

A Double Layered Photocatalytic Concrete Pavement: A Durable Application with Air-purifying Properties

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Abstract

Photocatalytic concrete constitutes a promising technique to reduce a number of air contaminants such as NO_x and VOC's, especially at sites with a high level of pollution: highly trafficked canyon streets, road tunnels, urban environment, etc. The use of a double layered concrete (or two lift concrete) provides a durable solution by allowing the insertion of photoactive TiO₂ in the top layer of the concrete pavement and recycled concrete aggregates in the bottom layer, without jeopardizing the durability of the pavement. In contact with light, the TiO₂ is activated and able to reduce different pollutants in the air. A double layered concrete with photocatalytic materials in the top layer has been constructed in March 2011. This was done in the framework of a broader environmental sustainability project ECO2PROFIT, which deals with reduction of the emission of greenhouse gasses and sustainable production of energy on industrial estates in the frontier area between Flanders and Holland. This paper focuses on the construction of the double layered concrete in Wijnegem and on the influence of different parameters on the photocatalytic efficiency of the pavement.

Keywords: Double layered concrete, photocatalysis; air purification.

Introduction

Emission from the transport sector has a particular impact on the overall air quality because of their rapid rate of growth: goods transport by road in Europe has increased by 54 % since 1980, while in the past 10 years passenger transport by road in the EU has gone up by 46 % and passenger transport by air by 67 %. The main emissions caused by³ motor traffic are nitrogen oxides (NO_x), hydrocarbons (HC) and carbon monoxide (CO), accounting for respectively 58 %, 50 % and 75 % of all such emissions [Goossens, 2006]. These pollutants have an increasing impact on the urban air quality. In addition, photochemical reactions resulting from the action of sunlight on NO₂ and VOC's (volatile organic compounds) lead to the formation of 'photochemical smog' and ozone, a secondary long-range pollutant, which impacts in rural areas often far from the original emission site. Acid rain is another long-range pollutant influenced by vehicle NO_x emissions and resulting from the transport of NO_x, oxidation in the air into NO₃- and finally precipitation of nitric acid with harmful consequences for building materials (corrosion of the surface) and vegetation.

Heterogeneous photocatalysis is a promising method for NO_x abatement. In the presence of UV-light, the photocatalytic active form of TiO₂ present at the surface of the material is activated by UV-light to abate the pollutants in the air. The translation from laboratory results to real cases is starting. Different applications are

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implemented in Belgium in order to see the influence of the photocatalytic materials on real scale and to determine the durability of the air purifying capacity over time.

Heterogeneous photocatalysis, a process for air purification

Air purification through heterogeneous photocatalysis consists of different steps: under the influence of UV-light, the photoactive TiO_2 at the surface of the material is activated. The use of TiO_2 in combination with cement leads to the transformation of among others NO_x into NO_3^- , which is adsorbed at the surface due to the alkalinity of the concrete, thereby creating a synergetic effect. Subsequently, the deposited nitrate will be washed away by rain. A more detailed description of the process as well as of the testing methods can be found in [Ohama, 2011].

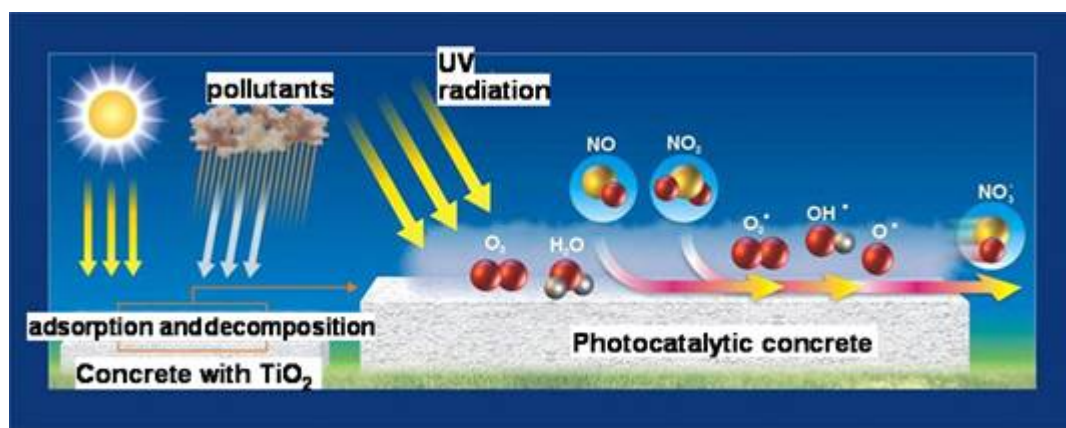


Figure 1 – Schematic of photocatalytic air purifying pavement (CTG).

