Environmental Benefits of Innovative Photocatalytic Cementitious Road Materials

G.L. Guerrini, A. Beeldens, M. Crispino, G. D'Ambrosio and S. Vismara

Abstract

Air pollution is a prominent critical issue of vehicles. The toxic pollutants are harmful to the environment, hazardous to human health and difficult to degrade by natural means. Therefore a significant amount of efforts have been done on road pavements that directly interact with vehicles. Basing on the synergetic effect of cement and titanium dioxide discovered in recent years new road pavements were developed. In particular, photocatalytic cementitious road materials can represent a key element to improve air quality, thanks to their ability to accelerate the natural reaction of oxidation.

This paper deals with the development of several types of photocatalytic cementitious road pavements, such as paving blocks, asphalt concrete filled up with a photocatalytic slurry and concrete roads.

Large laboratory and field-testing programs have been conducted measuring the environmental effectiveness by means of a specific set-up and in-situ sources, respectively. Functional and mechanical tests have also been performed on the materials studied to investigate their behavior under traffic loadings. Indeed, road pavements have to guarantee both de-polluting effects and performances usually required to a road pavement wearing course, according to the current Standards. The large research activity conducted till now clearly showed the significant contribution of such innovative materials to the improvement of air quality, reducing the nitrogen oxides concentration up to 60% in some local weather conditions. They can represent a new frontier of the research aimed at reducing air pollutants, for environmental friendly solutions.

The findings underline the benefits of the inclusion of titanium dioxide in concrete pavements.

Introduction

The constant increase of traffic and, consequently, air pollutants concentration represent one of the main problems in urban areas. Many attempts have been made indoor and outdoor to improve air quality, exploiting the synergetic effect of cement materials and photocatalysts, in particular, titanium dioxide (TiO_2). Its stability, strong photo-oxidation power, together with its safety for human body, makes the titanium dioxide in its anatase form the most suitable photocatalyst.

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The photocatalysis mechanism involves electro-generated electrons and holes that act as oxidizing and reducing agents in presence of sunlight, leading to a degradation of pollutants into non-noxious compounds (Fujishima et al. 1999). TiO_2 has been proved to be very effective in the reduction of pollutants such as nitrogen oxides (NO_x), aromatics, ammonia, and aldehydes. Further, the use of TiO_2 in combination with cementitious materials has shown a favorable synergistic effect in the reduction of pollutants (Cassar et al. 2007) (Guerrini, 2010). Indeed, in comparison with other photocatalytic building materials, these special binders (and their corresponding products) are able to absorb the NO_x on the surface, to transform them in non-noxious ions and to block them in form of salts (nitrates), Figure 1. These substances can be easily removed from the surface by means of the rain (lixiviation) or of washing actions. A similar degradation can be observed for other pollutants (Strini et al. 2005), with different mechanism. Finally, in the particular case of NO_x reduction, as an indirect consequence, it is possible to demonstrate that the production of ozone is strongly inhibited in the atmosphere and a further environmental advantage is evident.

This study focuses on the nitrogen oxides reduction, the most critical harmful substances with their high concentration in urban air, due to the increasing traffic volumes. In particular, nitrogen dioxide (NO_2) is the gas considered as a reference in the urban limit emissions, as well as PM 10 (particulate matters lower than 10 mm).
For several years, the photocatalytic cementitious products have been widely used for building applications all over the world in order to obtain depolluting actions.

