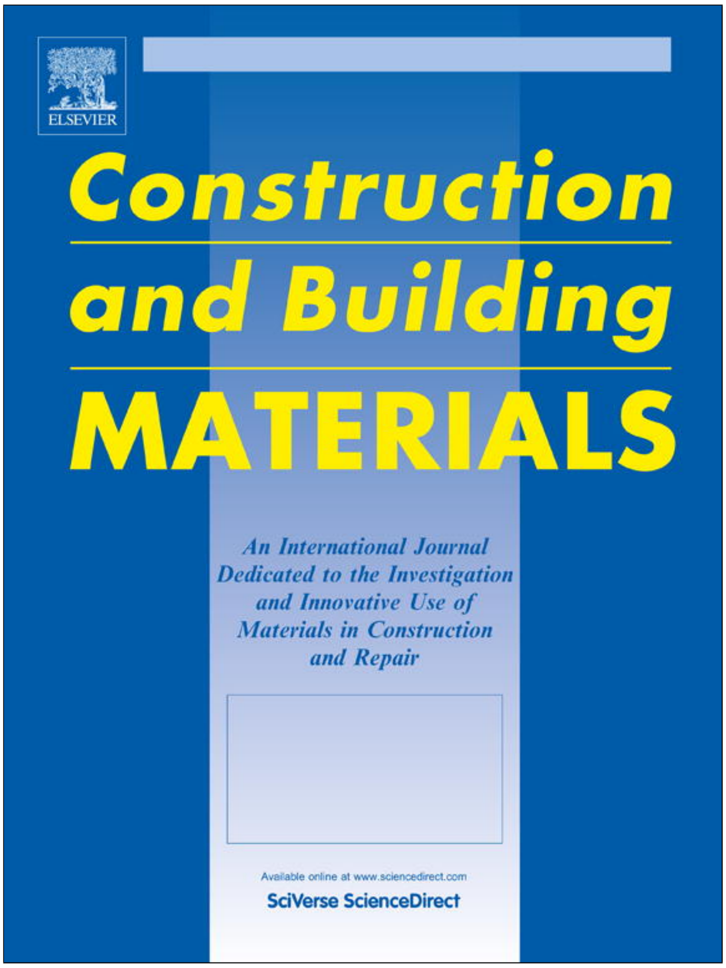
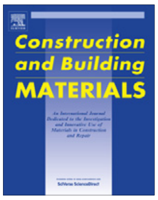


Construction and Building Materials 35 (2012) 874–883

Contents lists available at SciVerse ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat



Pervious concrete with titanium dioxide as a photocatalyst compound for a greener urban road environment

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HIGHLIGHTS

- ▶ Pervious concrete, surface treated with photocatalytic titanium dioxide, showed high pollutant removal efficiency.
- ▶ The photocatalytic effect on nitrogen oxide (NO) removal is more efficient than VOCs (toluene and trimethylbenzene) removal.
- ▶ The reduction of infiltration rates due to surface treatments can still satisfy the hydrological design standard.

ARTICLE INFO

Article history:
Received 11 December 2011
Received in revised form 17 April 2012
Accepted 29 April 2012

Keywords:
Pervious concrete
Photocatalyst
Titanium dioxide
Pollution
Environment

ABSTRACT

The United States is facing the problem of controlling air pollution from vehicle emissions, especially in growing urban areas. This study investigates the photocatalytic effect of titanium dioxide (TiO_2) applied onto pervious concrete pavement to remove some of these pollutants from the air, so that pervious concrete pavement can be installed for two sustainable applications: storm water management and air pollutant removal. The photocatalyst, TiO_2, activates with UV radiation to oxidize air pollutants, such as nitrogen oxides (NO_x) and volatile organic compounds (VOCs). This study compared different methods to apply TiO_2 onto the surface of pervious concrete and measured the photocatalytic activity of the concrete, the infiltrating characteristics of the pervious concrete, and its ability to withstand environmental impact. High pollutant reductions were seen with a driveway protector mix, a commercial water-based TiO_2 preparation, TiO_2 in water, a cement–water slurry with low cement concentration, and the commercial PURETI coating. It was found that nitrogen oxide (NO) was efficiently removed with each of these treatments, while VOCs displayed more variability in removal efficiency. Different coating methods can cause different degree of infiltration rate reduction depending on the specific design of coating materials while none of the application methods decreased the infiltration rates below levels applicable for standard hydrological design. When pervious concrete was compared to traditional concrete, pervious concrete showed higher NO reductions.

1. Introduction

The demand for pavement increases as cities grow. Though pavement may be beneficial for transportation, it can have negative impacts on the environment. Most pavements used are impermeable, resulting in more surface water runoff and less groundwater recharge. Effort has been put into reducing the impermeable surfaces of buildings by placing "green" roofs on them, but there are still parking lots, sidewalks, and miles of roadways that stretch throughout cities. Implementing permeable pavements whenever possible will have significant benefit to storm water management [1,2], reduced heat island effect [3,4], and reduced pavement noise due to traffic [3,5], hence, produce a more sustainable transportation environment in urban cities.

Emissions from vehicle traffic cause air pollutant problems throughout the world. There have been many attempts to reduce emissions, from encouragement of carpooling and public transportation to redesigning the vehicles themselves. However, there are still emissions polluting the air to a significant degree. The UK is currently facing a fine of $500 million for London exceeding the PM_{10} particle pollution limits more than 35 times for the entire year [6]. The PM_{10} particles are mainly from vehicles, factories, and construction. A London study found that a primary school near a high traffic street left the school children vulnerable to significant air pollution exposure [7]. The London study also confirmed the benefit of applying photocatalytic coating to materials on a large scale to reduce air pollution in urban areas.

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0950-0618/$ - see front matter Published by Elsevier Ltd.
http://dx.doi.org/10.1016/j.conbuildmat.2012.04.097

The photocatalyst, titanium dioxide (TiO_2), is a naturally occurring compound that can decompose gaseous pollutants with the presence of sunlight. Applying TiO_2 to pavement can help remove emission pollutants right next to the source, near the vehicles that drive on the pavement itself, although limitations of the practical application of such technology could exist. One of the limitations is that surface coatings to traditional pavements may lose their effectiveness due to surface wear. Pervious pavement provides a sustainable solution to address such limitation. The rougher surface and higher porosity of pervious pavement will retain more TiO_2 particles and contribute to better photocatalytic effect for air purification on sunny days. In addition, water will be infiltrated into underground system through the pervious structure of pavements for storm water management.

This paper therefore aims to identify the effectiveness of applying TiO_2 to the surface of pervious concrete pavement to produce a greener urban road environment. Several coating methods were compared for their influence on permeability, pollutant removal effectiveness and their resistance to outside environmental impacts.

