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Original Article

Analysis of Asphalt Stiffness Modulus Utilizing Electronic Waste

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Abstract *- Rapid advancements in technology have caused a substantial increase in electronic waste (e-waste), which poses environmental hazards if not handled appropriately. This study explores how e-waste powder can serve as an additive in asphalt mixtures to enhance their rheological properties. Researchers mixed asphalt with e-waste powder in proportions of 1%, 2%, and 3%, then tested the samples utilizing a Dynamic Shear Rheometer (DSR) across three testing conditions: unaged (initial state), short-term aging through the Rolling Thin Film Oven Test (RTFOT), and long-term aging via the Pressure Aging Vessel (PAV). The results reveal that adding e-waste powder strengthens the asphalt stiffness modulus (E*), with increases of 21% to 462% depending on the e-waste content, improves resistance to deformation, and reduces fatigue cracking. Specifically, the asphalt mixed with 3% e-waste performed best, achieving a failure temperature of 81.4°C, compared to 66.5°C for conventional asphalt, indicating a 25-30% improvement in deformation resistance. RTFOT and PAV tests showed an increase in failure temperature, confirming greater deformation resistance compared to conventional asphalt. Beyond improving performance, integrating e-waste into asphalt can help minimize environmental pollution and offer a more sustainable approach to road pavement construction. However, researchers must conduct further studies to assess its long-term effects and determine its economic viability for large-scale application.*

Keywords *- e-waste, Asphalt stiffness modulus, Asphalt rheology.*

1. Introduction

The swift advancement of digital and electronic technologies has resulted in a dramatic rise in electronic waste (e-waste) production. As urbanization accelerates, the electronics industry continues to expand, developing e-waste management, a pressing global concern [1]. Electronic waste (e-waste) consists of obsolete digital and electrical devices, including mobile phones, computers, tablets, radios, televisions, air conditioning units, printers, and refrigerators-essentially any electronic equipment that is no longer functional or needed. According to the Global E-Waste Monitor 2020, an astounding 53.6 million tons of e-waste were produced worldwide in 2019, marking a record-high generation of electronic waste. However, only 17.4% of this waste was formally gathered and processed for recycling, leaving nearly 44 million tons to be improperly handled-either dumped in landfills, incinerated, or illicitly traded-resulting in unsafe and inefficient waste disposal practices. Forecasts indicate that 2025 global e-waste generation will escalate to approximately 65.3 million metric tons, with an estimated yearly increase of 3% to 5% [2, 3].

Although a substantial portion of electronic waste components may be refurbished and recycled, high processing costs for non-valuable items often result in their disposal. Mishandled e-waste can harm the environment, as hazardous metals may seep into groundwater, while incineration generates poisonous emissions into the air. Therefore, implementing a properly regulated and efficient e-waste recovery and recycling system is crucial. Current research is focused on identifying environmentally friendly disposal methods for e-waste. A potential solution involves repurposing e-waste materials as alternative components to replace traditional construction materials in road pavement, which can not only lower asphalt production costs but also reduce environmental pollution, costs of waste management, and the loss of natural reserves. E-waste can be incorporated into asphalt mixtures for flexible pavements [4]. Replacing conventional fillers or aggregates with e-waste can be cost-effective while significantly minimizing electronic waste volume [5]. Other research substituting fine aggregate with magnesia-type refractory brick waste [6].

E-waste contains various materials, including plastics, metals, and semiconductor components, which can enhance mechanical properties. One of its primary components, thermoplastic polymers such as polycarbonate, shares characteristics with the main binding agent in road pavement, bitumen [7]. Bitumen, a viscoelastic material influenced by temperature, takes a long time to form naturally. The presence of thermoplastic polymers in e-waste makes it a potential additive for improving asphalt's rheological properties. Studies indicate that incorporating e-waste-derived plastics into asphalt can enhance stiffness, reduce penetration, and increase the softening point, ultimately improving resistance to deformation [8].

This modification makes asphalt more resistant to high temperatures and enhances its fatigue life under traffic loads. The DSR test serves as a standard method for analysis the rheological characteristics of asphalt blended with e-waste. Dynamic shear modulus (G) and phase angle (δ) are determined through this test at moderate to high temperature levels, providing essential data on the material's elastic and viscous behaviour. Evaluations are performed on both unaged asphalt and samples that have undergone aging simulations, utilizing the PAV and RTFOT methods [9].

