Cadmium Water Pollution Associated with Motor Vehicle Brake Parts

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Abstract. With increasing industrial growth, there is a greater need to understand factory production processes, the resulting products, and the pollution caused by the fabrication processes leading to these products. Cadmium (Cd) is used in the electro-less Nickel-Cadmium bath phase of the brake manufacturing process, which provides the brake coating that produces corrosion-resistant brake parts. During the operation, the friction created during braking corrodes the Cd layer and releases Cd particles into the environment. Cd particles can enter water bodies and drinking water supplies through stormwater runoff. This research will first examine Cd pollution associated with motor vehicle brake discs from cradle to grave. Following this comprehensive look into the role of Cd in the brake manufacturing process as well as Cd speciation in natural waters, three interventions are proposed to prevent Cd pollution associated with brake parts: (i) Carbon-reinforced silicon carbide as an alternative for metal based brake parts; (ii) bacteria “coating” instead of Cd coating; (iii) permeable roads that can effectively remove Cd from runoff with nearly 98% reduction. A discussion into the advantages and disadvantages of each proposition are provided with this presentation.

1. Introduction

Nowadays a significant amount of heavy metal originating from anthropogenic sources, is emitted from road traffic into the environment. Traffic-born heavy metals contaminants usually enter as solid particles. And this kind of pollution can affect water, air, and soil compartments [1][2]–[6]. Moreover, non-exhaust vehicular emissions including wear and tear of brake parts, clutches, tires, and road surfaces can result in street dust. The most critical chemical elements of concern in the manufacturing process of vehicle brakes are asbestos, Cadmium, Chromium (VI), Lead, and Mercury [7]. Because of the persistency and long half-life of heavy metals, these contaminants will accumulate in their recipients. They usually have higher concentration in surface water sediments, sewage sludge, and the top layer of soil. Several studies have shown that traffic-emitted heavy metals have harmful effects on both humans and other organisms’ health [8][9]. A range of heavy metals arise from road traffic and some of these contaminants like Zinc and Copper require attention due to their quantity. However, other pollutant metals like Lead, Cadmium, and Antimony (Sb), despite being released in lower amounts, are hazardous because of their high toxicity. Some of the heavier metals in street dust are known to be generated entirely from brake wear [10][11]. The important source of heavy metals particle emissions from motor vehicles is associated with brake parts such as brake lining materials, and brake drums or discs [11]. Lead and Cadmium are used in the electroless nickel coatings which is a part of brake manufacturing, and they can provide protective properties such as hardness, solderable,
lubricious, and corrosion resistance [12]. During fast and quick braking, the friction caused by kinetic energy leads to extensive heat in the brake parts, thus emitting cadmium particles. Most of the rapid brake wear occurs through traffic lights, corners, road interactions, and forced braking [13]. Disc brake pads and drum brake linings contribute to Cadmium releases into the environment through road dust [14]. Given the significant threat posed to human health, and adverse effects on ecosystems [15]. The European Commission (EC) and the United States Environmental Protection Agency (USEPA) have both set limits on the non-exhaust related emissions ensuing from automobiles such as brake wear. Also, they force automotive industries to search for environmentally-friendly and economically viable solutions [16]. Although various studies have been conducted on heavy metal pollution and particle emissions from motor vehicles, to the Authors’ knowledge, there is no comprehensive study for evaluating Cadmium contaminants associated with motor vehicle brake parts and provides a solution for removing and reducing this pollution from the environment. The objective of this paper is to better understand the pathway of Cadmium contamination from motor vehicle brake wear and ending up in the environment. This will in turn provide insight into how this contamination be prevented. Also, by studying the brake disc manufacturing process phases and the reasons for using Cadmium in this process, a new framework can be proposed for using new “green technologies” that can effectively eliminate Cadmium pollution.

