Next-Generation Sustainable Architecture: Buildings as Air Pollution Remediators

Research into photocatalytic architectural materials has been progressing for over ten years and this emerging technology offers building professionals a renewed opportunity to contribute toward sustainable goals by enabling the design of radiation-active architectural facades that can lead to potential advances in passive air pollution remediation.

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Air pollution is a severe problem for a large number of urban centers globally. It is caused by high population density factors, such as urban industrialization and high concentrations of fossil fuel use in transportation and energy generation. The looming energy and environmental crises additionally aggravate urban air pollution problems. Architecture and design traditionally have not been seen as making an active contribution to air remediation efforts. Such efforts have mostly been legislative or over-reliant on new technology. While higher standards and regulations for building use, materials, and methods have made notable progress in reducing air pollution, buildings continue to use 30-40% of our energy resources and existing and new building technologies have yet to reach their full potential. In view of the undeniable probability that the AEC professions will face a dire 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 technologies is the use of photocatalytic additives in the production of concrete for architectural and structural applications. Photocatalytic cement uses daylight to react with and neutralize common air pollutants such as nitrogen and sulfur oxides, carbon monoxide, and VOC’s – the reaction takes place on the surface of the concrete and the resulting inert nitrates can be washed off manually or by rain .

This paper reports on the research methods, designs and conclusions of a collaborative project that incorporates environmentally derived data into the design of building façade components made of innovative photocatalytic concrete. In resulting computer simulations the team has been able to show a substantial increase in photo catalytic reaction. Consequently, physical photocatalytic panels were fabricated, tested for photocatalytic activity, and the results compared to the initial computer simulations. The work

Test Location Latitude:	40°36’16.46”N
Test Location Longitude:	75°21’38.85”W
Test Date:	07/26/13
North Angle:	22.5°

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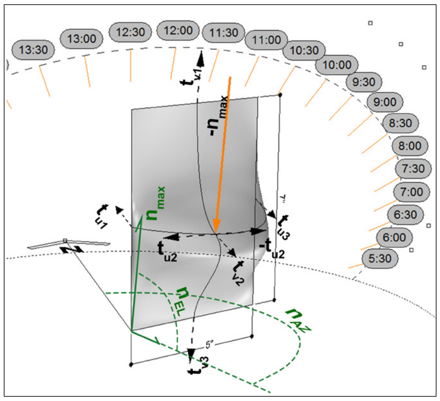


Figure 1: Design parameters(above) and panel generation – the surface is constrained by face normal angles, modeled in *Rhinoceros®* (below).

herein serves as the basis for forthcoming research into the use of photocatalytic cements in building design and their potential role in remediating urban air pollution.

BACKGROUND OF PHOTOCATALYTIC CEMENTS

As early as the 70’s titanium dioxide (TiO_2) was identified is a photocatalyst [1]. 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 titanium dioxide (TiO_2) in levels reported between 3-5% gives the resulting concrete photo-catalytic properties

The environmental benefits of using photocatalytic cement are considerable – in addition to eliminating air-pollutants and its self-cleaning properties, it allows for reduced clinker content, provides comparable strength to Type I early-strength concretes, and the resulting concrete has relatively high reflectivity. All of these make the use of this new concrete a sensible contribution to environmental protection and rehabilitation. To date, however, titanium dioxide photocatalysts have been used sparingly in conventional concrete facades, mostly in European structures, and more commonly in paving products. Besides direct mixing of TiO_2 powder into concrete, other techniques have been used, such as sputtering, spray-coating, and sol-gel dip coating. These techniques, however, often provide poor adhesion to the respective substrate and as a result their performance suffers in aggressive outdoor environments.[2]

DESIGN APPROCH

A team comprised of faculty from Architecture and Environmental Engineering has developed a computer algorithm that utilizes data from site conditions as a means of optimizing component geometry to its location. Data like incident solar *radiation*[3], *absorbed* and *transmitted* solar energy[4], and *photo-synthetically active radiation*[5] is correlated to specific properties of construction materials early in the design process.