In the case of concrete pavement blocks, the photoactive TiO_2 is added to the wearing layer of the paver which is approximately 8 mm thick. In the case of concrete pavements, the TiO_2 is added in the top layer (40 mm thick). The fact that the TiO_2 is present over the whole thickness of the upper layer means that even if some abrasion takes place by the traffic, new TiO_2 will be present at the surface to maintain the photocatalytic activity. This has been shown through the long-term results of the efficiency of the pavement blocks placed at the Ventwegen in Antwerp [Beeldens, 2008].

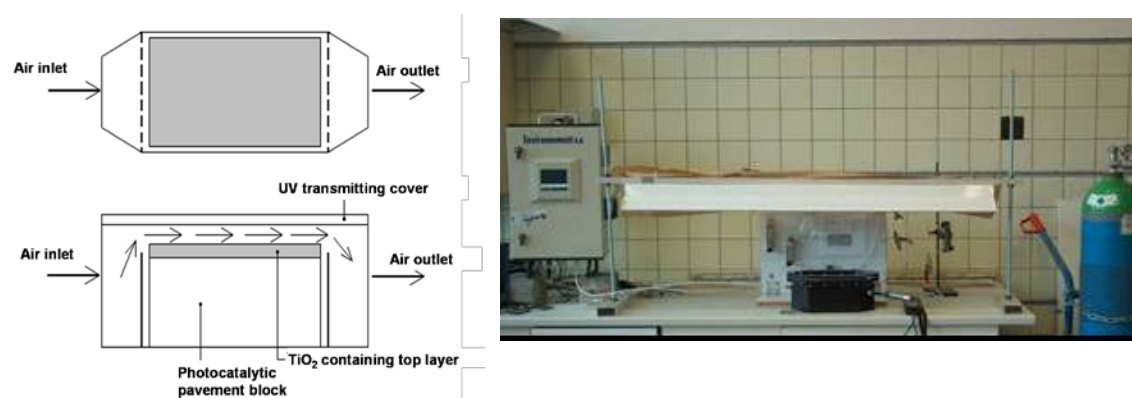


Figure 2 – Schematic and photo of measurement set-up according to ISO 22197-1 (2007) at the BRRC.

The efficiency of photocatalytic materials is tested in the laboratory according to different methods. In the flow-through method according to ISO 22197-1 (2007),

the air, with a concentration of 1 ppmV of NO, passes over the sample, which is illuminated by a lamp with light intensity equal to 10 W/m² in the range between 300 and 400 nm, as illustrated in figure 2. Afterwards, the NO_x (NO + NO₂) concentration is measured at the outlet. In the framework of the preparation of a European standard (CEN TC-386), a new testing method following the continuous stirred reactor principle is tested.

The influence of different test parameters affecting the photocatalytic reaction has been investigated such as temperature, light intensity, relative humidity, contact time (surface, flow velocity, height of the air flow over the sample...). In general, it can be stated that the reduction of NO_x is higher with a longer contact time (larger surface area, lower air velocity, smaller height of air flow, higher turbulence at the surface), a lower relative humidity and a higher intensity of incident light.

The relative humidity is also an important factor as is illustrated in figure 3. Clearly, the reduction of the NO_x concentration in the outlet air decreases with increasing relative humidity (RH). This has to do with the fact that the water in the atmosphere plays a role in the adhesion of the pollutants at the surface and with the competition effect that can arise between water molecules and NO_x in the air with increasing RH. Hence, the photocatalytic reaction is most efficient in dry environments.