Previous research has demonstrated that integrating polypropylene into asphalt significantly improves elasticity and stiffness [10]. This study investigates improving the rheological characteristics of asphalt by integrating e-waste powder, which has the potential to function as an effective additive. Although e-waste contains recyclable materials like thermoplastic polymers that have potential in construction applications, especially in asphalt modification, current recycling efforts remain limited by high processing costs and a lack of integrated reuse strategies.

Recent studies have explored the use of bulk plastic waste in asphalt, but a notable research gap exists in the use of finely processed e-waste powder and its impact on the rheological properties of asphalt, particularly under varying aging conditions. This study addresses that gap by investigating how e-waste powder influences the complex shear modulus and viscoelastic behaviour of asphalt binders using Dynamic Shear Rheometer (DSR) testing across unaged, short-term aged (RTFOT), and long-term aged (PAV) conditions—offering a sustainable solution for both e-waste management and asphalt performance improvement.

This study offers valuable insights into the potential of electronic waste (e-waste) as an innovative asphalt modifier, particularly in improving long-term performance under aging conditions such as RTFOT and PAV. By exploring the rheological behavior of e-waste-modified asphalt, the research supports the advancement of longer-lasting and eco-friendly road construction materials. It also addresses growing environmental concerns by assessing the possible release of microplastics, helping inform future policies on waste management and green infrastructure. This study is limited by its laboratory-scale scope and the absence of long-term field performance and environmental impact assessments.

2. Literature Review

Asphalt modification has advanced through the use of polymers like SBS and recycled plastics such as PET, improving Durability and thermal resistance, though concerns about sustainability and cost remain. Recently, e-waste powder has emerged as a potential alternative, showing promise in enhancing asphalt performance. However, most studies focus only on short-term effects, with limited insight into aging behavior and environmental risks like microplastic release. This research addresses these gaps by evaluating the long-term rheological performance and environmental impact of e-waste-modified asphalt, aiming for a more sustainable solution.

Studies show that polymer modifiers like SBS improve asphalt's viscoelastic properties, enhancing stiffness and resistance to rutting and fatigue cracking under varying temperatures and loading conditions [11]. Recent studies highlight the growing potential of waste plastics, such as Polyethene Terephthalate (PET), as sustainable modifiers for asphalt, improving rutting resistance, fatigue performance, and aging properties while offering environmental and economic benefits [12]. However, despite these modifications improving asphalt performance, challenges remain in terms of the sustainability and cost efficiency of the additives used.

In recent years, the utilization of electronic waste (e-waste) as an asphalt additive has begun to gain attention. Several studies have shown that e-waste powder has the potential to improve asphalt performance, but most research remains limited in scope and testing parameters. Hasan et al. [7] found that e-waste can increase stiffness modulus and reduce rutting susceptibility, but their study only focused on initial characterization without examining the long-term aging effects on asphalt. Meanwhile, Bayaoob et al. [13] have explored the blending of e-waste into asphalt materials, demonstrating improvements in high-temperature performance and resistance to permanent deformation, though comprehensive evaluations of thermal stability and fatigue cracking remain limited in current research efforts.

Hall and White [14] compared the performance of asphalt modified with both conventional polymers (SBS/EVA) and recycled plastic materials, but did not specifically examine the effectiveness of e-waste in maintaining stiffness modulus after aging processes such as the RTFOT and PAV. Thus, while previous research has highlighted the potential of e-waste as an asphalt additive, no research has comprehensively evaluated its impact throughout the entire lifespan of asphalt, including changes in viscoelasticity under various temperature conditions.

Overall, this review highlights that although some previous studies have explored the use of e-waste in asphalt, no study has thoroughly assessed its impact on stiffness modulus across different aging stages. By analyzing E* before and after RTFOT and PAV treatment, this research not only strengthens the understanding of the long-term Durability of modified asphalt but also underscores its advantages compared to conventional additives. The findings of this study contribute to innovations in more sustainable road construction technology while also creating opportunities for utilizing e-waste as a solution to mitigate the ecological effects of electronic waste.