2. Background

Literature reported that photocatalytic material can be activated by ultraviolet (UV) radiation ($\lambda < 390$ nm) to decompose organic materials like components of dirt (soot, grime, oil, and particulates), biological organisms (mold, algae, bacteria, and allergens), airborne pollutants (VOC, tobacco smoke, NO_x, and SO_x), and chemicals that cause odors [8]. The decomposition products are oxygen, carbon dioxide, water, sulfate, nitrate, and other inorganic molecules. Titanium dioxide (TiO_2) is one of the most popularly used photocatalyst which can be used in pavement engineering for reducing vehicle emission pollutants due to its many advantages. TiO_2 is relatively low cost, and has fast reaction at ambient operating conditions (room temperature, atmospheric pressure). When TiO_2, as a photocatalyst, is activated by UV light with a wavelength below 387 nm, a wide spectrum of organic contaminants can be converted to water and CO_2. During this process, no chemical reactants must be used and no side reactions are produced [9]. Fig. 1 illustrates the photocatalytic effect of TiO_2 on pavement in a transportation environment. Pollutants from vehicle exhaust adsorb to the pavement. The TiO_2 coating on the pavement surface activates with the ultraviolet sunlight to break down the pollutants. The final products are then desorbed from the pavement.

Photocatalytic materials can also be used for self-cleaning. When photocatalytic oxidation decomposes staining compounds that are absorbed on a surface, the surface is cleaned and converted into a highly hydrophilic state [10]. Stains on the TiO_2 treated hydrophilic surface can be washed away easily, having a self-cleaning function, as the water flushes between the stain and the hydrophilic TiO_2. Some successful examples are glasses, tiles, and concrete [11]. Photocatalytic concrete is starting to be used more in architectural and civil engineering projects in Europe and Asia as a self-cleaning material. Some benefits of photocatalytic concrete are that it decomposes chemicals that contribute to soiling and air pollution, keeps the concrete cleaner, and reflects much of the sun's heat and reduces heat gain because of its white color [8]. Commercial photocatalytic cement, TX Active, was developed by Italcementi, and has been used on buildings such as Paris' Charles de Gaulle Airport, Rome's Dives in Misericordia church, and Bordeaux's Hotel de Police.

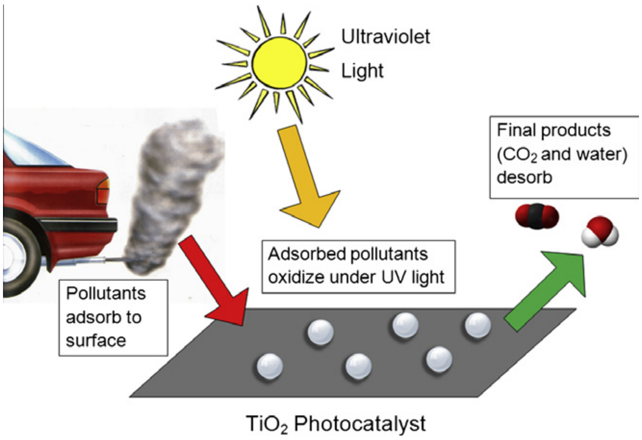

Fig. 1. Photocatalytic effect of titanium dioxide on pavement.

The performance of photocatalysis can be affected by environmental factors, such as light wavelength and intensity, relative humidity, temperature, and wind. The best results for the photocatalytic effect are with higher temperatures and light intensities greater than 300 nm [12]. Other factors that may affect the photocatalytic effect of TiO_2 when applied to concrete include porosity, aggregate type, aggregate size, application method, and applied wear. One study observed better retention of TiO_2 particles on the sample surface and a higher toluene removal efficiency when samples had higher porosity [13]. Higher humidity was reported to have lower efficiency in nitric oxide removal [14]. Coatings without fines were reported to have higher nitric oxide removal efficiency than coatings with fines [14]. As reported by Hassan et al. [15], because the weathering simulation exposed some of the TiO_2 particles embedded in the surface, applying the loaded-wheel test seemed to improve the nitric oxide removal efficiency [15]. Applying rotary abrasion seemed to decrease the nitric oxide removal efficiency.

Research is being conducted on finding application methods for TiO_2 to resist against traffic loading and natural weathering on pavements. A Louisiana study reported three different methods for applying TiO_2 to the surface of traditional concrete pavement [15]. They applied a cement–water coating with sand fines and TiO_2 nanomaterial (Cristal Millennium PC105), an ultra-thin water-based TiO_2 coating (PURETI), and sprinkled nano-sized TiO_2 particles to the fresh concrete surface prior to curing. The cement–water coating with 5% content of TiO_2 had the highest NO removal, producing 26.9% efficiency of NO removal before applied abrasion, and maintaining above 20% efficiency of NO removal after rotary abrasion and loaded-wheel tests. The NO removal was tested for 5 h using an environmental setup with room temperature, 50% humidity, fluorescent lamps, a flow rate of 9 L/min, and an initial NO concentration of 410 ppb.

In Hong Kong, TiO_2 coated concrete paving blocks were exposed to environmental conditions for 4 months and 12 months at 5 different pedestrian roads [16]. The photocatalytic activity of the TiO_2-coated paving blocks decreased in heavy pedestrian traffic areas, as contaminants accumulated on the surface [16]. The non-pedestrian areas did not significantly affect the NO_x removal activity of the paving blocks. Washing the blocks with water did not fully recover the photocatalytic activity. Reactive surface area was lost from the accumulation of dust, dirt, oil, grease, and even discarded chewing gum [16].

Most existing studies have focused on applying TiO_2 on non-pervious pavements. This places some challenges in improving the photocatalytic effect due to several reasons. Since direct interaction of TiO_2 with UV light is very critical, mixing TiO_2 into traditional concrete can only have limited NO_x reduction effectiveness at the air/solid interface. The process was observed to improve after the concrete material was abraded (some cement paste was peeled off and more TiO_2 was exposed at the surface) [15]. The durability of the photocatalytic effect becomes another challenge if TiO_2 is applied to highly trafficked highways through surface material adhesion. The dynamic tire-pavement interaction under shear and abrasion impact can dislodge coated TiO_2 particles at the surface, leaving untreated pavements.

To maximize the effect of air purification in pavements through the TiO_2 photocatalytic reaction, coating TiO_2 on the substrate of pervious concrete could have a number of benefits. As compared to traditional concrete pavements which have low porosities and relatively smooth surface textures, pervious concrete pavements have much higher porosities and rougher surface features. The higher void ratio and the increased concave surface texture (due to surface voids) with more surface area could enhance the bonding and durability of the applied TiO_2 at the surface, reduce impacts due to traffic abrasion and climate (snow, ice, water, heat, etc.), and increase the direct contact between TiO_2 and natural light. At the same time, pervious concrete pavement allows water to infiltrate completely through it so that rainwater can filter into the ground and replenish groundwater resources [3]. Pervious concrete will also not have a significant contribution to the urban heat island effect like traditional non-pervious pavements do [4]. Installing pervious concrete may reduce costs in installing drainage and stormwater systems, reduce the urban heat island effect and noise, improve roadway skid resistance, and prevent hydroplaning. In summary, TiO_2 treated pervious concrete pavement can be widely used for pedestrian sidewalks, bike lanes, parking lots, roadway shoulders, and urban low traffic streets for its stormwater benefits and air quality purification, resulting in a greener urban living environment.