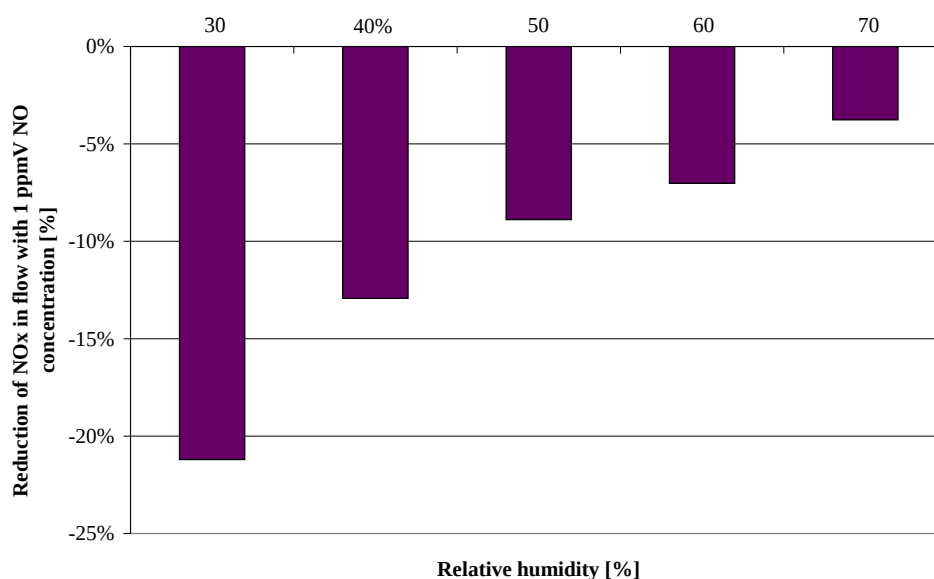


Figure 3 – Effect of relative humidity on photocatalytic efficiency.

Double layered concrete pavement as durable road construction

Double layered concrete pavements (DLCP) or two-lift paving constitute a technique by which a concrete top layer is placed wet-on-wet over a concrete bottom layer. This paving technique is optimal for the application of photocatalytic material in the concrete since it allows to limit the application of the (expensive) TiO₂ to the top layer. This will not jeopardize the efficiency of the photocatalytic material since it is only active at the surface of the material.

Scarcity of aggregates, advances in materials knowledge and construction equipment, and increasing demands for pavement surfaces that meet specific noise, durability and safety objectives are prompting the need to consider DLCP as a sustainable technique for building pavements. The thinner upper course makes it possible to use fine, hard materials in order to obtain a more important noise reduction

as well as a durable skid resistance. The thicker lower course allows the use of less noble and cheaper aggregates without jeopardizing the quality of the pavement.

In the framework of the INTERREG project ECO2PROFIT, a double layered concrete road pavement was applied in an industrial zone in order to obtain a sustainable pavement which helps to reduce the overall footprint of the industrial zone.

Optimization of the concrete composition toward air purifying capacities

Prior to the placing of the concrete on site, an optimization of the top layer was done in the laboratory. Three different types of photocatalytic materials were used: TiO_2 -containing cement, TiO_2 to be added during mixing to the fresh concrete and TiO_2 to be spread as dispersion on the surface of the dried concrete.

Incorporating the TiO_2 in the mass has the advantage of a more durable, but lower efficiency since the TiO_2 will continuously be present, even after wearing of the top layer. On the other hand, the initial cost will be higher (higher TiO_2 content, necessity for double layered concrete) and only the TiO_2 at the surface will be active. In contrast, dispersing a TiO_2 solution on the surface will provide a more direct action, and a lower initial cost (one layer concrete, normal cement). In this case, however, the longevity of the photocatalytic action could be questioned because of decohesion of the dispersion from the surface. Both solutions were studied in the preliminary phase of the project. Four different types of photocatalytic materials were tested: One commercially available photocatalytic cement, two types of TiO_2 to be added to the concrete mix and one dispersion to be put on the surface of the concrete after hardening. Besides the effect of the type of TiO_2 , the effect of the curing compound and of the surface finishing method were looked at. The most important conclusions are recalled here, more detailed results can be found in [Beeldens, 2011].

