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BEST PRACTICES FOR PREVENTATIVE MAINTENANCE AGAINST MOLD AND MILDEW GROWTH OF CONCRETE BRIDGE ELEMENTS

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ABSTRACT: Biodeterioration on concrete surfaces of vertical elements of bridges represents a serious challenge to the US highway infrastructure especially in hot and humid states. The objective of this study is to present a qualitative analysis of successful methods and practices currently used to prevent and eliminate biofilm development on concrete surfaces. These baseline data are currently used by the Louisiana Department of Transportation and Development (LADOTD) to establish a maintenance protocol against biofilm in the state. To achieve this objective, a survey of current highway practices with respect to adopted cleaning and prevention methods was conducted. Further, a cost analysis between the most promising methods was conducted to determine which technique is the most suited for the transportation industry in terms of safety, performance, durability, and cost. Results of the qualitative analysis suggests that the main cause of biodeterioration of concrete surfaces is caused by micro-organisms' activity present at the surface. In addition, current practices used to prevent and clean biofilms growth are pressure washing, cleaning with biocides, and addition of photocatalytic nano titanium dioxide (TiO_2) in the concrete mix or as a surface coating. From prevention and cleaning perspective, the use of photocatalytic nano TiO_2 as a surface coating appears to be the most promising method in preventing microbial growth. However, TiO_2 coatings may not perform successfully in areas in the shade or under the side of bridges.

KEYWORDS: Concrete, Biodeterioration, survey, Control of biodeterioration, Biofouling

1 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 aesthetic reasons but also due to its influence on the performance and integrity of the structure [1-4]. 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 [5]. 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.

Figure 1. Biofilm Sites in Louisiana

Current methods for cleaning and eliminating biofilm development on highways and bridges include pressure washing, sweeping, brushing, sand blasting, dry-ice (CO_2) blasting, and soda blasting, but these methods have shown poor results since biofilms continue to develop in the structures in short periods of time [6]. Furthermore, constantly treating highways and bridges would be economically unsustainable given the large extent of the work to be performed, the equipment and personnel needed to accomplish these tasks, and the safety of workers during cleaning. Therefore, there is a critical need to identify a more practical alternative than currently available mechanical and periodical cleaning methods.

Several methods for dealing with biofilm issues have been suggested in the literature [7, 10]. These methods include the use of chemicals and physical controls such as biocides (oxidizing agents, aldehydes, acids, chlorine, etc.), pressure control, temperature control, humidity control, UV rays, titanium dioxide (TiO_2) photocatalyst, and zeolite compounds. However, the application of chemical compounds to the entire system could be cost-prohibitive and environmentally damaging [7-10]. 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, a cost analysis between the most common methods was conducted to determine which technique is the most suited for the transportation industry in terms of safety, performance, durability, and cost.

2 BACKGROUND

2.1 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 [11]. This research was the first laboratory investigation that linked microorganisms to concrete deterioration. Since then, several investigations have been conducted demonstrating the adverse impacts of microorganisms on concrete elements under different microbial species and conditions. Gu et al. (1998) demonstrated the effects of fungal and bacterial species on concrete. This research demonstrated and quantified the weight loss, which translates into deterioration of concrete samples incubating microorganisms [12]. 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 [13]. Other investigations have shown a direct correlation between water-to-cement ratio and biodeterioration [14-16]. 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.

2.2 Cleaning and Preventive Methods

Two main categories of treatment methods have been identified for biofilm issues: cleaning methods and preventive methods [6]. 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 (CO_2) 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 [7, 8]. These methods have been effective in eliminating biofilms; however, they have to be applied periodically in order to restrict the redevelopment of the biofilms [6].

In industrial facilities, it has been a common practice to employ mechanical forces to remove biofilm from their sustaining surface. The most common methods are pressurized water, sand blasting, dry-ice blasting, and soda blasting. However, microorganisms invisible to the naked eye such as bacteria, which are commonly found in biofilm communities have a higher resistance to these methods and tend to regenerate and re-colonize the surface after such treatments have been applied, eventually leading to a full regeneration of the biofilm.

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. As previously mentioned, this method is effective in removing stains that are generally caused by biofilm development, dirt, and debris from surfaces. 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, such as the final deposition of the water utilized for pressure washing, are making this method more difficult to employ, since water utilized to clean bridges and highways could be contaminated with chemicals that could represent a threat to water streams [17, 18].