3. Research objective and scope

The objective of this study is to evaluate the effectiveness of TiO_2 treated pervious concrete by comparing different TiO_2 application methods for their capability of pollutant reduction, maintaining the infiltrating characteristic of the pervious concrete, and withstanding environmental damage. A laboratory environmental setup was used to evaluate the pollutant removal efficiency due to the photocatalytic effect of the TiO_2. Since a major focus of this application is in the transportation environment, three different gaseous pollutants that present significant levels in automobile exhaust were tested: toluene, trimethylbenzene, and NO. Infiltration was tested to ensure the surface treatments did not reduce the infiltrating characteristic of the pervious concrete. The material's durability to outside environmental impact is also evaluated.

The desired end result is to find a TiO_2 surface treatment that would work effectively at removing pollutants from the air, while using the least amount of TiO_2 as possible to reduce costs and make this application possible in the field. Several TiO_2 concentrations were tried with different surface treatment methods, from 1 g to 140 g of TiO_2 used per 465 cm^2 of surface treatment area. Because 4 g of TiO_2 per 465 cm^2 surface area (86.1 g/m^2) worked effectively at removing pollutants (over 90% of TMB mixing ratio reduction) for several treatment methods, this rate was used in the final evaluation of treatments discussed in this paper.

4. Substrate sample preparation

Pervious concrete samples were made using No. 4 sieve size (4.75 mm) narrowly graded aggregates, Type I Portland cement, and a water–cement ratio of 0.29, to a target porosity of 25%. The water–cement ratio was chosen based on the recommendation from ACI 522 [17]. Blocks made out of concrete were used as forms for top compaction. To compact, these compactor forms were placed on top of each sample that was freshly poured into the mold and were tapped from the top with a rubber mallet hammer. The samples were covered and left to cure for 7 days. One traditional (non-pervious) concrete sample was prepared as a control sample, with a water–cement ratio of 0.48. Each sample was approximately 12 in. long, 6 in. wide, and 2 in. thick (304.8 mm × 152.4 mm × 50.8 mm).

4.1. Porosity of substrates

The porosities (P) of the samples were calculated from the measured dry mass (W_d) and submerged mass (W_s) for each sample. Shown below is the relationship used to calculate porosity, where ρ_w and V_t are the density of water and total volume of sample respectively [18].

$$P(\%) = \left(1 - \frac{\frac{W_d - W_s}{\rho_w}}{V_t}\right) \times 100 \tag{1}$$

All samples used in this study were fairly consistent with porosity, ranging from 24.23% to 26.10%, with an average of 25.13%.

5. Surface applications

5.1. Application methods

Ultra-fine (nano-scale) titanium dioxide PC105 (Anatase) supplied by Cristal Global was used in this study for surface treatment except otherwise noted. In other words, except for the commercial water-based TiO_2 and the Pureti product, all other application methods are based on PC 105 TiO_2. In total, eight application methods were evaluated in this study, which include:

1. C**ommercial water-based TiO_2 (CWB)**: it consisted of Cristal Global's S5-300B commercial water-based TiO_2 brushed onto the surface of pervious concrete.
2. **Cement–water slurry high (CWSH)**: it consisted of cement, water, and TiO_2 uniformly mixed together and brushed onto the surface of pervious concrete. The slurry was relatively thick compared to method 3.
3. **Cement–water slurry low (CWSL)**: it consisted of a thin slurry with low cement concentration and TiO_2 uniformly mixed together and brushed onto the surface of pervious concrete. The coating was brushed on with one or two coatings, just to cover the surface. This coating did not seem to clog as many pores method 2 did.
4. **Driveway protector mix (DPM):** it consisted of a transparent liquid driveway protector (siliconate, water-based concrete sealer) and TiO_2 uniformly mixed together and brushed onto the surface of pervious concrete.
5. **TiO_2 in water (TIW):** it consisted of water and TiO_2 uniformly mixed together and brushed onto the surface of pervious concrete.
6. **PURETI (PUR):** it consisted of the PURETI commercial water-based TiO_2 applied to the surface with a special electrostatic sprayer by the PURETI producer.
7. C**ement/aggregate mix (CAM):** it was a thin layer of pervious concrete with finer aggregate size and TiO_2 mixed in. This could be used as a special application when surface maintenance is needed for pervious concrete.
8. C**ement/aggregate mix with higher TiO_2 concentration (CAMH)**: it was the same application method as method 7 but with higher TiO_2 concentration.

For each application method, two specimens were prepared and tested. In addition, three types of control specimens were included in the testing plan. They included: plain pervious concrete with no

TiO_2 (PPC), plain traditional concrete with no TiO_2 (PTC), and traditional concrete coated with the CWSH method (TCC). The selection of the CWSH coating method for traditional concrete was to compare the results with literature. Except for the CWB, PUR, and CAMH application methods, all methods maintained the same TiO_2 rate of 0.06 g/in.^{2} (8.61×10^{-5} g/mm^2). Table 1 summarizes the proportions of the materials used for each application method. Fig. 2 shows an example of some TiO_2 coated samples.

5.2. Infiltration rate

Infiltration characteristics of pervious concrete were determined before and after the surface coating applications. Non-pervious concrete in general could not infiltrate water, so it was not tested for infiltration. The test followed standard ASTM C1701 (2009), but applied to the smaller scale samples by using a smaller 4-inch diameter pipe. The pipe was attached to the sample surface using plumber's putty at two locations, centered at 3 in. (76.2 mm) from the left and right sides of the sample. 2000 mL of water was poured through the pipe and timed. Each side (left and right) of each sample was tested 3 times and the overall average for each sample was calculated. The infiltration rate was calculated as shown in Eq. (2), where d is the diameter of the pipe and t is the infiltration time.

$$Infiltration\ rate = \frac{\left(\frac{volume\ of\ water\ infiltrated}{area\ of\ surface\ infiltrated\ through}\right)}{time\ to\ fully\ infiltrate} = \frac{\left(\frac{2000mL}{\frac{\pi}{4}d^2}\right)}{t} \qquad (2)$$

Two samples per type of surface coating were tested, and the average infiltration rates before and after applied surface coatings are shown in Table 2. It should be noted that the TIW method was not tested for infiltration because the coating would come off with the touch of a hand and could wash off with water. Also, no infiltration test was performed on non-pervious concrete sample.

After TiO_2 surface treatments were applied, all samples except for the two cement/aggregate mixes (CAM and CAMH) had noticeable, but not significant decreases in infiltration rates. The CAM and CAMH samples both did not change significantly in infiltration rate. The cement–water slurries, CWSH and CWSL, changed the most, and CWB, DPM, and PUR each had less than 30% decrease in infiltration rate. It should be noted that all infiltration rates after surface coating are more than sufficient for hydrological designs of pervious concrete systems [19]. In practice, flow rates for water through pervious concrete are typically 480 in./hr (3.4 mm/s) [20]. All samples in this study had higher infiltration rates than this even after surface treatments.

