

Research Article

Study on Engineering Application and Degradation Efficiency of Nanoscaled TiO₂ Used as Photocatalytic Fog Sealing

Mengchen Li,¹ Zhizhong Zhao ^{[b},¹ Haizhi Li,² Yanmin Wang ^{[b},¹ Qingliang Wang,¹ Xingxing Zhu,¹ and Liang Fan³

¹School of Civil Engineering, Shandong Jiaotong University, Jinan 250023, Shandong, China
²Shandong LuQiao Group Co. Ltd, Jinan 250014, Shandong, China
³Shandong Transportation Research Institute, Jinan 250100, Shandong, China

Correspondence should be addressed to Zhizhong Zhao; 86994896@qq.com

Received 10 May 2021; Revised 24 June 2021; Accepted 3 July 2021; Published 14 July 2021

Academic Editor: Alessandro Martucci

Copyright © 2021 Mengchen Li et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

There exists a great difference of the photocatalytic degradation efficiency between nanoscaled TiO_2 modified-emulsified asphalt applied as the fog sealing under the indoor and outdoor environment. Much efforts have been made by many investigators to study this issue. However, most of them focus on the ideal condition, ignoring the degradation efficiency examination of TiO_2 in the actual engineering practice. A series of field tests are carried out, accompanied with laboratory experiments, to analyze and consequently compare the photocatalytic degradation efficiency of nanoscaled TiO_2 in the indoor and outdoor conditions, respectively. Regression analysis was employed to investigate the influence factors of degradation efficiency, by which formula of function of factors influencing degradation efficiency and degradation efficiency deviation equation are obtained. The results show that when the degradation efficiency of NO₂ in the laboratory test is as high as 63%, the degradation efficiency affected by the environmental factors is only 25% in the actual engineering practice. Based on the measurement data, detection indicators and criteria can be provided, which is of great significance in the establishment of the construction quality control system.

1. Introduction

With the development of research on nanosized materials recently, their engineering applications have been widely expanded. The application of nanosized photocatalysis materials in water treatment, air purity, and other environmental protection fields has become a hot topic of social concern [1]. Among those, the photocatalysts represented by nano-TiO₂ can undergo strong redox reactions under UV radiation [2], which have been widely studied by domestic and foreign scholars for the degradation of automobile exhaust. Among those, numerous investigations on the photocatalysts represented by nano-TiO₂ adopted as the degradation of automobile exhaust have been carried out, owing to its characteristic of strong redox reactions exposed under UV radiation [3].

Du et al. [4, 5] found that nanoscaled TiO_2 photocatalytic materials would be able to degrade NO_X , HC, CO, and other

components included in automobile exhaust. Wu et al. [6, 7] proposed that the degradation efficiency of nanosized TiO₂ used as coated materials is better than doped materials. A study on the purification performance of TiO₂ modifiedemulsified asphalt used as a thin overlay was conducted by Wu and Ping [8]. The result showed that the degradation performance is positively correlated with temperature and UV irradiance. In conclusion, nano-TiO₂, with its capacity for degrading automobile exhaust, plays an important role in improving the air quality. Most aforementioned research studies are primarily concerned on the degradation efficiency of nano-TiO₂ under an ideal condition of laboratory experiments, while rare attention has been paid to its actual application. Besides, there are few studies on the examination of TiO₂ degradation efficiency in practical construction.

Therefore, to capture the physical process of TiO_2 degradation and grasp a better understanding of the

underlying mechanism, a series of comprehensive field tests accompanied with laboratory experiments are desired, which motivates this study. Main objectives of this paper are to comparing the degradation efficiency of atmospheric pollutants under both indoor and outdoor conditions, considering the photocatalytic process of TiO_2 and its influencing factors, revealing the rule of the photocatalytic effect with influencing factors and exploring the mechanism that causes the deviation of degradation efficiency exposed to these two aforementioned environments. These results are undoubtedly of great significance to improve degradation efficiency and consequently beneficial to establish quality control systems in the construction.

2. Laboratory Experiments' Setup

According to the mechanism of photocatalytic degradation [9, 10], nano-TiO₂ could degrade atmospheric pollutants under UV radiation. The laboratory experiments were conducted to study its degradation efficiency, by which mixture proportion and optimal spraying amount of modified-emulsified asphalt applied as the fog sealing, from an indoor-environment perspective, could be determined. Meanwhile, the results of laboratory experiments could provide the fundamental basis for the field test construction.