Preventive Methods

Preventive methods consist of the addition of certain compounds into the concrete mix or as surface coatings such as titanium dioxide (TiO_2) and zeolite to restrict the colonization and growth of microorganisms on the concrete surface. Results have shown that these compounds prevent biofilm proliferation. Recent research proposed the use of compounds such as zeolite and TiO_2 in the concrete mix to control the growth and reproduction of biofilm communities on concrete structures [10, 14]. Titanium dioxide can be used to construct concrete surfaces that are capable of self-cleaning when irradiated 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 [19]. Kurtis investigated the resistance of concrete tiles with TiO_2 to biofilm development. A set of control concrete tiles were compared to tiles prepared with TiO_2-cement. Both sets of concrete tiles were inoculated with commonly found fungal species found in biofilm communities and tested for a given period of time. After the experiment, the concrete tiles that contained TiO_2 showed a strong resistance to the proliferation of biofilm communities, while the typical concrete tiles showed a substantial coverage by biofilms.

3 SURVEY OF STATE 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 biofilm growth 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 classification consists of eight different regions (Figure 2): Hot-Humid, Mixed-Humid, Hot-Dry, Mixed-Dry, Cold, Very Cold, Subarctic, and Marine. Phone interviews with experts were also performed to collect additional information from state agencies.

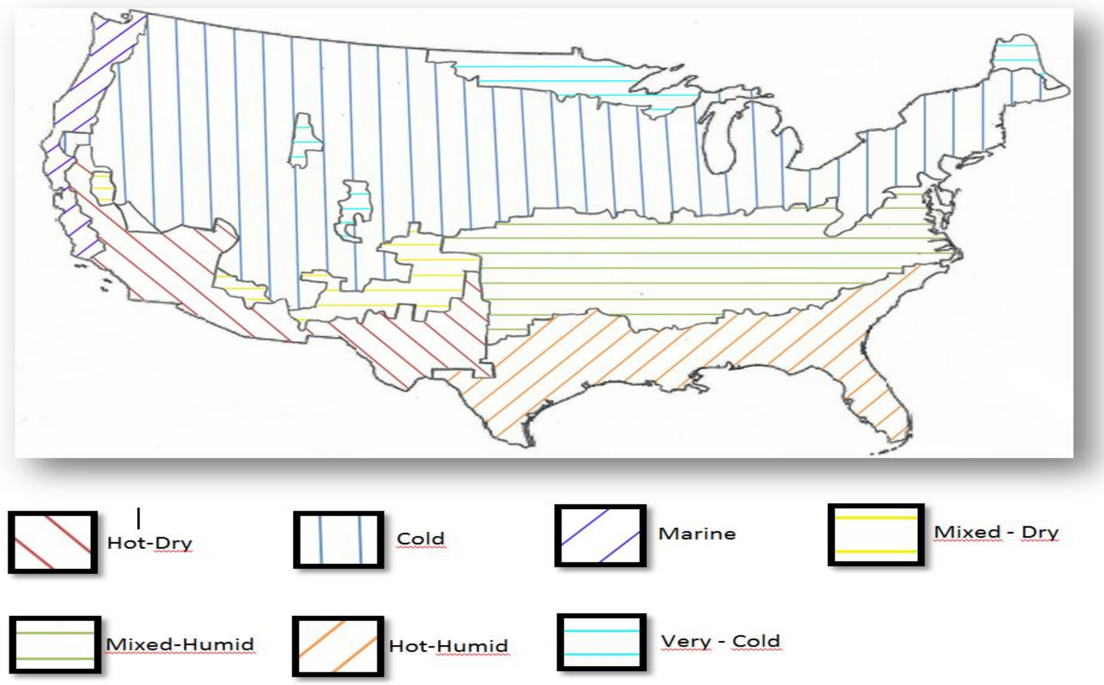


Figure 2. Climatic Regions (U.S. Department of Energy 2010)

4 RESULTS

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

4.1 Findings of the Literature Review

4.1.1 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 [7-9]. 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 [20-22].

