Laboratory Evaluation of Wear Particle Emissions and Suspended Dust in Tire–Asphalt Concrete Pavement Friction

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Abstract: This study aims to evaluate the tire–road-wear particles (TRWPs) and suspended dust generated based on the nominal maximum aggregate size (NMAS) of the polymer-modified stone mastic asphalt (SMA) mixtures indoors. The SMA mixtures containing styrene butadiene styrene (SBS) polymer and the NMASs of 19, 13, 10, 8, and 6 mm were used. Dust was generated from the wear of the tires and the pavement inside the indoor chamber by using the laboratory tire–road-wear particle generation and evaluation tester (LTRWP tester) developed by Korea Expressway Corporation (KEC). In this method, a cylindrical asphalt-mixture specimen rotates in the center, and a load is applied using three tires on the sides of the test specimen. During the test, a digital sensor was used to measure the concentration for each particle size. After the test was completed, the dust was collected and weighed. According to the test results, the generated TRWP emissions were reduced by approximately 0.15 g as the NMAS of the SMA mixture decreased by 1 mm. TRWP emissions decreased by 20% when using the 6 mm SMA mixture compared to the 13 mm SMA mixture. For practical application, a predicted equation of TRWP emissions estimation was developed by using the concentration of suspended dust measured by the digital sensor in the LTRWP tester. LTRWP can be used as an indoor test method to evaluate pavement and tire materials to reduce the amount of dust generated from tire and pavement wear.

Keywords: tire–road-wear particle emissions; suspended dust; SMA mixture; nominal maximum aggregate size

1. Introduction

According to the Suspended Dust Management Manual (2021) by the Ministry of Environment of the Republic of Korea, suspended dust accounts for 50.3% of the total PM$_{10}$ fine dust (particulate matter in the atmosphere that is smaller than or equal to 10 µm) generated. Of this 50.3%, resuspended road dust comprises 28.3%, indicating that dust generated on roads significantly impacts the concentration of fine dust in the atmosphere [1].

Dust generated on roads consists of a combination of complex particles such as tire-wear particles (TWPs), road-wear particles (RWPs), and microplastic particles (MPs). However, the term “tire wear” is used frequently, and inconsistent definitions such as “road particles” (RPs) and “asphalt pavement-tire wear particles” (APWP) are also used in the relevant literature. Therefore, in this paper, the term “tire-road wear particles” (TRWPs) is used to accurately describe particles generated from the wear of both the pavement surface and tires due to friction on roads [2–4].

Resuspended road dust consists of TRWPs generated from the friction between asphalt mixtures and tires, along with dust from external sources that accumulates on the road surface and is dispersed into the atmosphere due to turbulence caused by moving vehicles. As it is challenging to predict the exact sources and amounts of dust flowing in from external sources, identifying the sources of fine dust by sector and controlling TRWPs is the most practical way to reduce resuspended road dust [5]. Thus, a study that quantitatively
determines the relationship between TRWPs and various asphalt mixtures and driving environments is required.

TRWPs are generally discussed in terms of their contribution to particulate matter (PM) in the atmosphere and the amount of TRWP emissions [2,3,5]. TRWPs refer to the fine particles generated from the wear and tear of road surfaces and tires. Factors affecting the generation of TRWPs include tire characteristics (such as size, tread depth, structure, air pressure, temperature, and contact area), road surface characteristics (such as pavement type, aggregate, binder, texture, porosity, and humidity), vehicle operation characteristics (such as speed, acceleration, and braking), and vehicle characteristics (such as vehicle weight, load distribution, wheel position, power output, steering, braking system, and suspension condition). For example, highways built with asphalt material generate more suspended dust from the friction between tires and the pavement surface compared to highways built with cement material [5]. Among the influencing factors, the nominal maximum aggregate size (NMAS) of pavement determines the road surface condition in contact with tires and has a relatively high impact on TRWP generation [3].

