Feasibility of using platinum tailings as a mineral filler in asphalt production

S.T. Mudenge, Y. Akanbi & M.E. Rahman
University of the Witwatersrand, Johannesburg, South Africa

D. Kalumba
University of Cape Town, Cape Town, South Africa

ABSTRACT: This study investigated the feasibility of substituting Platinum tailings (PtT) for fly ash as a mineral filler in asphalt production. Partial substitutions of 20%, 40%, 60% and 80% as well as total replacement were evaluated. To assess the geochemical and engineering properties of the samples, laboratory tests which include Scanning Electron Microscope (SEM), Marshall stability and flow and Indirect Tensile Strength (IDTS) tests were performed. The SEM showed that the substitution of fly ash which has a spherical morphology with angular PtT could potentially improve particle interlocking, stiffness and load bearing capacity although the angularity would decrease workability. Due to the detection of chromium in the PtT, leachate tests are required to assess the release of heavy metals and mitigate potential hazards. The optimum substitution was 60% PtT which resulted in an 18% increase in tensile strength. Although the Marshall tests revealed a slight decrease in stability of 7% and a 26% increase in flow, the values were within the permissible range. These findings demonstrated that the partial substitution of fly ash with PtT can improve cracking and fatigue resistance, enhance tensile strength and extend pavement life while reducing the environmental footprint of tailings storage facilities and the risks associated with their construction.

1 INTRODUCTION

Asphalt, a composite material comprising of aggregates (crushed rock, gravel or sand), mineral filler (fine mineral particles less than 75µm in size) and a binding agent (typically bitumen) is used for road construction and maintenance. Each component serves a distinct function, the aggregates are the structural components which resist loads, mineral fillers fill the voids and reduce permeability while bitumen binds the aggregates and filler into a cohesive mixture. Mineral fillers also serve the same function as aggregates of resisting stresses imposed on the pavement; hence, the type of filler has a significant influence on pavement durability.

Common types of mineral fillers include fly ash, hydrated lime, cement flue dust, ground limestone and rock dust. Several studies have investigated alternative fillers such as asbestos powder, brick dust and rice husk (Chen et al. 2011; Zhang, 2011; Sargin et al. 2013). Previous studies have assessed the use of different types of tailings as a filler substitute. Gao et al. (2024) investigated the feasibility of using molybdenum tailings as a limestone substitute in asphalt. The results showed that the tailings asphalt mastic yielded a higher viscosity, rutting factor and creep stiffness compared to the limestone mastic. Wei et al. (2022) observed that while the use of iron tailings as a mineral filler increased the anti-rutting performance, it lowered the workability and low temperature cracking resistance of the asphalt.

Lei et al. (2024) conducted a comparative study between copper tailings mastic and limestone mastic and found that copper tailings delivered a rougher surface and larger specific surface area which could potentially lead to improved filler-particle interaction. It was also reported that copper tailings improved the mastic softening point but reduced its ductility. The recycling of platinum tailings (PtT) as an asphalt mineral filler, however, has not been investigated. Globally, South Africa is the leading producer of Pt with an estimated production rate of 120 metric tons/year which contributes to more than 70% of the world's platinum (Statista, 2024). Consequently, the country generates extensive volumes of PtT which are disposed in tailings storage facilities (TSFs) which inturn occupy vast areas of land. The valorisation of PtT could minimise the environmental and financial risks of TSF construction while promoting a circular economy. This study investigated the performance of PtT as a fly ash substitute in asphalt production.

