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The Use of Plastic Waste in Road Construction

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1.0 Introduction

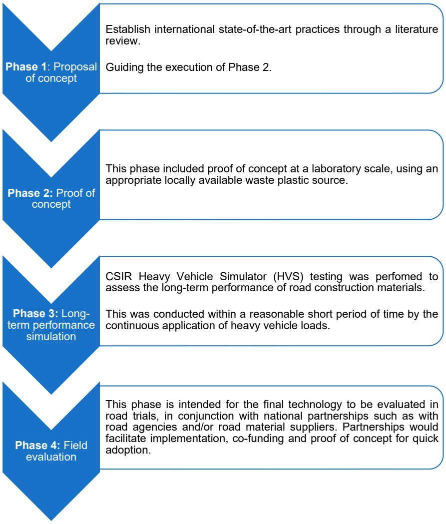
PlasticsSA's annual review estimated that 1 841 700 tons of plastics (including 337 700 tons of recyclate) were converted into products in 2019, with an input recycling rate (collected waste as a percentage of available plastics for recycling) of 45.7 per cent (PlasticsSA, 2019/2020). This indicates an estimated 18 per cent recycle content of plastic products made in South Africa, with significant material leakages into the environment still occurring. According to Jambeck et al. (2015), unrecycled plastic materials usually end up being disposed of in landfills, through self-help or by littering. The study by Jambeck et al. (2015) ranks South Africa among the top 20 contributors to ocean plastic, with around 0.09-0.24 million metric tons of plastic waste ending up in the ocean annually.

The development of the local end-use market for waste plastic is crucial to increasing South Africa's plastic recycling rates, especially for low-value, problematic plastic fractions, such as polyolefins consisting mainly of polyethylene and polypropylene. The use of recycled and/or alternative materials such as plastics in road construction is beneficial not only in terms of sustaining the environment, since naturally occurring materials will be conserved but as a means of reducing construction costs.

Recycled plastics are being investigated worldwide not only as a green investment, but also for improved pavement durability (Milad et al., 2020). The objectives of the study were to screen, evaluate and implement existing international technologies in line with South African design standards and specifications for materials in road construction.

The main research question was whether low value waste plastics can be optimised as alternative road construction materials in South Africa. The approach to answering this research question was to review the international literature on this topic and identify the best practices that could be effectively localised in South Africa. A secondary research question investigated existing asphalt road standards and specifications to determine whether they should be modified to facilitate the use of plastics as alternative

Figure 1: Methodology adopted during the research project



Establish international state-of-the-art practices through a literature review.

Guiding the execution of Phase 2.

This phase included proof of concept at a laboratory scale, using an appropriate locally available waste plastic source.

CSIR Heavy Vehicle Simulator (HVS) testing was perfomed to assess the long-term performance of road construction materials.

This was conducted within a reasonable short period of time by the continuous application of heavy vehicle loads.

This phase is intended for the final technology to be evaluated in road trials, in conjunction with national partnerships such as with road agencies and/or road material suppliers. Partnerships would facilitate implementation, co-funding and proof of concept for quick adoption.

FIGURE 1

materials that could improve overall pavement performance and sustainability.

2.0 Methodology

The methodology implemented for this study consisted of the following phases shown in Figure 1. Only the first three phases were completed during this study.

3.0 Review of the literature

3.1 Approach

The aim of the literature search was to summarize the effect of the addition of waste plastic to asphalt mixes in terms of performance. This, in turn, served as a guide for the laboratory phase whereby bitumen or asphalt mix was modified with waste plastic.

In the literature review, a two-pronged approach was adopted based on the two asphalt modification methods, commonly known as the 'wet' and 'dry' methods:

- Reports of the low-cost, low-tech 'dry' modification of asphalt were investigated. The method consisted of adding various unsorted plastic waste to hot mix asphalt (HMA) aggregates prior to adding bitumen (Vasudenvan et al., 2010).
- In the second approach, waste plastic is added directly to bitumen and is commonly known as the "wet" method. Due to the use of a consistent source of modifier, the "wet" method results in a more controlled outcome.

