Louisiana Transportation Research Center

Final Report 532

Investigation of Best Practices for Maintenance of Concrete Bridge Railings

by

Marwa Hassan, Ph.D., P.E.

Louisiana State University

4101 Gourrier Avenue | Baton Rouge, Louisiana 70808
(225) 767-9131 | (225) 767-9108 fax | www.ltrc.lsu.edu

TECHNICAL REPORT STANDARD PAGE

1. Report No. **FHWA/LA.13/532**	**2. Government Accession No.**	**3. Recipient's Catalog No.**

4. Title and Subtitle **Investigation of Best Practices for Maintenance of Concrete Bridge Railings**	**5. Report Date** January 2015 **6. Performing Organization Code** LTRC Project Number: 12-3C State Project Number: 30000660
7. Author(s) Marwa Hassan, Ph.D., P.E.	**8. Performing Organization Report No.** **LSU**
9. Performing Organization Name and Address Louisiana State University Department of Construction Management Louisiana State University Baton Rouge, LA 70803	**10. Work Unit No.** **11. Contract or Grant No.**
12. Sponsoring Agency Name and Address Louisiana Department of Transportation and Development P.O. Box 94245 Baton Rouge, LA 70804-9245	**13. Type of Report and Period Covered** **Final Report** **June 2012 - June 2013** **14. Sponsoring Agency Code** LTRC

15. Supplementary Notes

16. Abstract

Biodeterioration on concrete surfaces of vertical elements of bridges represents a serious challenge to the highway infrastructure in Louisiana. This report aims to document the causes of biodeterioration of concrete surfaces and to document current conventional and state-of-the-art practices implemented to prevent and clean biofilm. A comprehensive literature review of previous research has been carried out in order to determine the cause and mechanisms of the biodeterioration as well as to identify current methods that state DOTs have implemented in order to maintain their bridges and allow them to function in optimal structural and performance conditions. A survey was developed and distributed among different state DOTs to determine current prevention and cleaning practices and their effectiveness. This review will serve as a baseline for future research projects on this topic as identified by the results of the synthesis. Results suggest that the main cause of biodeterioration of concrete surfaces is caused by micro-organisms' activity present at the surface. Furthermore, available methods 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. From a prevention and cleaning perspective, the use of photocatalytic nano TiO_2 in the concrete mix appears to be the most promising method in preventing microbial growth. However, further validation of this treatment is needed.

17. Key Words Concrete, Biodeterioration, Control of biodeterioration, Biofouling	**18. Distribution Statement** **Unrestricted. This document is available through the National Technical Information Service, Springfield, VA 21161.**

19. Security Classif. (of this report) N/A	**20. Security Classif. (of this page)** None	21. No. of Pages	22. Price

Project Review Committee

Each research project will have an advisory committee appointed by the LTRC Director. The Project Review Committee is responsible for assisting the LTRC Administrator or Manager in the development of acceptable research problem statements, requests for proposals, review of research proposals, oversight of approved research projects, and implementation of findings.

LTRC appreciates the dedication of the following Project Review Committee Members in guiding this research study to fruition.

LTRC Manager
Tyson Rupnow
Senior Concrete Research Engineer

Members
Chris Abadie
John Eggers
Bill Temple
Buzzy Wegener
Mike Moss
Steven Sibley
Rhett Desselle

Directorate Implementation Sponsor
Janice Williams, P.E.
DOTD Chief Engineer

Investigation of Best Practices for Maintenance of Concrete Bridge Railings

by

Marwa Hassan, Ph.D., P.E.
Performance Contractors Distinguished Assistant Professor
Department of Construction Management and Industrial Engineering
Louisiana State University
3218 Patrick F. Taylor
Baton Rouge, LA 70803
e-mail: marwa@lsu.edu
Tel: (225) 578-0189

LTRC Project No. 12-3C
State Project No. 300-00-660

LTRC Administrator/Manager
Tyson Rupnow, Senior Concrete Research Engineer

conducted for

Louisiana Department of Transportation and Development
Louisiana Transportation Research Center

January 2015

ABSTRACT

Biodeterioration on concrete surfaces of vertical elements of bridges represents a serious challenge to the US highway infrastructure. This report aims to document the causes of biodeterioration of concrete surfaces and present conventional and innovative practices used to prevent and clean biofilm. A comprehensive literature review of previous research was conducted in order to determine the causes and mechanisms of the biodeterioration as well as to identify the current methods that different state DOTs have implemented in order to maintain their bridges and allow them to function in optimal structural and performance conditions. A survey was developed and distributed among different state DOTs to determine current preventing and cleaning practices and their effectiveness. Results of the literature review suggest that the main cause of biodeterioration of concrete surfaces is micro-organisms' activity present at the surface. Furthermore, the current practices used to prevent and clean biofilms growth are pressure washing, cleaning with biocides, and addition of photocatalytic nano TiO_2 in the concrete mix. From a prevention and cleaning perspective, the use of photocatalytic nano TiO_2 in the concrete mix appears to be the most promising method in preventing microbial growth. However, further validation of this treatment is needed.

Based on the results of this synthesis, a comparative analysis was conducted to identify strengths and weaknesses of each treatment method. Based on this analysis, the research team recommends that a follow-up study be conducted in order to identify biofilm mechanisms in Louisiana and to conduct an experimental program to test a number of cleaning and preventive methods in the laboratory. Four research tasks were developed for the follow-up study. Based on the results of the follow-up study, a recommended state of practice should be developed to address biofilm growth in Louisiana. The developed practice should present recommend application of preventive methods as well as modifications to current concrete design and production practices in order to minimize or delay biofilm growth.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

OBJECTIVES

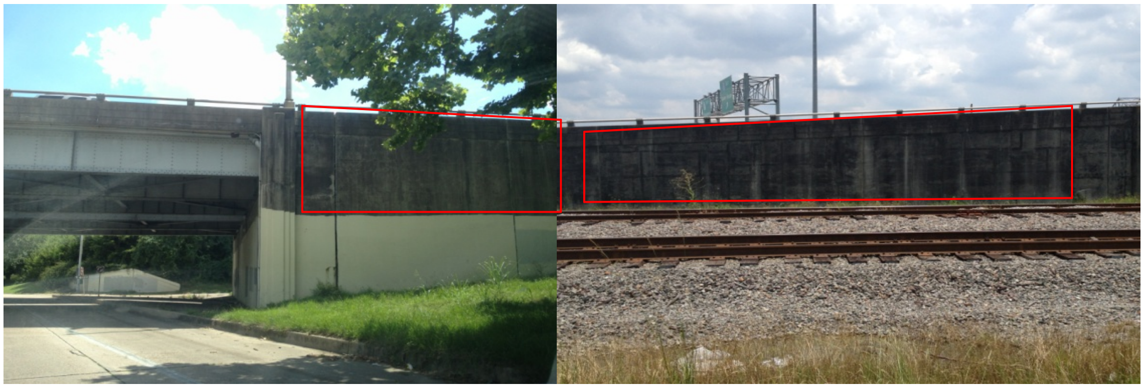
The primary objective of this study was to conduct a comprehensive literature review to determine causes of concrete biodeterioration and to present current practices employed or evaluated for cleaning and maintaining vertical concrete elements on bridges. The goal of this review is to identify possible preventive maintenance alternatives or construction materials that will enhance the resistance of these structures to biofilm growth and in turn reduce labor, costs, and traveling time delays.

SCOPE

To achieve the aforementioned objectives, a comprehensive review of previous research studies was conducted to investigate the main types of microorganisms involved in the development of biofilms on concrete surfaces and the following deterioration. A questionnaire survey was conducted in order to identify current practices used by different state DOTs. Collected information was used to conduct a comparative analysis that summarizes and compares each maintenance and preventive technique in terms of cost, effectiveness, schedule, and environmental impact. Based on the results of this synthesis, the research team developed the details for a follow-up study in order to identify biofilm mechanisms in Louisiana and to conduct an experimental program to test a number of cleaning and preventive methods in the laboratory.

INTRODUCTION

The development of biofilms on concrete structures has a negative impact on aesthetics as well as on the performance and integrity of concrete structures *[1-5]*. Biofilms develop and grow easily when the right conditions are present, such as high relative humidity (60 to 100%) and temperature (70 to 95°F). These conditions are encountered in the hot-humid climatic region, which includes the state of Louisiana *[6]*. As a consequence, visible stains and a relatively fast deterioration of bridges, roads, highways, and other structures are encountered in the state of Louisiana. This issue has triggered public complaints which, as a result, have raised the need to find a practical and economic solution to be used by the Department. Figure 1 (a and b) illustrates concrete elements with biofilm growth in LA (concrete walls), in Baton Rouge, Louisiana. Figure 1(a) is located on the I-10 overpass on Dalrymple Drive, and Figure 1(b) is located on the I-10 exit towards Lafayette in Port Allen. Both concrete surfaces show clear signs of biofilm activity, characterized by black stains.



(a) (b)

Figure 1
Development of biofilms on concrete structures in Louisiana

To address this problem, this study conducted a comprehensive literature review to identify the causes and types of biofilm deterioration and surveyed state agencies on currently used methods to prevent and eliminate biofilm development on concrete surfaces. It also identified other DOTs facing similar problems and the methods they use to prevent biofilm growth. In addition, the report also surveyed private companies that clean biofilm growth on concrete surfaces across the US to identify innovative solutions to this issue. A comparative analysis between the widely used cleaning methods was conducted and presented in order to determine which method(s) should be evaluated for possible implementation in Louisiana.

Results showed that 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 on the structures over time *[7]*. 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 to preventative maintenance cleaning methods are needed.

Innovative methods for dealing with biofilm issues have been suggested *[1, 3]*. These methods include the use of chemical control methods such as biocides (oxidizing agents, aldehydes, acids, chlorine, etc.) and physical control methods, such as temperature control, humidity control, UV rays, etc. However, since physical control methods depend upon climatic control, which cannot be achieved in highways and bridges exposed to the environment, these methods are not recommended as viable solutions. Further, the application of chemical compounds to the entire concrete infrastructure could be cost-prohibitive and environmentally damaging *[3, 8]*.

A newly-developed method that is presented in this report is the use of environmentally-friendly coating treatments or additives that can prevent and kill biofilms. These treatments include nano Titanium Dioxide (TiO_2) photocatalyst and zeolite compounds, which have a service life of 3-10 years [*9-10*]. However, a follow-up experimental study should be conducted to evaluate the performance and cost-effectiveness of these methods.

LITERATURE REVIEW

Causes and Mechanisms of Concrete Biofouling

The most important cause of concrete biofouling (i.e., stains, discoloration, etc.) is the growth of microorganisms at the surface. Microorganisms are living beings that are too small to be seen with the naked eye; they can be detected with a microscope. It is important to have a basic understanding of how microorganisms grow on concrete surfaces as well as which microorganisms cause concrete deterioration. The most common types of microorganisms involved in bio-fouling of concrete are bacteria, fungi, algae, and lichens *[5, 11]*.

Bacteria

Bacteria are very small organisms with sizes usually smaller than one micron (1µm) *[12]*. These are unicellular (one cell) organisms whose genetic materials are not contained in a nuclear membrane as shown in Figure 2. They are also known as "prokaryotes." Bacteria can create formations like chains, pairs, clusters, and other groupings. The reproduction of bacteria is a simple process of division called binary fission, where a bacterium subdivides into two equal daughter cells *[13-14]*.

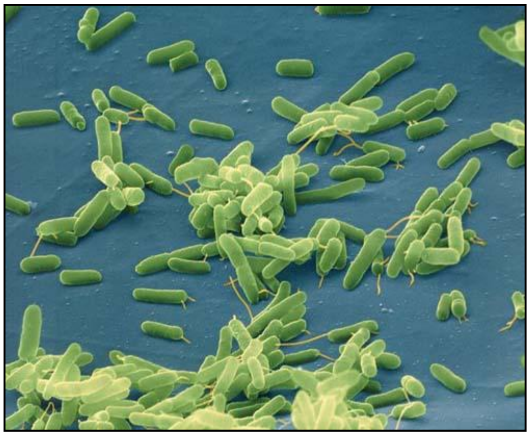


Figure 2
Microscopic image of bacteria *[14]*

When bacteria grow on surfaces, they do not cause any visible stains like other microorganisms; therefore, they do not affect the aesthetics of construction materials [*15*]. However, some bacteria types have been shown to deteriorate concrete as shown in Figure 3, such as Thiobacillus concretivorus, later renamed as Thiobacillus thiooxidans, and others have been related to health problems*[16-17]*. Bacteria can be found everywhere; they can live and reproduce in water, air, soil, skin, and even food *[7]*.

Figure 3
Acid producing bacteria penetrating and colonizing concrete *[18]*

The main types of bacteria responsible for causing damage on concrete surfaces include cyanobacteria, nitro-bacteria, sulfur-reducing bacteria, and sulfur-oxidizing bacteria *[12]*. Table 1 shows the deteriorating effects that some types of bacteria have on concrete. The types of bacteria listed in Table 1 are classified as either autotrophic or heterotrophic, and aerobic or anaerobic bacteria based on their lifestyles. However, they all have different needs for pH and temperature. Cyanobacteria are the only type of bacteria that have a wide range of temperatures and pH requirements; this means that it can survive under different environmental conditions. The other types of bacteria show a more limited range for temperature and pH requirements. This information can be useful in order to identify what kind of bacteria might be present in different locations and to diagnose causes of concrete bio-fouling. The deterioration that these microorganisms exert on concrete range from increase in crack sizes, solubilization of cement components, concrete corrosion, and chemical changes *[2; 11; 19]*.