Parameters like geographic coordinates, design test day, and a panel orientation from North , are entered into a modified code ported into *vb.net* [6] and integrated into *Grasshopper*[7] by Ted Ngai[8] The coding algorithm enables 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, n_{AZ}, and 79.52° elevation, n_{EL}. Figure 1 illustrates the generation of the panel surface.

COMPUTER SIMULATION

The new concrete panel with the above surface is simulated in Grasshopper and compared against a vertically oriented flat surface of equal overall height, width, and depth, and in identical orientation. The comparison shows a 13.57% increase of surface area of the proposed panel compared to that of the flat panel, which leads to 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

An interesting observation is that the panel's performance is not related to its size. Comparisons of a number of different size scales produce density patterns with varying aesthetic readings and fabrication implications but, importantly, all of them result in identical total areas of surface available for photocatalysis and identical amount of surface area with higher exposure to radiation than that of a flat panel. Therefore, 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. For convenience of fabrication the chosen panel size is 5 inches x 7 inches.

TESTING FOR CATALYTIC ACTIVITY

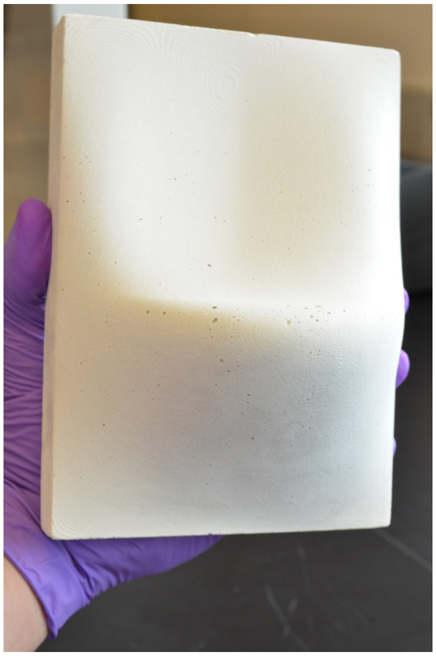
A master panel was 3d-printed on a ZCorp ZPrinter 650. A silicone mold was prepared and a design panel (A) was cast at 65°F and Relative Humidity of 85% to serve as a test specimen. An additional flat panel (B) of identical dimensions was cast for comparison. The concrete was prepared using cement manufactured by Essroc with normalized content of titanium (Ti) 10.2% by weight . The concrete mix was prepared using a cement to fine aggregate ratio of 1:3 and a water to cement ratio of 0.3. The fabricated panels were demolded 24 hours after casting and water-cured for 6 days.

Scanning Electron Microscopic (SEM) photos were taken of prepared titanium dioxide concrete with a Hitachi TM-1000 Tabletop Microscope equipped with Energy-dispersive X-ray spectroscopy (EDS). SEM photos were taken of the concrete samples at 180x and 2000x magnification. 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.

The titanium dioxide (TiO_2) concrete sample measured 10.2% by weight for titanium, Figure 2. However, it should be noted that these are normalized values, and oxygen was not detected. For example, silicon (Si) was detected from sand, and the silicon was quantified at 29.9% instead of the mass portion which would truly be attributed to silica (silicon dioxide). Therefore, the 10.2% titanium value was considered on the mass basis of all other elements which exclude oxygen as part of the mass fraction.

RHODAMINE B METHOD

Rhodamine B is a tracer dye that biodegrades due to photon absorption or direct photolysis. Solar radiation exposure changes the dye color intensity and can be used as an indicator of the efficiency of panel photocatalytic capacity with respect to panel configuration. The panel with the greatest dye degradation would indicate the panel with the greatest photocatalytic capacity for air pollution removal.



Element	Weight %
Aluminum (Al)	2.2
Silicon (Si)	29.9
Sulfur (S)	2.1
Calcium (Ca)	55.7
Titanium (Ti)	10.2

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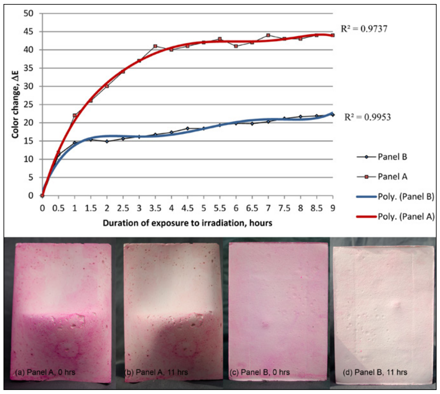
Figure 2: Panel A cast (above) and EDS summary results for 180x magnification view of Titanium Dioxide Concrete (below).



