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Clean by Concrete: Use of Photocatalytic Concrete enables Buildings to be Passive Environmental Remediators

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Abstract

It is assumed today that buildings should contribute positively towards energy and environmental sustainability. However, few buildings aim to remediate the environment and even fewer aim to do so with passive non-mechanical means. Emerging research in photocatalytic architectural concrete has drawn a renewed attention to the role that building facades can play in contributing toward the profession's sustainable goals while improving value. We will report on the work carried out by a team comprised of faculty from Architecture and Environmental engineering that incorporates environmentally derived design and innovative photocatalytic concrete into the design of a panelized concrete façade.

Keywords: Clean, concrete, photocatalytic, concrete, buildings, passive, environmental, remediators.

Introduction

Urban air pollution is a problem of growing magnitude. Densely populated urban centers suffer from compounded urban industrialization, high density use of internal combustion vehicles, and burning of fossil fuels for energy generation, among others. Air remediation efforts have mostly been legislative or over-reliant on new technology. While higher standards and regulations for building use, materials, and methods have made significant progress in air pollution reduction, existing and new architectural technology has yet to fulfill its potential.

In view of the undeniable probability that we will face a dire environmental transformation in our lifetimes, more than ever we need a creative involvement with technology and its role in architectural design. An example of an innovative use of existing technology is the use of photocatalytic concrete additives in architectural and structural applications. Activated by light, photocatalytic cement reacts with common air pollutants, such as volatile organic compounds (VOCs), carbon monoxide, nitrogen and sulfur oxides, aldehydes, benzenes and chlorinated aromatic compounds. The resulting inert nitrates can be washed of manually or by rain. Research into photocatalytic cements has been progressing over the last several decades, however, this emerging technology is commercially available mostly in paving products, whose applications have been proven promising in decomposing urban air pollutants such as nitrogen oxides (NO_x).

Background of Photocatalytic Cements

As early as the 70's, titanium dioxide (TiO_2) was identified as a photocatalyst[1]. A photocatalyst is a substance that when exposed to light accelerates a chemical reaction. During exposure to UV-light TiO_2 forms oxidizing holes and photogenerated electrons, which create highly oxidative and reductive constituents. Included in these oxidative constituents are hydroxyl radicals (OH●). When VOCs are exposed to hydroxyl radicals from a photocatalyst, the VOCs can be completely destroyed. Additionally, as long as the photocatalyst is exposed to UV light, the UV-light/ TiO_2 photochemical reaction continues to yield oxidative and reductive constituents in perpetuity. Titanium dioxide (TiO_2) is a non-toxic material widely used in personal care products and paints as a white pigment. When producing photocatalytic concrete, the conventional Portland cement, silica sand, crushed stone, and water are mixed – but the addition of TiO_2 in levels reported between 3-5% gives the resulting concrete photocatalytic properties. Besides direct mixing of TiO_2 powder into concrete, a number of other techniques have been used often resulting in poorsubstrate adhesion and inconsistentphotocatalytic performance in aggressive outdoor environments[2].

The cement contains titanium dioxide, which acts asa photocatalyst activated when exposed to daylight. The photocatalytic reaction converts hazardous NOx into harmless NO3. On a sunnyand clear day the process can eliminate up to 90% of air pollutants. In cloudy skies when the UV radiation is low up to 70% of the pollutants can still be eliminated. The photocatalytic reaction does not consume the photocatalyst and is carried out in perpetuity[3]. The accumulated nitrates, dirt, and organic debris inhibit the efficiency of the reaction – the exposed surface must be clean in order to perform.

In addition to the significant environmental benefits of eliminating air-pollutants, using photocatalytic cement allows for reduced clinker content, resulting concrete is comparable in

strength to Type I early-strength concretes and can have relatively high reflectivity. The use fophocatalytic concrete can have sensible application in projects requiring not only concrete environmental protection and but, perhaps more significantly, environmental rehabilitation.

Approach

Our team used a computer algorithm that utilizes data from site conditions to modify a given surface geometry for maximum photocatalytic activity. In resulting computer simulations we were able to show a substantial increase in photocatalytic reaction. Consequently, physical photocatalytic panels were fabricated, tested for photocatalytic activity, and the results compared to initial computer simulations.

The inspiration for the developed method of design comes from a common north-eastern winter effect: in the sunny days that follow a heavy snowfall a peculiar melting pattern is often developed. Trees, fence posts and rails modulate the amount of sun hitting the ground snow - the variable sun exposure within an opaque frame creates a wave-like topology of now, (figure-1).