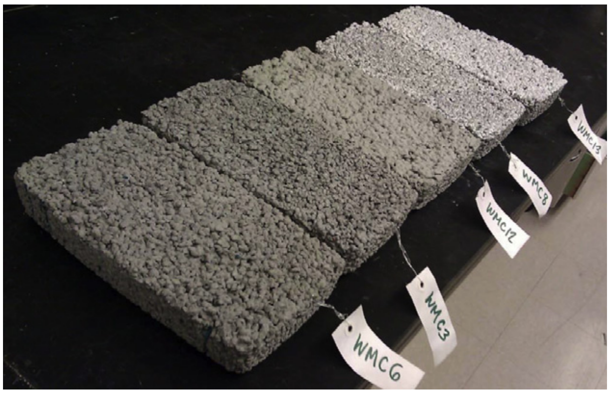

Fig. 2. TiO_2 coated pervious concrete samples.

Table 2
Infiltration rates before and after surface coating applications.

Sample	Before surface application avg. infilt. rate (mm/s)	After surface application avg. infilt. rate (mm/s)	Decrease in infiltration rate (%)
CWB	15.40 ± 0.49	12.23 ± 1.00	20.60
CWSH	18.27 ± 3.28	7.62 ± 0.01	58.29
CWSL	17.40 ± 3.09	8.44 ± 3.08	51.50
DPM	16.76 ± 3.95	11.65 ± 4.03	30.49
PUR	15.70 ± 2.59	13.83 ± 2.92	11.92
CAM	14.75 ± 0.99	14.19 ± 1.25	3.85
CAMH	9.07 ± 1.44	9.39 ± 0.63	−3.49*
PPC	15.77 ± 1.46	–	–

– This data is not applicable.

* Implying no infiltration change. The negative value could be due to testing variations.

6. Environmental test

6.1. Environmental system setup

A laboratory environmental system was used to evaluate the pollutant removal efficiency due to the photocatalytic effect of the TiO_2. The setup included a 150 L Teflon chamber maintaining 75 °F (23.89 °C) temperature and 25% humidity, two small fans inside for uniform mixing, and six 25 W black lights. Inside the chamber, the sample surface sat about 16 in. (406.4 mm) below

Table 1
Summary of surface treatment material details.

Surface treatment type	Ultra-fine TiO_2 (g)	Surface material contents (% of surface coating by weight)					
		Ultra-fine TiO_2 (%)	Cement (%)	Water (%)	Aggregate (%)	Driveway protector (%)	Commercial water-based TiO_2 (%)
PPC	0	0	0	0	0	0	0
PUR		(treatment applied commercially)					
CWB	0	0	0	0	0	0	100.00
PPC	0	0	0	0	0	0	0
DPM	4	14.29	0	0	0	85.71	0
TIW*	4	11.76	0	88.24	0	0	0
CWSL*	4	9.82	9.82	80.37	0	0	0
CAM	4	0.46	17.67	9.23	72.65	0	0
CWSH	4	5.01	49.99	45.00	0	0	0
CAMH	10	1.15	17.18	9.59	72.09	0	0
PTC	0	0	0	0	0	0	0
TCC**	4	5.01	49.99	45.00	0	0	0

* The TIW coating was later washed off and replaced with CWSL coating.

** The traditional concrete control was later coated with CWSH method, making it become TCC.

the chamber lights. The irradiance of the lights were measured and compared to the solar irradiance on the roof in October and November (Fig. 3). The 25 W lights were within the wavelength region (below 387 nm) where TiO_2 is photoactive. Most of the 25 W lights output wavelength was between 300 and 400 nm. The irradiance of the 25 W lights was approximately 6.11 W/m^2, comparable to a cloudy fall day in Pullman, Washington.

Three different gaseous pollutants that are present in automobile exhaust, toluene, trimethylbenzene (TMB) and nitrogen oxide (NO), were tested. Fig. 4a shows the chamber setup for the toluene and TMB pollutants. The chamber was a static set-up with average initial mixing ratios of approximately 43 and 35 parts per billion by volume (ppbV) mixing for toluene and TMB respectively. Toluene and TMB were injected from a syringe pump at a controlled flow rate and the dispensed liquid evaporated under a flow of warm clean air (17 SLPM) produced by an AADCO zero air generator. The mixture flowed through the environmental chamber. When the desired concentrations were reached, the flow into the chamber was closed off, the UV lights were turned on, and the reductions in VOCs were measured by a Proton Transfer Reaction Mass Spectrometer (PTR-MS). The PTR-MS periodically sampled from the chamber over time, drawing ~ 100 mL of air from the chamber with each sampling.

The NO pollutant measurement used a flow-through experiment (Fig. 4b). The average initial concentration of NO was approximately 410 ppbv and the air flow rate was 17 L/min. NO from a compressed gas cylinder (Scott Marrin Inc.) containing 500 ppmv of NO was diluted to 410 ppbv using mass flow controllers. The air flowed continuously through the chamber and NO was measured at the chamber exit. When the steady-state concentration of NO was reached, the UV lights were turned on and the reduction in the pollutant concentration was measured by the TECO NO_x analyzer.

6.2. Environmental test results

A summary table of the environmental chamber results for each surface coating type before any applied abrasive effects is shown in Table 3. Also indicated in Table 3 is the detail information about the TiO_2 concentration rate for each application method, for comparison purpose. Note that the results shown for the pervious concrete samples are an average of at least two samples tested per surface coating type. Fig. 5 shows the graphical results of toluene and TMB. Fig. 6 shows the graphical results of NO. Because the NO was applied as a flow-through experiment, a relationship was found to convert the flow-through data into static data so that the results can be directly compared to the toluene and TMB data which were measured under static conditions. The toluene, TMB, and NO data are compared side-by-side in the summary Table 3. A flow-through chamber at steady-state concentration has the relationship in Eq. (3), where $C(t=\infty)$ is the concentration at steady state, C_{in} is the initial ambient concentration, n is the exchange rate (air flow rate per volume), and k is the decay rate due to chemical oxidation (h^{-1}).

$$C(t=\infty) = \left[\frac{C_{in}n}{n+k}\right] \tag{3}$$

The equation for describing the rate of change in the static experiments is stated in Eq. (4), where $C(t)$ is the chamber concentration at time t, C_0 is the initial chamber concentration, and k is the same decay rate, as found in the flow-through relationship.

$$C(t) = C_0 e^{-kt} \tag{4}$$

The chamber results for each of the three pollutant types, toluene, TMB, and NO, are presented in terms of percent reduction of the pollutant, calculated using Eq. (5), where X is the measured molar mixing ratio in units of parts per billion by volume (ppbV).

$$\%\ Reduction = \left(\frac{X_{final} - X_{initial}}{X_{initial}}\right) * 100\% \tag{5}$$

When observing the removal efficiency of different pollutants due to photocatalytic TiO_2, as shown in Figs. 5 and 6, for most surface treatment methods, NO was removed most effectively followed by TMB and then toluene. For example, for CWB and PUR applications, NO reduction reached over 95% in less than half an hour, while only 62% and 45% Toluene reduction were achieved in 120 min, for CWB and PUR respectively.

Several surface treatment methods showed significant pollutant reduction, among which CWB, DPM, TIW, CWSL, and PUR were the highest with over 89% for TMB reduction and over 95% for NO reduction (static). There was not one method that had the highest reduction in all pollutants simultaneously; some methods reacted better with certain pollutants than others. DPM showed the highest static NO reduction, CWSL showed the highest static TMB reduction, and TIW showed the highest static toluene reduction. Further testing with TIW was stopped, as the coating would not stick well to the surface and would come off with the touch of a hand.