2.1. Procedures of Laboratory Experiments. The materials adopted in the laboratory experiments included SMA-13 asphalt mixture, Degussa nanosized P25 photocatalytic material imported from Germany, and cationic emulsified asphalt.

A specialized-manipulated closed chamber with size of $50 \text{ cm}^* 50 \text{ cm}^* 40 \text{ cm}$ is served as the test equipment [11]. In order to obtain better observation, the chamber is made of quartz glass. An air inlet and an air outlet hole are reserved on the both sides for NO₂ gas input and emission respectively. To be more specific, the inlet hole is connected to a canister of NO₂ through a rubber tube, while the outlet hole is connected to an air pump and a MOT100-NO_X NO_x detector through a rubber tube. Moreover, a M60 light source box is installed outside the chamber as an ultraviolet light source, which power density of UV lamp is 300 W/m². Detailed experimental device is shown in Figure 1(a), and the adopted NO_x detector is represented in Figure 1(b).

According to the Standard Test Methods of Bitumen and Bituminous Mixture for Highway Engineering (JTGE20-2019), two rutting structures with а size 30 cm*30 cm*10 cm were, respectively, cut into specimens with dimensions of 15 cm long*15 cm wide*5 cm high to simulate asphalt pavement. Generally speaking, the catalytic reaction is divided into a surface reaction. Thus, prior to the introduction of the porous structure, e.g., zeolite powder and nano-CaCO₃, into nano-TiO₂ [12, 13], the exhaust should be adsorbed onto the surface of the catalyst for degradation. On the one respect, owing to the strong capacity of carrying and adsorption, zeolite powder could adsorb automobile exhaust into the pore channel, leading to the increment of the contact area between pollutants and nano-TiO2 and the

improvement of the degradation efficiency in consequence. Moreover, nano-CaCO₃ is characterized as a porous structure and possesses a great specific surface area. Thus, it could enhance the adhesion of modified-emulsified asphalt, as well as increase the adsorption area. In addition, Nano-CaCO₃ itself could promote the conversion process of NOx into calcium nitrate [14, 15].

Nano-TiO₂, nano-CaCO₃, zeolite powder, and polyvinylpyrrolidone (PVP) were introduced into 100 ml emulsified asphalt, following the mixture-ratio of 1:1:2: 0.04. Stirring the mixture thoroughly until the modifiedemulsified asphalt dropped TiO₂ was obtained. Extreme care is taken to ensure that the ultimate mixture for experiments is homogeneous. Then, the mixture was sprayed to the surface of the aforementioned specimens where it is allowed with the volume of 0.3 kg/m^2 and 0.4 kg/m^2 , respectively, to form the fog sealing. Figure 2 shows the comparison between ordinary specimens and specimens covered with fog sealing. These specimens were both set outside to aerate for an hour and then put into two closed boxes. Opening the light source box, the NO₂ with an initial concentration of 20 ppm was injected into the box. This test lasted for two hours. The degradation efficiency, according to equation (1) [16-18], could be calculated by comparing the amount of NO₂ contained in these two specimens within two hours:

$$Z = \frac{(D_0 - D_1)}{D_0},$$
 (1)

where Z represents the degradation efficiency of nitrogen dioxide, D_0 denotes the concentrations of nitrogen dioxide without UV illumination in the system, and D_1 denotes the concentrations of nitrogen dioxide with UV illumination in the system. The power of the UV lamp used in the laboratory is 18, and the UV band is 365 nm [19, 20].

2.2. Results and Analysis of Laboratory Experiments. Figure 3 illustrates the degradation efficiency of NO_2 in the specimens covered with different amounts of TiO_2 .

As shown in Figure 3, the NO₂ degradation efficiency is affected by lasting time and spraying volume. With the time extension of the decomposition, its degradation efficiency of NO₂ increases gradually. The degradation efficiency of NO₂ exceeds 60% for both conditions when time extended to 120 mins. The more the spraying volume of modifiedemulsified asphalt, which means the amount of catalyst per unit area is increased, the higher the degradation efficiency of exhaust. However, too much spraying amount will cause the modified-emulsified asphalt to run away. Moreover, the usage of fog sealing could be closely bonded with the old pavement and make full use of the degradation efficiency of TiO₂. Therefore, in actual engineering, it is recommended to apply the fog sealing for construction.