Figure-1
Environmentally controlled topologies (Copyright: Authors)

This undulating topology is the result of the interplay of the incident solar energy and the thermal inertia of the snow - the crests have absorbed less energy, while the opposite is in effect in the valleys. The parameters that determine the tangents of incline and inflection are related to the site's longitude and latitude, the receiving surface orientation relative to north, duration of solar exposure, and others. In relation to these observations, weset out to utilizesite-specificdata as a means of customizing a particular surface for optimal solar exposure. Further, climate data such as yearly or daily *incident solar radiation, absorbed and transmitted solar energy, and photosynthetically active radiation*, is available from local weather stations and can serve to extrapolate additional design information[3].

Panel generation

Our team determined the test lab location and chose 07/26/2013 as the design test day, (table-1).

Table-1
Design Parameters

	Test Location Latitude: 40°36'16.46"N
	Test Location Longitude: 75°21'38.85"W
	Test Date: 07/26/2013

Parameters like geographic coordinates, design test day, and a panel orientation from North, are entered into a modified version of code by Ted Ngai[4] and integrated into *Grasshopper*[5]. The codeuses publicly available solar calculation algorithms, which enabled us to analyze the daily incident solar radiation amounts and determine that the highest amount of radiation over a day (sunrise to sunset) will fall on a plane with a normal vector, n(max), at 174.58° azimuth, az(n), and 79.52° elevation, el(n), (figure-2).

The above normal vector is used to construct a panel surface of a limited number of tangents, (figure-3). At this point the panel is generated in absolute units.

Fabricating the Test Panel

First, we printed a 3d master panel and fabricated a silicone mold. We cast the design panel, Panel Type A, at 65°F and Relative Humidity of 85%. An additional flat panel, Panel Type B, of identical dimensions was cast for comparison. We prepared the concrete mix using a cement to aggregate ratio of 1:3 and a water to cement ratio of 0.3. The fabricated panels

were de-molded 24 hours after casting and water-cured for 72 hours.

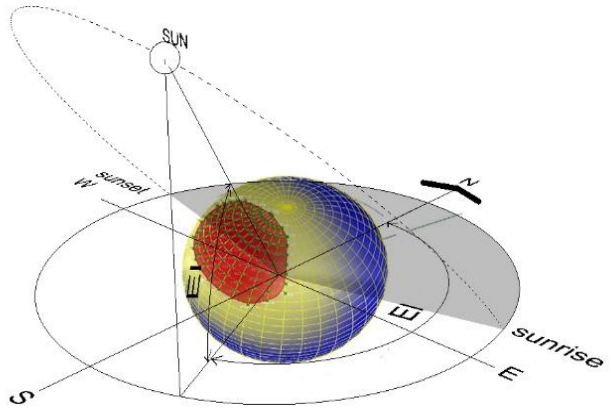


Figure-2
Maximum daily cumulative radiation, in red is shown surface receiving 90% of total daily incident solar radiation (Copyright: Authors)

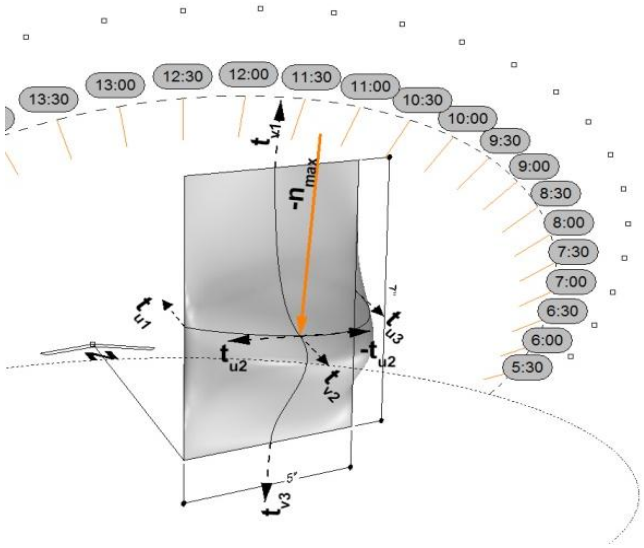
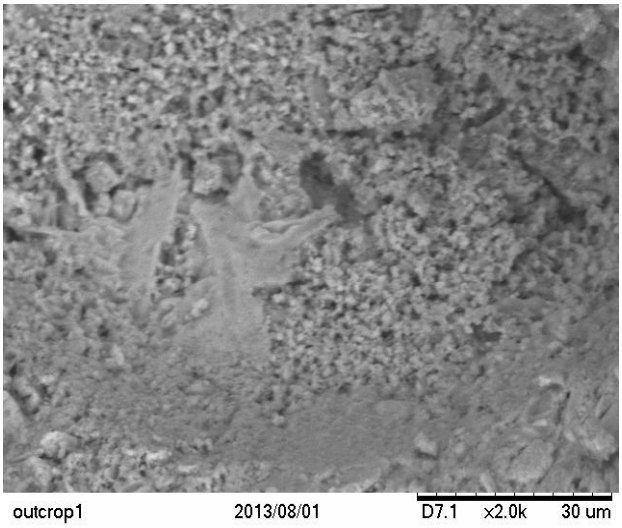


