

Accelerated Pavement Testing (APT) of a test section surfaced with an asphalt wearing coarse containing plastic waste incorporated using the 'wet method'

TRB Specialty Conference submission number:

Michelle A. Smit

Council for Scientific and Industrial Research

Meiring Naude drive, Gauteng, South Africa

Tel: (+27) 84 645 4829 Email: MSmit3@csir.co.za

Frederik Christoffel Rust

Pavement Engineering Research Consultancy

Hermanus, South Africa

Tel: (+27) 82 447 6098 Email: chris@perc.co.za

Georges Mturi

Road Materials Consulting (Pty) Ltd

Postnet Suite 101, Private Bag X19, Menlo Park, Pretoria, 0102, South Africa

Tel: (+27) 83 210 0198, Email: gmturi@rmcsa.co.za

Refiloe Mokoena

Council for Scientific and Industrial Research

Meiring Naude drive, Gauteng, South Africa

Tel: (+27) 72 312 8713 Email: rmokoena@csir.co.za

Richard Ntombela

Dow Southern Africa (Pty) Ltd

Spaces Design Quarter, Leslie Road, Fourways, Johannesburg, 2191, South Africa

(+27) 71 212 0929, Email: richard.ntombela@dow.com

Herman Marais

Much Asphalt

PO Box 49, Eerste River, 7103, South Africa

Tel: (+27) 11 423 1004, Email: herman.marais@aeciworld.com

Ray Govender

WBHO Construction

53 Andries Street, Wynberg, Johannesburg, 2090, South Africa

Tel: (+27) 11 321 7641, Email: ray.govender@wbho.co.za

Keywords: *plastic waste in road construction, hot mix asphalt, wet modification method*

Acknowledgments: The project was co-funded by WBHO (for construction of the granular layers), Dow (for the manufacturing and paving of the asphalt surfacing), ROMH Consulting and the Department of Science and Innovation (for the pavement design of the pavement structure), Much Asphalt (for their partial contribution towards HVS testing), and the rest of the HVS testing was funded by the CSIR.

ABSTRACT

The incorporation of plastic waste in road pavement materials presents a promising opportunity for sustainable infrastructure development. In South Africa, introducing any innovation requires compliance with national performance criteria and guidance from mechanistic-empirical design methods. This study evaluated the rutting resistance performance of a road pavement section surfaced with plastic waste modified asphalt (PWMA) produced via the wet method – where plastic waste is integrated into the bituminous binder before mixing.

An Accelerated Pavement Testing (APT) program was adopted for the permanent deformation testing of a coarse continuously-graded asphalt wearing course modified with plastic waste. The PWMA was produced with post-consumer recycled plastic waste and also incorporated a Reactive Elastomeric Terpolymer (RET). Test sections were constructed in Gauteng, South Africa, comprising a reference asphalt (based on a standard unmodified bitumen used in South Africa) structure and a PWMA layer. Both sections were subjected to simulated traffic loading using a Heavy Vehicle Simulator (HVS) at speeds of 12km/h, varying wheel loads (40, 60 and 80 kN dual wheel load), and controlled temperatures reflective of local pavement conditions. Performance monitoring involved surface and embedded measurement tools, including Road Surface Deflectometer (RSD), Multi Depth Deflectometer (MDD), standard straight edge, thermocouples and temperature buttons.

After 2.9 million equivalent standard axles (ESALs) of HVS loading, the PWMA section demonstrated enhanced rutting resistance, with an average rut depth of 7.2 mm, compared to 10.4 mm for the reference section, which reached a maximum rut of 12mm. These results align with laboratory findings, confirming that the addition of plastic waste increases the structural integrity of asphalt layers by enhancing resistance to permanent deformation. This study supports the potential for adopting PWMA in South African road infrastructure to meet national performance standards and sustainability goals.

INTRODUCTION

South Africa is ranked amongst the top 20 contributors of ocean plastic worldwide, with 0.09-0.24 million metric tons of plastic ending up in the ocean per year (Jambeck *et al.*, 2015). Developing end-user markets for plastic waste is considered critical to increasing recycling rates and decreasing leakages into the environment (Mturi *et al.*, 2021a & 2021b). Road construction as an end-user market for recycled plastic is being investigated worldwide not only as a green investment but also for improving pavement durability (Milad *et al.*, 2020). The road construction industry is governed by national standards to ensure the material, physical, mechanical, performance, and application requirements of road surfaces and pavements. Thus, before these alternative materials, such as plastic waste materials and plastic waste modified materials, can enter the market; they must comply with specification requirements and regulations (Rampersad, 2022).

Introducing plastic waste into asphalt can be achieved through two popular methods, referred to as the 'dry method' and 'wet method' of incorporation, respectively. For the 'dry method', softened plastic waste at high temperatures is smeared onto the aggregate surface before bitumen addition. This method has

been investigated successfully in over 5,000 kilometres of roads in at least 11 states in India (Suaquita, 2019). In the second approach, plastic waste is used to modify bitumen prior to the manufacture of the asphalt mix, commonly known as the 'wet method'. Although this approach has been widely researched, South African standards require an appropriate degree of *in situ* compatibility or storage stability of the plastic waste and bitumen blended material, so as not to compromise the in-service performance of the asphalt road, which required customized research and field validation.

The Council for Scientific and Industrial Research (CSIR), together with national and international industry partners, evaluated the incorporation of plastic waste into asphalt through both the 'dry method' (O'Connell *et al.*, 2024; Mturi *et al.*, 2025a) and 'wet method' (Mturi *et al.*, 2021a & 2021b; Pholo *et al.*, 2024) to establish performance data for the feasibility of using these materials in terms of engineering properties for South African traffic loading and climatic conditions. Trial sections were constructed and accelerated pavement testing (APT) conducted using the South African Heavy Vehicle Simulator (HVS). The HVS has been used over a forty-year period to evaluate innovative pavement designs and materials with significant impact (Rust *et al.*, 1997; Du Plessis *et al.*, 2008) that currently include plastic waste, nano-modified emulsions and bio-cementation to upgrade marginal materials (Smit *et al.*, 2022, Smit *et al.*, 2021, Rust *et al.*, 2020).

This article focuses on the HVS performance evaluation of a test section constructed with PWMA adjacent to a control section with an asphalt layer containing a typical unmodified binder used in South Africa as a comparison (reference) point. The approach aimed to validate the stiffening effect with the plastic waste modification of bitumen that improves permanent deformation resistance at high temperatures, as was shown with laboratory asphalt test results (Pholo *et al.*, 2024). Consequently, it required simulating South African traffic speed and levels, as well as maximum pavement temperatures where the asphalt layer is more susceptible to permanent deformation.

