Title: Pervious Concrete with Titanium Dioxide as a Photocatalyst Compound for a Greener Urban Road Environment

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The United States is facing the problem of trying to control air pollution from vehicle emissions, especially in growing urban areas. This study innovatively investigates applying the photocatalytic effect of titanium dioxide (TiO$_2$) 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 weathering. A brief analysis on each application method with respect to material cost is also presented. 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. The PURETI coating had the least effect on reducing the infiltration rate of the pervious concrete. The driveway protector mix had the highest resistance against deicing chemical and freeze-thaw testing. When pervious concrete was compared to traditional concrete, pervious concrete showed higher NO reductions, whether the sample had TiO$_2$ coating on it or not.

**KEY WORDS**
Pervious concrete, photocatalyst, Titanium Dioxide, pollution, environment
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 stormwater 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 U.K. 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.

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. However, surface coatings to traditional pavements may lose their effectiveness due to surface wear. When TiO$_2$ is applied to pervious pavement, this provides two sustainable benefits in one material; air will be purified on sunny days, and water will be infiltrated on rainy days, in addition to having a rougher surface which may retain more TiO$_2$. With this innovative idea, this paper 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 extreme environmental conditions.

BACKGROUND

In the sunlight, TiO$_2$ is activated by ultraviolet (UV) radiation ($\lambda < 390$ nm) to oxidize air pollutants, such as nitrogen oxides (NO$_x$) and volatile organic compounds (VOCs), into other inorganic compounds. In a photocatalytic reaction with TiO$_2$, no chemical reactants are used. The TiO$_2$ does not get consumed in the reaction; so it can theoretically be used indefinitely. TiO$_2$ photocatalysis can be performed even in weak UV light (8). TiO$_2$ (anatase) has a wide band gap, thus only ultraviolet light with a wavelength below 387 nm is absorbed (9, 10).

Photocatalysts activated by UV lights will decompose organic materials like 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 (11). After they have been catalyzed, the materials break down into oxygen, carbon dioxide, water, sulfate, nitrate, and other inorganic molecules.

When photocatalytic oxidation decomposes staining compounds that are absorbed on a surface, the surface is cleaned and converted into a highly hydrophilic state (8). Stains on the TiO$_2$ treated hydrophilic surface can be washed away easily, having a self-cleaning function, as

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the water flushes between the stain and the hydrophilic TiO$_2$. Some successful examples are glasses, tiles, and concrete (12). 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, it keeps the concrete cleaner, and it reflects much of the sun’s heat and reduces heat gain because of its white color (11).

TiO$_2$ is recently found to be an excellent photocatalyst to be used in pavement engineering for reducing vehicle emission pollutants (13). Figure 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.

![Figure 1: Photocatalytic effect of titanium dioxide on pavement.](image)

Research is still 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 (14). 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 hours 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 (15). The photocatalytic activity of the TiO$_2$-coated paving blocks decreased in heavy pedestrian traffic areas, as contaminants accumulated on the surface (15). 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 (15).

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) (14). 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. Therefore, 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). 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.

**RESEARCH OBJECTIVE**

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$_2$. Because a major focus of this application is in the transportation environment, three different gaseous pollutants that are present 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 environmental damage (freeze-thaw condition with de-icing agent) is also evaluated.
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. All specimens were lightly compacted as typical in pervious concrete placements, and designed for a target porosity of 25%. The samples were covered and left to cure for 7 days. In addition, 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 inches long, 6 inches wide, and 2 inches thick (304.8 mm x 152.4 mm x 50.8 mm).

Porosity
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 \( \rho_w \) and \( V_t \) are the density of water and total volume of sample respectively (16).

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

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

SURFACE APPLICATIONS
Application Methods
Ultra-fine titanium dioxide PC105 supplied by Cristal Global was used in this study for surface treatment except otherwise noted. In total, eight application methods were evaluated in this study, which include:

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.
4. Driveway protector mix (DPM): it consisted of a transparent liquid driveway protector 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. **Cement/aggregate mix (CAM):** it was a thin layer of pervious concrete with finer aggregate size and TiO₂ mixed in. This could be used as a special application when surface maintenance is needed for pervious concrete.

8. **Cement/aggregate mix with higher TiO₂ concentration (CAMH):** it was the same application method as method 7 but with higher TiO₂ 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 TiO₂ (PPC), plain traditional concrete with no TiO₂ (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 TiO₂ rate of 0.06g/in² (8.61*10⁻⁵ g/mm²). The details about the TiO₂ concentration rate for each application method are summarized in Table 2. Figure 2 is a photograph of representative TiO₂ coated samples.