2. Cadmium properties and advantages for use in the motor vehicle brake manufacturing process

At the plating phase of the brake manufacturing process, the produced brake parts are placed into a bath known as the electro-less nickel bath, which contains Cadmium (Cd) and sometimes lead. it is a chemical process that deposits a layer of Nickel and Cd on the desired surface [17]. This electro-less Nickel-Cadmium coating makes a unique metal finishing, which results in an exceptional bonding surface for adhesives, higher solderability, and corrosion resistance [12] while at the same time being quite cost-effective [17] [18]; hence, its popularity. Cadmium, which is recognized as one of the most hazardous heavy metal contaminants [19], is a ductile chemical metal that belongs to the group 12 element in d block and period 5 with atomic number 48. F.Strohmeyer discovered Cadmium in 1817 from Zinc ore, and its electronic configuration is [kr] 4d10 5s2 with concentration in the earth's crust as 0.015 ppm. Greenockite (CdS) is the most common mineral on earth and Cd can also be found as a by-product from Sulfide deposits, Copper, Lead, and Zinc [20]. Cadmium is widely used in automotive industry because of its unique properties such as corrosion protection coating for iron and steel, easy solderability, low coefficient of friction, good lubricity and compressive strength, and suitable price. When Cd is applied on metal surfaces such as iron and steel, it will act as a sacrificial coating by corroding before the substrate metal to which it adheres. In addition, Cd acts as a smoothing phase in the electro-less coating phase provides luster and color [12]. Analysis has shown that 100% of Cd usage is by industry, and 7% of that usage is by the coating industry in the brake manufacturing process.

3. Releasing Cadmium particle emissions from motor vehicle brake parts to the environment

A moving object has kinetic energy and to stop the object, this energy must be removed. Usually, a frictional force is used to remove this energy. The most common way to create friction is to use mechanical brakes that inhibit movement through the brake pads. The brake pads convert kinetic energy into heat through friction forces. This is the process of braking [21]. During fast and hard braking, friction cause extensive heat in motor vehicle brake parts, and particle emissions result from converting the kinetic energy of the motor vehicle to thermal energy and heat in the brake parts. Most of the rapid brake wear occurs at traffic lights, corners, road interactions, and at any point requiring forced braking [13]. As noted, Cd is used in the car brake production process at the plating stage. Although electro-less Nickel coating which includes cadmium and lead has been used for a long time in motor vehicle brake parts manufacturing process, up until 2003, neither automotive suppliers nor brake manufacturers were aware that electro-less Nickel coating baths contained Cd and Lead [12].
This coating process applies a uniformly thick layer of metal that includes Cd on the brake parts, that behaves as a sacrificial metal that will corrode and wear due to use and exposure to environmental conditions. These particles enter the environment as street dust. Cadmium is one of the most hazardous toxic heavy metals emissions from motor vehicle brake parts, and when emitted to the environment through road and street dust, the natural environment cannot use the metal in any cycling process. Thus, Cd contamination has become an issue for environmental sustainability and ecosystems around the globe [22].

4. Potential pathways in contamination of the environment by Cadmium

Cadmium enters drinking water resources directly from releasing contaminant sources to the groundwater and surface water or from deposition from air pollution to surface water, from street dust and runoff, soil runoff to surface water, and from rocks and soils leaching into groundwater [23]. Thus, Cd from motor vehicle brake parts will enter to water bodies either through runoff, which can go directly to the surface waters, or through sub-surface channels. Moreover, Cd bioaccumulation and biomagnification across aquatic and terrestrial ecosystems have to be considered in the risk to both human and environmental health [24]. As with most nutrients, cadmium has a water column distribution of biologically important in aquatic ecosystems. At the surface, heavy metal concentration is extremely low because of organic matter decomposition. However, the heavy metals concentration will increase at depth. Cd is a perfect example of a metal that has a column distribution in water and soil. Also, the amount of Cd accumulation in fossilized marine invertebrates can be used for evaluating past Cd concentration in the aquatic ecosystems by correlating the concentration to that of current marine invertebrates [24][25].

