https://doi.org/10.1016/j.wear.2017.04.004

Durability of Epoxy-Bonded TiO_2-Modified Aggregate As A Photocatalytic Coating Material for Asphalt Pavement Under Vehicle Tire Polishing

D. Wang[1], Z. Leng[2*1], M. Hüben[3], J. Kollmann[1], M. Oeser[1]

[1]Institut of Highway Engineering Aachen, RWTH Aachen, Germany

[2]Department of Civil and Environmental Engineering, Hong Kong Polytechnic University

[3]Fraunhofer-Institute for Molecular Biology and Applied Ecology, Germany

- **Abstract:** Within the scope of this study, a new method to construct air-purifying asphalt pavements coated with TiO_2 modified aggregate was developed and evaluated with regard to feasibility, performance and durability. Two methods, namely the surface coating method and the pore filling method, were adopted to produce the TiO_2 modified aggregate; their durability performances in terms of both photocatalytic efficiency and mechanical performance under vehicle tire polishing applied by the Aachen Polish Machine (APM) were investigated and compared. The test results of this study indicated that it is feasible to build durable photocatalytic pavements with the developed method and spreading materials designed in this study. Both TiO_2 modification methods provided spreading aggregate with excellent and comparable NO degradation rates before polishing. However, the pore filling method exhibited a better long-term NO degradation efficiency. Both method yielded

[1]Corresponding Author: Zhen Leng, PhD, Assistant Professor, Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, PN: (852)27666007

spreading aggregate with excellent long-term skid resistance and surface texture properties after vehicle tire polishing.

Keywords: environment-friendly road surface; photocatalytic activity; nitrogen dioxide, nitrogen oxides; titanium dioxide (TiO_2), wearing resistance

Highlights:

- A new approach to modify asphalt pavement with TiO_2 modified aggregate for air purifying purpose was developed.
- Aachen Polishing Machine equipped with real tires was used to simulate the vehicle tire polishing in the laboratory to evaluate the durability under traffic.
- Two methods, namely the surface coating and pore filling methods, were adopted to produce TiO2 modified aggregate.
- Both methods provided durable skid resistance and surface texture.
- Both methods provided satisfactory initial NO_x removal efficiency.
- The filling method provided better long-term NO_x removal efficiency.

1. Introduction

Roadside air pollution caused by automobile exhausts is a serious environmental concern, especially in urban cities with high traffic and population densities. Nitrogen oxides (NO_X), one of the most hazardous substances from vehicle emission, are harmful to both the atmospheric environment and human health. Conventionally, various measures such as using cleaner fuel and installing gas-cleaning equipment in vehicle exhaust systems have been implemented to counteract this issue by reducing the emissions from vehicle. Recently, studies have been conducted on photocatalytic pavements which have the capability of degrading NOx into harmless substances [1, 2, 3]. The air-purifying functionality of photocatalytic pavements is achieved by incorporating or coating the pavement with catalysts, in most cases titanium dioxide (TiO_2), which are capable of degrading nitric oxide (NO) and nitrogen dioxide (NO_2) under ultraviolet (UV) irradiation [2, 3, 4, 5]. Before being applied in photocatalytic pavement, TiO_2 had been used as a self-cleansing material in many fields due to its air purifying function [6, 7]. Under UV irradiation, TiO_2 generates powerful oxidizing agents, which have very the potent capability of oxidizing NO_X to nitric acid (HNO_3), which is the final product of the degradation process. Trace amounts of HNO_3 have limited effects on the pavement performance, and can be washed away by rainwater easily and without concern [4, 6, 7].

To achieve a satisfactory air-purifying performance, TiO_2 particles should be exposed to UV light and brought in direct contact with NO_X pollutants. Correspondingly, it is important for the coating materials of photocatalytic pavements to have sufficient contact area among TiO_2 particles, pollutants and sunlight and to have sufficient resistance against vehicle tire polishing. In addition, it is necessary to ensure that the incorporation of TiO_2 particles does not compromise the original mechanical performance of pavements, such as skid resistance and other mechanical properties related to wear due to traffic.