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 [23-24]. The process by which biofilms affect concrete structures can be divided into three steps [20]:

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 have a low bioreceptivity due to the high levels of alkalinity (pH levels between 11 and 13). However, the interactions between the concrete element and CO_2 molecules present in the environment cause these high levels of alkalinity to drop, until it reaches levels that allow biofilms to colonize. After these levels are reached, different species of microorganisms start to colonize the surface creating biofilm communities. Biofilm communities excrete organic and inorganic acids that react with concrete, solubilizing cement components. Microorganisms then start to penetrate into the concrete matrix increasing the concrete porosity, which then changes concrete's coefficient of diffusion and internal conductivity. Therefore, corrosion of the steel reinforcement becomes easier for oxidizing and corroding agents present in the environment.

Surface roughness, water to cement ratio, and photocatalytic TiO_2 concrete mixtures have been identified as important parameters that influence bioreceptivity of concrete [9, 13, 15]. The study conducted by Guillite 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) [14] showed that water-to-cement ratio and open porosity were important parameters in concrete bioreceptivity.

4.1.2 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 [25]. 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.

4.1.2.1 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 allergenic; that is why they still have to be removed after killing them with biocides [26]. 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. Blasting methods are also known as abrasive methods. These methods clean materials and surfaces by removing the contaminants settled in them and also a small percentage of the layer of the substrate.

a) Sandblasting. Abrasive blasting shown in Figure 3 is commonly known as sandblasting. This is a process that consists of propelling a stream of abrasive materials 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 [27]. Compressed air or centrifugal wheels are the most common mechanisms to propel the blasting media. There are several variants of this process, such as shot blasting; which uses copper, zinc, aluminum, and steel as the blasting medium, dry ice blasting; which employs CO_2 pellets, bead blasting; which uses glass particles as the blasting medium, sandblasting; which employs sand (silica) as the blasting method, but has been related to lung problems, and soda blasting; which uses Sodium Bicarbonate (NaHCO3) as the blasting media.

Figure 3. **Sand and Soda Blasting**

b) Soda Blasting. 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, graffiti removal, masonry cleaning, and boat hull cleaning. Soda blasting became very popular in the early 1980s when it was selected by the engineers of the state of New York to clean the Statue of Liberty without causing any harm to its exterior [28].

c) **Dry Ice (CO_2) Blasting.** Dry ice blasting uses CO_2 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 [29].

d) **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 [17, 18].

4.1.2.2 Eradication Methods

a) **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. Generally, gas or vapor biocides are used to decontaminate materials that have already been colonized by microorganisms. Liquid and powder forms are often used to prevent their growth (e.g. quaternary ammonium compounds are constantly used in pools to prevent the growth of algae). Biocides are the most effective chemicals to eliminate and prevent microbial growth because of their broad variety, intensity, and spectrum [7]. However, these chemicals can be dangerous for humans and animals, which necessitate precautions in selecting the biocide by considering spectrum of the biocide, toxicity of the biocide, and effects on construction materials.

There are many different kinds of biocides used for cleaning. Some of the most common biocides used for cleaning materials are composed by the following chemicals: oxidizing agents, aldehydes, alcohols, phenolics, organic acids, quaternary ammonium/phosphonium compounds, and isothiazolinones. The use of the biocide and its characteristics varies depending on which chemical compound they contain. For instance, one of the most common oxidizing agents is chlorine. This compound has been used for many years in both the domestic and industrial world, mainly because of its low cost. Other oxidizing agents are ozone, hydrogen peroxide, and other halogens. Different biocides have different modes of action in order to eradicate microbial activity.

b) 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 [2]. However, it is virtually impossible to control these parameters outdoors.
To eliminate biofilms in industrial equipment, it is very common to implement variations to pressure and temperature. Usually, these variations are implemented in closed elements and equipment such as pipelines and boilers where they are easy to control [7, 8]. UV rays, microwaves and gamma rays have also been employed in order to restrict microorganisms' growth [7, 8]. Gamma radiation has also been successfully implemented to eliminate fungal growth from books after flooding events [8]. Although physical methods have been successfully applied in certain industries and fields, it is unlikely that these methods would be successful in highway infrastructure, because it is virtually impossible to control variables such as temperature, humidity, and pressure for long periods of time in outdoors.

4.1.2.3 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 in concrete elements [9, 30].

a) Titanium Dioxide Photocatalyst Coating. Titanium dioxide 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 [31-33]. Super-hydrophilicity is defined as the ability of the material to have a water contact angle of approximately 0o 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. Both processes take place simultaneously on the TiO_2 surface. The following section explains the mechanism behind both processes.