3. Research on Field Test

The asphalt pavement covered with photocatalytic fog sealing for testifying the practical degradation efficiency of TiO_2 was laid on a section of Shanda Road in Jinan. A



FIGURE 1: Experimental setup. (a) Schematic representation of the experimental setup. (b) MOT100-NO $_X$ NO $_x$ detector.



FIGURE 2: (a) Normal specimens. (b) Specimens covered with fog sealing.



FIGURE 3: Degradation efficiency of NO_2 in the specimens with different amounts of TiO_2 .

comparative testing scheme was adopted in the field tests, by the approach of deploying the monitoring points at both the intersection and the middle part of Shanda Road. Monitoring systems, involving the H6-type air quality warning system and the LGH-1054-type dust online monitoring system, were placed in the corresponding sites to achieve real-time monitoring for air pollutants. These are on the basis of the specifications, such as Specification and Test Procedures for Ambient Air Quality Continuous Automated Monitoring System for SO₂, NO₂, O₃, and CO (HJ 654-2013) and Specification and Test Procedures for Ambient Air Quality Continuous Automated Monitoring System for PM10 and PM2.5 (HJ 653-2013). The on-site actual degradation efficiency of TiO₂ in asphalt pavement would be obtained by comparing the concentration of pollutants before with that after construction at each monitoring point.

3.1. Construction Program. To ensure the reliability of the subsequent comparison for indoor and outdoor measurements, raw materials used in the field test were consistent with the laboratory experiment, and the emulsion was prepared on site.

According to the mixture ratio of modified-emulsified asphalt examined from the laboratory test, nano-TiO₂, nanocalcium carbonate, zeolite, and PVP-3000 were added to the water tank containing the emulsifier in sequence [19, 20]. After thoroughly stirring for approximate an hour, the ultimate modified-emulsified asphalt would be used for fog sealing. Under the premise that the road surface was cleaned and the markings were well protected [21, 22], the modified-emulsified asphalt was sprayed with the volume range of 0.3 kg/m^2 to 0.5 kg/m^2 by the fog sealing truck. Figure 4 shows the construction site.

3.2. Results and Analysis of Field Tests

3.2.1. Clustering Analysis of Pollutant. The data obtained by the preconstruction site air quality monitoring are shown in Figure 5.

Figure 5 demonstrates that the concentrations of PM2.5 and PM10 experienced a similar variation trend, and other concentrations of pollutants also experienced similar variation trends. Thus, R-type cluster analysis, i.e., assemble similar variables and select representative variables, is conducted for PM2.5, PM10, SO₂, NO₂, CO₂, TVOC, O₃, and so forth. Figure 6 and Table 1 give the clustering results.

The similarity judgment is that two cases, whose approximations are close to one, could be seen as the same class. It is concluded that pollutants can be divided into four categories by this judgment and the above clustering results graph: PM2.5 and PM10 as a class, SO₂, CO, and TVOC as a class, NO₂ as a class, and O₃ as a class. Therefore, the seven variables are turned to four variables for analysis by dimension reduction. In order to further monitor by local environmental monitoring stations conveniently, PM2.5, SO₂, NO₂, and O₃ were selected as the four typical representative indicators for pollutants. Since the photocatalysts' function requires the stimulation of UV, with the

consideration that 11 am to 14 am is the time of the day when UV intensity is strongest, the effect of photocatalyst on the degradation of exhaust can be exerted effectively right at that time. Besides, the data in the middle-part of the road are more stable than the intersection. Therefore, only the four pollutants in the middle part of the road from 11 AM to 14 PM were analyzed in the following data processing.

3.2.2. Analysis of On-Site Pollutant Degradation Efficiency and Its Influencing Factors. The monitoring results of the air pollutants after construction are shown in Figure 7, and the degradation efficiency of field pollutants is shown in Figure 8.