Several studies have analyzed the effect of NMAS on TRWP generation. Some studies have theoretically deduced that smaller NMASs lead to less tire wear. Hongying Liu et al. verified through the Cantabro test that asphalt mixtures with small NMASs had higher pavement wear resistance than asphalt mixtures with large NMASs [6]. However, there are also studies with results contradicting this research finding. Rustem Gayfutdinov et al. empirically stated that the larger the NMAS, the higher the wear resistance of the pavement [7]. B. Snilsberg et al. utilized the Prall test and road simulator to support the aforementioned hypothesis [8]. The contradicting results of these two theories are based on how the conditions of the tires contacting the road pavement surface have been considered [9]. In the relationship between the NMAS and the mean profile depth (MPD), which describes the texture scale of the pavement surface, the MPD decreases as the NMAS decreases, making the texture of the pavement surface smoother [10]. Therefore, in the case of mixtures of small particles with small NMASs, the contact area between the road surface and the tire increases, which disperses the contact pressure. This can contribute to reducing tire wear in the case of regular tires. For studded tires, mixtures with large NMASs provide stronger structural resistance. Studded tires have pins made of metal or other hard materials embedded in the tire’s surface, thereby increasing traction on icy roads. These tires can cause considerable wear on asphalt road surfaces, and mixtures with large NMASs may have greater resistance to pavement wear.

All-season regular rubber tires have been used. Therefore, the Korea Expressway Corporation (2019) took into account the advantages and drawbacks of existing equipment and designed and developed the LTRWP tester, which allows direct friction between the side face of a gyratory-compacted asphalt-mixture specimen and a rubber tire in a chamber capable of controlling the conditions of the environment. It seems that the wearing of the side face of the specimen cannot represent practical tire–pavement wearing. However, it should be noted that past studies evaluated the effect of anisotropy on small specimens by comparing 100 mm tall small specimens extracted horizontally and vertically from gyratory-compacted specimens. It was concluded that the anisotropic effects of gyratory-fabricated specimens were insignificant [11–13].

The purpose of this study is to evaluate the TRWP emissions generated according to the NMAS of PSMA mixtures using the LTRWP tester. In addition, a predicted equation of TRWP emissions was developed by using the concentration of suspended dust measured by the digital sensor in the LTRWP tester.

2. Research Method

2.1. Research Content and Scope

This study was conducted to evaluate the concentrations of suspended dust and TRWP emissions of the PSMA mixture for each NMAS using the LTRWP tester, which was developed to analyze the wear particle emissions generated due to the friction between the
This study was conducted to evaluate the concentration of suspended dust and TRWP emissions generated due to the friction between the pavement surface and tires. Furthermore, this study analyzed the correlation between the concentration of suspended dust and TRWP emissions (Figure 1).

![Figure 1. Research procedure.](image)

To evaluate the effect of TRWP emissions on the concentration of fine dust in the atmosphere, the dust concentration in the atmosphere inside the chamber, which was altered due to TRWP's, was measured using a light-scattering sensor installed inside the chamber, as shown in Figure 2, by classifying the dust concentration into PM mass and particle count [5]. The light-scattering method is a technique that indirectly determines the concentration of fine dust by drawing in particulate matter in the atmosphere and measuring the intensity of light scattered when light is irradiated onto the particulate matter. However, errors may occur depending on the chemical properties and moisture [14]. TRWP emissions (g) are measured using the gravimetric method. After completing the experiment, the dust loaded at the bottom of the chamber is collected, weighed, and used for analysis. For the road pavement specimen, PSMA was used, which is commonly used in the surface layer of highways in South Korea.