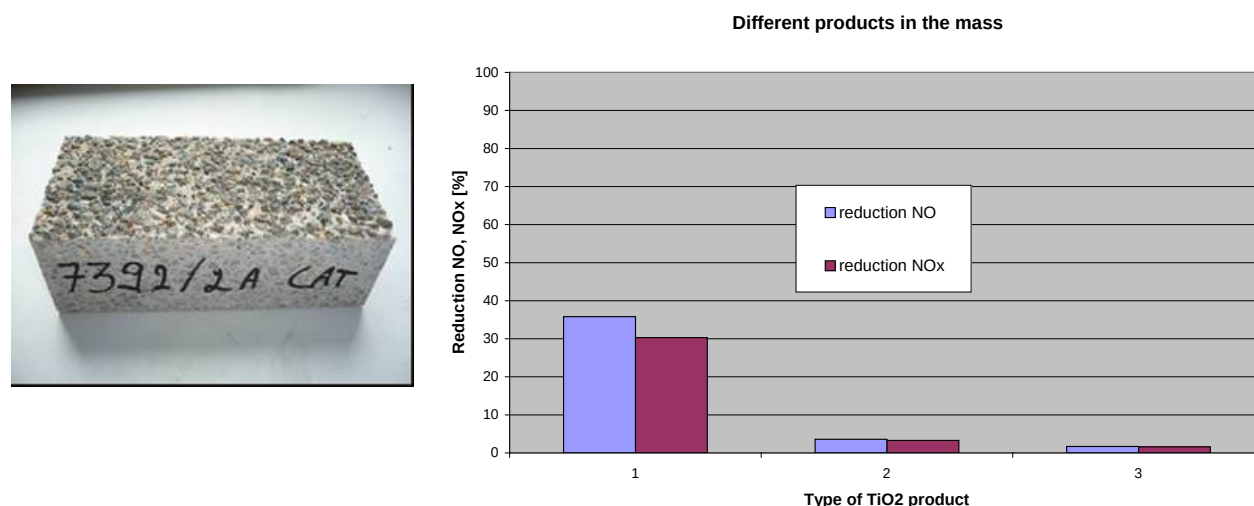


Figure 4 – Effect of different photocatalytic products mixed in the mass of the concrete (1 = commercially available photocatalytic cement – 2 and 3 = TiO_2 pigment added to concrete mixture) (no curing compound applied, washed out surface).

The addition of the TiO_2 to the fresh mixture has a large influence on the workability of the mixture. In some cases, no slump could be measured on the fresh mixture, even after addition of a large amount of superplasticizer. Also the influence of the type of TiO_2 on the air purifying capacity is an important factor, as shown in figure 4. This emphasizes once more the need for a European standard in order to be

able to check the efficiency the photocatalytic materials under controlled and comparable circumstances.

Also the application of a curing compound has a major effect on the immediate air purifying efficiency of the material, as is illustrated in figure 5. As was expected, the curing compound shields of the TiO_2 from the pollutants in the air. The efficiency will only appear after the curing compound is removed from the surface, i.e. by the influence of the traffic or by the degradation through the sunlight. As will be discussed further in the paper, the effect of the curing compound disappears after some months in use.

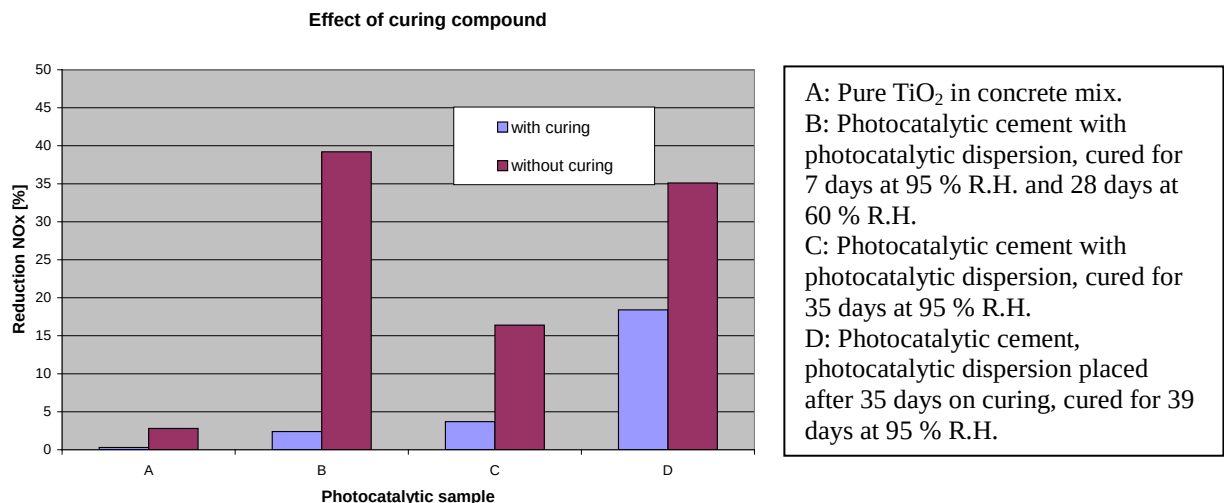


Figure 5 – Effect of curing compound on photocatalytic efficiency (different products, mass and/or dispersion, with and without curing).