When pervious concrete was compared to traditional concrete, the pervious concrete showed higher static NO reductions, whether the sample had TiO_2 coating on it or not. When samples had a cement-slurry coating of 5% TiO_2, the pervious concrete (CWSH) showed 85.0% static NO reduction, while traditional concrete (TCC) showed 42.2% static NO reduction. Plain pervious

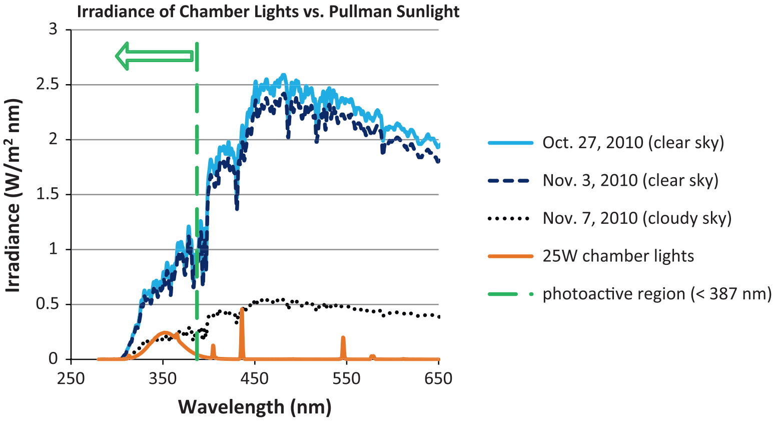

Fig. 3. Comparison of the six environmental chamber 25 W black lights and Pullman, WA fall solar irradiances.

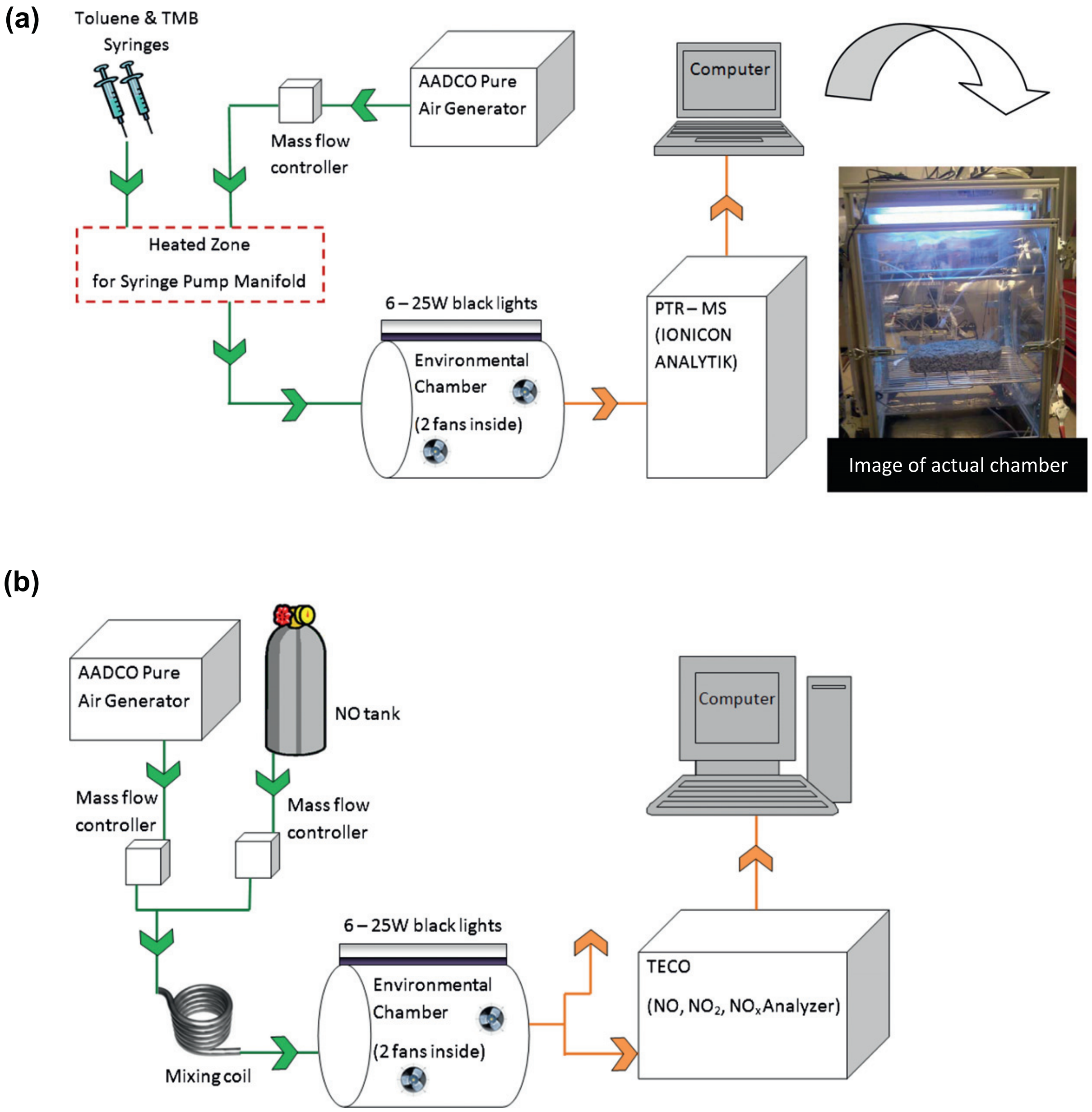

Fig. 4. Environmental chamber set-up for (a) Toluene and TMB injection and (b) NO injection.

concrete (PPC) showed a static NO reduction of 8.3%, while plain traditional concrete (PTC) showed a static NO reduction of 5.4%. Part of the reason could be attributed to photocatalytic compounds that may originally exist in the concrete such as zinc oxide (ZnO). Pervious concrete performed better than traditional concrete most likely due to the increased surface areas of its high porosity material structure. Further research is needed to confirm this hypothesis.

6.3. Effect of TiO_2 concentration rate on photocatalytic reaction

Because the driveway protector mix (DPM) treatment method showed promising results in reducing the pollutants in the environmental chamber and is easy for field application, four more samples with this method were prepared to compare the DPM's effectiveness at 5%, 10%, 15%, and 18% concentration of TiO_2. The original DPM that was first tested on the final-evaluation samples had 14.29% TiO_2. Fig. 7 shows the NO converted-to-static chamber results for the different DPM concentrations. As shown, the results for the different TiO_2 concentrations of DPM treatment were not too different, as they all produced between 94% and 98% NO reduction for a 30 min reaction time. This shows that the DPM treatment could still be effective with a smaller amount of TiO_2 as low as 5% by weight of the driveway protector mix, which will save in material costs for the TiO_2.

