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Evaluation of the Environmental Impacts of Titanium Dioxide Photocatalyst Coatings for Pavements Using Life-Cycle Assessment

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ABSTRACT

The use of Titanium Dioxide (TiO_2) ultrafine particulates as coating for concrete pavement have received considerable attention in recent years as these coatings can trap and absorb organic and inorganic air pollutants by a photocatalytic process. Despite these promising benefits, the promotion of TiO_2 coatings based on a single factor such as air quality does not provide a complete evaluation of this technology and may omit critical environmental factors that should be considered in sustainable material selection decision-making process. The objective of this study was to determine the life-cycle assessment of TiO_2 coating technology. To achieve this objective, a life-cycle inventory (LCI) that quantifies the energy, abiotic raw material inputs, and emission of TiO_2 coatings from cradle to grave was developed. Based on this inventory, life-cycle impact assessment of TiO_2 coatings for concrete pavement was determined using the BEES impact assessment model. The use of titanium dioxide coating has a positive effect on four main environmental categories: acidification, eutrophication, criteria air pollutants, and smog formation. However, during production phases and due to the consumption of fossil energy, titanium dioxide will cause an increase in global warming, fossil fuel depletion, water intake, ozone depletion, and impacts on human health. Based on the overall environmental performance of this product, life cycle assessment shows that titanium dioxide coating has an overall negative score of -0.70 indicating that the addition of this surface layer will have an overall positive effect on the environment.

Keywords: Titanium dioxide, sustainable concrete pavement construction, life-cycle assessment, life-cycle inventory.

INTRODUCTION

Major forces like climate change and rapid depletion of resources have resulted in initiating a strong movement toward sustainability as consumption of raw materials has dramatically increased and air quality in the vicinity of large cities has been linked with serious health hazards to the public. As a result, air pollution has been gradually decreasing in recent years to reach its lowest level in 2003. Even though the economy has expanded by over 150% since the 1970s, the aggregate total emissions for the six major air pollutants (Carbon Monoxide [CO], Nitrogen Oxides [NO_x], Sulfur Dioxide [SO_2], Particulate Matter [PM], Volatile Organic Compounds [VOCs], and Lead [P_b]) have been cut from 301.5 million tons per year to 147.8 million tons per year (*1*). To further improve air quality, the federal government issued an executive order in 2007 to the Environmental Protection Agency (EPA) to cut greenhouse gas emissions from motor vehicles by taking action under the Clean Air Act.

In spite of the aforementioned accomplishments, air quality is still a major problem in many states including Georgia, Louisiana and California as the Air Quality Indicator (AQI) level of particle matter (PM 2.5) and ground level ozone frequently goes up to 200 indicating unhealthy conditions for the public (*2*). These high ground level ozone ratings are caused by nitrogen oxides and volatile organic compounds in the air which in turn are caused by high traffic volumes and combustors. Many organic compounds and air pollutants including nitrogen oxides and sulfur dioxide can be decomposed by Ultraviolet (UV) radiation but this process is extremely slow. Photocatalysis compounds such as titanium dioxide can accelerate oxidation and decomposition of organic and inorganic compounds extensively (*3*). Photocatalysis compounds can be utilized to construct air purifying concrete pavements by integrating titanium dioxide particles within the pavement surface. These particles can trap and absorb organic and inorganic particles in the air removing harmful NO_x gases in the presence of UV light (sunlight). Implementation of this technology by coating $7000m^2$ of road resulted in a 60% drop in nitrogen oxides concentration in the air in Milan in 2002 (*4*). In addition, their super hydrophilic properties allow them to self clean in the presence of rain.

Despite these promising benefits, the promotion of TiO_2 coatings based on a single factor such as air quality does not provide a complete evaluation of this technology and may omit critical environmental factors that should be considered in the selection of sustainable materials. This single-factor selection approach has long been used in the transportation industry to select products based on minimum initial cost or minimum life-cycle economic analysis. However, with the current trend towards sustainable construction, the deficiencies of conventional economic approaches became apparent and a life-cycle approach, known as life-cycle assessment (LCA), has been introduced to quantify the impacts of a product across its entire service life on the environment including climate change, fossil fuel depletion, human health, and acidification potential.