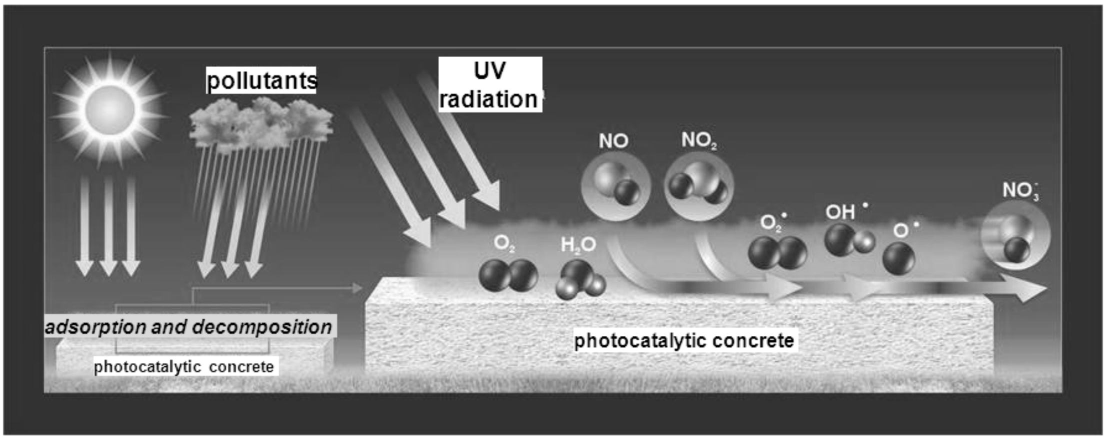

Figure 1: Mechanism of photocatalytic degradation

Materials applied for this purpose were previously developed and validated at laboratory scale. However, for the first field applications the attempt to demonstrate the in-situ performances was necessary by adopting dedicated experimental test protocols and using specific analysis equipment. One of the first significant examples represented by the European project PICADA (Photocatalytic Innovative Coverings Applications for De-pollution Assessment), where an experimental activity for the validation of the photocatalytic process by means of a street canyon was carried out to evaluate the effects of wall surface-coated with a photocatalytic coating (www.picada-project.com, 2011). In this project, the effect of photocatalytic materials on air quality was demonstrated thanks to the correlation between in situ results and the developed model (Plassais et al. 2007). After the PICADA project, other in-situ monitoring campaigns were carried out in some experimental projects, with positive results, such as:

- Borgo Palazzo street in Bergamo, Italy (a city road built with paving blocks) (Guerrini 2009)
- Rue Jean Bleuzen in Vanves (Paris), France (concrete city road) (Gignoux, 2010)
- Umberto I city road tunnel in Rome, Italy (vault coated with a photocatalytic paint) (Guerrini 2012)

A reliable estimation of photocatalytic surfaces produced with cement-based materials, within the 2010 year is around 2.000.000 m^2 (2,400,000 sq. yards). Horizontal surface applications (paving blocks, industrial pavements, whitetopping, etc.) comprise approximately 50% of the total. Most of projects were developed in Europe, especially Italy, France, Belgium and Germany.

In this paper, the available applications of TiO_2-based photocatalysis in the field of road construction are briefly presented. Indeed, several kinds of photocatalytic pavements have been developed in recent years for different performance and architectural needs. Both laboratory and full-scale field experiments have been conducted using materials with the proper amount of photocatalyst to guarantee the best response in terms of environmental, mechanical, functional and economical features. Some examples of photocatalytic solutions will be presented.
Further, some on-going research projects are presented hereafter.

Laboratory tests

The depollution effectiveness of photocatalytic materials is measured by means of a NO_x test equipment, able to reproduce plausible in-service conditions in terms of gas concentration, gas flow rate in controlled conditions of UV light, temperature and air humidity. Most tests are carried out in NO_x flow-through conditions, conducted with a fixed concentration of NO_x (the NO_x content is set to 0.55 ppm, of which 0.15 ppm of NO_2 and 0.4 ppm of nitrogen oxide - NO) in nitrogen, corresponding to a possible atmospheric pollution (Italian standard UNI 11247-2010 "Determination of the degradation of nitrogen oxides in the air by inorganic photocatalytic materials: continuous flow test method"). The result of the test can be expressed as the NOx photocatalytic decomposition percentage of a sample under UV radiation. The intrinsic photocatalytic activity and the degradation rate are also derived. The set-up is showed in Figure 2.