Currently, different methods have been attempted to apply TiO_2 particles onto both asphalt and concrete pavements, such as: a) mixing TiO_2 with water solution or asphalt emulsion and then spraying them onto road surface [3, 8], b) Using nano-TiO_2 particles as asphalt modifier [9, 10, 11], c) incorporating TiO_2 to crumb rubber surface and then spraying the TiO_2-crumb rubber mixture onto pavement surface during the construction process [12], and d) coating asphalt pavement surface with asphalt emulsion containing micro pores embedded with nano-TiO2 particles [13]. However, so far none of abovementioned methods provide a sufficient NO_X removal efficiency and durability allowing for a wider practical application.

In Germany, the process of bonding spreading aggregate to pavement surfaces with epoxy has been used as an effective treatment method to restore or improve the surface characteristics of pavements (Figure 1) [14]. This surface treatment method provides multiple beneficial functions, such as improving skid resistance, reducing traffic noise, and enhancing smoothness.

Inspired by this treatment method, this study aims to develop a new method to construct photocatalytic pavements by incorporating TiO_2 particles into the spreading aggregate. As this form of modification consists of applying TiO_2 modified material onto the surface of preexisting pavement surfaces it is of upmost importance to systematically evaluate the durability of spreading materials in terms of both photocatalytic functionality and mechanical properties under tire polishing. To achieve this objective, TiO_2 modified aggregates were prepared with two different processes, namely the surface coating method and the void filling method. The TiO_2 modified aggregates were then bonded onto asphalt pavement surface to provide the photocatalytic functionality in addition to other functions such as skid resistance etc.. Since there is no direct contact between TiO_2 and asphalt in these two methods, the asphalt surface is protected from the the photocatalytic processes. Moreover, a high durability of photocatalytic function is expected, because TiO_2 particles in the aggregate may keep rising even the aggregate particles are polished. To evaluate the durability and polishing resistance of the photocatalytic TiO2 modified aggregate layer, the unique custom-designed Aachen Polishing Machine (APM), was applied to simulate the vehicle tire polishing effect in the laboratory. The APM is equipped with real vehicle tires to enable a polishing simulation which represents conditions in reality very well. Both the NO_x degradation efficiencies and the skid resistances of the photocatalytic pavements prepared with the new approach before and after APM polishing were measured to evaluate and compare the performances of two methods aggregate modification with TiO_2.

2. Materials and Testing Program

2.1 Photocatalyst

The photocatalytic efficiency of TiO_2 modified materials is dependent on various factors, such as TiO_2 content, UV irradiation intensity, and TiO_2 type. In this study, an antase type TiO_2, labelled as VU7, was used, because previous studies have shown that VU7 provided the highest NO-decomposition rate among various common types of TiO_2 available in Germany [15, 16]. Some basic properties of VU7 are shown in Table 1.

2.2 Test sample preparation

2.2.1 Preparation of TiO_2 modified aggregate

In this study, the photocatalytic coating layer was prepared by spreading TiO_2-modified aggregate onto a thin layer of epoxy resin onto an asphalt pavement surface. As Figure 2 shows, two methods were adopted to prepare the TiO_2 modified aggregate, namely the surface coating method and pore filling method. In the surface coating method, the neat aggregate is mixed with cement, water and 4 M.-% TiO_2 in a rotating drum, leading to aggregate coated with TiO_2-cement film. In the pore filling method, a porous aggregate, basalt lava, which has a void content of approximately 25 Vol.%, was used. The basal lava aggregate was first submerged in a 4 M.-% TiO_2 cement suspension below atmospheric pressure for one hour to allow TiO2 cement to penetrate into the surface pores of the aggregate. Before complete curing of the cement mortar the excessive cement was manually removed from the aggregate surfaces by means of brushes, where after the aggregate was oven dried at 105°C until constant mass.

The different methods underwent systematic investigations with regard to their mechanical strength, polishing resistance and wear/abrasion resistance, confirming that the modified aggregate complies with the respective requirements as shown in **错误!未找到引用源。**. The impact crushing tests applies a defined crushing energy onto the unbound aggregate after which the sample is passed through five sieves with defined mesh sizes. The percentage value remaining on each mesh is calculated; finally, the impact crushing value is calculated as the average value remaining on each mesh. The impact crushing value should be below the threshold value of 18. The polished stone value (PSV) represents the polishing resistance of an aggregate and is required to be higher than 51. The Chipping due to Freeze-Thaw-Cycles (FTC) represents the resistance of aggregate towards freeze-thaw-cycles. After ten

FTC the mass loss is recorded and is required to be below 1 M.-% (F_1).