When the amount of Zn is limiting, Zn may be replaced by Cadmium and result in increases in the phytoplankton growth rate, which also leads to an increase in the concentration of Cd in phytoplankton. X-ray absorption fluorescence spectroscopy (XAFS) illustrates that Cd can be replaced with Calcium in a vertebrates’ body such as fish’s body, and other animals like birds and chickens [23], [26][27]. So, not only does Cd enter the human body through contaminated water resources, but also it can enter through the food-chain from bioaccumulation and biomagnification. Some studies claimed that Cd pollution can be stored in green vegetables, potatoes, and rice, and therefore, another pathway to humans. Soil Cd pollution from particle emissions or landfills are recognized as additional pathways for Cadmium pollution [28][29].

5. Interventions

This paper proposes four different interventions to prevent Cd pollution associated with motor vehicle brake parts. These interventions are selected in different stages, which include interventions in the manufacturing process, permeable roads, and disposal of waste in landfills, which are explained below.

5.1. Carbon-reinforced silicon carbide as an alternative for metal based brake parts

The raw materials for the production of brakes are Iron and metals in general. Although Aluminum may be used in car brake beds, gray cast iron is the main material in this industry. Iron brake parts will be corroded easily during the operation, and to overcome this problem, iron brake parts are often plated with Cd which causes Cd pollution. Alternative materials for producing brake parts without the need for Cd in the plating process is therefore, desirable. Carbon fiber-reinforced silicon carbide is an environmentally-friendly alternative material for brake production. Ceramic brake parts produced by using Carbon fiber-reinforced Silicon Carbide without any need for Cd plating shows a high performance in both the manufacturing process and operation phase. Ceramic brakes were originally produced for military applications and spacecrafts in the early 1990s. In addition to its high mass-specific properties and high thermal stability, functional properties like low thermal expansion play a vital role in the new commercial applications like motor vehicle brake manufacturing [30]. Ceramic brake discs’ benefits in comparison with iron brake discs are: i) high chemical resistance, ii) corrosion resistance, iii) excellent heat resistance, iv) low wear rate, v) low density, vi) Accepts high thermal
shock, vii) Eco-friendly and non-toxic. The only limitation for ceramic brakes is the higher price. Although ceramic brakes have lots of advantages, they are more expensive than iron brakes. However, having a longer lifespan can make up for its higher price in a life-cycle comparison of the two types of parts. Ceramic brake parts have a lifespan 5 times longer than iron brake discs. Overall, the ceramic brakes’ comprehensive performance is better than steel fiber discs. Porsche built the carbon-ceramic brake disk in 2001 into the 911 GT2 as series equipment. Since that time, other premium brands use the benefits of this alternative brake material for more comfort and security [31], however, this use is not as pervasive as it should be, particularly for the manufacture of inexpensive vehicles.

5.2. Bacteria “coating” in place of Cd coating (Biomimicry)
Another alternative in brake parts manufacturing is using bacteria for coating instead of Cd. Bacteria coating is form of biomimicry, which means this method is inspired by nature. Gray cast iron brake parts will be corroded during the operation and braking when exposed to water and oxygen in the different environmental conditions. This corrosion results from a process called rusting or chemical oxidation. Although some kinds of bacteria can increase the speed of metal corrosion by attaching to the surface of a metal, there are some types of bacteria which can protect metals against corrosion and decay. Such as: *Pseudomonas fragi* and *Paenibacillus polymyxa*. In addition to these two type of bacteria, *Streptomyces sp* can provide hydrophilic properties on the metal surface to prevent corrosion [32][33]. *Pseudomonas fragi* is an effective bacteria based coating that can protect metals against corrosion. The maximum adhesion of *Pseudomonas fragi* to stainless steel surfaces is observed at the pH range of 7 to 8, which is also optimum for cell metabolism [34].

Bacteria can protect metals against corrosion through these three potential mechanisms: i) removing corrosion substances by consuming oxygen during aerobic respiration and microbial activities; ii) inhibiting the growth of corrosion-causing bacteria by corrosion-protective bacteria; and iii) through the formation of a protective layer, that could be produced by overproduction of Extracellular Polymeric Substances (EPS) by non-damaging microbes [35].