MATERIALS AND METHODS

Objective

The main objective of the HVS test was to evaluate the performance of a trial section that contains a PWMA layer compared with a control reference asphalt section, both constructed on top of the same standard pavement structure in terms of their respective bearing capacity and general performance under accelerated traffic. The main mode of failure that was investigated was total surface rutting with a failure criterion of 20 mm total rut at above ambient air temperature conditions. The terminal rut of 20 mm is specified in several South African pavement design and testing guidelines including COTO (2020) and TRH 4 (1996). Safety, riding quality and comfort and pavement distress progression (rutting beyond 20mm often accelerates distress like cracking) forms the base for the 20mm failure criteria. The research question was therefore: "Can the incorporation of plastic waste into bitumen via the 'wet method' improve the rutting performance of an asphalt layer?"

Test section construction

A trial section was constructed at the University of Pretoria APT test site with an ES 30 design (10 to 30 million equivalent standard axles or ESALs). The profiles of the trial section and the reference section are shown in Figure 1.

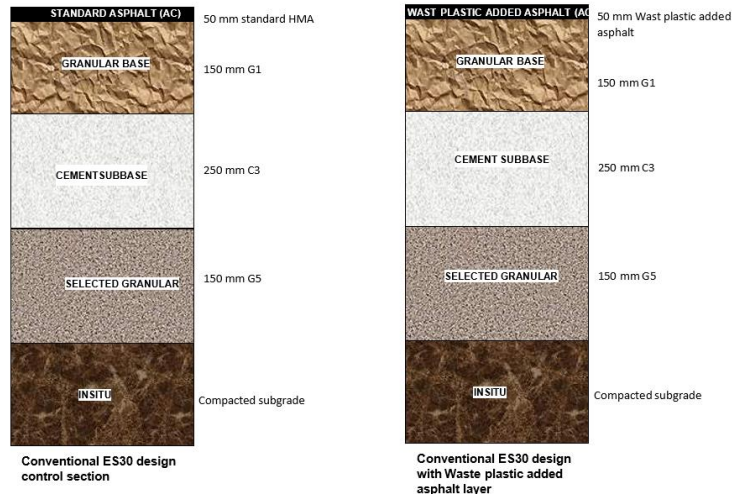


Figure Error! No text of specified style in document.: Conventional ES 30 design vs ES 30 design with a PWMA layer

The G1 material refers to a high quality crushed aggregate layer compacted to a high density. The specification is: sound crushed rock of nominal size 37.5 mm; Liquid Limit less than 25 and Plasticity Index less than 4; Linear shrinkage less than 2 %; compacted to 88 % of apparent relative density (COTO, 2020).

The C3 material is a lightly cement stabilised granular material with a UCS strength at 7 days of 1.5 MPa to 3.0 MPa (COTO, 2020).

The selected layer is an imported material compacted to provide a working platform for construction of the structural layers. The G5 material refers to a gravel with pebbles and small cobbles having the following specifications: Maximum particle size of 50 mm with a grading modulus (GM) between 1.5-2.5; Liquid Limit less than 30 and Plasticity Index less than 10; Linear shrinkage less than 5 %; California bearing ratio (CBR) more than 45 % at 95 % of maximum dry density (MDD) and swell less than 0.5 % at 100 % of MDD (COTO, 2020).

The compacted subgrade consisted of a G9 material with the following specifications: soil, gravel with a GM between 0.75-2.7; a Plastic Index lower than $(3 \times GM) + 10$; CBR more than 7 % at 93 % of MDD and swell less than 1.5 % at 100 % MDD (COTO, 2020).

Table 1 show the technical paving details of the asphalt layers.

Table 1: Technical paving details

Parameter	Plastic Waste Mix	Asphalt Reference Mix
Surfacing	50 mm Continuously graded coarse asphalt	
Base binder	70/100 penetration grade binder	50/70 penetration grade binder
Plastic waste	Yes	No
Chainage	0+000km to 0+050km	0+050km to 0+100km
Field compaction	93 ± 0.5%	
Paving width	4.2m	

The PWMA was based on a CSIR patent (Mturi *et al.*, 2025b) and consisted of a 70/100 penetration grade base binder conforming to SANS 4001-BT1 requirements and modified post-consumer polyolefin plastic waste (0-4 %) according to developed criteria for South Africa (Mturi *et al.*, 2021a & 2021b) to improve compatibility with bitumen. A Reactive Elastomeric Terpolymer (RET) was added (0-2%) to improve fatigue resistance properties. In contrast the reference mix was constructed using a 50/70 penetration grade bitumen, commonly used in flexible pavements for South Africa.

Conventionally, 50/70 penetration grade bitumen exhibits greater resistance to permanent deformation at high temperatures compared to 70/100 penetration grade bitumen due to its higher stiffness. This distinction is particularly significant under the test conditions employed, which involved elevated pavement temperatures and heavy loading scenarios. The use of the softer 70/100 penetration grade base bitumen in the PWMA, therefore, allowed for a direct assessment of the influence of plastic waste modification on high-temperature performance relative to the stiffer 50/70 penetration bitumen of the reference mix.

The trial section was constructed in such a way that the HVS test section could span the joint between the PWMA section and the reference section. Thus, both options could be tested in one HVS test in a direct comparison (Figure 2).

