used to add waste polyethylene. Size of particles added to binder can vary between 0.3 and 0.5 mm [26–28]. Generally, it is washed and dried then it is extruded [29–31], which is considered necessary if it is not clean. But if waste is clean, it is trimmed or grinded directly. Through collected studies, PE percentage that was added to binder varies between 1% and 10% by binder weight; commonly it is about 3% to 5%. Polymer that is incorporated into binder also differs, mixing temperature condition varies (150 °C to 180 °C), time of digestion varies (3 minutes to 4 hours), and valid mixing speed varies (120 rpm to 7200 rpm) [32].

Du et al. [33] mentioned that PE fibers/particles act as a bridge that prevents crack propagation. Asphalt with PE modified binder low-temperature properties are dependent mainly on ordinary asphalt binder properties and PE properties in addition to interaction between two material particles.

PE is separated mainly according to density value and degree of molecule branching. Many types of PE polymer could be used as additive materials. LDPE is a flexible and tough polymer known for its long branches that do not pack well into crystallites. When polymer chains become linear, polymer tends to become denser such as in HDPE. Molecules in HDPE are stronger to pack more closely. Ultra-high molecular weight polyethylene (UHMWPE) is associated with linear/long chains that carry load along backbone of the polymer. Cross-linked polyethylene (PEX) has cross and link together bonds, which improve chemical resistance properties and resistance at high temperature [34].

When ethylene polymerized under different conditions of pressure/temperature, a wide variability of polymers may result including greases, oils, hard/soft waxes in addition to plastics. Variability occurs due to changes in MW, within same MW. The variability occurs due to differences in polymer molecule structure. Solid polymer properties are found according to degree of crystalline which is affected by average distribution of MW, but mainly it is dependent on degree of chain branching [35].

PE material is considered as one of the most popular plastics that have been used for a long time. It is considered as a semi crystalline polymer material with well fatigue/wearing/chemical resistance in addition to wide variability in its properties. It is available in many forms [36]. PE general properties are provided in tables 1 [37]. More on PE properties and types comparison can be found in [38].

Bonds, such as unsaturated bond C=C, conjugated double bond C=C–C=C, vinyl $C=CH_2$, and oxygen-containing groups are very known chemical defects in PE. Concentrations of these defects were chosen in model systems to be approximately 3.24 mol/L (1 defect in a 1 × 2 × 3 supercell of PE). Although this value is greater than experimental counterpart (<~ 1 mol/L) separation between defects is already about 7 Å and above, being suitably large to model experimentally used density of defects. Electronic structure of PE with these defects were examined by computing Kohn-Sham energy levels, and thermodynamic and optical charge transition levels involving different charged states. PE illustrative images using scanning electron microscope (SEM) and particle morphology obtained after polymerization with chemical/physical characteristics are presented in Figures 1–4.

Table 1. Polyethylene properties [37]

Property	Value
Brittle point	-40 °C
Water absorption	(0.1–0.2) %
Thermal conductivity	0.29 W/mK
Chemical formula	$C_{10}H_8Q_4$
Specific gravity	1.459
Melting point	233 °C

USING WASTE POLYETHYLENE

Road construction

Retraction of environmentally commercial degradable PE material was studied in two levels. First, abiotic oxidation through air to simulate effect of compost environmental effect and second, through presence of microorganisms. Primary biofilm formation followed by fluorescence microscopy and later bacteria growth at surface of plastic material were observed using SEM. It was found that microbial growth generally occurred during existence of PE. Molecular magnification and broadening of MW distribution generally occurred next to preheating in air at 60 °C [42].

Using WPE is increasing daily. It becomes very clear that PE is used in every daily life

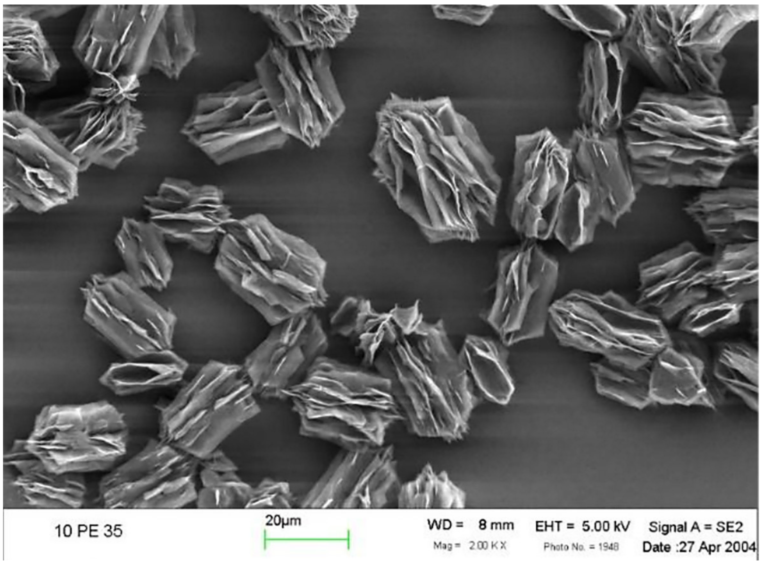

Figure 1. SEM image of PE, a common plastic. • SIZE: Scale bar represents 20 µm [39]

