

# Rutting and fatigue cracking characteristics of toner-modified asphaltic blends

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*Citation:*

Rambarran, S., Clark, A., Mohammed, S., Sangster, N., & Maharaj, R. (2026). Rutting and fatigue cracking characteristics of toner-modified asphaltic blends. *Journal of Smart Science and Technology*, 6(1), 37–47

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## ARTICLE INFO

*Article history:*

Received 27 March 2025  
Revised 13 September 2025  
Accepted 16 October 2025  
Online first  
Published 31 March 2026

*Keywords:*

waste toner  
recycling  
asphalt  
rheology  
e-waste

*DOI:*

10.24191/jsst.v6i1.121

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## ABSTRACT

The improper disposal of electronic waste, particularly waste toner cartridges, poses significant environmental challenges. This research investigated the application of waste toner powder, specifically the powder extracted from printer cartridges, as a modifier in asphaltic mixes to improve rheological characteristics, including fatigue cracking resistance and rutting resistance. Four (4) waste toners (A, B, C & D) were blended into Trinidad Lake Asphalt (TLA) and Trinidad Petroleum Bitumen (TPB) at concentrations of 0%, 5%, 10%, 15%, and 20%. The samples were analysed using dynamic shear rheology (DSR) testing to assess their mechanical properties. The results indicated that incorporating waste toner significantly improves asphalt's resistance to deformation and fatigue. The highest rutting resistance,  $G^*/\sin \delta$  was observed in the 20% Toner B at  $2.60 \times 10^5$  Pa, while the best fatigue cracking resistance,  $G^*\sin \delta$  was found in 5% Toner D at  $3.93 \times 10^2$  Pa. These findings suggest that waste toner-modified asphalt is a viable, sustainable alternative for road paving applications, contributing to both environmental conservation and infrastructure enhancement.

## 1. INTRODUCTION

Small Island Developing States, such as Trinidad and Tobago (T&T), face significant challenges in recycling and reusing waste materials due to limited infrastructure and policy implementation<sup>1</sup>. The increasing demand for electrical and electronic equipment has led to a corresponding rise in electronic waste (e-waste), with only 17.4% of the 53.6 million Mt generated in 2019 being formally collected and recycled<sup>1</sup>. Despite the implementation of toner cartridge return programmes by manufacturers, a substantial volume of waste toner is still improperly disposed of, contributing to environmental degradation<sup>2</sup>. According to recent studies, global e-waste generation is expected to reach over 74 million metric tonnes by 2030, but collection and recycling rates are still below 20%<sup>3</sup>. Improper disposal practices, especially for printer cartridges and toner powders, become more prevalent in T&T by the lack of comprehensive e-waste legislation and the lack of recycling facilities<sup>4</sup>.

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Printer cartridges and toner, which is powdered ink composed of thermoplastic resins, pigments, and additives, are particularly concerning, as they contain polymers, heavy metals, and potentially carcinogenic substances such as polycyclic aromatic hydrocarbons (PAHs)<sup>5</sup>. Incineration or landfilling of waste toner releases hazardous compounds into the environment, causing air pollution and long-term ecological damage<sup>6</sup>. Toner is considered a high-cost material by weight in its original form, however, the toner used in this study was sourced from discarded cartridges that are no longer suitable for reuse in printing. Once removed from the cartridge casing, the residual toner is often contaminated or degraded, limiting its reusability in printing applications. This makes it a zero-cost waste stream from a material recovery standpoint. Furthermore, the environmental cost of inappropriate disposal caused by the presence of synthetic polymers and heavy metals justifies investigating its repurposing in extensive infrastructure applications, such as asphalt modification. The plastic casings of toner cartridges take several years to decompose and when burned, they produce harmful dioxins<sup>7</sup>. Additionally, according to worldwide e-waste data, affluent countries produce more e-waste per person than developing ones, even though wealthier regions have more organised recycling programmes<sup>1</sup>.

To address these concerns, researchers have explored alternative recycling strategies including integrating waste toner into construction materials such as asphaltic blends<sup>8</sup>. The use of secondary materials in construction not only minimises waste but also enhances material properties, making asphalt modification a promising solution<sup>9</sup>. Several studies have demonstrated that modifying asphalt with waste toner can enhance its rheological properties, thus improving rutting resistance and fatigue cracking performance while contributing to sustainable waste management<sup>10</sup>. In particular, incorporating toner in asphalt reduces its reliance on virgin bituminous materials, lowers environmental impact, and promotes circular economy principles<sup>6,11</sup>.

The use of toner-modified asphalt has been particularly relevant in regions like T&T, where indigenous asphalt materials such as TLA and TPB provide a strong base for experimentation<sup>12</sup>. TLA, known for its durability and high resistance to deformation, has been widely used in paving applications worldwide, and integrating waste toner as an additive could further improve its properties<sup>13</sup>. This study investigates the rheological properties of four waste toners in asphaltic blends using the dynamic shear rheology (DSR) technique. The findings suggest that waste toner incorporation enhances the rheological characteristics of asphalt, making it a viable, environmentally sustainable solution for road paving applications.