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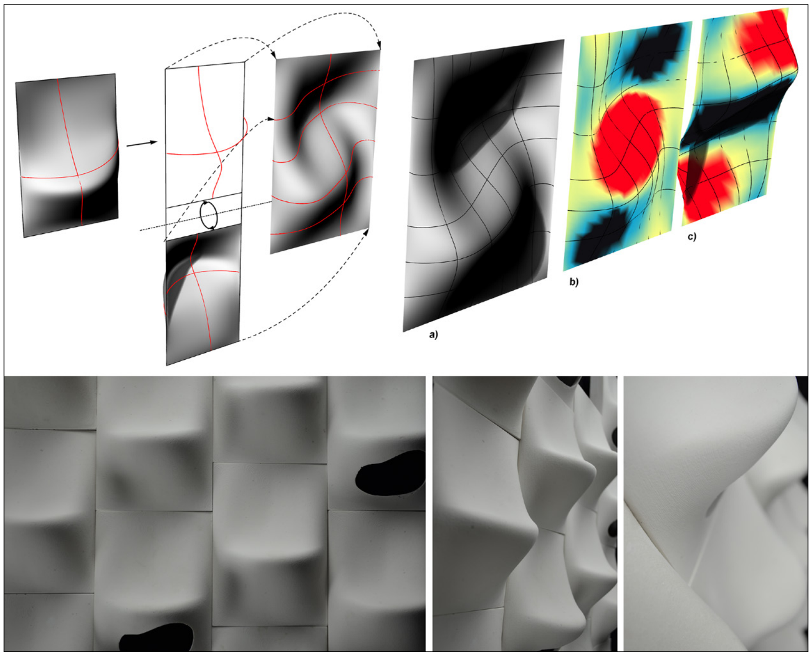

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Figure 3: The color variation (ΔE) of the Rhodamine B dye applied on the TiO_2 panels type A and B (above); The color variation of Rhodamine B coated TiO_2 specimens: (a) flat panel before test, (b) flat panel after 11 h irradiation, (c) design panel before test, (d) design panel after 11 h of irradiation (below).

Figure 4: Derivative surface generation, showing areas exposed to 90% of irradiation, in red, and 10% of daily irradiation, in black (above); panelised concrete façade physical mock-up (below).

To evaluate the color change in dye on the surface following exposure to sunlight, the panels were dip-coated with a Rhodamine B solution. Rhodamine B was supplied by Sigma Aldrich and a 1 mmol solution was prepared with distilled water. The Rhodamine B coated panels were air dried for 72 hours at room temperature.