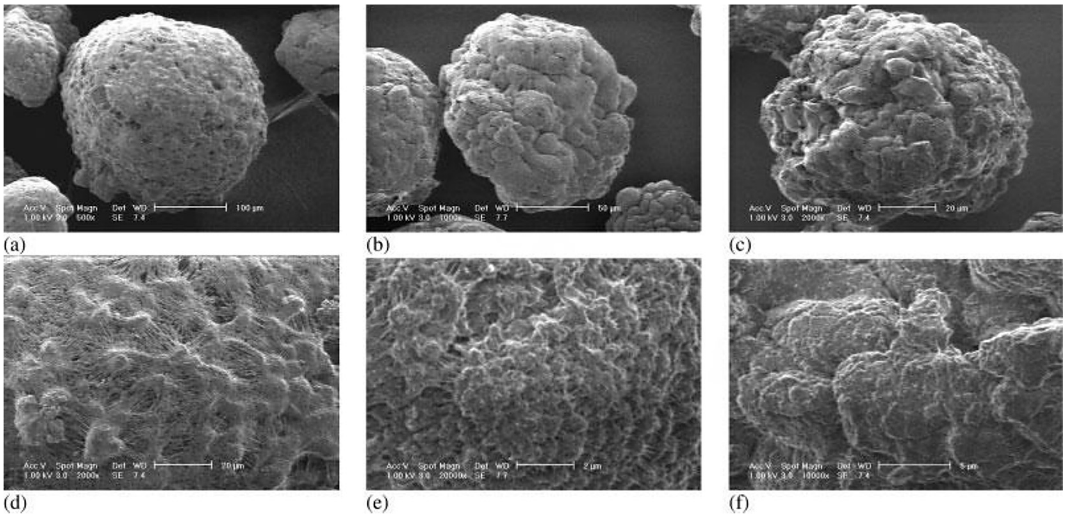

Figure 2. Particle morphology of PEs obtained after (a,d) 6, (b,e) 60, and (c,f) 300 min of polymerization [40]

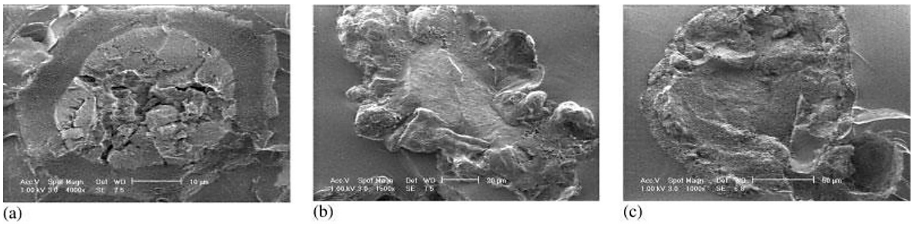

Figure 3. SEM cross-sectional imaging of PE particles obtained after (a) 6, (b) 60, and (c) 300 min of polymerization [40]

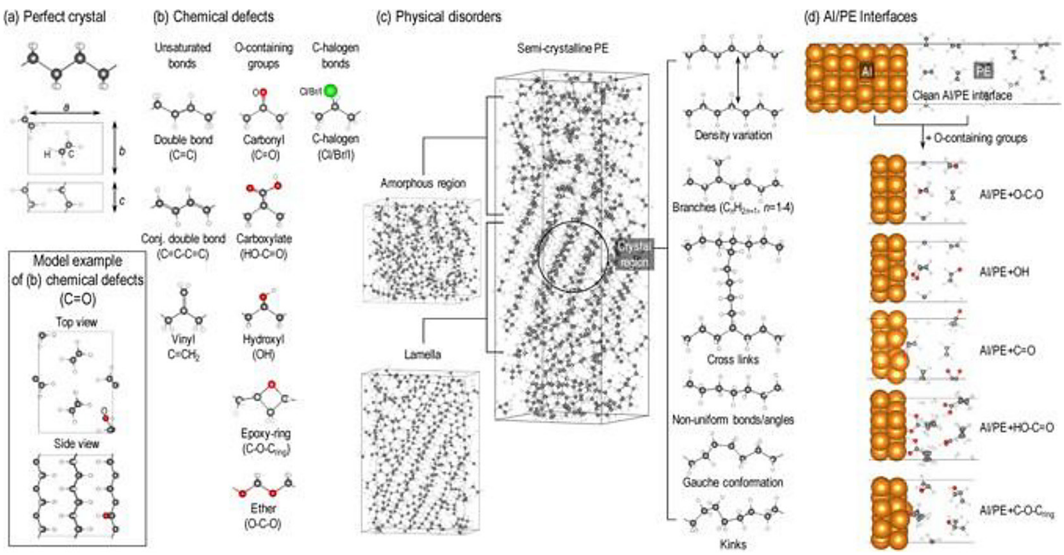

Figure 4. Chemical and physical properties of waste polyethylene [41]

activity. WPE demand in India is predicted to increase to 129% by 2023. Because of PE usage increment, pollution level caused by its consumption will increase inevitably, affecting every sort of environment including aquatic biome and terrestrial. Best method to reduce littering PE amounts is biological degradation [43].