## 2. METHOD AND MATERIALS

This study utilised TLA and TPB as the base asphaltic materials. These materials were selected due to their well-documented rheological properties and suitability for road paving applications<sup>12</sup> as shown in Table 1. The waste toners used in this study were sourced from discarded printer cartridges and classified into four distinct types: Toner A, B, C, and D. Each toner was characterised for its composition, particle size, and thermal stability before incorporation into the asphalt blends<sup>2</sup>. These toner materials primarily comprise a thermoplastic binder resin, colourant, and a variety of additives. Based on prior characterisation by Rambarran<sup>4</sup>, typical waste toner composition includes:

- (i) binder resins (approximately 45–60 wt%): usually styrene-acrylate copolymers or polyester, which impart thermoplastic properties,
- (ii) colourants (5–15 wt%): mainly carbon black or iron oxide, used for pigmentation and light absorption,
- (iii) charge control agents and metal oxides (1–5 wt%): added to regulate electrostatic properties during the printing process,
- (iv) waxes and lubricants (5–10 wt%): often polypropylene waxes or polyethylene glycol to control fusing and flow during printing, and
- (v) silica nanoparticles and flow agents (1–3 wt%): included to prevent agglomeration and improve powder handling.

Table 1. Source and characteristics of the TLA and TPB samples used in this investigation

	TLA	TPB
Source	Natural product mined from the Pitch Lake	By-Product
Packing	Drum	Drum
Penetration @ 25 °C (ASTM D5)	0–5	60–70
Specific Gravity (ASTM D70)	1.3–1.5 (g cm <sup>-3</sup> )	1.00–1.06 (g cm <sup>-3</sup> )
Softening Point (ASTM D36)	89–99 (°C)	225 (°C)
Flash Point (ASTM D92)	255–260 (°C)	49–56 (°C)

Source: Maharaj (2019)<sup>12</sup>

## 2.1 Sample preparation

A high-shear mixer was used to ensure homogeneity, operating at 160 °C for 30 minutes. The asphalt blends were prepared using the wet mixing method, in which pre-weighed toner powder was directly introduced into the heated bitumen phase under high-shear conditions. This approach ensured better dispersion and interaction between the toner particles and the asphalt matrix. Each asphalt blend was prepared with a total sample mass of 6.00 grams. Toner was incorporated at concentrations of 0%, 5%, 10%, 15%, and 20% by weight. For the 0% toner blends (control samples), only the base binder comprising TPB and TLA was used. Table 2 presents the measured binder mass and toner mass for each toner type. The temperature between 40 °C and 90 °C was selected based on the optimal viscosity range for asphalt mixing and modification<sup>8</sup>. The prepared blends were then stored in airtight containers to prevent contamination and degradation before testing<sup>14</sup>.

Table 2. Composition of toner-modified asphalt blends

Toner Type	Toner Concentration (%)	Actual Binder Mass (g)	Actual Toner Mass (g)	Total Mass (g)
A	0	6.0141	0.0000	6.0141
A	5	5.7126	0.3071	6.0197
A	10	5.4130	0.6005	6.0135
A	15	5.0970	0.9086	6.0056
A	20	4.8064	1.2009	6.0073
B	0	6.0060	0.0000	6.0060
B	5	5.7161	0.3047	6.0208
B	10	5.4023	0.6027	6.0050
B	15	5.1078	0.9036	6.0114
B	20	4.8010	1.2018	6.0028
C	0	6.0146	0.0000	6.0146
C	5	5.7002	0.3010	6.0012
C	10	5.4072	0.6039	6.0111
C	15	5.1037	0.9023	6.0060
C	20	4.8058	1.2036	6.0094
D	0	6.0135	0.0000	6.0135
D	5	5.7020	0.3175	6.0195
D	10	5.4052	0.6018	6.0070
D	15	5.1028	0.9017	6.0045
D	20	4.8004	1.2063	6.0067

Source: Author's own data

## 2.2 Rheological testing

Rheological properties were assessed by using the DSR in accordance with the Superpave Performance Grading (PG) system. The tests were conducted at multiple temperatures ranging from 40°C to 90 °C to evaluate temperature susceptibility<sup>8</sup>. The key performance parameters measured were:

- (i) Rutting resistance, ( $G^*/\sin \delta$ ): This parameter quantifies the blend's resistance to permanent deformation under repeated loading<sup>11</sup>.
- (ii) Fatigue cracking resistance, ( $G^*\sin \delta$ ): A lower value of this parameter indicates improved resistance to fatigue failure under cyclic stress<sup>13</sup>.