3.2 Dry Modification of Asphalt Mixes Using Plastic Waste

During the dry method, the plastic is softened to adhere to the aggregate, forming plastic coated aggregates (PCA). To date, more than 5,000 kilometres of roads with plastic waste have been laid in at least 11 states in India (Suaquita, 2019). Researchers who participated in the development of this method claim that the roads constructed using this technology are of better quality and do not require maintenance for the first five years. However, in many cases, these claims are difficult to confirm (Mturi et al., 2021). Other claims (Suaquita, 2019) are that this technology results in:

- no toxic gas emission,
- Cost savings,
- Better binding property,
- Higher softening points of the binder, and therefore the asphalt mix can withstand high temperatures and higher loads, and
- Improved waterproofing.

Apart from India, there are experiences elsewhere in the developed world. In 2015, MacRebur, a company based in Scotland, initiated a commercial plastic waste recycling project (McRebur, 2017).

MacRebur has developed and trialled three products (MR6, MR8 and MR10) made from plastic waste materials originating from domestic and industrial plastic waste sources. The trials have been carried out mostly in developed countries (e.g. Canada, US and Australia) (White and Reid, 2018; Mturi et al., 2021).

3.3 Wet Modification of Asphalt Mixes Using Plastic Waste

Modification using proprietary polymers such as styrene-butadiene-styrene (SBS) or ethylene vinyl acetate (EVA) exhibits superior performance compared to asphalt mixes modified with waste plastic (Casey et al., 2008). However, the cost of polymer modified bitumen (PMB) manufactured with virgin or proprietary polymers can be up to 30 per cent higher compared to unmodified bitumen in South Africa. Polyethylene waste, on the other hand, is generally available in large quantities with different mechanical properties and at low cost, making them good candidates as modifiers (Polacco et al., 2005).

Unfortunately, polyethylene is almost completely immiscible with bitumen due to its non-polar and non-aromatic nature (Behnood and Gharehveran, 2019). As a result, polyethylene-modified bitumen is a multiphase material with a tendency to phase separate (Ait-Kadi et al., 1996). This single fact has severely limited its use as a bitumen modifier for the "wet" method (Mturi et al., 2021). However, compatibility enhancement techniques exist; and employing multi-polymer and/or chemical modification of polymers are examples of techniques used to enhance the compatibility of the PMB blend. Various chemical modification techniques have been suggested in the literature, such as (Mturi et al., 2021):

- Grafting (reactive monomers are grafted onto polymers).

- Functionalization of the polymer with epoxy groups, acrylic acid, carboxylic acid, glycidyl methacrylate (GMA), etc.
- Chlorination of the polymer (this will increase its polarity and thus increase the compatibility between the polymer and bitumen) to result in better dispersion of polyethylene particles in bitumen (Behnood and Gharehveran, 2019).

4.0 Results and Discussion

International studies were found to lack consistency regarding the use of plastic waste in asphalt road applications. Key findings from the literature review include the following:

- Plastic modification of bitumen and asphalt was limited compared to conventional modifiers. It was concluded that this was a direct consequence of the poor compatibility between bitumen and plastic material (Polacco et al., 2005).
- There was a lack of consistency in the approach to investigating plastic as a bitumen modifier. Therefore, the results obtained by the researchers were only applicable to the relevant methodologies applied in their investigation (Mturi et al., 2021).
- Insufficient evidence is often presented to support research claims, environmental sustainability, and the establishment of a consistent source of plastic waste where the composition remains the same over time. Therefore, the experimental results were generally relevant to the modifier as received at a given time (Mturi et al., 2021).