To see the effect of surface treatment and more specifically of the exposed aggregates surface finish, a comparison among three different surfaces has been made: exposed aggregates, smooth (formwork side) and sawn surface, and this for one type of product. The results are depicted in figure 6. This shows that the exposed aggregates surface performs equally well as the smooth, formwork surface, but not as good as a sawn surface. This is the result of the combined action of less cement at the surface and higher surface porosity, two competing effects which in the end yield the final efficiency.

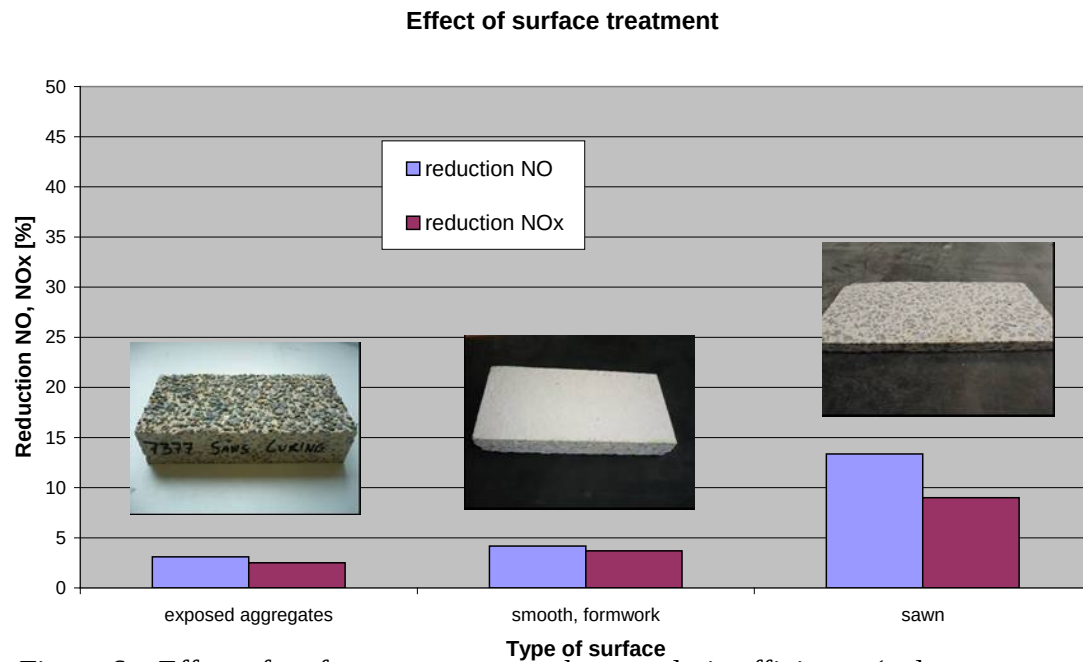


Figure 6 – Effect of surface treatment on photocatalytic efficiency (only one type of “less” active product in mass).

Based on these results and the optimization of the concrete composition, a proper selection of photocatalytic materials and of application procedures could be made, for the construction of double layered, photocatalytic concrete roads on the industrial zone “Den Hoek 3” in Wijnegem. A final choice has been made for the use of TiO_2 integrated in the cement. Additionally a zone will be covered with a TiO_2 dispersion. The sidewalks are onstructed with photocatalytic pavement blocks.

Double layered concrete at ‘Den Hoek 3’ in Wijnegem

Between the 15th and 18th of March 2011, the concrete pavement of the industrial zone in Wijnegem has been constructed. The concrete was placed in two layers, with an interval time of approximately 1 hour. The bottom layer had a thickness of 180 mm, the top layer as designed to be 50 mm. For the concrete of the bottom layer, 57 % of the coarse aggregates were replaced by recycled concrete aggregates. The composition of the concrete for the different layers is given in table 1. In order to cope with the cold temperatures (between 5 and 10°C), a mixture of CEM I (Portland cement) and CEM III/A (furnace blast slag cement) has been used for the top layer. For the top layer with TiO_2 , a commercially available cement with 4 % TiO_2 (by weight) is used.

Table 1 – Composition of the different concrete mixtures.