The objective of this study is to determine the life-cycle assessment of titanium dioxide coating that may be used in concrete pavement. To accomplish this objective, this study compiled a life cycle inventory (LCI) that quantifies the energy and emission of these coatings. Based on this inventory, life-cycle impact assessment of TiO_2 coating was conducted based on the Building for Environmental and Economic Sustainability (BEES) model, which was developed for life-cycle assessment of sustainable construction alternatives in the US. Life-cycle assessment was based on a hybrid life cycle methodology that followed both the International Organization for Standardization (ISO) 14040 standard for life cycle assessment and Input Output Analysis (IOA).

BACKGROUND

Life-Cycle Assessment

Life-cycle assessment (LCA), also known as cradle-to-grave analysis, is a methodological framework for quantifying the impacts and damages of a product or a service across its entire service life on the environment including climate change, fossil fuel depletion, human health, and acidification potential (*5*). Despite LCA is still an evolving methodology, it has found wide-spread applications in many areas such as auto-manufacturing, cleaning products, communication tools, and sustainable construction. As defined by the international organization for standardization (ISO) 14000 series, life-cycle assessment consists of four major steps (*6, 7*):

- **Goal and scope definition**, which provides a description of the system in terms of its boundaries and selection of a functional unit. The functional unit provides the basis of comparison between alternative products.
- **Life cycle inventory (LCI)**, which estimates the consumption of resources and the quantities of waste and emission associated with the production of titanium dioxide coating and its different components.
- **Life-cycle impact assessment (LCIA)**, which evaluates the impact of the product life-cycle in terms of selected impact categories. This may include factors such as global warming potential, fossil fuel depletion, impact on human health, and smog potential.
- **Life cycle interpretation**, which evaluates the results of LCIA by comparing the performance scores for all impact categories.

Despite its simplicity, the scope of LCA as defined by the ISO standard is limited due to the difficulty in obtaining reliable data in consumption and environmental releases associated with manufacturing processes and that cut-offs are needed in many cases (*8*). To address these shortcomings, economic input-output analysis (IOA) has been extended to assess the environmental impacts of manufacturing processes. This approach, which is based on the early work of Leontief (*9*), uses a matrix representation of the nation's economy to predict the effect of changes in one industry on others. Input-output analysis considers the relationship between the different economic sectors to determine how the output of one industry goes to another industry where it serves as an input. The economic outputs of the various industrial sectors were compiled in Input-Output (IO) tables that represent a fairly accurate representation of inter-industry flows (*10*).

While research had focused on determining the accuracy of IOA vs. conventional LCA, it appears that each approach provides a level of strength and weakness. While LCA utilizes specific data, it may provide an incomplete picture of a given technology due to cut-off practices that assume that components and processes with minimal mass representation may be omitted. In contrast, while IOA provides a complete representation of a given technology; the adopted data are less specific and aggregated. This has led to the development of hybrid analysis, which combines the strengths of both conventional LCA and IOA (*11*). Therefore, this approach was adopted in this research. Compilation of the required raw data was conducted manually and impact assessment was conducted based on the BEES 4.0 model.

The BEES 4.0 Model

The Building for Environmental and Economic Sustainability (BEES) model, which was introduced in the late 1990s by the National Institute of Standard and Technology, provides a systematic methodology to select sustainable construction alternatives that balance environmental and economic performances (*12*). Since environmental factors such as global warming potential and impacts on human health cannot be assessed using a regular monetary scale, the BEES model computes a single index for each considered factor in order to quantify the impact of a product on the environment. For instance, global warming potential is expressed in grams of carbon dioxide produced per functional unit of a product. The global warming index is calculated based on the following model:

$$\text{global warming index} = \sum_i m_i \text{ x } GWP_i \tag{1}$$

where,

m_i = mass (in grams) of harmful emission i per functional unit; and

GWP_i = conversion factor from one gram of harmful emission i to its equivalent of carbon dioxide.