The findings of the literature review informed three key decisions on the way forward for this study, namely:

- Both the wet and dry methods were to be investigated.
- The plastic waste to be investigated would be limited to polyethylene waste. In South Africa, polyethylene waste represents a considerable source of low value waste, being underutilized and easily accessible for recycling.
- Consistency in the characteristics of the modified asphalt mix was the goal of the plastic waste modification process. Hence, the following requirements of the waste plastic product for modifying bitumen were deemed necessary (Mturi et al., 2021):
- A handling criterion to ensure the product is not too fine that it ends up in the environment at the asphalt plant, and not too coarse to further complicate the blending/manufacturing process.
- A composition criterion was needed to ensure the waste product is consistent; therefore, properties such as densities, melting temperatures and purity criteria needed to be specified.
- A homogeneity criterion to guarantee a good mixture of the different waste plastic components to avoid poor blending, where properties could span the range of each of the components or even lower.
- Asphalt in-service criterion to prevent adverse effects at the in-service temperatures of South African asphalt roads.
- An environmental criterion to prevent leaching of waste plastic material beyond national limits/thresholds. Additionally, the waste product for the asphalt road industry needed to be processed through an environmentally friendly recycling chain.
- A performance criterion to ensure consistency of the effects produced by the plastic waste source towards asphalt modification, considering that the effects of modification depend not only on the properties of the waste plastic but also on the properties of the base bitumen.

The recommended requirements for the waste plastic product used for this study have been summarised in Table 1 (Mturi et al., 2021).


Photo by Sarah Chai from Pexels

Table 1: Requirements for the waste plastic material used to modify bitumen.

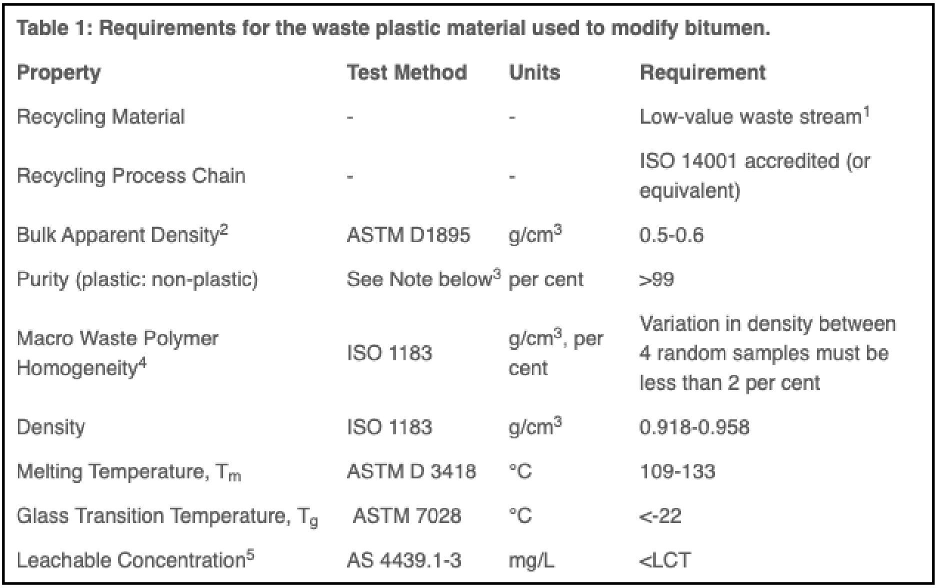


Table 1: Requirements for the waste plastic material used to modify bitumen.

Property	Test Method	Units	Requirement
Recycling Material	-	-	Low-value waste stream[1]
Recycling Process Chain	-	-	ISO 14001 accredited (or equivalent)
Bulk Apparent Density[2]	ASTM D1895	g/cm^3	0.5-0.6
Purity (plastic: non-plastic)	See Note below[3]	per cent	>99
Macro Waste Polymer Homogeneity[4]	ISO 1183	g/cm^3, per cent	Variation in density between 4 random samples must be less than 2 per cent
Density	ISO 1183	g/cm^3	0.918-0.958
Melting Temperature, T_m	ASTM D 3418	°C	109-133
Glass Transition Temperature, T_g	ASTM 7028	°C	<-22
Leachable Concentration[5]	AS 4439.1-3	mg/L	<LCT

[1] Currently non-recycled (or not fully recycled) so as not to create competition with current high value end markets or with plastic waste stream having high recycling rates.