	Under layer	Top layer with titanium dioxide	Top layer without titanium dioxide
Porphyry aggregate 4/7		970 kg/m ³	972 kg/m ³
Sand 0/4 mm	699 kg/m ³	733 kg/m ³	732 kg/m ³
Recycled concrete aggregate 4/20	574 kg/m ³		
Crushed gravel 16/32	441 kg/m ³		
CEM I 42,5 N (white cement) with 4 % titanium dioxide		442 kg/m ³	
CEM I 52,5 N	94 kg/m ³		106 kg/m ³
CEM III/A 42,5 N LA	281 kg/m ³		319 kg/m ³
Water	199 kg/m ³	178,5 kg/m ³	178 kg/m ³
Air entrainer	0,50 l/m ³	0,25 l/m ³	0,30 l/m ³
Plastifier	2,10 kg/m ³	3,40 kg/m ³	3,40 kg/m ³

Two slip form pavers were used to place the concrete. As can be seen in Figure 7, the color of the top layer is much lighter, due to the use of white cement and the presence of the TiO₂.



Figure 7 – Construction of the double layered concrete pavement.

The prescriptions for the concrete were taken from the SB 250 (prescriptions and demands imposed by the Flemish Road Authorities) and classic measurements were made on the fresh concrete as well as on the hardened concrete. The workability of the concrete was tested according to the Belgian standard NBN EN 12350-2 by slump measurements.

The air content was also measured on the fresh concrete according to the Belgian standard NBN EN 12350-7 § 5 as well as the apparent density according to NBN EN 12350-6.

The compressive strength at 28 days was determined on cubes, 150*150*150 mm³, made on site and cured immediately after demolding under water at 20°C. The results of the tests on the fresh mixture as well as on the hardened mixture are given in Table 2. The test results are the average from the results obtained on 1 mixer for the top layer without TiO₂, 7 mixers for the top layer with TiO₂ or 2 mixers in the case of the under layer.

Table 2 – Test results on fresh and hardened concrete.

	Slump [cm]	Air content [%]	Apparent density [kg/m ³]	Compressive strength after 28 days [Mpa]
Under layer	22,5	3,7	2345	65,9
Top layer with TiO ₂	59	5,72	2300	61,68
Top layer without TiO ₂	55	5,7	2290	69,6

An overview of the project is given in figure 8. The 3 arrows indicate the position where cores are drilled in order to determine the water absorption and the photocatalytic efficiency.

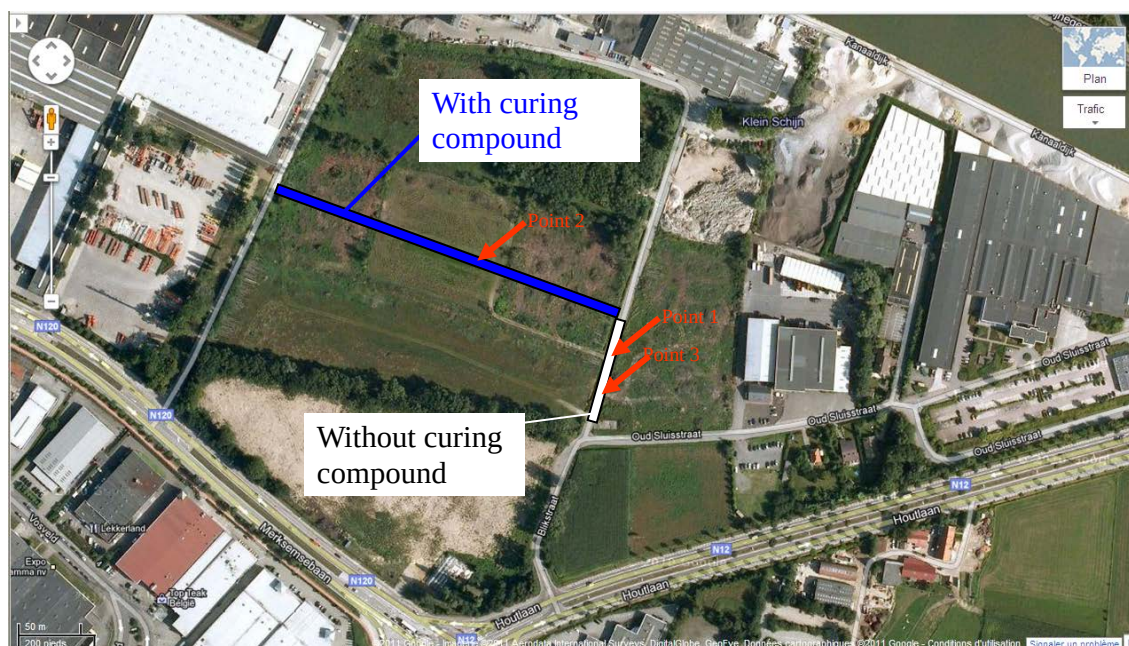


Figure 8 – Situation plan of the new industrial zone ‘Den Hoek 3’ in Wijnegem, Belgium [Google maps].

