3D Printed Pollution Absorbing Materials for Urban Environments

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INTRODUCTION

The goal of my research is to minimize health risks due to air pollution through the research and development of 3D printed pollution absorbing architectural materials. The World Health Organization states that 2.4 million people die each year from causes directly attributable to air pollution. Global populations suffer immensely from the impacts of both primary and secondary air pollutants, leading to an increase in respiratory diseases, skin diseases, eye-infections, and blindness. In urban environments, air pollution will continue to rise as vehicular traffic, construction projects, and global temperatures increase.[1] Hydrocarbons, nitrogen oxides, and particulate matter pose great risk to human health and safety when concentrated in human level respiratory zones. The overall objective of this research seeks to define prototypical pollution absorbing materials, to be adopted by the Architecture Engineering and Construction [AEC] Industry for application.

TiO2 Materials

The photocatalytic properties of TiO2 were discovered in 1972 by Dr. Akira Fujishima et al; paving ground for researchers and scientist to incorporate TiO2 into composite materials as an additive for imbedding sustainable properties in common construction materials.[2]

One of the first pollution absorbing materials to be sold commercially came as an additive to paint. TiO2 has been used for many years as a common pigment in white paint, but was discovered recently to also have photocatalytic properties in nano-scale form. TiO2 has been used in other architectural materials as an additive for 'self-cleaning' and 'air purifying' qualities. Self-cleaning glass was developed by Pilkington Glass in 2004 under the trade name of 'Activ™"; these surfaces work with the addition of a nano coating of TiO2 that exhibits photocatalytic properties. In 1997 the Mitsubishi Company developed a concrete paving unit "Noxer Block™" that is used to absorb pollution and has been used for many years on select streets of Italy and Japan.

Though these pollution absorbing designs use a standard set of traditional materials and forms, they lack a layer of architectural geography: design of form in relation to the nature of pollution. 'Geography' is essential to this research, and is used to address *where and what type of pollution* is found surrounding a buildings façade.

This research of AEC materials that can incorporate performance additives such as TiO2, seeks to address the following:

- *What geographic zones contain the highest concentrations of air pollution (e.g. street canyons, façade surfaces)*
- *What composites or materials enhance or degrade the addition of photocatalytic TiO2 additive?*
- *What surface design is best suited for the absorption of air pollution?*
- *What are economic and sustainable methods of manufacturing pollution absorbing materials?*

Other performance qualities of the TiO2 additive material include: self-cleaning, anti-fouling and antibacterial traits that are inherent to the catalytic process.[3] [4]In theory the prototype should also exhibit self-cooling characteristics and insulative values through the use of high light diffraction and high porosity. These qualities are imbedded in the material and form exhibited through the utilization of white Portland cement and the addition of a cast porous substrate.[5]

It is important to note that the prototype pollution-absorbing surface will last indefinitely, as the photo-catalytic properties of TiO2 do not degrade with time.[6]

Project Background

This paper represents the subject of a faculty research grant, awarded by the American University of Sharjah for the 2008-2009 academic year, as a collaborative effort between the principle author and mechanical engineer, Dr. Ahmed Farahani, Ryerson University. Preceding research projects at VergeLabs, included surveys of *material performance* in architecture; for example, research approaches architecture with postulations regarding pollution absorption through *form* (e.g. shape, scale and surface), material *composition* and *architectural location*. The background of this project stems from prior research of material porosity and pore utility in concrete. Materials with porosity alone exhibit traits such as insulative values, lightness and economy. These traits can be witnessed in high performance materials such as, aerogel composed of 99.8 percent air and 0.2 percent silica dioxide.[7] Aerogel, being one of the world's lightest materials also exhibits insulative values "…39 times more [insulating] than the best fiberglass."[8]Within the context of environmental traits that are sought within this research, these pores exhibit properties that are useful to pollution absorption lamination composites, by lending more surface area in the photocatalytic process.