[2] Apparent density figures are not comparable except for materials having the same specific gravity after moulding or forming.

[3] The purity of recycled plastics is not easy to determine due to the different parameters that define a plastic material. Typically, a combination of techniques, including differential scanning calorimetry (DSC) and Fourier-Transform Infrared spectroscopy (FTIR) may be used to qualitatively ascertain whether a batch of recycled material is from a single family of plastic, e.g. HDPE. Since the sorting processes are inefficient, it is typical to find traces of a different type of plastic in recycled pellets, for example, recycled PP (rPP) in recycled HDPE (rHDPE), and vice versa.

[4] This refers to individual pellets. To achieve the required level of homogeneity, consider mixing with a twin-screw extruder as opposed to a single screw extruder or using an appropriate compatibiliser. Note: with poor blending (i.e. poor mixtures), the properties of the waste plastic could span the range of each of the individual components or even lower.

[5] As per National Environmental Management: Waste Act, 2008 (Act No.59 of 2008) and the Waste Classification and Management Regulations, 2013: Regulation 8(1)(a).

For the wet modification process, the following recommendations were made for the modified bitumen with the waste plastic product (Mturi et al., 2021):

- Given that bitumen and the waste plastic product were found incompatible (Figure 2), the waste plastic material needed to be purposely reacted to the bitumen backbone to improve storage stability. To cross-link the waste plastic to the base

bitumen, modifications were required to introduce reactive sites.

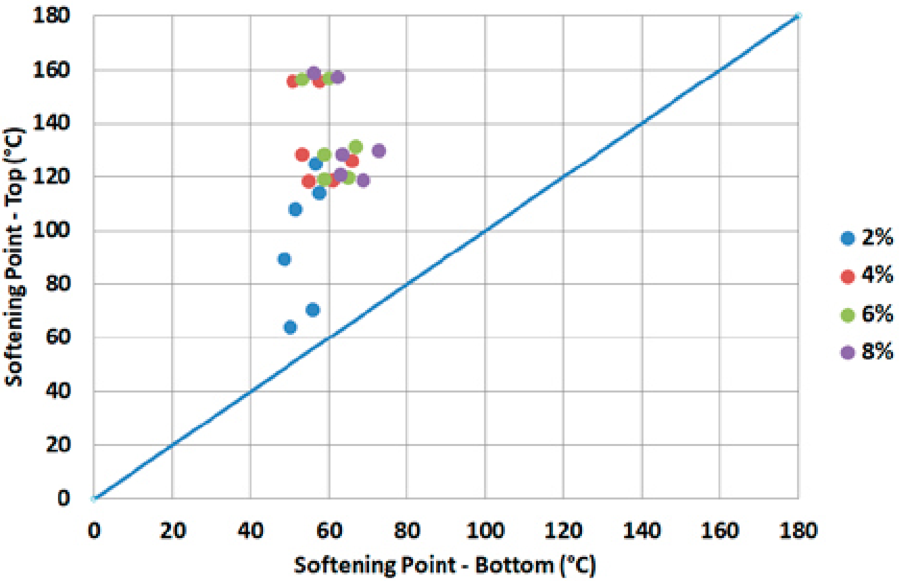


Figure 2: Storage Stability results for different percentages of polyethylene waste in bitumen.