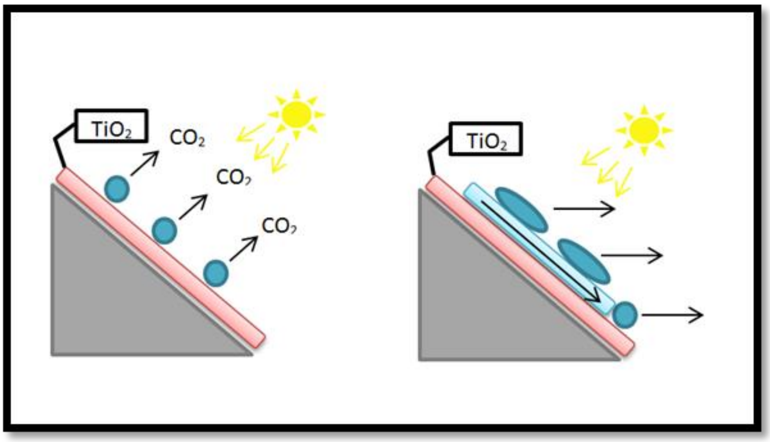


Figure 4. Super-hydrophilic process of TiO_2 *(35)*

b) **Photo induced super-hydrophilicity.** The anatase form of TiO_2 is considered to be a super-hydrophilic (hydro: water; philic: attraction) component when exposed to UV light. When irradiated by UV light, very low contact angles (approximately 0o) between water and supporting solid is obtained. This causes the water droplets to behave as a layer or a sheet, instead of individual circular droplets. Since TiO_2 is a semiconductor with a bandgap of about 3.0 eV, it produces electrons and holes when exposed to UV light [31-33]. The electrons released reduce Ti4+ cations to a Ti3+ state and the holes oxidize O_2- anions releasing oxygen atoms and creating vacancies in the titanium dioxide lattice structure. When the surface is washed, water molecules occupy these vacancies producing adsorbed OH groups and making the surface hydrophilic.

c) **Heterogeneous Photocatalysis.** Heterogeneous photocatalysis accelerates the natural decomposition process of harmful air pollutants and organic compounds. Photocatalytic reaction starts with the formation of electron-hole pairs initiated by energy that is greater than the band gap energy as previously described in photo induced super-hydrophilicity. Once irradiated with UV light, titanium dioxide forms highly oxidizing holes and photo-generated electrons resulting in hydroxyl radicals and superoxides, respectively [34]. The hydroxyl radicals are strong oxidants that rapidly decompose organic and inorganic compounds [36]. Thus, rather than just absorbing pollutants, common of traditional air purification methods, pollutants are decomposed to nonhazardous waste products with little energy requirements [34]. A number of studies have been carried out in order to test the self-cleaning and photocatalytic properties of TiO_2 in construction materials. Details of these studies have been presented elsewhere [25].

4.1.3 Comparative Analysis of Methods

Based on the findings of the literature review, Table 1 presents a comparison between the different treatment methods. As shown in this table, current methods for cleaning and eradication of biofilm development on highways and bridges such as pressure washing, sand blasting, dry-ice (CO_2) blasting, and soda blasting, require frequent applications. In addition, many of these methods have shown poor results since biofilms continue to develop on the structures over time. Further, continuously treating highways and concrete bridges would be economically unsustainable given the large extent of the work to be performed, and the equipment and labor hours needed to accomplish these tasks. This indicates that more practical alternatives for preventative maintenance cleaning methods are needed. Preventive methods such as TiO_2 and zeolites appear the most promising; however, further validation of these innovative techniques is needed prior to implementation. Further, TiO_2 coatings may not perform successfully in areas in the shade or under the side of bridges.

4.1.4 Survey Results

Twenty responses were received from a total of 50 questionnaires sent to the state agencies in the US, Figure 5. 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 coastal 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 (i.e., low humidity, very cold or hot temperatures).