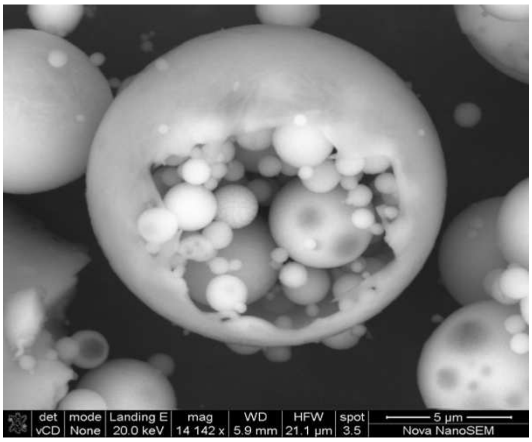
2 MATERIALS AND METHODS

2.1 *Material classification*

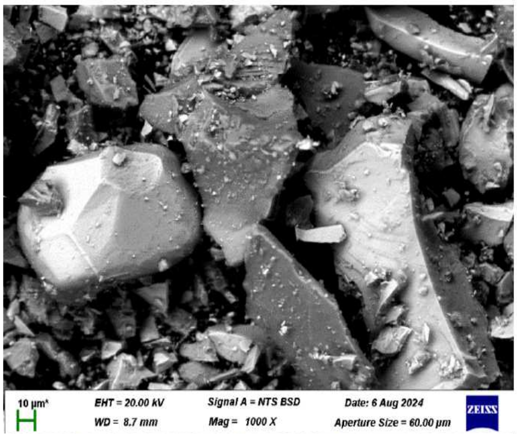
The research materials comprised of aggregates (sand and crushed stone of diameter 14 mm, 9.5mm, and 6 mm), commercially available fly ash, platinum tailings and 70/100 penetration grade bitumen. The classification tests included gradation analysis, consistency limits and particle density. The similarities between the fly ash and PtT were that both were non-plastic and were each classified as a silt, although fly ash had a higher fines content. The particle size of the PtT was below 75 µm and therefore met the requirement for use as a mineral filler. However, the PtT had a higher density of 3,71 g/cm^3 while the density of fly ash was found to be 2.39 g/cm^3.

2.2 *Geo-chemical analysis*

A Scanning Electron Microscope (SEM) was used to analyse the surface morphology and composition of the fly ash and PtT in accordance with the ASTM E986 standard. The SEM images showed the surface structure of each material to the nanometer-scale resolution. The fly ash surface structure predominantly consisted of spherical crystals while the PtT were angular and blocky as shown in Figures 1a and 1b.



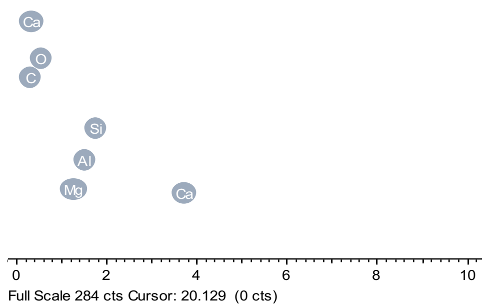
1a. Fly ash SEM image



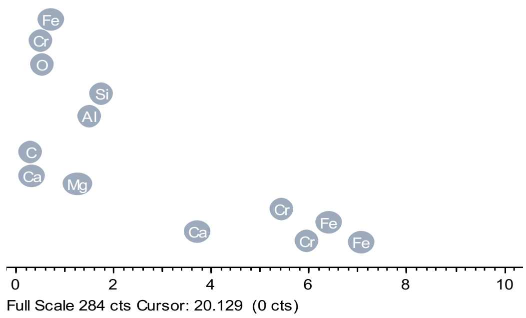
1b. Platinum tailings SEM image
Figure 1. Scanning electron microscope images

Based on the crystalline structures, substituting fly ash with PtT was likely to improve the load bearing capacity of asphalt because angular particles have a higher internal friction angle and are less susceptible to sliding or displacement (Stark et al. 2014). The angular shape also allows more interlocking of soil particles which improves load distribution. In addition, the close packing of angular particles reduces compressibility thereby increasing stiffness and resistance to deformation. However, the angularity of the Pt tailings would result in a less workable asphalt due to the reduced flowability. This could be resolved by adjusting the asphalt water content to improve lubriaction or blending the Pt tailings with fly ash resulting in a mix with optimum strength and workability characteristics.