- Provided compatibility is achieved, the following approach can be explored:
- Plastic waste material can be used to improve the rutting resistance properties of bitumen and act as a warm mix additive.
- The composition of the waste plastic and the dosage levels need to be controlled to avoid affecting bitumen performance properties.
- The waste plastic modified bitumen should always use a 70/100 penetration grade bitumen as the base binder.
- A 'TG1 (SABITA, 2015) plus' classification criteria be introduced prior to performance grading as per SATS 3208 (2021). Two grades be used for classifying the modified products: the current A-P1 grade for waste plastic modified binders exhibiting both rutting and fatigue properties, and a new A-P2 grade for less trafficked roads (e.g. rural roads) where improved rutting properties are needed without compromising fatigue properties. The recommendations are shown in Table 2.
- For the industry to adopt this process, the following issues will need to be addressed: (a) compatibility with other asphalt additives (warm mix additives,

Table 2: Properties of polymer modified binders for hot mix asphalt.

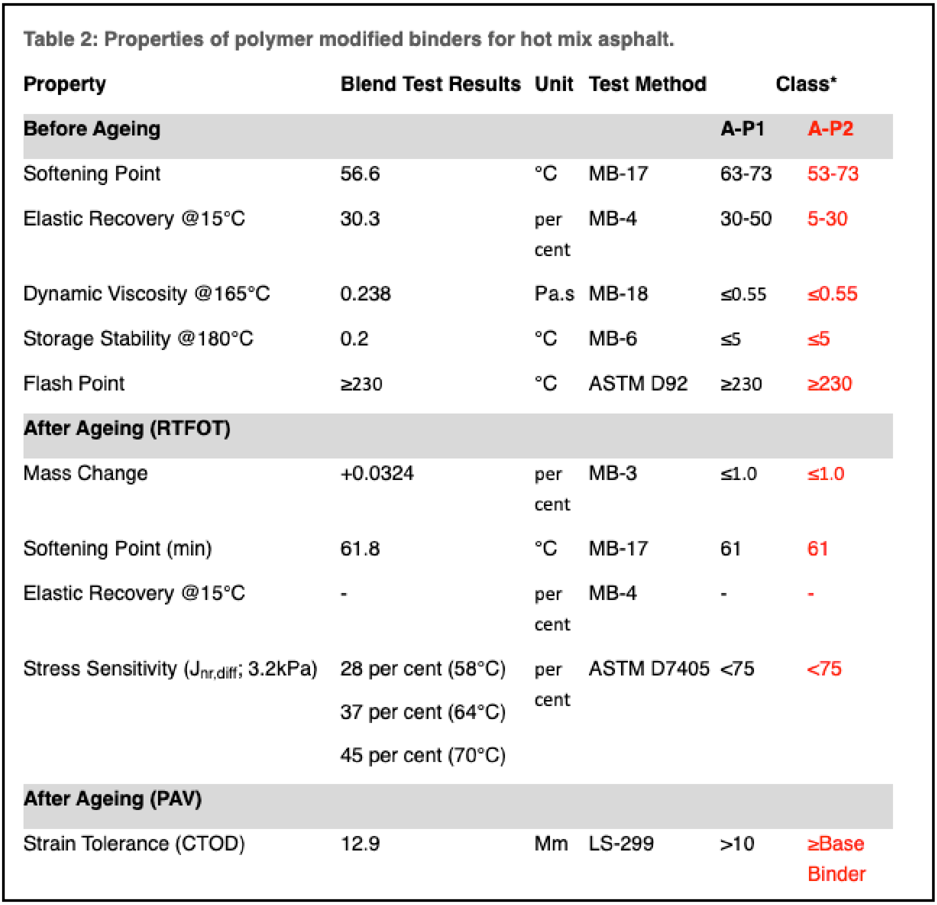


Table 2: Properties of polymer modified binders for hot mix asphalt.