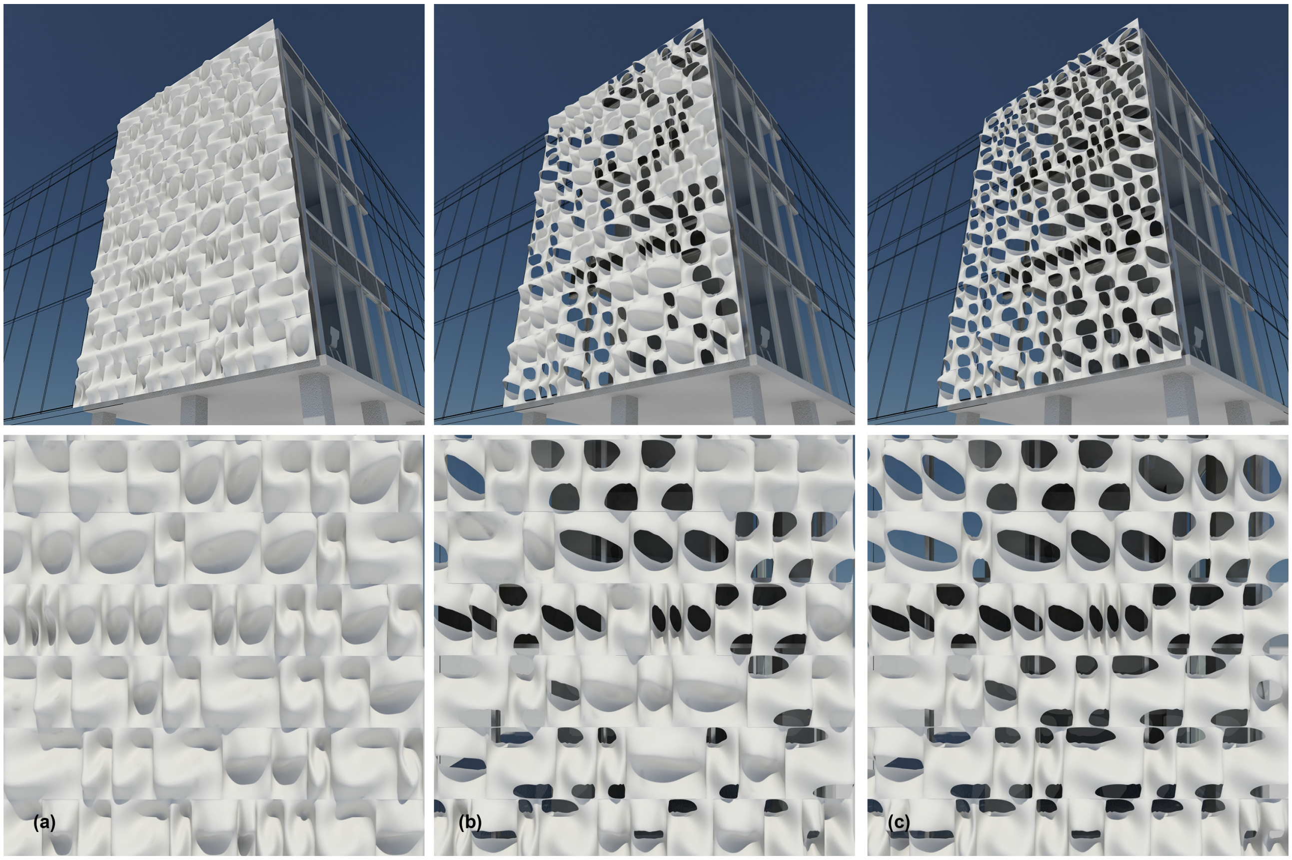
On the previously chosen design date, the design panel (A) and the flat panel (B) were located on a rooftop of the lab, shielded by possible glare and reflection from the ground or adjacent structures by a gray photographic muslin drop cloth, in full and direct exposure to the sun, and oriented according to the predetermined angle from North.

During the time of exposure to light radiation, images were taken with a Cannon D5900 equipped with a Variable Neutral Density filter. Measurements were made from 9 fixed sampling points on the surface of each specimen at 30 min. intervals from start of irradiation. The color changes of the Rhodamine B dye applied on the two specimens were expressed in CIE LAB colorimetric coordinates[9]. The nine measurements at a specified time intervals were averaged for subsequent calculations. The color variation (ΔE) was calculated 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.

RESULTS AND DISCUSSION

The color variation (ΔE) of the Rhodamine B dye applied on the TiO_2 panels type A and B are presented in Figure 3. The spikes in the values from both panels can be attributed to occasionally overcast sky and light scattering during the time of testing. Other factors, such as varying degrees of porosity of the concrete surface may also have contributed to a varying degree of discoloration.

It is clearly observed that for the flat panel (B) most of the color change happened in the first hour 1.5 hours, after which the increase of rate of color change was minimal. The slowing of the discoloration rate can be attributed



to the presence of relatively thicker layers of dye , which once discolored, may have acted as a barrier for the photo catalysis of any residual dye. The opposite was observed with the design panel (A). The color change in the design panel (A) kept increasing during the first 3.5 hours of exposure to irradiation at a higher rate than that of the flat panel (B). We establish that not only the rate of color change was higher and lasted longer, but the design panel (A) changed 44.6% more than the flat panel (B) - panel A photocatalysed the Rhodamine B dye 45.6% more than panel B.