The mixture is subjected to a successive load and frictional heat in this test; hence, the mixture may be deformed or damaged depending on the temperature conditions inside the chamber. Therefore, the optimal temperature conditions need to be determined to produce the suspension of wear particles during the rotational friction between the mixture and the tire. In this study, the test was conducted by setting the control temperature inside the chamber to range from −5 °C to 0 °C by referring to the previous research test results for different temperatures. The test began when the temperature inside the chamber was −5 °C. When the temperature reached 0 °C, the test was stopped. Subsequently, the temperature was cooled back down to −5 °C, and the test resumed. To reduce the cooling time, a dual cooling system was utilized, which supplied cooled air from both sides. Figure 3 presents the appearance of the mixture tested at the chamber temperatures of 15 °C to 20 °C, 0 °C to 5 °C, and −5 °C to 0 °C. We found that the mixture was not deformed when the control temperature was between −5 °C and 0 °C.
of 15 °C to 20 °C, 0 °C to 5 °C, and −5 °C to 0 °C. We found that ... R13 were placed around the cylindrical specimen at 0°, 120°, and 240°, and the load of each tire was set to 200 kgf.

Figure 2. Wear test and dust measurement method.

Figure 3. Visual inspection of specimen deformation by test’s starting temperature.

2.2. Experimental Method
2.2.1. Experimental Equipment and Dust Measurement Method

The TRWP test device used in this study is the laboratory tire–road-wear particle generation and evaluation tester (LTRWP tester) developed by the Korea Expressway Corporation. This device is designed to simulate the wear and friction between tires and road surfaces to generate and evaluate TRWPs.

Due to the simulation with small-scale experimental equipment, the actual tire-wear conditions were assumed to be represented by the side wear of the cylindrical specimen. This approach ensures the effective generation and evaluation of TRWPs under laboratory conditions.

The LTRWP tester simulates road and tire wear in the field by rotating and making the cylindrical PSMA-mixture specimen and tire inside the chamber come into contact with each other (Figure 4). Considering the size of the LTRWP tester, three passenger car tires of size 155/70, R13 were placed around the cylindrical specimen at 0°, 120°, and 240°, and the load of each tire was set to 200 kgf.

To measure the dust generated due to the friction between the mixture and the tires, a sensor for measuring suspended dust was installed inside the tester, and the PM concentration was measured at 10 s intervals. The cumulative TRWP emissions generated due to the rotational friction between the tires and the mixture were collected directly from the
bottom of the chamber after completing the test, and the collected TRWP emissions were weighed (Figure 5).

![Laboratory tire–road-wear particle generation and evaluation tester.](image)

**Figure 4.** Laboratory tire–road-wear particle generation and evaluation tester.

![TRWP emissions.](image)

**Figure 5.** TRWP emissions.

The size of TRWPs found on roads ranges from 4 μm to 264 μm [15]. In this study, the dust measured using the LTRWP tester was recorded by particle size by referring to the standards of the United States Environmental Protection Agency (EPA) [16]. For TRWP emissions (g), the wear particles accumulated at the bottom of the chamber were collected and weighed after the test was completed. The total suspended particulate (TSP) was recorded as the average total suspended dust concentration (μg/m³) with a particle size of 10 μm or less, and the PM was recorded as the average suspended dust concentration based on the range defined in Table 1.

<table>
<thead>
<tr>
<th>Classification</th>
<th>Particle Size (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TSP</td>
<td>PM₁₀ 5–10</td>
</tr>
<tr>
<td></td>
<td>PM₅ 2–5</td>
</tr>
<tr>
<td></td>
<td>PM₂ 1–2</td>
</tr>
<tr>
<td></td>
<td>PM₁ 0.5–1</td>
</tr>
<tr>
<td></td>
<td>PM₀₅ 0.3–0.5</td>
</tr>
<tr>
<td></td>
<td>PM₀₃ &lt;0.3</td>
</tr>
</tbody>
</table>

**Table 1.** Particle size classification.
2.2.2. Experimental Materials

For the evaluation of the suspended dust emissions generated for each NMAS of asphalt mixtures, the PSMA mixtures commonly used on highways were comparatively evaluated. For the asphalt, the PG76-22-grade asphalt was used, which contains the SBS-type rubber-modifying agent. Moreover, granite with a wear rate of 30% or less was used as the aggregate. Figure 6 shows the aggregate grading of SMA mixtures with the maximum aggregate sizes of 19, 13, 10, 8, and 6 mm.