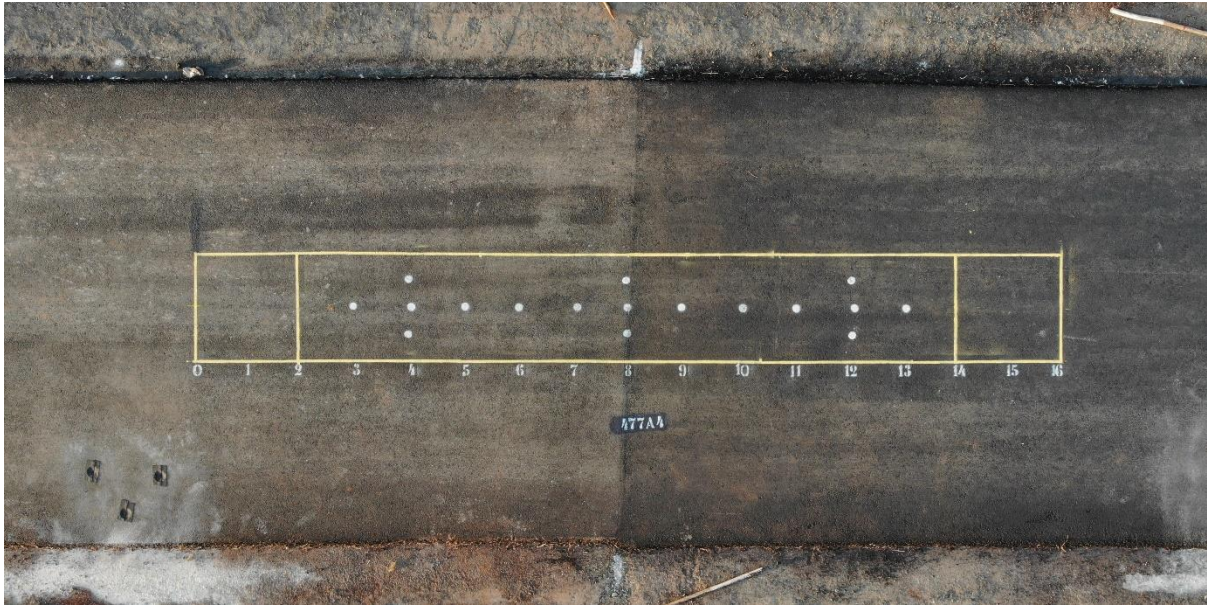


Figure 2: Aerial photo of the construction joint and HVS test section

HVS testing protocol

The standard South African HVS test protocol (SANRAL, 2021) was followed. Standard (40 kN dual wheel load, 80 kN axle loads) and high non-standard loads (60 kN dual wheel load, 120 kN axle load to 80 kN dual wheel load, 160 kN axle load) at a speed of about 12km/h were applied to the section to study the permanent deformation of the PWMA layer compared to that of the conventional asphalt. Although the wander pattern simulates actual traffic, a channelised HVS traffic pattern was used as is commonly employed for permanent deformation evaluation (Hugo and Martin, 2004).

The following HVS dual wheel load applications were therefore applied to both the reference asphalt layer section and the PWMA layer section simultaneously, using a constant tyre pressure of 780 kPa:

- 71, 857 repetitions of a 40 kN dual wheel load (simulating a standard 80 kN axle load);
- 89, 461 repetitions of a 60 kN dual wheel load (simulating a 120 kN axle load);
- 124, 856 repetitions of a 80 kN dual wheel load (simulating a 160 kN axle load);

The application of incrementally increasing loads was implemented to optimize the generation of ESALs within the project's time constraints. The increase served two main purposes:

- Controlled pavement conditioning – gradually increasing the load allows the pavement to undergo controlled conditioning, preventing premature failure.
- Adaptive load adjustments – Adjusting the load once a performance plateau is observed or project timeline and funding constraints.

This methodical approach allowed for the effective simulation of cumulative traffic loading while safeguarding the pavement from artificial premature failure, thereby enhancing the reliability of the performance data collected.

The total number of HVS repetitions applied to the HVS section was 286, 174. This equates to approximately 2.9 million ESALs under channelized trafficking or 5.2 million ESALs using equivalent comparable wandering traffic (Steyn, 2012). For this calculation the standard damage coefficient of 4.2 was used (Equation 1).

$$ESAL = N \times \left(\frac{L}{80}\right)^k$$

Where:

N = Number of load repetitions

L = Applied axle load in kN

80 = Standard reference axle load

k = Damage coefficient (typically 4.2 for flexible pavements in South Africa)

The damage coefficient represents the sensitivity of the pavement to axle loads. In South Africa, a value of 4.2 is typically adopted for flexible pavements, aligning with local calibration of mechanistic-empirical models and findings from HVS testing (COTO, 2020).

Several HVS-associated instruments and sensors (both embedded and non-embedded) were used to monitor the structural behaviour and environmental conditions on the HVS section during testing. The HVS section layout with associated embedded instrumentation is shown in Figure 3. The HVS-associated instruments and sensors included:

- CSIR Multi-Depth Deflectometer's (MDD's) – embedded at four locations;
- Standard straightedge – non-embedded;
- Thermocouples (k-type) – embedded at two different depths within the asphalt layer, at 8 locations along the test section;
- Temperature buttons – embedded at 6 locations along the test section;
- CSIR Road Surface Deflectometer (RSD) – non embedded; and
- Weather Station – non-embedded.

LAYOUT OF SECTION 477A4

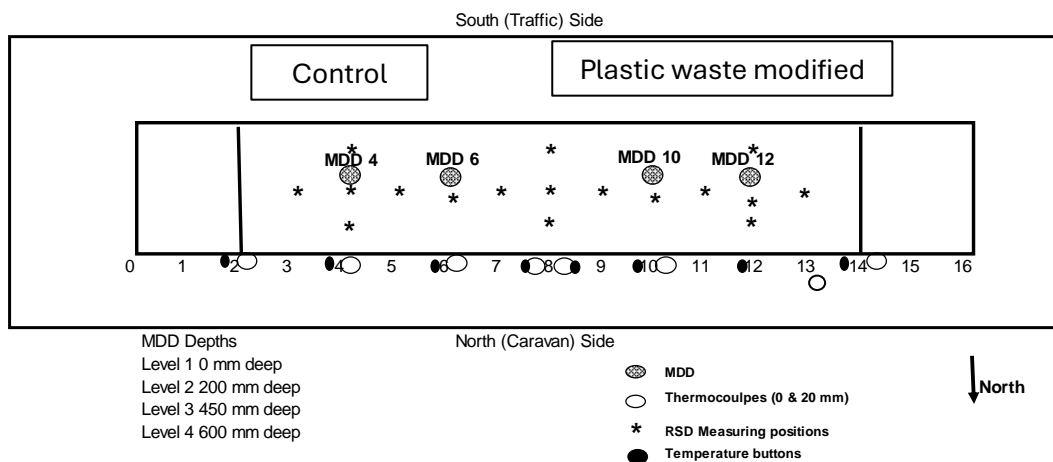


Figure Error! No text of specified style in document.: Test section and instrumentation layout

In addition to the traffic loading, the section was also subjected to temperatures higher than ambient air temperatures. Testing asphalt at high temperatures has been the norm internationally to account for hot climates or hot summer months. High temperatures can soften asphalt, given its viscoelastic nature, leading to permanent deformation under heavy traffic loads. Furthermore, the complex stiffness/viscosity-temperature relationships and stress sensitivity shown by certain bitumen additives (Mturi *et al.*, 2021b), have made it a challenge to predict the performance of asphalt at different temperature environments based on the testing at a single temperature condition. In addition to these needs, the HVS test was also subjected to temperatures higher than ambient air temperatures in an attempt to simulate maximum temperature conditions specified for Pretoria, South Africa (SATS 3208, 2021). The majority of climate models predict an increase in air temperatures in the near future, specifically, an increase in the average air temperatures and the frequency and duration of extreme temperatures. According to Mokoena *et al.* (2024) this will have a direct impact on asphalt pavement performance by increasing the potential for permanent deformation of pavements and the rate of age hardening of asphalt binders. Mokoena *et al.* (2024) interpolated maps of maximum pavement temperatures using an ensemble of climate models for predicted air temperatures for two 20-year periods, up to the years 2040 and 2060. According to these maps, Pretoria should expect a maximum pavement temperature of 64°C as indicated in Figure 4.