![TiO₂ coated pervious concrete samples](image)

**FIGURE 2 TiO₂ coated pervious concrete samples.**

**Infiltration Rate**

Infiltration characteristics of pervious concrete were determined before and after the surface coating applications. The test followed standard ASTM C1701 (17), 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 inches (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. Two samples per type of surface coating were tested, and the average infiltration rates before and after applied surface coatings are shown in Table 1. (The TIW method was not tested for infiltration because the coating was coming off by the touch of a hand and could wash off.)
with water.) The infiltration rate was calculated as shown in Equation 2, where \(d\) is the diameter of the pipe and \(t\) is the infiltration time.

\[
infiltration\ rate = \frac{\text{volume of water infiltrated}}{\text{area of surface infiltrated through}} \times \frac{\text{time to fully infiltrate}}{2000\ mL} = \frac{\pi d^2}{4t} \tag{2}\]

### TABLE 1 Infiltration Rates Before and After Surface Coating Applications

<table>
<thead>
<tr>
<th>Sample</th>
<th>BEFORE SURFACE APPLICATION Avg. Inflitr. Rate (mm/s)</th>
<th>AFTER SURFACE APPLICATION Avg. Inflitr. Rate (mm/s)</th>
<th>% Decrease in infiltration rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>CWB</td>
<td>15.40±0.49</td>
<td>12.23±1.00</td>
<td>20.60%</td>
</tr>
<tr>
<td>CWSH</td>
<td>18.27±3.28</td>
<td>7.62±0.01</td>
<td>58.29%</td>
</tr>
<tr>
<td>CWSL</td>
<td>17.40±3.09</td>
<td>8.44±3.08</td>
<td>51.50%</td>
</tr>
<tr>
<td>DPM</td>
<td>16.76±3.95</td>
<td>11.65±4.03</td>
<td>30.49%</td>
</tr>
<tr>
<td>PUR</td>
<td>15.70±2.59</td>
<td>13.83±2.92</td>
<td>11.92%</td>
</tr>
<tr>
<td>CAM</td>
<td>14.75±0.99</td>
<td>14.19±1.25</td>
<td>3.85%</td>
</tr>
<tr>
<td>CAMH</td>
<td>9.07±1.44</td>
<td>9.39±0.63</td>
<td>-3.49%*</td>
</tr>
<tr>
<td>PPC</td>
<td>15.77±1.46</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

* This data is not applicable.

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

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. CAM and CAMH both did not change much 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.

### ENVIRONMENTAL TEST

#### 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 25W black lights. Inside the chamber, the sample surface sat about 16 inches (406.4 mm) below the chamber lights. The irradiance of the lights were measured and compared to the solar irradiance on the roof in October and November (Figure 3). The 25W lights were within the wavelength region (below 387 nm) where TiO\(_2\) is photoactive. Most of the 25W lights output
energy was between 300-400 nm. The irradiance of the 25W lights was about 6.11 W/m², comparable to a cloudy fall day in Pullman, Washington.

![Irradiance of Chamber Lights vs. Pullman Sunlight](image)

**FIGURE 3** Comparison of the six photo-chamber 25W black lights and Pullman fall solar irradiances.

Three different gaseous pollutants that are present in automobile exhaust were tested: toluene, trimethylbenzene (TMB) and nitrogen oxide (NO). Figure 4-a 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 dispersed 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 (Figure 4-b. 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 NOx analyzer.
FIGURE 4 Environmental chamber set-up for (a) Toluene and TMB injection and (b) NO injection.

**Environmental Test Results**

A summary table of the results for each surface coating type before any applied abrasive effects is shown in Table 2. Note that the results shown for the pervious concrete samples are an average of at least two samples tested per surface coating type. Figure 5 shows the graphical results of toluene and TMB. Figure 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. A flow-through chamber at steady-state concentration has the relationship in Equation 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 (hr$^{-1}$).

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

[3]

The equation for describing the rate of change in the static experiments is stated in Equation 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.