Equivalency factors are provided by the BEES model based on research conducted by the U.S. Environmental Protection Agency. A similar approach is adopted for each environmental factor considered in the assessment process (*13*). In all, the BEES model considers 12 factors in its assessment of the net environmental effects of a construction alternative (see Table 1). Out of these 12 factors, two impacts were not considered in the assessment of photocatalytic titanium dioxide coating: Indoor Air Quality and Habitat Alteration. The reason for omitting the assessment of indoor air quality is evident as it is not applicable to outdoor construction activities. Habitat Alteration measures the potential for land use by humans to impact endangered species. It is mainly applied to assess the contribution of a product to landfills throughout its service life. Since the titanium dioxide layer will be applied to existing pavements, it was assumed that it may not increase the damage to endangered species.

In the interpretation phase, calculated impact performance measures are normalized with respect to fixed U.S. scale impact values. Normalized performance measures are then synthesized based on a set of weights reflecting the importance of each environmental factor as perceived by the user or the society. In this study, weights developed by the 2006 BEES Stakeholder Panel were re-calculated to reflect that the Indoor Air Quality and Habitat Alteration categories were not considered in our evaluation. These modified weights, which are presented in Table 1, reflect the importance of fossil fuel depletion, ozone depletion, ecological toxicity, air pollution, eutrophication potential, and acidification potential. Applying these weights provides a single performance score for the environmental impacts of a given product. A lower score indicates a technology that is more sustainable and environmentally-friendly and a negative score indicates that the product has a positive impact on the environment.

TABLE 1. Environmental Impact Factors Considered in the BEES Model

ID	Environmental Impact	Reference Substance	Description	Weights (%)
1	Global Warming	Carbon dioxide	Increase in temperature due to greenhouse gases	29
2	Acidification	Hydrogen ions	Affects all ecosystems	5
3	Eutrophication	Nitrogen	Undesirable shifts in ecosystems	6
4	Fossil Fuel Depletion	Surplus Megajoule (MJ)	Depletion of fossil fuel extraction	11
5	Indoor Air Quality	Not Considered		
6	Habitat Alteration	Not Considered		
7	Water Intake	Water	Water intake during production and service	8
8	Criteria Air Pollutants	Years of life lost	Particles leading to respiratory diseases	11
9-1	Human Health (noncancerous)	Toluene	Noncancerous health concerns	5
9-2	Human Health (cancerous)	Benzene	Cancerous health concerns	8
10	Smog Formation	Nitrogen oxide	Harmful effects on human health and vegetation	4
11	Ozone Depletion	CFC-11	Thinning of the ozone layer	3
12	Ecological Toxicity	2,4-D	Harm terrestrial and aquatic ecosystems	10

Titanium Dioxide

Titanium dioxide is produced by the wet sulphate process or the dry chloride process from ilmenite or rutile (*14*). The chloride process mixes natural or synthetic rutile with coke and chlorine to produce titanium tetrachloride and impurities are removed as chlorides. The resulting pure titanium tetrachloride is burnt in an oxygen flame to form titanium dioxide (TiO_2) and chlorine. These processes produce large size particulate materials (220-300nm). To produce nano-sized titanium dioxide particles, the intermediate product of the chloride process titanium tetrachloride vapor is oxidized in a flame aerosol reactor with organic precursors and organic compounds. Hydrochloric acid is sometimes circulated for regeneration of chlorine. In these processes, the particle growth is stopped by quenching the flame inside a critical flow nozzle of 1.5mm diameter which results in particle size with 5nm diameter (*15*).