Figure-3
Panel Generation – the surface is constrained by a limited number tangents and face normals, modeled in Rhinoceros® (Copyright: Authors)

SEM-EDS Concrete Analysis

To determine the chemical content of our working concrete, and particular the quantity of TiO_2, we took Scanning Electron Microscopic (SEM) photos of the cured titanium dioxide concrete with a Hitachi TM-1000 Tabletop Microscope equipped with Energy-dispersive X-ray spectroscopy (EDS). We took SEM photos of the concrete samples at 180x and 2000x magnification, (figure-4). The samples were analyzed for elements by using the EDS coupled with SwiftED-TM software, version 1.3. The EDS acquisition conditions were 120 seconds, 15.0 kV accelerating voltage, and for quantification all the elements were normalized.



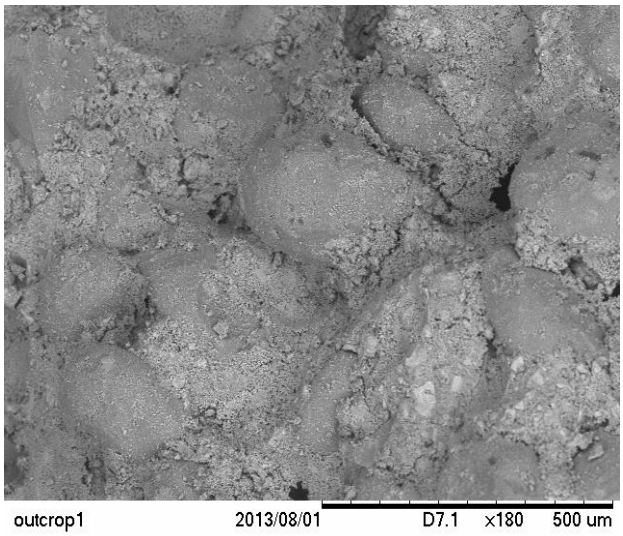


Figure-4
Scanning Electron Microscopic (SEM) photos of prepared titanium dioxide concrete at 180 magnification, left, and at 2000 magnification, right (Copyright: Authors)

SEM-EDS Results

The titanium dioxide concrete sample measured 10.2% by weight for titanium. However, it should be noted that these are normalized values, and oxygen is not detected. For example, silicon is detected from sand, and the silicon is quantified at 29.9% instead of the mass portion which would truly be attributed to silica (silicon dioxide). Therefore, the 10.2% titanium value is considered on the mass basis of all other

elements, which exclude oxygen as part of the mass fraction, (Table-2)

Table-2
EDS Summary results for 180x magnification view of Titanium Dioxide Concrete

Element	Weight %
Aluminum	2.2
Silicon	29.9
Sulfur	2.1
Calcium	55.7
Titanium	10.2

Testing for Catalytic Activity

Rhodamine B is a biodegradable tracer dye that can be used to evaluate the color change following exposure to sunlight. Studies suggest that either photon absorption or direct photolysis enable Rhodamine B dye degradation. Therefore, the change in dye color intensity with respect to panel geometry can be used as an indicator of the efficiency of the photocatalytic panel. The panel with the greatest dye degradation would indicate the panel with the greatest photocatalytic capacity for air pollution removal.

Following procedures outlined by Chen et al, we prepared a 1 mmol Rhodamine B solution with distilled water and dip-coated the panels to evaluate the color change in dye on the surface following exposure to sunlight[6]. Sigma Aldrich supplied Rhodamine B. The panels were air-cured for 72 hours at room temperature.