Table 1. Required Chemicals for Interfacial Polymerization Synthesis

Category	Method	Type	Environmental Concerns	Scheduling Interval	Abrasive	Cost	Comments
Cleaning	Sand Blasting	Mechanical	Yes	Once or twice per year	Yes	High	Labor Intensive
	Soda Blasting	Mechanical	Yes	Once or twice per year	Yes	High	Labor Intensive
	Dry Ice Blasting	Mechanical	No	Once or twice per year	Yes	Medium	Labor Intensive
	Pressure Washing	Mechanical	Yes	Once or twice per year	Yes	Medium	Labor Intensive
Eradication	Biocides	Chemical	Yes	Depends upon the type	No	Low	Does not affect material properties
	Physical Methods (control temp. and humidity)	Physical	No	Continuous	No	High	Impossible to control outdoors
Preventive	TiO_2 Coatings	Chemical	Yes	Once every 5-10 years	No	Medium	Self-clean under rain preventing biofilm growth
	Zeolite compounds	Chemical	Yes	Further Investigation Required	No	Medium	Resist bacterial induced deterioration

Figure 6 shows the total number of bridges maintained by each agency in the reporting states as well as the approximate overall bridge conditions for all bridges in the reporting states, on a scale from 1 to 10. The scale rating for bridge condition ranged from one to ten, ten being perfect or like new conditions and 1 being very poor conditions. On average, reporting agencies perceive that the maintained bridges have an overall score of 7 out of 10.

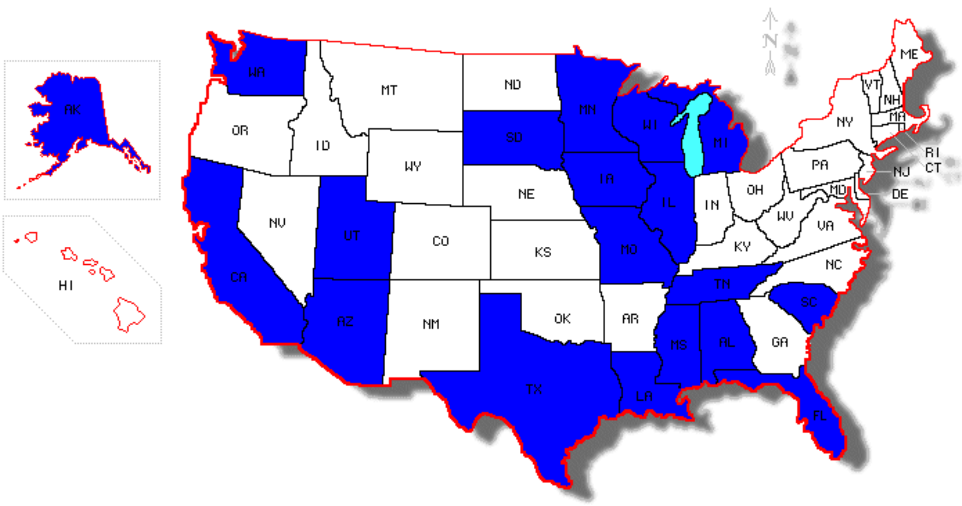


Figure 5. States Responding to the Survey

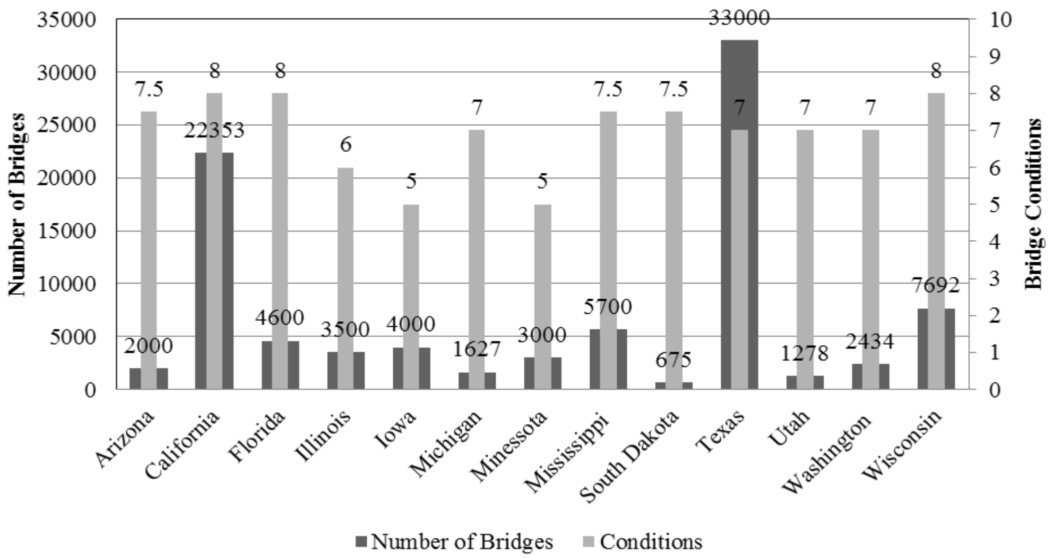


Figure 6. Number of Bridges and Conditions by State

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 7(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 this issue. 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 7(b) presents the percentage of responding states corresponding to each of the climatic regions of the US as defined by the DOE.