Fabrication Method

The method of fabrication my research explores, is the use of 3D printing to laminate composite base and additive materials. By placing successive layers of the pollution absorbing additive onto material surfaces, the printer builds a three dimensional object. This method is economically driven as it generates little waste, accommodates a variety of potential materials, and provides a high degree of accuracy. Digital models can be designed to specifically and precisely locate performance materials within or on a base material. These precise locations are determined by research of the finished unit's architectural location, or 'geography'. For example, if a structural building unit is designed to absorb air pollution from a *street canyon,* design considerations would include:

- Thickness of the concrete base material, for structural integrity
- Performance additive located on the one exterior surface only (does not include the mortar bed face)
- Life expectancy of host building versus material economy
- Physical bond between concrete base, porous substrate, and additive layer
- Surface durability concerns

APPROACH

A brief survey of TiO2 was conducted to acquire knowledge of market uses and locations of raw Titanium material. Noted in the Titanium World Report, half of the global resource of TiO2 is mined in Australia and over forty percent is mined in Brazil. While there are large deposits of TiO2 globally, there is also a high consumer demand for this resource, forcing prices to steadily increase. Economically driven, this research has explored what the least amount of TiO2 is needed to perform pollution absorbing characteristics.

Titanium is consumed worldwide for applications in pigments used in paint, cosmetics, paper goods, and plastic; a small percent is used for photocatalytic materials. The remaining percentage is used as welding rod and raw metal.

Three crystal formations of TiO2 are found naturally; however the anatase type has proven to be the best exhibitor of photocatalytic phenomena. The pollution absorbing trait is enhanced with the addition of mineral carbonates by providing additional chemical reactions and a physically bonded location for the deposition of TiO2.

The diagram below shows how anatase TiO2 "absorbs" pollution in a chemical reaction with concrete, ultra-violet light and precipitation to transform pollution into harmless nitrate salts (Figure 1). After catalization, the salts remain on the surface of the TiO2 until they are washed away.

Composite Design and Surface Characterization

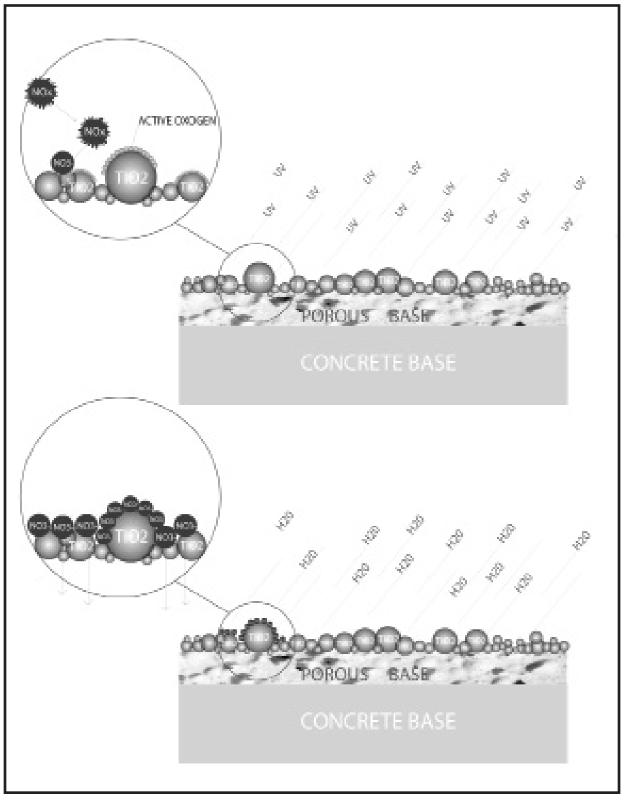

Figure 1: TiO2 and Concrete Photocatalytic Reaction, source: (Author 2009)

Analog design was conducted in the form of surface drawings translated into digital surfaces. Digital surfaces were designed and modeled using McNeel Rhinoceros 3D and Autodesk 3D Studio Max for output by the 3D Printer. Design considerations included understanding how materials found in nature absorb pollution. (e.g. The lotus leaf has a hydrophilic surface allowing its surface to be "self-cleaning") The designed surfaces were then studied for hydrophilic properties, as the cycle of pollution absorption includes precipitation 'washing' the harmless salts from the surface.