The SEM was also used to examine the elemental composition of the tailings. Fly ash posessed a high concentration of Calcium (Ca) in addition to Silicon (Si), Aluminium (Al) and Magnesium (Mg) and was therefore classified as a pozzolan due to the presence of calcium alumino- silicates (FHWA, 2003). The PtT mainly consisted of Iron (Fe) and Chromium (Cr) in addition to Si, Al, and Mg. The presence of a heavy metal, Cr, requires further chemical analysis to assess the type of Cr. Trivalent chromium Cr^{3+} is non-toxic whereas hexavalent chromium Cr^{6+} is a health and environmental hazard. Cr^{6+} can be reduced to Cr^{3+} by using a reducing agent or the Cr can be removed by various processes such adsorption, electrocoagulation and bioremediation (Azis et al. 2020). Figure 2 presents the elemental composition of the materials.



2a. Fly ash elemental composition



2b. Platinum elemental composition
Figure 2. Scanning electron microscope elemental composition

2.3 *Marshall stability and flow*

Marshall stability is defined as the peak resistance load obtained during a constant rate of deformation loading while Marshall flow is the corresponding measure of elastic and plastic deformation (ASTM D6926). The samples were prepared for Marshall tests in accordance with the ASTM D6926 standard. The procedure involved heating the materials to the prescribed temperature and mixing them thoroughly to form a homogenous mixture. The mixture was compacted using a Marshall compactor to form the asphalt specimen for testing. The standard ensures uniformity in preparing asphalt specimen and eliminates variability due to inconsistent compaction methods. Five concentrations of PtT were considered ranging from 20-100% and these were compared with the 100% fly ash asphalt. To ensure accuracy and repeatability, three samples of each concentration were prepared. The Marshall stability and flow value tests were performed on the compacted samples following the ASTM D6927 standard and the maximum load at failure and corresponding deformation was recorded.

2.4 *Indirect tensile strength*

Indirect Tensile Strength (IDTS) tests were performed following the ASTM D6931 standard. The procedure involved applying a compressive load along the vertical diametrical plane of the specimen which creates a horizontal tensile stress perpendicular to the applied load. The maximum load at failure was recorded and the tensile strength was computed using the maximum load and the specimen dimensions. The IDTS has several implications which include a direct measurement of mechanical strength and resistance to cracking under tensile stresses due to traffic loads, temperature fluctuations or environmental factors (ASTM D6931). IDTS is also used to assess fatigue life, materials with a high IDTS possess better fatigue resistance; a higher ability to withstand repeated loading cycles without failure.

Table 1 summarises the laboratory tests which were performed on fly ash, PtT and asphalt specimen.

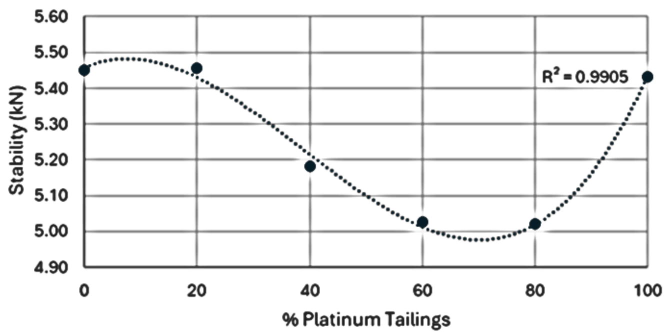
Table 1. Laboratory tests

Test	Standard	Significance	No. of tests
Sieve analysis	ASTM D6913	Particle size distribution	4
Laser diffraction analyser	ASTM E3340	Suitability of using platinum tailings as a filler	4
Consistency limits	BS 1377-2	Material behaviour under varying moisture conditions	6
Scanning electron microscope	ASTM E986	Surface morphology and elemental composition	6
Preparation of Asphalt mixture	ASTM D6926	Consistent and reliable samples	18
Marshall stability and flow	ASTM D6927	Maximum load capacity and deformation	18
Indirect tensile strength	ASTM D6931	Mechanical strength, resistance to cracking and fatigue	18