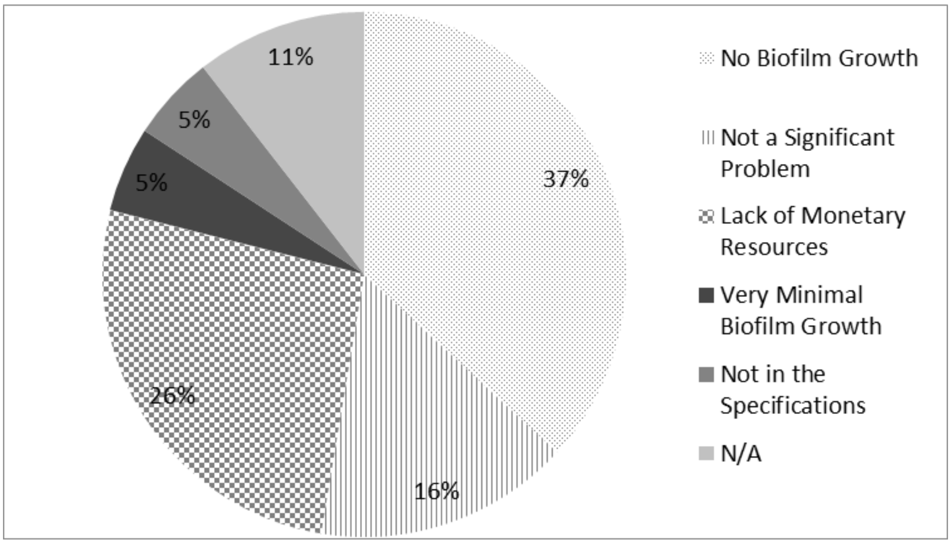
All the states corresponding to the Hot-Humid climatic region reported biofilm issues as expected. Figure 8 shows how many states reported biofilm growth in each climatic region. As expected, the states that are located in regions with high temperatures and humidity are the ones that are reporting visible biofilm growth on concrete structures. It is important to mention that none of the participating states responded to the question: “What methods are currently being employed to address biofilm issues?” The reason is that none of the states that participated are currently employing any treatment method to address biofilm issues.

4.1.5 Cost Analysis

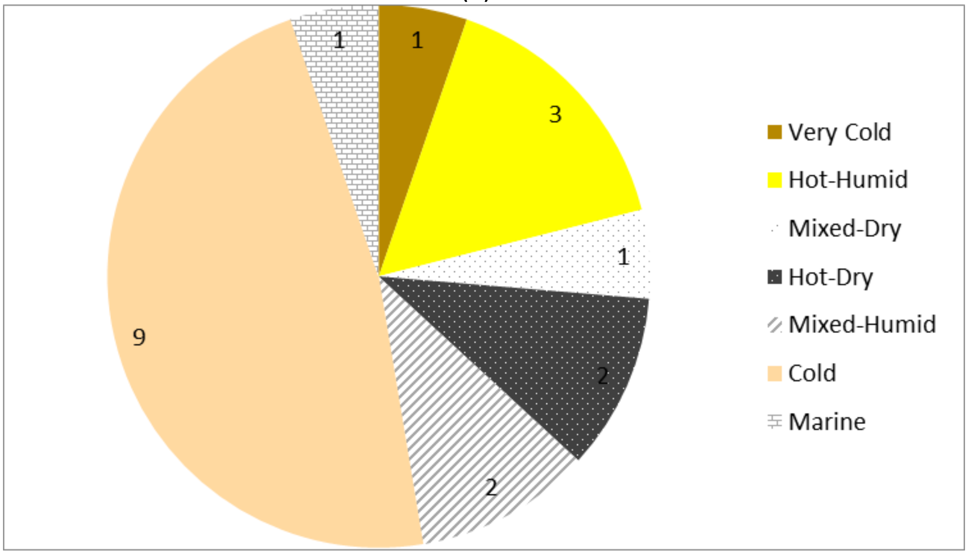
To identify the most appropriate methods to eliminate biofilm growth on concrete bridge elements, it is important not only to consider the effectiveness of the technique but also its cost. Because of environmental issues, biocides were excluded from this analysis. Although biocides can be employed to eliminate biofilms, strict environmental regulations make its use on concrete bridge elements over water streams very difficult. 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 [35]. Table 2 summarizes the results of the cost analysis and compares four treatment methods over a period of five years. The total cost over five years was estimated by multiplying the one-time cost by the number of application times in five years. According to this comparison, it seems that on a cost basis, TiO_2 coating is the most cost-effective method since it is only applied once during a period of five years, while the other methods are applied once or twice each year. 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 TiO_2 coatings are estimated to last up to 5 years of service. While photocatalytic cements appear cost-effective, this method requires a significant amount of UV and rainwater exposure. This means that TiO_2 coatings may not perform successfully in areas in the shade or under the side of bridges.