During 2020 only 400 million tons of WPs were produced worldwide. Because of bad recycling applications, millions of tons of WPE pollutants accumulate in environment every year. PE is an elastic material that is chemically stable/non-biodegradable. Ordinary disposal methods include mainly incineration and landfilling. However, these methods are of high cost, not sustainable, and lead to an increase in environmental burden. Therefore, research has focused on biodegradation of WPE [44].

Regardless of PE sources, its environmental accumulation leads to serious problems. Estimations predict that 79% of WPE is sent to landfills storage [45].

As time passes, this PE waste will bear natural light oxidation. Sun's ultraviolet and warmth rays will splint C-H bonds in original polymer structure to shoot additives/plasticizers from polymer to environment and form greenhouse gases, which represents a serious environmental problem [46].

PE waste degradation processes are divided into non-biological and biological. photo and thermal oxidation, liquefaction of hydrothermal and chemical hydrolysis occurs through non-biological process. All these treatments are applied in early stages of degradation process [44].

Asphalt binder

Effect on penetration

Some previous studies have been conducted to investigate impact of adding different ratios of PE to asphalt binder. Recently, many tests by Wang et al. [1] showed a remarkable reduction in penetration when PE is added to asphalt binder. Melting PE to form homogenous materials and adding it to asphalt with suitable percentage resulted in better-modified bitumen properties. Excessive amounts of PE lead to segregation in resulted bitumen mix. A harder binder with significant increment in penetration values resulted when 10% of PE was added to 80/100 penetration grade asphalt. Optimum PE content of 10% provided satisfactory and better results than other contents according to Rahman et al. [47].

Novel low MW NH_2 terminated PE (NPE) material was utilized to overcome storage stability problem of PE modified asphalt. Adding NPE resulted in decreasing penetration values, adding 3% of NPE by weight resulted in 28.2% penetration reduction and adding 5% of NPE reduced penetration by 34.1%. Results showed remarkable improvement for NPE modified mixtures according to Li et al. [48]

Sathishkumar and Jeyapriya [49] found that adding LDPE to bitumen decreases penetration by 13.6%. Similarly, adding LDPE to (80/100) grade binder by using it to coat aggregate particles resulted in decreasing needle penetration values according to Afroz Sultana and Prasad [50].

Penetration values after adding HDPE to asphalt cement generally decreased. 35% decrement in penetration values occurred when only 5% of HDPE was added by weight, which reflected remarkable enhancements in resistance to deformation according to Attaelmanan et al. [20]. Relatively, a similar result was found by Afroz Sultana and Prasad [50] after adding HDPE modifier to asphalt binder. Adding grained HDPE to asphalt mixture reduced penetration values especially when 12% of HDPE was added to asphalt mixture by weight according to Gupta and Singh [2].

According to Punith and Veeraragavan [51], using reclaimed PE as a modifier reduced penetration values. Optimum value of 5% PE by weight provided best increment in penetration. Needle penetration values decreased in modified binders that used grafted PE according to Vargas et al. [52]. There is an assent among many researchers that as amount of added PE increases, asphalt binder penetration values decrease. A similar conclusion is reported in García-Travé et al. study [26].

Moreover, Yan et al. [53] tried to modify asphalt binder using reclaimed low-density polyethylene (RPE) and waste tire rubber (WTR) to indicate their effect on rheological properties of resulted modified asphalt. After adding different ratios of (RPE) and WTR to asphalt binder, binding beam rheometer (BBR) and dynamic shear rheometer (DSR) tests were conducted. A significant decrease in penetration was reported.

Milkowski [12] recommended that utilizing a small PE percentage with catalyst decreased penetration for modified asphalt by 50.7 pen at 25 °C. According to Fang et al. [54] penetration values decrease when preparation temperature of waste (PE) modified asphalt increases.

Effect on softening point

Adding PE to 80/100 penetration grade asphalt up to 10% increased softening point because PE modifier was associated with high softening temperature according to Rahman et al.

[47]. Moreover, it was found by Wang et al [1] that softening points were increased when PE was added to asphalt binder which results with significant effete in asphalt binder.

According to Bale [55], adding WPE on a heating temperature (100 to 160) °C enhances binding proprieties when softened in bitumen which ends up with adjustable mixture and lay for asphalt pavement layers; in addition to that it ends up with more durable, strong, and environment friendly roads.

Moreover, softening point increased by 14.28% according to Sathishkumar and Jeyapriya [49] when LDPE was added. As a similar result, softening point temperatures increase when LDPE was added which relies on increase in traffic volumes and extreme weather conditions. Adding LDPE and HDPE to (80/100) grade binder by using it to coat aggregate particles results in increasing softening point values according to Afroz Sultana and Prasad [50].

Al-Hadidy and Yi-qiu [17] concluded that higher softening points were noticed for modified binders than ordinary one. Similarly, softening point increased significantly when 5% of PE was utilized as modifier by weight according to Punith and Veeraragavan [51]. Similar results were reported by Vargas et al. [52] using grafted PE as a modifier for asphalt showing significant increase in softening point of binder.

Al-Dubabe et al. [18] found that adding LDPE resulted in increase of softening to about 3% of original asphalt in comparison with (2–5) % increments range when 3% of PE was added. Least increment was found for an ordinary binder with a softening point of 51 °C. Largest value was found for a binder with softening point of 42 °C [20]. Yan et al. showed that effect of adding low-density RPE and WTR with asphalt led to an increment in softening point [53].