Typical values of NOx abatement ranges between 10 and 30 gNOx/year/m^2, so that we can calculate a NOx removal of 10-30 kg/NOx/year for 1000 m^2 of cement-based pavement.

Another test can be used for the determination of the air-purification performance of photocatalytic materials, according to the ISO 22197-1 standard.

It is also possible to carry out such tests on using manufacts (e.g. paving blocks) or cores extracted from the pavements, in order to evaluate the in-service performances of the structure (Guerrini 2009, Gignoux 2010). This approach is very useful for determining the possible effect of dirt particles deposited on the surface, which can influence the depolluting effect of the active surface (Guerrini 2009).

Field tests

On the laboratory promising findings, the effectiveness of the photocatalytic surface layers has been evaluated on large scale, proving the ability of the photocatalytic concrete to reduce NO and NO_2 content in the air.

Measuring the effectiveness of photocatalytic surface in real conditions has been carried out in several pilot projects. Data from these projects in Italy, beginning in 2002, yielded NO_x reduction of approximately 60% compared to an asphalt surface control (Plassais et al. 2007, Guerrini and Peccati 2007). After a series of positive results, further in-field testing was discouraged by the complexity of the measurements (due to the influence of local atmospheric conditions) and the costs for monitoring.

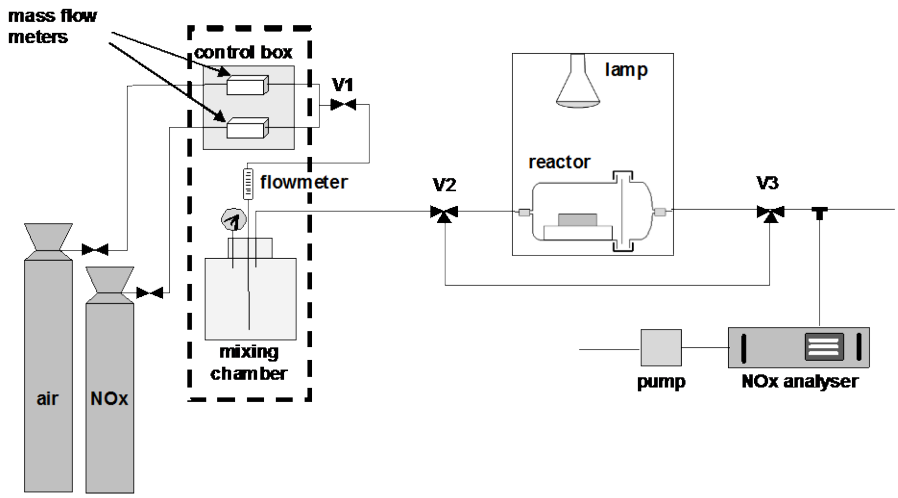

Figure 2: A schematic view of the "continuous flow" method (UNI 11247-2010)

Innovative photocatalytic cementitious road materials

Several types of cementitious road materials with photocatalytic properties were developed and large laboratory and in-field campaigns were conducted to get a better understanding of their effect on environment and surface and mechanical features.
Currently, there are several, possible solution for the construction of photocatalytic roads and pavements, using cement-based materials (Figure 3):

1. Interlocking paving blocks for roads, parking areas, shopping areas, sidewalks, crossroads, traffic calming zones and bike routes;
2. pre-cast or ready-mix concrete pavements.

Photocatalytic paving blocks. Concrete blocks found large applications, Figure 4. They were demonstrated to give contribution to the air quality improvement in Japan, Italy, France, Belgium and North America (Beeldens and Redant 2007, Poon and Cheung 2007).

In this category of pavements can be also included other concrete manufacts, which can be produced using photocatalytic cements: slabs, plates and curbs. They can be white, grey, or colored.