Table 2. Cost Analysis Comparisons for Four Common Treatment Methods

Method	**Square Foot Price ($/sq. ft.)**	**Application Interval**	**Total Cost Over 5 Years ($/sq. ft.)**
Pressure Washing	1.88	Once or twice a year	9.8 - 19.6
Sand Blasting	5.58	Once or twice a year	29.6 – 59.2
Dry-Ice Blasting	2.00	Once or twice a year	10.4 – 20.8
Titanium Dioxide Coating	0.75	Once every 5 years	0.75



(a)



(b)

Figure 7. (a) Reasons Why Biofilms were not considered a Concern and (b) Distribution of Climatic Regions

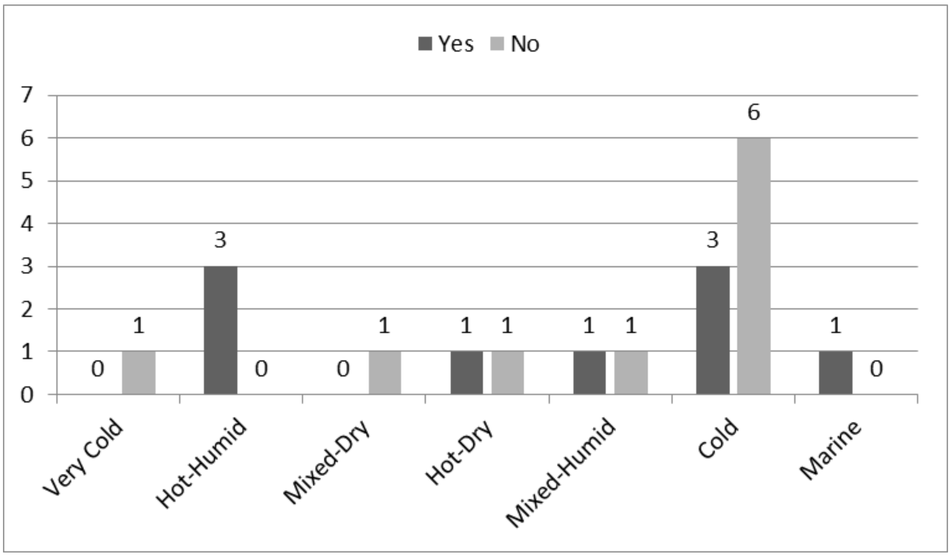


Figure 8. Positive Mold Growth by Climatic Region

5 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, a cost analysis between the most common methods was conducted to determine which technique is the most suited for the transportation industry in terms of safety, performance, durability, and cost. The literature review showed that the following methods are currently being used to fight biofilm growth on concrete surfaces:

- Pressure Washing
- Sandblasting
- CO_2 Blasting
- Soda Blasting
- Application of Biocides
- Temperature, Pressure, and Humidity control
- UV rays, Gamma rays, and microwaves
- TiO_2 (titanium Dioxide) in the concrete mixture and TiO_2 coatings
- Zeolite Coatings.

Based on the results of the survey, it appears that pressure washing and TiO_2 coatings are the only methods applicable to the transportation industry. Given its long lasting effect, TiO_2 coatings seem to have an advantage over pressure washing, since TiO_2 coatings are 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 a difficult task as stricter environmental regulations are emerging.

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