Moreover, García-Travé et al. [26] found that as amount of added PE increases, softening point of binder increases while penetration decreases, which results in characteristics that are more rigid with higher permanent deformation resistance especially at high temperatures.

To get higher stability asphalt concrete mixture and less thermal susceptibility, 5% of PE in addition to 2% of catalyst was added to mixture in a trial to increase modified softening point, result showed a 27.2 °C after using PE and catalyst according to Milkowski [12].

Using HDPE asphalt binders resulted in strengthening asphalt cement rheological properties, 69% increment occurred in softening point for modified cement when 5% HDPE was added by weight. Softening point of virgin asphalt was raised by 69% at 5%wt. HDPE according to Ataelmanan et al. [20].

Using WPE as a modifier for base asphalt was affected by materials preparation temperature; softening point of waste (PE) modified asphalt increases as preparation temperature increases and best preparation temperature was found at 190 °C according to Fang et al. [54].

Effect on ductility

It was proven that adding NPE results in good ductility increment especially at low temperatures according to Li et al. [48]. Moreover, Kakar et al. [10] showd that WPE enhanced stiffness of binder at high temperatures.

Ductility values increased by 18.86% when LDPE was added according to Sathishkumar and Jeyapriya [49], in a similar manner adding LDPE and HDPE to (80/100) grade binder by using it to coat aggregate particles resulted in decreasing ductility values according to Afroz Sultana and Prasad [50]. Ductility values remains at its minimum ranges of specification, but a significant reduction in weight loss percentage was noticed which reflects better durability than original asphalt according to Al-Hadidy and Yi-qiu [17].

PE that was mixed with asphalt binder formed a multiphase system that contained considerable asphaltence that was not absorbed by polymer. Therefore, viscosity of mixture was enhanced significantly. According to Tuˇsar et al. [56], adding 5% of PE waste to 95% bitumen at low temperatures resulted in a more elastic combination but at higher temperatures, it resulted in a more viscoelastic binder.

Utilizing reclaimed PE as a modifier reduced ductility. Optimum value of 5% PE by weight provided best increment in ductility values according to Punith and Veeraragavan [51]. Ductility values decrease when preparation temperature of WPE modified asphalt increases, especially when 190 °C was used to prepare materials according to Fang et al. [54].

Adding RPE and WTR to asphalt binder according to Yan et al. [53] enhanced rheological properties by increasing complex modulus and rotational viscosity for modified binder at both high and intermediate temperatures. No clear conclusion was reached at low temperatures since m values and stiffness decrease with addition of RPE and WTR.

Adding PE to binder resulted in significant ductility reduction, which reflects more brittle behavior for modified binder at low temperatures [57]. A 35% reduction in ductility resulted after adding 5% of PE to binder at 25 °C [30] in comparison with 97% at 15 °C [53].

Stiffness/elasticity increased when reclaimed geo-membranes scraps composed of LDPE and polyester fibers were used according to García-Travé et al. [26] which means this is a suitable modifier.

Effect on specific gravity

Lower specific gravity for bulk density resulted as PE content increased, as a result to adding low density material according to Sharma and Dubey [58].

Specific gravity values increased when PE was added as a modifier, higher increment in specific gravity occurred when 5% of PE was added by asphalt weight according to Punith and Veeraragavan [51].

Effect on rheological properties

Wang et al. [1] tests indicated that asphalt binder with PE showed a comparable complex shear to ordinary binder modulus at cold temperatures, but high temperatures lead to higher modulus values compared to ordinary values, in addition to higher phase angle values showed at high temperatures. Kakar et al. [10] showed that addition of WPE to binder causes a significant increase in complex modulus at all frequency and temperature ranges, which reflects a better rutting resistance performance. Two different types of PE were blended with binder to show effect on thermal and mechanical behavior, and it resulted in improving rutting resistance in considerable manner.

Incorporation WPE enhanced asphalt pavement rheological properties such as phase separation/storage stability, problems concerning storage stability were limited according to Kumar and Sreeram [59].

To study effect of using recycled PE on future fatigue cracking/rutting of modified asphalt pavement, sections were designed according to Mechanistic-Empirical Method. Life cycle cost was used to determine additive type and content suitability. Using 30 years design period results showed good impact for PE in controlling predicted rutting and fatigue cracking when using dry/wet mixing processes according to Abdalfattah et al [60]. As greater quantities of PE were added, higher increment in complex modulus (G*) of binder were reported in addition to significant reduction in phase angle (δ) of binder which resulted in a better permanent deformation resistance (better rutting resistance) in comparison with ordinary binder.

Tuˇsar et al. [56] found that ordinary binder is more susceptible to permanent deformation in comparison with PE blends when adding 5% of PE waste in 95% bitumen. In addition, better fatigue performance and stress life is reported for PE blends. Adding 5% of PE is stated by Ahmedzade et al. [61] to provide best performance.

Experimental results by Wang [30] showed that modified PE asphalt storage stability is not good and cannot easily be solved by adding a stabilizer. To enhance compatibility of asphalt with PE, rubber plastic was added and resulted in effective improvement in compatibility of asphalt with PE and enhancement of its physical characteristics.

