Best Practices for Maintenance of Concrete Bridge Elements against Mold and Mildew Growth

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ABSTRACT

Bio-deterioration of concrete surfaces on vertical elements of bridges represents a serious challenge to the highway infrastructure in Louisiana, not only for its poor aesthetic appeal but also because of the accelerated deterioration that biofilm causes on concrete. This paper investigates the causes of biofilm proliferation on concrete, the consequences that these living organisms have on concrete, and the best methods used to control and eliminate biofilm growth on concrete. A literature review was conducted and a survey was developed and distributed among different states DOTs to determine current biofilm preventing and cleaning practices and their effectiveness. The survey results show that not all the states have biofilm growth, and that those that do, are located in warm and humid geographical locations. Results also suggest that the main cause of bio-deterioration of concrete surfaces is caused by micro-organisms’ activity present at the surface. Furthermore, current practices used to prevent and clean biofilms growth are pressure washing, biocides, and addition of self-cleaning photocatalytic nano titanium dioxide (TiO2) coatings to concrete surfaces. Results also suggest that the use of self-cleaning photocatalytic nano TiO2 coatings appears to be the most effective method in preventing microbial growth on concrete surfaces.

Key words: Titanium dioxide, Self-cleaning concrete surfaces, bridges, biofilm growth, bio-deterioration.

INTRODUCTION

The development of biofilms on concrete structure (layer of mildew, mold, bacteria, fungus, yeasts or any combination) has a negative impact not only due to aesthetics reasons but also due to its influence on the performance and integrity of the structure (Adamo and Violante 2000; Bastidas-Arteaga et al. 2008). Biofilms develop easily when the right conditions are present, such as high relative humidity (60 to 98%) and temperature (70 to 95°F). These conditions are encountered in the hot-humid climatic region, which includes the state of Louisiana. As a consequence, visible stains and a relatively fast deterioration of bridges, roads, highways, and other structures are encountered in Louisiana. This issue has triggered public complaints,
which as a result have supported the need to find a practical and economic solution to be adopted by the Louisiana Department of Transportation and Development (LADOTD) to address biofilm issues. Figure 1 (a and b) presents concrete elements in Louisiana that show clear signs of biofilm activity, characterized by the black stains.

![Biofilm Sites in Louisiana](image)

(a) (b)

**Figure 1. Biofilm Sites in Louisiana**

The objective of this study is to present a detailed review of successful methods and practices currently used to prevent and eliminate biofilm development on concrete surfaces. These baseline data are currently used by LADOTD to establish a maintenance protocol against biofilm in the state. To achieve this objective, a survey of current DOTs practices with respect to adopted cleaning and prevention methods was conducted. Further, an economic analysis between the most common methods was conducted to determine which method is the most suited for the transportation industry in terms of safety, performance, durability, and cost.

**BACKGROUND**

**Biodeterioration of Concrete**

Concrete biodeterioration was reported in 1945 by Parker, who investigated the extensive corrosion process that was developing in concrete walls inside sewage systems (Parker 1945). Since then, several investigations were conducted demonstrating the adverse impacts of microorganisms on concrete elements under different microbial species and conditions. Guillite and Dreesen (1995) evaluated the biodeterioration of different construction materials (aerated concrete, gobertange stone, modern mortar, brick, and petit granite) by measuring the difference in bioreceptivity. The authors concluded that materials like concrete and aerated concrete are more susceptible to biofilm development because of their high porosity when compared to materials with lower porosities such as granite. Other investigations have shown a direct correlation between water-to-cement ratio and biodeterioration (Giannantonio et al. 2009; Dubosc et al. 2011). These investigations have proved that the higher the water-to-cement ratio is, the more susceptible the concrete surface becomes due to an increased area for moisture and nutrient retention.
Cleaning and Preventive Methods

Two main categories of treatment methods have been identified for biofilm issues: cleaning methods and preventive methods (Ray and Hanks 2012). Cleaning methods are those employed to eliminate biofilm communities from concrete surfaces, while preventive methods focus on preventing initial colonization and reproduction of microorganisms on the concrete surface.

Cleaning Methods

Cleaning methods can be divided into two subcategories: mechanical methods and eradication methods. Pressure washing, sand blasting, soda blasting, dry-ice (CO₂) blasting, have all been shown to clean surfaces from biofilms. Eradication methods like biocides, UV rays, microwaves, gamma rays have been shown to kill or eliminate microbial life settled on surfaces (Bott 2011; Allsopp et al. 2004). In highways and bridges maintenance activities, it has been a common practice to employ mechanical forces to “clean” stained concrete and remove dirt and debris from its surface. The most common method has been pressure washing. However, biofilm can redevelop in short periods of time after this method has been applied, since it does not completely remove all the microorganisms from the biofilm community. Furthermore, stronger environmental restrictions in some states (e.g., New York), such as the final deposition of the water utilized for pressure washing, are making this method more difficult to employ.