As illustrated in Figure 7, the quantities of atmospheric pollutants after construction underwent an overall declination tendency with occasional fluctuations. This phenomenon is inseparable from the changes in the field environment. Figure 8 shows that the degradation efficiency of PM2.5 is as high as 83%, while that of others are about 22%–35%. According to the photocatalytic mechanism, SO₂, NO₂, O₃, and such components would be degraded into nontoxic substances under UV radiation [23]. The resultants could be adsorbed on the road surface because of the adsorption of calcium carbonate and zeolite powder. Consequently, the quantity of pollutants was declined, which is one of majority sources of PM2.5 [24]. With the reduction of vehicle exhaust, the amount of PM2.5 was significantly reduced.

According to the on-site monitoring data, the degradation efficiency of atmospheric pollutants is greatly influenced by the changes in the environment. Therefore, the factors affecting the degradation efficiency of TiO_2 within seven days after construction were analyzed. The corresponding on-site environmental situations and the strength division of UV are listed in Table 2. The strength division of UV can be obtained according to the UV index in the WMO (see in Table 3).

For simplicity, all environmental factors should be marked. First is the weather. Specifically speaking, sunny days, cloudy days, and light rain are labeled, respectively, from zero to two. The next factor is relative humidity. The average value of the relative humidity within seven days was reported to be 77% after construction. Herein, the relative humidity, lower than the average value, is defined as the low humidity with a mark of zero, while higher than the average value is defined as the high humidity and marked as one. Since the humidity in summer is above 70% in general and almost around 30% in the other three seasons, thus the low/ high humidity here is mainly associated with summer. The last factor is UV. When the UV is weak, it is marked as zero. By analogy, the UV intensity from the moderate level, strong, very strong, and extremely strong should be signed from one to four, respectively. The variation of NO₂ is taken as an example to analyze the measurement, and the results are shown in Figure 9.

Figure 9 presents that the UV intensity, temperature, and humidity have significant effects on the catalytic decomposition efficiency of TiO_2 . The higher the humidity, the



FIGURE 4: Construction field of fog sealing. (a) Fog sealing truck. (b) Postconstruction site.



FIGURE 5: The amount of pollution before construction.



FIGURE 6: Cluster results of pollution.

Case	PM2.5	PM10	SO ₂	NO_2	СО	O ₃	TVOC
PM2.5	1.000	0.999	0.407	0.435	0.524	-0.047	0.656
PM10	0.999	1.000	0.448	0.457	0.562	-0.070	0.690
SO ₂	0.407	0.448	1.000	0.773	0.978	-0.345	0.921
NO ₂	0.435	0.457	0.773	1.000	0.784	-0.112	0.637
CO	0.524	0.562	0.978	0.784	1.000	-0.399	0.953
O ₃	-0.047	-0.070	-0.345	-0.112	-0.399	1.000	-0.450
TVOC	0.656	0.690	0.921	0.637	0.953	-0.450	1.000

TABLE 1: Cluster approximation matrix of pollution



FIGURE 7: The amount of pollution after construction.



FIGURE 8: Degradation efficiency of TiO₂.

lower the concentration of NO_2 . This phenomenon could be ascribed to the reason that the hole electron pair generated by nano-TiO₂ can adsorb large amounts of water molecules, resulting in more production of anions and free radicals, which are characterized with the strong redox ability. Besides, the NO₂ concentration is much smaller on sunny days than on rainy days. This phenomenon is attributed to the fact that when the UV intensity is higher, nano-TiO₂ possesses a greater ability of generating hole electron pairs, and thus, the degradation efficiency of TiO₂ is higher [25].

TABLE 2: Environmental conditions within seven days after construction.

Time	Weather	Temperature (°C)	Relative humidity (%)	UV index	Grade of UV index
2020.06.27	Light rain	23-32	74	5	Strong
2020.06.28	Light rain	21-32	74	5	Strong
2020.06.29	Cloudy to sunny	23-33	74	11	Extremely strong
2020.06.30	Sunny to cloudy	24-33	75	9	Very strong
2020.07.01	Sunny	25-31	73	7	Very strong
2020.07.02	Light rain	24-32	81	1	Weak
2020.07.03	Cloudy to light rain	24-31	88	5	Strong

TABLE 3: Grade of UV inten	isitv
----------------------------	-------

UV index	0-2	3-4	5–6	7–9	>10
Grade of UV index	Weak	Moderate	Strong	Very strong	Extremely strong



FIGURE 9: Influence of various factors on NO_2 degradation efficiency. (a) Humidity and weather factors on NO_2 degradation efficiency. (b) Humidity and UV intensity factors on NO_2 degradation efficiency.