Moreover, base asphalt binder properties at low temperatures are better than PE modified asphalt binder properties, this result was returned to use improper testing methods according to Du et al. [33]. Using grafted PE at higher temperature improved performance of modified blend in terms of flow activation energy/rutting resistance according to Vargas et al. [52].

Additive materials were used to improve rheological properties of natural asphalt. Results showed that adding LDPE with eggshell waste to asphalt enhanced rheological properties of ordinary binder which was indicated after conducting laboratory tests according to Nejres et al. [62].

Incorporation 5% of HDPE in bitumen at medium and high temperatures enhanced fatigue/rutting resistance according to Fernandes et al. [21].

To improve durability of pavement, different research tried using different types of modifiers showing different performance for modified binder. Experiments done by García-Travé et al. [26] using reclaimed geo-membranes scraps composed of LDPE and polyester fibers showed better permanent deformation resistance/better fatigue life for modified binder.

Using RPE and WTR with asphalt binder showed a significant decrease in modified asphalt phase angle values according to Yan et al.

[53]. Using recycled PE with 150/200 grade asphalt improved resistance of fatigue cracks and rutting for modified binder according to Fuentes-Auden et al. [63].

Using WPE as an asphalt modifier resulted in improving deformation resistance and making it better than ordinary asphalt according to Hu et al. [31].

During asphalt modification process, WPE aged as preparation temperature increased. Using 190 °C as a preparation temperature for WPE modified asphalt was best preparation temperature that ensured best stability values according to Fang et al. [54].

Adding LDPE resulted in enhancing all-rheological properties of ordinary asphalt binders according to Al-Dubabe et al. [18].

Asphalt mixture

Effect on Marshall stability

To enhance properties of asphalt mixture, tests were done on modified mixtures after adding PE to 80/100 penetration grade asphalt by Rahman et al. [47]. Optimum asphalt content was determined, and further experiments were done on modified mixture to show impact of adding PE. Flow, unit weight, stability, and voids were studied. PE was added to asphalt mixtures up to 10% to enhance Marshall stability values and provides satisfactory and better results than other contents. Based on test results for using PE as a modifier to asphalt mixtures, best PE content was 6% giving best stability – result showed what reached up to 31.79% increment compared to ordinary asphalt mix according to Sharma and Dubey [58].

Using LDPE in thin asphaltic overlays resulted in enhancing modified mixture characteristics, saving needed cost, and reducing hazardous environment effect. Different contents of LDPE were used to show effect of adding such modifier. Results showed a great Marshall stability increment that reached up to 48%, best Marshall stability value is associated with 6% of LDPE according to Abduljabbar et al. [3]. One of the most used modifiers for asphalt cement was LDPE which was used to enhance bituminous mixes characteristics. Adding 2.5% of LDPE improved Marshall stability significantly according to Panda et al. [64].

Adding HDPE to hot mix asphalt (HMA) enhanced performance/properties of HMA. Different contents of HDPE were used to determine its optimum content which reflected best properties. Results showed that adding 4% of HDPE by weight was associated with best properties under medium traffic loading. Marshall stability reached 1630.48 kg after adding 4% of HDPE according to Issa et al. [63].

Adding PE to enhance (70/100) penetration and to show its effect on storage stability and morphological showed that LDPE improved mechanical properties. Large and small percentage of linear LDPE was studied for rheological characteristics and showed that LDPE spread through modified mixture matrix which reflected better linking between polymer chains and results in better storage stability according to Polacco et al. [65].

Different stability values were reported for asphalt mixtures according to their deformation resistance. Kakar et al. [10] found that adding PE to asphalt mixtures restricted particles movement and reduced storage stability problems in modified mixtures. Moreover, in a study done for bituminous concrete mixed with WP, results showed that there is a considerable increase in Marshall properties and stability for modified mixture according to Sanyog and Khan [66].

Adding LDPE and HDPE to (80/100) grade asphalt binder by using it to coat aggregate particles improved aggregate characteristics, stability values were enhanced if an optimum percent of PE reaches 80%. Therefore, there is a chance to use less quality aggregate and coat it with PE to improve its properties and to reduce economic cost according to Afroz Sultana and Prasad [50]. In addition, Marshall test stability values increased by 28.46% when LDPE was added according to Sathishkumar and Jeyapriya [49].

Yadav [67] concluded that use of WPE to coat aggregates was preferable than utilizing it as a bitumen modifier. That was applied by heating aggregates to about 160 °C, then sending it to mixing process while plastic was added. Coating process ended within one minute, then bitumen was added to hot-coated plastic particles at 160 °C. This criterion ended up with a 6% increment in Marshall stabilities value, significant reduction in Marshall flow, and enhancement of deformation resistance.

Vatsal Patel et al. stated that maintenance cost approaches zero and cost of construction also decreases significantly when WPE was used. Marshal stability values enhanced and became larger, potholes and stripping almost reduced while bonding between mixture ingredients enhanced in addition to that rutting significantly became less [68].

WPE was cleaned, washed, and used as a raw material with asphalt binder and resulted in improving Marshall characteristics of modified mixture. Marshall stability values increased when PE was added up to 4% by weight but after that its effect reflected and started decreasing [69].