Titanium dioxide particles crystallize in two forms, anatase and rutile. Anatase is a meta-stable phase that transforms into rutile at high temperatures (*16*). Research has shown that titanium dioxide in the anatase phase is a more powerful photocatalyst than rutile in environmental purification (*17*). Anatase titanium dioxide under UV-light can be used to remove harmful organic toxics and pollutants from the air and aqueous environments including nitrogen oxides (NO_x), ammonia, volatile organic compounds (VOC) including toluene, sulfur oxides (SO_x), and chlorophenol (*18-21*). Therefore, recent studies have attempted to utilize it as concrete pavement coating to purify the air (*22*). To accomplish this, ultrafine/nano titanium anatase particles are mixed with cement, water, and aggregates to produce a thin surface layer that is applied to concrete pavements and used for air purification. In the presence of light, the pollutants are oxidized and precipitated on the pavement surface. These pollutants are then removed from the surface by rain using a self-cleaning process.

Evaluation of concrete pavements treated with titanium dioxide provided promising results as recent research shows that a thin surface coating is able to remove a significant portion of NO_x and SO_x pollutants from the atmosphere when placed as close as possible to the source of pollution (*22*). The efficiency of this technology depends on the size of the surface exposed, the concentration of pollutants, the light intensity, and the ambient temperature. Porosity of the surface is also important as the NO_x removal ability is improved as the porosity is increased. Photocatalytic activity decreased by approximately 8% with aging of the surface but stabilized at the age of 90 days (*23*).

A number of studies evaluated the effects of titanium dioxide on concrete strength and durability (*24*, *25*). The use of titanium dioxide as nanofiller was reported to increase strength, improve concrete density and durability, and reduce its porosity. In one study, titanium dioxide added as 1% of the concrete binder increased the abrasion resistance of plain concrete by as much as 180% (*24*). However, the use of a high content of titanium dioxide may adversely affect the abrasion resistance of the produced concrete mixture.

PROBLEM FORMULATION

A life-cycle inventory (LCI) was developed for a titanium dioxide coating to provide a compilation of the energy requirements, material inputs, and the emissions associated with its extraction, production, installation, use and end of life options. Prior to development of the LCI, the system boundary, which defines the limits of the life-cycle inventory, was set. Figure 1 presents the system boundary for the developed life-cycle inventory.

As shown in Figure 1, the developed LCI considers energy and emissions associated with the manufacturing of titanium dioxide, production of aggregate, plant operations, cement and surface mix production, and titanium dioxide coating placement (including transportation to the site and site worker transport). However, the developed LCI does not consider energy, materials, and emissions associated with the production or construction of the supporting concrete pavement. In addition, it does not consider energy associated with the production of fuels known as precombustion, or energy associated with manufacturing of equipment needed to produce titanium dioxide. Emissions associated with background processes including production of fuels and equipment were quantified using Input-Output life cycle assessment.

For the purpose of this study, the surface mix thickness was assumed to be 5mm and the nominal maximum aggregate size used in the mix was 2.36mm. In addition, it is assumed that the surface mix consists of ultrafine titanium dioxide anatase, cement, filler (sand with a maximum nominal size of 2.36mm), and water in the ratio of 0.1:1:3:0.4 and is applied on the pavement surface. These mixture properties were based on lab tests conducted to quantify the air pollutants removal rate (*23*).