Initial research of material interactions, performance synergistic effects, and the CNC method of material deposition, revealed certain possible forms within fabrication size restrictions. As a surface, the performance TiO2 laminate can be added upon a host base material, such as a pre-existing concrete brick. This proposal is economical and efficient, especially within the context of the global community, where concrete is a primary building material. The added deposited surface is designed in thickness for areas with higher concentrations of pollution. Other considerations include the physical and chemical bond to the pre-existing concrete unit. This host surface must undergo a series of adaptation (e.g. cleaning, casting porous substrate) before it can be placed in the 3D printer. The micro geographic context of material surface is explored, which includes: overall form, topography (for larger surface area), and physical bonds between concrete base, porous substrate and TiO2 deposition.

Designed surfaces consist of micro-topographical terrains. This is an essential method of form generation, as increased surface area exposed to the polluted environment physically interacts with larger amounts of pollutants. Digital models are designed to specifically and precisely locate performance materials onto the concrete base material. These precise locations are determined by research

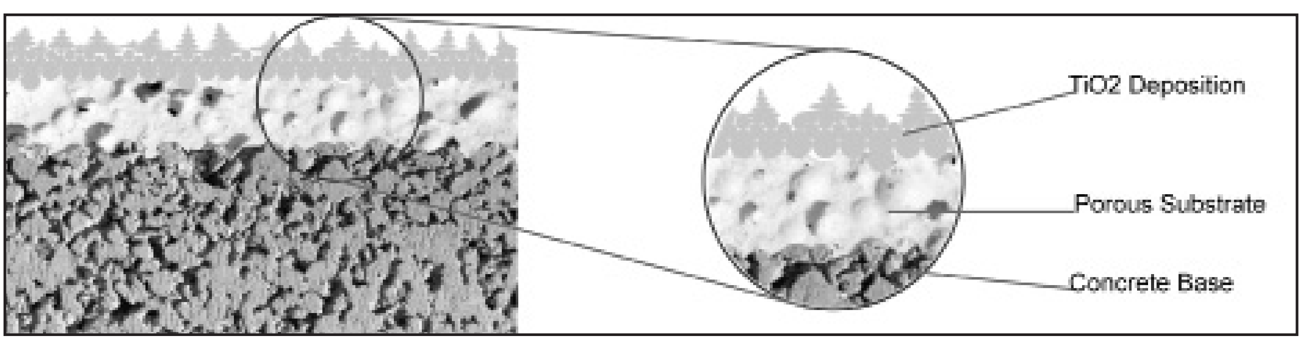

Figure 2: Composite lamination illustrating micro-topography source: (Author 2009)