Grained HDPE provided better characteristics for asphalt mixture, 12% of HDPE provide best stability increment according to Gupta and Singh [2].

In a study about using WPE in low noise asphalt mixes, PE did not melt purely during mixing process and worked as an elastic segment in modified mixture. This indicated that both PE and binder act as elastic material at low temperatures, but at high temperatures PE acts elastically and binder acts viscoelasticity according to Kakar et al. [70]

Moreover, using polyethylene terephthalate (PET) as a part of bitumen in bituminous asphalt mixtures using both dry and wet process with PET contents starting from 0 to 10% by bitumen weight, resulted in increase of Marshall stability values until 8% of PET by weight was added. Then Marshall stability started to decrease when 10% of PET was added according to Chaudhary et al. [71].

Since storage stability for asphalt mixtures after adding PE was poor, effect of adding rubber plastic in addition to PE was studied and results revealed that styrene-butadiene-styrene block copolymer (SBS) could be melted with WPE to form new composite modifier that overcome storage stability problem for modified mixture according to Wang [30].

Adding LDPE as an additive to asphalt concrete mixtures increased deformation resistance and better resistance for permanent deformations because it increased stability and reduced deformation according to Punith and Veeraragavan [51].

According to Attaelmanan et al. [20], blending different ratios of HDPE with 80/100 grade asphalt as a modifier showed better performance for modified HDPE asphalt mixtures than ordinary asphalt mixtures, especially when using 5% of HDPE by asphalt weight. This conclusion was generalized after studies on Marshall stability, Marshall quotient (MQ), tensile strength ratio, tensile strength, resilient modulus, and flexural strength for modified/unmodified asphalt mixtures.

Furthermore, Hınıslıoğlu and Ağar [72] studied effect of HDPE modified binder using different ratios of HDPE, different mixing time and mixing temperature resulted in significant increase in Marshall strength (stability) and Marshall quotient values, in addition to considerable increase in deformation resistance. 4% of HDPE blended at 165 °C for 30 minutes showed best deformation resistance because of considerable increase in stability. Adding 5% of HDPE increased Marshall Stability values of modified mix by 13% according to Attaelmanan et al. [20].

According to Awwad and Sheeb [73] PE was used to improve asphalt mixture properties. Different types of PE were used to coat aggregate. HDPE and LDPE were used. It was found that using grinded HDPE as a modifier gave better properties, especially when 12% by weight was used. Stability values were enhanced significantly and reached 2347 kg.

Aiming to enhance reclaimed polyethylene (RPE) properties, polymer modified asphalt mixture grafted by maleic anhydride (MAH) to form RPE (RPE-g-MAH) in availability of dicumyl peroxide (DCP) was used to study its effect on stability of modified mixtures at high temperatures. Results revealed that stability of modified mixture improved clearly at high temperatures and low temperatures according to Ma et al. [28].

Blending of WPE with asphalt sowed better stability at high temperatures even though it did not react with asphalt itself according to Fang et al. [54].

Effect on flow

Adding waste LDPE to asphalt cement increased stability values by 48% and increased flow by 33% according to Abduljabbar et al. [3]. Flow values increased by 39.59% when LDPE was added which reflected a good increase in flow properties according to Sathishkumar and Jeyapriya [49].

Blending different ratios of RPE with (80/100) grade showed that modified mixture is better than ordinary mixtures (without PE) in terms of temperature susceptibility/rutting resistance, especially when 5% of PE was added by asphalt weight. This result was concluded by Punith and Veeraragavan [51] in a wide test program including resilient modulus/dynamic creep/indirect tensile/Hamburg wheel track tests.

Results showed that adding HDPE up to 6% by weight is associated with best flow values under medium traffic loading according to Issa et al. [74]. Moreover, it was found that flow values decreased when PE was added according to Gupta and Singh [2].

Modified asphalt concrete mixture flow values generally were higher than that for ordinary asphalt concrete mixture. Using un-grinded HDPE as a modifier provided higher flow values than mixtures modified using other forms of modifier. Using LDPE resealed continuous increase in flow, which was not similar to other types of modifiers, which started to decline after reaching peak according to Awwad and Sheeb et al. [73].

According to Lastra-González [19], PE homogeneity and availability in addition to huge amounts of materials needed to construct roads make it fit economic criteria. PE is used with ordinary asphalt to form a modified asphalt mixture using dry method because of its simplicity. Test results indicated that using PE increased stiffness of modified mixture.

As PE was added up to 4% by weight, Marshall characteristics enhanced significantly. Values of Marshall flow decreased which reflected greater deformation resistance to heavy traffic loading according to Prusty [75].

Effect on VMA and air voids

Adding PE to 80/100 penetration grade asphalt up to 10% enhanced voids properties of modified mixture according to Rahman et al. [47]. Dense graded asphalt mix with PE is preferably used in pavements construction in terms of best stiffness, stability, and voids properties.

Results showed that adding HDPE in different ratios between 2% and 10% provided VMA values within specifications, but air voids were superior at 4% and 8% respectively according to Issa et al. [74].

VFB, VA and VMA are still within specification after adding PE according to Gupta and Singh [2]. A similar study concluded that when PE was added, VA, VMA, VFB values were still at required specifications and void spaces decreased in mix according to Prusty [75].