7. Durability of the surface application methods

To observe the effects of environmental impact on the surface coatings, the other set of final-evaluation samples with the treatments, CWB, CWSH, CWSL, DPM, PUR, CAM, CAMH, and PPC, was placed outside to have actual weather exposure (an outside durability test). The samples sat outside for the entire summer in Pullman, Washington from May 13, 2011 to September 21, 2011. They endured temperatures ranging from 98 °F to 33 °F and precipitation from 0 to 0.77 in. Fig. 8 shows

Table 3
Summary of environmental chamber results before weathering.

Sample	TiO_2 (g/mm^2)	% of surface coating that is TiO_2	Static chamber (120 min)		Flow-through chamber (29.83 min) total% NO reduction	NO decay rate, *k* (1/hr)	Converted static chamber (29.83 min) total% NO reduction (%)
			Total% toluene reduction	Total% TMB reduction			
Empty	chamber	–	–	2.48	12.35	1.38	0.09
4.61							
PPC	–	–	15.06 ± 0.28	29.86 ± 8.83	2.51 ± 0.19	0.17	8.31
PTC	–	–	–	–	1.61	0.111	5.37
TCC	8.61×10^{-5}	5.01	–	–	13.95	1.102	42.19
CWB	5.27×10^{-4} (water-based TiO_2)	100 (water-based TiO_2)	61.86 ± 14.06	94.64 ± 1.85	52.46 ± 2.07	7.50	97.59
CWSH	8.61×10^{-5}	5.01	13.23 ± 1.62	81.65 ± 1.50	35.97 ± 1.64	3.82	85.04
CWSL	8.61×10^{-5}	9.82	78.82 ± 9.22	97.26 ± 0.63	50.79 ± 0.49	7.01	96.94
DPM	8.61×10^{-5}	14.29	61.65 ± 10.77	93.87 ± 1.09	53.27 ± 3.63	7.79	97.92
TIW	8.61×10^{-5}	11.76	91.98 ± 3.08	96.34 ± 1.08	51.30 ± 2.43	7.15	97.14
PUR	2.02×10^{-6}	–	43.42 ± 1.79	89.50 ± 4.05	48.29 ± 3.13	6.37	95.79
CAM	8.61×10^{-5}	0.46	21.62 ± 4.30	68.28 ± 5.99	19.11 ± 3.46	1.62	55.35
CAMH	2.17×10^{-4}	1.15	–	–	32.97 ± 1.73	3.34	81.03

– This data is not applicable or is unavailable.

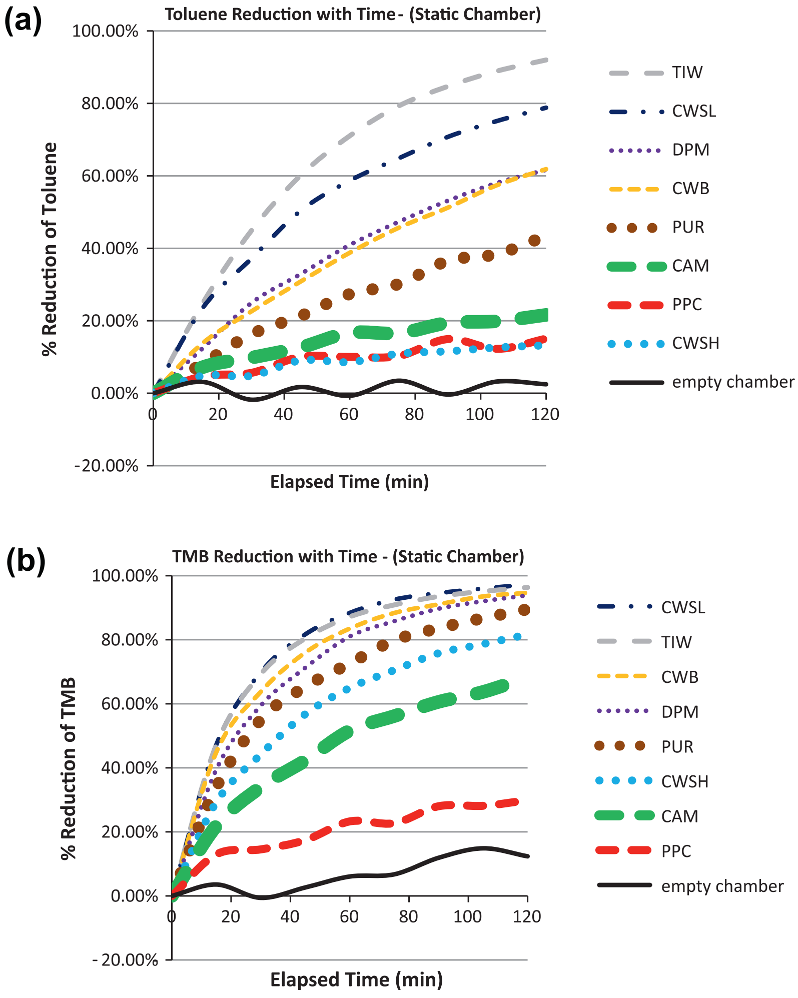

Fig. 5. Environmental chamber results for static chamber reduction in (a) Toluene and (b) TMB before weathering.

the NO converted-to-static chamber results for the samples before weathering, after 3 months of weathering, after 4 months of weathering, and after they had been washed with a soft bristle brush and water after 4 months of weathering. Regular tap water was used to simulate practical engineering process of washing.

All samples showed significant decrease in their NO% reductions after weathering. Most samples showed improvement after

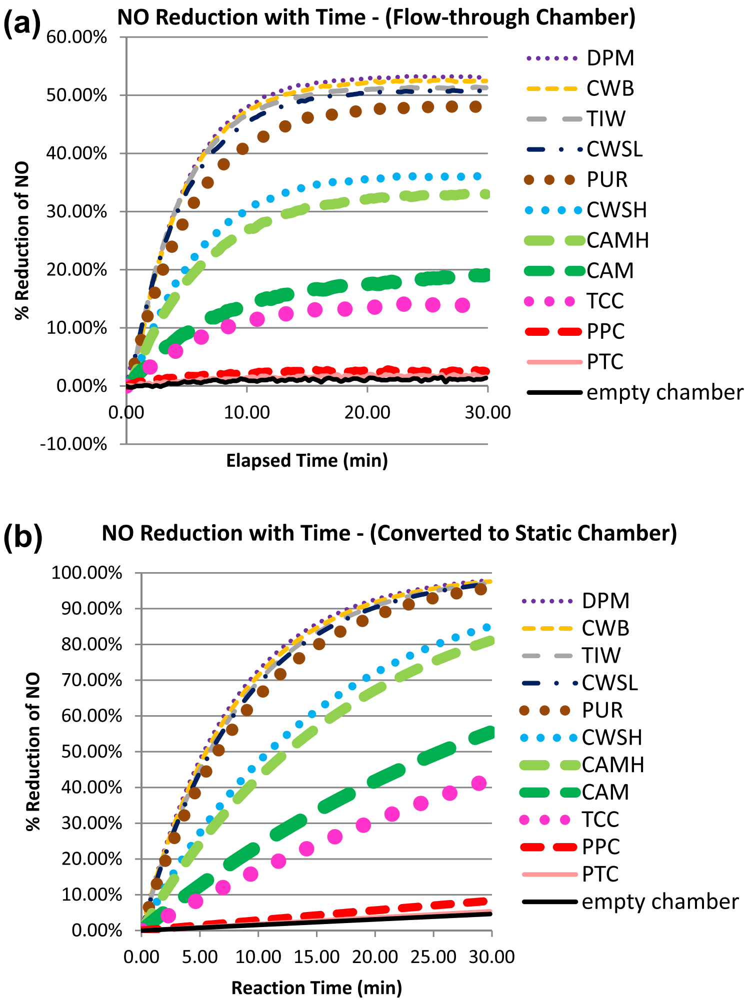

Fig. 6. Environmental chamber results for NO reduction before weathering with (a) flow-through chamber data and (b) converted to static chamber data.