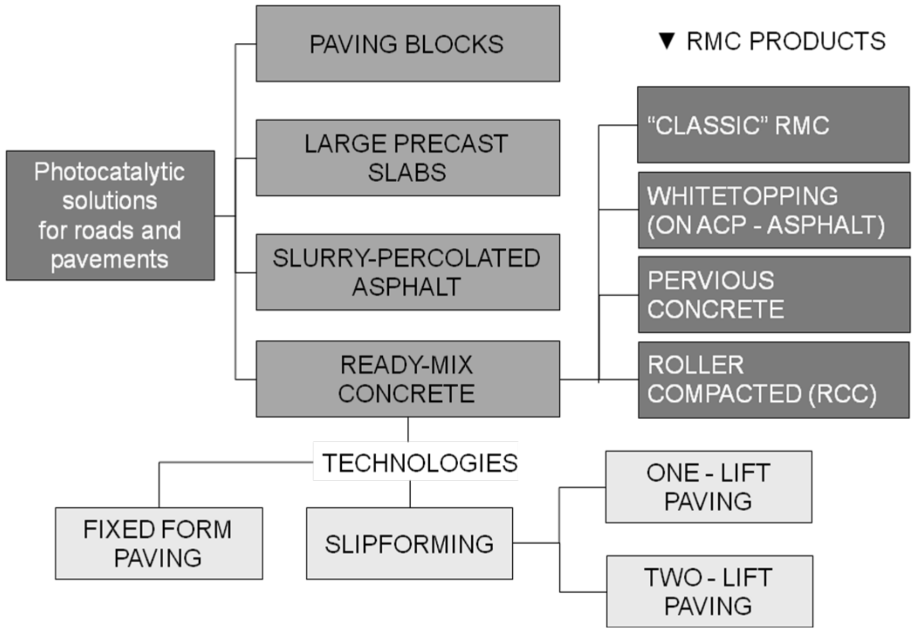

Figure 3: Possible photocatalytic solutions for roads and pavements

Figure 4: Two examples of paving blocks (left) and slabs (rights) applications.

These manufacts requires an adequate design approach in order to be applied for roads, squares and parking lots where the service loads are relevant. If some problems of deterioration can arise with a consequent production of dirt, the photocatalytic performances are reduced (see below).

In a recent study, in order to perform a photocatalytic evaluation of some paving blocks in a city street (Guerrini 2009), an original, experimental set-up for NOx depollution tests was used, including a special reactor which could contain an entire block, instead of a small specimen), Figure 5. This test can reproduce a typical situation of a polluted street, in urban environment.

In these conditions, results – expressed as an NO_x% abatement, after 60 min of light irradiation – are absolutely relative and referred to the geometry of the blocks. The values cannot be compared with those of standard tests.

- installed: blocks extracted and tested "as is" (dusty blocks)
- cleaned/washed: test repeated on the same blocks, cleaned, washed and dried
- warehouse: test on paving blocks available for substitution (stock)

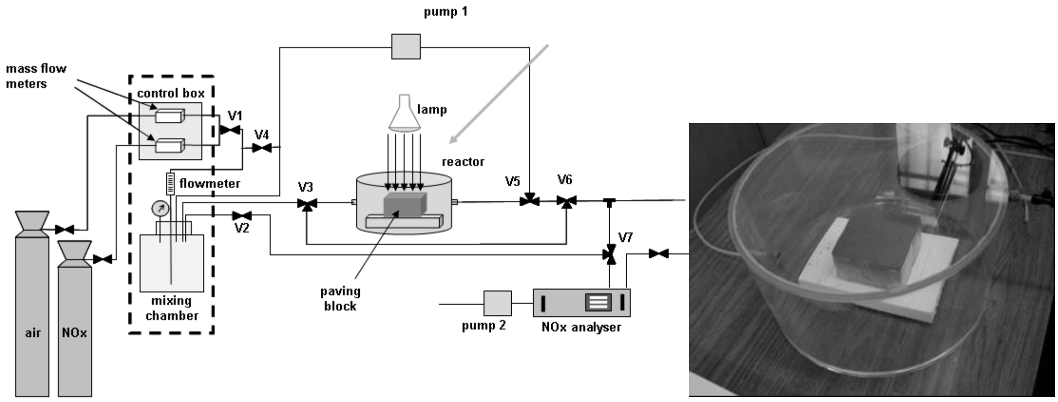

Figure 5: A view of the developed testing equipment (NOx gas recirculation method)