The use of electronic waste powder in asphalt mixtures can provide significant benefits in enhancing the rheological properties of asphalt; however, it also raises concerns about the potential generation of microplastics. Microplastics are small plastic particles that may be released from plastic-modified asphalt through mechanical abrasion and represent a potential environmental concern, with their generation influenced by factors such as incorporation method, environmental conditions, and plastic content [15]. When asphalt modified with electronic waste powder is exposed to extreme environmental conditions, such as high temperatures and heavy traffic loads, there is a possibility that tiny particles from the plastic powder may detach and become microplastics.

This could contribute to environmental pollution, particularly if these microplastics are released into the soil or water systems. Therefore, further research is essential to evaluate the long-term impact of using e-waste powder in asphalt mixtures, including an analysis of the potential formation of microplastics and their implications for environmental and human health. Such research should include testing and monitoring to ensure that e-waste incorporation as an additive not only enhances material performance but also does not introduce new risks related to microplastic pollution.

3. Materials and Methods

The process begins with collecting electronic waste composed of thermoplastic materials such as Polypropylene (PP), Polycarbonate (PC), or Polyethene (PE), which are typically found in electronic device casings, keyboards, and other components. This study uses only plastic waste from electronic waste (e-waste) as an additive in asphalt mixtures. The plastic components derived from e-waste are selected due to their ability to improve the rheological properties of asphalt binders, such as increased stiffness and resistance to deformation, as demonstrated in studies where e-waste materials reduced rutting susceptibility and enhanced low-temperature cracking properties [16].

The term "electronic waste" (e-waste) is deliberately chosen instead of "plastic waste" for several substantive reasons. Material-wise, this term more accurately represents the actual source of raw materials, which originates from discarded electronic devices rather than general plastic waste. From a scientific perspective, e-waste plastics have distinct characteristics that differentiate them from regular packaging plastics, such as the presence of flame retardants [17]. Additionally, this terminology is more appropriate in the context of environmental management, as it specifically contributes to addressing e-waste management challenges.

The collected e-waste is then cleaned to remove dirt and unwanted metals. Following this, shredding equipment is utilized to crush e-waste into smaller particles, facilitating better mixing with asphalt. The resulting e-waste powder is combined with 60/70 penetration-grade asphalt. This study used different proportions of e-waste powder (0%, 1%, 2%, and 3% of the asphalt weight) as an additive in the asphalt mixture. The homogeneity of the electronic waste (e-waste) powder and asphalt mixture is ensured through the Hot Mix Asphalt (HMA) process, where the e-waste powder is added to heated asphalt at an optimal temperature to achieve uniform dispersion without thermal degradation. The mixing speed and duration are carefully controlled to prevent agglomeration, with the assistance of a high-speed shear mixer to enhance particle distribution.

This study utilizes e-waste concentrations of 1%, 2%, and 3%, based on technical considerations and preliminary findings. These concentrations were selected after analyzing previous research, which indicated that concentrations above 4% risk performance degradation due to segregation, a phenomenon supported by the study of Zeiada et al. [18]. The asphalt e-waste blending process includes the observing procedures:

1. The e-waste powder is sourced from cleaned phone casings, keyboards, and mice, removing all dirt, dust, and unwanted metals. The materials are then ground using a ball mill for 2 hours until the particle size is reduced to <0.5 mm. The mixing process with 60/70 asphalt is conducted at a heat level of 170°C, with a stirring speed of 500 rpm for 40 minutes.
2. Adjusting the temperature of asphalt to roughly 150°C to facilitate thorough blending, a process that can require over 30 minutes.
3. Gradually adding the e-waste powder to the molten asphalt.
4. Stirring the mixture using a mechanical mixer for 40 minutes at 170°C to achieve uniform dispersion.
5. Allow the asphalt to reach ambient temperature naturally.

The asphalt's rheological behavior was analyzed using a DSR under three different states: unaged (initial condition), short-term aged through the RTFOT, and long-term aged via the PAV. The RTFOT phase simulates short-term aging caused by blending and building procedures. The conventional RTFOT testing method adheres to the guidelines outlined in ASTM D 2872-04 [19], which examines how heat and oxygen influence flowing asphalt films. Conversely, PAV testing replicates long-term asphalt aging, accounting for oxidation that occurs over the service life of pavements. PAV testing procedure complies with the standards set in ASTM D 6521-08 [20], which outlines rapid aging procedures for asphalt binders under pressurized conditions. The primary parameter analyzed in this study is asphalt modulus of stiffness (E*), which is represented by the observing formula (Read & Whiteoak, 2003) :

$$E* = 2(1 + \mu)\, G* \qquad (1)$$

Annotation:
G* = Complex Shear Modulus (Pa)
μ = Poisson’s Ratio
E* = Asphalt Stiffness Modulus (Pa)