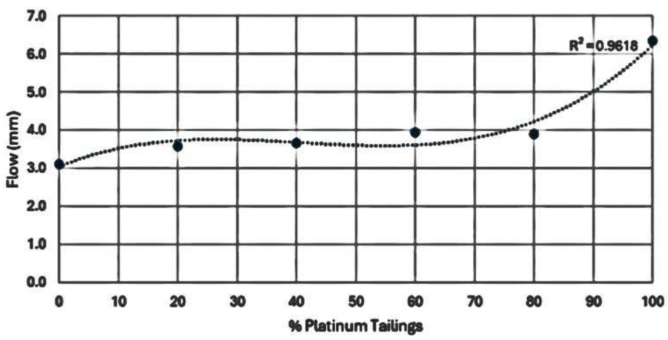
3 RESULTS ANALYSIS AND DISCUSSIONS

3.1 *Effect of Platinum tailings on the stability and flow of asphalt*

Conventional asphalt comprising of 100% fly ash had a Marshall stability value of 5.45 kN and a flow of 3.1 mm. There was a marginal increase in stability of 0.01 kN and a correspondingly slight increase in flow of 0.5mm when the fly ash was substituted with 20% PtT. Further increase of PtT concentration produced a steady decline in stability and increase of flow. The 60% and 80% PtT substitutions yielded the lowest stability of 5.02 kN and a flow of 3.9 mm. Replacement of fly ash with 100% PtT restored the asphalt stability to the initial value, however, it yielded the highest flow of 6.3 mm. Figure 3 presents the Marshall stability and flow test results. The regression analysis resulted in high R2 values of 0.99 and 0.96 for the stability and flow respectively which demonstrated a strong correlation between the observed data and the expected trend, signifying a reliable dataset.



3a. Marshall stability vs platinum tailings concentration



3b. Marshall flow vs. platinum tailings concentration
Figure 3. Marshall stability and flow test

The Marshall stability test results showed that the total replacement of fly ash with PtT was detrimental to asphalt. Although the Marshall stability remained constant, the flow doubled, increasing by 103%. The increased flow can be attributed to the removal of the calcium hydroxide and calcium silicate hydrate (C-S-H); the binding agent found in fly ash. At 20% PtT the stability remained high with a slight increase in flow due to the high fly ash and consequently binding agent concentration. The decrease in stability with increased PtT concentration could have been caused by the reduced filler effect as more fly ash was removed. Compared to PtT, fly ash had a higher proportion of fine particles that can fill voids between the aggregate mix resulting in increased density, reduced porosity and higher stability.

The total replacement of fly ash restored the original stability because of the high concentration of angular PtT which possess high internal friction and therefore higher stability. Overall, the Marshall test results did not show any gains in substituting fly ash with PtT. However, the maximum reduction in stability and increase of flow was marginal at 7% and 26% respectively. The Australian Asphalt Pavement Association (AAPA, 2004) states that the permissible limit for asphalt stability is 5 kN, while the allowable flow range is 2 - 6 mm. Therefore, although the 60% PtT concentration reduced the asphalt stability and increased the flow, the values were within the allowable range.

3.2 *Effect of platinum tailings on the tensile strength of asphalt*

The 100% fly ash asphalt had an IDTS of 466 kN. The IDTS continued to increase steadily with increase of PtT concentration up to a peak value of 548 kN at 60% PtT substitution. This was considerably higher than the typical IDTS values which range between 250 - 400 kPa as reported by Cetin (2013), thus demonstrating the gains of incorporating PtT. Thereafter, there was a decline in strength as the PtT concentration increased, with the 100% PtT concentration yielding the lowest IDTS of 454 kN. The IDTS test results are presented in Figure 4. The statistical analysis generated an R2 value of 0.91 denoting a strong correlation.