2.2.2 Coating asphalt pavement with TiO_2 modified aggregate

After the TiO2 modified aggregates were prepared, they were bonded onto asphalt pavement surface with an epoxy coating layer. A test section was built at the Institute of Highway Engineering at Aachen, Germany. The pavement was manufactured with a small paver and a rolling compactor so that the applied asphalt mixture and the given circumstances represent those encountered in practice as shown in Figure 2. Before spreading the TiO_2 modified aggregate, the asphalt pavement surface was coated with epoxy resin, on top of which the TiO_2-modified aggregate, 2 to 5mm in size, was spread and compacted. The amount of epoxy was determined so that the spreading material particles were embedded to half of the diameter of the largest grains. Finally, the excessive spreading material was swept away using a broom after the epoxy resin had hardened. Figure 3 illustrates the process of applying TiO_2-containing spreading material to the asphalt pavement surface.

2.3 **Testing program**

2.3.1 Measurement of NO_x degradation efficiency

As Figure shows, a test apparatus of the Fraunhofer Institute for Molecular Biology and Applied Ecology (IME) manufactured in accordance with ISO 22197-1 was used in this study to measure the NO_x degradation efficiency of the testing samples with the standard dimensions of 10 cm × 5 cm × 1 cm [17].

Before each test, the surface of the testing sample was first cleaned with a brush and water. Then, the sample was irradiated at an intensity of 700 W/m^2 for 1 hour and slowly shaken for 1 hour in ultra-high quality (UHQ) water. After drying for 1 hour at 60°C, the sample was stored in a dehydrator until the measurement was taken. Both the microscopic and macroscopic surface attachments were removed through this pre-treatment and the surface was transferred to a defined initial state.

A moisturized mixture of synthetic air and NO was then injected into the measurement cell holding the testing sample. The amount of NO was regulated so that a constant rate of 1 ppm was in the gas mixture. The volume flow was controlled at 1 L/min by a Fisher+Porter precision measuring tube. The relative humidity of the gas mixture was controlled between 50 and 60% during the test.

The measurement cell was irradiated and the NO content in the outflow gas mixture was continuously monitored according to the principle of chemiluminescence. During the radiation, the temperature was controlled between 25 and 30°C. As Figure 5 shows, the radiant energy of the xenon-lamp was 304 W/m^2 within the wavelength range of 290 to 800 nm. Within the wavelength range of 300 to 400 nm, which is relevant to the photo catalysis, the radiant energy was 46 W/m^2, which is comparable to the radiation intensity of the sun at mid-latitudes.

2.3.2 Simulation of long-term tire polishing

Continuous exposure to traffic in reality necessitates an assessment of the spreading material durability under vehicle tire polishing over the course of its lifetime. Therefore, in the test section described in Section 2.2.2, after the epoxy resin was completely cured, core samples with a diameter of 225 mm were extracted. These cores were then embedded into concrete plates and subjected to the polishing load applied by APM for 300 minutes, which represents the cumulative loading exerted by traffic over 8 to 15 years.

As Figure 7 shows, the APM applies shear stresses to the test plates by providing superimposed translational and rotational motion. The translational motion is achieved by a horizontally movable sled onto which the test plates are fixed, while the rotational motion is realized by rotating two polishing wheels around the vertical axis. The polishing tires have a pressure of 0.2 MPa and an imposed load of 200 kg. The sled moves back and forth horizontally 9 times per minute, while the tires spin 41 rotations per minute. The horizontal distance between the centers of the two tires is 55 cm; the velocity of the circular motion is therefore about 1.2 m/s. Such configuration allows the entire test plate subjected to an equal polishing effect. Since dust on the road consists of about 60 to 80 M.-% SiO_2 by [18], quartz powder was applied during the tests as a polishing agent. The polishing agent and water are spread evenly over the surface at a rate of 27±7 g/min. Based on the findings of the previous studies, a polishing duration of 300 min was selected, because the test samples will reach equilibrium after 300 min of polishing after which little or no changes would be observed by further polishing [19, 20].