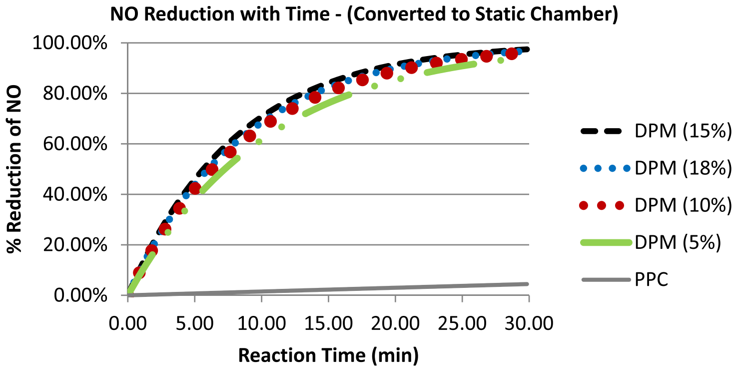

Fig. 7. Environmental chamber results for NO reduction with varying TiO_2 concentrations of DPM coating application.

washing, but none of them reduced NO at the level they once had before weathering. DPM had the highest resistance to weathering, with a 96.91% static NO reduction before weathering and a 73.81% static NO reduction after 4 months weathering. The CWB and CWSL treatments also resisted fairly well. PUR started with a high static NO reduction of 94.44% before weathering and ended with a low static NO reduction of 5.66% after 4 months weathering. Note that these results are based on testing one sample per sample type. No repetition test was conducted because it is a time consuming test, and the consistency with each type was seen during the initial chamber testing. Due to the time constraints of the project and limitations of equipment use, the toluene and TMB pollutant reduction was not measured after weathering.

7.1. Cost analysis

An approximate estimate for the material cost of each treatment method that was used in the final-evaluation sample sets

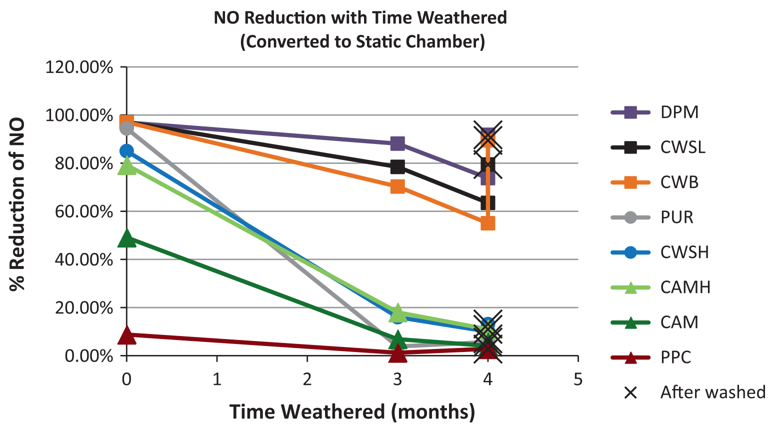

Fig. 8. Environmental chamber results for NO reduction after 0, 3, and 4 months of weathering, and after washing the samples after 4 months of weathering.

for durability testing (CWB, CWSH, CWSL, DPM, PUR, CAM, and CAMH) is shown in Table 4. This is based on the rates without bulk-discounts or labor costs. The rate for commercial water-based TiO_2 (S5-300B) and ultra-fine TiO_2 (PC105) are each about $20.40 per kg. The PURETI coating application is about $0.10 per ft^2. The driveway protector (Seal-Krete) is about $18.18 per gallon. Type I Portland cement is about $12 per 42 kg. Small pea-rock aggregates are about $39 per ton. A column of the overall effectiveness of toluene, TMB, and NO reduction, as well as the decrease in infiltration rate for each coating method is also shown in Table 4 to provide an overview of the cost-effectiveness of each application.

Based on the estimation in Table 4, the cost to apply TiO_2 as a pavement surface treatment could vary widely, depending on what coating method is selected. Prices will range from the CWB method being the most expensive at $10.70 per m^2 to the PUR method being the least costly at $1.08 per m^2. It could also vary depending on how much area it would be applied onto. A large extensive area would receive bulk discounts on the materials compared to the smaller samples used in this project for laboratory testing. Overall, the cost for TiO_2 application is relatively affordable.

8. Summary and future work

Pavements may be highly exposed to polluted air. Applying TiO_2 to pavements might enhance the removal of emissions at street level. Unlike traditional non-pervious pavements, the high porosity and surface roughness of pervious concrete pavement allow more TiO_2 particles to have direct contact with UV lights and thus improve removal efficiency. The open pore structure of pervious concrete might also protect TiO_2 particles from traffic loading and environmental weathering. In addition to being a sustainable transportation facility for stormwater runoff management, pervious concrete pavement, when coated with TiO_2 and widely implemented in urban roads and highway shoulders, may result in improved air quality and thus a multi-phase cleaner transportation environment for future generations. For example, placing TiO_2 coated pervious concrete in school loading lanes where school buses stop and park frequently could help reduce the high NO_x emissions from the diesel engines of the buses, therefore, offer a cleaner environment to the children.

Of the different pollutants tested for photocatalytic reduction in this study, NO typically reacted most effectively followed by TMB and toluene. The highest reductions in pollutants were seen with the driveway protector mix (DPM), the commercial water-based TiO_2 (CWB), the TiO_2 in water (TIW), the low cement–water slurry (CWSL), and the PURETI coating (PUR), each showing over 95% static NO reduction and over 89% static TMB reduction. The coatings that performed low in pollutant reduction may have resulted from the TiO_2 particles being blocked from the other materials mixed in. For example, CWSH and CWSL had the same amount of TiO_2 in them, but the CWSH may not have performed as well in reducing

Table 4
Material cost for each coating type.