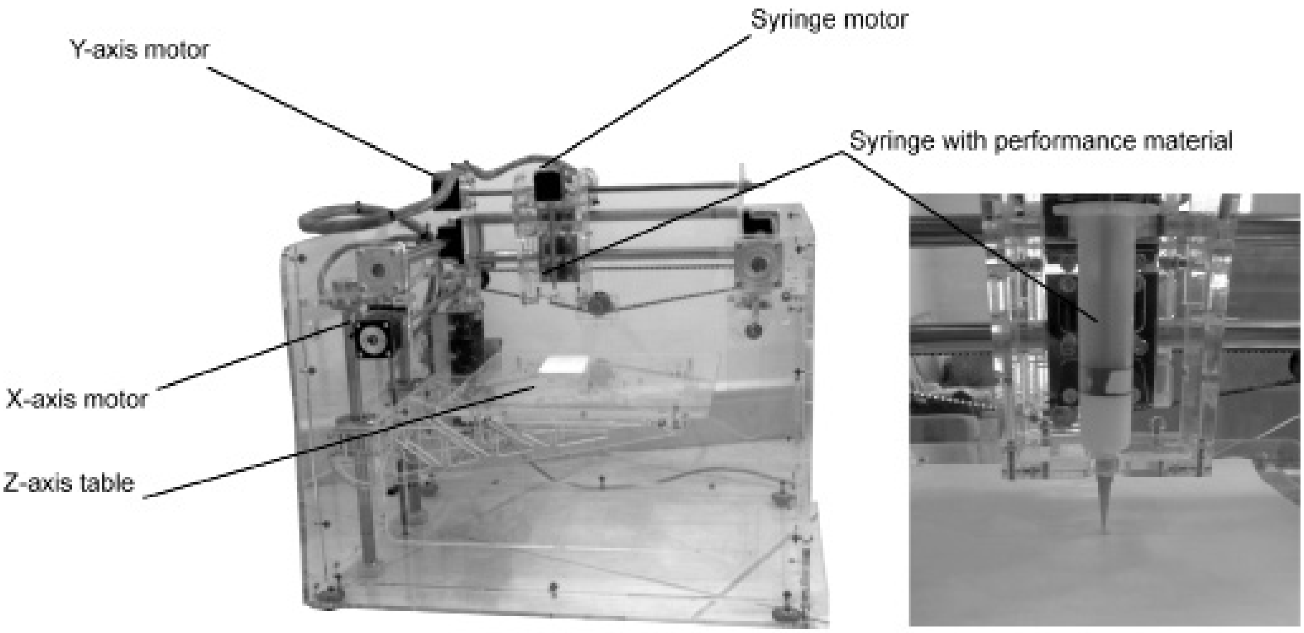

Figure 3: 3D Printer, source: (Author 2009)

of the finished unit's architectural location, or 'geography'. The surfaces are manufactured in "dots" and aggregate to form the topographical surface as illustrated in (Figure 2). The performance material does not cover the entire base unit, rather is located precisely where needed. Background for this research includes the study of organisms and plants that are located through conditions, e.g. tree branches extend outward and upward seeking the best light.

Fabrication and Assembly

A desktop 3D Printer was first fabricated from a series of open source instructions. Software used to run the 3D printer is also open-source and modified for the purposes of this research.

The components of the 3D printer include x, y, and z motors to move the carriage side to side and up and down (Figure 3). A motor also moves the piston in the syringe to 'deposit' material in the form of a dot onto the concrete base surface.

Mix ratios for the TiO_2 material are tested for moisture, fluidity and composition. The addition of concrete accelerators and retardants are explored to find the best suited mix for rapid manufacturing; additives explored are all natural forming compositions to insure sustainability. Changes are made in the software to reflect the materials composition including the speed of the carriage motors and syringe plungers. The composition of the performance material includes: Kronos Worldwide LLC Titana nano TiO_2, $CaSo_4$ [binder], and tap water.

Architectural Design

Upon the knowledge of understanding limitations of the 3D Printer, and nature of the pollutants; architectural designs are achieved through the notation of several design considerations. Criteria that determine the overall architectural design include, but are not limited to:

- Climate
- Heat Index
- Pollution Behavior and Typology
- Pollution Concentration
- Air flow
- Surface Area
- Hydrophilic surface action
- Human interaction

The location selected for this research is found in street canyons with the pollution absorbing material located in human respiratory zones. Urban environments with tall buildings framing a street can cause pockets of pollution to form due to vehicu-