2.3.3 Measurement of surface characteristics of aggregate coating layer

To evaluate the effect of polishing on the surface characteristics of the TiO_2 modified aggregate coating layer, the following tests were conducted: 1) the pendulum test (SRT) according to EN 13036-4 to measure the skid resistance (Figure 8a); 2) the Wehner/Schulze (PWS) test according to EN12697-49 to measure the dynamic skid resistance at 60km/h according to EN 12697-49 (Figure 8b); and 3) the outflow test according to EN 13036-3 to measure the horizontal drainage capability (Figure 8c).

3. Results and Discussion

3.1 NO degradation efficiency

Figure 9 presents the decomposing rates of NO for typical samples prepared by the surface coating and pore filling methods before polishing. As it shows, the initial NO decomposition rate was zero and increased sharply after UV irradiation was applied to the test sample. After around 10 minutes, an equilibrium state was reached inside the chamber, with an NO degradation rate of approximately 41.5% for both samples. It is evident that without tire polishing, both methods were effective in degrading NO; the difference in NO degradation efficiency between the two modification methods is very minor.

3.2 Durability/Polishing resistance of photocatalytic properties

The NO decomposition test results of the samples after polishing are shown in Figure 10. As expected, regardless of the TiO_2 modification methods, the 300-min APM polishing significantly reduced the NO-decomposition rates of both samples. For the samples prepared with the surface coating method and the pore filling methods, the NO decomposition rates dropped to approximately 10% and 15% respectively after polishing. The reduction is mainly due to the fact that continuous polishing removed part of the active TiO_2-modified mortar at the top surface of the aggregate. Between the two methods, the pore filling method exhibited a NO-decomposition rate 50 % higher than that of the surface coating method. The microscopies of the TiO_2 modified aggregates after polishing (Figure 11 and Figure 12) clearly show that there were many residual TiO_2 particles embedded in the pores of the polished basalt lava, which were not affected by the tyre polishing. These embedded TiO_2 particles contribute to the increased durability of the photocatalytic performance of the TiO_2 modified aggregate prepared with the pore filling method.

It is worth noting that 4 M.-% TiO_2 content was used in this study for all cement mortars. Previous studies conducted by the researchers of this study have shown that an increased content of the TiO_2 to 7 or 10 M.-% may further increase the NO-decomposition rates, while maintaining satisfactory mechanical performance of the aggregate [15]. This study has shown that applying spreading aggregate modified with cement mortar containing 4 M.-% TiO_2 is capable of reducing the total NO-emissions from traffic by 10% to 15 % under the most unfavourable polishing circumstances, which can already make significant contribution to the roadside air quality improvement and emission control.

3.3 Durability of mechanical properties

In addition to the NO decomposition efficiency, it is important to ensure the durability of the mechanical performance of the spreading aggregate.

Skid resistance tests were conducted on the modified spreading material to ensure that safety in traffic is not compromised due to the inevitable polishing process. However, the high abrasiveness of the spreading material prevented measurements with the SRT as well as the PWS as it severely wears and even damages the rubber on the measuring devices. The polishing process removes ragged edges and protrusions and consequently smoothens the micro texture leading to a decreased skid resistance.

As Table 6 shows, after the polishing under the most unfavourable circumstances, the SRT and PWS values of the samples prepared with both modification methods exceed the threshold values specified in the regulation of the German Road and Transportation

Research Association [25, 26], indicating durable and satisfactory skid resistance of the testing samples. These two tests represent the skid resistances of a testing surface at relatively low vehicle speed (SRT: approximately 10 km/h) and high vehicle speed (PWS: 60 km/h). The outflow test results show that the outflow times of samples prepared with both methods are 1 s, which is far below the maximum value of 30 s [25], implying sufficient surface texture depth after polishing. In summary, the post-polishing test results indicated that the spreading aggregate modified by both the surface coating and pore filling methods have excellent mechanical durability in terms of both skid resistance and surface texture depth.