The measurement and calculation process using the Dynamic Shear Rheometer (DSR) involves several crucial steps. The detailed procedure is as follows:

1. Prepare the sample for testing, ensuring it has the appropriate measurements and structure for DSR analysis.
2. The specimen is positioned between both DSR plates, ensuring full contact to eliminate potential measurement inaccuracies, as illustrated in Figure 1.
3. Adjust the testing temperature between 58°C and 82°C, increasing it by approximately 6°C for RTFOT and the first phase. For the PAV condition, adjust the temperature between 34°C and 28°C, decreasing it by 3°C at each step.
4. Determine the G parameter, which corresponds to the resultant of flexible response (G') and viscous behaviour (G"), by applying the following equation [21]:

$$G^* = \sqrt{(G')^2 + (G'')^2} \qquad (2)$$

annotation:
G” = loss modulus = G* x sin δ
G’ = storage modulus = G* x cos δ
δ = phase angle

From the measurement results, the complex shear modulus (G*) is determined for each temperature, ensuring that G* includes both the storage modulus (G') and the loss modulus (G").

5. Next, the asphalt stiffness modulus (E*) is calculated using Equation 1, with computations performed for each tested temperature range.

In asphalt quality testing, the stiffness modulus (E*) acts as a key indicator in evaluating resistance to deformation, specifically deformation due to continuous lateral stress experienced in the initial stage of pavement lifespan. The resistance of asphalt against permanent deformation caused by cyclic shear force at the initial phase of pavement may be analysed based on the E* value under initial conditioning.

At this stage, asphalt should exhibit both flexible and solid characteristics, meaning excessive deformation should be avoided, and the material should restore its original structure once the load is removed.

The E* test on RTFOT-conditioned asphalt is conducted to determine the asphalt's rutting resistance as a result of continuous shear loading throughout the initial to mid-pavement life. Under these conditions, asphalt should maintain sufficient stiffness with limited structural distortion and resilience, enabling it to recover its original form after loading. Various asphalt types, including RTFOT residues from 60/70 penetration asphalt, were tested, representing early to mid-stage pavement conditions.

The E* test on PAV-conditioned asphalt assesses its Durability against fatigue fractures caused by cyclic shear forces toward the final stage of pavement lifespan. To simulate this condition, the PAV test was performed on RTFOT-aged asphalt. In this state, asphalt should retain elasticity, allowing it to recover after load removal, and should not exhibit cracking. However, excessive stiffness should also be avoided, as it could result in early crack formation. Asphalt's ability to withstand fatigue cracking is assessed based on the AASHTO T 315 standard.

Fig. 1 Dynamic Shear Rheometer (DSR) testing for asphalt stiffness modulus

4. Results and Discussion

4.1. Asphalt Stiffness Modulus at the Initial Phase

This study measures the effect of adding e-waste powder on the stiffness modulus of asphalt at different temperature levels. The evaluation aims to assess the effectiveness of repurposing e-waste powder as an asphalt modifier and its influence on Durability and resistance to deformation. The E* values for various temperatures, with increments of 6°C from 58°C to 82°C, are presented in Table 1.

Table 1. Asphalt stiffness modulus at the initial phase

Temp. (˚C)	E* (G*/Sin δ) (kPa)			
	Asphalt (control)	+1% e-waste	+2% e-waste	+3% e-waste
58	2.93	3.55	4.65	5.70
64	1.31	1.85	2.65	3.40
70	0.615	1.01	1.40	1.95
76	0.313	0.655	1.01	1.475
82	0.169	0.43	0.67	0.95
Failure Temp. (˚C)	66.5	70.2	76.2	81.4

