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Understanding the Effects of Plastic Fines as a Bitumen Modifier on the Performance Properties of Hot Mix Asphalt †

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Abstract: The mechanical properties of most asphalt binder may not be sufficient to withstand the increased load requirements experienced by flexible pavement in practice, especially in regions notorious for severe climatic conditions. This necessitated the need to often enhance the properties of asphalt binder so that it can counteract most pavement distresses such as rutting and moisture susceptibility. In this study, economical industrial waste plastic dust (IWPD) from high-density polyethylene (HDPE) origin was used to modify base bitumen whose penetration grade was 60/70 and its effect on moisture susceptibility and rutting potential of hot-mix asphalt (HMA) were investigated thereafter. The IWPD were added at varying percentages (3%, 6%, and 9%) to the base bitumen by weight of the optimum bitumen content. Afterwards, Marshall Stability and indirect tensile strength ratio were performed on HMA samples produced with the IWPD-modified bitumen blends to evaluate respectively its rutting and moisture susceptibility. Based on the results obtained from the analysis, it was found that the modified blends of bitumen enhance the properties of the conventional bitumen. More importantly, the modified blend of bitumen with 6% IWPD content gave optimal result in terms of the increment of rutting resistance and improvement of moisture susceptibility of HMA.

Keywords: Flexible pavement; industrial waste plastic dust; hot-mix asphalt; moisture susceptibility; rutting; tensile strength ratio

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1. Introduction

Proper asphalt mixture design is paramount for ensuring the durability as well stability of flexible pavements, especially considering the increasing traffic volumes resulting from population growth. The continuous exposure to heavy traffic and repetitive loading has a detrimental effect on the rheological properties and overall performance of flexible pavements. Bitumen, an essential component of asphalt concrete in flexible pavements, acts as the binding material and consists of hydrocarbons that significantly influence the performance of bituminous pavements [1]. Hence, the use of poorly characterized binder mixtures in hot-mix asphalt (HMA) exposes the flexible pavement to various distresses that can compromise its integrity [1, 2].These inadequately characterized binders contribute to several types of pavement failures, with fatigue cracking, rutting, and moisture susceptibility being extensively studied, particularly in Nigeria [3].

Rutting is a longitudinal surface depression that occurs along the wheel paths in most flexible pavement. It is an incremental permanent strain or plastic deformation that is generated in poorly designed and constructed flexible pavement during repetitive traffic loading [4, 5, 6]. It is followed subsequently by conspicuous upheaval along the sides of the rut, fatigue cracking, surface loss, hence decreases pavement life [7, 8]. Moisture susceptibility which is associated with the presence of moisture in pavement, affects asphalt mixture strength, accelerate several modes of failure such as rutting, raveling, stripping, bleeding, and cracking in an asphalt pavement [9] which in-turn, escalate maintenance costs [10, 11, 8]. Strategies to improve this failure mode, involve incorporation of modifiers into the asphalt binders [12, 13, 14, 15]. While most polymer-modified binders are known to improve performance, they are expensive and hard to find, which makes the production cost of the binders modified with them to be high. [16, 17] and availability challenges have led to exploration of industrial-based modifiers like polymer-based waste [18, 19, 20, 21].

Industrial waste, a significant global concern, prompts exploration of sustainable solutions. In Nigeria, polymer-based industrial waste poses disposal challenges due to depleting landfills amid urbanization [22]. Incorporating such waste into pavement construction can alleviate environmental impact and resource depletion [23, 24]. This study focuses on utilizing polymer-based industrial waste to improve asphalt mixture properties, particularly using high-density polyethylene (HDPE) waste. HDPE-modified asphalt has demonstrated enhanced rutting resistance and moisture susceptibility mitigation [25].

The research assesses the potential of industrial waste plastic dust (IWPD), generated during HDPE plastic manufacturing, to enhance bitumen properties, focusing on rutting resistance and moisture susceptibility.