![ Aggregate grading of mixtures with maximum aggregate sizes of 19 mm, 13 mm, 10 mm, 8 mm, and 6 mm. ]

Figure 6. Aggregate grading of mixtures with maximum aggregate sizes of 19 mm, 13 mm, 10 mm, 8 mm, and 6 mm.

To satisfy the design porosity of 2.5%, asphalt binder contents of 6.1%, 6.6%, 6.9%, 7.1%, and 7.2% were used for the PSMA mixtures with NMASs of 19, 13, 10, 8, and 6 mm, respectively. The plastic deformation resistance of the SMA mixtures was evaluated, and the results showed that the mixtures all satisfied the quality standards for dynamic stability of 3000 cycles/mm or more (Table 2).

<table>
<thead>
<tr>
<th>PSMA 6 mm</th>
<th>PSMA 8 mm</th>
<th>PSMA 10 mm</th>
<th>PSMA 13 mm</th>
<th>PSMA 19 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Void(%)</td>
<td>2.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Asphalt Content(%)</td>
<td>7.2</td>
<td>7.1</td>
<td>6.9</td>
<td>6.6</td>
</tr>
<tr>
<td>Dynamic Stability (Cycles/mm)</td>
<td>7284</td>
<td>9658</td>
<td>4723</td>
<td>4323</td>
</tr>
</tbody>
</table>

Table 2. Mix design of 6 mm, 8 mm, 10 mm, 13 mm, 19 mm.

The asphalt mixture was compacted 100 times using a gyratory compactor at a rotation angle of 1.25° and a rotation speed of 30 revolutions per minute to fabricate a cylindrical test specimen with a diameter of 150 mm and a height of 180 mm.
3. Results

3.1. Analysis of TRWPs for PSMA Mixtures

The analysis of TRWPs was conducted in two stages. In the first stage, the wear particles suspended during the test were measured by their cumulative number (particle count) and average PM mass concentrations using a real-time measurement sensor to analyze the wear particle generation trend. In the second stage, given that all wear particles generated during the experiment were accumulated at the bottom of the chamber, they were collected after the test was completed. The collected wear particles were recorded as TRWP emissions (g) and analyzed.

Figure 7 plots the trend of dust generated over time to determine the LTWRP test time. In the graph shown in this figure, the x-axis denotes the test time, while the y-axis denotes the cumulative number of wear particles. As this cumulative number is extremely large, it was expressed as an exponent. During the initial 100 h, the slope of the number of dust particles generated varied. However, after 100 h, the slope tended to remain constant. In this study, the test was conducted for 100 h to evaluate the number of wear particles generated according to the maximum aggregate size of the asphalt mixture. Therefore, the cylindrical specimen was tested for 100 h at a speed of 40 km/h after applying the load of the tires, thereby simulating a total of 4000 km of road driving.

![Figure 7](image)

**Figure 7.** Results of cumulative number of wear particles over LTRWP test time.

Table 3 shows the results of the test conducted on the suspended dust concentrations (μg/m³) and TRWP emissions (g) for different NMASs of the PSMA mixtures.