Table 1
Principal effects of bacteria on RC structures [5]

Bacteria Type	Lifestyle	Temperature and pH ranges	Damage on concrete
Cyanobacteria	Autotrophic, aerobic or anaerobic	- 60 to 85 °C - Wide range of pH	Generate tensile stresses leading to an increment in the size of cracks
Nitrobacteria	Heterotrophic and anaerobic	- 18 – 25 °C - pH < 7.5	Nitrifying bacteria produce calcium nitrate by solubilizing some cement components
Sulfur-reducing bacteria	Heterotrophic and anaerobic	- 25 – 44 °C - 5.5 < pH < 9	Produce H_2S that is used for the sulfur-oxidizing bacteria to produce sulfuric acid. (concrete corrosion)
Sulfur-oxidizing bacteria	Heterotrophic and anaerobic	- 25 – 44 °C - 2 < pH < 9	Produce sulfuric acid, acetic acid, sulfates, sulfur, sulfites and polythionates that affect concrete chemically

Fungi

The fungi category includes molds, mildew, yeasts, and mushrooms. These organisms may be multicellular or unicellular, depending on the species. The most common species of fungi are molds. Molds usually create visible biofilms called *mycelia*, which are composed of *hyphae* (large filaments) *[13]*. Fungi do not ingest nutrients, instead, absorbing them. All fungi are chemoheterotrophs, which mean that they require organic compounds as nutrients *[13]*.

Fungi are different from plants; while plants get their nutrients through photosynthesis, fungi absorb nutrients from the substrate on which they grow, by secreting enzymes that breakdown cellulose material around them. Just like bacteria, fungi can be found under a wide range of climatic conditions. However, fungi accounts for a larger fraction of the biomass of the planet than humans *[7]*. That is why humans always come in contact with different species of fungi. Out of approximately 100,000 species of fungi that have been identified, only several hundred can produce mycotoxins, which are toxic compounds thought to be produced by the organism to defend itself *[7]*. Figure 4 shows concrete damage caused by fungi.

Figure 4
Concrete damage caused by fungi *[19]*

Fungi consist of two main components: the *Hyphae* and the *Spores* (See Figure 5). *Hyphae* are large vegetative filaments that are part of fungi. As a fungus grows, more *hyphae* will be created. Large mass of *hyphae* is also known as mycelia. *Spores* are the reproduction mechanisms of fungi. *Spores* are very small, ranging from 2 to 20 µm (microns). When a fungus matures, it will produce spores and send them airborne or waterborne to create new colonies. Because of their small sizes, spores are respirable, and some fungi species create spores that may be allergenic to some humans. Spores can travel in water or air, landing on surfaces; when provided with the right conditions such as humidity and nutrients, they can form new colonies *[7]*. Generally, fungi can be found in places where temperatures range from 25 to 30°C *[2]*.

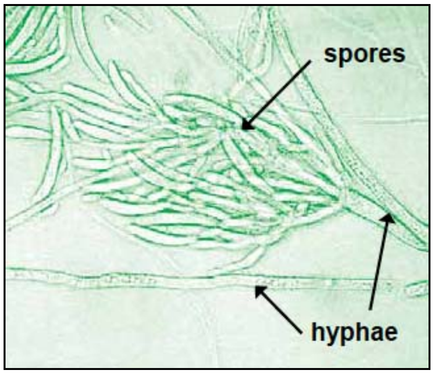


Figure 5
Fungi parts *[20]*

Fungi can affect concrete by two means: mechanical and chemical. Mechanical deterioration of concrete is produced by the penetration of the *hyphae* (a component of fungi) into the concrete microstructure. The chemical deterioration occurs because some species of fungi produce organic and inorganic acids that can precipitate salts *[2]*. Table 2 presents information on common molds and their characteristics. This table shows the water activity requirements for some of these species, which can be used in order to prevent its growth by reducing surface's humidity. Water activity represents the intensity with which water associates with other materials, it is defined as the vapor pressure of a liquid divided by that of the pure water at the same temperature. The higher the water activity of a substance or material is, the higher the tendency of that material to support microorganisms.

Table 2
Common molds and characteristics *[7]*

Fungi	Toxicity	Water IIF	WA (%)	Characteristics
Ascospores	▲	●		Found everywhere
Aspergillus	▲	●	70-82	Outside on plant debris. Indoors on a variety of substrates
Fusarium	▲	●	86-91	Outdoors on soil and plants. Indoor in humidifiers and on wet cellulose building materials.
Pithomyces				Not common indoors, but may grow on paper
Stachybotrys	▲	●	94	Outdoors on decaying plant matter. Indoors on water damage building materials, cellulose material like ceiling tiles, drywall, insulation backing, paper, textiles.
Tricoderma	▲		90	Indoors on textiles, wet cellulose materials and paper. It can produce T-2 toxin. It has been associated with immune-comprised individual.

Legend

▲ = Water intrusion indicator fungus capable of producing mycotoxins

● = Water intrusion indicator fungus

IIF = Intrusion indicator fungus

WA = Water Activity

Life-Cycle of Fungi. The life-cycle of fungal microorganisms shown in Figure 6 starts when a spore lands on a substrate that can provide enough nutrients and humidity. After the spore lands on a supportive substrate, it will start growing filamentous structures called hyphae, spreading them in a circular shape. When the mycelia has been formed, fungi will start creating sporangia, which is the structure that holds the spores, and finally, the spores are released to the air or water and create new colonies in another supportive substrate.

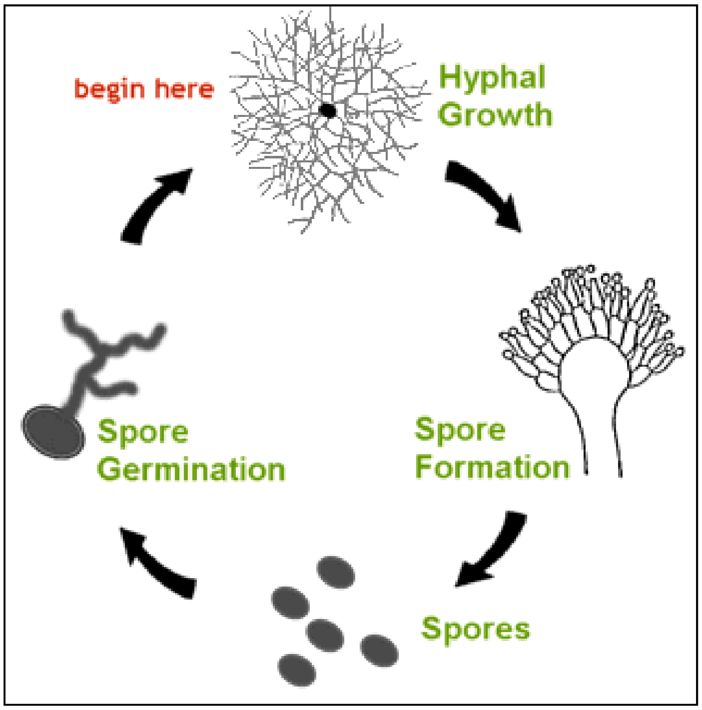


Figure 6
Life-cycle of fungi *[21]*

Microbial Volatile Organic Compounds (MVOCs) and Health Effects. Fungi can generate gases as product of the reaction of the enzymes produced by fungi to dissolve nutrients. These gases are known as Microbial Volatile Organic Compounds (MVOCs). MVOCs have been related to irritation and problems experienced by susceptible individuals, but are not a serious risk generally. The MVOCs correspond to the musty smell that these microorganisms generate, typical in indoor spaces supporting mold growth. MVOCs may cause irritant reactions in humans. Usually, these reactions cease when the person is removed from the environment that contains the MVOCs. The typical reactions are: headaches, burning eyes, rashes, and rhinitis. In addition, fungi cause some infectious diseases including athlete’s foot, ringworm, and yeast infections *[7]*.

Algae (singular: Alga)

Algae organisms can reproduce sexually and asexually. They come in a large variety of shapes. Their cell walls contain cellulose, similar to plants. Because of their photosynthesis process, they do not require organic compounds; they just need air, sunlight, and a relatively high amount of water or humidity (when compared to other microorganisms) *[13]*. A microscopic image of algae is shown in Figure 7. Algae can affect concrete by absorbing minerals from concrete such as calcium, magnesium, and silica *[2]*. Figure 8 shows example of concrete stained by algae and how it was restored by cleaning.

Figure 7
Microscopic image of algae *[22]*

Figure 8
Concrete colonized by algal species (green algae); before and after cleaning *[23]*

Lichens

Lichen is a combination of fungi and green algae. These two organisms support each other symbiotically to survive. Fungus provides water to algae and algae take from the fungus inorganic substances. This characteristic of the lichen allows it to survive in very hostile habitats. Lichens are usually the first organisms to colonize newly exposed surfaces *[13]*. These organisms excrete organic acids that can deteriorate (weather) the substratum on which they grow (chemical bio-deterioration), and also can physically deteriorate it by disaggregating the minerals by expanding and contracting its mycelium *[1, 24]*. Figure 9 shows damage induced on a granite surface by lichens.

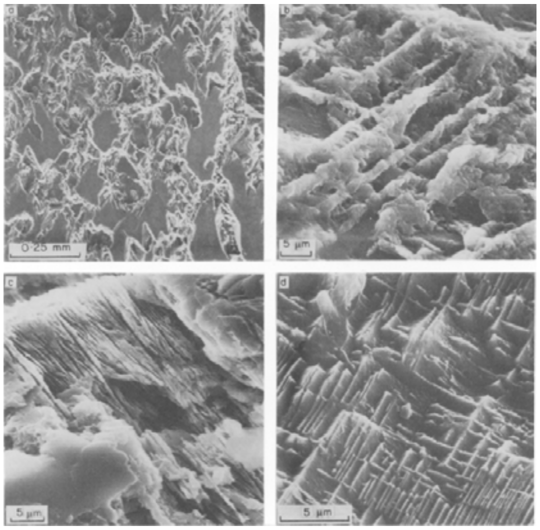


Figure 9
Surface damage caused by crustose lichens. Images show etched out minerals from granite (SEM images) ***[1, 24]***

Factors Affecting Biofilm Growth

Microorganisms responsible for biodeterioration, are capable of colonizing and growing on concrete in aggressive environments, when certain favorable conditions are present such as availability of water and low levels of pH *[2,12]*. These conditions include *[2]*:

- Relative humidity between 60 and 98%
- Long cycles of humidification and drying, or freezing and defrosting
- High CO_2 concentrations
- High concentrations of chloride ions or other salts (marine-like environments)
- Elevated concentrations of sulfates and small amounts of acids (sewer pipes or residual water treatment plants.

Nutrient Needs of Microorganisms

Microorganisms need nutrients in order to survive on any surface. Autotrophic (photosynthetic) microorganisms such as cyanobacteria and algae absorb carbon from CO_2 emissions in the atmosphere and use sunlight as an energy source. Heterotrophic organisms need organic material as a direct nutrient *[5]*. Table 3 presents the nutrient needs for different types of microorganisms, based on their nutritional category *[25]*.

Table 3
Classification of microorganisms based on their nutritional requirements [25]

Nutritional Category	Energy Source	Carbon source	Groups of Organisms
Photoautotrophs or Photolithotrophs	Sunlight (photosynthetic organisms)	CO_2	**Aerobic Organisms:** -Cyanobacteria -Algae (Bacillariophyta or diatoms) -Algae (Chlorophyta) -Lichens -Mosses and liverworts -Higher plants
Chemoautotrophs or chemolithotrophs	Redox reactions (photosynthetic organisms)	CO_2	**Aerobic organisms:** -Hydrogen bacteria -Iron bacteria -Nitrifying bacteria -Sulfur-oxidizing bacteria
Photoheterotrophs or photoorganotrophs	Sunlight (photosynthetic organisms)	Organics	**Aerobic Organisms:** -Photosynthetic bacteria -Some algae
			Anaerobic organisms: -Green and purple sulfur bacteria -Purple non-sulfur bacteria
Chemoheterotrophs or chemoorganotrophs	Redox reaction (chemosyntetic organisms)	Organics	**Aerobic Organisms:** -Actinomycetes -Animals -Fungi -Respiratory bacteria
			Anaerobic organisms: -Fermentable bacteria -Denitrifying bacteria -Sulfur-reducing bacteria

Mechanism and Effect of Biofilm Growth on Construction Materials

In order to identify methods to control and prevent the colonization and formation of biofilms on concrete surfaces, it is important to identify the main types of microorganisms responsible for the production of the visible stains, explain how they colonize concrete surfaces, and the mechanisms of these microorganisms for deteriorating concrete surfaces. Construction materials including concrete have a characteristic called bioreceptivity, which is the capability of such material to host or allow living species to colonize it *[5, 26]*. When biofilms develop in concrete surfaces, they are able to deteriorate the surface by two mechanisms *[5]*:

- By absorbing components present in the substrate (concrete) and using them as nutrients, and/or,
- Producing organic and inorganic acids that attack concrete's components solubilizing them.

Gaylarde et al. divided biodeterioration of concrete material into three types *[5]*:

1. Physical or mechanical biodeterioration;
2. Fouling or soiling (aesthetic); and,
3. Chemical.

The first type of biodeterioration (physical or mechanical) takes places when microorganisms change the physical structure of the material by growing or moving, but not by using the substratum as a nutrient source. The second type (fouling and soiling) occurs when a layer of microbes (biofilm) develops in the material surface. This biofilm is created by microorganisms: dead microorganisms, excreted products, and/or metabolic products. Fouling and soiling of a material surface will cause a visible stain on the surface, which usually affects the aesthetic aspect of the material but not its performance. The last type of biodeterioration (chemical) occurs due to two factors: (1) excreted product of microorganisms as organic or inorganic acids, which affect the material's microstructure and components, and (2) microorganisms use the surface (substratum) as a nutrient source.

When a construction material such as concrete becomes colonized by microorganisms, the humidity and microstructure of the material surface changes. Consequently, the roughness of the surface increases, rendering the surface more capable for growth and attachment of microorganisms. Minerals contained in Portland cement and aggregates can be used by microorganisms directly as nutrients and in other cases they can be solubilized by microbial metabolites *[5]*. The solubilization of minerals in the concrete mix is caused by metabolic reactions of microorganisms present in the surface. Nitrifying bacteria and *Nitrosomas* produce nitric acids in their metabolic processes, nitric acids then solubilize calcium present in cement and form soluble calcium nitrate *[5]*. When this process (solubilization of minerals) occurs, the microstructure of the surface becomes unstable and the deterioration process starts.