By using bacteria coating, we are able to coat metal products to prevent corrosion. These types of bacteria can provide a coating layer of about 10 nanometers thick on the metal surfaces. Also, this coating is able to withstand huge temperature differences from freezing to boiling. In addition, this coating is an environmentally-friendly alternative to the harmful coatings currently used [33]. The advantages of bacteria coating outweigh its drawbacks because it is eco-friendly and has high performance in making corrosion resistance properties on the metal surfaces. The only drawback for bacteria coating is the complex process required to achieve the coating, which requires a more complex technology in comparison with chemical coatings such as Cd plating [33].

5.3. Permeable roads (Biomimicry)
In recent years, several stormwater runoff treatment methods and systems have been developed to treat runoff in traffic areas before discharging into local groundwater and surface water. Heavy metals washed from brake and tire wear, fuel combustion, street dust into water bodies can result in health and environmental problems [36]. Increasing impermeable surfaces such as roads and pavements due to urbanization have increased surface runoff, and these impermeable surfaces have also destroyed nature's ability to filter out pollution. Increasing impermeable surfaces such as roads and pavements have increased surface runoff, and effectively the environment’s natural ability to filter out pollution. Permeable roads or porous asphalt can rebuild this capacity for removing heavy metals, and to also improve stormwater runoff management; thus, permeable roads are inspired by nature and constitute a form of biomimicry. The distinguishing feature is its very high surface permeability: porous asphalt permeability is of the order of 284 liters per minute [37][38].

A typical porous asphalt road structure includes a surface course, a filter course, and a reservoir course. The infiltration rate at the surface, the size of each course, the depths, and kinds of filter media materials, all influence the degree for removing various contaminants. Porous asphalt showed a high performance in removing six common toxic heavy metal contaminants (Cd, Cu, Pb, Ni, Cr, and Zn)
from stormwater runoff [39]. While, different kinds of filter media exhibit different performances in removing each type of contaminant, permeable roads with any kind of filter media will result in some degree of heavy metal pollution reduction. Retaining dissolved and particulate substances commonly involves a mechanical process such as sedimentation or filtration followed by a filter material that traps the particles. One of the high performance configurations is a filter media that includes zeolite or basalt as bed material[40]. This filter material can remove Cd pollution by approximately 74%. Moreover, another experiment which showed the high performance in Cd removal studied four different subbase materials: limestone, basalt, sandstone, and gravel. These materials removed 98% Cd (pH 6.5; Cd concentrations of 0.04 mg L\(^{-1}\)) [37][38]. Porous asphalt is a popular structure because of its performance in removing heavy metals improving stormwater management, improving stormwater runoff quality, reducing spray to drivers and pedestrians, and reducing the entry of contaminated water into water sources. However, permeable roads have some disadvantages. They eventually clog and require regular maintenance. Also, in very high traffic roads with heavy trucks, they have a shorter lifespan in comparison with conventional impermeable roads and asphalts [41].

6. Conclusions
Cadmium is extensively used in the car brake production process at the plating stage. During fast and hard braking, friction causes extensive heat in the brake part, thereby, converting the kinetic energy of the motor vehicle to thermal energy and heat in the brake part and thereby leading to emissions of Cd particles into the environment. Most of the rapid brake wear occurs at traffic lights, corners, road interactions, and forced braking, which result in road dust. This contaminant road dust can enter different environmental compartments such as soil and water. Three interventions were suggested in this paper to prevent the entry of Cd contamination from the productions and use of brake parts: carbon-reinforced silicon carbide as an alternative for metal-based brake parts; bacteria “coating” in place of Cd coating (biomimicry); and permeable roads (also a form of biomimicry).

Future work for this study involves research into the proposed bacteria coating for use in place of various metals and its impact to the environment. How the bacteria’s functions in this role and its related advantages must be effectively conveyed to manufacturers who are using Cd coating. Also, permeable roads which is another biomimicry intervention must be carefully studied in terms of maintenance and life-cycle analysis.