2. Materials and Method

2.1. Materials

The study used 60/70 penetration grade bitumen from Ringardas Nigeria Limited. Its properties are presented in Table 1. Crushed granite stone and dust obtained from a quarry in Akamkpa, Cross River State, were utilized as coarse aggregate and mineral fillers respectively, while natural sand obtained from a river in Ikot Osom, Akwa Ibom State, was used as fine aggregate. Figure 1 and Table 2 display respectively the gradation curve and the physical properties of the aggregates used in this study. The physical properties were all determined based on American Society for Testing and Materials standards procedures.

Table 1. Physical Properties of Base Bitumen.

Test	60/70 Value	Standard Requirement
Penetration at 25 °C (0.1 mm)	67	60–70
Softening point (°C)	48.5	min 46
Brookfield rotational viscosity at 135⁰C (Pa.s)	0.56	<3000 mPa.s
Flash Point (°C)	250	min 230
Specific gravity (g/cm^3)	1.02	1.01–1.06

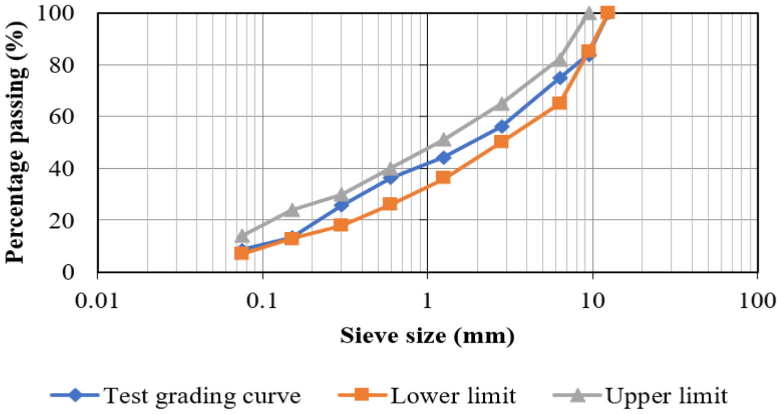

Figure 1. Aggregate gradation curve.

Table 2. Physical properties of aggregate.

Aggregate	Test	Value	Standard Requirement
Coarse aggregate	Water absorption	1.99	≤2%
	Loss Angeles abrasion	23.9	<30%
	Apparent specific gravity	2.66	2.6–2.9
Fine aggregate	Apparent specific gravity	2.61	2.5–2.8
	Water absorption	2.78	≤2%
Filler	Apparent specific gravity	2.70	2.5–2.8

HDPE plastics from Dakkada in dust form were used as IWPD. It's sourced from a plastic company in Akwa Ibom, Nigeria, producing HDPE household items. See Table 3 for IWPD properties, and Figure 2 for its appearance.

Table 3. Physical properties of IWPD.

Test	Value	Standard Requirement	Standard Adopted
Melting Temperature	130 °C	255 °C	ASTM D3418 [26]
Density	0.9439 kg/m^3	0.88–0.96 kg/m^3	ASTM D4883 [27]
Melt Flow Index	19.8 g/10 min	-	ASTM D1238 [28]

Figure 2. IWPD modifier.

2.2. Method

2.2.1. Preparation of IWPD—modified Blend

Modified bitumen blends were produced by thoroughly mixing base bitumen and IWPD through a wet process in a high-shearing mixer at 160 °C and 3800 rpm for 40 min, with IWPD added at 3%, 6%, and 9% of optimal bitumen content of 5.35%

2.2.2. Indirect Tensile Strength and Tensile Strength Ratio

The study employed the indirect tensile strength (ITS) test, assessing asphalt mixture tensile properties linked to rutting and cracking using ASTM D6931 [29] and AASHTO-T283 [30] procedures. Six cylindrical specimens each for unmodified and modified blends were prepared, with three of the specimens conditioned as described in the AASHTO-T283 [30]. Specimens underwent compressive force application along the diametrical plane at a stable deformation rate until failure, calculating ITS using Equation (1) for both types.

$$\mathrm{ITS} = \frac{2L_s}{\pi t_s d_s} \tag{1}$$

where, ITS (Pa); L_s represents the maximum applied load on specimen (N); t_s represents the thickness of specimen (mm); and d_s = diameter of specimen (mm)

Tensile Strength Ratio (TSR), assessing moisture damage resistance, was calculated using the ratio of conditioned (wet) to unconditioned (dry) indirect tensile strength according to Equation (2).

$$\mathrm{TSR} = \frac{\mathrm{ITS}_{\mathrm{wet}}}{\mathrm{ITS}_{\mathrm{dry}}} \tag{2}$$

where, TSR is the tensile strenght ratio; $\mathrm{ITS}_{\mathrm{wet}}$ is the indirect tensile strenght at wet condition; and $\mathrm{ITS}_{\mathrm{dry}}$ is thetensile strenght at dry condition.