A similar explanation can be found in Sanchez-Silva and Rosowsky, which states that reinforced concrete structures' integrity can be affected by microorganism activity *[12]*. Sanchez-Silva and Rosowsky described a three-step process by which microorganisms can compromise the integrity of a concrete structure *[12]*:

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 generally shows high levels of alkalinity, with pH levels between 11 and 13. When concrete shows these high levels of pH, it is almost immune to colonization by microorganisms because only a few species can develop in such high levels of pH, these species are called *Alkalinophilic [27].* Given time, the interaction between concrete and CO_2 in the environment gradually decreases its pH levels, eventually reaching levels that allow bacteria to colonize and grow on concrete (pH 9-9.5) *[12].* After reaching these levels of pH, different species of bacteria and microorganisms start to form a biofilm on the concrete surface. This biofilm starts a deterioration process where different organic and inorganic acids, which are excreted by microorganisms, react with concrete solubilizing cement components. The microscopic sizes of microbes allow them to penetrate deep within the concrete matrix by filtering through the micro cracks and capillarity of concrete. The penetration of microorganisms into the concrete matrix results in an increased concrete porosity, which then changes the 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.

Once the reinforced steel is exposed to the environment, it becomes susceptible to the effects of corroding agents. The corrosion process of the reinforcing steel starts when the concentration of chloride on the steel surface surpasses a certain established value *[28].* The corrosion process generates corrosion products that start to fill the voids and open spaces between the steel and concrete. Finally, when these spaces are filled with corrosion products, the stress produced by their expansion increase until it exceeds the tensile strength of concrete and creates cracks *[12, 28].*

Table 4 shows the effects of different microorganism's activity on construction materials. Depending on the activity that the microorganism performs (physical presence, acid production, etc.), different kinds of effects will be produced on the surface of the material acting as a substrate (wood, polymers, concrete, stone, paint, etc.). The consequences can range from discoloration and retention of water to degradation of material, corrosion and weakening and dissolution of the material acting as the substrate.

Table 4
Effects of microorganisms on building materials *[5]*

Microorganisms	Activity	Effect(s)	Material
Algae, photosynthetic bacteria	Physical presence	Increased growth of heterotrophic organisms	Any clean surface
Fungi, bacteria; Filamentous fungi	Hydrolytic enzymes	Breakdown of components; Degradation of short-chain additives	Wood, painted surfaces, polymers, mortar, concrete
Fungi, actinomycetes, cyanobacteria, algae	Filamentous growth	Disaggregation of material	Stone, concrete, mortar, wood
Fungi, bacteria	Acid production	Corrosion	Stone, concrete, mortar
All	Mobilization of ions	Weakening and dissolution	Stone, concrete, mortar
Organic acid producers, e.g., fungi	Chelation of constituent ions	Weakening and dissolution	Stone, concrete, mortar
Algae, cyanobacteria	Uptake of H^+ ions by cells	Alkaline corrosion	Stone
All	Release of polyols (e.g., glycerol, polysaccharides)	Disruption of layered silicates	Siliceous stone

Deterioration of Concrete Due to Microbial Activity

Colonization and growth of microorganisms in concrete elements causes significant aesthetic and structural deterioration. Bacteria, cyanobacteria, fungi, lichens, and algae are among the most typical microorganisms that colonize, create biofilms, and affect construction materials' surfaces adversely *[5, 11]*. The first research study that proved that concrete surfaces could be deteriorated by microbial activity was performed in 1945 by C. D. Parker *[16]*. Unlike previous research studies that failed to provide substantial evidence for the causes of corrosion of concrete surfaces in sewer systems, this research was able to determine the cause of concrete deterioration. Parker concluded that the deterioration of concrete in the inner side of sewer pipelines was caused by sulfuric acids produced by a bacteria (*Thiobacillus Concretivorus*) present on the concrete surface. This bacterium absorbs the hydrogen sulfide typical of a sewer environment (H_2S) and transforms it into the corrosion-causing sulfuric acid (H_2SO_4). Parker created an apparatus to expose concrete blocks to an enriched atmosphere of H_2S and NH_3 as shown in Figure 10.

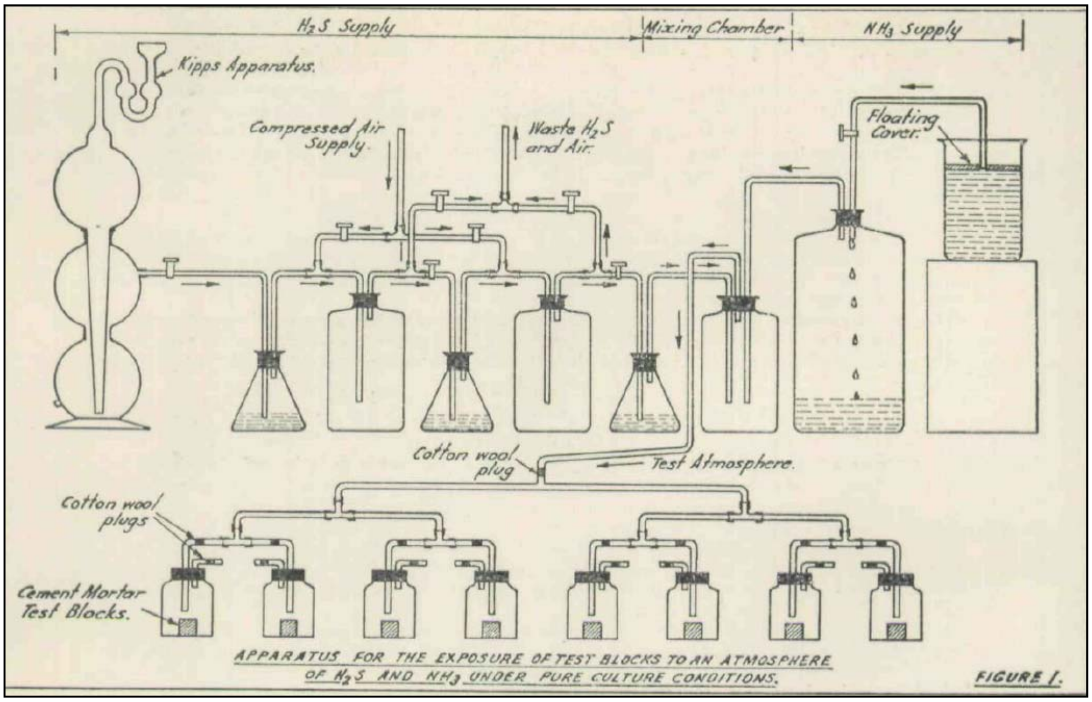


Figure 10
Laboratory test performed by Parker to test the effects of the bacterium on concrete *[16]*

Using the laboratory setup presented in Figure 10, concrete blocks were inoculated with specimens found in corroded concrete inside sewer pipes for a period of 3 to 4 months until the corrosion was visibly evident, as shown in Figure 11. This research provided evidence that demonstrated that more investigation on microorganisms and their deteriorating effects on concrete surfaces is needed.

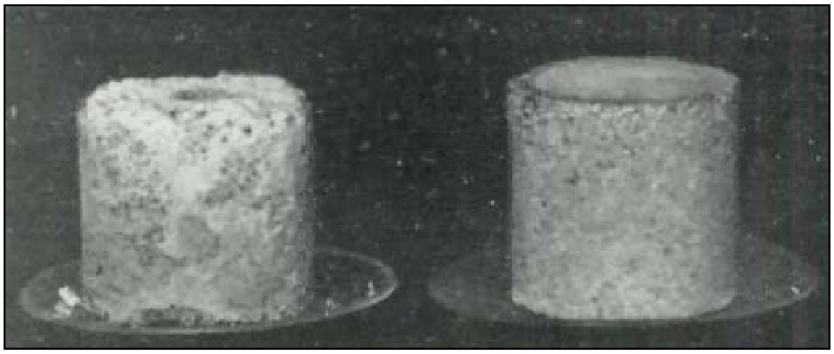


Figure 11
Corroded concrete block after removal of corroded material *[16]*

Concrete elements under the effects of microorganisms for a prolonged time can show significant staining and weight loss that can be a threat to both their aesthetic and structural integrity *[16, 29]*. Sand and Bock also conducted laboratory-controlled experiments trying to quantify the amount of deterioration in the form of loss of material produced by isolated bacteria strains. The bacteria strains were collected from corroded concrete of sewer pipes. Concrete blocks were exposed to an H_2S rich environment inside a chamber, and sprayed with the isolated bacteria strains (T. intermedios/novellus, T. neapolitanus, T. thiooxidans) for a period of 9 to 12 months. The results of the experiment showed that the highest damage to concrete was caused by the strain T. thiooxidans, which, in one of the experiments, resulted in a medium value of 3.3% of material loss. However, these experiments simulated the conditions where concrete is exposed to a sewer-like environment, which is different from the one that highway infrastructure is exposed to in outdoors.

Deterioration of Highway infrastructure Concrete Elements Due to Presence of Micro-Organisms. Gu et al. demonstrated the effects of fungi on the degradation of concrete *[17]*. In this experiment, concrete samples were inoculated with *Fusarium* sp. (fungal specie) and *T. intermedius (bacteria).* During the first month of inoculation, the Portland cement samples demonstrated similar Ca^{2+} release for both species. For the remainder of the experiment, the concrete inoculated with Fusarium sp. showed higher levels of calcium release with 24% of weight loss compared to the 18% weight loss of the concrete inoculated with T. intermedius as shown in Figure 12. This experiment was the first to show that biofilms composed by, not only bacteria, but also fungal species have deteriorating effects on concrete. Furthermore, it showed how significant the weight loss of concrete elements can be when exposed to microorganisms.

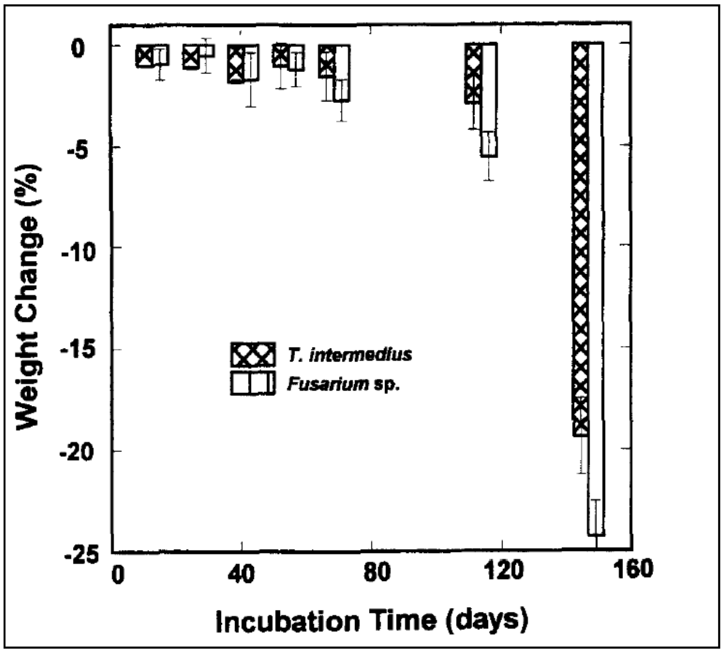


Figure 12

Percentage of weight change of concrete blocks inoculated with Thiobacillus intermedius and Fusarium sp. ***[17]***

Surface roughness, water to cement ratio, and photocatalytic TiO_2 cement mixtures have been identified as important parameters that influence bioreceptivity of concrete *[26, 30, 31]*. Bioreceptivity of concrete has been shown to increase as the surface roughness increases. Guillite and Dreesen conducted an experimental program to test different construction materials including aerated concrete, gobertange stone, modern mortar, brick, and petit granite, as shown in Figure 13. The experiment was conducted to test the bioreceptivity of these materials to microorganisms. Results showed that the construction materials with the highest porosity had the highest bioreceptivity *[26]*. Similarly, the vegetative cover of the construction materials after a period of 6 months was found to be higher in the materials where the porosity was higher as shown in Table 5.

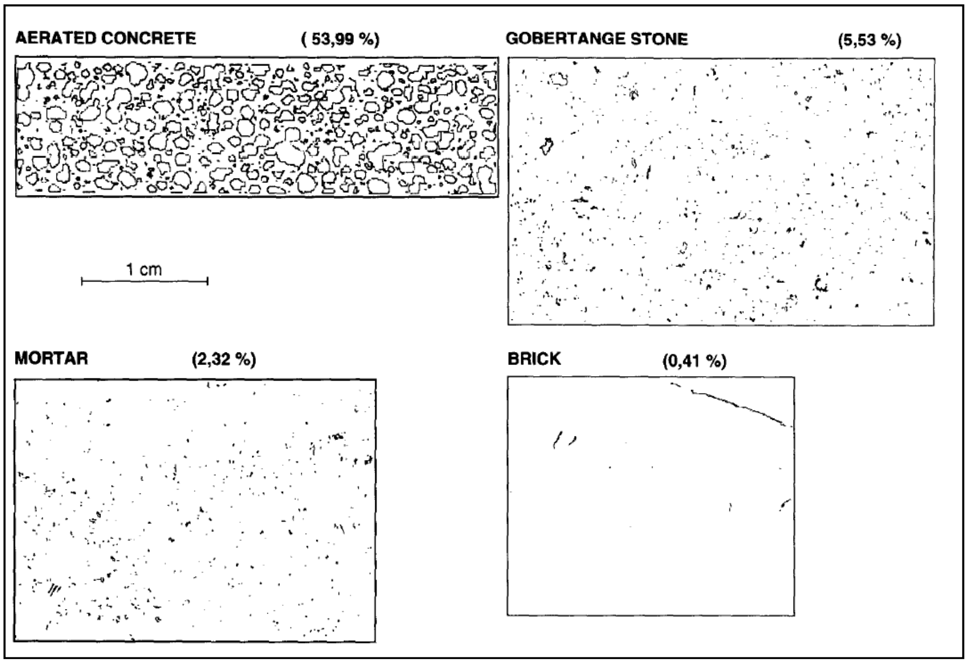


Figure 13

Macro-porosity values in percentage of the materials tested in the experiment. The values were obtained through automated image analysis *[26]*

Table 5

Percentages of vegetation coverage on the tested construction materials *[26]*

Material	Aerated Concrete	Gobertange Stone	Modern Mortar	Brick	Petit Granit
Macroporosity Values (%)	53.99	5.53	2.32	0.41	Less than 0.1%
Maximum Vegetation Cover	100	100	60	60	30
Mean Cover	93±7	82±19	53±15	38±25	5±9

Another study investigated how the percentage of the covered area varied with porosity and water cement ratio. Results are shown in Figure 14 *[30, 31]*. As surface roughness of concrete increased, void ratio also increased, creating more space for water retention, which can support microorganism growth. In addition, water/cement ratio has been proved to influence the bioreceptivity of concrete to certain deteriorating species of microorganisms. As the water proportion in a concrete mix increased, the permeability of concrete also increased, thus resulting in larger areas for moisture and nutrient retention *[30, 31]*.