Property	Blend Test Results	Unit	Test Method	Class*	
Before Ageing				**A-P1**	**A-P2**
Softening Point	56.6	°C	MB-17	63-73	53-73
Elastic Recovery @15°C	30.3	per cent	MB-4	30-50	5-30
Dynamic Viscosity @165°C	0.238	Pa.s	MB-18	≤0.55	≤0.55
Storage Stability @180°C	0.2	°C	MB-6	≤5	≤5
Flash Point	≥230	°C	ASTM D92	≥230	≥230
After Ageing (RTFOT)					
Mass Change	+0.0324	per cent	MB-3	≤1.0	≤1.0
Softening Point (min)	61.8	°C	MB-17	61	61
Elastic Recovery @15°C	-	per cent	MB-4	-	-
Stress Sensitivity ($J_{nr,diff}$; 3.2kPa)	28 per cent (58°C) 37 per cent (64°C) 45 per cent (70°C)	per cent	ASTM D7405	<75	<75
After Ageing (PAV)					
Strain Tolerance (CTOD)	12.9	Mm	LS-299	>10	≥Base Binder

*A refers to hot mix asphalt and P refers to plastomer

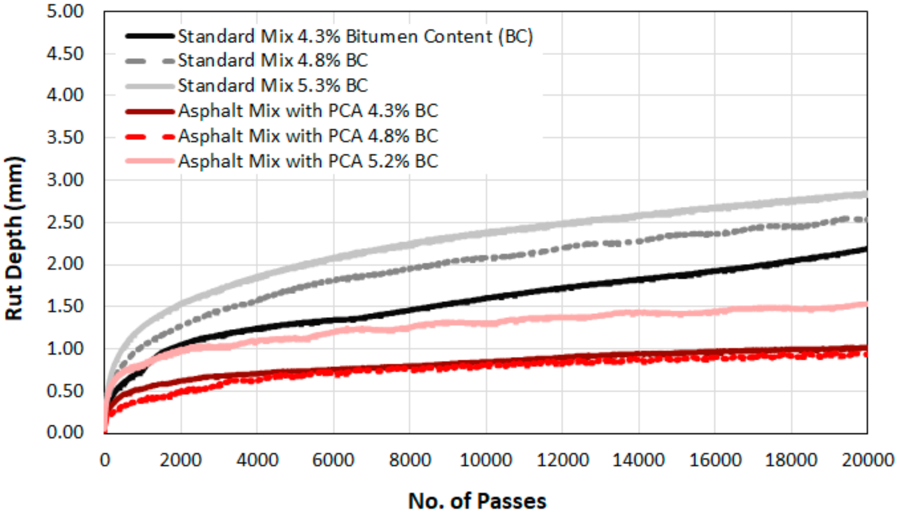
There is potential to use low-density plastic waste to design rut-resistant asphalt mixes

adhesion agents, etc.), (b) insolubility of polyethylene in solvents used for binder content and recovery analysis, and (c) recycling of asphalt mixes with waste plastic.

For the dry modification process, it was concluded that there is potential to use low-density plastic waste to design rut-resistant asphalt mixes due to the following findings (Mturi et al., 2021) as per the tests stipulated in SABITA Manual 35/TRH 8 (SABITA, 2019):

- The volumetric properties of the asphalt mix with the waste plastic met the criteria specified in SABITA Manual 35/TRH 8 (SABITA, 2019).

Figure 3: Rut depth vs. number of passes using the Hamburg Wheel Tracking Test.



- The results of the Hamburg Wheel Tracking Test (HWTT) indicated a higher maximum rut depth for the standard mix without PCA after 20,000 passes at 50°C, compared to the asphalt mix with PCA (Figure 3). This was based on the asphalt mix with PCA exhibiting more elastic behaviour and greater stiffness at these temperatures.
- The Black Space diagram (Figure 4) of the two mixes showed that at low temperatures, the two mixes exhibit similar stiffness and elastic behaviour. The Black Space diagram therefore predicts similar low cracking performance for the two mixes.
- Having similar stiffness and elastic behaviour at intermediate temperatures (at loading frequencies greater than 1Hz), the fatigue cracking performance of both the asphalt mix with PCA and the standard asphalt mix without PCA were comparable based