3. Result and Discussion

Tensile Strength Ratio

Figure 3 displays unconditioned and conditioned ITS for modified and unmodified bitumen blends. Unconditioned and conditioned ITS increase with higher IWPD content. Unmodified asphalt mixture had dried and wet ITS of 0.9 MPa and 0.65 MPa. Figure 4 shows TSR results, revealing rising TSR with increased IWPD content. Blends with 6% and 9% IWPD achieved the highest TSR of 81%, indicating significant moisture damage resistance, meeting super-pave standards. Beyond 6% IWPD, marginal TSR differences are observed, attributed to increased viscosity and improved asphalt-aggregate adhesion, reducing moisture susceptibility [31].

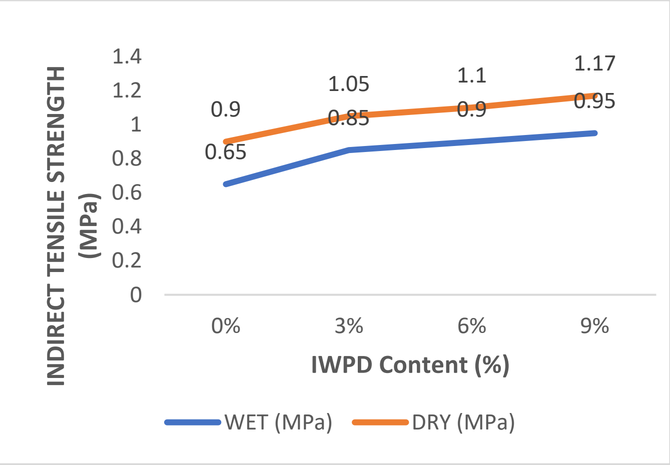

Figure 3. Indirect tensile strength at various percentages of base and modified bitumen.

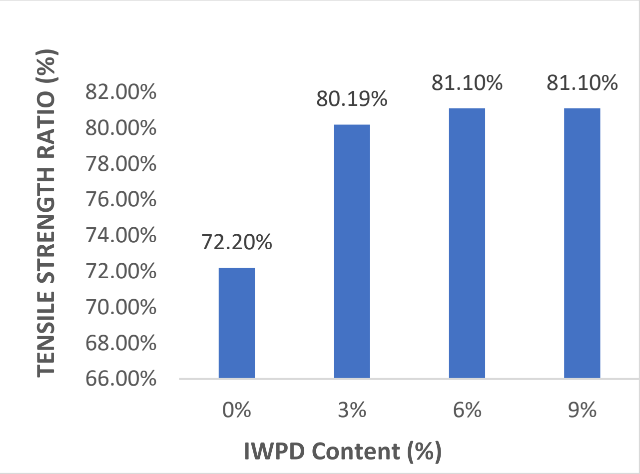

Figure 4. Tensile strength ratio of base and IWPD modified bitumen at various percentages.

4. Conclusion

Improvement in asphalt mixtures to resist pavement distresses like rutting and moisture susceptibility can be achieved by used of industrial waste plastic dust as bitumen modifier. In the present study, the following conclusions can be drawn:

1. Based on tensile strength ratio analysis, modification of bitumen with IWPD improved moisture susceptibility. However, beyond 6% IWPD, there might be no significant improvement in moisture susceptibility. Therefore, 6% modification content may be deemed desirable.
2. The modification of bitumen with IWPD led to an improvement in the rutting potential of the asphalt mixture. Although at content beyond 6%, resistance to rutting might be reduced. Hence, like in the case of moisture susceptibility, optimal performance of IWPD for rutting improvement might be effective at 6% by weight of bitumen.

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