We placed the prepared panels on the roof top of the lab, ensuring direct solar radiation would reach the panels unobstructed by trees and the glare from adjacent buildings. The panels were exposed to sun-light from sunrise to sunset on the test date. We took measurements from the surface of each specimen at 30 min intervals from start of irradiation, (figure-5).

During the time of exposure to sun light, from sunrise to sunset on the test date, we took RAW images at 30 min intervals with a Cannon D5900 camera equipped with a Variable Neutral Density filter[7]. The color changes of the Rhodamine B dye were expressed in CIE LAB colorimetric coordinates[8].

We took measurements from 9 fixed sampling points on the surface of each test panleat 30 min intervals from start of solar exposure. Then, we averaged the nine measurements at a specified time and calculated the color variation (ΔE) as follows:

$$\Delta E = [(\Delta a)^2 + (\Delta b)^2 + (\Delta L)^2]^{1/2},$$

where Δa, Δb, ΔL were the differences of coordinates a, b, and L before irradiation and at the specific time of irradiation.

The color variation (ΔE) of the Rhodamine B dye applied on the TiO_2 panels type A and B are illustrated in the figure below,(Figure 6). It is clearly observed that for the flat Panel Type B, most of the color change happened in the first 1.5 hours, after which the color change increased minimally. The opposite was observed with the designed PanelType A. The color change in the Panel Type A kept increasing during the first 3.5 hours of exposure to irradiation at a higher rate than that of the flat Panel Type B. We establish that not only the rate of color change was higher and lasted longer, but the Panel Type A changed color 44.6% more than the plat panel. This is aclear indication that Panel Type A photocatalysed the Rhodamine B dye more efficiently than Panel Type B.

Applications

An important observation is that the panel's performance is not related to the size of the individual panle but to the total area of surface available for photocatalysis in the panel assembly. For instance an array of smaller panels will have an identical amount of surface area with exposure to radiation than that of a single panel with dimensions equal to the overall array of small panels. The size of the panel can respond to aesthetic considerations or be derived from typical construction material dimensional modules, but for the purposes of testing for photocatalytic activity the panels size is not significant.

Scaled Prototype

We produced a physical mock-up of the panelized concrete surface with overall dimensions 6ft x 6ft, figure-5. We resisted assigning a particular scale to the prototype - it served as a test for the tectonic and aesthetic implications of applying the panel system at various scales. We observed that the panelized system had a pattern whose properties were governed by the strictly oriented topology of the initial panel, (figure-7).

Topological Equivalency

Using the previously established panel as a prototypical model, a we developed a derivative surface that is topologically equivalent in both vertical and horizontalaxes – this allows it to perform in terms of photocatalysis identically on each side and regardless of the direction of its vertical orientation, (figure-8).

We compared the Grasshopper simulations of the topological surface compared against a vertically oriented flat surface of equal overall dimensions and saw a 13.57% increase of surface area and an overall increase of total surface available for photocatalysis. In addition, 76.45% of surface area of the proposed panel has higher exposure to radiation than the flat panel of equal overall dimensions. 13.58% of the proposed surface is exposed to 75% of total accumulated daily radiation.

As we mentioned earlier, the above performance comparisons are not affected by proportional changes in overall size of panels.

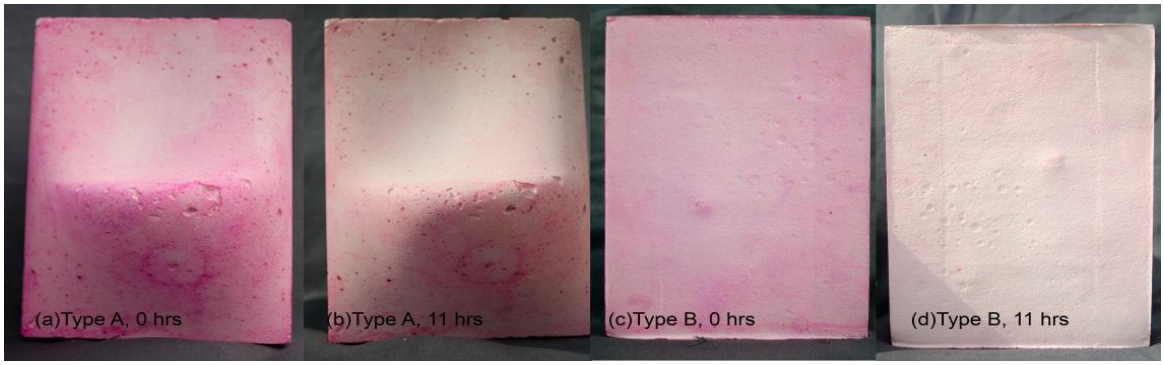


Figure-5

The color variation of Rhodamine B coated TiO_2 test panels: (a) flat panel before test, (b) flat panel after 11 hours of solar exposure, (c) design panel before test, (d) design panel after 11 hours of solar exposure (Copyright: Authors)