4. Conclusions and Recommendations for Future Research

Within the scope of this study, a new method to construct air-purifying asphalt pavements with TiO_2 modified aggregate was developed and evaluated with regard to feasibility, performance and durability were evaluated. Two methods, namely the surface coating and pore filling methods, were adopted to modify aggregate, and their durability performances in terms of both photocatalytic efficiency and mechanical performance under vehicle tire polishing were investigated and compared. The following points summarize the major findings of this study:

- It is feasible to build durable photocatalytic pavement with the developed method and designed spreading material in this study.
- Both TiO_2 modification methods, i.e., the surface coating method and pore filling method, provided spreading aggregate with excellent NO degradation rates before polishing (both approximately 40%). However, the pore filling method provided a

better NO degradation efficiency after 300-min APM polishing (15% in compassion to 10% obtained with the coating method).

- Aggregate modified with both methods exhibit excellent long-term skid resistance and surface texture properties after vehicle tire polishing.
- Field testing indicated that the method allows for the surface treatment to be completed within a few hours, enabling early traffic opening and thereby reducing the limiting influence on traffic flow.

In future study, it is recommended to further optimize the TiO_2 composition so as to shift the photocatalytic effect to lower and more abundant frequencies (as opposed to UV) for an even higher NO decomposition rate. In addition, the feasibility of using synthetic aggregate, such as high strength ceramsite and blast furnace slag, as the spreading aggregate to carry TiO_2 cement mortar should also be investigated due to their high mechanical strength. Finally, life cycle cost analyses and environmental impact assessments should be conducted to quantify the sustainability of the method developed in this study.

5. Acknowledgement

The work underlying this project was carried out under FE 09.0146/2010/HRB on behalf of the Federal Ministry of Transport and Digital Infrastructure in Germany, represented by the Federal Highway Research Institute. The funding support of the Germany/Hong Kong Joint Research Scheme (G-PolyU506/15) is also highly appreciated.

6. References

[1] Ao, C. H., and Lee, S. C. Indoor air purification by photocatalyst TiO_2 immobilized on an activated carbon filter installed in an air cleaner. *Chemical engineering science*, Vol. 60, 2005, pp. 103-109.

[2] Ballari, M. M., and H. J. H. Brouwers. Full Scale Demonstration of Air-purifying Pavement. *Journal of Hazardous Materials*, Vol. 254, 2013, pp. 406-414.

[3] Chen, M., and Y. Liu. NO_X Removal from Vehicle Emissions by Functionality Surface of Asphalt Road. *Journal of Hazardous Materials*, Vol. 174, No. 1, 2010, pp. 375-379.

[4] Agrios, A.G., and P. Pichat. State of The Art and Perspectives on Materials and Applications of Photocatalysis over TiO_2. *Journal of Applied Electrochemistry*, Vol. 35, No.7, 2005, pp. 655-663.

[5] Zhao, J., and X. Yang. Photocatalytic Oxidation for Indoor Air Purification: A Literature Review. *Building and Environment*, Vol. 38, No. 5, 2003, pp. 645-654.

[6] Fujishima, A. Electrochemical Photolysis of Water at A Semiconductor Electrode. *Nature*, Vol. 238, 1978, pp. 37-38.

[7] Chen, M., and J. Chu, NOx photocatalytic degradation on active concrete road surface-From experiment to real-scale application, *Journal of Cleaner Production*. Vol.19, 2011, pp. 1266-1272.

[8] Brovelli, C. and Crispino, M. Photocatalytic suspension for road pavements: investigation on wearing and contaminant effects. *Journal of Materials in Civil Engineering*. Vol. 25, 2012, pp. 548-554.

[9] Hassan, M., L. N. Mohammad, S. Asadi, H. Dylla, and S. Cooper. Sustainable Photocatalytic Asphalt Pavements for Mitigation of Nitrogen Oxide and Sulfur Dioxide Vehicle Emissions. *Journal of Materials in Civil Engineering*, Vol. 25, No. 3, 2012, pp. 365-371.

[10] Hassan, M., H. Dylla, S. Asadi, L. N. Mohammad, and S. Cooper. Laboratory Evaluation of Environmental Performance of Photocatalytic Titanium Dioxide Warm-Mix Asphalt Pavements. *Journal of Materials in Civil Engineering*, Vol. 24, 2011, pp. 599-605.