References
[1] F. Talebzadeh, R. Zandipak, and S. Sobhanardakani, “(2) (PDF) CeO\(_2\) nanoparticles supported on CuFe\(_2\)O\(_4\) nanofibers as novel adsorbent for removal of Pb(II), Ni(II), and V(V) ions from petrochemical wastewater.” https://www.researchgate.net/publication/304068379_CeO\(_2\)_nanoparticles_supported_on_CuFe\(_2\)_O\(_4\)_nanofibers_as_novel_adsorbent_for_removal_of_PbII_NiI
[2] P. Budai and A. Clement, “Spatial distribution patterns of four traffic-emitted heavy metals in urban road dust and the resuspension of brake-emitted particles: Findings of a field study,” Transp. Res. Part Transp. Environ., vol. 62, pp. 179–185, Jul. 2018, doi: 10.1016/j.trd.2018.02.014.
[3] C. Bilos, J. C. Colombo, C. N. Skorupka, and M. J. Rodriguez Presa, “Sources, distribution and variability of airborne trace metals in La Plata City area, Argentina,” Environ. Pollut., vol. 111, no. 1, pp. 149–158, Jan. 2001, doi: 10.1016/S0269-7491(99)00328-0.
[4] E. Manno, D. Varrica, and G. Dongarrà, “Metal distribution in road dust samples collected in an urban area close to a petrochemical plant at Gela, Sicily,” Atmos. Environ., vol. 40, no. 30, pp. 5929–5941, Sep. 2006, doi: 10.1016/j.atmosenv.2006.05.020.
[5] X. Lu, L. Wang, L. Y. Li, K. Lei, L. Huang, and D. Kang, “Multivariate statistical analysis of heavy metals in street dust of Baoji, NW China,” J. Hazard. Mater., vol. 173, no. 1–3, pp. 744–749, Jan. 2010, doi: 10.1016/j.jhazmat.2009.09.001.
[6] P. Wahlin, R. Berkowicz, and F. Palmgren, “Characterisation of traffic-generated particulate matter in Copenhagen,” *Atmos. Environ.*, vol. 40, no. 12, pp. 2151–2159, Apr. 2006, doi: 10.1016/j.atmosenv.2005.11.049.

[7] T. Grigoratos, *Non-Exhaust Emissions An Urban Air Quality Problem for Public Health Impact and Mitigation Measures*. 2018.

[8] W. Quiroz, I. De Gregori, P. Basilio, M. Bravo, and M. G. Lobos, “Heavy weight vehicle traffic and its relationship with antimony content in human blood,” *J. Environ. Monit.*, vol. 11, no. 5, p. 1051, 2009, doi: 10.1039/b815838j.

[9] J. F. Sandahl, D. H. Baldwin, J. J. Jenkins, and N. L. Scholz, “A Sensory System at the Interface between Urban Stormwater Runoff and Salmon Survival,” *Environ. Sci. Technol.*, vol. 41, no. 8, pp. 2998–3004, Apr. 2007, doi: 10.1021/es062287r.

[10] J. H. J. Hulskotte, G. D. Roskam, and H. A. C. Denier van der Gon, “Elemental composition of current automotive braking materials and derived air emission factors,” *Atmos. Environ.*, vol. 99, pp. 436–445, Dec. 2014, doi: 10.1016/j.atmosenv.2014.10.007.

[11] A. Thorpe and R. Harrison, “Sources and properties of non-exhaust particulate matter from road traffic: A review” | Elsevier Enhanced Reader. https://reader.elsevier.com/reader/sd/pii/S0048970800658X?token=49A31E4399D29DAD6BCB5D498145AAB8D2500A6511FFCE01235FA6955C4F6BAFE5E6F9D78505A511E3EFC9C71DA9AB04 (accessed Jul. 10, 2020).

[12] R. N. Duncan, “Electroless nickel and the end-of-life vehicle directive,” pp. 1–15, 2006.