Preventive Methods

Preventive methods consist of the addition of certain compounds into the concrete mix such as Titanium Dioxide (TiO₂) and zeolite to restrict the colonization and growth of microorganisms on the concrete surface. Results have showed that these compounds prevent biofilm proliferation. Recent research proposed the use of compounds such as zeolite and TiO₂ in the concrete mix to control the growth and reproduction of biofilm communities on concrete structures (Haile et al. 2010; Giannantonio et al. 2009). TiO₂ can be used to construct concrete surfaces that are capable of self-cleaning when irritated with UV from sunlight and washed by rainwater. TiO₂’s self-cleaning ability is a result of a combination of the photo induced super-hydrophilic and photocatalytic properties of the material (Fujishima & Zhang 2006). Kurtis investigated the resistance of concrete tiles with TiO₂ to biofilm development. After the experiment, the concrete tiles that contained TiO₂ showed a strong resistance to the proliferation of biofilm communities, while the typical concrete tiles showed a substantial coverage by biofilms.

SURVEY OF STATE OF PRACTICES

The current state of practices adopted by highway agencies to address biodeterioration was reviewed through a comprehensive survey. The survey was developed and conducted to collect information from all the states’ highway agencies regarding bridge maintenance procedures for cleaning of concrete bridge structures. The survey also quantified how many states have encountered biofilm growth on concrete elements as is the case in Louisiana. Furthermore, the survey aimed at collecting information, from the states that have biofilm growth on concrete structures, on the maintenance process or processes implemented by these states to handle biofilms issues. The main questions in the survey were as follows:
Number and approximate conditions of bridges in the state;
Is there biofilm growth on concrete structures in your state?
Is there a maintenance program to address this issue?
If no, what is the reason for not treating it?
What methods are currently being employed to address biofilm issues?

The survey was distributed nationwide following the climatic regions classification adopted by the Department of Energy. This climatic regions classification consists of eight different regions (Figure 2): Hot-Humid, Mixed-Humid, Hot-Dry, Mixed-Dry, Cold, Very Cold, Subarctic, and Marine. To include a representation of all climatic regions, at least one response from each region was included. However, the subarctic climatic region was not included in the survey. Phone interviews with experts were also performed to collect additional information from state agencies.

![Figure 2 Climatic Regions (U.S. Department of Energy 2010)](image)

RESULTS
Findings of the comprehensive literature review, survey of state of practice, and phone conversations are presented in the following sections.

Findings of the Literature Review

Biofilms Development and Impact on Concrete Elements
Results of the literature review indicate that microorganisms of different types (bacteria, fungi, mold, mildew, algae, lichens, and protozoa) can colonize concrete surfaces and form biofilm communities (Bott 2011; Allsopp 2004; Kurth 2008). These biofilm communities are very diverse but they all have a need for nutrients that can be obtained from the substrate, on which the biofilm community is formed, from sunlight, from water or humidity, from the surrounding air, and/or from the biofilm community itself (Sanchez-Silva & Rosowsky 2008; Bastidas-Arteaga et al 2008; Kumar and Kumar 2009).
Biofilms have a detrimental effect on concrete structures due to the weathering of the surface. It was estimated that approximately 30% of the weathering of construction materials including concrete are caused by biological sources (DeGraef 2005; Sand 2001). The process by which biofilms affect concrete structures can be divided into three steps (Sanchez-Silva and Rosowsky 2008): (1) Colonization and initial deterioration of concrete surface; (2) Penetration of microorganisms into the concrete matrix; and (3) Initiation and propagation of cracks within the concrete.

Immediately after construction, concrete elements contain high levels of alkalinity (pH levels between 11 and 13). However, the interactions between the concrete element and CO₂ molecules present in the environment cause these high levels of alkalinity to drop, until it reaches levels that allow biofilms to colonize. Surface roughness, water to cement ratio, and photocatalytic TiO₂ cement mixtures have been identified as important parameters that influence bioreceptivity of concrete (Kurth 2008; Guillitte and Dreesen 1995; Dubosc 2011). The study conducted by Guillitte and Dreesen tested different construction materials with different porosities to determine if porosity or surface roughness had a relationship to bioreceptivity. It was shown by this study that construction materials with higher porosities and surface roughness were easier for microorganisms to colonize. A study conducted by Giannantonio et al. (2009), showed that water-to-cement ratio and open porosity were important parameters in concrete bioreceptivity.