[11] Mohammad, L., Hassan, M. and Cooper, S. Mechanical characteristics of asphaltic mixtures containing titanium-dioxide photocatalyst. *Journal of Testing and Evaluation*, Vol. 40 (6): 1-8.

[12] Liu, W., Wang, S., Zhang, J. and Fan, J. Photocatalytic degradation of vehicle exhausts on asphalt pavement by TiO2/rubber composite structure. *Construction and Building Materials*, Vol.81, 2015, pp: 224-232.

[13] Leng, Z., and H. Yu. A Novel Method of Coating Titanium Dioxide onto Asphalt Pavements Based on Breath Figure Process for Air-purifying Purpose. *Journal of Materials in Civil Engineering*, Vol. 28, No.5, 2015, 04015188.

[14] Wang, D., A. Schacht, X. Chen, P. Liu, M. Oeser, and B. Steinauer. Innovative Treatment to Winter Distresses Using a Prefabricated Rollable Pavement Based on a Textile-Reinforced Concrete. *Journal of Performance of Constructed Facilities*, 10.1061/(ASCE)CF.1943-5509.0000719 , C4014008, 2014.

[15] Wang, D., Leng, Z., Hüben, M., Oeser, M., & Steinauer, B.. Photocatalytic pavements with epoxy-bonded TiO_2-containing spreading material. *Construction and Building Materials*, Vol. 107, 2016, pp. 44-51.

[16] EN 196-1 (2005). Methods of Testing Cement - Part 1: Determination of Strength, 2005.

[17] ISO 22197-1. Fine Ceramics (Advanced Ceramics, Advanced Technical Ceramics) - Test Method for Air Purification Performance of Semiconducting Photocatalytic Materials - Part 1: Removal of Nitric Acid, 2008.

[18] Wang, D., A. Schacht, X. Chen, M. Oeser, and B. Steinauer. Machbarkeitsstudie für die innovative Bauweise "Vorgefertigte und aufrollbare Straße". *Bautechnik,* 90(10), 2013, pp. 614-621.

[19] Wang, D., X. Chen, C. Yin, H. Stanjek, M. Oeser, and B. Steinauer. Influence of Freeze-Thaw on the Polishing Resistance of Coarse Aggregates on Road Surface. *Construction and Building Materials,* 64, 2014, pp. 192–200.

[20] Wang, D., and X. Chen, C. Yin, M. Oeser, H. Stanjek, and B. Steinauer. Study of Micro-texture and Skid Resistance Change of Granite Slabs during the Polishing with the Aachen Polishing Machine. *Wear,* 318, 2014, pp. 1–11.

[21] EN 196-1 (2005). Methods of Testing Cement - Part 1: Determination of Strength, 2005.

[22] Wang, D., X. Chen, C. Yin, M. Oeser, and B. Steinauer. Influence of Different Polishing Conditions on the Skid Resistance Development of Asphalt Surface. *Wear,* 308, 2013, pp. 71-78.

[23] The Technical Delivery Terms for Aggregates in Road Construction (TL Gestein-StB 04), Edition 2004/Version 2007.

[24] EN 1097-2, Tests for Mechanical and Physical Properties of Aggregates – Part 2: Methods for the Determination of Resistance to Fragmentation, 2010.

[25] The Guideline for the Assessment of Road Skid Resistance in Wet Condition, German Road and Transportation Research Association, 2012.

[26] Huschek, S.: Die Griffigkeitsprognose mit der Verkehrssimulation nach Wehner/Schulze, Bitumen, S. 14-18, 01/200

List of Figures and Tables

Figures:

Tables:

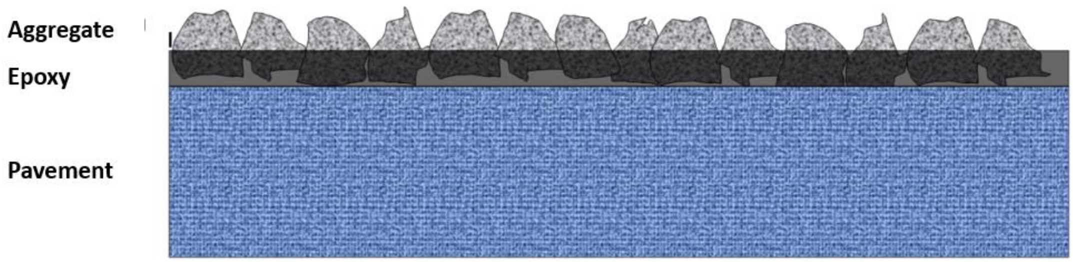

Figure 1: Surface treatment of asphalt pavement with epoxy-bound spreading material


(a) (b)

Figure 2: TiO_2 modified aggregate prepared by means of: (a) Coating method; (b) Filling method

(a) (b) (c)

Figure 2: Asphalt mixture paving of test section: (a) test section before asphalt paving; (b) paving of asphalt mixture; (c) compaction of asphalt mixture

(a) (b) (c)

Figure 3: Application of the epoxy resin and spreading material: (a) application of epoxy resin; (b) application of spreading materials and removal of excess aggregate; (c) final asphalt pavement surface treated with spreading material

(a) (b)

Figure 5: Measurement of NO degradation efficiency: (a) Sunset radiation apparatus and Horibo NO analyzer; (b) test specimen (10 cm × 5 cm × 1 cm)

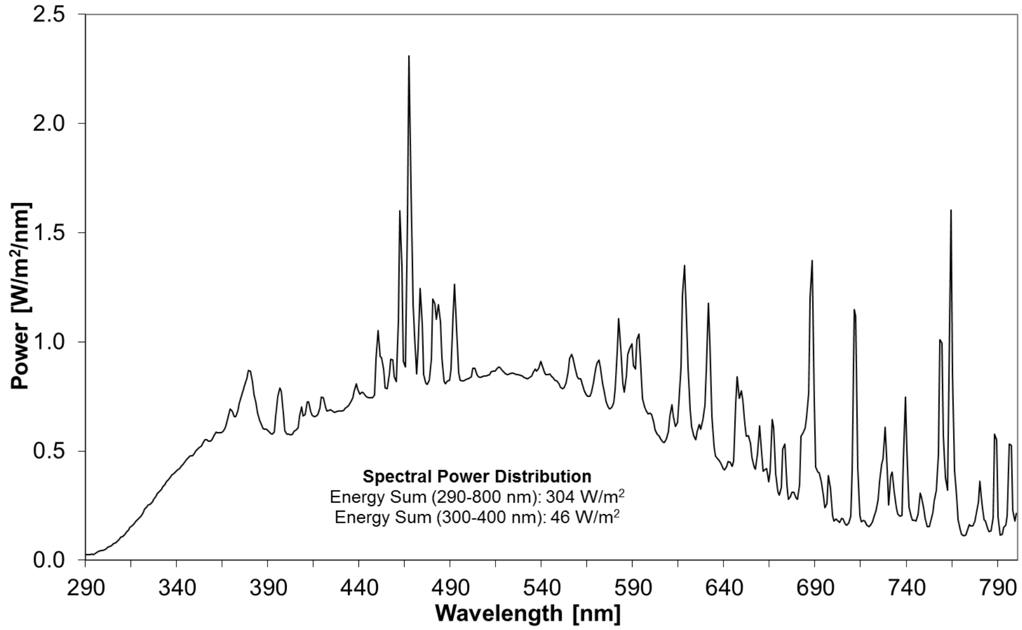

Figure 6: Spectral power distribution of the xenon-lamp light

Figure 7: Aachen polishing machine (APM)

(a) (b) (c)

Figure 8: Tests to measure surface characteristics of asphalt pavements with epoxy-bound spreading material: (a) Pendulum test; (b) W/S test; (c) Outflow test