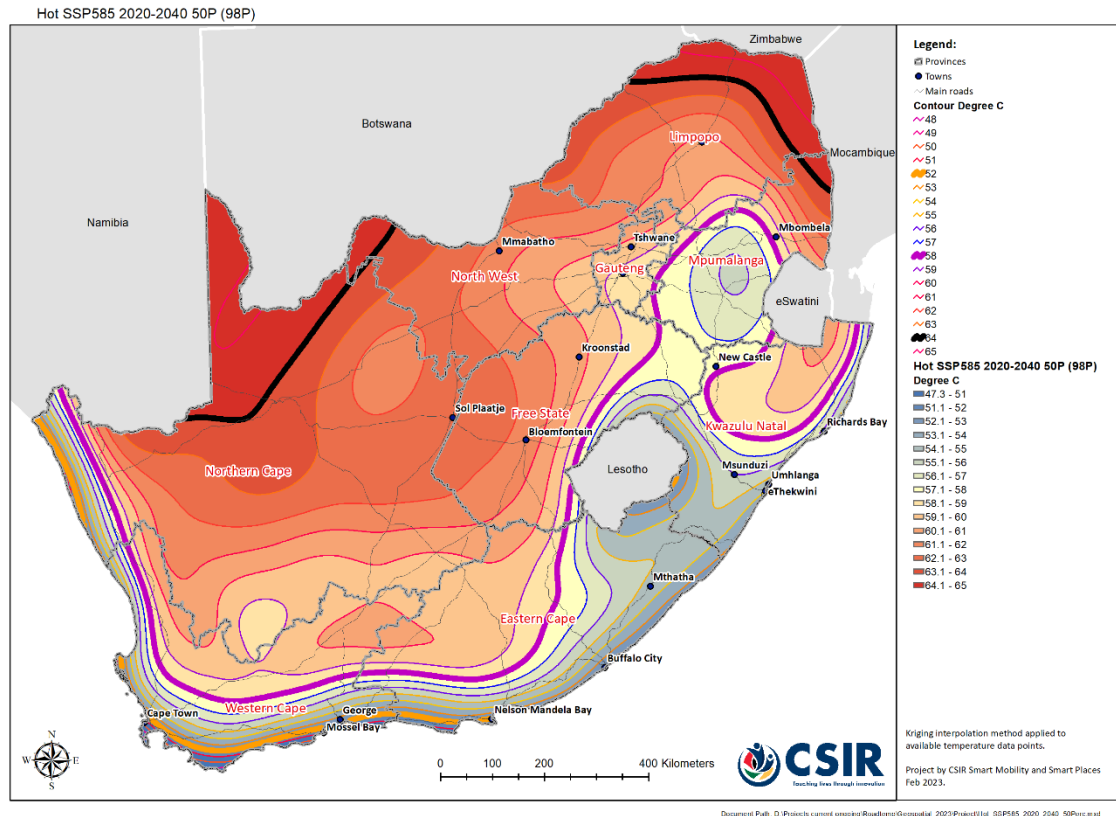


Figure 4: Projected 7-day maximum pavement temperature between 2020 and 2040 at 20 mm depth (Mokoena *et al.*, 2024)

During the HVS test, temperatures were increased using heaters located close to the section and covered with tarps to maintain the heat (Figure 5). Simple open-element heaters with a basic temperature control system that switches off once the set temperature is reached were used during testing. These heaters were fabricated by the CSIR HVS team back in the 1980's for temperature controlled HVS testing. Placed side-by-side they span the full length of an HVS test section, curved at the top to direct the heat down to the pavement.



Figure 5: Heater set up on the HVS section.

Pavement temperatures were monitored using the following methods:

- Thermocouples installed at different locations and depths. The thermocouples allowed the team to monitor the temperature continuously in real time.
- Temperature buttons were installed in the pavement at several locations using a similar methodology as previous Long Term Pavement Performance (LTPP) studies conducted in South Africa (Denneman, 2024) (Figure 6). Temperature button measurements were automatically taken every 40 minutes to save on power and storage. These instruments are wireless with on-board power and storage, however they do not have the capability of real time data transfer. The buttons were removed at the end of the test and data extracted. The data is displayed in Figure 7.