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

[4]

### TABLE 2 Summary of Results for Each Application Type Before Abrasion

<table>
<thead>
<tr>
<th>Sample</th>
<th>TiO$_2$ (g/mm$^2$)</th>
<th>% of surface coating that is TiO$_2$</th>
<th>Static Chamber (120 min)</th>
<th>Flow-through Chamber (29.83 min)</th>
<th>NO decay rate, $k$ (1/hr)</th>
<th>NO reduction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>total % toluene reduction</td>
<td>total % TMB reduction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>empty chamber</td>
<td>-</td>
<td>-</td>
<td>2.48%</td>
<td>12.35%</td>
<td>1.38%</td>
<td>0.09</td>
</tr>
<tr>
<td>PPC</td>
<td>-</td>
<td>-</td>
<td>15.06±0.28%</td>
<td>29.86±8.83%</td>
<td>2.51±0.19%</td>
<td>0.17</td>
</tr>
<tr>
<td>TCC</td>
<td>8.61*10$^{-5}$</td>
<td>5.01%</td>
<td>-</td>
<td>-</td>
<td>1.61%</td>
<td>0.111</td>
</tr>
<tr>
<td>CWB</td>
<td>5.27*10$^{-4}$ (water-based TiO$_2$)</td>
<td>100%</td>
<td>61.86±14.06%</td>
<td>94.64±1.85%</td>
<td>52.46±2.07%</td>
<td>7.50</td>
</tr>
<tr>
<td>CWSH</td>
<td>8.61*10$^{-5}$</td>
<td>5.01%</td>
<td>13.23±1.62%</td>
<td>81.65±1.50%</td>
<td>35.97±1.64%</td>
<td>3.82</td>
</tr>
<tr>
<td>CWSL</td>
<td>8.61*10$^{-5}$</td>
<td>9.82%</td>
<td>78.82±9.22%</td>
<td>97.26±0.63%</td>
<td>50.79±0.49%</td>
<td>7.01</td>
</tr>
<tr>
<td>DPM</td>
<td>8.61*10$^{-5}$</td>
<td>14.29%</td>
<td>61.65±10.77%</td>
<td>93.87±1.09%</td>
<td>53.27±3.63%</td>
<td>7.79</td>
</tr>
<tr>
<td>TIW</td>
<td>8.61*10$^{-5}$</td>
<td>11.76%</td>
<td>91.98±3.08%</td>
<td>96.34±1.08%</td>
<td>51.30±2.43%</td>
<td>7.15</td>
</tr>
<tr>
<td>PUR</td>
<td>2.02*10$^{-6}$</td>
<td>-</td>
<td>43.42±1.79%</td>
<td>89.50±4.05%</td>
<td>48.29±3.13%</td>
<td>6.37</td>
</tr>
<tr>
<td>CAM</td>
<td>8.61*10$^{-5}$</td>
<td>0.46%</td>
<td>21.62±4.30%</td>
<td>68.28±5.99%</td>
<td>19.11±3.46%</td>
<td>1.62</td>
</tr>
<tr>
<td>CAMH</td>
<td>2.17*10$^{-4}$</td>
<td>1.15%</td>
<td>-</td>
<td>-</td>
<td>32.97±1.73%</td>
<td>3.34</td>
</tr>
</tbody>
</table>

This data is not applicable or is unavailable.
FIGURE 5 Results for Static chamber reduction in (a) Toluene and (b) TMB after 120 minutes
When observing the removal of different pollutants due to photocatalytic TiO$_2$, NO reacted most effectively followed by TMB and then toluene. NO reduction reached over 95% static NO reduction in less than half an hour for many cases. Toluene was reduced usually less
than 60% static in 120 minutes. All three pollutant types had an increasing curve trend for percent reduction with time. After performing nonlinear (intrinsically linear) regression analysis, the percent reduction of Toluene showed closer to a \( \ln(time) \) relationship. The percent reductions in TMB and NO both showed closer to a \( -inv(time) \) relationship.

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 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.