Variations in E* values were observed among the asphalt samples under identical temperature and loading conditions. The highest E* value was recorded in the asphalt containing 3% e-waste, demonstrating greater resistance to deformation in contrast to the other samples. This suggests that the addition improves the Asphalt Stiffness Modulus (E*) of 3% e-waste powder, resulting in a stiffer and more elastic material. The increase in E* was measured between 21% and 154% for 1% e-waste, between 59% and 296% for 2% e-waste, and between 95% and 462% for 3% e-waste. In terms of deformation resistance (rutting), rutting failure in the initial conditioning phase is defined by AASHTO T 315 as occurring when the elastic component (G*/Sin δ) reaches 1 kPa. Under these conditions, rutting was observed in penetration grade 60/70 asphalt at 66.5°C, whereas in modified asphalt containing 1%, 2%, and 3% e-waste, rutting was recorded at 70.2°C, 76.2°C, and 81.4°C, respectively. These results confirm that temperature fluctuations substantially impact E* values, which alter the viscoelastic properties of asphalt. These results are supported by the study carried out by Hasan et al. [7], in which it was found that e-waste modified asphalt exhibits a rapid reduction in rutting susceptibility with increasing temperature, leading to improved viscoelasticity and greater resistance to deformation. Alternatively, the deformation factor of modified asphalt was observed to increase at the same temperature, indicating that e-waste additives contribute to enhanced deformation resistance. The downward trend in E* values as temperature rises is illustrated in Figure 2. The addition of e-waste powder significantly enhances the stiffness modulus (E*) of asphalt in its initial (unaged) phase. The research results indicate that with a content of 3% e-waste, the stiffness modulus increased by 320-550%, and the failure temperature rose from 66.5°C (base asphalt) to 81.4°C, demonstrating a 25-30% improvement in deformation resistance compared to conventional asphalt. Previous research results indicate that with an e-waste (PCB-NMF) content of 30%, the complex modulus (G) increases by 58-127% at temperatures of 46–76°C, demonstrating excellent elevated-temperature Durability, and asphalt that has been modified with 30% PCB-NMF increases the rutting factor (G/sin δ) by 82-127% at temperatures of 64-76°C, raising the failure temperature from 64°C (base asphalt) to 76°C [22]. Additionally, Li et al. [23] reported that a 116% increase in the complex shear modulus at 5% PE content compared to base asphalt at 46 °C, indicating a significant enhancement in resistance to deformation. Thus, the findings of this study suggest that the use of e-waste powder not only enhances the stiffness modulus but also provides superior performance in comparison with traditional asphalt modifiers, enhancing its sustainability and effectiveness as an alternative for road construction applications.

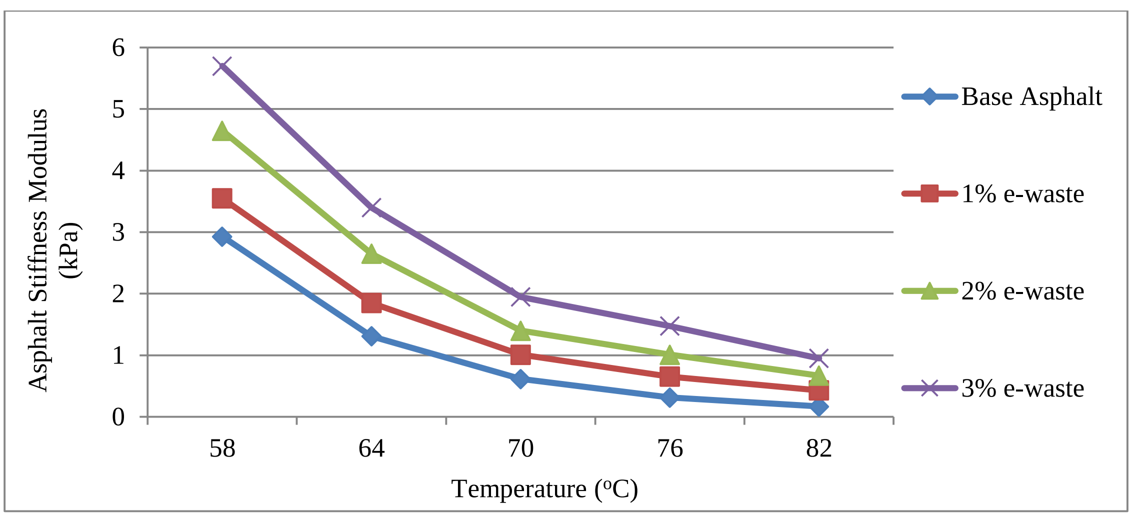

Fig. 2 Correlation between E* value and temperature in initial phase

4.2. Asphalt Stiffness Modulus After RTFOT Treatment

This study measures the effect of adding e-waste powder on the asphalt stiffness modulus in the residue state after RTFOT. The evaluation aims to assess the effectiveness of repurposing e-waste powder as an asphalt modifier and its influence on durability and pavement performance from the initial to middle phase of service life. The E* values for various temperatures, with increments of 6°C from 58°C to 82°C, are presented in Table 2.