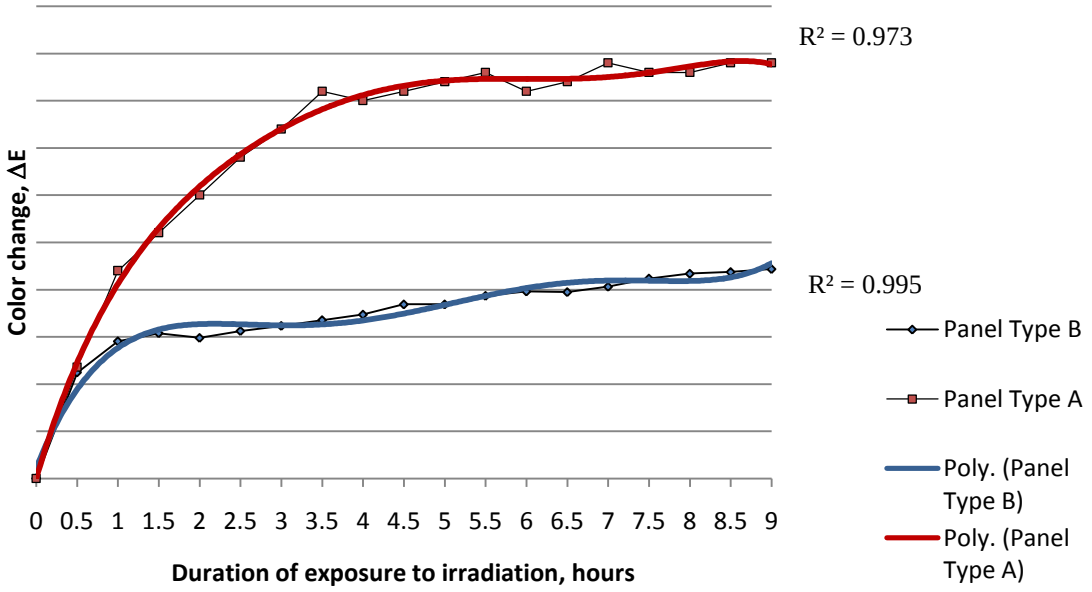


Figure-6

The color variation (ΔE) of the Rhodamine B dye applied on the TiO_2 panels type A and B (Copyright: Authors)

Figure-7

Panelized concrete façade mock-up (Copyright: Authors)

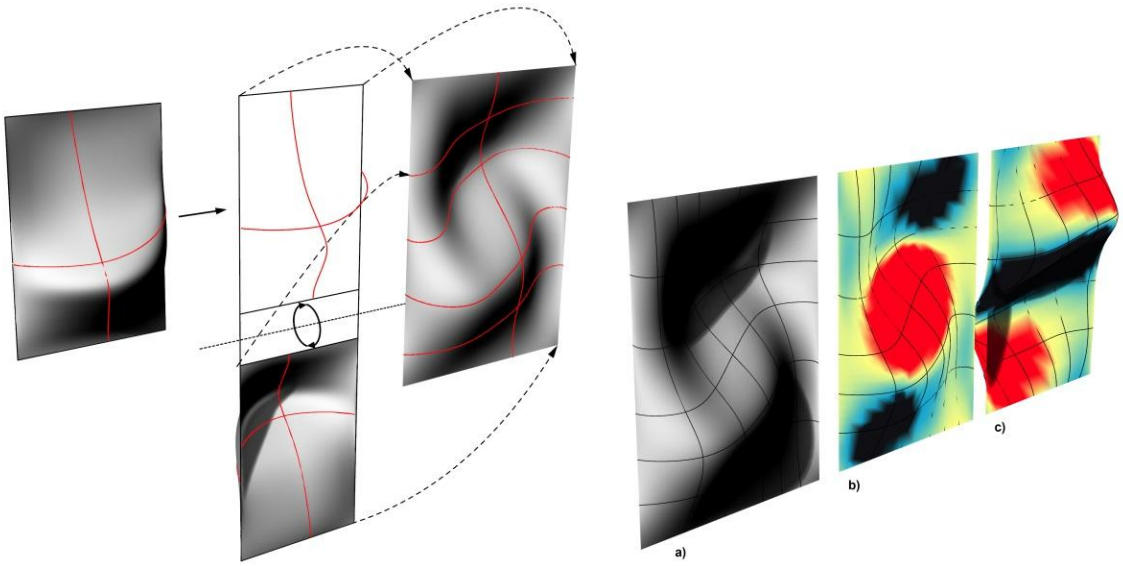


Figure-8
Derivative surface generation, showing areas exposed to 90% of irradiation, in red, and 10% of daily irradiation, in black (Copyright: Authors)