Figure 6: Temperature button

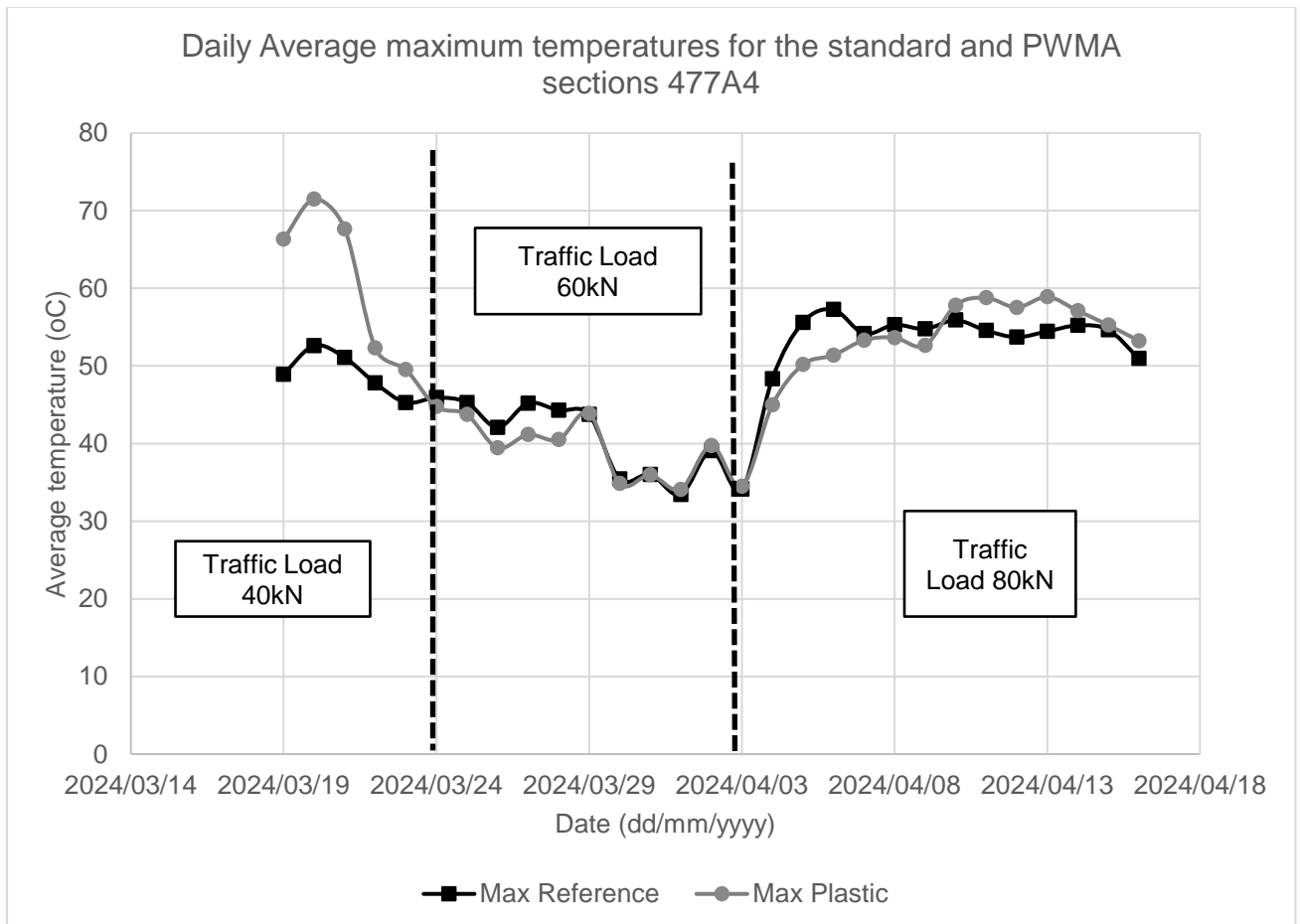


Figure 7: Daily Average maximum temperatures for the reference asphalt layer and PWMA layer

It can be observed from Figure 7 that it was difficult to maintain the temperature of the two sections within acceptable limits in the early stages of testing. This was due to power constraints prohibiting all

the heaters to operate at the same time and lack of cover provided by the tarps which was fixed by the addition of a generator and tarps. From 16/03/2024 to 22/03/2024, the PWMA layer had an average temperature of 20 °C higher than the reference asphalt layer. Despite this initial temperature differential, the PWMA section demonstrated superior resistance to permanent deformation compared to the reference mix section as shown in the results and discussion section of this paper. It should be noted that deflection data was not adjusted for temperature since the heaters were switched off and moved away, then the pavement allowed to cool down (also for safety reasons) before deflection measurements were taken.

RESULTS AND DISCUSSION

Weather data

Rainfall data was collected daily using a standard rain gauge over the full duration of HVS testing (Figure 8). A total of 112mm of rain was recorded during the one-month period of HVS testing, particularly between the 4th of April 2024 and the 9th of April 2024. Ambient air temperatures were recorded using the established weather station on-site. These temperatures were recorded over the full duration of HVS testing. The average maximum temperature during testing was 30.7 °C and average minimum temperature was 21.6 °C.



Figure 8: Rain gauge

Road surface deflectometer (RSD) deflections

The RSD elastic deflections as measured under a 40 kN, 60 kN and 80 kN measurement wheel load are shown in Figure 9. It can be noted that the average RSD deflection of the PWMA section was only slightly higher (0.01 mm) than that of the reference asphalt section during the first two phases of testing. When the trafficking load increased to 80 kN, the PWMA section showed an average 0.1 mm higher surface deflection compared to the reference asphalt layer. The elastic deflections measured in both

sections are relatively low at around 0.3 mm and 0.36 mm for the PWMA section and 0.2 mm for the reference section. This is indicative of the high strength of the underlying layers. This variability is within acceptable limits for field-constructed pavements, typically influenced by factors such as construction tolerances, layer compaction variations, and inherent material inconsistencies. In this context, variability in RSD deflections of around 0.01 mm to 0.15 mm is considered normal for accelerated pavement testing, reflecting minor differences in material properties and compaction uniformity that do not compromise overall pavement performance.

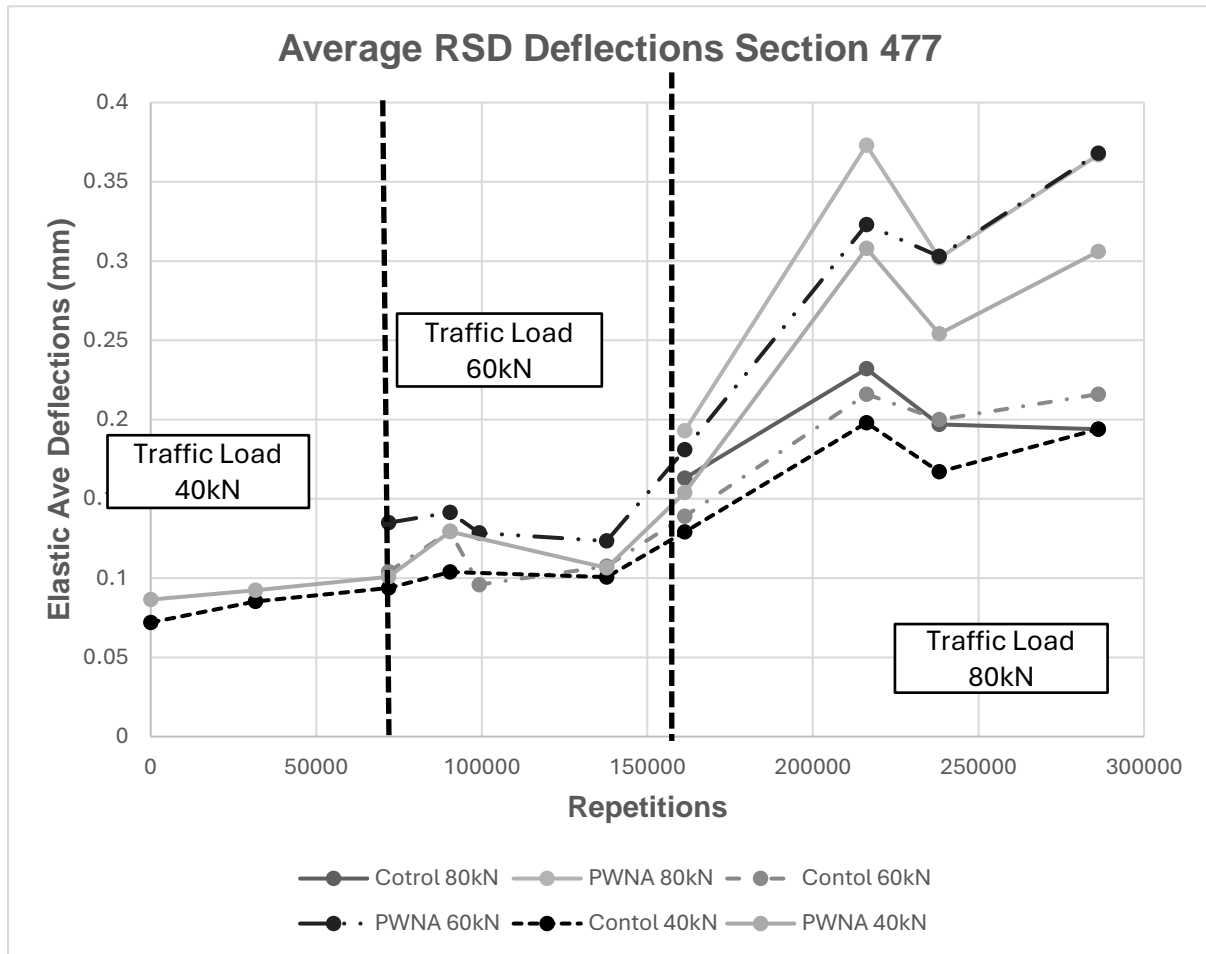


Figure 9: RSD elastic deflections measured on the test section under various wheel loads