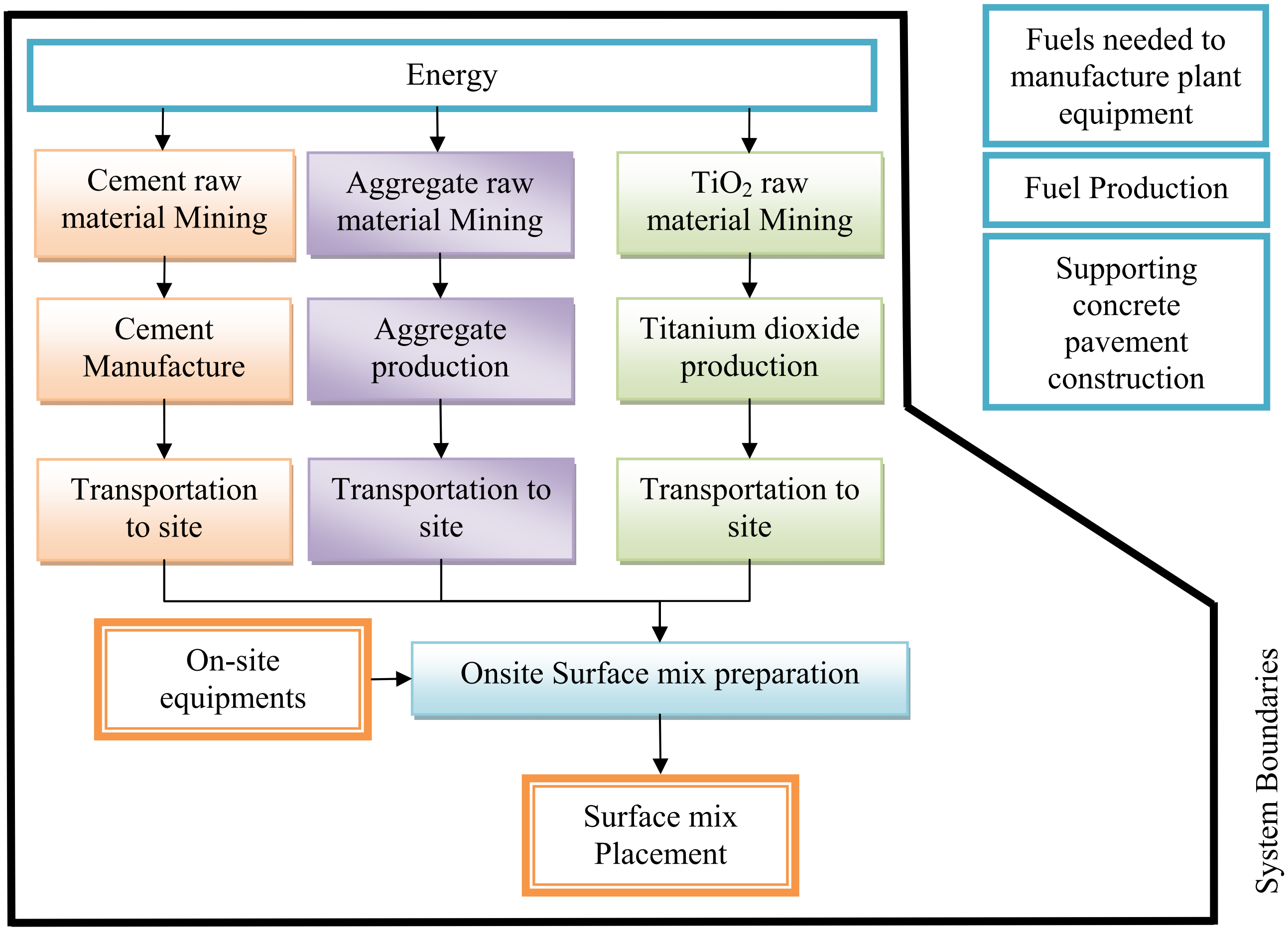

FIGURE 1 Titanium dioxide coating system boundary

Data Sources

A wide range of published reports and databases were reviewed to identify energy and emission data for each process and activity defined as part of the system boundary. Table 2 presents the general sources of data for each main process identified in the life-cycle inventory. Whenever data was limited or not available, the economic input output life cycle assessment (EIO-LCA) model developed at Carnegie Melon was used (*26*). This model calculates the economic and environmental impact from production across the entire supply chain in any of the 491 commodity sectors in the US economy. The net environmental impact of the titanium dioxide coating was calculated as follows:

Net Environment Impact = Environmental Impact of the Surface Mix – Environmental Purification Effect of the Mix (2)

While a number of environmental damages are associated with the production of the titanium dioxide surface coating and its components, the use of this technology is expected to contribute positively to the purification of the atmosphere during service. Therefore, a negative net environment impact as predicted from Equation (2) would indicate that the use of this technology is beneficial to the environment. In contrast, a positive net environmental impact as predicted from Equation (2) would indicate that this technology has an overall detrimental effect on the environment. The functional unit considered was the mix needed to cover one lane-kilometer of pavement surface (3.2m x 1000m). It is worth noting that energy consumption was divided in terms of the type of fossil fuel used (i.e., natural gas, fuel, and coal) since the rate of fuel depletion differs from one type to the other.