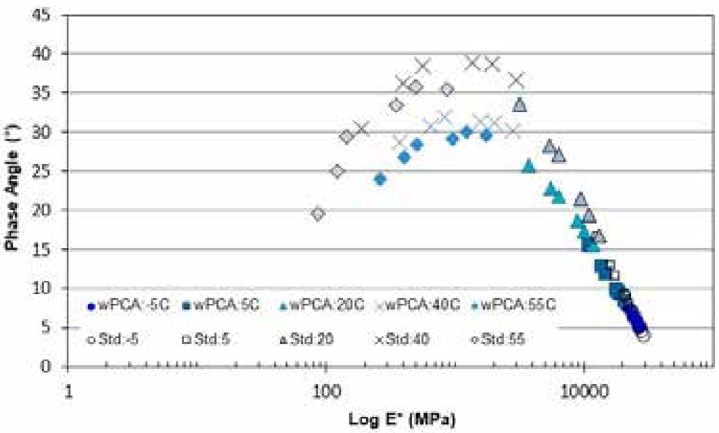
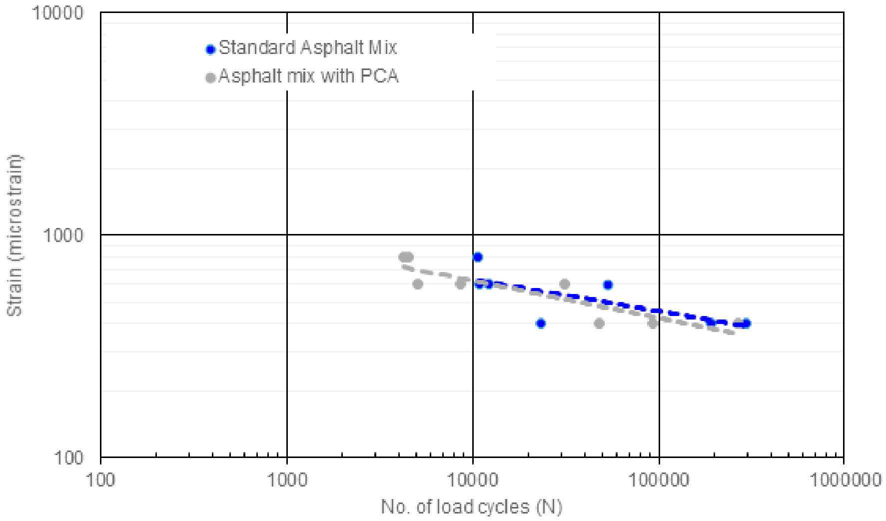


Figure 4: Black Space diagram for standard mix (Std) and asphalt mix with PCA (wPCA).

Figure 5: Fatigue life at a temperature of 10°C and a frequency of 10Hz.



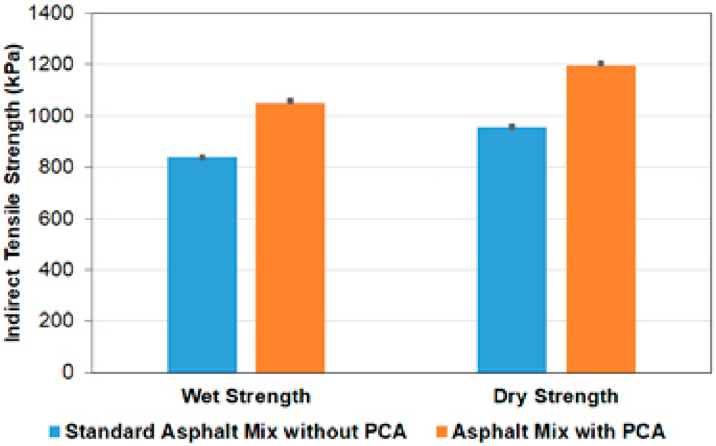
on the results of the four-point bending beam test (Figure 5).

- The asphalt mix with PCA met the workability criteria specified in SABITA Manual 35/TRH 8 (SABITA, 2019). This was based on the evaluation of the compaction data, where the voids of the asphalt mix with PCA after 45 gyrations did not exceed the design voids by more than 3 per cent.

For specific asphalt mix designs, the characterisation of asphalt performance indicated that waste plastic can have an extra binding effect in an asphalt mix.