<table>
<thead>
<tr>
<th>Concentration (μg/m³)</th>
<th>PSMA 6 mm</th>
<th>PSMA 8 mm</th>
<th>PSMA 10 mm</th>
<th>PSMA 13 mm</th>
<th>PSMA 19 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM0.3</td>
<td>2.43</td>
<td>1.41</td>
<td>1.82</td>
<td>1.32</td>
<td>1.35</td>
</tr>
<tr>
<td>PM0.5</td>
<td>3.52</td>
<td>1.35</td>
<td>1.98</td>
<td>1.70</td>
<td>2.76</td>
</tr>
<tr>
<td>PM1.0</td>
<td>2.70</td>
<td>1.61</td>
<td>1.61</td>
<td>2.29</td>
<td>2.48</td>
</tr>
<tr>
<td>PM2</td>
<td>3.07</td>
<td>2.48</td>
<td>2.81</td>
<td>3.62</td>
<td>4.25</td>
</tr>
<tr>
<td>PM5</td>
<td>0.46</td>
<td>0.47</td>
<td>0.58</td>
<td>0.61</td>
<td>0.94</td>
</tr>
<tr>
<td>PM10</td>
<td>0.77</td>
<td>0.86</td>
<td>0.99</td>
<td>1.08</td>
<td>1.97</td>
</tr>
<tr>
<td>TRWP Emission (g)</td>
<td>2.0</td>
<td>2.2</td>
<td>2.4</td>
<td>2.5</td>
<td>3.3</td>
</tr>
</tbody>
</table>

In Table 3, the suspended dust concentration was categorized into PM0.3, PM0.5, PM1, PM2, PM5, and PM10 based on the PM size and the average of the suspended dust
concentrations (μg/m³) recorded at 10 s intervals over 100 h was calculated. TRWP emission denotes the total amount of wear generated, and the weight (g) of the accumulated dust collected after completing the wear test was recorded for the TRWP emissions.

According to the experimental results, the TRWP emissions collected after the completion of the test increased consistently as the NMAS of the PSMA mixture increased. A linear relationship equation showed the tendency of TRWP emissions to increase by approximately 0.15 g when the NMAS increased by 1 mm.

Figure 8 presents certain specific test results. The TRWP emissions increased by 10%, 9%, 4%, and 32% when the NMASs increased from 6 mm to 8 mm, 8 mm to 10 mm, 10 mm to 13 mm, and 13 mm to 19 mm, respectively. In general, SMA mixtures with a maximum aggregate size of 13 mm are used. However, it was evaluated that the tire–pavement wear was reduced by 20% when the SMA mixture with a maximum aggregate size of 6 mm was used.

![Figure 8](image-url)  
*Figure 8. Results of the TRWP emission tests on PSMA mixture with maximum aggregate sizes.*

It is determined that the wear reduction tendency based on the NMAS of the PSMA mixture evaluated in this experiment is attributed to the fact that the surface roughness of smaller aggregates increases the contact area of the tire compared to larger aggregates, thereby distributing the load and reducing wear.

Figure 9 demonstrates the TSP test results for each NMAS of the PSMA mixture. The average TSP of all test mixtures was measured to be 11 μg/m³, the maximum TSP value for the 19 mm PSMA mixture was 13.7 μg/m³, and the minimum TSP value for the 8 mm PSMA mixture was 8.2 μg/m³. As the NMAS of the mixture increased, the TSP also tended to increase, similar to the results of the TRWP emission experiment. However, the TSP of the 6mm PSMA mixture showed a higher value than the TSP measurements of mixtures with other aggregate sizes, contrary to the results of the TRWP emission experiment.

Although the TSP generated in the 6 mm PSMA mixture is higher than the test results for other mixtures, the TRWP emissions were measured to be low. It can be interpreted that although it took a long time for the generated dust to be suspended in the atmosphere, the total amount of dust generated was low. Furthermore, it can be predicted that more small particles of PM₂ or smaller are generated from the 6 mm PSMA mixture than other mixtures.