TABLE 2 Sources for Energy and Emission Data

Process	Data Type	Source	Reference
Aggregate production	Energy	U.S. Census Bureau	(*27*)
Aggregate production	Emission	U.S. EPA Fire Database	(*28*)
TiO_2 Manufacture	Energy	Osterwalder et al. 2006	(*29*)
TiO_2 Manufacture	Emission	Input Output Analysis	(*26*)
Concrete surface mix Production and Installation	Energy	Concrete LCI Report	(*30*)
Concrete surface mix Production and Installation	Emission	Input Output Analysis	(*26*)

Cost Data

In a competitive industry like the construction industry, it is very important to quantify the economic performance of the proposed titanium dioxide coating. Therefore, ultrafine/nano titanium dioxide producers were contacted. Contacts with the producers showed that the average market price of this technology was $15/kg. Based on the selected surface mix design, this translates into an added cost of $4.3 per m^2 of surface mix or an added cost of $17.1 per m^3 of installed concrete pavement assuming a concrete layer thickness of 254mm. Assuming a concrete cost of $420 per m^3, the use of titanium dioxide coating will result in an added cost of approximately 4% per m^3 of installed concrete. As the interest in this technology increases especially in the neighborhood of large metropolitan areas, it is expected that the unit cost of titanium dioxide coating will significantly decrease as this technology has the potential of achieving economy of scale.

RESULTS

Table 3 summarizes the results of the hybrid life-cycle inventory analysis developed for titanium dioxide coating considering a functional unit of one lane-km. Results of this analysis are presented for the surface mixture and titanium dioxide production separately as well as for the whole product. It is worth noting that environmental impacts and energy consumption presented in this table relate to all the processes taking place during production including manufacturing of the individual components such as cement manufacturing, aggregate mining and extraction, transportation, etc.

TABLE 3 Energy Consumption and Emission Releases during Production of Titanium Dioxide Coating

Effects	Concrete Mixture	Titanium Dioxide	Total
Conventional Air Pollutants (tons)	0.053	0.170	0.223
Greenhouse Gases (tons of CO_2 equivalents)	3.117	23.16	26.28
Toxic Air Releases (kg)	1.630	75.80	77.43
Energy (MJ)	685.4	837	1522.4

Figure 2 presents the normalized environmental burdens and relieves associated with titanium dioxide coating in a logarithmic scale. Environmental burdens relate to the manufacturing processes taking place during production, construction, and installation of this product. Environmental relieves relate to the ability of this product to purify the atmosphere during service. As shown in this figure, the use of titanium dioxide will have a positive effect on acidification, eutrophication, critical air pollutants, and smog formation. During production phases and due to the consumption of fossil energy, titanium dioxide will cause an increase in global warming, fossil fuel depletion, water intake, ozone depletion, and human health. However, based on the overall environmental performance of this product as predicted from Equation (2), life cycle assessment shows that titanium dioxide coating has an overall negative score of -0.70 indicating that the addition of this surface layer will have an overall beneficial effect on the environment.