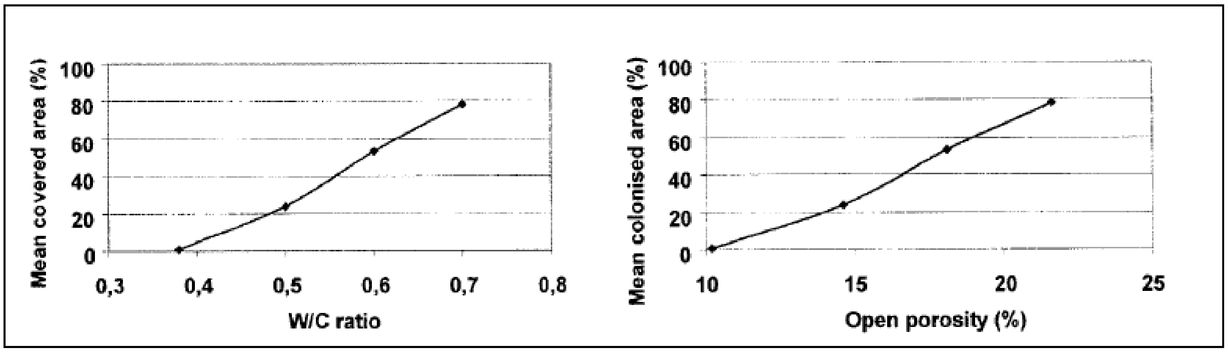


Figure 14
Percentage of mean covered area vs. water-to-cement ratio (left) and open porosity (right) *[31]*

A similar relationship was observed in the experiment conducted by Giannantonio et al. and is shown in Figure 15 *[30]*. The coverage of the biofilm layer increased as the water-to-cement ratio increased.

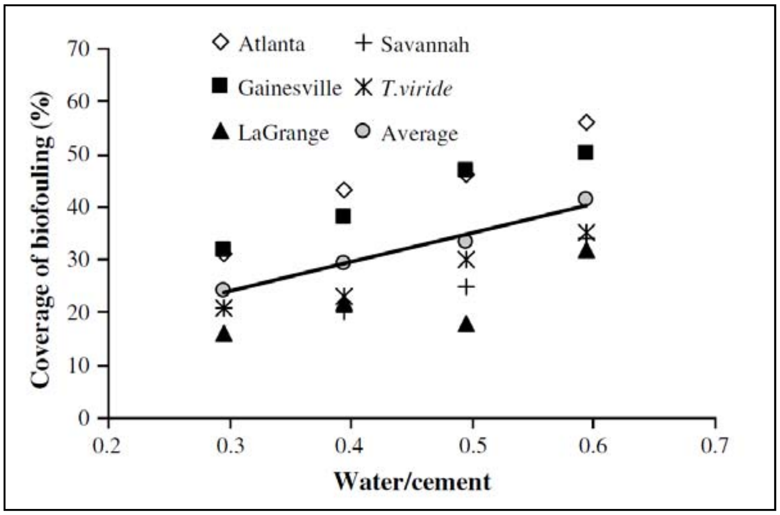


Figure 15
Coverage of Biofouling vs. water-to-cement ratio *[30]*

Research performed by Trejo et al. investigated the causes of deterioration on the concrete surfaces of bridges in Texas *[32]*. The deterioration on these bridges was found in the form of large stains, black crusts, and deterioration of the concrete surface. At first, the deterioration was attributed to the influence of acidic waters near and in contact of concrete bridges' parts.

However, after an investigation of the waters surrounding the bridges, the study discounted that the water was responsible for the deterioration because they showed normal acid levels and concluded that the deterioration in the concrete was caused by the presence of microbes in the concrete surface. The study also revealed that the damage caused was proportional to the quantity of microbes present as shown in Figure 16, and that the microbe species present were, in fact, producing the acids that caused the deterioration (stains). The study recommended further investigation to determine the rate of deterioration of concrete attacked by microbial species and procedures and techniques to mitigate this attack *[32]*.

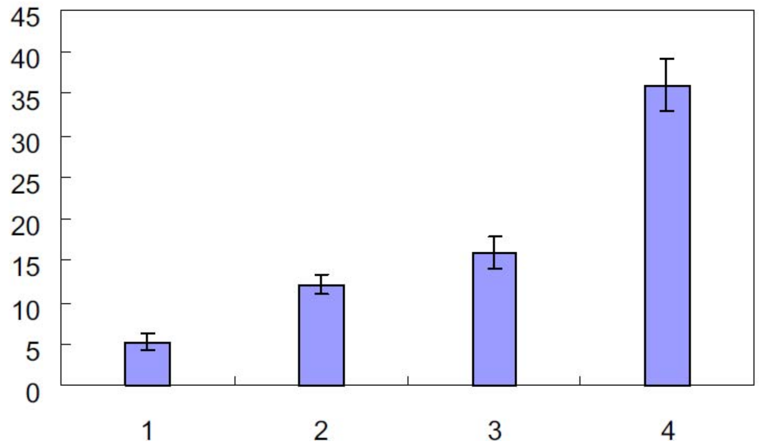


Figure 16

Concrete deterioration state versus quantity of microbes present in x10^6 cells/g (1 - undeteriorated concrete, 2 - slightly deteriorated, 3 - moderately deteriorated concrete, and 4 - severely deteriorated concrete) ***[32]***

Cleaning and Prevention Methods of Biofouling

Preventing and cleaning microbial growth in construction materials has always been a challenge. It is especially difficult to determine the best and most effective methods to prevent or control, and clean microorganisms present on concrete surfaces, given the broad variety of species and their specific characteristics. The prevention or cleaning method will often depend on the physiology of the microorganisms' variety colonizing the concrete. Moreover, controlling biofilms growth on highway infrastructure is even harder, since it is virtually impossible to control humidity in the environment, one of the most important factors that influence microorganism growth.

This report classifies control and cleaning methods as methods to eliminate microbial growth into three groups: *cleaning, eradication, or prevention. Cleaning and eradication* methods are used to eliminate microbial activity from surfaces where biofilm growth have already been established. *Prevention methods* are used for surfaces free from microbial activity to prevent, control, or minimize biofilm growth.

Cleaning Methods of Biofilms

Biofilms can be removed from their substrate by implementing mechanical procedures to detach microorganisms. These methods are the most recommended 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 *[33]*. 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 removing a small percentage of the layer of the substrate.

Sandblasting. Abrasive blasting, shown in Figure 17, is commonly known as *sandblasting.* This is a process that consists in 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 *[34]*. Compressed air or centrifugal wheels are the most common mechanisms to propel the blasting media. There are several variants of this process, such as shotblasting, 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 ($NaHCO_3$) as the blasting media.

Figure 17
Abrasive blasting *[35]*

Soda Blasting. Soda blasting, shown in Figure 18, is an abrasive but gentle cleaning method that is increasing in popularity. The process involves the use of Sodium Bicarbonate ($NaHCO_3$) 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. Other methods such as sand blasting were discarded because they could cause damage to the materials of the Statue of Liberty *[36]*.

Figure 18
Soda blasting of a steel container prior to repainting *[37]*

The equipment used to perform soda blasting operations is called a soda-blaster, shown in Figure 19. The soda-blaster consists of a blast generator, high pressure compressed air, moisture decontamination system, blast hose, and a blast nozzle *[36]*.

Figure 19
Soda-blasting machine *[38]*

Dry Ice (CO_2) Blasting. Dry ice blasting shown in Figure 20, uses CO_2 as the blasting medium. Carbon dioxide, shown in Figure 21, 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 *[39]*.

Figure 20
Dry-Ice blasting process *[40]*

Figure 21
Dry-ice blasting medium (pellets) *[34]*

Pressure Washing. Pressure washing, shown in Figure 22, is a method that is used in order to remove contaminants from surfaces. The process consists in 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 *[41, 42]*.

Figure 22
Pressure washing of a concrete deck *[41]*

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 they come in many forms, such as liquid, powder, or 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 *[3]*. However, these chemicals can be dangerous for humans and animals, which is why precautions have to be considered before selecting a biocide:

- **Spectrum of the biocide.** It is important to determine the kind of microorganisms that are causing the deterioration. Some biocides have specialized effect on a specific type of microorganism such as bacteria or algae. Other biocides have a broader spectrum and can attack a larger variety of microorganisms but it is always important to make sure that the microorganisms responsible for the deterioration are going to be targeted by the biocide that is going to be applied.

- **Toxicity of biocides.** Biocides are toxic products designed to kill life forms, and depending on the biocide, they can be dangerous for humans, animals, and plants. When planning to use biocides in places that can represent a threat to human or animals, the level of toxicity must be considered.

- **Effect on materials.** The biocide chosen must not change any property of the material on which it is going to be applied. Some biocides can corrode steel, change the color of certain surfaces, and deform plastics.

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 will vary depending on which chemical compound they contain.

Oxidizing agents. 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. Ozone has become very popular in the water supply industry where it is used to purify potable water.

Aldehydes. These compounds have good water solubility and vaporize well. Among them, Formaldehyde and Glutaraldehyde have broad spectrums. Glutaraldehyde is commonly used in the medicine industry to clean and disinfect surgical equipment.

Alcohols. These chemicals are broadly used for hand-disinfectant lotion because of their effects on bacteria and viruses. However, these chemicals evaporate very quickly and are not commonly used as biocides.

Phenolic. These compounds were some of the first effective biocides. Usually, these biocides target bacteria, but some variations of phenolic compounds can be used to target fungi as well. Some phenolic compounds have very strong odor and some others are very persistent in the environment, which is why their use is limited.

Organic acids. Weak organic acids as acetic, propionic, lactic, sorbic, and benzoic are often used in the food industry as preservatives and to prevent the growth of molds and yeasts in fruit juices and fermented milk products.

Quaternary ammonium/phosphonium compounds. These chemicals have a broad spectrum as biocides when not used in combination with anionic surfactants, and high levels of protein and salts, which decrease their effects. One of the best characteristics of these compounds is that they can be used as long-term biocides.

*Isothiazolinones***.** These chemicals are one of the newest technologies in biocides. Isothiazolinones are commonly used as dry-film preservatives in paints, adhesives, sealants, and plastic films.

Table 6 presents information on how different biocide compounds, such as chlorine, hypochlorite, phenols, izothiazolinones, etc., affect microbial activity. Different biocides have different modes of action in order to eradicate microbial activity. These modes of action range from oxidizing actions, which destroys cell walls; membrane active components, which affect membrane integrity; and a number of microbial processes inhibitors that restrict a vital process of the microorganism eventually resulting in death.

Physical Methods. Physical methods are 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 enough 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 *[3, 8]*. UV rays, microwaves, and gamma rays have also been employed in order to restrict microorganisms' growth *[3, 8]*. Gamma radiation has also been successfully implemented to eliminate fungal growth from books after flooding events *[8]*.

Table 6
Mechanism of action of biocides *[8]*

Compounds	**Mode of Action**
Hypochlorite, bromine, Ozone.	**Oxidizing**, eliminates cells' walls and constituents
Quaternary ammonium compounds, alcohols, parabens.	**Membrane active**, affects transport mechanisms and affects membrane integrity
Phenols, adehydes, formaldehide, condensates, and parabens.	**Protein denaturation**

Izothiazolinones, bronopol, dibromodicyanobutane.	**Protein synthesis inhibitor,** bind with thiol groups in cell affecting enzyme activity
IPBC, carbendazim.	**Nuclear division inhibitor,** DNA synthesis inhibition
Imazalil, tebuconazole, propiconazole.	**Membrane synthesis inhibitor**, prevents the synthesis of ergosterol in fungi
Diuron, irgarol, terbutryn.	**Photosynthesis Inhibition,** affects electron transport

Even though physical methods have been successfully applied in certain industries and fields, it is unlikely that these methods would succeed in highway infrastructure because it is virtually impossible to control variables such as temperature, humidity, and pressure for long periods of time outdoors. UV rays, gamma rays, and microwaves will also show negative results because of the difficulty of the application of these techniques in open environments and also because of the magnitude of the size of highway infrastructure elements.

Preventive Methods

New technologies in prevention of microorganisms' growth are currently being explored. The use of Titanium Dioxide (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, 12]*.

Titanium Dioxide Photocatalyst Coating. Titanium dioxide can be used to construct 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 *[43]*. Super-hydrophilicity is defined as the ability of the material to have a water contact angle of approximately 0^o 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 23. Both processes take place simultaneously on the TiO_2 surface. The following section explains the mechanism behind both processes.

