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Introduction:

An endowed professorship position is one of the highest honors bestowed upon our faculty. Professors are recommended based on their excellence in teaching, scholarly work and commitment to the Wentworth community. We are very grateful for the donors for their continued generosity that allows this great work to continue!

Here are the past reports of all of the great work from our endowed professors:

- 2017-2018 Report
- 2018-2019 Report

Wentworth has the following endowed professorships in place:

1. Blittersdorf Professorship
2. Douglas C. Elder Professorship
3. Henry C. Lord Professorship
4. William E. Roberts Professorship
5. Francis A. Sagan Professorship
6. Douglas D. Schumann Professorship

1. Alumnus **David Blittersdorf** is a generous benefactor of the Institute and a Wentworth Trustee. He is a graduate of the class of 1977 with an associate’s degree in Mechanical Design Engineering Technology. He went on to earn his bachelor’s degree in Mechanical Engineering from the University of Vermont in 1981. Mr. Blittersdorf is the President and Chief Executive Officer of AllEarth Renewables, a company he founded that designs and manufactures grid-tied solar PV tracking systems. Mr. Blittersdorf is an accomplished entrepreneur and trained engineer with more than three decades of experience in the renewable energy industry, seeking to help prepare humanity for future energy constraints. He has sustained an impressive career building successful renewable energy companies based on innovative and reliable products, with a focus on lean manufacturing and responsibility to people, profits and the planet.
The Blittersdorf Professorship is awarded to a superior faculty member whose scholarly work, teaching and service have uniquely contributed to their field or to the mission of Wentworth Institute of Technology. This faculty member will help build Wentworth’s current strengths in sustainable engineering, technology, design and management. He/she will also provide EPIC learning opportunities in this area which can include projects such as renewable energy, smart-grid technology, biodiesel generation, waste heat recovery, green roof design, solar desalination, solar thermal and solar/wind power designs, among many other opportunities. The Blittersdorf Professorship is a three-year appointment with the possibility for renewal for two additional years.

2. Alumnus Douglas C. Elder, former Trustee and generous benefactor of the Institute, earned an associate’s degree in architectural construction in 1958, and was awarded an honorary degree in 2002. Mr. Elder was honored for his longtime service and support of the Institute, as well as his commitment to civic activities. He is the former owner of Elder Lumber and has also run a real estate management company.

The Douglas C. Elder Professorship is awarded to an outstanding faculty member who will provide instruction in construction operations, analysis and design of structural systems/infrastructure and managing the construction process. Selection criteria will include: (a) has successfully completed one year of teaching at Wentworth and has the appropriate terminal academic credentials in technology or engineering, (b) is recognized for his/her technical and teaching skills, and (c) is recognized for making contributions to his/her discipline through active scholarship, applied research, and/or active part-time consulting. The Douglas C. Elder Professorship is a three-year appointment. Previous recipients may be eligible for reconsideration three years after their last appointment. Should no new candidate meet the criteria, re-appointment of the incumbent for a period of one to three years is possible.

3. Alumnus Henry C. Lord was a graduate of the classes of 1912 and 1913, earning a degree in Mechanical Drafting Technology. The Henry C. Lord Professorship was established via his bequest to support a professor in the Electronic Engineering Technology department for the support of curricula, faculty and students of that department in the interests of continuing academic excellence.
4. Mr. Ken Roberts is a Trustee Emeritus and parent of a Wentworth alumnus, and created this Fund in honor of his grandfather, William E. Roberts, who in the 1940’s taught drafting at the former Boston Technical High School. Mr. Roberts is a retired financial executive with over forty years of experience with public and private high technology companies. He has served as Vice President and Chief Financial Officer of Foster-Miller, Inc., of Waltham, MA, which provided engineering services for corporate and government clients; Vice President, Treasurer and Chief Financial Officer of Massachusetts Computer Corporation of Westford, MA, a manufacturer of micro supercomputers; and Senior Vice President and Treasurer of Dynatech Corporation of Burlington, MA, a diversified manufacturer of high technology instrumentation. Mr. Roberts was formerly Chairman of the Board of Candela Corporation and director of a start-up technology company. The William E. Roberts Professorship is awarded to an outstanding faculty member who provides instruction in computer-aided design, manufacturing and engineering (CAD/CAM/CAE). The faculty member will have (a) successfully completed one year of teaching at Wentworth and has the appropriate terminal academic credential in technology or engineering, (b) is recognized for his/her CAD, CAM and/or CAE technical and teaching skills, and (c) is recognized for making contributions to his/her discipline through active scholarship, applied research, and/or active part-time consulting. The William E. Roberts is a three-year appointment. Previous recipients may be eligible for reconsideration three years after their last appointment. Should no new candidate meet the criteria, re-appointment of the incumbent for a period of one to three years is possible.