Immediately after placing the concrete, a retarder was added at the surface and the concrete was covered with a plastic sheet. After the top surface was washed out after 24 hours, part of the road has been covered with curing compound; part of the road was covered with a plastic shield in order to prevent dehydration of the concrete during the first days. By this, the influence of the curing compound on the short term and long term photocatalytic efficiency can be investigated. In a later stage a TiO_2 dispersion will be sprayed on the surface.

An average water absorption of 5,6 % in the case of the use of curing compound and 5,5 % in the case of the use of a plastic sheet for curing was measured. As can be seen in figure 9, a good adhesion between the top layer and the bottom layer was obtained. This is also confirmed by the pull-off tests, done on the test section.



Figure 9 – Core taken from the pavement.

The photocatalytic efficiency of the top layer was measured in two ways: in the laboratory on cores taken from the surface at the places indicated in figure 8 and on site with a special measuring box, shown in figure 10.

The on site box is developed in order to be able to evaluate the photocatalytic properties of the concrete pavement over time and to compare the different sites among each other. It does not measure the overall purification of the air around the pavement but enables to measure the durability of the photocatalytic efficiency. The on site measurement technique consists of a glass frame, which is screwed air-tight on the surface and is covered with a plexiglass, UV-transparent lid. The NO-concentration, the relative humidity and the air flow are taken similar to the laboratory test set-up, i.e. 1000 ppbV NO-concentration, 50 % R.H., and an air flow of 3 l/min. The total surface covered by the box is 700*300 mm². Natural sunlight is used to activate the surface.



Figure 10 – Measurement of the photocatalytic efficiency on site and in the laboratory, on cores taken from the site.

The results of the measurements on site are given in figure 11 for the measurements done on the surface which was covered with a curing compound and in figure 12 for the measurements done on the surface which was covered with a plastic sheet for curing. The measurements were done 5 months after the placement of the concrete, on the 17th and 18th of August, 2011.

The results indicate first of all a large influence of the relative humidity. The NO_x -abatement is lower when the relative humidity increases and higher when the NO_x -abatement decreases. The influence of the sun light intensity (measured through the UV intensity) is also visible, but on a different scale: variations over shorter time do not influence the NO_x concentration, it is the average sun light intensity over a longer period which is determining the NO_x abatement reached.