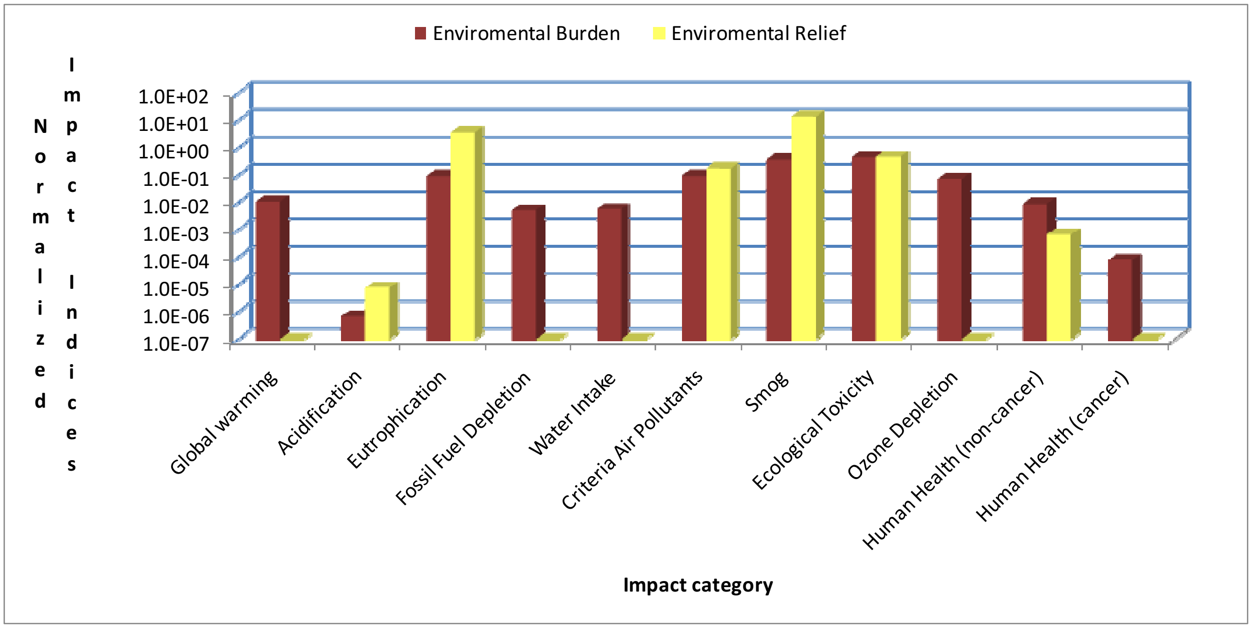

FIGURE 2 Environmental burdens and relieves of titanium dioxide coating

With respect to smog formation, titanium dioxide coating reduces the emission of nitrogen oxides and toluene to the atmosphere. These pollutants react with sunlight to result in detrimental effects on human health and vegetation. With respect to critical air pollutants, titanium dioxide coating reduces the emission of nitrogen oxides, which relate to combustion activities and traffic operations. The reduction of these pollutants help avoid aggravate respiratory conditions such as asthma. With respect to eutrophication, titanium dioxide reduces the emission of ammonia, nitrate, and phosphorus. These pollutants cause an increase in algae growth, which consumes significant portion of the oxygen under water and leads to death of other species such as fish. With respect to acidification, titanium dioxide absorbs nitrogen compound and ammonia. These pollutants affect the health of humans, trees, and animals.

It is worth noting that the environmental burdens associated with titanium dioxide as shown in Figure 2 are not significant but are nonetheless considered sources of concerns that should be assessed for the viability of this technology. For instance, the normalized impact index for global warming associated with the production and installation of normal concrete required for one lane-km is 3.92. Therefore, the increase in global warming potential due to the use of titanium dioxide coating is only 0.07%. Similarly, Figure 3 presents the increase in the environmental impacts of normal concrete when titanium dioxide coating is used. These results indicate that while titanium dioxide may effectively purify the atmosphere from harmful pollutants such as nitrogen oxides (NO_x), toluene, and ammonia, its contribution to the overall environmental impacts of concrete construction is minimal.