### 3. RESULT AND DISCUSSION

Minor variations in the 0% toner data between Fig. 1 and Fig. 3 may be attributed to experimental uncertainty or temperature/frequency sensitivity of the DSR testing. Although the same base asphalt was used, each test condition was independently performed, which could result in slight deviations in the measured  $G^*/\sin \delta$  and  $G^*\sin \delta$  values. The incorporation of waste toner into asphalt blends significantly influenced the rheological properties, enhancing their resistance to both rutting and fatigue cracking. Rutting resistance, measured by  $G^*/\sin \delta$ , improved notably with increasing concentrations of waste toner. The highest value,  $2.60 \times 10^5$  Pa (Fig. 1), was observed in the blend with 20% concentration for Toner B at 90 °C, making it the most effective in minimising permanent deformation. Toner D, also at a 20% concentration, exhibited the second-highest rutting resistance value of  $2.17 \times 10^4$  Pa at 90 °C. Blends of Toner A and C revealed similar trends, showing that the optimal dosage varied by toner type, with concentrations of 5% and 20% generally delivering superior performance. The findings align with Superpave specifications<sup>15</sup>, which recommended maximising  $G^*/\sin \delta$  to improve resistance to deformation under high temperatures and heavy loads.

#### 3.1 Comparison with earlier studies

##### *Rutting resistance ( $G^*/\sin \delta$ )*

The highest rutting resistance was found in the current investigation at 20% Toner B ( $\approx 2.60 \times 10^5$  Pa), indicating a significant improvement in deformation resistance after repeated loading. Although the absolute values were lower due to variations in binder composition, Rambarran et al.<sup>4</sup> found improved rutting resistance in toner-modified TLA, which is consistent with the result in this study. In a parallel manner, Sadiq et al.<sup>6</sup> found that adding toner to petroleum bitumen improved its stiffness and resistance to rutting, but that the benefits diminished at 15%. A more recent research by Itoua et al.<sup>16</sup> verified that carbon black and toner resins function as stiffening agents, increasing  $G^*/\sin \delta$  values. The current findings further support these observations by indicating that toner type strongly influences optimum dosage, with Toner B outperforming others at high concentrations, likely due to its resin and pigment composition.

##### *Fatigue cracking resistance ( $G^*\sin \delta$ )*

Fatigue cracking resistance showed an inverse trend to rutting resistance. At low dosage, the 5% Toner D blend achieved the lowest  $G^*\sin \delta$  value of  $3.93 \times 10^2$  Pa at 90 °C, highlighting its effectiveness in enhancing fatigue resistance through improved binder elasticity. In addition, the higher dosage of 20% Toner C blend recorded a  $G^*\sin \delta$  value of  $1.04 \times 10^4$  Pa at 90 °C, demonstrating strong resistance to fatigue failure under elevated thermal conditions. This result is in line with the basic concept presented by Maharaj et al.<sup>10</sup> and supported by Shah et al.<sup>7</sup>, who highlighted that polymeric modifiers improve fatigue resistance and elasticity at specific dosages but can cause brittleness when overapplied. Toner resins and pigments change binder viscoelasticity, reducing phase angles and enhancing fatigue resistance at optimal concentrations, according to a recent research by Itoua et al.<sup>16</sup>.

Similarly, Siddiq et al.<sup>6</sup> demonstrated that waste toner and recycled LDPE blends increased fatigue cracking resistance while preserving rutting performance, underscoring the significance of hybrid modification techniques and dosage optimisation. The current results expand on previous observations by demonstrating toner-specific optima: Toner D achieved maximal fatigue resistance at lower concentrations ( $\approx 5\%$ ), whereas Toner C performed best at higher concentrations. This highlights the necessity of adjusting toner dose according on binder type and service circumstances. Long-term pavement durability depends on striking a compromise between rutting resistance and fatigue resistance, especially in tropical regions where binders are subjected to significant heat loads.

##### *Temperature susceptibility*

TLA blends continuously outperformed TPB blends, and performance declined as the temperature rose to 90°C. This is in line with Maharaj's<sup>12</sup> findings that the higher softening point of TLA contributes to improved high-temperature stability. In this study, toner change further improves the TLA performance envelope, making it especially appropriate for tropical regions.

### 3.2 Supporting evidence and mechanistic insights

#### *Toner composition and compatibility*

The inherent composition of toner can account for the observed rheological improvements. According to Parthasarathy<sup>2</sup> and Rambarran et al.<sup>4</sup>, toner is made up of silica additives, waxes, carbon black, and thermoplastic resins. While silica and waxes promote dispersion and lessen agglomeration, resins and carbon black boost stiffness and rutting resistance. In a study conducted by Shah et al.<sup>7</sup>, the high-shear wet-mixing methodology used here (160 °C, 30 min) ensures uniform distribution of toner particles and maximises performance benefits.

#### *Binder-modifier interactions*

Interactions between binders and modifiers are also crucial. In contrast to petroleum bitumen, Widyatmoko & Elliott<sup>13</sup> showed that plastomeric modifiers interact well with natural asphalts, producing stronger stiffness and smaller phase angles. This explains why, at high temperatures, TLA blends consistently performed better than TPB blends. In line with the viscoelastic behaviour described by Itoua et al.<sup>16</sup>, the observed decrease in phase angle ( $\delta$ ) throughout optimal toner dosages suggests increased elasticity and decreased viscous dissipation.