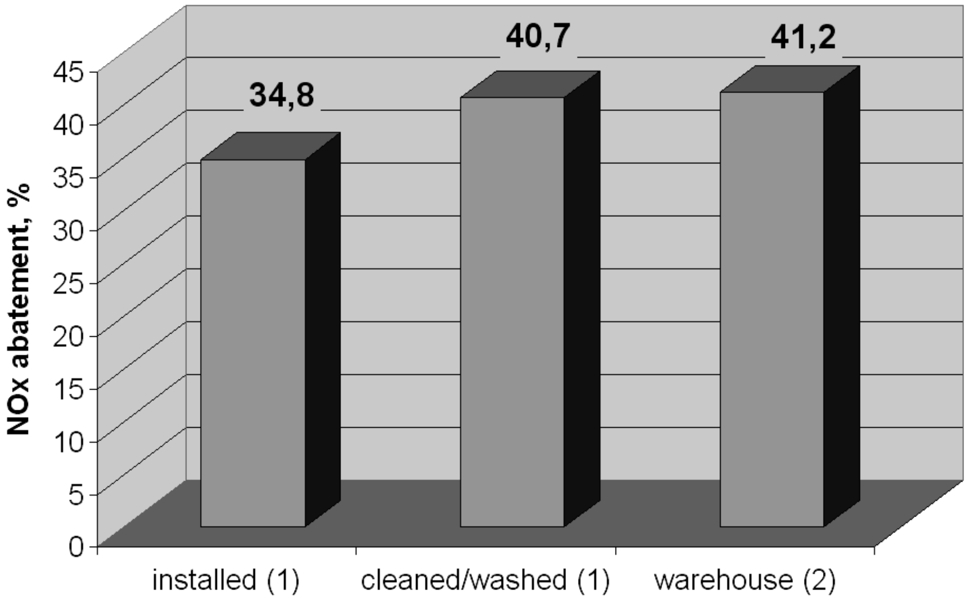

Figure 6: Test results for paving blocks (Guerrini 2009)

Dusty blocks were firstly tested in their "as-is condition" and showed a lower depolluting activity, with respect to the "in-stock (warehouse) blocks" (15-16%), Figure 6. They recovered the initial performances (corresponding to the reference warehouse values) after a brushing, washing and drying treatment and a further NO_x test.

Small differences among some blocks performances can also be due to the presence of other substances, which are hard to be removed (oil, grease, sticky materials…). This presence could slightly reduce the active surface of the blocks (not observed on the surface of the tested elements). So, the photocatalytic action is more evident, when the street is clean.

Paving blocks and slabs have been the first, relevant application in terms of installed surfaces (especially in Italy), due to their peculiarity (two layers of concrete, only the top layer is photocatalytic, 6-10 mm). The cost of photocatalytic cement is not more than 20% higher than conventional cement and the cost of installed photocatalytic concrete is only 3-4% higher than conventional concrete (Data by Italcementi).

Durability of photocatalytic performances is the same of the manufact in itself, as the photocatalyst is the whole top layer (Cassar 2004).

Slurry infiltrated in an asphalt pavement. Combining an open grade asphalt concrete with a photocatalytic cementitious slurry, high performances road pavements can be obtained (Guerrini and Grelaud 2009), Figure 7.

Some experimental studies were conducted in the past, to evaluate the advantages of both peculiar technology of bituminous asphalt combined with cement mortar or slurry and photocatalytic technology (Crispino and Lambrugo 2007, Crispino and Lambrugo 2008, Crispino et al. 2008).