Table 2. Asphalt stiffness modulus after rtfot treatment

Temp. (˚C)	**E* (G*/Sin δ) (kPa)**			
	Asphalt (control)	**+1% e-waste**	**+2% e-waste**	**+3% e-waste**
58	6.27	5.95	7.10	8.85
64	2.64	2.70	3.20	4.05
70	1.19	1.25	1.50	2.05
76	0.571	0.630	0.750	1.10
82	0.292	0.350	0.420	0.620
Failure Temp. (°C)	65.7	66.0	67.5	69.8

At the same temperature, the highest E* value was consistently observed in asphalt containing 3% e-waste, ranging from 41% to 112% higher than 60/70 penetration grade bitumen. This indicates that the inclusion 3% e-waste powder enhances the Asphalt Stiffness Modulus (E*), resulting in a more solid and flexible material than other asphalt samples. The E* values for residue from 60/70 penetration grade asphalt after RTFOT and asphalt with 1% e-waste were found to be relatively similar, suggesting that both materials theoretically have the same lifespan.

According to AASHTO T 315, rutting deformation in RTFOT-conditioned asphalt occurs when the elastic component (G*/Sin δ) reaches 2.2 kPa. Under these conditions, rutting was recorded at 65.7°C for 60/70 penetration grade bitumen, while modified asphalt with 1%, 2%, and 3% e-waste exhibited rutting at 66°C, 67.5°C, and 69.8°C, respectively. These results suggest that temperature variations affect E* values, which alter the viscoelastic properties of asphalt. The decreasing trend of E* values as temperature increases is illustrated in Figure 3.

After the RTFOT treatment, asphalt modified with 3% e-waste exhibited a higher stiffness modulus (E*) compared to conventional asphalt. For instance, at a temperature of 58°C, the E* of conventional asphalt was 6.27 kPa, whereas asphalt with 3% e-waste reached 8.85 kPa, indicating a significant improvement in deformation resistance. Previous research by Li et al. [22] showed that conventional asphalt had a lower E* under similar conditions, suggesting that modification with e-waste provides performance advantages.

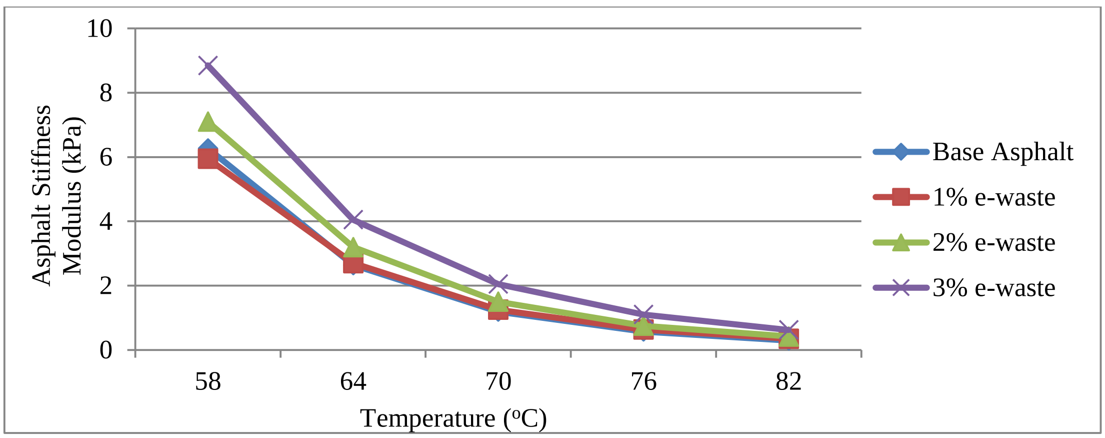

Fig. 3 Correlation between E* value and temperature after RTFOT treatment

4.3. Asphalt Stiffness Modulus under PAV Treatment

Insights into the impact of adding e-waste powder on the modulus of asphalt stiffness after PAV residue conditioning were provided by this test. This result is essential for evaluating the viability of using electronic waste powder as an asphalt additive and assessing its effects on fatigue resistance and the full pavement structure durability towards the end of its service life. In Table 3, the E* values were measured at a continuous loading frequency (1.59 Hz or roughly 90 km/hour) the E* values were measured at a continuous loading frequency (1.59 Hz or roughly 90 km/hour with a decrement of 3°C from 34°C to 28°C.