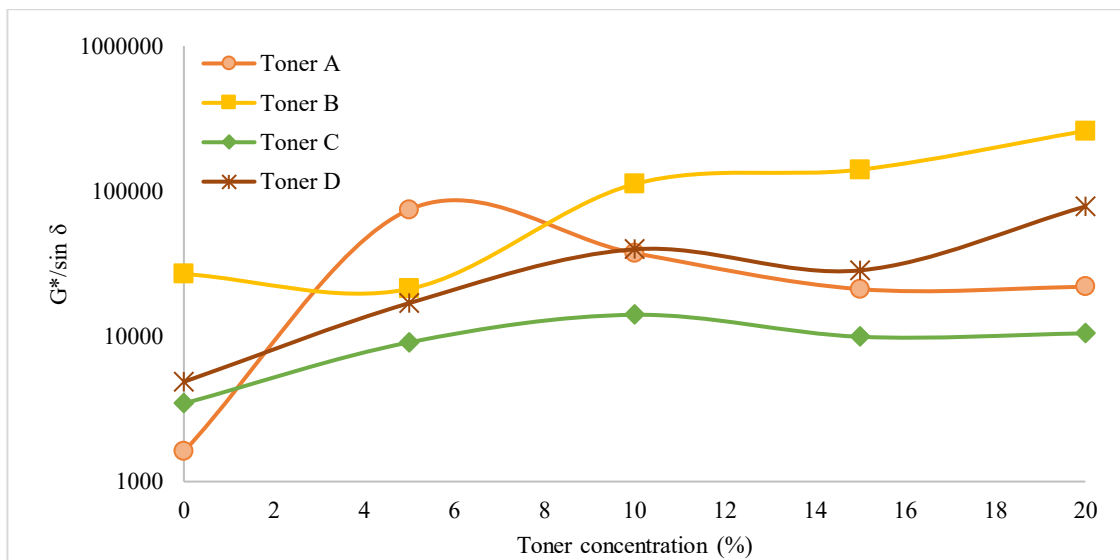


Fig. 1. An illustration of the rutting resistance parameter ( $G^*/\sin \delta$ ) plotted for waste toners (A, B, C & D) at 60 °C and 1.59 Hz

Source: Author's own data

Fatigue cracking resistance, represented by  $G^*\sin \delta$ , showed an inverse trend to rutting resistance, with lower values indicating better performance. Among the blends, 20% Toner C achieved the lowest  $G^*\sin \delta$  value of  $1.04 \times 10^4$  Pa at 90 °C (Fig. 2), indicating its superior resistance to fatigue cracking. Conversely, higher concentrations of Toner B (20%) resulted in diminished fatigue resistance, as evidenced by its elevated  $G^*\sin \delta$  value of  $2.40 \times 10^5$  Pa. These findings highlight the importance of optimising toner concentrations to balance the trade-offs between rutting resistance and fatigue cracking resistance, ensuring improved longevity and durability of the asphalt.

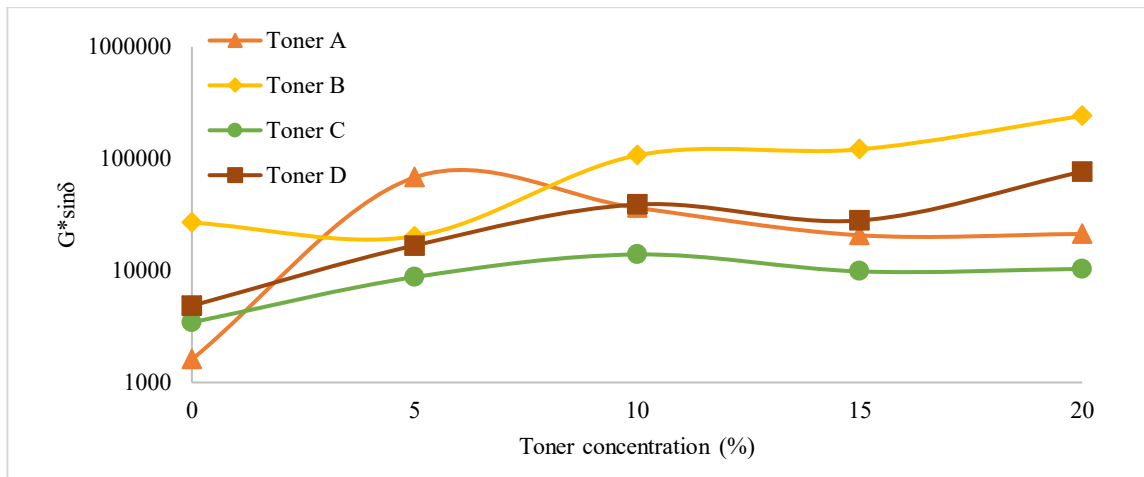


Fig. 2. An illustration of the fatigue cracking parameter ( $G^* \sin \delta$ ) plotted for waste toners (A, B, C & D) at 60 °C and 1.59 Hz.