Therefore, in the routine application of photocatalytic fog sealing, much artificial measurements should be manipulated to compensate the lack of ultraviolet and low humidity. For example, hanging the UV lamps upon the head of street lights and sprinkling water regularly. Under the association with such artificial efforts, nano-TiO₂ would be stimulated to generate a large number of hole electron pairs and fully release its redox ability. As a consequence, the degradation efficiency of nano-TiO₂ could be improved.

To further study the effects of various factors on the degradation efficiency of nano-TiO₂ and verify the above conclusions, the linear regression equation of dependent variable Y on independent variable X was established. The amount of NO₂ should be treated as the dependent variable, while temperature, humidity, and UV intensity should be treated as the independent variables. Therefore, Y is the amount of NO₂, X_1 represents the weather, X_2 represents humidity, and X_3 represents UV intensity. The corresponding coefficients are listed in Table 4.

According to the correlation coefficients listed in Table 4, the multiple linear regression equation is obtained:

TABLE 4: Correlation coefficient of linear regression equation.

Coefficient								
	Unnormalized coefficient		Normalized coefficient		t	Significance		
	Beta	Stderr	Beta	Stderr				
Value	1.714	3.615			0.474	0.640		
Weather	10.086	2.016	1.746	0.349	5.003	0.000		
Humidity	-9.219	1.520	-0.902	0.149	-6.066	0.000		
UV	0.132	1.186	0.033	0.300	0.111	0.913		

$$Y = 10.086X_1 - 9.219X_2 + 0.132X_3 + 1.714.$$
(2)

The specific amount of pollutants and their degradation efficiency with the variation of the temperature, humidity, and UV intensity could be calculated via this formula. Also, the field environment could be adjusted through above artificial methods to meet the target value of degradation efficiency.

TABLE 5: Correlation coefficient of linear regression equation.

		0	m · ·			
Coefficient						
	Unnormalized coefficient		Normalized coefficient		t	Significance
	Beta	Stderr	Beta	Stderr		C C
Value	0.480	0.000				0.000
Degradation efficiency in the field	0.630	0.000	1.000			0.000

TABLE 6: Correlation coefficient of the linear regression equation.

Coefficient						
	Unnormalize	ed coefficient	Normalized coefficient		4	C:: C
	Beta	Stderr	Beta	Stderr	L	Significance
Value	-5.950	0.000				0.000
Degradation efficiency in the field	0.100	0.000	1.000			0.000

4. Comparative Analysis of Pollutant Degradation Efficiency in Two Different Environments

Equation (2) can control the degradation efficiency of pollutants in practical construction by changing the environment. However, the mixture proportion test and raw material performance test cannot be referred to in the laboratory test. Therefore, it is necessary to compare and analyze the deviation of pollutant degradation efficiency in two different environments. On the one hand, it can ensure construction quality. On the other hand, the degradation efficiency of atmospheric pollutants in the laboratory test and the spraying amount of fog sealing can be determined by controlling the degradation efficiency of pollutants in the field.

The results of the laboratory test and field test are shown, respectively, in Figures 3 and 8. The differences between the two cases can be obtained by comparing the monitoring results. When the spraying amount of modified-emulsified asphalt used as fog sealing is equal, the degradation efficiency of NO₂ in the laboratory test is far greater than it in the field testing. The former degradation efficiency is as high as 63.5% comparing to that of 25% under the harsh conditions in the field tests. The reason for the phenomenon is that the environment in the laboratory test is ideal, while the field test is eager to be influenced by multiple environmental factors. Thus, it can be found that the degradation efficiency of atmospheric pollutants in practical applications is at least 39% of the effect in the laboratory test. Regression analysis can be used to get the degradation efficiency of pollutants in laboratory tests from the target values in the field. The spraying amount of modified-emulsified asphalt can be obtained by the degradation efficiency of pollutants in laboratory tests. The degradation efficiency of NO₂ can be taken as an example.