Similar to the hypothesis of this study, Figure 10 demonstrates that the 6 mm PSMA mixture exhibits a higher concentration of PM₂ or smaller suspended dust compared to the measurement values of other mixtures. In the test results of PM₅ or larger suspended dust, the 6 mm PSMA mixture exhibits a lower suspended dust concentration than that of other mixtures.
Therefore, the concentration of newly generated suspended dust was measured, in addition to the concentration of the previously generated suspended dust still floating in the atmosphere, at each concentration measurement cycle (0.1 Hz). Hence, it is deemed that the cycle is stabilized in which newly generated wear particles from the friction between the mixture and the tires are suspended by the tires, specimen rotating inside the tester, and the airflow flowing in from the cooler.

Similar to the hypothesis of this study, Figure 10 demonstrates that the 6 mm PSMA mixture exhibits a lower suspended dust concentration than that of other mixtures. In the test results of PM sizes, the 6 mm PSMA mixture exhibits a higher concentration of PM0.3 or smaller suspended dust compared to other mixtures, and the measurement values of other mixtures. In the test results of PM0.5 or larger suspended dust, the 6 mm PSMA mixture exhibits a lower suspended dust concentration than other mixtures.

It can be interpreted that in the case of suspended dust that is light and has small particle sizes (PM2 or smaller), the suspended dust stays in the atmosphere for prolonged periods due to a vortex created by the tires, specimen rotating inside the tester, and the airflow flowing in from the cooler. Therefore, the concentration of newly generated suspended dust was measured, in addition to the concentration of the previously generated suspended dust still floating in the atmosphere, at each concentration measurement cycle (0.1 Hz). Hence, it is deemed that irregular measurement tendencies are caused by this phenomenon.

In contrast, for suspended dust that is relatively heavy and has large particle sizes (PM3 or larger), the time suspended dust stays in the atmosphere is reduced due to the sedimentation effect caused by gravity. Therefore, the cycle is stabilized in which newly generated wear particles from the friction between the mixture and the tires are suspended in the atmosphere, and previously suspended particles settle down to the bottom. Conse-
sequently, the suspended dust concentration tends to increase according to the NMAX of the mixture.

As shown in Figure 11, the concentrations of PM$_5$ and PM$_{10}$ suspended dust exhibited high coefficients of determination (0.9 or higher) in their relationship with NMAS. In the case of PM$_5$, the suspended dust concentration increased by approximately 0.04 µg/m$^3$ when the NMAS of the mixture increased by 1 mm. For PM$_{10}$, the suspended dust concentration consistently increased by approximately 0.09 µg/m$^3$ as the NMAS of the mixture increased by 1 mm.

![Figure 11](image_url)

**Figure 11.** Relationship of PM$_{5}$ and PM$_{10}$ suspended dust concentrations in PSMA mixtures with maximum aggregate sizes.

3.2. Development of the TRWP Emission Estimation Equation Based on Suspended Dust Concentration

3.2.1. Selection of Variables

As shown in Figure 9, TSP and TRWP emissions tend to increase according to the NMASs of the PSMA mixtures. Based on this relationship, an analysis was conducted to estimate the TRWP emissions accumulated at the bottom of the chamber, without directly collecting them, by utilizing the suspended dust concentration measured in real time through sensors.

Figure 12 illustrates the relationship between the concentration of suspended dust by PM size and TRWP emissions in order to select independent variables for regression analysis. It can be seen that for PM$_5$ and PM$_{10}$, the TRWP emissions tend to increase when the suspended dust concentration increases. However, no specific tendency was found in the analysis results for the remaining PM sizes.

The suspended dust concentrations for PM$_{0.5}$, PM$_{0.5}$, and PM$_1$ exhibited coefficients of determination ($R^2$) of 0.5 or lower with the TRWP emissions (Table 4). As suspended dust particles with smaller particle sizes are greatly affected by turbulence, it can be deemed that the cycle of the suspension of dust particles generated inside the chamber and the settling of these dust particles is not stabilized, similar to the interpretation of Figure 9. On the other hand, the coefficients of determination for the relationship between the suspended dust concentrations for PM$_3$, PM$_5$, and PM$_{10}$ and TRWP emissions were 0.7 or higher, exhibiting a high explanatory power for interpreting TRWP emissions based on these concentrations.
3.2.2. Regression Analysis

The variables used in regression analysis to develop an estimation equation may suffer from multicollinearity issues because dust particles from the same mixture are classified by size.