Source: Author’s own data

Temperature variations had a notable effect on performance, with higher temperatures generally reducing both rutting and fatigue cracking resistance. At 60 °C,  $G^* \sin \delta$  values were the highest for 20% Toner B, indicating that it performed better under moderate tropical conditions. However, when the temperature was increased to 90 °C (Fig. 3), the resistance of most blends decreased. Pure TLA exhibited superior temperature susceptibility compared to TPB, thus confirming TLA's suitability for high-demand scenarios such as airport runways. TPB, on the other hand, showed the poorest performance, underscoring its limitations for use in tropical climates without modification.

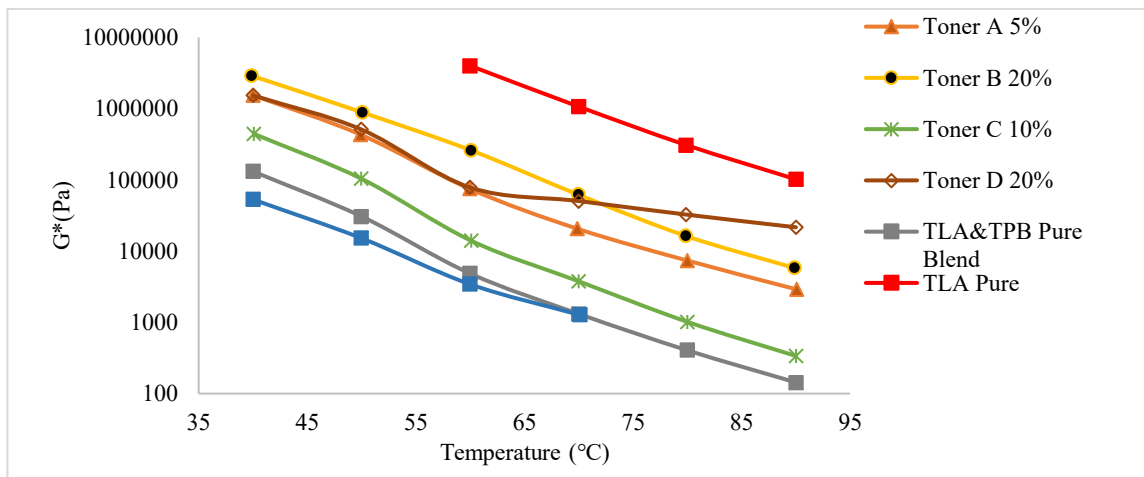


Fig. 3. The impact of temperature on the rutting resistance for each of the optimal toner blends ( $G^* \sin \delta$ )

Source: Author’s own data

Fig. 4 shows that all  $G^* \sin \delta$  values for each blend gradually decreased as temperature increased, indicating an increased in fatigue cracking resistance. The maximum fatigue cracking resistance occurred for all the blends at 90 °C except for Pure TPB, which occurred at 70 °C with a  $G^* \sin \delta$  value of  $1.21 \times 10^3$  Pa. The lowest  $G^* \sin \delta$  value ( $1.43 \times 10^2$  Pa) from the trend above was TLA & TPB pure blend at 90 °C. With respect to the various optimised toner blends, 5% Toner D had the maximum fatigue resistance at 90 °C and the lowest  $G^* \sin \delta$  value of  $3.93 \times 10^2$  Pa, and 5% Toner B had the lowest fatigue cracking resistance (highest  $G^* \sin \delta$  value) of  $5.56 \times 10^2$  Pa.