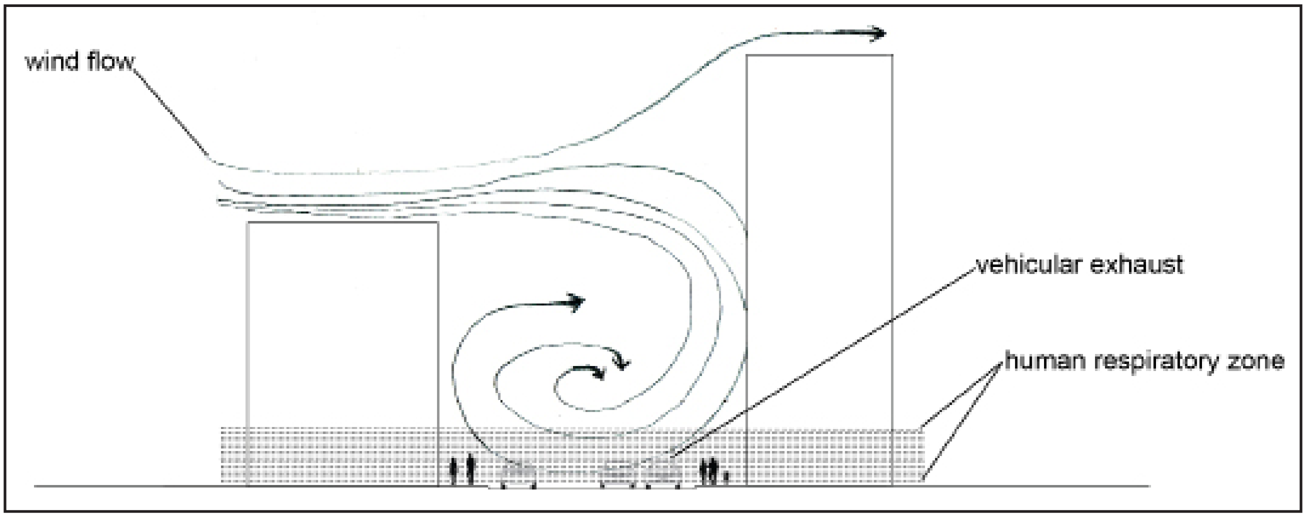

Figure 4: Street Canyon, source: (Author 2009)

lar exhaust.[9] Pollution in a street canyon becomes trapped within the human respiratory zone as noted with the wind current (figure 4).

Ideal façade locations for the pollution absorbing material are illustrated in (figure 5). In climates with high heat, pollution can pose a greater health risk. This diagram illustrates a southern façade, which could potentially be clad with the pollution absorbing material [rendered in Figure 5 as white dots] thereby absorbing more pollution from the environment.

As previously mentioned, the pollution absorbing material printed onto individual units, does not cover the entirely of the material, rather is deposited where necessary.

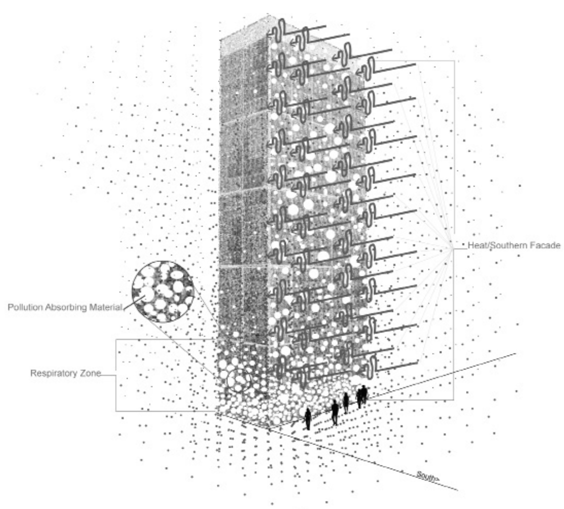

Figure 5: Southern Façade source: (Author 2009)

OUTCOMES

Traditional concrete bricks used as base units were procured in the local market [Dubai, United Arab Emirates] measuring: 20cm x 10cm x 6cm.

Three test surfaces were prepared with 2mm, 3mm, and 5mm porous substrates consisting of white Portland cement, filler sand and a natural foaming agent. After curing the surfaces were lightly sanded for leveling purposes in preparation for the 3D Printer (Figure 6). Brick surfaces untreated with the porous substrate have an R-Value of .80 [Colorado Energy] The addition of the porous substrate adds and estimated .2 R-Value per mm of insulative value.

3D Printer Assembly and Testing

When using the 3D Printer, surface models need to be designed in accordance to the machines capabilities in fabricating with a low viscosity cement material. Deposition surface tests were made to explore surface form and properties of the 3D printer (Figure 7).