Small increase in voids of mineral aggregates resulted when using HDPE and LDPE. Result showed that when using 12% of HDPE or LDPE by weight, air voids percent were within specifications. Normally, air voids in modified mixture decrease as PE content increases at beginning but after that, it starts to increase according to Awwad and Sheeb [73].

Effect on water sensitivity

Asphalt binder durability was enhanced after adding LDPE because incorporating LDPE improved water sensitivity. Best moisture resistance occurred with a high content of LDPE up to 6% according to Abduljabbar et al. [3]. Using different ratios of HDPE with 80/100 grade asphalt resulted in less moisture and temperature sensitivity for asphalt modified mixture, especially when 5% of HDPE was added by asphalt weight according to Attaelmanan et al. [20].

Generally, when adding WPs, asphalt engineering characteristics, such as rutting resistance, water damage resistance, flow value, stiffness, in addition to indirect tensile strength values improved according to Lingyun et al. [76].

Adding PE as a modifier to asphalt mixtures with a content less than 1.5% showed less susceptible to moisture when compared with ordinary mixture according to Poulikakos et al. [23]. Water absorption or moisture susceptibility for modified mixes improved as a result of adding 2.5% of LDPE according to Panda et al. [64].

Moisture sensitivity values for modified mixes that used PET were improved when PET was added, especially using dry process according to Chaudhary et al. [71]. Water absorption of bitumen was controlled using PE, which prolonged service life of pavement according to Prusty [75].

Effect on dynamic modulus

As a grant result for humid climate and extreme temperatures, PE prolong pavement life by decreasing ordinary distresses according to Gupta and Singh [2]. PE asphalt mixtures revealed lower rate of creep and greater modulus of creep when compared with ordinary mixture according to Poulikakos et al. [23]

Fatigue resistance did not significantly increase after using PE to modified asphalt mixture according to Lastra-González [19]. A similar result was reported about rutting resistance of mixture modified with RPE grafted by maleic anhydride (MAH) to form RPE (RPE-g-MAH) according to Ma et al. [28].

According to Panda et al. [64], adding 2.5% of LDPE to asphalt cement improved fatigue life/

Table 2. Effect of adding polyethylene on properties of asphalt binder and mixture

Author	Criteria	Results
Habib et al. [79]	Adding PE to 1.5 by wt%	Did not change softening point. Penetration values decreased as polymer percent increased
Casey et al. [80]	Adding more than 6 wt % of PE	Did not provide sufficient result. When PE is added viscosity values increase. High PE content leads to reduced penetration value. When adding more PE, Phase angle separation increased
Dalhat et al. [81]	Adding PE/2% increase in PE content	leads to an increase in PG temperature approximately one level. Rutting resistance values for modified asphalt with PE showed better performance than conventional mix
Ho et al. [82]	Using PE wax/ Using low and large MW PE	Using PE wax makes blinding process easier and results with no phase separation. Using low and large MW PE were able to disperse in binder
Fuentes-Auden et al. [63]	Using recycled PE	Recycled PE leads to good increment in modulus, viscosity, rutting resistance
Yousefi [83]	Adding LDPE	LDPE disperses perfectly within binder
Singh et al. [84]	Adding maleic anhydride with PE	Adding maleic anhydride with PE to binder enhance binder rheological properties
Zhang et al. [25]	Adding LLDPE	Penetration and ductility enhanced when LLDPE is used
Vargas et al. [52]	Adding HDPE	Softening point values and penetration of asphalt enhanced when HDPE is added
Jun et al. [85]	Adding LDPE with other modifiers.	Storage stability of binder increased when LDPE is added with other modifiers
Nuñez et al. [86]	Adding LDPE with other modifiers	Addition LDPE with other modifiers to asphalt improved fatigue resistance of binder
Wang et al. [1]	Adding different ratios of PE to asphalt binder	Reduction in penetration Excessive amounts of PE lead to segregation Softening points were increased
Rahman et al. [47].	Adding different ratios of PE to 80/100 penetration asphalt binder	Significant increment in penetration Increased softening point values. Because of low melting point of WPE, fire point and flash point of PE modified binder reduced as PE increased up to 10% by weight
Li et al. [48]	Novel low MW NH_2 terminated PE (NPE) material	Decreasing penetration values. Good ductility increment
Sathish Kumar et al. [49]	Adding LDPE to (80/100) grade asphalt.	Decreases penetration values. Softening point increased by 14.28%
Afroz Sultana et al. [50]	Adding LDPE to grade asphalt. Adding HDPE modifier to asphalt binder	Decreases penetration values. Decrement in penetration values. Increasing softening point values
Attaelmanan et al. [20]	Adding HDPE to asphalt cement	Decrement in penetration values occurred when only 5% of HDPE was added by weight. Softening point of virgin asphalt was raised
Gupta and Singh [2]	Adding grained high HDPE to asphalt mixture	Reduced penetration values. Viscosity of mixture enhanced significantly
Punith and Veeraragavan [51]	Using reclaimed PE as a modifier	Reduced penetration values. Reduced ductility values, best optimum value of 5% PE by weight provided best increment in ductility values
Vargas et al. [52]	Using grafted PE	Needle penetration values decreased. Significant increase in softening point of binder.