Multi depth deflectometer (MDD) deflections

The surface MDD deflections under a 40 kN testing wheel load are shown in Figure 10. Only the surface deflections are shown since the deflections measured in the bottom layers were less than 0.1 mm. MDD 4 and MDD 6 were in the reference asphalt layer section and MDD 10 and 12 were located in the PWMA section. As shown in Figure 10 the peak deflection of the reference was on average only 0.01 mm lower than that of the PWMA section until the trafficking load was increased to 80 kN at 161, 318 repetitions. After 286, 174 repetitions the average peak deflection of the PWMA section was 0.14 mm higher compared to the reference asphalt layer section. The elastic deflections measured in both sections are

low and are indicative of the high strength of the underlying layers. The variation observed between the PWMA and reference sections can be ascribed to natural variability due to construction and natural variation in materials.

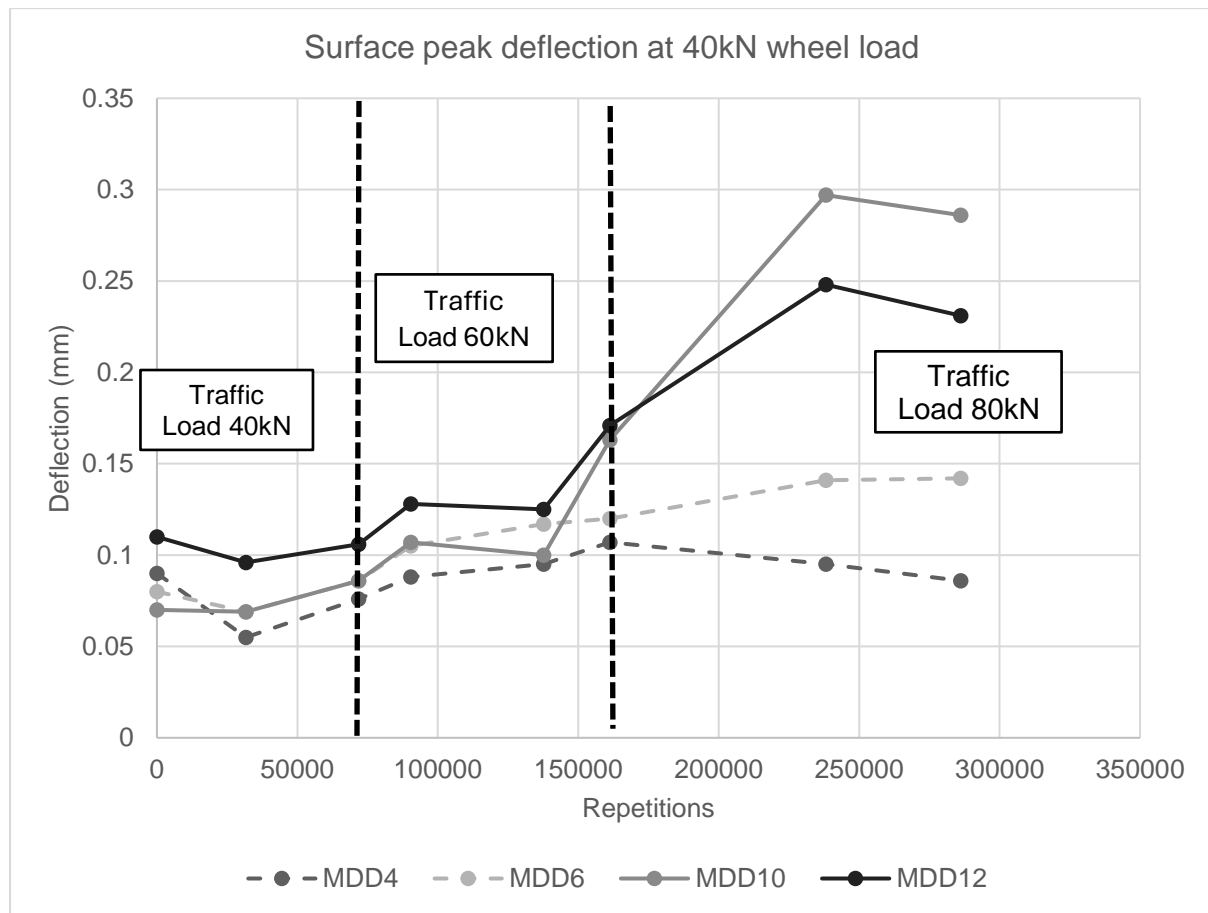


Figure 10: MDD elastic deflections measured on the test section under a 40 kN wheel load

Permanent deformation

The permanent deformation measurements for the reference and PWMA sections are shown in Figure 11. For the reference asphalt layer section, the final total average surface rut measurement is 10.4 mm after about 2.9 million ESALs (using a damage coefficient of 4.2) under channelised trafficking or 5.2 million ESALs using equivalent comparable wandering traffic (Figure 11). The maximum rut depth was 12 mm. The PWMA section had a final total average surface rut measurement of 7.2 mm after about 2.9 million ESALs (using a damage coefficient of 4.2) under channelised trafficking or 5.2 million ESALs using equivalent comparable wandering traffic. The maximum rut depth was 8 mm. Thus, the PWMA section showed a 30% reduction in permanent deformation and visually showed less distress compared to the reference asphalt section (Figure 12). For the reference asphalt section using linear extrapolation ($R^2=0.9031$) the terminal rut of 20 mm will be reached after 5.9 million ESALs (using a damage coefficient of 4.2) under channelised trafficking or 10.7 million ESALs using equivalent comparable wandering traffic. For the PWMA section using the same linear extrapolation ($R^2=0.8137$) the terminal rut of 20 mm will be reached after 9.0 million ESALs (using a damage coefficient of 4.2) under channelised trafficking or 16.2 million ESALs using equivalent comparable wandering traffic.