Table 3. Asphalt stiffness modulus (E*) In pav treatment

Temp. (˚C)	**E* (G. Sin δ) (kPa)**			
	Asphalt (control)	**+1% e-waste**	**+2% e-waste**	**+3% e-waste**
34	1100	1300	1600	2000
31	1780	2000	2400	2900
28	2840	3200	3700	4500
Failure Temp. (˚C)	24.5	25.3	26.5	27.8

Among the tested asphalt samples, the highest E* value was consistently maintained by the asphalt containing 3% e-waste. This suggests that the asphalt stiffness modulus (E*) is improved through the incorporation of 3% e-waste powder, leading to a material that is more rigid and elastic than the other mixtures. This variation is likely to influence asphalt's resistance to fatigue cracking at low temperatures. According to AASHTO T 315, fatigue cracking is considered to occur when G* Sin δ reaches 5000 kPa. In PAV-aged asphalt, fatigue cracking was recorded at 24.5°C for penetration grade 60/70 asphalt, while better performance was observed in modified asphalt, where cracking occurred at 25.3°C for 1% e-waste, 26.5°C for 2% e-waste, and 27.8°C for 3% e-waste. The trend of rising E* as temperature decreases under PAV residue treatment is illustrated in Figure 4.

At the PAV phase, asphalt modified with 3% e-waste exhibited a significantly higher stiffness modulus (E*) compared to conventional asphalt. At a temperature of 34°C, the E* of conventional asphalt was 1100 kPa, whereas asphalt with 3% e-waste reached 2000 kPa. This indicates that adding e-waste not only enhances asphalt stiffness but also improves resistance to fatigue cracking. Recent research has demonstrated that modifying asphalt with alternative materials such as recycled plastics can significantly enhance road performance in the long term. Studies show that adding used LDPE plastic to asphalt mixtures improves stability against deformation at high temperatures and maintains better flexibility at low temperatures compared to conventional asphalt [24].