Morever, Yan et al. [53]	Modify asphalt binder using RPE	BBR and DSR tested. A significant decrease in penetration. Enhances rheological properties by increasing complex modulus/rotational viscosity for modified binder
Milkowski [12]	Using small percentage of PE with catalyst	Decreased penetration values for modified asphalt by 50.7 pen at 25Co. Increase modified asphalt softening point
Fang et al. [54]	Adding PE to binder.	Penetration values decrease when preparation temperature of WPE modified asphalt increases. Softening point of WPE modified asphalt increases. Ductility values decreases when preparation temperature of WPE modified asphalt increases
Bale [55]	Adding WPE on a heating temperature (100–160) °C	More durable, strong, and environmentally friendly roads. Enhance binding proprieties when softened in bitumen
Al-Hadidy and Yi-qiu [17]	5% of PE was used as modifier by weight	Higher softening points were noticed for modified binders than ordinaries one. Ductility values remains at its minimum ranges of specification
Tuˇsar et al. [56]	Adding 5% of PE waste in 95% bitumen at low temperatures	Resulted with more elastic combination but at higher temperatures it is resulted in more viscoelastic binder
Sharma and Dubey [58]	PE added as a modifier	Specific gravity values for bulk density result as PE content increases

resilience modulus. According to Al-Ghannam [77], adding PE to asphalt mixtures revealed better rheological properties for modified mixture than those of ordinary asphalt.

LDPE enhanced mechanical characteristics of asphalt including resistance for high temperature shear according to Attaelmanan et al. [20]. A 59% increase in MR value occurred when 5% of HDPE was added to asphalt and 55% increment in MQ value occurred which reflects better-modified binder's resistance for deformation.

Effect on deformation and strength

Adding waste LDPE to asphalt binder enhanced deformation resistance to relatively low temperature crack and control its progression according to Abduljabbar et al. [3]. At intermediate temperature, values of indirect tensile strength increased significantly after adding LDPE.

Deformation resistance of modified mixture under heavy loads was enhanced when PE was added since PE decreased flow according to Gupta and Singh [2]. Using PE in asphalt mixture-controlled pavement deformation enhanced fatigue resistance and led to better adhesion between aggregate and asphalt according to Awwad and Sheeb [73].

Permanent deformation resistance was enhanced when PE was used in asphalt according to test results according to Poulikakos et al. experiments. Attention should be noticed when PE was added more than 5% by weight since rutting could appear [23]. Adding PE led to higher indirect tensile strength values.

To find a solution for cracks that occurred rapidly in cold regions, WPE was used to study its effect on mixture. PE content significantly affected mixture rutting resistance and low temperature cracking. At optimum percent of 8% of PE, mixture flexural strength improved according to Jew et al. [78]. Using grafted PE at high temperature improved rheological properties of asphalt best rutting resistance and flow energy occurred with modified asphalt according to Vargas et al. [52].

Tensile strength for modified asphalt mixture after adding 5% of HDPE was greater than tensile strength for ordinary mixtures according to Attaelmanan et al. [20] experiments. Modulus of rupture/stiffness for modified asphalt mixture after adding HDPE was greater than that for ordinary asphalt mixtures because modified asphalt viscosity is greater than that of ordinary asphalt. Adding HDPE in asphalt mixtures tightened cracking potential at low temperatures according to Du et al. [33].

Effect on density

Bulk density values for asphalt mixtures with PE were generally less than that of ordinary asphalt mixture. Maximum value of bulk density for modified mixture occurred when 12% of PE was added by mixture weight. Higher bulk density values were associated with HDPE and reached 2.28 gm/cm^3 according to Awwad and Sheeb [73].

Lower values for bulk density resulted when LDPE content that was added to asphalt mixtures increased according to Sharma and Dubey [58].

Additional findings about adding PE to asphalt binder and mixture are listed in Table 2.

CONCLUSIONS

The following conclusions are reached:

Adding WPE is a preferable option to enhance asphalt binder mechanical characteristics and save environment. Countries that produce PE in high quantities are looking for suitable ways to get rid of it. Through several previous studies, tests and research have demonstrated effect of adding PE; penetration values, ductility and all rheological properties for modified binder were enhanced, and softening point temperatures were decreased. Rutting resistance was improved when PE blended binder was used with asphalt and crack prorogation was controlled. Higher levels of safety were reached when PE was used with binder because flash and fire points were increased. Blending and mixing criteria of PE affected asphalt binder properties.

Adding WPE to asphalt mixtures improved Marshall Stability values, decreased flow values, strengthened air void related characteristics in addition it improved modified mixture strength and deformation resistance values. It must be confessed that utilizing PE as an asphalt modifier using suitable ratios is recommended to enhance all required properties.

Using different types of PE with asphalt showed more interest, recently. Using PE as a modifier in construction processes for pavements is useful in many ways. However, it is still not employed in its best manner. Extra funds are needed to do more studies and extra recommendations are needed to have a full image and to make decision step stronger. As a result, this work can help in solving some constraints and inspiring additional research to improve usage of PE for binder modification.

Since PE blended binder was not that effective when dealing with high temperature ranges, a realistic solution is needed.

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