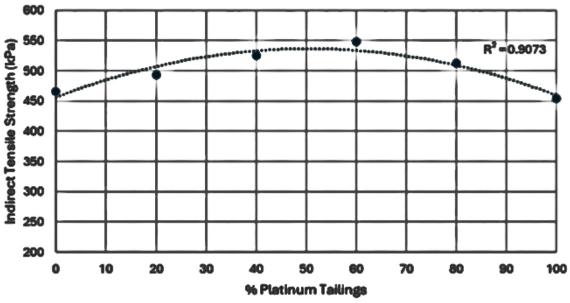


Figure 4. Indirect tensile strength

From Figure 4, it can be seen that the IDTS increased with increasing PtT concentration up to the peak value. This confirmed the SEM observations; the substitution of spherical flyash particles with angular PtT increased the asphalt strength due to the higher internal friction angle of angular tailings. The strength gain reached a peak value at 60 % PtT yielding a strength improvement of 18%, however, the complete replacement of fly ash decreased the IDTS by 3%. There was consistency in the Marshall flow and IDTS test results as both tests affirmed that total substitution of fly ash undermined asphalt deformation resistance and load-bearing capacity.

There are several factors which can be attributed to the IDTS decline for substitutions exceeding 60% which include the reduced workability which results in a mix that is harder to compact. Inadequate compaction leads to higher void content which reduces the strength while increasing susceptibility to moisture damage and differential settlement when subjected to traffic loads (Speight, 2016). Angular surfaces also have larger surface areas and therefore require more binder for coating. Hence, for a given uniform mix, the 100% PtT had insufficient binder content causing particle segregation and ultimately loss of strength. Increasing the binder content to the required levels would have cost implications, thus making it less economically viable.

Based on these findings, the optimum mineral filler was found to be 60%PtT and 40% fly ash. The increased IDTS is a key indicator of improved tensile properties such as enhanced resistance to cracking under traffic loads or temperature fluctuations, higher load-bearing capacity and improved pavement durability. The partial substitution resulted in a well graded filler of angular and rounded particles with reduced voids and increased strength.

4 CONCLUSIONS

The valorisation of tailings into construction materials constitutes sustainable waste management practices which provide environmental and socio-economic benefits. This study examined the performance of platinum tailings (PtT) as a fly ash substitute in asphalt production. Scanning electron microscope images revealed that the angularity of the platinum tailings could improve the strength and stiffness of asphalt due to a higher internal friction angle, improved particle interlocking and lower sliding potential. However, the presence of chromium would require a toxicity assessment to be undertaken to assess the level of contamination and the formulation of an appropriate remediation technique. The tailings did not have a positive effect on the asphalt stability and flow as the 100% fly ash filler yielded better properties due to its pozzolanic constituents. The indirect tensile strength, however, showed that the 60% PtT concentration possessed the highest tensile strength resulting in an asphalt with improved tensile properties. Hence, the optimum mix was found to be 60%PtT and 40% fly ash demonstrating that a blended mix of angular and rounded particles could improve the tensile strength of asphalt by 18%.

5 RECOMMENDATIONS

This study mainly focused on the physical properties of the materials, yet tailings often contain toxic substances such as heavy metals and chemicals, hence, the need for chemical analysis tests and environmental impact studies to assess the environmental and health risks. While the mechanical properties have been examined, further research should evaluate the rheological properties of the mastics by conducting rotational viscosity, bending beam and dynamic shear rheometer tests. Comparative studies can also be performed to analyse the substitution of other types of mineral fillers with PtT and distinguish the optimum mix. In addition, the long-term stability should be assessed through extended field trials and accelerated aging tests.

To support the broader adoption of platinum tailings, it is essential to review and update industry standards and regulations. Collaboration between industry stakeholders and regulatory authorities is required to facilitate the incorporation of PtT as an acceptable mineral filler in asphalt production.

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