The proposed panels in a façade application

As we mentioned earlier, the above performance comparisons are not affected by proportional changes in overall size of panels. For instance, a 10 ft by 10 ft undulating surface will outperform a 10 ft by 10 ft flat concrete surface by the same percentage (approx. 44.6%) as a similar comparison between panels 10 times bigger. However the latter will have a larger amount of surface performing by for photoactalysis. The bigger the area and the longer photocatalytic concrete is exposed to sunlight the larger amount of air pollutants will be catalyzed. Scaling the performance of photocatalytic concrete up to the size of building can only practically be done by arraying panels in a systemic way, rather than simply building them larger. The following images are part of a study that examines the feasibility of outfitting an existing concrete façade with photocatalytic panels. The building is on Fenchurch Street in London, UK and the façade in focus is 62degrees from North and 22 stories high, with overall dimensions of 50 ft (16 m) by 220 ft (68 m), figure-9. The previously described algorithm takes into account the facades geo-location, and orientation. Based on solar radiation calculations we determined the vector of most desirable orientation and generated a panel surface. We chose 2 ft (1.2 m) module size that relates to control joints and assumed structural characteristics of the existing concrete exterior walls of the building. Each of the photocatalytic panels has overall dimensions 2 ft (1.2 m) high, 2ft 7-1/2 in (0.8 m), 1-1/2 in (0.04 m) thick. The panel weights approximately 160 lbs (72 kg) each. The panels maintain a 1 inch gap between the panel and the existing building exterior and perform as a secondary ventilated concrete screen, Figure 10. The shape of the panel area is derived from observations and interpretations of traffic smoke dissipation. We see a distinct opportunity to position the panels in specific patterns that closely respond to shaded and sun-lit parts of the buildings (for the obvious reason that incident sun light is needed for their performance), or patterns of wind turbulence (as it relates to the behavior and areas of concentration of air pollution), or flow of rain water (as it pertains to keeping the panel surface clean and available for photocatlaysis).

Figure-9
Existing building with south-eastern concrete façade (Copyright: Authors).

Figure-10
Building façade with attached photocatalytic concrete panels, left, and close-up of photocatalytic concrete panels (Copyright: Authors)

Conclusion

Given the plethora of design work produced on the basis of surface geometry the project so far contributes an alternative lens through which to assess such work – especially in the context of the impending environmental crisis. As we continue to develop and test further prototypes for the wall surface, an optimal form will be discovered. So far we have prioritized performance-driven parameters over explicit hypothesis on shape and aesthetics.

The quantifiable benefits of applying the proposed design methodat an urban scale have not been studied. The exact quantity of VOCs or NOx that gets fully decomposed by a square foot of photocatalytic concrete surface, for instance, is impractical to measure outside the controlled lab environment. Our computer simulations and prototype tests leave us confident that the analytical data that we have collected is scalable – that we can expect with a fair degree of certainty that the large scale effect of using photocatalytic concrete in building facades will positively and continually contribute to air pollution remediation.

We, indeed, live in a time defined by simultaneous crises of many kinds – most physically manifested in the contemporary state of buildings in the city[9]. We believe that what constitutes a current reading of the aesthetic and cultural norms that define Architecture must include the critique of functionalist parametricism underlying in this research work. We are interested in understanding how material performance is affected by its use in a building as well as understanding how the method and form in which materials are used in a building are driven by that material's performance. We see this research project in a disciplinary landscape between material science and architecture. We believe that doing so is yet another way to address the important goals for the future of the architectural profession, one of which is to re-define the functional interaction between the elements and the built environments. We believe that a good path to achieving this through pragmatic use of digital technologies and the environmentally conscious application of innovative materials.

Acknowledgement

The second author presented in abbreviated format the technical aspects and findings from the beginning stages of this project at Façade Tectonics #14, January 9-12, University of Southern California, Los Angeles, CA. There were no proceedings published.

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