Adopting this hybrid solution, it is possible to construct a concrete pavement without joints, whose structural performances can be varied from high punching strength (for industrial pavements) to semi-flexible performances (for roads). Void percentage can be chosen in order to obtain the best performance in terms of elastic modulus and tensile strength.

A surface post-treatment (rutting) is sometimes recommended in order to obtain desired skid values.

This type of pavement is available in different colors, by adding inorganic pigment into the slurry. Further architectural improvements can be obtained by using colored aggregates.

Two experimental fields were completed in Italy in 2010 (Ancona and Carpiano-Milan), for the performances evaluation of this solution for highways and roads, Figure 8. Some projects have been already approved, in Italy.

Other Countries where this technology is widely adopted are France and Spain.

Ready-mix concrete. Ready mix concrete pavements have also been studied, with the intent to optimize structural performance, architectural needs and photocatalytic properties for the ideal cost/performances ratio.

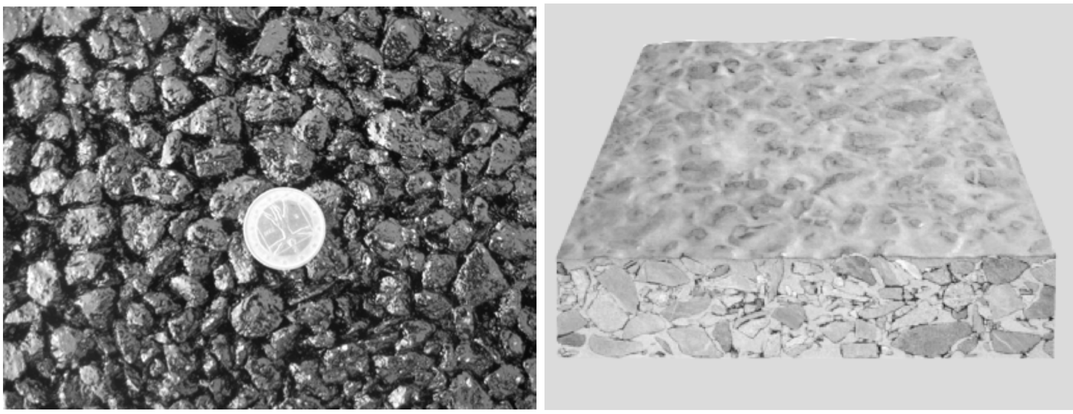

Figure 7: Open-grade asphalt (left) and an example of the pavement obtained (right).

Figure 8: Field tests for highways (left) and roads (right).

In other words, it is absolutely not difficult to complete a photocatalytic concrete pavement (by substituting the traditional Portland cement with the photocatalytic cement) but the solution must be economically acceptable, without very high extra prices per surface area.

In this sense, two-layers (thin whitetopping) or low thickness solutions seem to be reasonable, considering their long-term durability.

A specific example of ultra-thin solution is represented by the industrial concrete pavements that are completed with a thin layer (10-30 mm) of a abrasion-resistance photocatalytic mortar, grey or colored, with a "fresh on fresh" method.

One-lift paving. The one-lift paving technology was successfully applied in the Rue Jean Bleuzen – Porte de Vanves (Paris - France):

- Traffic: 13.000 cars/day.
- Geometry: length: 300 m (photocatalytic)
- Thickness of photocatalytic concrete: 120 mm
- Total photocatalytic surface: about 6000 m^2 (64583 square feet)
- Upper surface: exposed aggregate concrete overlay (retarding admixture)
- Sidewalks: Photocatalytic precast paving flags and curbs

A periodical sampling of cores from the pavement was also done, for laboratory testing. The core surfaces were contaminated with tires residue and consequently, their photocatalytic activity was lower than that of the original material. The initial values were obtained again after washing.

A NO_x monitoring campaign was carried out by LROP (Western Paris Regional Transport Research Laboratory), for one year (Gignoux L., 2010).