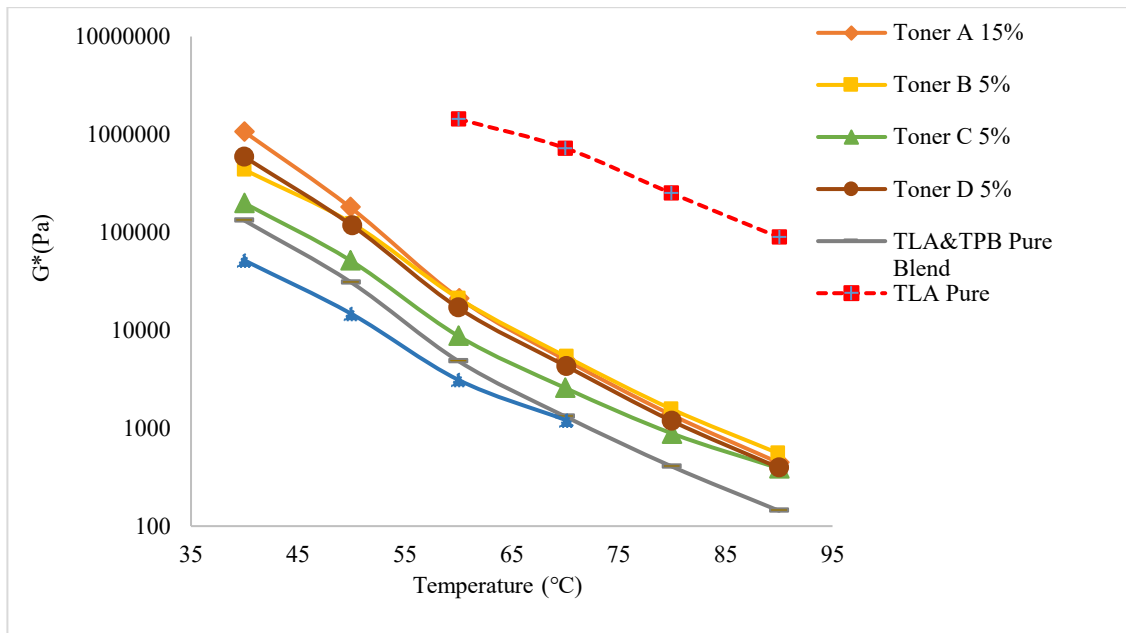


Fig. 4. The impact of temperature on the fatigue cracking resistance for each of the optimal toner blends ( $G^* \sin \delta$ )

Source: Author’s own data

The black curve analysis provided further insights into the performance of the modified blends by evaluating stiffness ( $G^*$ ) and elasticity ( $\delta$ ) across different frequencies and temperatures. Optimal performance was observed for blends containing 5% and 20% Toner (A, B, C & D) as these blends exhibited high stiffness and low phase angles, indicating reduced deformation and enhanced elasticity. These results suggest that specific toner concentrations optimise the viscoelastic properties of asphalt blends, making them suitable for diverse road paving applications. The black curves for the four (4) waste toners (A-D) at various blends are shown in Fig. 5–8.