**DURABILITY OF THE SURFACE APPLICATION METHODS**

The resistances of the TiO\(_2\) coatings were evaluated against exposure to deicing chemicals using a modified version of ASTM C672 (18). Since the samples were pervious concrete, it was impossible to maintain a puddle of solution on the surface, as the ASTM standard C672 required. A more realistic drained approach was followed, similar to the test method suggested by another pervious concrete study (19). Samples were placed in containers with three \( \frac{1}{10} \) inch (2.54 mm) holes drilled into the bottom. A solution with 9% by mass of calcium chloride was poured onto the surfaces of each sample until the sample was covered with solution 6 - 12 mm above the surface. While placed inside a 14 ft\(^3\) (0.392 m\(^3\)) freeze-thaw chamber, solutions were allowed to slowly drain into separate containers at \( 70 \pm 30 \) mL/min. One cycle in the freeze-thaw chamber consisted of two hours at \(-18^\circ C\) and 2 hours at \(10^\circ C\). The deicing solution was changed every 12 cycles, and the experiment was performed for 36 cycles. The amount of NO reduction by each sample was tested in the environmental chamber after 0 cycles, 12 cycles, and 36 cycles. The results are shown in Figure 7 with static chamber data. No repetition test was conducted because it is a time consuming test.
**FIGURE 7** Results for NO reduction after 0, 12, and 36 freeze-thaw cycles and exposure to deicing chemical.

By the end of 36 cycles, most pervious concrete specimens were heavily damaged, indicating low resistance to calcium chloride solution. Out of the samples that remained, DPM had the highest resistance to the deicing agent and freeze-thaw cycles, with a 95.10% static NO reduction before any testing and a 77.68% static NO reduction after 36 cycles. Other sample types ended with below 54% static NO reduction after 36 cycles.

**COST ANALYSIS**
An approximate estimate for the material cost of each coating method is shown in Table 3. 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.

Though some of the coating types are more costly than others, the effectiveness of the coating type also needs be considered, and has been included into Table 3. Coatings like CWB and DPM are higher in material cost than the other coatings, but they also perform the highest in removing air pollutants. PUR has the lowest cost, is effective at removing air pollutants, and the reduction in infiltration rate is low. It is however less durable under the affect of deicing chemical and freeze-thaw cycles. Therefore, the selection of different TiO$_2$ surface methods should consider comprehensively with respect to pollutant removal efficiency, durability, cost, and needs of the project.
TABLE 3 Material Cost & Observed In-Lab Pollutant Reduction for Each Coating Type

<table>
<thead>
<tr>
<th>Coating type</th>
<th>MATERIAL COST</th>
<th>OBSERVED POLLUTANT REDUCTION</th>
<th>Converted Static Chamber (29.83 min)</th>
<th>% Decrease in infiltration rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>total material cost ($/ft$^2$)</td>
<td>total material cost ($/m^2$)</td>
<td>Static Chamber (120 min)</td>
<td>total % toluene reduction</td>
</tr>
<tr>
<td>commercial water-based TiO$_2$ (CWB)</td>
<td>0.9955</td>
<td>10.70</td>
<td>61.86±14.06%</td>
<td>94.64±1.85%</td>
</tr>
<tr>
<td>cement-water slurry (CWSH)</td>
<td>0.1860</td>
<td>2.00</td>
<td>13.23±1.62%</td>
<td>81.65±1.50%</td>
</tr>
<tr>
<td>driveway protector mix (DPM)</td>
<td>0.3876</td>
<td>4.17</td>
<td>61.65±10.77%</td>
<td>93.87±1.09%</td>
</tr>
<tr>
<td>Pureti (PUR)</td>
<td>0.1000</td>
<td>1.08</td>
<td>43.42±1.79%</td>
<td>89.50±4.05%</td>
</tr>
<tr>
<td>cement-water slurry low (CWSL)</td>
<td>0.1655</td>
<td>1.78</td>
<td>78.82±9.22%</td>
<td>97.26±0.63%</td>
</tr>
<tr>
<td>cement/aggregate mix (CAM)</td>
<td>0.3045</td>
<td>3.27</td>
<td>21.62±4.30%</td>
<td>68.28±5.99%</td>
</tr>
<tr>
<td>cement/aggregate mix high (CAMH)</td>
<td>0.3030</td>
<td>3.26</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

- This data is unavailable

SUMMARY AND CONCLUSIONS

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 to school parking lots where school buses stop and park frequently could help reduce the high NOx 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 performed lower in reducing 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 the deicing chemical and freeze-thaw testing, maintaining a 77.68% static NO reduction after 36 freeze-thaw cycles. 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. Each coating type in this study could be useful for different purposes. For example, because the DPM maintained its high photocatalytic activity after exposure to deicing chemical and freeze-thaw cycles, this type of coating could be used in a highly abrasive environment, like on the shoulders of a highway or on busy sidewalks adjacent to a road. The CWB could be used for aesthetic 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 is suitable for wide low traffic area where the surface abrasion is low.

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REFERENCES