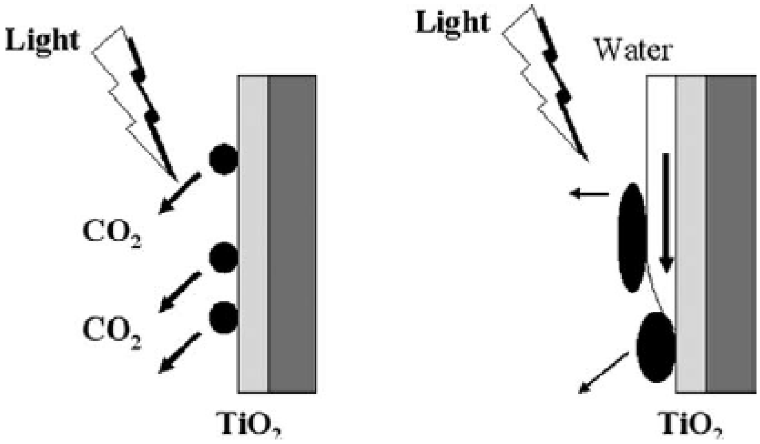


Figure 23
Super-hydrophilic process of TiO$_2$ *[43]*

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 0^o) between water and supporting solid is obtained (Figure 24). This causes the water droplets to behave as a layer or a sheet, instead of individual circular droplets as shown in Figure 25.

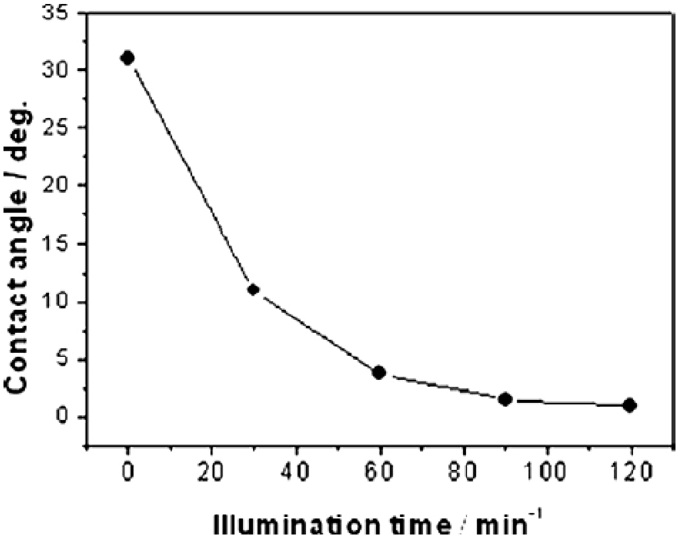


Figure 24
Water contact angle as a function of time under UV illumination *[43]*

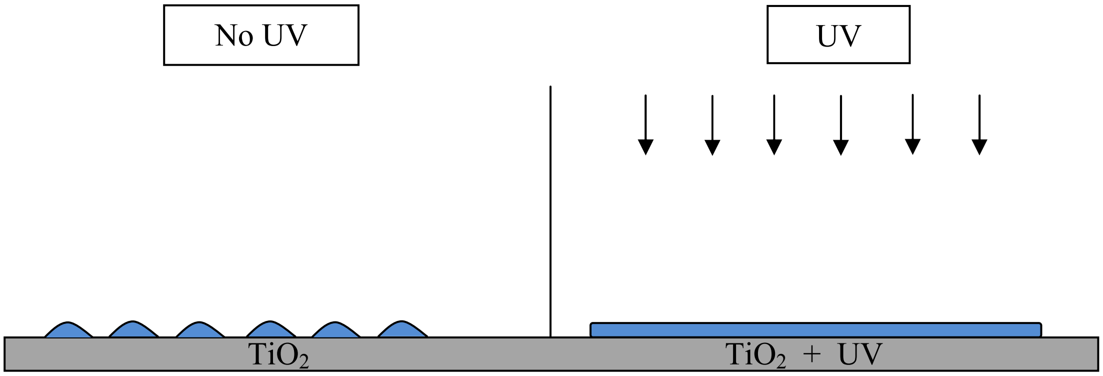


Figure 25
TiO_2's super-hydrophilicity

Since TiO_2 is a semiconductor with a bandgap of about 3.0 eV, it produces electrons and holes when exposed to UV light *[44]*:

$$TiO_2 + 2hv \longrightarrow 2e^- + 2h^+ \qquad (1)$$

The electrons released reduce Ti^{4+} cations to a Ti^{3+} state and the holes oxidize O^{2-} anions releasing oxygen atoms and creating vacancies in the titanium dioxide lattice structure as shown in Figure 26:

$$Ti^{4+} \longrightarrow Ti^{3+} + e^- \qquad (2)$$

$$4h + 2O_2^{2-} \longrightarrow O_2 \qquad (3)$$

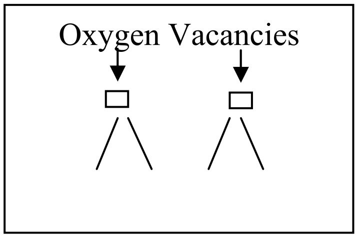


Figure 26
TiO_2's super-hydrophilicity (Part I)

When the surface is washed, water molecules occupy these vacancies, as shown in Figure 27, producing adsorbed OH groups and making the surface hydrophilic.

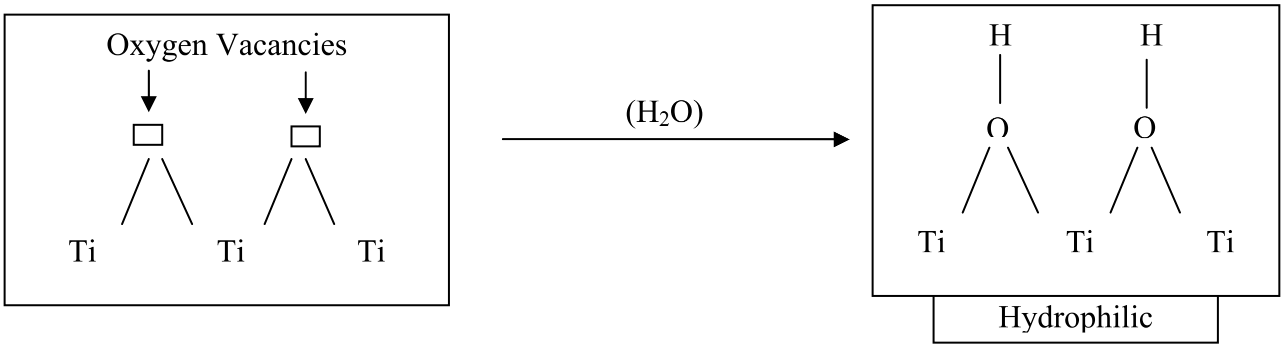


Figure 27
TiO_2's super-hydrophilicity (Part II)

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 *[45]*:

$$TiO_2 + hv \rightarrow h^+ + e^- \qquad (4)$$

$$OH^- + h^+ \rightarrow OH^* \qquad (5)$$

$$O_2 + e^- \rightarrow O_2- \qquad (6)$$

The holes, h+, and the electron pair, e-, are the produce of powerful oxidizing and reductive agents *[46]*. The hydroxyl radicals and superoxides have been proven to play an important role in the photodegradation reactions *[45]*. The hydroxyl radicals, OH*, are strong oxidants that rapidly decompose organic and inorganic compounds, while the superoxide ions, O_2- , are the reduction pathways *[47]*. Thus, rather than just absorbing pollutants, common of traditional air purification methods, pollutants are decomposed to nonhazardous waste products with little energy requirements *[45]*.

Photocatalytic and self-cleaning performance of TiO_2 surfaces. A number of studies have been carried out in order to test the self-cleaning and photocatalytic properties of TiO_2 in construction materials. Giannantonio et al. conducted a study to describe the fouling of concrete surfaces by diverse fungal genera, extracted from existing contaminated concrete surfaces *[30]*. In their study, they examined how different fungal genera could affect different types of concrete compositions, surface finishes, and water-to-cement ratio. The sampling for the microorganisms to be used in their experiment was performed in four outdoor concrete sites in Georgia. The sites sampled showed typical fouled concrete characteristics such as black crusts covering large sections of the concrete surface. Mortar tiles of 6 x 6 x 0.4 cm with variations in cement composition, water-to-cement ratio, supplementary cementing material (SCM) additions, and surface finishes, were prepared in order to determine the susceptibility of different types of concrete to microbial growth. The variations of the mortar tiles were prepared as follows: one standard mix containing Holcim GU I/II cement with no SCM addition and brushed surface; three tiles with Holcim GU + limestone, Essroc I/II, and Essroc I/II + TiO_2 cement, respectively; three tiles with water-to-cement ratio of 0.3, 0.4, 0.6, respectively; ten tiles with SCM additions of fly ash: 10-18-25 in percentage, slag: 10-25-50 in percentage, silica fume: 5-10-15 in percentage, metakaolin: 8% respectively; and two tiles with polished surface finishes of 120 grit and 600 grit, respectively.

All the mortar tiles were inoculated with the fungal media collected and placed inside previously sterilized incubation chambers. The inoculated tiles were sprinkled with a nutrient substance to simulate outdoor environmental conditions. After the controlled laboratory experiment was carried out, most of the tiles showed biofouling characteristics. A strong statistical relationship between water-to-cement ratio and the coverage of biofouling was observed. The tiles with water-to-cement ratio of 0.3 showed significantly lower coverage of the biofouled area than those with water-to-cement ratio of 0.6. These results suggest that concrete structures with lower water-to-cement ratios are less susceptible to biofouling, which also agrees with the results obtained by Dubosc et al. in 2001 *[31]*.

The mortar tiles with photocatalytic TiO_2 addition showed a strong resistance to the colonization of microorganisms when compared to a tile with the same cement composition and same inoculated genera, but without TiO_2. The results of this experiment suggest that the use of photocatalytic cements in construction materials may prevent and mitigate the biofouling of the concrete surfaces.

As previously mentioned, application of biocides is among the most common methods to eliminate microbial life *[3, 8]*. Research performed by Fonseca, A. et al. compared three products: the use of two conventional biocides, Biotin T®, commonly used for cleaning monuments, and Anios D.D.S.H®, another common biocide used as an antiseptical product in hospitals, and TiO_2 in its anatase form *[48]*. Laboratory experiments and in-situ experiments were implemented in order to determine the anti-microbial effects of the three products selected.

For the laboratory tests, mortars were manufactured using Portland cement and lime, and the mortars containing TiO_2 were prepared using the same specifications but adding nanocrystaline anatase powder to the mix. After preparation, all mortars were inoculated with a photosynthetic culture and incubated for a period of four months to ensure biological growth. Afterwards, the mortar slabs without TiO_2 were treated with the two evaluated biocides. Finally, two weeks after, all mortar slabs were analyzed in order to quantify the amount of microbial life present.

The in-situ experiments were performed in two external walls of the *Palacio Nacioanal da Pena (Sintra)*. The two external walls selected showed extensive colonization by a diverse community of microorganisms. After the two locations were selected, the three products were brushed and sprayed against the biofouled walls on small areas of 50 cm^2. After the experiment was conducted and both the experimental mortar slabs and the treated surfaces on the in-situ site were analyzed to quantify microbial life present, the best results were obtained in both cases by the surfaces and slabs containing TiO_2.

Zeolite compounds. Haile and Nakhla tested the inhibitory effect to microorganism growth of zeolite compounds as coatings for concrete [10]. The experiment consisted of inoculating concrete tiles with an isolated bacterium (Th. Thiooxidans). The concrete tiles were coated with antimicrobial zeolite, and as control, uncoated tiles and blank zeolite coated tiles without antimicrobial agent were used. The concrete tiles were immersed in a basal nutrient medium with th. Thiooxidans. In order to determine the antimicrobial properties of zeolite coatings on concrete, dry cell unit weight (to quantify the increase in the number of microorganisms), and solubilization of metals in the cement paste were measured. SEM images of the concrete specimens were taken before and after the inoculation with the bacterium as shown in Figure 28.

Images A, B, and C in Figure 28 correspond to concrete tiles without zeolite coatings before (A) and after (B and C) exposure to the bacterium. The deterioration of the concrete surface of these specimens after exposure is visible (B, C). Concrete specimens coated with both antimicrobial zeolite and blank zeolite, demonstrated the resistance of zeolite to bacterial induced corrosion (images D, E, F, G, H). It was concluded from this experiment that concrete specimens with zeolite coatings are resistant to bacterial induced corrosion by th. Thiooxidans.