4. Alumnus Frank Sagan was a 1933 graduate of Wentworth’s Aircraft Mechanics program and a generous benefactor to the Institute. Mr. Sagan had a long career as an Industrial Arts teacher. The Francis A. Sagan Professorship will be awarded to an outstanding faculty member to provide instruction in civil, environmental, mechanical and other engineering disciplines, and/or innovative disciplines as dictated by changing times. The Francis A. Sagan Professorship is an appointment for two years with the ability to apply for renewal for a third year.

5. Alumnus Douglas Schumann is a longtime, generous benefactor, former Trustee and current Trustee Emeritus. Mr. Schumann graduated in 1964 with a degree in Aircraft Maintenance Technology and received an Honorary Degree from Wentworth in 2008. He is the CEO of P-Q Controls, Inc-Q Controls, a
company that was established in 1973 as a producer and supplier of industrial joysticks and controls, and has since grown into one of the largest manufacturers of its kind. For over 40 years P-Q Controls has been an industry leader in the outdoor/off-highway controls market. Mr. Schumann provides generous support to students at the Institute through an endowed scholarship. His lead contribution enabled the Institute to renovate the existing library, culminating in the newly-opened Douglas D. Schumann Library & Learning Commons - an innovative learning space enabling students to congregate and study in a state-of-the-art facility.

The Douglas D. Schumann Professorship is awarded to a deserving faculty member with a preference for Wentworth’s Department of Electronics and Mechanical Electromechanical Engineering, Mechanical Engineering Technology, Electronic Engineering Technology, and Computer Engineering Technology. The Douglas D. Schumann Professorship is an appointment for three years.
Impact:

The primary goals for my HC Lord Professorship proposal were centered on helping student projects succeed where they otherwise may have had trouble succeeding without the funds. That has so far taken a few different forms: undergraduate research stipends and salary, student course and senior design project materials, professional conference attendance, and student conference presentation funding.

The following highlight my efforts from January 2019 to present, with a separate budget report for each year (2019, 2020) at the end.

Undergraduate Research:

In the spring semester of 2019, I was able to provide stipends for four undergraduate student co-op projects. These students had agreed to do an unpaid co-op with me, including projects in computer architecture, mobile device security, and software installation and exploration (Cadence Software for the ECE department). Each student was given a $500 stipend as a means of pay once the Lord funds were accessible. Additionally, an iPod touch was purchased for hardware testing, which is still in use today for the mobile device security project.

In the fall, this security project was continued by Julian Peters, who received a full co-op salary of $8,512. His results have led to new projects, including Julian and two others working on a senior design project in the same area, and we will be preparing the work for publication in the summer/fall of 2020.

Additionally, Professor Marisha Rawlins (my mentee) and I discussed the groundwork for her research project building a robot for STEM education and outreach to underprivileged children. Along with her co-op student (BSCO), Joshua Moorehead, they have designed the robot, and I helped purchase the parts for the prototype.