This was observed with improved bitumen-aggregate adhesion and resulted in an increase in the tensile strength as determined from the Modified Lottman test (see Figure 6).

Figure 6: Indirect tensile strength results of a standard asphalt mix without PCA and an asphalt mix with PCA.



The constructed asphalt overlays (Figure 7) were designed for a total traffic loading of between 3 and 30 million equivalent standard axles (MESA) of 80kN (E80's) and were trafficked for a total of 476,294 HVS repetitions, which equates to 4.79 million E80s (using a damage coefficient of 4.2) under channelized trafficking (or 8.59 million E80s using equivalent comparable wandering traffic) at standard and non-standard loads on both sections (Akhalwaya et al., 2021).

The following HVS load applications were applied using a constant tyre pressure of 740kPa:

- 158,564 channelized repetitions of a 40kN dual wheel load (simulating a standard 80kN axle load);
- 93,210 repetitions of a 60kN dual wheel load (simulating a 120kN axle load);
- 186,796 repetitions of an 80kN dual wheel load (simulating a 160kN axle load) in the dry state; and
- 37,724 repetitions of an 80kN dual wheel load (simulating a 160kN axle load) in the wet state.

Figure 7: Construction of the HVS sections on road P159/1 (R80) in Gauteng, South Africa.

The comparative evaluation of performance test results from HVS testing was based on the following:

- Construction of two test sections consisting of a 50mm asphalt mix with PCA compared to a 50mm standard mix without PCA.
- Both test sections were constructed on a standard existing South African pavement structure containing unstabilized granular layers.
- The test sections achieved acceptable quality control for the HVS testing, even though higher percentages of voids were observed for the asphalt mix with PCA.

Based on the initial long-term performance simulation using a single wet HVS test, it was concluded that there is potential to use low-density plastic waste to design rut-resistant HMA mixes due to the following results:

- For the pavement structure paved with the standard mix without PCA, the true rut was physically measured in the post-mortem HVS investigation and was recorded as 6.69mm. For the pavement structure paved with the asphalt mix containing PCA, the true rut as measured physically in the post-mortem HVS investigation was recorded as 4.63mm. This result indicated that the asphalt mix with PCA performed slightly better than the standard mix despite having a higher percentage of voids.
- The results of permanent deformation/rutting were significantly lower than the South African warning rut level of 12.5mm and the terminal rut level of 20mm, indicating acceptable performances in terms of permanent deformation for both test sections for the applied traffic and environmental conditions.
- Although only a single HVS test was completed, both test sections appeared to be relatively insensitive to the magnitude of the HVS wheel load, especially in the dry state. This implies that the pavement structures for both test sections will likely not be overly sensitive to overloading.
- Based on the selected aggregates, the use of plastic waste can also be used to improve moisture sensitivity performance. However, there is a need to provide handling guidelines to ensure that asphalt mixes with PCA are mixed, transported and compacted appropriately.

5.0 Conclusions

The findings showed potential in using specified waste plastic materials to design rut resistant asphalt mixes without compromising other asphalt performance requirements. The approach requires the adoption of the necessary criteria to establish a consistent source of plastic waste. The research also highlighted the need to understand the mechanism that improves rut resistance to ensure that this benefit is realized through the control of performance criteria and handling of the asphalt mix. Furthermore, the research identified requirements for measuring additional asphalt properties that would quantify the contribution of the asphalt layer to safety, health and environmental sustainability.

Feedback originating from this research was directed at the South African government and industry stakeholders. The purpose was to encourage the use of plastic waste for environmental benefits, as well as for improved performance of road surfaces. Industry adoption of the technology will require the development of guidelines that will provide guidance in assessing use of waste plastic, and standard documents that will identify mechanical properties, application and impact potential of the developed waste plastic-based materials in road construction. This will lead to a better understanding of the suitability of plastic-based waste materials in road projects and therefore lower the risk of premature failure of roads.

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