To address this challenge, a multicollinearity analysis was conducted on the selected variables (suspended dust concentrations for PM$_{0.3}$, PM$_{5}$, and PM$_{10}$). Multicollinearity refers to the phenomenon in which highly correlated variables are included among variables used in regression analysis, which degrades the estimation precision of regression coefficients. Multicollinearity can be verified using the variance inflation factor (VIF), as shown in Equation (1). The VIF indicates the extent to which one independent variable can be explained by the other variables. In general, a VIF of 10 or higher implies that there is a high multicollinearity.

\[
VIF_i = \frac{1}{1 - R^2_i},
\]

where VIF is the variance inflation factor, $i$ is the result of the selected dependent variable among the independent variables, and $R^2$ is the coefficient of determination.

According to the VIF analysis results, PM$_2$ had a VIF of 5 or less, as shown in Table 5, so multicollinearity issues did not occur. However, the VIF for the suspended dust concentrations for PM$_5$ and PM$_{10}$ was 10 or higher; this result indicates multicollinearity issues.

### Table 4. $R^2$ for the relationships between TRWP emissions and suspended dust concentrations by PM size.

<table>
<thead>
<tr>
<th>Size of Particulate Matter</th>
<th>Coefficient of Determination</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM$_{0.3}$</td>
<td>0.372</td>
</tr>
<tr>
<td>PM$_{5}$</td>
<td>0.002</td>
</tr>
<tr>
<td>PM$_{1}$</td>
<td>0.039</td>
</tr>
<tr>
<td>PM$_{2}$</td>
<td>0.705</td>
</tr>
<tr>
<td>PM$_{5}$</td>
<td>0.983</td>
</tr>
<tr>
<td>PM$_{10}$</td>
<td>0.976</td>
</tr>
</tbody>
</table>
Table 5. VIF (variance inflation factor).

<table>
<thead>
<tr>
<th></th>
<th>PM(_2)</th>
<th>PM(_5)</th>
<th>PM(_{10})</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM(_2)</td>
<td>4.63429</td>
<td>-7.7378</td>
<td>3.68703</td>
</tr>
<tr>
<td>PM(_5)</td>
<td>-7.7378</td>
<td>78.9991</td>
<td>-71.734</td>
</tr>
<tr>
<td>PM(_{10})</td>
<td>3.68703</td>
<td>-71.734</td>
<td>69.0127</td>
</tr>
</tbody>
</table>

The fact that a dust particle size of PM\(_{10}\) is commonly used to evaluate suspended dust in the road environment field was considered in this study. Hence, PM\(_5\) was excluded, which has multicollinearity issues, and a multiple regression analysis was conducted using the suspended dust concentrations for PM\(_{10}\) and PM\(_2\) to develop the TRWP emission estimation equation.

The results of the TRWP emission regression analysis using PM\(_{10}\) and PM\(_2\) showed an adjusted coefficient of determination of 0.9758, indicating a high explanatory power for the estimation equation. However, as shown in Table 6, the regression coefficient for PM\(_2\) was a negative number, and the \(p\)-value was greater than or equal to 0.05, indicating it did not satisfy the significance level. The regression coefficient for PM\(_{10}\) was a positive number, showing a relationship between general concentration and TRWP emissions. Furthermore, the \(p\)-value was less than or equal to 0.05, indicating it satisfied the significance level.