[14] E. Adamec, E. Jarosz-Krzemińska, and R. Wieszala, “Heavy metals from non-exhaust vehicle emissions in urban and motorway road dusts,” *Environ. Monit. Assess.*, vol. 188, no. 6, p. 369, Jun. 2016, doi: 10.1007/s10661-016-5377-1.

[15] W. Zglobiicki, M. Telecka, S. Skupiński, A. Pasierbińska, and M. Koziel, “Assessment of heavy metal contamination levels of street dust in the city of Lublin, E Poland,” *Environ. Earth Sci.*, vol. 77, no. 23, pp. 1–11, Dec. 2018, doi: 10.1007/s12665-018-7969-2.

[16] O. Aranke, W. Algenaid, S. Awe, and S. Joshi, “Coatings for Automotive Gray Cast Iron Brake Discs: A Review,” *Coatings*, vol. 9, no. 9, p. 552, Aug. 2019, doi: 10.3390/coatings9090552.

[17] B. A. Graves, “Putting the brakes on LEAD & CADMIUM,” *Prod. Finish.*, vol. 68, no. 10, Art. no. 10, Jul. 2004.

[18] “MANUFACTURING BRAKE DISC.” Accessed: Jul. 13, 2020. [Online]. Available: https://shodhganga.inflibnet.ac.in/bitstream/10603/196217/16/16_chapter%20208.pdf.

[19] D. Butt, K. Dowling, and P. Vinden, “Assessment of Cadmium Distribution in Some Australian Krasnozems by Sequential Extraction,” *Water. Air. Soil Pollut.*, vol. 190, no. 1–4, pp. 157–169, May 2008, doi: 10.1007/s11270-007-9588-5.

[20] H. Sharma, N. Rawal, and B. B. Mathew, “THE CHARACTERISTICS, TOXICITY AND EFFECTS OF CADMIUM,” 2015. /paper/THE-CHARACTERISTICS-%2CTOXICITY-AND-EFFECTS-OF-Sharma-Rawal/8c4d8d28a8820c51081fe87e7db3e38326d9bd67 (accessed Jul. 13, 2020).

[21] A. Muir, “How the braking system works,” *How a car works*. https://www.howacarworks.com/basics/how-the-braking-system-works.

[22] Buyun Du *et al.*, “Environmental and human health risks from cadmium exposure near an active lead-zinc mine and a copper smelter, China,” *Sci. Total Environ.*, vol. 720, p. 137585, Jun. 2020, doi: 10.1016/j.scitotenv.2020.137585.

[23] T. W. Lane and F. M. M. Morel, “A biological function for cadmium in marine diatoms,” *Proc. Natl. Acad. Sci.*, vol. 97, no. 9, pp. 4627–4631, Apr. 2000, doi: 10.1073/pnas.090091397.

[24] W. Wang, “Interactions of trace metals and different marine food chains,” *Mar. Ecol. Prog. Ser.*, vol. 243, pp. 295–309, 2002, doi: 10.3354/meps243295.
[25] Y. Xu, L. Feng, P. D. Jeffrey, Y. Shi, and F. M. M. Morel, “Structure and metal exchange in the cadmium carbonic anhydrase of marine diatoms,” *Nature*, vol. 452, no. 7183, pp. 56–61, Mar. 2008, doi: 10.1038/nature06636.

[26] S. V. Hohl et al., “Trace Metal and Cd Isotope Systematics of the Basal Datangpo Formation, Yangtze Platform (South China) Indicate Restrained (Bio)Geochemical Metal Cycling in Cryogenian Seawater,” *Geosciences*, vol. 10, no. 1, p. 36, Jan. 2020, doi: 10.3390/geosciences10010036.

[27] D. Swandulla and C. M. Armstrong, “Calcium channel block by cadmium in chicken sensory neurons,” *Proc. Natl. Acad. Sci.*, vol. 86, no. 5, pp. 1736–1740, Mar. 1989, doi: 10.1073/pnas.86.5.1736.