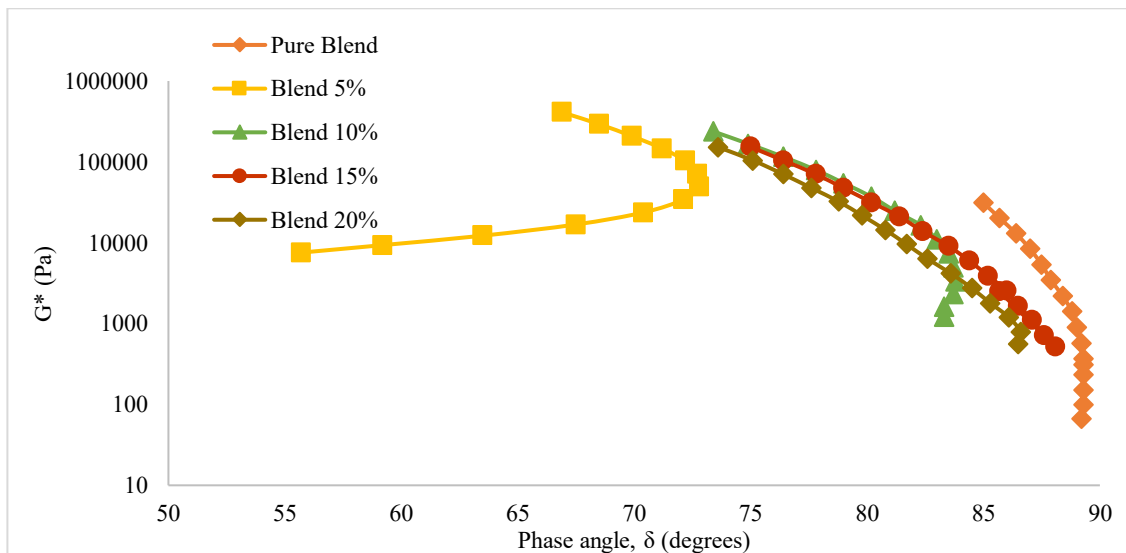


Fig. 5. Black curves for waste toner A blends measured at 60 °C and 1.59 Hz

Source: Author’s own data

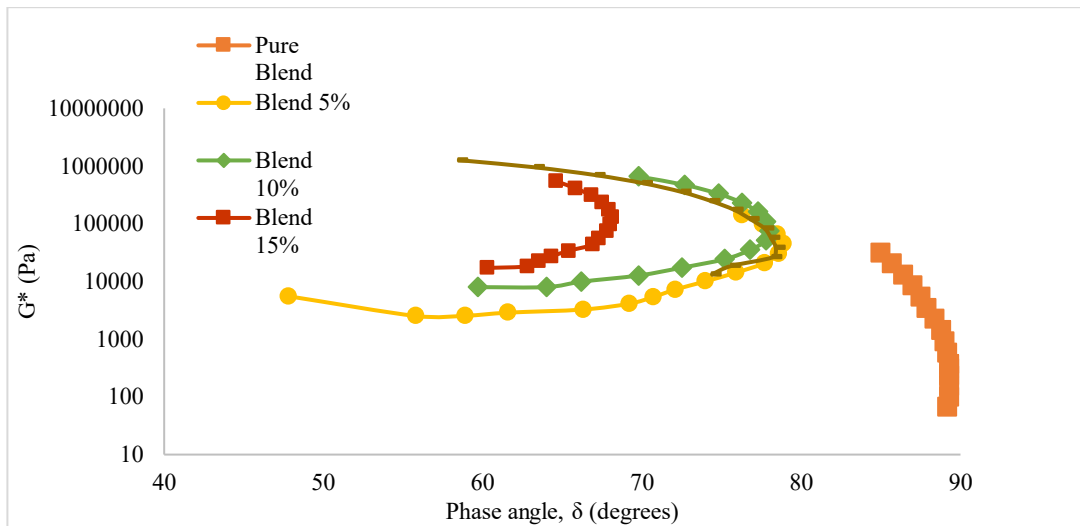


Fig. 6. Black curves for waste toner B blends measured at 60 °C and 1.59 Hz

Source: Author’s own data

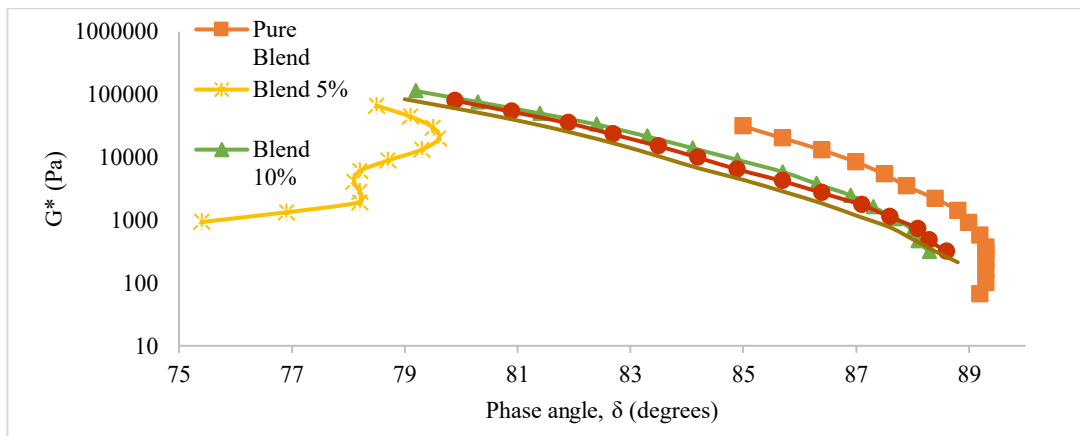


Fig. 7. Black curves for waste toner C blends measured at 60 °C and 1.59 Hz

Source: Author’s own data

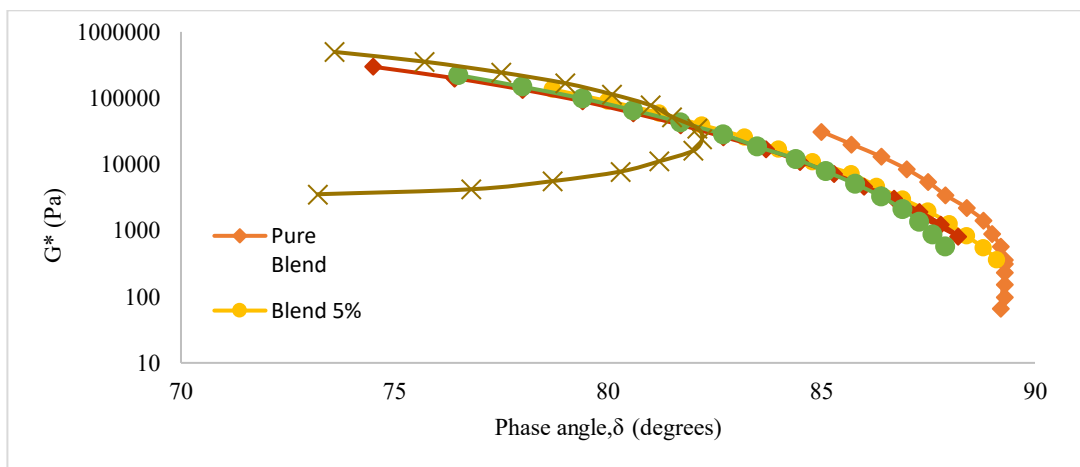


Fig. 8. Black curves for waste toner D blends measured at 60 °C and 1.59 Hz

Source: Author’s own data

Due to variations in the base compositions and methods of interaction with the asphalt matrix, the various toner types may have varied ideal toner concentrations. Higher polymer resin or pigment content toners, for instance, may be more compatible with bitumen, resulting in greater dispersion and improved viscoelastic performance at higher concentrations. On the other hand, saturation effects or agglomeration may cause other toners to operate best at lower dosages. These discrepancies might also result from variances in surface chemistry, particle size distribution or thermal softening behaviour. Future research involving thorough material characterisation and repeated testing could elucidate these influences, even though this study did not isolate every compositional variable.