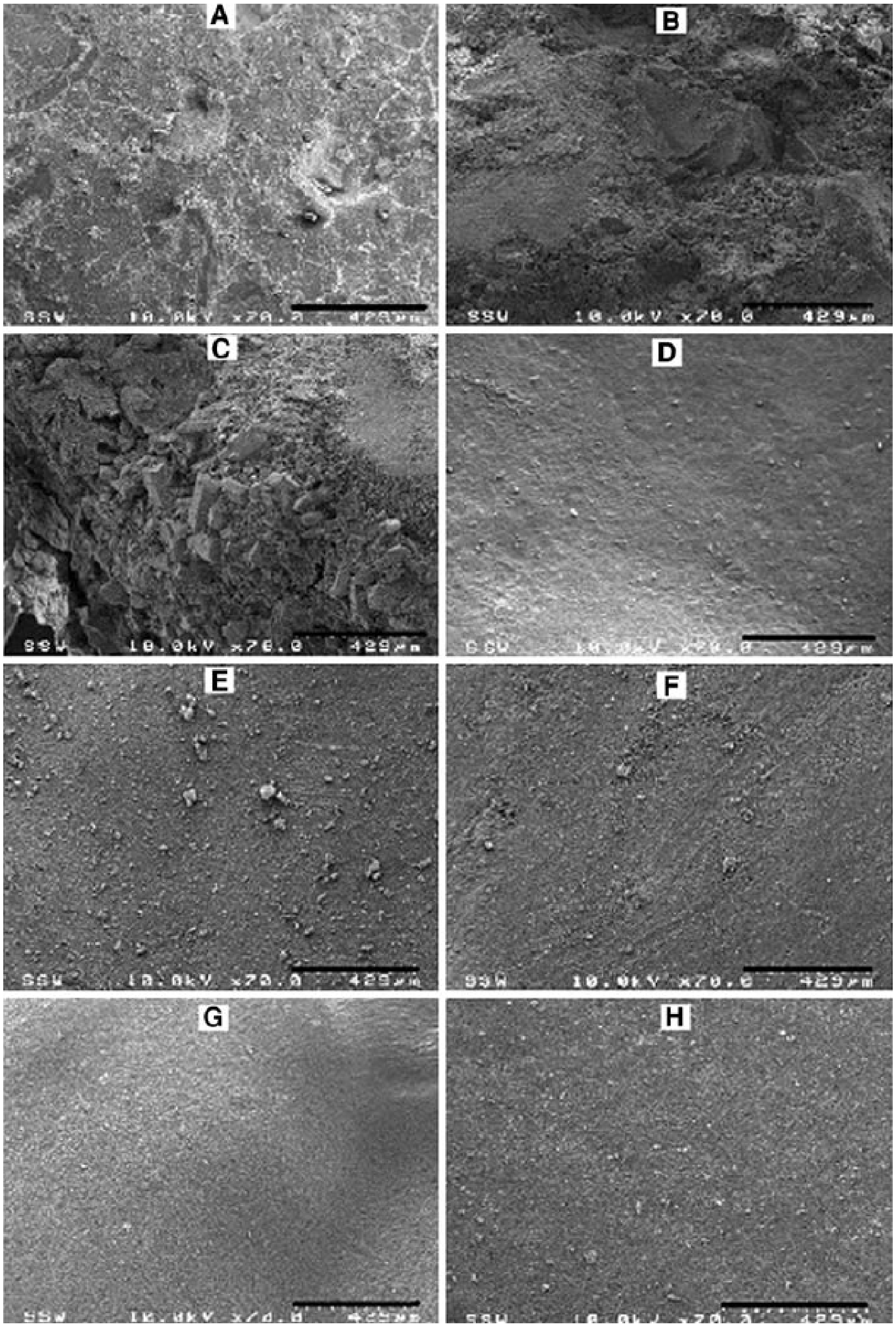


Figure 28

SEM images of concrete tiles. A, B, and C: concrete tiles without zeolite coatings. D, E, and F: concrete tiles coated with zeolite without antimicrobial agent. G and F: concrete tiles coated with antimicrobial zeolite *[10]*

SURVEY OF STATE PRACTICES

To investigate current maintenance practices performed by state highway agencies across the U.S., a survey questionnaire was developed. The objective of this questionnaire was to determine which states face biofilm issues, whether or not scheduled or non-scheduled maintenance procedures are employed, and if so, what methods are being employed. The survey was created and conducted to collect information from all state highway agencies regarding bridge maintenance procedures for cleaning concrete bridge structures. The survey identified the states that face biofilm growth on concrete elements, as is the case in Louisiana. Further, the survey was intended to collect information from the states that have biofilm growth on concrete structures and of the maintenance process or processes implemented by these states to handle biofilms issues. The survey was distributed nationwide. The research team intended to collect information from the different climatic regions according to the classification adopted by the Department of Energy. As shown in Figure 29, this classification consists of 8 different regions: Hot-Humid, Mixed-Humid, Hot-Dry, Mixed-Dry, Cold, Very Cold, Subarctic, and Marine.

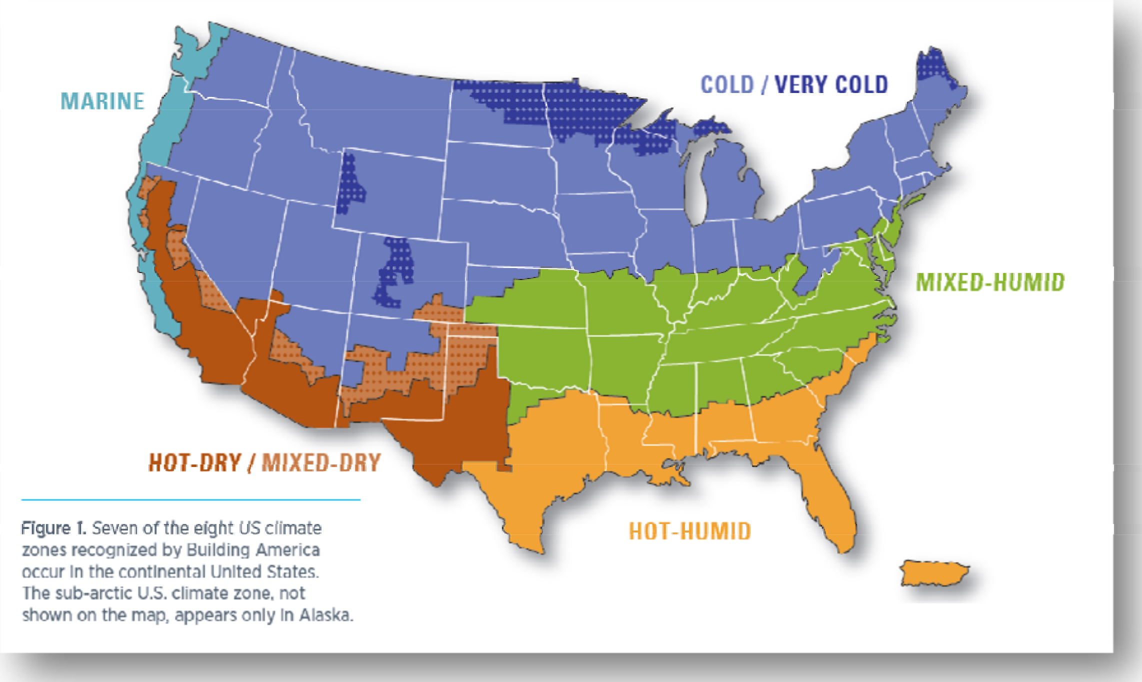


Figure 29
Climatic Regions (U.S. Department of Energy 2010)

The research team was successful in collecting information from all climatic regions with at least one response from each region. However, the subarctic climatic region was not considered in the survey. Phone interviews with experts were also conducted to collect additional information from state agencies. A copy of the survey is presented in Appendix A of this report.

Survey Results

A total of 50 questionnaires were sent to the state highway agencies. 20 states responded accounting for 40% of the states as shown in Figure 30. Table 7 presents the list of states that responded to the survey as well as their climatic classification. The relatively low response rate is because many states do not face biofilm problems due to the pertinent climatic conditions and, therefore, decided to not participate in the survey. While the response rate was low, the research team is confident that the 20 responses represent the majority of the states that face biofilm issues with their concrete highway infrastructure.

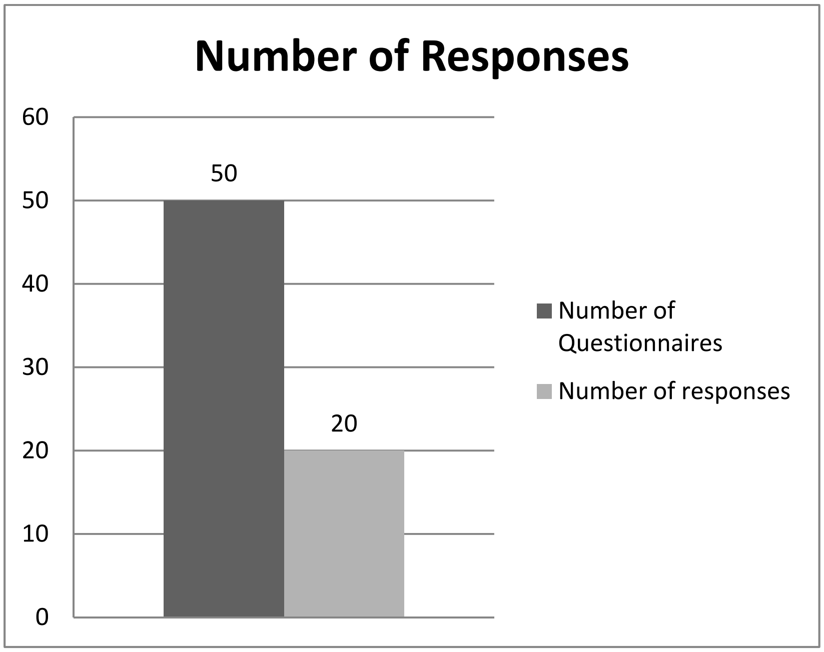


Figure 30
Total number of questionnaires and responses received

Table 7
Details of responding states to the survey

State	Climatic Region	Growth
Alabama	Hot-Humid	Yes
Alaska	Very Cold	No
Arizona	Hot-Dry	No
California	Mixed-Dry	No
Florida	Hot-Humid	Yes
Illinois	Cold	Yes
Iowa	Cold	No
Louisiana	Hot-Humid	Yes
Michigan	Cold	No
Minnesota	Cold	No
Mississippi	Hot-Humid	Yes
Montana	Cold	No
South Carolina	Mixed-Humid	Yes
South Dakota	Cold	No
Tennessee	Mixed-Humid	No
Texas	Hot-Dry	Yes
Utah	Cold	Yes
Washington (State)	Cold	Yes
Washington (Southwest)	Marine	Yes
Wisconsin	Cold	No

Figures 31 and 32 show the number and condition of the bridges in the states that responded to the survey. Figure 31 shows the total number of bridges maintained by each agency in each state while Figure 32 shows the approximate overall bridge conditions for all bridges in the reporting states, on a scale from 1 to 10 - 10 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, i.e., good conditions. The results obtained from the survey suggest that 10 of the 20 states that responded to the questionnaire have experienced some kind of visible biofilm (mold, mildew, fungal, or bacterial) growth on concrete structures, as shown in Figure 33.

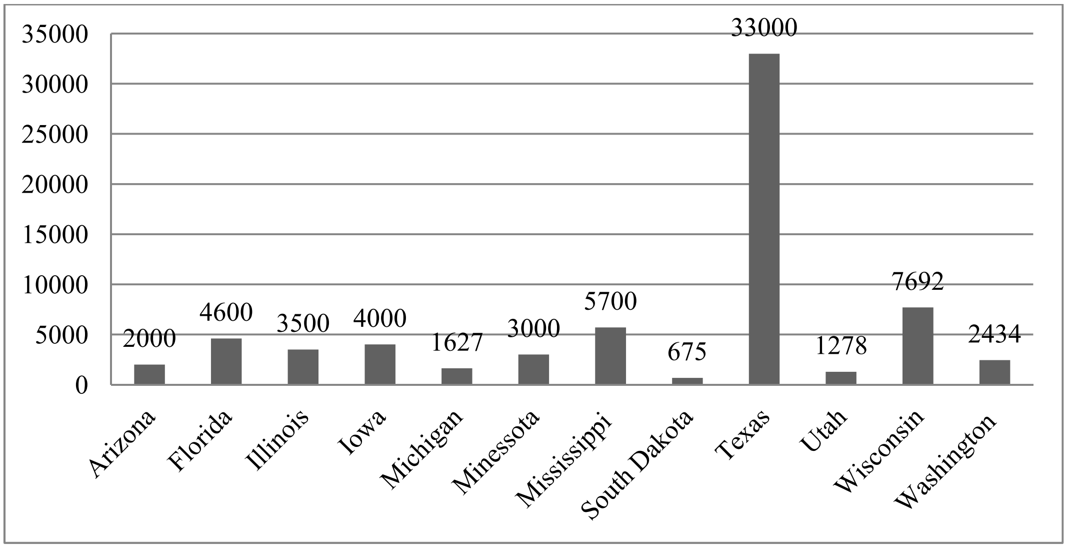


Figure 31
Number of bridges by state

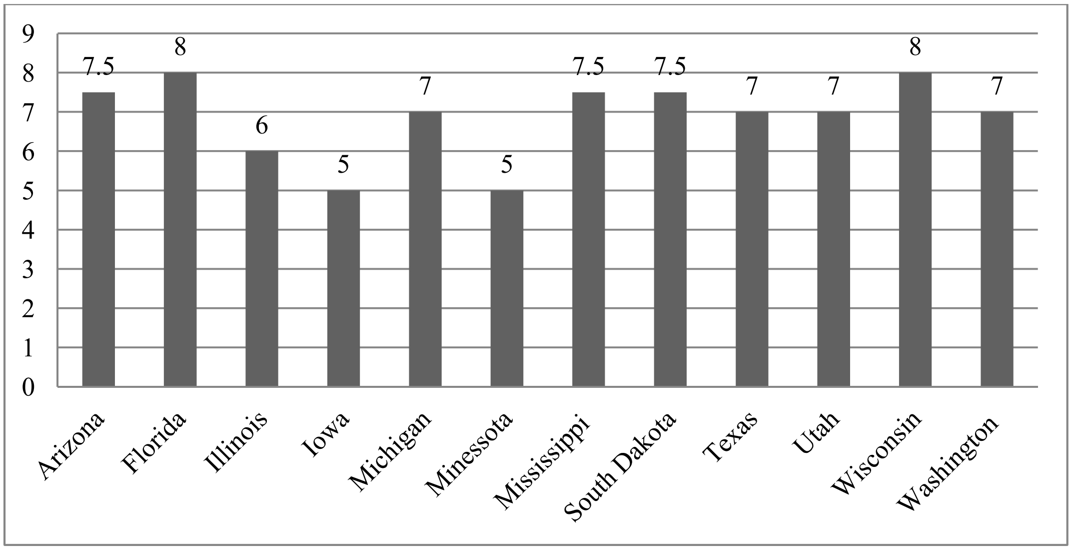


Figure 32
Approximate overall bridge conditions

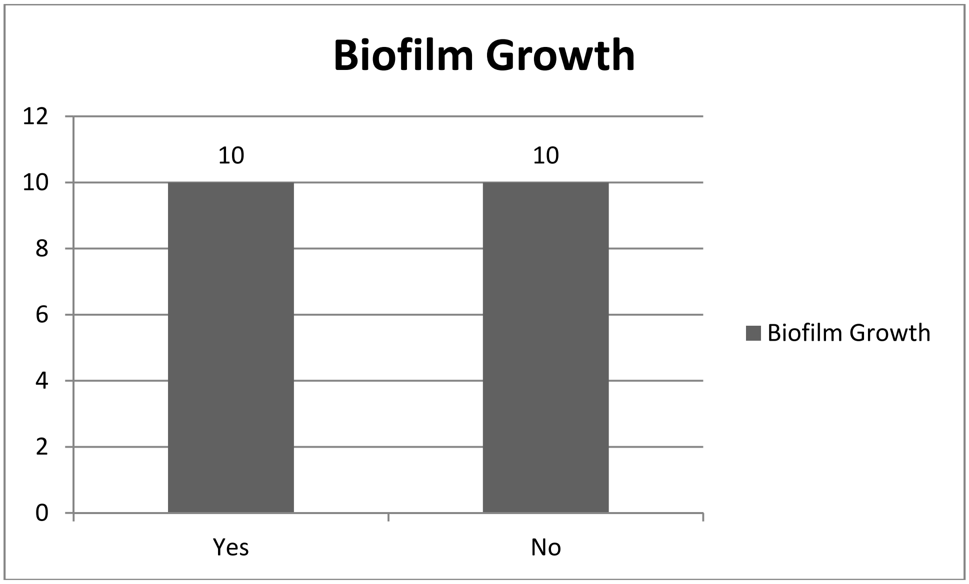


Figure 33
States with biofilm growth and states without biofilm growth

Although biofilm growth develops on concrete surfaces in multiple states, some 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 34, where 37% of the states stated that there was no growth, which can be, in most cases, attributed to the climatic conditions of the state (low humidity levels, very cold or hot temperatures). Of the states, 26% expressed that although they have biofilm growth, there was a lack of monetary resources to deal with this issue, as it does not present a danger to the structural integrity of the bridge. Another 16% 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 they do have minor mold or mildew growth but they did not consider it a problem, since the visible stains were minimal. States that treated the issue reported that they only treat it in places where it was visible enough to cause public concern or in areas that had high traffic concentrations. The most predominant method of treatment reported by the states was pressure washing.