The minimum degradation efficiency of NO_2 in the field is set as the independent variable, and the degradation efficiency in the laboratory test is the dependent variable. Therefore, the practical degradation efficiency of NO_2 is X value, and the degradation efficiency of NO_2 in the ideal condition is Y value. The deviation equations of degradation efficiency under the indoor and outdoor environment were established by regression analysis. The correlation coefficients are shown in Table 5.

The equation can be obtained by regression analysis which is as follows:

$$Y = 0.63X + 0.48. \tag{3}$$

The degradation efficiency of NO₂ in the laboratory test is set as the independent variable, and the spraying amount of modified-emulsified asphalt is the dependent variable. Therefore, the degradation efficiency of NO₂ in the laboratory test is set as the Y value, and the spraying amount of modified-emulsified asphalt is the Z value. The correlation coefficients obtained using regression analysis are shown in Table 6.

The equation can be obtained as follows:

$$Z = 0.1Y - 5.95. \tag{4}$$

According to equations (3) and (4), on the one hand, the minimum degradation efficiency of pollutants in the field test can be obtained by the spraying amount of the modifiedemulsified asphalt. On the other hand, the corresponding degradation efficiency in the laboratory test can be obtained by target values in the field test to test the mix proportioning design of modified-emulsified asphalt and raw material performance. The above formula could provide test indexes and standards for construction quality and lay the foundation for establishing an on-site construction quality control system.

5. Conclusions

A series of field tests are carried out, accompanied with laboratory experiments, to analyze and consequently compare the photocatalytic degradation efficiency of nanoscaled TiO_2 in the indoor and outdoor conditions, respectively. Based on the measurement data, the following conclusions can be drawn.

Firstly, laboratory experiments are carried out to determine the mixture proportion and optimal spraying amount of modified-emulsified asphalt applied as the fog sealing. Meanwhile, the results of laboratory experiments could provide the fundamental basis for the field test.

Second, in practical applications, the degradation efficiency of atmospheric pollutants is vulnerable to environmental factors such as temperature, humidity, and UV intensity. With the increment of the UV intensity and the growth of the humidness, the catalytic ability of the hole electron pairs generated by nano-TiO₂ becomes stronger, leading to the higher degradation efficiency of automobile exhaust. Through the linear regression analysis, the established regression equations is established, with the content of pollutants as the dependent variable and temperature, humidity, and UV intensity as the independent variables, thus to quantitatively study the influence of various factors on vehicle exhaust.

Third, the degradation efficiency of atmospheric pollutants in practical applications is only up to 39% of that in the laboratory test under the same spraying amount. The established degradation efficiency deviation equation based on this phenomenon could determine degradation efficiency in the laboratory test and the spraying amount of fog sealing could be obtained step by step, to satisfy the target of pollutant efficiency degradation in the field. Besides, it could examine the mix-proportion design of modified-emulsified asphalt and raw material performance for improving field construction quality.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References

- Y. Kuang, Z. Zhang, X. Ji, and X. Zhang, "Study on nano-TiO₂ photocatalytic cement paste with automobile exhaust degradation capacity," *Journal of Functional Materials*, vol. 48, no. 2, pp. 2241–2246, 2017.
- [2] S. Xu, S. Li, S. Li, Li Zhi, J. Li, and Y. Niu, "Development and evaluation of stabilizer for automobile exhaust gas degradation materials application in pavement," *China Journal of Highway and Transport*, vol. 32, no. 4, pp. 114–121, 2019.
- [3] L. W. Rui, G. Peng, W. Y. Hua, D. X. Qian, and X. S. Fa, "Automobile exhaust degradable asphalt mixture development and engineering application," *Bulletin of the Chinese Ceramic Society*, vol. 40, no. 4, pp. 1405–1412, 2021.
- [4] X. Du, H. Xu, Q. Guan, and X. Han, "Degradation efficiency of different density nano-TiO₂ on the factors of automotive emission," *Journal of Highway and Transportation Research and Development*, vol. 24, no. 10, pp. 155–158, 2007.