From the environmental perspective, the use of waste toner in asphalt blends provides a sustainable solution to the growing e-waste problem. By partially substituting virgin asphalt binders with toner, this approach can reduce the demand for non-renewable bituminous resources and minimise carbon emissions associated with asphalt production. For instance, incorporating just 5% toner by weight into a typical binder formulation could divert substantial amounts of waste toner from landfills if adopted at scale for national road maintenance. However, several challenges may hinder widespread adoption, including variability in toner quality, collection logistics, and the lack of regulatory standards for asphalt modifiers derived from e-waste. Furthermore, long-term environmental impacts such as potential leaching of residual metals or organics from the pavement surface must be evaluated through aging and durability studies. Despite these limitations, the application presents a promising step toward circular economy practices in construction. Globally, e-waste generation reached 53.6 million Mt in 2019, with only 17.4% formally recycled<sup>1</sup>. By repurposing waste toner into asphalt, this study offers a viable pathway to reduce the environmental and health risks associated with improper disposal, including air pollution<sup>17</sup> and contamination from heavy metals and carcinogenic compounds. Additionally, this approach aligns with international initiatives such as the Basel Convention<sup>18,19</sup>, and supports the circular economy by transforming waste into valuable resources<sup>20</sup>. It is recommended that future work investigate the long-term field performance of these blends under varying climatic and load conditions to further validate their potential for large-scale infrastructure projects.

#### 4. CONCLUSION

This study highlights the substantial potential of adding waste toner to asphalt mixtures as a sustainable and performance-boosting addition. The findings demonstrate that waste toner improves critical rheological properties, such as rutting resistance ( $G^*/\sin \delta$ ) and fatigue cracking resistance ( $G^*\sin \delta$ ), aligning with Superpave specifications for optimal asphalt performance. The best results were achieved with 20% Toner B for rutting resistance, exhibiting a  $G^*/\sin \delta$  value of  $2.60 \times 10^5$  Pa, while 20% Toner C demonstrated superior fatigue cracking resistance with a  $G^*\sin \delta$  value of  $1.04 \times 10^4$  Pa at 90 °C. Variability in the optimal performance concentrations among toners could be attributed to intrinsic variations in their base compositions, which impact how they interact with asphalt. These variations include filler properties, heat behaviour, and polymer resin content. Furthermore, this difference might have been caused by a lack of repeated samples and possible measurement uncertainty, even when mixing and testing procedures were standardised. These optimised blends exhibited improved stiffness, elasticity, and resistance to deformation, supported by high  $G^*$  and low phase angle values, with Superpave guidelines for enhanced binder performance<sup>13</sup> making them suitable for road paving applications in tropical regions. Additionally, the study underscores the environmental benefits of repurposing waste toner and addresses the global challenge of e-waste management. By providing an effective recycling pathway, this approach reduces the environmental impact of improper toner disposal, supports circular economy initiatives, and aligns with international waste management policies such as the Basel Convention. Future research should focus on field testing, economic analysis, and scalability to validate these findings and promote the widespread adoption of toner-modified asphalt blends. Overall, this study offers a promising solution to enhance infrastructure resilience while contributing to sustainable development and environmental protection.

#### 5. ACKNOWLEDGEMENTS / FUNDING

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

## 6. CONFLICT OF INTEREST STATEMENT

The authors declare that there was no conflict of interest.

## 7. AUTHORS' CONTRIBUTIONS

Conceptualisation: R. Maharaj, & S. Rambarran

Data curation: Not applicable

Methodology: R. Maharaj, & S. Rambarran

Formal analysis: S. Mohammed, A. Clark, R. Maharaj, & S. Rambarran

Visualisation: Not applicable

Software: Not applicable

Writing (original draft): R. Maharaj, S. Rambarran, A. Clark. & S. Mohammed

Writing (review and editing): R. Maharaj, S. Rambarran, A. Clark., N. Sangster, & S. Mohammed

Validation: Not applicable

Supervision: R. Maharaj, & N. Sangster

Funding acquisition: Not applicable

Project administration: Not applicable

## 8. DECLARATION OF GENERATIVE AI IN THE WRITING PROCESS

During the preparation of this work, the author(s) used ChatGPT (Open AI) in order to improve language clarity, grammar and overall readability. After that, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

## 9. DATA AVAILABILITY/SUPPLEMENTARY MATERIALS

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

## 10. ETHICS STATEMENT

The authors declare that this research did not involve human or animal subjects. All experimental procedures were performed following the institutional Safety, Health, and Environmental (HSE) protocols of The University of Trinidad and Tobago.

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