APPLICATIONS

Using the previously established panel as a prototypical model a derivative surface was developed that is topologically equivalent in both short and long axes – this allows it to perform identically on each side in terms of photo-catalysis, Figure 4. Shown in red are areas exposed to 90% of irradiation and in black are illustrated areas exposed to 10% of daily irradiation. The concrete material in the black areas can be seen as under-performing in terms of photocatalytic capacity as such may be used for placing voids in panel surface for functional or aesthetic purpose.

A 1/4-scaled physical mock-up of the panelized concrete façade was produced, Figure 4, bottom. It served as a test for the tectonic and aesthetic implications of applying the panel system at various scales – the scale of a 4-story building facade is shown in Figure 5.

CONCLUSION

The proposed design method is intended to augment existing building

Figure 5: Perspective and elevation study: (a) opaque, (b) 25% open, (c) 50% open.

materials and technology and their interface with any particular construction method is generic. In addition to linking environmental parameters to formal design criteria applicable to an innovative material, this research project so far has led to the discovery that the increase or decrease in overall size of the panels does not affect their performance. In order to go beyond the critique of functionalist parametricism the authors' intent is to test through both mock-ups and simulations panels of varying scales for aesthetic and stylistic interpretations. The work herein is part of the team's research into the use of photo catalytic cements in building design and their potential role in remediating urban air pollution. Presently large scale empirical studies gave not been carried out and an important aspect of this research will be to empirically verify the proposed panels' performance in catalyzing air pollutants and attempt to quantify the exact impact of photocatalytic concrete surfaces on an urban and on a global scales.

ENDNOTES

1. A. Fujishima, K. Honda. 1975. "Electricity from photosensitization of titanium " Nature 253(1975) 719-720.

2. Ramirez, Anibal Maury, Kristof Demeestere, Nele De Belie, Tapio Mäntylä, and Erkki Levänen. 2010. "Titanium dioxide coated cementitious materials for air purifying purposes: Preparation, characterization and toluene removal potential". Building and Environment. 45 (4): 832-838.

3. *Radiation* is a process by which electromagnetic energy is propagated through space. This process is to be distinguished from other forms of energy transfer such as conduction and convection. Source: Glossary of Meteorology. Accessed January 19, 2013. http://amsglossary.allenpress.com/glossary/search?id=radiation1

4. *Absorption* is the process by which solar energy is captured by a building material, reducing its available amount. *Transmittance* is the fraction or percent of a particular frequency or wavelength of electromagnetic radiation that passes through a building material without being absorbed or reflected. Source: Glossary of Solar Radiation Resource Terms. Accessed January 13, 2013. http://rredc.nrel.gov/solar/glossary/

5. *Photosynthetically active radiation* designates the spectral range of solar radiation that photosynthetic organisms are able to use in the process of photosynthesis, mostly overlapping with the spectrum of light visible to the human eye. Photons at shorter wavelengths tend to be damaging to cells, while photons at longer wavelengths do not carry enough energy to initiate photosynthesis.

6. *Visual Basic .NET* is an object-oriented programming language designed by Microsoft.

7. *Grasshopper*™ is a graphical algorithm editor integrated with Rhinoceros' 3-D modeling tools. Rhinoceros, also known as Rhino, is a 3-D modeling software.

8. Ted Ngai, "incident solar | analemma." Posted on February 1, 2009. Accessed June 22, 2012. www.tedngai.net

9. In 1976, the *Commission Internationale d'Eclairage* (CIE) established the CIE Lab color system capable of displaying every color perceived by the human eye. Unlike RGB colors that are screen-dependent and CMYK colors that vary with printer, ink and paper characteristics, CIE Lab colors are device-independent and remain consistent on monitors, printers and scanners. The CIE Lab color mode has a lightness component (*L*), an ***a*** component (representing values on a green-red axis) and a ***b*** component (representing values on a blue-yellow axis).