The application of linear extrapolation in this context is justified by the observed linear trend in rut depth accumulation with increasing ESALs, as evidenced by the high coefficients of determination ($R^2 = 0.9031$ for the reference section and $R^2 = 0.8137$ for the modified section). This approach aligns with practices outlined in the South African Pavement Engineering Manual (SAPEM), which supports linear projections for performance estimations when empirical data exhibits strong linear correlations.

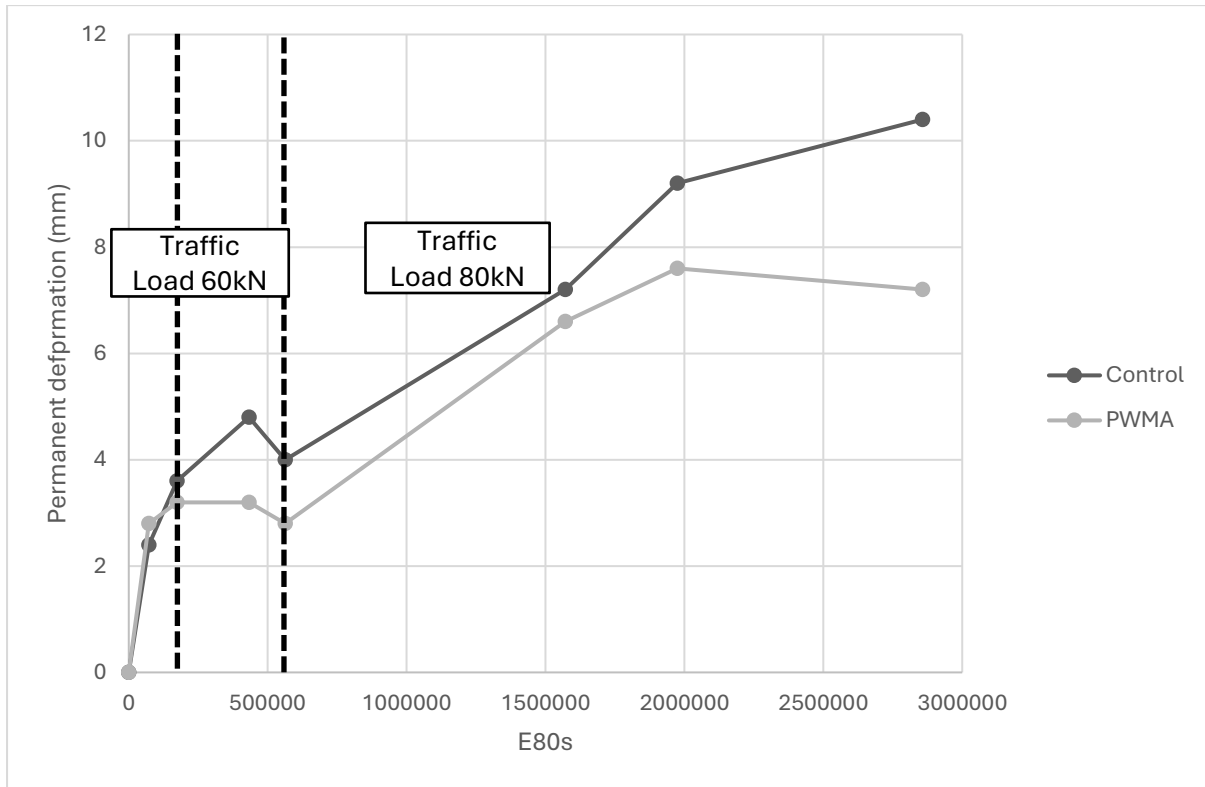


Figure 11: Average permanent deformation measured on the test section 477A4

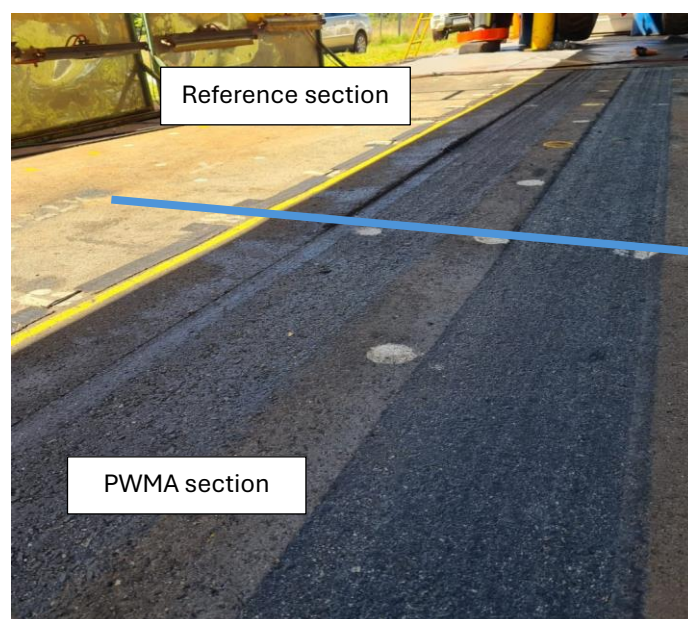


Figure 12: Test section 477A4 after HVS testing

FINDINGS AND CONCLUSION

This paper describes the performance, under HVS testing, of two pavement structures with the same underlying layers but different asphalt wearing course, namely a reference asphalt section based on a standard 50/70 penetration grade binder used in South Africa and a PWMA section. The performance evaluation reported is based on a single HVS test and as such, all findings made are site-specific within the limitations of the testing parameters and the quality of construction. Therefore, the results should be verified through further HVS testing.

Key findings and implications of the study:

1. Enhanced rutting resistance with plastic waste modification

The PWMA, despite utilizing a 70/100 penetration grade bitumen, which is considered less rut-resistant than a 50/70 penetration grade bitumen, exhibited a final average surface rut depth of 7.2 mm after 2.9 million ESALs under channelized trafficking and 5.2 million ESALs with equivalent wandering traffic. The maximum rut depth recorded was 8 mm. In contrast, the reference asphalt section with a 50/70 penetration grade bitumen reached a final average surface rut depth of 10.4 mm under the same trafficking conditions, with a maximum rut depth of 12 mm.

These findings demonstrate that the plastic waste modification significantly enhanced the high-temperature performance of the softer 70/100 penetration grade bitumen, resulting in improved rutting resistance that outperformed the stiffer 50/70 penetration grade bitumen. This improvement is attributed to the stiffening effect provided by plastic waste incorporation, which mitigates the base binder softening at elevated temperatures.