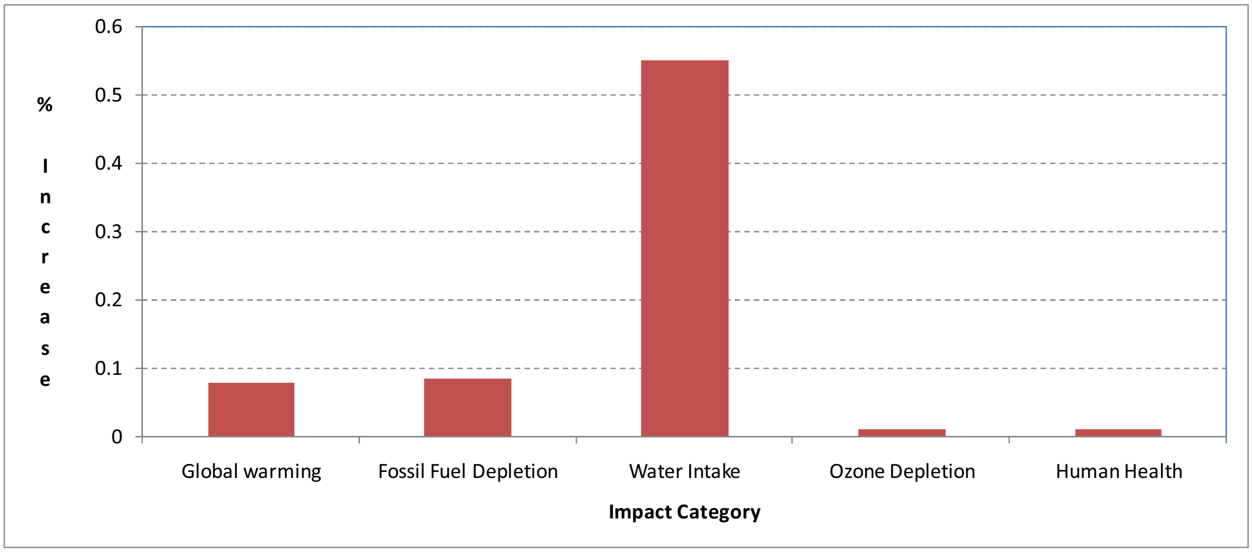

FIGURE 3 Contribution of titanium dioxide coating to the overall environmental impact of concrete (1 lane-km)

CONCLUSIONS

The use of titanium dioxide coating for pavements has received considerable attention in recent years to improve air quality in the vicinity of large metropolitan areas. Despite its promising benefits, the promotion of titanium dioxide based on a single factor such as air purification, does not provide a realistic and complete evaluation of this technology and may omit critical environmental factors that should be considered in the decision-making process. Therefore, this study adopted a life-cycle assessment methodology to quantify the environmental impacts of this technology. Life-cycle assessment was based on a hybrid life cycle methodology that followed both the International Organization for Standardization (ISO) 14040 standard for life cycle assessment and Input Output Analysis (IOA). Based on the analysis conducted, the following conclusions may be drawn:

- The use of titanium dioxide coating has a positive effect on four main environmental categories: acidification, eutrophication, criteria air pollutants, and smog formation. However, during production phases and due to the consumption of fossil energy, titanium dioxide coating will cause an increase in global warming, fossil fuel depletion, water intake, ozone depletion, and human health.
- Based on the overall environmental performance of this product, life cycle assessment shows that titanium dioxide coating has an overall negative score of -0.70 indicating that the addition of this surface layer will have an overall positive effect on the environment.
- The use of titanium dioxide coatings is considered a positive improvement and support further evaluation of this technology. However, in order to achieve full potential of the technology further fate and exposure studies are needed to quantify the effects and quantities of by products resulting from the photocatalysis process and to determine the toxicological effects of nano particles such as titanium dioxide.

This study represents a first step towards evaluating the ecological footprint of ultrafine/nano materials in construction applications and guiding the development of new ultrafine products towards a net reduction of resource requirements and emissions. Based on the results presented in this study, further research is recommended to consider factors omitted in the analysis such as maintenance and rehabilitation activities, end-of-life recycling options, and variation of adopted data with project size and location. Research is also needed to quantify effects of byproducts resulting from purification and long-term effectiveness of this technology.

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