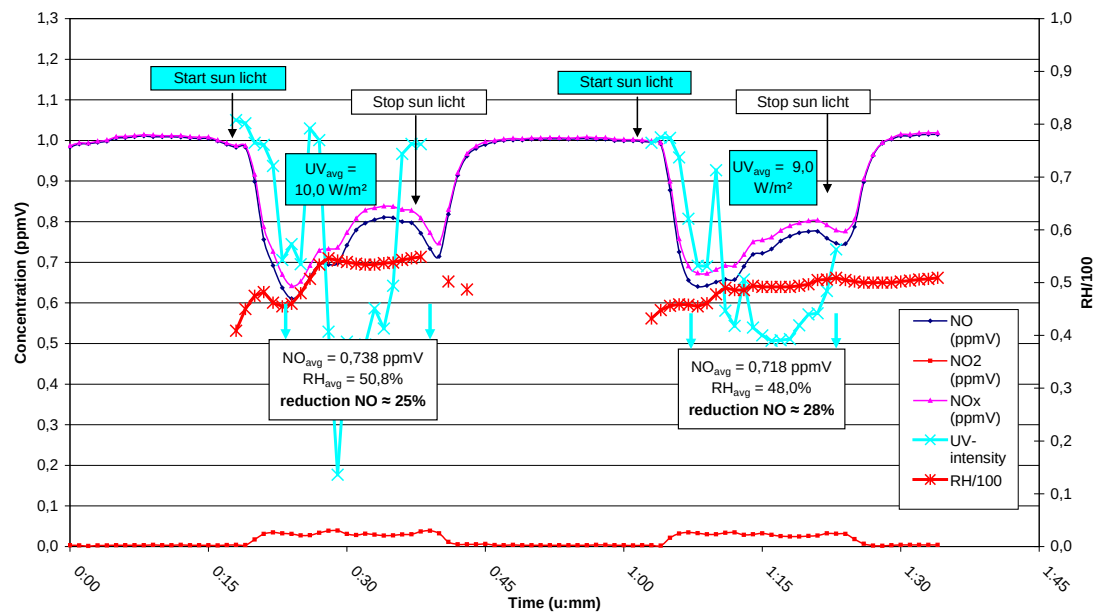


Figure 11 – NOx concentration measured at the outlet in the zone cured with a curing compound.

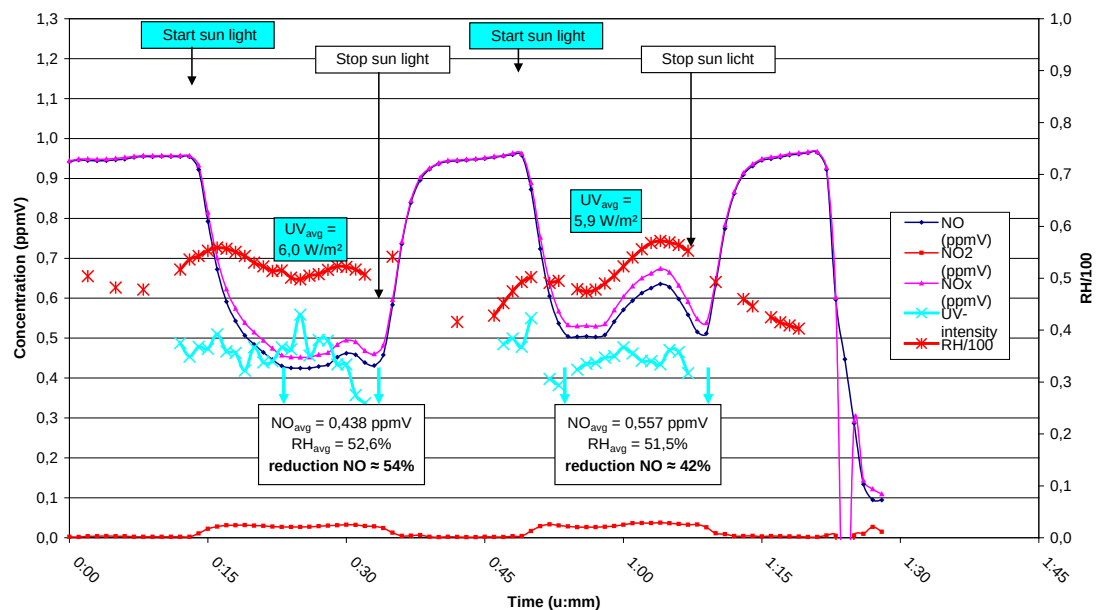


Figure 12 – NOx concentration measured at the outlet in the zone cured with a plastic sheet.

The results obtained on site are in line with the results obtained in the laboratory, taking into account the difference in surface, R.H. and light intensity. The measurements will be repeated over time in order to see the influence of ageing and of traffic on the photocatalytic efficiency.

Conclusions and perspectives

In the framework of the INTERREG+ project ECO2PROFIT, a double layered concrete road was constructed in an industrial zone. Almost 60 % of the coarse aggregates of the bottom layer were replaced by recycled concrete aggregates. The top layer contained TiO_2 in order to obtain photocatalytic activity to reduce the air pollution in that zone. An extensive laboratory research was done in order to optimize the photocatalytic efficiency and to determine the influence of different parameters such as the application of curing compound and the surface treatment of the concrete.

The curing compound will decrease the photocatalytic efficiency during the first months after application, but will disappear over time. The exposed aggregate technique is not ideal for the photocatalytic efficiency since in this case a lot of aggregates are present at the surface and the TiO_2 is only present in the paste. The application of a dispersion could lead to a better result. This will be tested in the near future.

The measurements of the photocatalytic activity on site showed promising results. An activity comparable to the activity measured in the laboratory is obtained. Measurements done in the future will have to confirm the durability of this efficiency.

These measurements will also indicate the influence of traffic and environment on the photocatalytic behaviour. New measurements will be carried out in the summer of 2012.

Acknowledgements

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