2. Extended pavement life expectancy:

Extrapolated projections suggest that the PWMA will reach the terminal rut depth of 20 mm after approximately 9.0 million ESALs under channelized loading or 16.2 million ESALs under wandering traffic. In comparison, the reference asphalt is estimated to reach the same failure criterion after 5.9 million ESALs (channelized) or 10.7 million ESALs (wandering).

This represents a 52% increase in channelized traffic life and a 51% increase under wandering conditions, highlighting the potential for more durable pavements with reduced maintenance costs.

3. Structural integrity of the underlying layers:

Both the Road Surface Deflectometer (RSD) and Multi-Depth Deflectometer (MDD) deflections for the PWMA and reference sections were measured as relatively low, indicative of strong underlying layers. Although slightly higher deflections were observed in the modified section when the loading increased to 80 kN, the differences are consistent with typical construction variability and material heterogeneity. These differences fall within acceptable limits for field pavement construction, suggesting that plastic waste modification does not compromise structural integrity. Importantly, this indicates that plastic waste modified 70/100 penetration grade bitumen not only rivals but exceeds the rutting resistance performance of a 50/70 penetration grade bitumen *in situ* within the asphalt layer under accelerated loading, presenting a viable and alternative modification practice

from the popular virgin polymers used in South Africa to obtain better binder grades for improved high temperature deformation resistance.

The findings from this study demonstrate the viability of using plastic waste as a bitumen modifier to enhance the rutting resistance of asphalt pavements. They suggest that PWMA could be a sustainable solution for extending pavement lifespan, reducing life-cycle costs and assisting with bitumen shortages because it can utilise softer bitumen grades when they are the only available grades nationally. Future research to look at including long-term field validation, fatigue cracking resistance and cost-benefit analysis.

REFERENCES

- COTO. 2020. Standard Specifications for Road and Bridge Works for South African Road Authorities (Draft Standard). Chapter 4: Earthworks and pavement layers: materials. The South African National Roads Agency SOC Limited, Pretoria.
- Denneman E, 2007. The application of locally developed pavement temperature prediction algorithms in Performance Grade (PG) binder selection, Proceedings of the 26th Southern African Transport Conference (SATC), Pretoria.
- Du Plessis L, FC Rust, E Horak and WA Nokes (2008). Cost Benefit Analysis of the California HVS Program. Proceedings of the APT conference in Madrid, October 2008.
- Hugo, F. and Martin, A.E., 2004. Significant findings from full-scale accelerated pavement testing, National Cooperative Highway Research Program (NCHRP) Synthesis 325, Transportation Research Board, Washington, United States of America.
- Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., Narayan, R. and Law, K.L. (2015). Plastic Waste Inputs from Land into the Ocean. *Science*, 347(6223), pp. 768-771.
- Milad, A., Ali, A.S.B. and Yusoff, N.I.B. (2020). A Review of the Utilisation of Recycled Waste Material as an Alternative Modifier in Asphalt Mixtures. *Civil Engineering Journal*, 6, pp. 42-60.
- Mokoena R, Mturi G, Mateyisi M, Sias J, Maritz J. The use of bias-corrected climate model projections for bituminous binder selection for the construction of resilient asphalt roads. *J. S. Afr. Inst. Civ. Eng.* 2024;66(2), Art. #1678, 17 pages. <http://dx.doi.org/10.17159/2309-8775/2024/v66n2a2>
- Mturi, GAJ, O'Connell, JS, Akhalwaya, I., Ojijo, VO, Mofokeng, T., Ncolosi, N., & Smit, M. A. (2021a). The use of plastic waste in road construction. In *Sustainability Handbook* (3rd ed., pp. 98–107).
- Mturi, GAJ, O'Connell, JS, George, T, Ojijo, V, Mofokeng, T, Akhalwaya, I, Ncolosi, N and Smit, MA. (2021b). The Use of Plastic Waste in Road Construction Case Study 3: Demonstration Section of the Dry Modification Process Part I: A laboratory feasibility
- Mturi, G., Ncolosi, N., O'Connell, J., & Simelane, M. (2025a). The incorporation of the plastic-coated aggregates into a South African asphalt mixture. *Road Materials and Pavement Design*, pp. 1–16. <https://doi.org/10.1080/14680629.2025.2460483>
- Mturi, GAJ, Ojijo, V, Mofokeng, T, & Letwaba, J. (2025b). Modified Waste Plastic Bitumen Mixture for Asphalt and Process for Production Thereof (2025/03353). *South African Patent Journal*, ISSN 2223-4837, Vol 58, No. 04.
- O'Connell, JS, Mturi, GAJ, & Simelane MS (2024). [The dry modification method for incorporating polyolefin plastic waste in asphalt: International experiences and opportunity for implementation in South Africa](#). In *Sustainability Handbook* (8th ed., pp. 156–165).

Pholo, KJ, Quaninoo, HA, and Mturi, GAJ (2024) Roads constructed using Plastic waste mixed with bitumen. Proceedings of the SATBinderrr conference in Pretoria, September 2024

Rampersad, A (2022) The Use of Plastic Waste in Road Construction Case Study #3: Demonstration Section of the Wet Modification Process Phase 2: Construction Report (Asphalt Quality Assurance) by A Rampersad

Rust, FC, Kelwick SV, Kleyn ED, and Sadzik EM (1997). The Impact of the Heavy Vehicle Simulator (HVS) Test Programme on Road Pavement Technology and Management. 8th International Conference on Asphalt Pavements to be held in Seattle, USA, August 1997.

Rust, FC; M.A. Smit , I Akhalwaya , G.J. Jordaan and L du Plessis. (2020). Evaluation of two nano-silane-modified emulsion stabilised pavements using Accelerated Pavement Testing. International Journal for Pavement Engineering: 21(9).

SANRAL (2021). APT protocol guideline. South African National Roads Agency, Pretoria, South Africa.

South African National Roads Agency Ltd (SANRAL). (2013). South African Pavement Engineering Manual (SAPEM), Chapter 10: Pavement Design. SANRAL, Pretoria.

Smit MA, Akhalwaya I and Rust FC (2021). Laboratory Evaluation of Alternative Cost-Effective Pavement Materials. Proceedings of the South African Transport Conference 2021, Pretoria.

Smit MA, Akhalwaya I, Rust FC and Ramdas VM (2022). Induced calcium carbonate precipitation (MICP) for road construction. South African Transport Conference, Pretoria.

Steyn. W.J.vdM, 2012 Significant finding from full-scale accelerated pavement testing, National Cooperative Highway Research Program (NCHRP) Synthesis 433, Transportation Research Board, Washington, United States of America

Suaquita, D.M., (2019). Plastic Roads made in India - Recycling Waste. [online] Available at: www.ideassonline.org/public/pdf/PlasticRoadsIndia-ENG.pdf [Accessed 12 April 2019]