Fabrication tests are currently in progress with the 3D printer on gypsum surfaces prior to test with

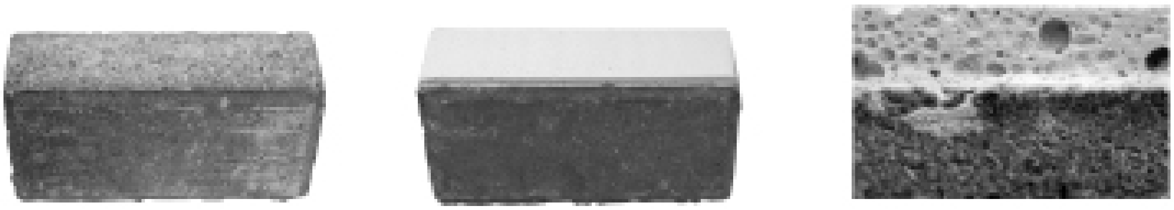

Figure 6: Base Unit preparation process with porous substrate and detail, Source: (Author, 2009)

prepared base units. Software adjustments for the specific deposition material are being made to reflect viscosity, flow, path speed, path height, path width and deposition rate. This process is time consuming and dependent on a variety of ambient factors including, temperature and humidity.

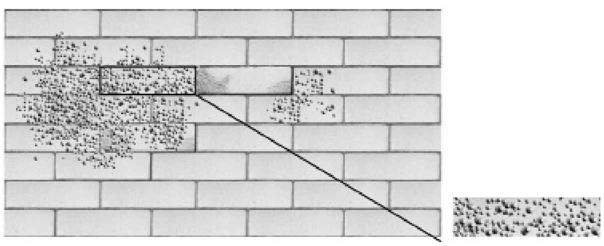

Figure 7: Deposition test tile illustrating micro-topography height and detail, Source: (Author, 2009)

Façade Design

Façade designs are also designed in the macro scale, as the material surface changes over time, displaying the amount of pollution collected; visually expressing the material's behavior. Through honest expression of actual performance, the material's appearance results from its positive environmental impact; posing an extension of social consciousness into the built environment. This perspective differs from our granted perception of material performance, whereby we see materials functioning silently.

This material interaction takes place on a chemical scale as well as the physical dust shelf collection. As the photocatalytic process takes place, the converted pollution remains on the surface until washed away (Figure 8). This phenomenon allows for an opportunity to design for this 'capture' in the form of micro-topographic shelves and overall form.

Goals

My research is currently in preparation of short-run production for testing in-situ. Field tests located in street canyon environments will lend new data in regards to overall performance and comparative evaluation. My research seeks to absorb pollution in the form of particulate matter and reduce the PM concentration by 70 to 20 micrograms per cubic meter. In-situ tests as well as laboratory tests will be conducted with the final fabricated prototypes to indicate the volume of pollution collected. Efforts are currently underway to reduce the time necessary to prepare and print each surface on prepared base units.

As *street canyons* and southern facades in hot climates would benefit from pollution absorbing materials, there is also potential for additional AEC applications including non-load bearing screens used in parking garages, where high levels of pollutants are concentrated within and released into our respiratory zone.

CONCLUSION

It is integral to the development of sustainable practices that we as designers and scientists have true understandings of potential solutions that contend with our context of pollution. There are many synergistic benefits the use of TiO_2 extends to the AEC industry beyond pollution control: desiccant systems and antimicrobial surfaces are already common applications used in the industry.[10] It would be a great benefit if more than one performance could be embodied in one material, leading to fewer materials used in construction, and less construction demolition waste in landfills. Part of the nature of 3D printing is the versatility of multi-material matrix, where many materials can be utilized.

This research will continue fabricating additional prototypes with more material composites. The ap-