- [6] L. Wu, C. Hui, X. Li, and H. Chen, "Research progress of nano TiO₂ photocatalysis technology applied in ecological road," *New Chemical Materials*, vol. 47, no. 1, pp. 33–37, 2019.
- [7] Y. Tan, L. Li, W. Peng, and Z. Sun, "Application performance evaluation on material of automobile exhaust degradation in asphalt pavement," *China Journal of Highway and Transport*, vol. 23, no. 6, pp. 21–27, 2010.
- [8] P. Wu and X. Wang, "Purification performance of thin layer cover of TiO₂ modified asphalt," *Journal of Jiangsu University(Natural Science Edition)*, vol. 38, no. 1, pp. 113–118, 2017.
- [9] P. Sun, Research on Construction Quality Controling System of Asphalt Pavement Based on Key Indicators, TianJin university, Tianjin, China, 2012.
- [10] A. Hu and C. Tang, "Progress in Research of the nanosized TiO₂ photocatalytic materials and their application in environment protection," *Journal of Functional Materials*, no. 6, pp. 586–589, 2001.
- [11] S. Yan, F. Wang, F. Chi, and Y. Y. Wang, "Study on degradation efficiency of automobile exhaust by glass bead nano-TiO₂ composites," *Journal of Highway and Transportation Research and Development*, vol. 37, no. 6, pp. 138–144, 2020.
- [12] G. Chen, "A way to remove car exhaust gas-"eco-paint" will be available soon," *Light Vehicles*, vol. 82, no. 3, 2004.
- [13] H. Xin, "European scientists develop successful polysiloxane eco-coatings," *Silicone and Fluorine Information*, vol. 38, no. 5, 2005.
- [14] C. F. Xia, Y. Wang, Y. S. Jing, and C. Q. Ling, "Study on influence of nano-TiO₂ paving method on road performance of semi-flexible pavement," *Journal of China*, vol. 40, no. 6, pp. 58–61, 2020.
- [15] C. Yi, S. Tong, and M. Ge, "Heterogeneous reactions of NO2 on individual atmospheric particleby ramanmicro-spectrometry," *Spectroscopy and Spectral Analysis*, pp. 465-466, 2014.
- [16] L. Sun, H. Xu, J. Li, and L. Liu, "Research on treatment effects of nanometer titanium dioxide on automobile exhaust and application methods," *Journal of Highway and Transportation Research and Development*, vol. 28, no. 4, pp. 153–158, 2011.
- [17] G. Zhang, Y. Xu, W. Chen et al., "Experimental study on degradation efficiency of photocatalyst coating on permeable asphalt pavement against automobile exhaust," *Subgrade Engineering*, vol. 34, no. 5, pp. 89–93, 2019.
- [18] A.-A. Salarian, Z. Hami, N. Mirzaei et al., "N-doped TiO 2 nanosheets for photocatalytic degradation and mineralization of diazinon under simulated solar irradiation: optimization and modeling using a response surface methodology," *Journal* of Molecular Liquids, vol. 220, pp. 183–191, 2016.
- [19] J. Hui and H. Wu, An Apparatus for Determining the Permeability of Asphalt Mixes, 2020.
- [20] S. Wang, J. Liu, X. Zhao, and W. He, A Method for Preparing Color Micro-Surface Treatment Based on Titanium Dioxide Nanopaste, 2019.
- [21] J. Xu and Z. Wang, "Material characteristics and construction process of fog seal layer," *Advanced Material Industry*, vol. 15, no. 1, pp. 65–67, 2013.
- [22] W. Zhao, Q. T. Gui, W. F. Du et al., "Performance evaluation of mineral emulsified asphalt fog seal coating," *Material. Transport Research*, vol. 6, no. 5, pp. 45–51, 2020.

- [23] X. Zhou, "Application of nanomaterials in road base pavement," *China Highway*, vol. 9, no. 13, pp. 95–97, 2020.
- [24] Li Pei, Experimental Study on Nanometer Titanium Dioxide Coating of Environmental protection in City Road Application, Beijing Municipal Engineering Research Institute, Beijing, China, 2014.
- [25] L. Cheng-Hu, L. Rui-Yang, and Y. Ren, "Application of photocatalysis technology of nano-TiO₂ in asphalt pavement," *Transport Research*, vol. 1, no. 5, pp. 75–81, 2015.