Cleaning and Prevention Methods for Biofilm Growth

This section summarizes the most common cleaning and prevention methods for biofilm growth identified in this study; additional details have been presented elsewhere (Hassan 2013). It is noted that the selection of prevention or cleaning methods will often depend on the physiology of the microorganisms’ variety colonizing the concrete. Moreover, controlling biofilms growth on highway infrastructure is a major challenge, since it is virtually impossible to control humidity in an open environment and this is one of the most important factors that influence microorganism growth.

Cleaning Methods of Biofilms

Biofilms can be removed from their substrate by implementing mechanical procedures to detach microorganisms. These methods are the most common methods to eliminate biofilms because by successfully applying these methods, there is no need to use chemicals such as biocides that can have strong negative effects on health and environment. Furthermore, microorganisms such as mold (dead or alive) can be allergic; that is why they still have to be removed after killing them with biocides (U.S. Environmental Protection Agency 2012). Methods that can be used in order to remove biofilms from concrete include blasting methods, which include soda blasting, dry ice blasting, and sand blasting, and other methods such as pressure washing, and scrubbing or brushing of the concrete surface.

Sandblasting. Abrasive blasting shown in Figure 3 is a process that consists in propelling a stream of sand towards a given surface at high pressure in order to clean it from contaminants, remove paints and coatings, smoothen or roughen the surface, or even shape it (American Society for Testing and Materials 2012). Compressed air or centrifugal wheels are the most common mechanisms to propel the blasting media.
Soda Blasting. is an abrasive but gentle cleaning method that is increasing in popularity. The process involves the use of Sodium Bicarbonate (NaHCO₃) as the cleaning medium, applied against a surface using compressed air. This method is very effective for cleaning surfaces, paint stripping, automotive restoration, industrial equipment maintenance, rust removal, and graffiti removal.

![Soda Blasting](image)

**Figure 3. Sand Blasting**

Dry Ice (CO₂) Blasting. Dry ice blasting uses CO₂ as the blasting medium. Carbon dioxide is a non-poisonous, liquefied gas, which is relatively cheap when compared to the other blasting materials. One of the advantages of this method is that it is environmentally-friendly, and contains no secondary contaminants such as solvents or grit media, which can be found in other blasting materials (ColdJet 2011).

Pressure Washing. Pressure washing is a method that is used in order to remove contaminants from surfaces. The process consists of pumping water at high pressures against a surface to remove dirt, paint, coatings, or any other undesired loose particles. It is a common practice for highway maintenance agencies to implement this method in order to clear their roads and bridges from debris, dirt, grease, and contaminants. The New York State Department of Transportation employs this cleaning technique in their bridges and roads to either clean the surface, or to prepare the surface for the application of sealants or coatings.

Eradication Methods

Biocides. The most common method of killing microbial life is by the application of biocides - (bio: life form; cide: killer). Biocides are a versatile solution because it comes in many forms such as liquid, powder, gas. Biocides are the most effective chemicals to eliminate and prevent microbial growth because of their broad variety, intensity, and spectrum (Bott 2011). However, these chemicals can be dangerous for humans and animals, which necessitate precautions in selecting the biocide by considering spectrum of the biocide and toxicity of the biocide.

Physical Methods are also used in order to eradicate microbial life. In the housing industry, it is a common and recommendable practice to control humidity in places where mold growth is developing in order to restrict its growth. As discussed in previous sections, biofilms start to develop when high humidity and temperatures ranging from 25 to 30°C are available (Bastidas-Arteaga et al. 2008). However, it is
virtually impossible to control these parameters outdoors in order to prevent biofilm growth.

Preventive Methods

New technologies on prevention of microorganisms’ growth are currently being explored. The use of TiO$_2$ and zeolite compounds as additives in the concrete mix have been shown to reduce the growth and development of biofilms (Kurth 2008, Sanchez-Silva & Rosowsky 2008).

**Titanium Dioxide Photocatalyst Coating.** TiO$_2$ can be used to construct surfaces that are capable of self-cleaning when irritated with UV from sunlight and washed by rainwater. TiO$_2$’s self-cleaning ability is a result of a combination of the photo induced super-hydrophilic and photocatalytic properties of the material (Fujishima and Zhang 2006). Super-hydrophilicity is defined as the ability of the material to have a water contact angle of approximately 0° while photocatalysis is defined as the ability of the material to decompose pollutants when irritated by UV light. In this process, bacteria and organic build is decomposed by photocatalysis while dust and organic contaminants are washed away by rain by the photo induced super-hydrophilicity as shown in Figure 4.