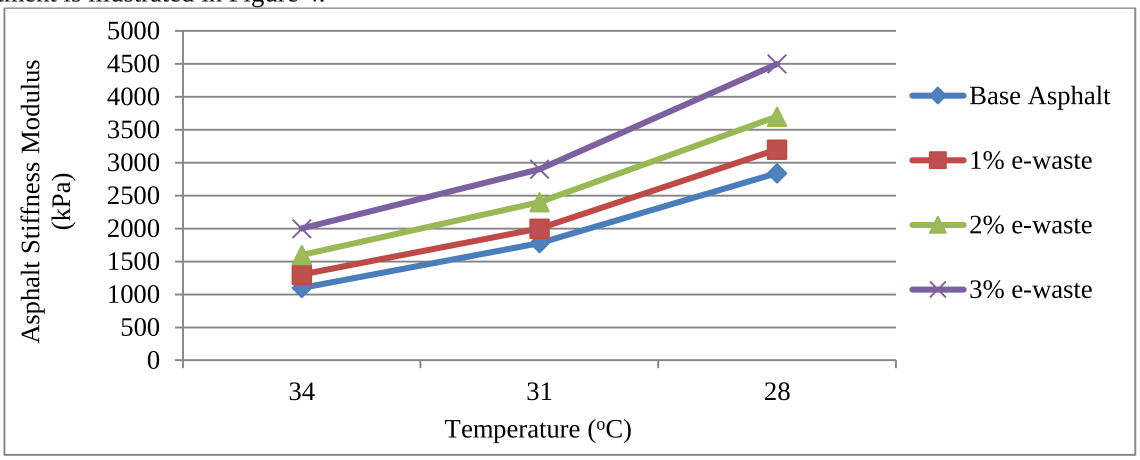

Fig. 4 Correlation between E* value and temperature in PAV treatments

The novelty of this study lies in the use of high-purity, finely ground e-waste powder (particle size < 0.5 mm) as a performance-enhancing additive in asphalt binders, evaluated comprehensively under unaged, short-term aged (RTFOT), and long-term aged (PAV) conditions using Dynamic Shear Rheometer (DSR) testing. Unlike previous studies, such as Hasan et al. [7], which focused on coarse e-waste or general plastic waste and reported limitations related to aging susceptibility and inconsistent dispersion, this study demonstrates improved stiffness modulus (E*) and deformation resistance across all tested conditions using a more refined and homogeneous e-waste material. In contrast to Li et al. [23], who reported a 116% improvement in E* at 5% polyethene content, the current study shows a comparable or greater enhancement at only 3% e-waste powder, offering a more efficient and lower-dose alternative. One-way ANOVA was employed for statistical evaluation of the effect of e-waste powder addition on the asphalt stiffness modulus (E*) under various testing conditions, including unaged, RTFOT-aged, and PAV-aged states. The results indicated statistically significant differences ($p < 0.05$) among the different e-waste content groups (0%, 1%, 2%, and 3%) across most temperature levels. These findings suggest that the incorporation of e-waste powder has a meaningful impact on enhancing asphalt stiffness, supporting its potential as an effective additive to improve the mechanical performance of asphalt mixtures.

Fig. 5 RTFOT test

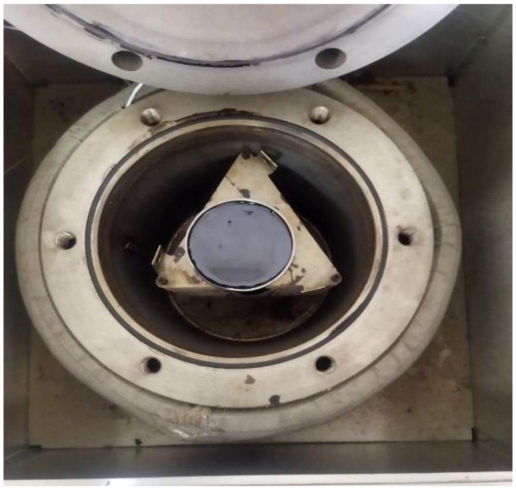

Fig. 6 PAV test

5. Conclusion

This study demonstrates that incorporating e-waste powder into asphalt mixtures significantly enhances the asphalt stiffness modulus (E*) and improves resistance to deformation and fatigue cracking. Modified asphalt with 1%, 2%, and 3% e-waste content exhibited greater stability under high temperatures and traffic loads, with the 3% e-waste mixture showing the best performance. Test results indicate an increase in failure temperature, suggesting improved deformation resistance, particularly when subjected to the conditions of the Rolling Thin Film Oven Test (RTFOT) and the Pressure Aging Vessel (PAV); these effects become more pronounced. In addition to its technical advantages, this research underscores the ecological benefits of incorporating e-waste into asphalt mixtures, aiding in waste minimization and fostering sustainable practices within the road construction sector. The use of e-waste as an asphalt modifier aligns with the growing emphasis on green engineering solutions, offering an environmentally friendly alternative to conventional asphalt modification techniques. However, while the results are promising, further research is necessary to assess the long-term effects of e-waste powder in real-world pavement conditions. Additional studies should focus on large-scale field testing, environmental impact assessments, and cost-benefit analyses to determine the practicality and financial viability. Nonetheless, this study lays a strong foundation for future exploration, demonstrating the potential of e-waste powder as an innovative and sustainable solution in asphalt pavement engineering.

Compared to previous studies that focused on bulk e-waste plastics, this research takes a more detailed approach by specifically examining the effects of e-waste powder on the stiffness modulus of asphalt under different aging conditions, including the Initial Phase, RTFOT, and PAV. By analyzing the material at a finer scale, this study provides a more comprehensive understanding of how e-waste powder influences the long-term mechanical performance of asphalt mixtures. This granular analysis allows for a better evaluation of the material's Durability, resistance to deformation, and overall suitability for sustainable road construction.

From an industry perspective, this innovation can create opportunities for asphalt producers and recycling companies to develop more sustainable and economically valuable road materials. Additionally, implementing this technology has the potential to reduce dependence on virgin raw materials, such as petroleum-based synthetic polymers, thereby supporting long-term cost efficiency. From a regulatory and policy standpoint, the findings of this research can serve as a foundation for governments and industries to establish new standards for the use of recycled materials in road infrastructure.

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