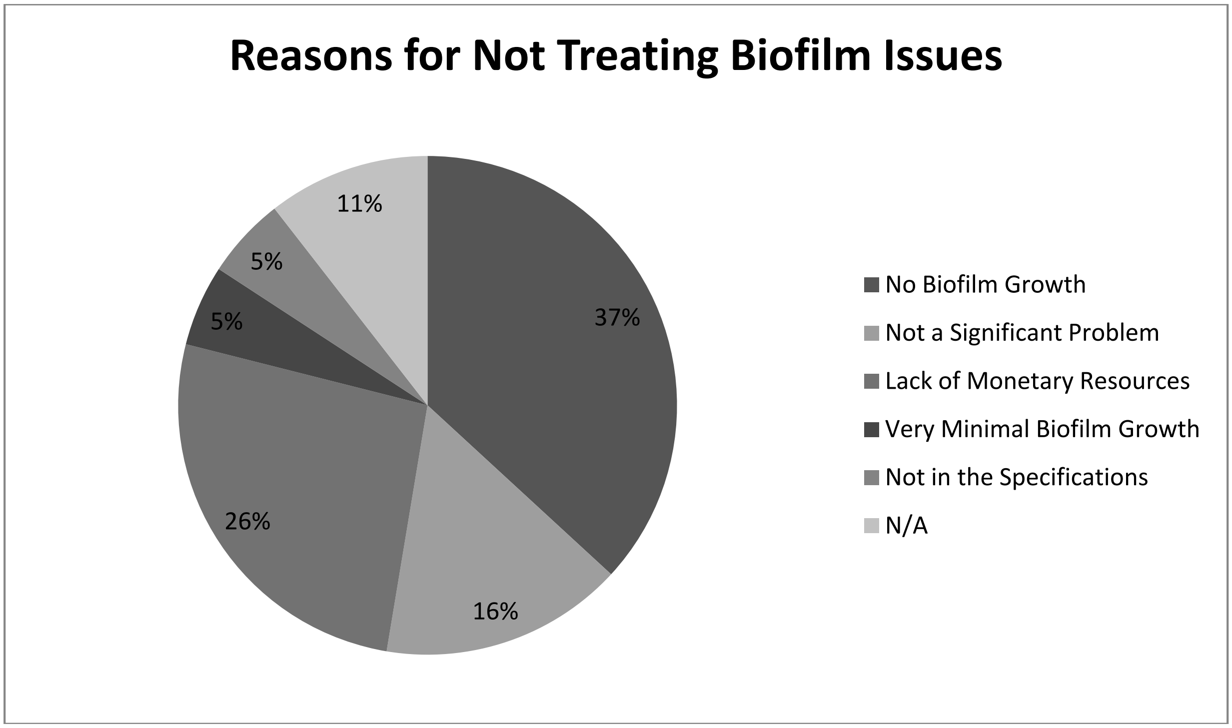


Figure 34
Reasons why biofilms were not considered a concern

Climatic conditions play a very important role in biofilm development. As discussed previously in this report, the literature review has shown that biofilm development is only possible where relatively high levels of humidity and temperature are present. Figure 35 presents the number of responding states in each of the climatic regions of the U.S. as defined by the DOE. All the states corresponding to the hot-humid climatic region reported biofilm issues as expected. Figure 36 shows how many states reported biofilm growth in each climatic region.

It is important to mention that none of the participating states responded to the questions 8-13. The reason is that none of the states that participated are currently employing any treatment method to address biofilm issues.

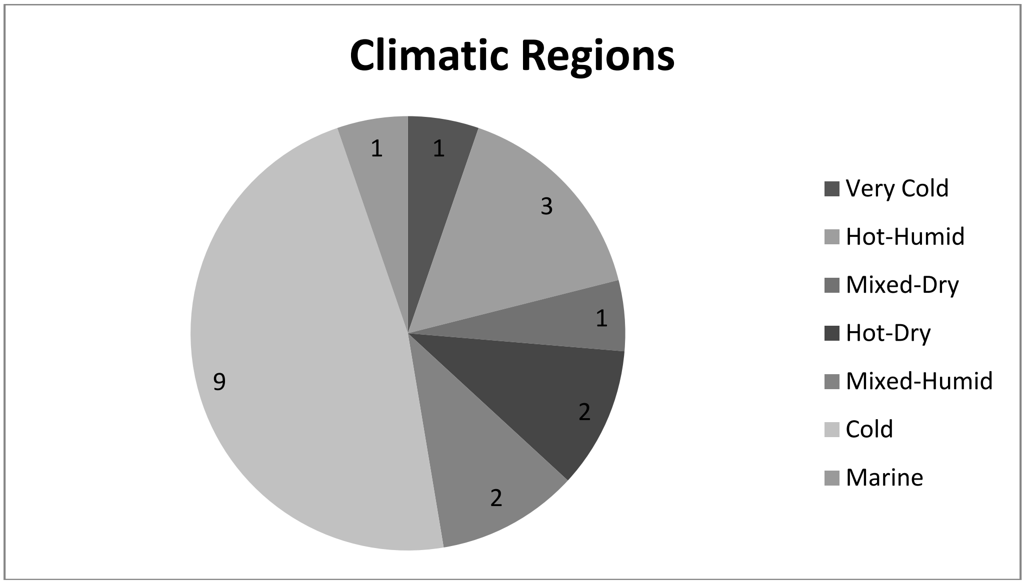


Figure 35
Distribution of climatic regions

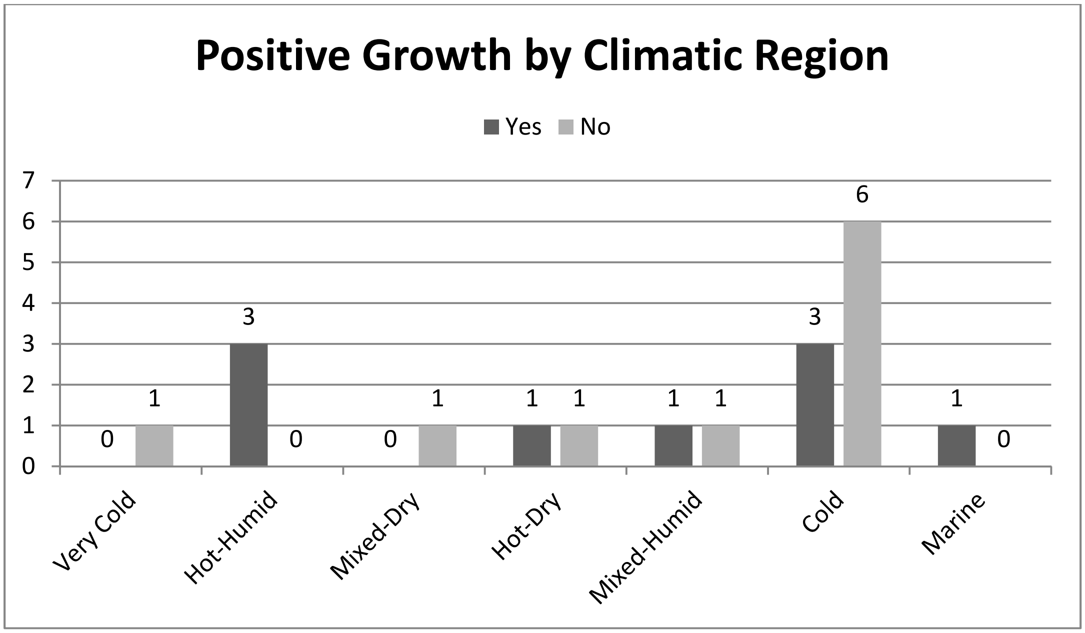


Figure 36
Positive mold growth by climatic region

COMPARATIVE ANALYSIS OF METHODS

Based on the results of the study, Table 8 presents a comparative analysis 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, these methods have short-term results since biofilms continue to develop on the structures over time if the cleaning methods are not applied regularly (1-5). Further, follow-up phone calls with state DOTs noted that 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 such as pressure washing. This indicates that more practical alternatives to 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.

Table 8
Comparative analysis of different treatment methods for biofilm

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	TiO2 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

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, TiO2 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 TiO2 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 TiO2 coatings may not perform successfully in areas in the shade or under the side of bridges.

Table 9
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

SUMMARY AND CONCLUSIONS

The primary objective of this study was to conduct a comprehensive synthesis to determine causes of concrete biodeterioration and to present current practices employed or evaluated for cleaning and maintaining vertical concrete elements on bridges. The goal of this synthesis was to identify possible preventive maintenance or construction materials that will enhance the resistance of these structures to biofilm growth and in turn reduce labor, costs, and traveling time delays. Emphasis was given to the methods used in states with climatic conditions similar to the ones encountered in Louisiana (i.e., hot-humid climatic conditions). Survey results showed that that none of the states that participated are currently employing any treatment method to address biofilm issues. Literature review showed that the following methods are currently being used to fight biofilm growth on concrete surfaces:

- Pressure washing
- Sandblasting
- CO2 blasting
- Soda blasting
- Application of biocides
- Temperature, pressure, and humidity control
- UV rays, Gamma rays, and microwaves
- Use of titanium dioxide in the concrete mixture and application of TiO2 coating
- Zeolite coating.

Based on the results of the survey and literature review, 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 are expected to last up to 10 years of service based on manufacturer's warranty, 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.

Results of the synthesis also showed that concrete mix design parameters, especially porosity and water/cement ratio, play an important role in controlling biofilms. As surface roughness of concrete increases, void ratio also increases, creating more space for water retention, which can support microorganism growth. In addition, water/cement ratio has been proved to influence the bioreceptivity of concrete to certain deteriorating species of microorganisms. As the water proportion in a concrete mix increases, the permeability of concrete also increases, thus resulting in larger areas for moisture and nutrient retention.

Based on the results of this synthesis, a comparative analysis was conducted to identify strengths and weaknesses of each treatment method. Based on this analysis, the research team recommends that a follow-up study be conducted in order to identify biofilm mechanisms in Louisiana and to conduct an experimental program to test a number of cleaning and preventive methods in the laboratory. Four research tasks were developed for the follow-up study. Based on the results of the follow-up study, a recommended state of practice should be developed to address biofilm growth in Louisiana. The developed practice should present recommended application of preventive methods as well as modifications to current concrete design and production practices in order to minimize or delay biofilm growth.

RECOMMENDATIONS FOR FUTURE RESEARCH

Based on the results of this study, the research team recommends that a follow-up study be conducted in order to identify biofilm mechanisms in Louisiana and to conduct an experimental program to test a number of cleaning and preventive methods in the laboratory. Based on the results of the follow-up study, a recommended state of practice should be developed to address biofilm growth in Louisiana. The developed practice should present recommended application of preventive methods as well as modifications to current concrete design and production practices in order to minimize or delay biofilm growth. To this end, the following four research tasks are recommended for the follow-up study.

Task 1: Sample and test bacteria and fungi from concrete highway infrastructure

The objective of this task is to sample biofilm and stained areas from the concrete highway infrastructure in Louisiana. Sampling should consider bridge substructure elements and bridge barriers located in different regions of the state. Samples will be transported to the laboratory and tested to determine the types of bacteria and fungi that predominantly attack concrete bridges in Louisiana. This information is important to identify a treatment method that is suitable for the types of biofilm growth in the state.

Task 2: Prepare laboratory concrete samples

The objective of this task is to prepare a number of concrete samples that may be used in the laboratory evaluation of different treatment methods against biofilm growth. While prepared concrete samples should follow a typical mix design adopted in the state, it is recommended that different water/cement ratios and porosities be evaluated as studies have showed that these factors play a strong role in combating biofilm growth.

Task 3: Laboratory performance of preventive methods

The objective of this task is to treat prepared concrete samples to different preventive methods including TiO_2 and zeolite compounds, and to compare the performance of these samples to control samples against biofilm growth and material loss. Laboratory testing should be conducted for an extended period of time (at least one year) to assess the service life of these preventive methods. Results of the laboratory program will also allow determining the effects of concrete mix design parameters on biofilm growth and prevention.

Task 4: Cost-effectiveness of preventive methods and development of treatment guidelines

The objective of this task is to assess the cost-effectiveness of preventive methods for combating biofilm growth and to develop a maintenance strategy for application of these coatings by the Department. Based on these results, a recommended state of practice should also be developed to address biofilm growth in Louisiana. The developed practice should present recommended application of preventive methods as well as modifications to concrete design and production practices in order to minimize or delay biofilm growth.