![Figure 4. Super-hydrophilic process of TiO$_2$ (Fujishima & Zhang 2006)](image)

**Survey Results**

Twenty responses were received from a total of 50 questionnaires sent to the state agencies in the US. The response rate received accounted for a total of 40%; it is noted that two responses were received from Washington State representing the marine and coast climatic regions in the state. As expected, many states elected not to participate in the survey because the issue of biofilm growth was not critical for them given the prevailing climatic conditions in these states (low humidity levels, very cold or hot temperatures). The results obtained from the survey suggest that ten of the states that responded to the questionnaire have experienced some kind of visible biofilm (mold, mildew, fungal, or bacterial) growth on concrete structures. Although biofilm growth develops on concrete surfaces, some states do not take any actions in order to control or solve this issue. The survey inquired about the reason why biofilm growth was not being treated. Responses are shown in Figure 5(a), where 22% of the responses stated that there was no growth, this can be in most cases attributed to the climatic conditions of the state (low humidity levels, very cold or hot...
temperatures). 29% of the responses expressed that there was a lack of monetary resources to deal with these issues. Another 21% reported that biofilm growth was not considered a significant issue; therefore, it was not being treated. Many of the states that reported not having mold or mildew growth explained that while they did have mold or mildew growth, they did not consider it a major problem, since the visible stains were minimal. In case these states treated the issue, they only did it in places where it was visible and had high traffic concentrations. Climatic conditions play a very important role in biofilm development. Literature review has shown that biofilm development is only possible when relatively high levels of humidity and temperature are present. Figure 5(b) presents the percentages of responding states corresponding to each of the climatic regions of the US defined by the DOE. All the states corresponding to the Hot-Humid climatic region reported biofilm issues as expected.

![Figure 5](image)

**Figure 5.** (a) Reasons Why Biofilms were not considered a Concern and (b) Distribution of Climatic Regions

**COST ANALYSIS**

To identify the most appropriate methods to eliminate biofilm growth on concrete bridge elements, it is important that not only to consider the effectiveness of the method but also its cost. According to the RSMeans Open Shop Building Construction Data, the costs of pressure washing, sand blasting, dry-ice blasting, and titanium dioxide coatings were estimated (R.S. Means Company 2013). Table 1 summarizes the results of the cost analysis and compares four treatment methods over
a period of five years. According to this comparison, it seems that on a cost basis, TiO₂ coating is the most cost-effective method. Furthermore, according to the literature review, mechanical cleaning methods such as pressure washing and sand blasting must be applied once or twice a year to prevent colonization from microorganisms while TiO₂ coatings are estimated to last up to 5 years of service.

Table 1. Cost Analysis Comparisons for Four Common Treatment Methods

<table>
<thead>
<tr>
<th>Method</th>
<th>Square Foot Price ($/sq. ft.)</th>
<th>Total Cost Over 5 Years ($/sq. ft.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure Washing</td>
<td>1.57</td>
<td>7.85-15.7</td>
</tr>
<tr>
<td>Sand Blasting</td>
<td>4.95</td>
<td>24.75-49.5</td>
</tr>
<tr>
<td>Dry-Ice Blasting</td>
<td>2.00</td>
<td>10-20</td>
</tr>
<tr>
<td>Titanium Dioxide Coatings</td>
<td>0.75</td>
<td>0.75</td>
</tr>
</tbody>
</table>

SUMMARY AND CONCLUSIONS

The objective of this study was to present a detailed review of successful methods and practices currently used to prevent and eliminate biofilm development on concrete surfaces. Further, an economic analysis between the most common methods was conducted to determine which method is the most suited for the transportation industry in terms of safety, performance, durability, and cost. The literature review showed that numerous methods are currently being used to fight biofilm growth on concrete surfaces. Based on the results of the survey, it appears that pressure washing and TiO₂ coatings are the only methods applicable to the transportation industry. Given its long lasting effect, TiO₂ coatings seem to have an advantage over pressure washing, since TiO₂ coatings is expected to last up to 5 years of service, while pressure washing must be performed on a periodical basis (approximately once a year). Furthermore, water usage and disposal over water streams is becoming a more difficult task as stricter environmental regulations are emerging.

REFERENCES