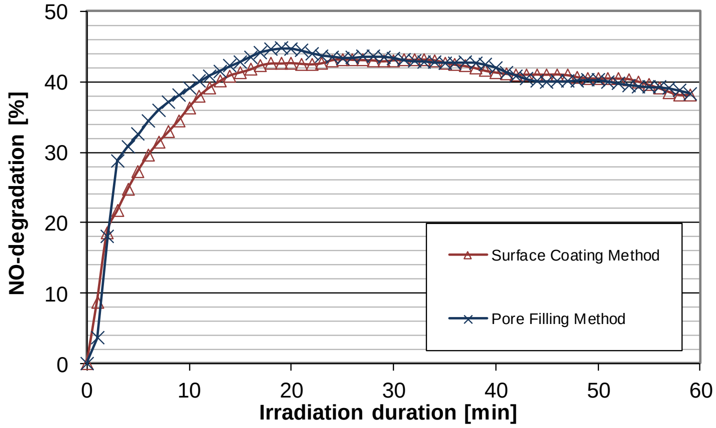

Figure 9 Reduction of nitric oxide before simulated polishing

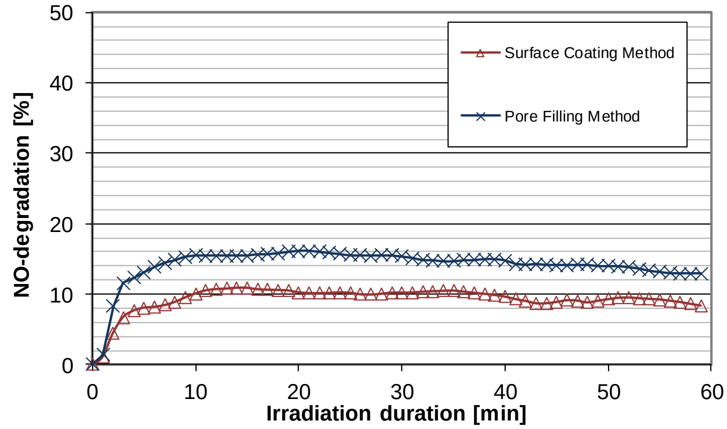

Figure 10: Reduction of nitric oxide after polishing

Figure 11: Polishing effect on TiO_2 modified aggregate (surface coating method): before (left) and after (right) polishing

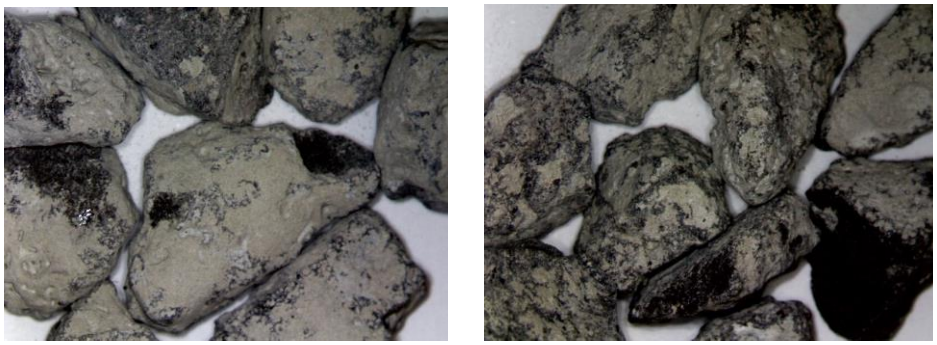

Figure 12: Polishing effect on TiO_2 modified aggregate (pore filling method): before (left) and after (right) polishing

Table 4: Basic properties of the selected TiO_2: Antanase

Label	Mineralogical Type	Grain Size (nm)	Surface Area (BET) (m2/g)	pH	TiO_2 content (M.-%)
VU7	Anatase	15	90	1.5	99

Table 5: Mechanical properties of spreading material and requirements

Requirements	Method 1	Method 2
Impact crushing according to DIN EN 1097-2 (reference value: SZ_{18})	11.5	17.8
Polished stone value (PSV) according to DIN EN 1097-8 (reference value: 51)	58	55
Chipping after freeze-thaw-cycling according to DIN EN 1367-1 (Reference value: F_1)	F_1	F_1

Table 6 Results of pendulum test, W/S test, and outflow test after 300 min polishing

Requirements	Method 1	Method 2
Pendulum Test (SRT) according to EN 13036-4 (>65)	65.4 (±0.3)	68.8 (±0.7)
Wehner/Schulze (PWS) according to EN 12697-49 (>0.45)	0.491	0.493
Outflow time according to EN 13036-3 (<30s)	1	1