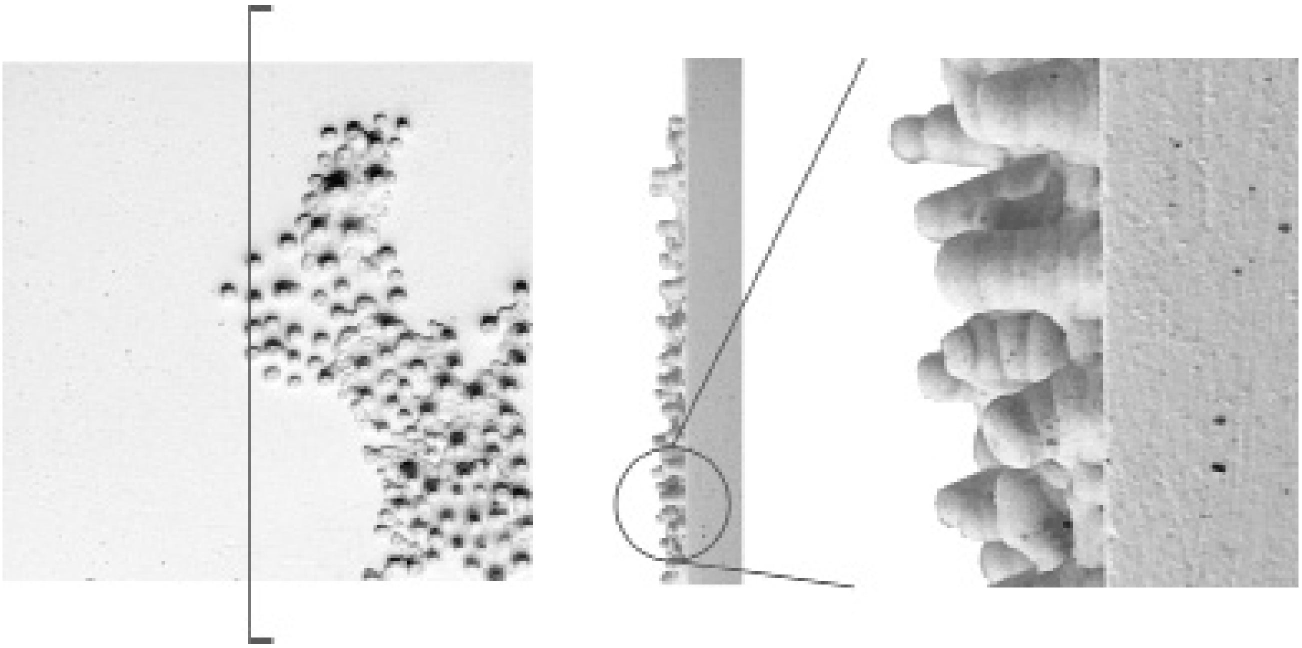

Figure 8: Macro illustration of varying micro-topographical tiles, Source: (Author, 2009)

propriation of economy of means within design and science is critical for achieving a more environmental, ecological and humanitarian environment.

Importance to AEC Industry

Air pollution rises with increased temperature, making the warmer climates more susceptible to associated health risks. The current global climate crisis requires a reconsideration of materials used in construction projects.

Each year large sums of money are spent on building maintenance, including the monetary and environmental expenses of washing the exterior facades. These prototypes not only absorb pollution, but also maintain self-cleaning properties due to the photocatalytic process.

The use of digital fabrication technology is becoming more ubiquitous worldwide in architectural construction and manufacturing. This fabrication method allows for materials and components to be more precise while reducing manufacturing waste. 3D Printing also allows for mass customization. Within unit design, algorithmic generators could tailor form and surface to specific local environmental conditions.

Benefits of this research include increased human safety through material appropriation. These prototypes will provide cleaner air, lower building maintenance, and life cycle responsibility, as the materials are biodegradable and do not contain toxic coatings or hazardous waste.

Cleaner air is essential to overall human health, when used efficiently these prototype materials could reduce healthcare cost for respiratory problems, especially for individuals living or working in high dense urban environments.

Potential Applications

Based upon the results of finding appropriate locations for the use of performance lamination composites, there are potential architectural geographic locations with concentrated areas of high pollution:

- Buildings located within street canyons (see figure 4)
- Building façade walls (Located at street level)
- Vehicular infrastructure (Retaining walls)
- Interior tiles (Wall and Floor)
- Exterior tiles (Wall and Pavement)

CAPTIONS AND FIGURE CREDITS

Figure 1: TiO2 and Concrete Photocatalytic Reaction, source: (Author 2009)
Figure 2: Composite lamination illustrating micro-topography source: (Author 2009)
Figure 3: 3D Printer, source: (Author 2009)
Figure 4: Street Canyon, source: (Author 2009)
Figure 5: Southern Façade source: (Author 2009)
Figure 6: Base Unit preparation process with porous substrate and detail, Source: (Author, 2009)
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ENDNOTES

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