Two-lift paving. As part of the reconstruction of Route 141 in St. Louis between Ladue Road and Olive Boulevard, the Missouri Department of Transportation (MoDOT), in collaboration with the Federal Highway Administration, the National Concrete Pavement Technology Center at Iowa State University's Institute for Transportation, the Essroc Italcementi Group, and Lehigh Hanson, Inc., has started an extensive research on the environmental benefits of using concrete made with an innovative new cement product in the construction of highways.

In this project – which represents the first application of a photocatalytic concrete for a road in U.S.A. – a monitoring campaign will be carried out to verify the efficiency of two different solutions:

1) A photocatalytic concrete mainline pavement
2) A photocatalytic pervious concrete (see below) shoulder pavement

The mainline pavement material will be applied using a two-lift paving strategy, which involves the placement of two wet-on-wet layers of concrete instead of a single, homogeneous layer. The lower, base level layer is expected to be constructed with less expensive materials (e.g., a low cementitious-material content base lift) which will then be overlaid with a thinner top wearing-course of concrete containing photocatalytic cement.

The shoulder pavement element of this research effort involves photocatalytic cement, which will be used in a pervious (rather than conventional) concrete application. Together, this set of innovative mainline and shoulder paving materials, including both a two-lift photocatalytic mainline pavement and a photocatalytic pervious shoulder pavement, are believed to represent one of the most technically advanced and environmentally-friendly concrete pavement systems ever employed.

This project was officially presented in occasion of the national two-lift concrete paving open house, hosted by the National Concrete Pavement Technology Center (NCPTC) in Chesterfield, MO - USA (September 2010). This experimental road was constructed in October 2011 (Figure 9) and the monitoring campaign will last for one year, at least. Pervious shoulders will be constructed in May 2012.

Pervious concrete. Pervious concrete is a promising 'green' solution. Its mix design must incorporate the correct blend of aggregate that allows adequate drainage of recyclable rainwater.

From the photocatalytic point of view, this solution really offers high specific surfaces and corresponding high depolluting performances. However, pervious concrete does provide a lower compressive strength than that of conventional concrete, so that its use can be limited for specific road and pavement applications.

Other sustainable projects for road applications.

A photocatalytic wooden concrete was applied to a section of noise barriers along Highway 401, near the Highway 404 Interchange in Toronto, starting in the summer of 2011. For this study (which includes an air quality monitoring campaign over the course of one year), the Ontario Ministry of Transportation (MTO) is partnering with the Ministry of Environment, the University of Toronto, Armtec (a noise barrier manufacturer), and Essroc Italcementi Group, Figure 10 (http://www. dcnonl .com/article/id48919).

In the framework of Life+ European project "Photopaq", an experimental campaign was carried out in the "Leopold II" tunnel in Brussels (Belgium). For this test, a photocatalytic skim coat was applied on a partial section of the tunnel (about 100m) as well as a dedicated UV lighting system for activating the photocatalytic effect (photopaq.ircelyon.univ-lyon1.fr 2011).

Figure 9: Two-lift photocatalytic concrete paving, in Chesterfield, MO (October 2011)

Figure 10: Photocatalytic concrete walls in Toronto (October 2011)

A wide utilization of coatings and paints possessing depolluting properties seems to be particularly interesting for urban contexts, especially in case of their utilization close to busy roads and highways.

Conclusions

The experimental analysis carried out demonstrated that photocatalytic road materials could affect significantly air quality, reducing pollutant concentrations, through the beneficial presence of adequate photocatalysts. The large amount of measurements of nitrogen oxides abatements in laboratory as well as in situ, reported in this paper, have widely proved the enhancement of these kind of innovative materials and have created a linkage between results obtained in the two different contexts.

Concrete solutions here described seem to be very promising for the implementation of photocatalytic solutions. Paving blocks are already widely utilized; slurry-infiltrated open-grade asphalts, ultra-thin whitetopping and pervious concrete have a reliable quality but further experimental trials are needed to confirm their cost effectiveness.

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