Coating type	Material cost		Observed pollutant reduction			
	Total material cost ($/$ft^2$)	Total material cost ($/$m^2$)	Static chamber (120 min)		Converted Static chamber (29.83 min) total% NO reduction	Decrease in infiltration rate (%)
			Total% toluene reduction	Total% TMB reduction		
Commercial water-based TiO_2 (CWB)	0.9955	10.70	61.86 ± 14.06	94.64 ± 1.85	97.59	20.60
Cement–water slurry (CWSH)	0.1860	2.00	13.23 ± 1.62	81.65 ± 1.50	85.04	58.29
Driveway protector mix (DPM)	0.3876	4.17	61.65 ± 10.77	93.87 ± 1.09	97.92	30.49
Pureti (PUR)	0.1000	1.08	43.42 ± 1.79	89.50 ± 4.05	95.79	11.92
Cement–water slurry low (CWSL)	0.1655	1.78	78.82 ± 9.22	97.26 ± 0.63	96.94	51.50
Cement/aggregate mix (CAM)	0.3045	3.27	21.62 ± 4.30	68.28 ± 5.99	55.35	3.85
Cement/aggregate mix high (CAMH)	0.3030	3.26	–	–	81.03	−3.49

– This data is unavailable.

pollutants because it had more cement mixed in it. CAM and CAMH may have been able to perform better if their cement concentrations were lowered. Of the five coatings with the highest pollutant reductions, PUR had the lowest effect on reducing the infiltration rate of the pervious concrete, with an 11.92% reduction in infiltration rate after the surface treatment. DPM had the highest resistance against weathering, maintaining a 73.81% static NO reduction after 4 months of weathering and a 91.80% static NO reduction after washing the samples after 4 months of weathering. The deeper pores of the pervious concrete show to help remove the pollutants, as pervious concrete showed higher static NO reductions when compared to traditional concrete.

When DPM coatings were compared at different TiO_2 concentrations (5%, 10%, 15%, and 18% TiO_2), all four concentrations had similar results for NO reduction, maintaining between 94% and 98% static NO% reduction. This shows that the DPM coating can still work well with lower amounts of TiO_2. Future research is recommended to further evaluate the most cost-effective application rate for the DPM coating.

This study identified some promising surface coating methods including CWB, DPM, CAM, CAMH, and PUR. Each of the coating type may be more suitable for specific applications. The CWB could be used for esthetic reasons, where the white color of the DPM is not desired; the CWB is a transparent coating. The white color of the TiO_2 particles seen in the DPM coating could potentially be used as pavement marking materials, at the same time achieving air purification effect. The CAM and CAMH coating, TiO_2 mixed into thin pervious concrete overlay, could be used as a pavement maintenance technique to address minor surface raveling and cracking distresses at the same time produce photocatalytic effect. The PUR is a cost-effective light coating, which may be used for wide low traffic area where the surface abrasion is low. The long-term durability of the PUR coating should be further studied.

Because the TiO_2 application on pavements for photocatalytic oxidation is still a relatively new area, more research should be conducted prior to application in the field. The coatings still need be tested for resistance in the fall, winter, and spring months, as well as be tested for resistance to vehicle abrasion. The effect of the TiO_2 to the texture and friction properties of the pavement will need to be studied; the tire-to-pavement interaction (abrasion resistance) should be observed with these coatings. More in-depth research should also be conducted to investigate the overall effect of the photocatalytic reaction and if any, harmful chemical compound could be produced during such reaction to adversely affect the environment and human health before the wide application of the photocatalytic materials for improved environment benefit.

Acknowledgments

The authors gratefully acknowledge the funding support by the Transportation Northwest (TransNow) through the USDOT and Washington State University Capital Planning and Development, along with donations from Cristal Global and PURETI, Holcim Inc., and Atlas Sand & Rock for titanium dioxide, cement, and aggregates respectively.

References

[1] Brown D. Pervious Concrete Pavement: A Win-Win System. Concrete Technology Today, vol. 24(2). Portland Cement Association (PCA), CT032, 2003.

[2] Montes F, Haselbach L. Measuring hydraulic conductivity in pervious concrete. Environ Eng Sci 2006;23(6):960–9.

[3] Yang J, Jiang G. Experimental study on properties or pervious concrete pavement materials. Cem Concr Res 2003;33:381–6.

[4] Haselbach L. Pervious concrete and mitigation of the urban heat Island effect. In: Presented at 88th annual meeting of the transportation research board, Washington, DC; 2009.

[5] Olek J, Weiss WJ, Neithalath N, Marolf A, Sell E, Thornton WD. Development of quiet and durable porous portland cement concrete paving materials. Publication SQDH 2003-5, final report, HL 2003-18, Purdue University; 2003.

[6] Morales A. London exceeds Europe's annual pollution goal 4 months into year. Bloomberg. <http://www.bloomberg.com/news/2011-04-21/london-exceeds-europe-s-annual-pollution-goal-four-months-into-year.html> [accessed 01.06.11].

[7] Moussiopoulos N, Barmpas F, Ossanlis I. Numerical study for the potential abatement of air pollution with the use of photocatalytic façade covering materials in London. In: Presented at 10th international conference on environmental science and technology, Kos Island, Greece; 2007.

[8] Chusid M. Photocatalysts keep concrete clean and depollute the air we breathe. Precast solutions; 2006. <http://www.solutions.precast.org/precast-concrete-depollution-and-photocatalysis-case-study> [accessed 02.01.11].

[9] Nonami T, Hase H, Funakoshi K. Apatite-coated titanium dioxide photocatalyst for air purification. Catal Today 2004;96:113–8.

[10] Hashimoto K, Irie H, Fujishima A. TiO_2 photocatalysis: a historical overview and future prospects. Jpn J Appl Phys 2005;44(12):8269–85.

[11] Puzenat E. Photocatalytic self-cleaning materials: principles and impact on atmosphere. Eur Phys J Conf 2009;1:69–74.

[12] Katzman L. Building toward a cleaner environment: a new role for an existing product, TiO_2. Sasaki Associates Inc.; 2006. <http://ideas.sasaki.com/files/attachments/user370/cleaner%20environment.pdf> [retrieved 02.01.11].

[13] Ramirez AM, Demeestere K, De Belie N, Mantyla T, Levanen E. Titanium dioxide coated cementitious materials for air purifying purposes: preparation, characterization and toluene removal potential. Build Environ 2009;45:832–8.

[14] Dylla H, Hassan MM, Mohammad LM, Rupnow T, Wright E. Evaluation of the environmental effectiveness of titanium dioxide photocatalyst coating for concrete pavement. In: Transportation research board 89th annual meeting (Publication No. 10-0963). Washington, DC; 2010.

[15] Hassan MM, Dylla H, Mohammad LN, Rupnow T. Effect of application methods on the effectiveness of titanium dioxide as a photocatalyst compound to concrete pavement. In: Presented at 89th annual meeting of the transportation research board, Washington, DC; 2010.

[16] Chai-Mei Yu J. Deactivation and regeneration of environmentally exposed titanium dioxidde (TiO_2) based products. Testing report departmental order Ref. No. E183413, Environmental protection department (EPD), HKSAR; 2003.

[17] ACI Committee 522. 522R-10 Report on Pervious, Concrete; 2010. p. 38.

[18] Montes F, Valavala S, Haselbach L. A new test method for porosity measurements of portland cement pervious concrete. J ASTM Int 2005;2(1).

[19] Montes F, Haselbach L. Measuring hydraulic conductivity in pervious concrete. Environ Eng Sci 2006;23(6):960–9.

[20] Pervious concrete pavement: an overview (n.d.). Pervious pavement.org. <http://www.perviouspavement.org/> [retrieved 05.11.11].