Table 6. Results of multiple regression analysis (PM\(_2\), PM\(_{10}\), and TRWP emissions).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Estimate</th>
<th>Standard Error</th>
<th>t-Value</th>
<th>(p)-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>1.38363</td>
<td>0.30837</td>
<td>4.48687</td>
<td>0.04625</td>
</tr>
<tr>
<td>PM(_2)</td>
<td>-0.0317</td>
<td>0.15143</td>
<td>-0.2091</td>
<td>0.85374</td>
</tr>
<tr>
<td>PM(_{10})</td>
<td>1.05541</td>
<td>0.21884</td>
<td>4.82271</td>
<td>0.04041</td>
</tr>
</tbody>
</table>

After conducting the correlation analysis and multicollinearity verification and performing the sign verification and significance level determination through the regression analysis, we considered it appropriate to estimate the TRWP emissions based on the suspended dust concentration for PM\(_{10}\). Table 7 lists the regression analysis results of the suspended dust concentration for PM\(_{10}\) and the TRWP emissions. The linear regression analysis was conducted using a suspended dust concentration for PM\(_{10}\), which is the single independent variable, and TRWP emissions, which is the dependent variable. The analysis results yielded a coefficient of determination of 0.9761, demonstrating a high explanatory power for the estimation equation. Moreover, the \(p\)-value was less than or equal to 0.05, which satisfied the significance level.

Table 7. Results of regression analysis (PM\(_{10}\) and TRWP emissions).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Estimate</th>
<th>Standard Error</th>
<th>t-Value</th>
<th>(p)-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>1.325668</td>
<td>0.111523</td>
<td>11.88698</td>
<td>0.00128</td>
</tr>
<tr>
<td>PM(_{10})</td>
<td>1.015995</td>
<td>0.091742</td>
<td>11.07448</td>
<td>0.001577</td>
</tr>
</tbody>
</table>

The TRWP emission estimation equation determined through the regression analysis is shown in Equation (2).

\[
\text{TRWP Emission (g)} = 1.015995\text{PM}_{10} + 1.325668
\]  

(2)

where TRWP Emission is the total estimated amount of wear particles (g), and PM\(_{10}\) is the average suspended dust concentration for PM\(_{10}\) measured at a frequency of 0.1 Hz (\(\mu\text{g/m}^3\)).
4. Conclusions

This study aimed to evaluate the concentration of suspended dust and TRWP emissions of the PSMA mixture for each NMAS using the LTRWP tester, which was developed to analyze the wear particle emissions generated due to the friction between the pavement surface and tires. The main results of this paper are summarized as follows.

1. The results of analyzing the tendency of wear particle generation using the LTRWP tester show that the cumulative number of wear particles over the test time has a directly proportional relationship with a coefficient of determination ($R^2$) of 0.98. Therefore, the tendency for a certain level of wear to occur regularly over time was verified.

2. Suspended dust concentrations (for PM$_{2}$ and smaller) measured in real time by the sensor did not show any particular tendency with the NMAS of the PSMA mixture. However, for PM$_{5}$ and larger, the suspended dust concentration tended to increase as the NMAS increased.

3. In the correlation analysis between the suspended dust concentration and TRWP emissions, PM$_{2}$ did not satisfy the significance level of the estimation equation, and PM$_{5}$ was excluded due to multicollinearity issues. Hence, the TRWP emission estimation equation was developed using the suspended dust concentration for PM$_{10}$.

4. According to the results of the wear test for each NMAS of the PSMA mixture, RWP emissions increased by approximately 0.15 g as the NMAS increased by 1 mm. Thus, it was found that the TRWP emissions decreased by 20% when using the 6 mm SMA mixture compared to the 13 mm SMA mixture.

The findings derived in this study are identical to past studies in terms of the NMAS SMA effects on TRWP emissions [6,9,10]. However, it should be noted that this study has several limitations. Future research should include additional experiments with various binder types, asphalt mixtures, gradations, aggregate types, test temperatures, speeds, and loads to better understand TRWP generation. Analyzing the environmental and economic impacts of the results is also crucial. Finally, researchers should propose management strategies for TRWPs to contribute to practical problem-solving.

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