REFERENCES

1. Adamo, A. & Violante, P. (2000). Weathering of rocks and neogenesis of minerals associated with lichen activity. *Applied Clay Science.* 16 229-256.
2. Bastidas-Arteaga, E., Sánchez-Silva, M., Chateauneuf, A., & Silva, M. R. (2008). Coupled reliability model of biodeterioration, chloride ingress and cracking for reinforced concrete structures. *Structural safety*, *30*(2), 110-129
3. Bott, T. R. (2011). *Industrial Biofouling: Occurrence and Control*. Elsevier
4. de la Torre, M. A., Gomez-Alarcon, G., Vizcaino, C., & Garcia, M. T. (1992). Biochemical mechanisms of stone alteration carried out by filamentous fungi living in monuments. Biogeochemistry, 19(3), 129-147.
5. Gaylarde, C., Ribas Silva, M., & Warscheid, T. (2003). Microbial impact on building materials: an overview. *Materials and Structures*, *36*(5), 342-352
6. Department of Energy, US energy information administration, Annual Energy Review, DOE/EIA-0384(2010), October 2011. Al-Asmar, H.R., Jones, B.W. and Matteson, D.K., 2010
7. Ray, G. & Hanks, C. (2012). Mold Control and Remediation Training Handbook.
8. Allsopp, D., Seal, K. J., & Gaylarde, C. C. (2004). *Introduction to biodeterioration*. Cambridge University Press.
9. Kurth, J. (2008) *Mitigating biofilm growth through the modification of concrete design and practice*. Thesis. Georgia Institute of Technology
10. Haile, T., & Nakhla, G. (2010). The inhibitory effect of antimicrobial zeolite on the biofilm of Acidithiobacillus thiooxidans. *Biodegradation*, *21*(1), 123-134.
11. Sand, W. (1997). Microbial mechanisms of deterioration of inorganic substrates—a general mechanistic overview. *International Biodeterioration & Biodegradation*, *40*(2), 183-190.
12. Sanchez-Silva, M., & Rosowsky, D. V. (2008). Biodeterioration of construction materials: state of the art and future challenges. *Journal of Materials in Civil Engineering*, *20*(5), 352-365.
13. Tortora, G. J., Funke, B. R., Case, C. L., & Johnson, T. R. (2004).*Microbiology: an introduction* (Vol. 9). San Francisco: Benjamin Cummings.

14. McKinney, L. (2009). Tricking bacteria to cure diseases. *The Daily Galaxy*. Retrieved 11/29/2012 from http://www.dailygalaxy.com/my_weblog/2009/01/trick ing-bacter.html
15. Escadeillas, G., Bertron, A., Blanc, P., & Dubosc, A. (2007). Accelerated testing of biological stain growth on external concrete walls. Part 1: Development of the growth tests. *Materials and structures*, *40*(10), 1061-1071
16. Parker, C. D. (1945). The corrosion of concrete. *Australian Journal of Experimental Biology and Medical Science*, *23*(1), 81.
17. Gu, J. D., Ford, T. E., Berke, N. S., & Mitchell, R. (1998). Biodeterioration of concrete by the fungus Fusarium. *International biodeterioration & biodegradation*, *41*(2), 101-109.
18. Linabond Eurasia Limited. (n.d.). *Linabond Eurasia Limited*. Retrieved 11/29/2012 from http://linabond-eurasia.com/coating.html
19. Giannantonio, D. J., Kurth, J. C., Kurtis, K. E., & Sobecky, P. A. (2009b). Molecular characterizations of microbial communities fouling painted and unpainted concrete structures.I*nternational biodeterioration & biodegradation*, *63*(1), 30-40.
20. Iowa Soybean Association. (2010). Major groups of plant pathogens: fungi. *Soybean diseases*. Retrieved 11/29/2012 from http://iasoybeans.mobi/publications/diseases/intro/pathogens/fungi.php
21. Power Vac America. (n.d.). *Power Vac America*. Retrieved 11/29/2012 from http://www.powervacamerica.com/newsletter/vol4issue2/vol4issue2_article1.htm
22. Inhabitat (2012), www.inhabitat.com
23. Eco-Wares. (n.d.). Cleaners. *Eco-Wares*. Retrieved 11/29/2012 from http://www.eco-wares.com/Picture-Gallery_ep_44.html
24. Wilson, M., & Jones , D. (1983). Lichen weathering of minerals: Implications for pedogenesis. *Geological Society*, *11*, 5-12. Retrieved from Sciencedirect.com
25. Kumar, R., & Kumar, A. V. (1999). *Biodeterioration of stone in tropical environments: an overview*. Getty Conservation Institute.
26. Guillitte, O., & Dreesen, R. (1995). Laboratory chamber studies and petrographical analysis as bioreceptivity assessment tools of building materials. *Science of the total environment*, *167*(1), 365-374.

27. Madigan, M. T., Martinko, J. M., Parker, J., Fernández, C. R., & Pérez, M. S. (2004). *Brock biología de los microorganismos* (Vol. 10). Madrid: Prentice hall
28. Stewart, M. G., & Val, D. V. (2003). Multiple limit states and expected failure costs for deteriorating reinforced concrete bridges. *Journal of Bridge Engineering*, *8*(6), 405-415.
29. Sand, W., & Bock, E. (1991). Biodeterioration of ceramic materials by biogenic acids. *International Biodeterioration*, *27*(2), 175-183.
30. Giannantonio, D. J., Kurth, J. C., Kurtis, K. E., & Sobecky, P. A. (2009a). Effects of concrete properties and nutrients on fungal colonization and fouling.International Biodeterioration & Biodegradation, 63(3), 252-259.
31. Dubosc, A., Escadeillas, G., & Blanc, P. J. (2001). Characterization of biological stains on external concrete walls and influence of concrete as underlying material. *Cement and Concrete Research*, *31*(11), 1613-1617
32. Trejo, D., de Figueiredo, P., Sanchez, M., Gonzalez, C., Wei, S., & Li, L. (2008). *Analysis and Assessment of Microbial Biofilm-mediated Concrete Deterioriation* (No. SWUTC/08/476660-00008-1). Southwest Region University Transportation Center.
33. U.S. Environmental Protection Agency. (2012). *Mold Training Course.* U,S, Environmental ProtectionAgency. Http://www.epa.gov/mold/publications.html Retrieved 10/12/2012 from http://www.epa.gov/mold/moldcourse/moldcourse.pdf.
34. American Society for Testing and Materials. (1997). *Selection of Cleaning Techniques for Masonry, Concrete, and Stucco Surfaces.* (E 1857 - 97). Retrieved 10/30/2012 from ASTM Standards. http://www.astm.org/
35. Eye On Sandblasting & Painting Ltd. (n.d.). What is sandblasting. *Eye On Sandblasting & Painting Ltd.* Retrieved 12/05/2012 from http://www.eyeonsandblasting.com/
36. Pickard, B. Soda Blasting FAQs. *EHow.* Retrieved 10/29/2012 from http://www.ehow.com/about_5437754_soda-blasting-fa qs.html
37. Mid atlantic sods dry ice blasting, (accessed 12/2012) http://www.soda-dryiceblast.com/commercial-gallery.php
38. Maine Soda Blasting. (n.d.). Maine Soda Blasting. *Maine Soda Blasting.com.* Retrieved 12/05/2012 from http://www.mainesodablasting.com/

39. ColdJet. CO_2 (Dry Ice) Blasting - The Rising Star in Industrial Cleaning Applications. *What Is Dry* *http://www.coldjet.com/en/products/dry-ice-blasting/*

40. Pure Air Systems. (2011). Dry Ice Blasting Mold Removal . *Pure Air Systems* . Retrieved 12/05/2012 from http://www.pureairhomes.com/crawlspace-mold-removal-ga/dry-ice-mold-removal/

41. New York State Office of Structures (2007). *Maintenance Cleaning and Washing of Bridges- US Customary*. Rep. no. EI 07-032. New York: n.p. *NYSDOT Engineering Instructions*. Web. July-Aug. 2012. https://www.dot.ny.gov/portal/pls/portal/mexis_app.pa_ei_eb_admin_app.show_pdf?id=6797

42. NY Office of Transportation Maintenance (2008). *FUNDAMENTALS OF BRIDGE MAINTENANCE AND INSPECTION*. Rep. N.p., Sept. 2008. Web. July-Aug. 2012. https://www.dot.ny.gov/divisions/operating/oom/transportation-maintenance/transportation-maintenance-general/bridge-maint

43. Fujishima, A., & Zhang, X. (2006). Titanium dioxide photocatalisys: present situation and future approaches. *Comptes Rendus Chimie,* 9(5-6), 750-760. Retrieved from sciencedirect.com

44. Fujishima, A., Rao, T.N., & Tryk, D.A. (2000). Dioxide photocatalysis. *Journal Of Photochemistry and Photobiology C: Photochemistry Reviews.* 1 1-21.

45. Fujishima, A. & Honda, K. (1972). Electrochemical Photolysis of Water at a Semiconductor Electrode. *Nature.* 238 37-38.

46. Shao, J. & Yang, X. (2003). Photocataytic Oxidation of indoor air purification: a literature review. *Building and Environment.* 38 645-654.

47. Hunger, M., Husken, G., & Brouwers, J. (2008). Photocatalysis Applied to concrete products, Part 1: Principles and test procedure. *Materials Science, ZKG International.* 61 77-85.

48. Fonsecaa, A., Pinab, F., Macedoc, M., Leald, N., Romanowska-Deskinse, A., Laize, L., Gómez-Boleaf, A., and Saiz-Jimeneze, C., (2010), “Anatase as an alternative application for preventing biodeterioration of mortars: Evaluation and comparison with other biocides.” International Biodeterioration & Biodegradation. Volume 64, Issue 5, August 2010, Pages 388–396.

APPENDIX A – SURVEY

Questionnaire for LADOTD Research Project on Evaluating Best Practices for Cleaning and Maintaining Concrete Bridge Railings from Biofilm Growth

The Louisiana Department of Transportation and Development is currently evaluating best practices employed or evaluated for cleaning and maintaining concrete bridge railings and vertical structures from biofilm growth (mold, mildew and fungus) across the nation. Biofilms growing on concrete bridge railings and vertical surfaces create stains on concrete, which not only have negative impacts on its aesthetic value but also its durability. Many DOT's clean and use coatings to prevent biofilms from forming. The goal of this review is to identify possible preventive maintenance practices or construction materials that will enhance the resistance of these structures to mildew growth and in turn reduce labor, costs, and traveling time delays. Based on this review, the research team will identify and summarize current cleaning methods, predicted cleaning schedules, and preventive measures to rehabilitate and preserve these structures.

We would like to ask for your assistance in providing us with information about your state experience with various cleaning and maintaining methods used to prevent growth of biofilms (mold, fungus and mildew) on concrete structures. Please return the completed questionnaire to Marwa Hassan, Assistant Professor, Louisiana State University, through email to marwa@lsu.edu or by mail to 3128 Patrick f Taylor hall, Baton Rouge, LA 70803. This information will be used to help develop better control strategies of biofilm (mold, fungus and mildew growth) on concrete bridges in Louisiana. Your input is greatly appreciated. Should you have any questions regarding this questionnaire, please call Marwa Hassan at (225) 578-9189. The results of this survey will be shared with the respondents.

Please return the questionnaire by December 1, 2012. We appreciate your timely response.

- **Thanks**

Section 1: Background Data

1) What is the number of concrete bridges maintained by your agency?

2) On a scale of 1-10, (10 represents a bridge with new or like-new conditions, and 5 and above as good conditions), rate the condition of Concrete bridges in your agency?

Section 2: Significance

3) Is concrete mildew growth or staining on vertical surfaces of the bridge a concern for your agency?

☐ *Yes*

☐ *No*

4) If yes, is there a preventative maintenance program to address this issue?

Yes ☐

No ☐

5) If No, Why is it not a concern?

☐ *Lack of Monetary resources*

☐ *Other: please explain why?:*

6) If No, and the reason is lack of funding, would you address the issue if funding becomes available?

Yes ☐

No ☐

7) Is concrete bridge railings cleaning and maintenance part of your state annual bridge maintenance program?

Yes ☐

No ☐

Section 3: Performance

8) Of the following cleaning/treatment methods, which biofilm (mold, fungus and mildew) prevention methodology is used or has been evaluated in your state for concrete bridge railings and vertical surfaces in the past ten years and what were their general performances?

Cleaning/ Treatment Method	Is the procedure scheduled/ or done on need basis?	Is it performed by the agency or contracted?	If scheduled, provide frequency of application	Relative performance of method against concrete stains			
				1 - 3	3 to 6	No improvement	Negative contribution
Cleaning (i.e., rotating brushes, etc.)							
Pressure Washing							
Paints							
Other Preventative coatings							
Sealants							
Combination of treatments							

Comments

If a combination of treatments is used, please describe it here:

If performance depends on other factors, please mention them here:

If cost depends on other factors, please mention them here:

Section 4: New construction/Special Purpose additives

9) Are you adding additives to the concrete mix to reduce the growth rate/eliminate biofilms?

☐ ***Yes***

☐ ***No***

10) If yes, please name the additive,

11) Are you adding special finishes to the concrete mix to reduce the growth rate/eliminate biofilms?

☐ ***Yes***

☐ ***No***

12) If yes, please name the finishing material

Section 5: Additional Information

13) ***Other than the treatment methods identified in this survey, does your state have experiences with other biofilm (mold, fungus and mildew) control treatment or cleaning methods?***

☐ Yes

☐ No

Comments

Section 6: Contact information

Please provide your contact information so we can follow up with you:

State:

DOT District:

Contact Person name:

Email:

Phone:

Fax:

This public document is published at a total cost of $250 42 copies of this public document were published in this first printing at a cost of $250. The total cost of all printings of this document including reprints is $250. This document was published by Louisiana Transportation Research Center to report and publish research findings as required in R.S. 48:105. This material was duplicated in accordance with standards for printing by state agencies established pursuant to R.S. 43:31. Printing of this material was purchased in accordance with the provisions of Title 43 of the Louisiana Revised Statutes.