[28] E. ul Islam, X. Yang, Z. He, and Q. Mahmood, “Assessing potential dietary toxicity of heavy metals in selected vegetables and food crops,” *J. Zhejiang Univ. Sci. B*, vol. 8, no. 1, pp. 1–13, Jan. 2007, doi: 10.1631/jzus.2007.B0001.

[29] J. K. Saha, N. R. Panwar, and M. V. Singh, “Determination of lead and cadmium concentration limits in agricultural soil and municipal solid waste compost through an approach of zero tolerance to food contamination,” *Environ. Monit. Assess.*, vol. 168, no. 1–4, pp. 397–406, Sep. 2010, doi: 10.1007/s10661-009-1122-3.

[30] R. W. Rice, “Fabrication of Ceramics with Designed Porosity,” in *Ceramic Engineering and Science Proceedings*, vol. 23, H.-T. Lin and M. Singh, Eds. Hoboken, NJ, USA: John Wiley & Sons, Inc., 2002, pp. 149–160.

[31] M. Krupka and A. Kienzle, “Fiber Reinforced Ceramic Composite for Brake Discs,” Oct. 2000, pp. 2000-01–2761, doi: 10.4271/2000-01-2761.

[32] N. Kip and J. A. van Veen, “The dual role of microbes in corrosion,” *ISME J.*, vol. 9, no. 3, pp. 542–551, Mar. 2015, doi: 10.1038/ismej.2014.169.

[33] “How soil bacteria can protect against corrosion in steel.” https://phys.org/news/2017-06-soil-bacteria-corrosion-steel.html (accessed Jul. 19, 2020).

[34] M. Simões, L. C. Simões, and M. J. Vieira, “A review of current and emergent biofilm control strategies,” *LWT - Food Sci. Technol.*, vol. 43, no. 4, pp. 573–583, May 2010, doi: 10.1016/j.lwt.2009.12.008.

[35] H. A. Videla and L. K. Herrera, “Understanding microbial inhibition of corrosion. A comprehensive overview,” *Int. Biodeterior. Biodegrad.*, vol. 63, no. 7, pp. 896–900, Oct. 2009, doi: 10.1016/j.ibiod.2009.02.002.

[36] M. Garg, Caterina Valeo, R. Gupta, S. Prasher, N. R. Sharma, and P. Constabel, “Integrating natural and engineered remediation strategies for water quality management within a low-impact development (LID) approach,” *Environ. Sci. Pollut. Res.*, vol. 25, no. 29, pp. 29304–29313, Oct. 2018, doi: 10.1007/s11356-018-2963-5.

[37] C. Valeo and R. Gupta, “Determining Surface Infiltration Rate of Permeable Pavements with Digital Imaging,” *Water*, vol. 10, no. 2, p. 133, Jan. 2018, doi: 10.3390/w10020133.

[38] D. P. Sounthararajah, P. Loganathan, J. Kandasamy, and S. Vigneswaran, “Removing heavy metals using permeable pavement system with a titanate nano-fibrous adsorbent column as a post treatment,” *Chemosphere*, vol. 168, pp. 467–473, Feb. 2017, doi: 10.1016/j.chemosphere.2016.11.045.

[39] M. Huber, H. Hilbig, S. C. Badenberg, J. Fassnacht, J. E. Drewes, and B. Helmreich, “Heavy metal removal mechanisms of sorptive filter materials for road runoff treatment and remobilization under de-icing salt applications,” *Water Res.*, vol. 102, pp. 453–463, Oct. 2016, doi: 10.1016/j.watres.2016.06.063.

[40] R. Biela, T. Kucera, and J. Konecny, “Use of Sorption Materials for Removing Cadmium from Water,” *IOP Conf. Ser. Earth Environ. Sci.*, vol. 221, p. 012133, Mar. 2019, doi: 10.1088/1755-1315/221/1/012133.

[41] “Hardscaping 101: Eco-Friendly Paving Solutions,” *Gardenista*, Apr. 30, 2015. https://www.gardenista.com/posts/eco-friendly-paving-solutions/ (accessed Jul. 19, 2020).