Without the funds, the students would not have had the necessary materials and tools to complete their co-op research. This would have weakened their experience and delayed forward progress on the overall project.
Senior Design Projects:

ENGR 5000 provides students with real-world hands-on project experience. As one of the instructors, I have made the funding opportunity provided me by the HC Lord Professorship available to all student groups (whether they are in my section, or the sections of the other instructors, Douglas Dow and Joe Santacroce). Students were required to fill out an application explaining how their project would benefit from the funds, why those parts were necessary, and they had to agree that I would keep their project prototype for advertising purposes at open houses. As these projects are typically self-funded by the students, it can place an unfair burden on the student groups to either lower their standards for materials or pay high costs out of pocket. The funding provided them with an outlet, allowing them to think about the right part for the project, not just part they could afford. This was done in both 2019 and 2020. In 2019, we used approximately $1,500 and in 2020 (to date) have used over $1000. I expect more to be requested in the summer semester, now that students are not on campus, but still need parts.

In some cases, this has not only taken the financial burden off the students but has allowed them to improve their projects with the proper equipment and components.

Additionally, since the department will now own the parts, they can either be repurposed for future teams and projects or be used to help recruit students that come to visit our campus. These types of projects have already been used on display at open houses to show prospective students the type of things we work on in ECE senior design. The HC Lord fund will thus have a direct impact on getting the best students to come to our department and be a part of our program.

Student Conference Travel:

As a faculty member, I strongly encourage students to get involved with professional societies and publishing their research in conferences. While some avenues are available for these students to receive travel funds, I have added to their budget through the HC Lord Fund. Alex Epstein and Azad Deihim are both BSCO seniors (in my ENGR 5000 course) with research publications in conferences in New Zealand and Ohio, respectively. They each presented a paper at the conference that they may not have otherwise been able to afford. I am dedicated to helping research at WIT and the HC Lord fund has provided me with that opportunity.

In 2020, I planned to continue funding student travel, including ASEE-NE in Bridgeport, Connecticut for senior design teams, the AAAS conference in Washington DC for two representative students (Alyssa Vallese and James
Bednar), and the ASEE national conference in Montreal for Garry Ingles, a student who did a co-op with me in the summer of 2019. Because of COVID-19, the ASEE national conference was changed to virtual (online only). Both Garry and I are registered to attend (and present) virtually. The AAAS conference was postponed to September. The students are already hoping to go, and I planning to support it. The ASEE-NE regional conference has been postponed, and if the new time works, I will fund teams to attend.

**Senior Design Event:**

Prior to this year, senior design courses exist largely in their major’s silo, with minimal, if any, communication between departments. At the August showcase, students often see projects from other departments that are like their own. In order to help breakdown these silos and help inter-department communication, I organized an event for all the CECS senior design courses. At this event, students posted their ideas for projects and were able to talk to others about it. I also included information about Intellectual Property (with Joe Martel-Foley) and invited the library to provide information on their resources. There was food provided, and the leftover food was distributed to students and student groups as to not be wasted.

Next year, we hope to improve the number of students who attend, include external partners, and include more internal resources (Tech Sandbox, Library, Accelerate, IEEE, manufacturing center). I plan to use the Lord professorship funds again and hold the event earlier in the semester. It is also my hope to get more participation from other majors, as ECE and BME were the primary participants this year.

**MATE ROV:**

As the IEEE faculty advisor and MATE ROV advisor, I have committed some funds to their project and travel. First, every month, we pay fees for a website for their documentation. Paula Sakey and I also worked to add $5000 to the budget to help pay for the team’s travel and extra costs. This ended up being unnecessary for 2020, as the competition was cancelled. I have committed to the team going forward for additional funding.

**Dearborn STEM Academy Workshops:**

In April of 2020, along with other faculty, we hosted 30 high school students who are interested in engineering. As part of the day, we planned to have workshops which required materials. Some inexpensive, easy-to-use parts were purchased so students could take them home with them (Chibitronics). The professorship helped to pay for these materials to give these students a hands-on experience. After the parts were purchased, the COVID-19 pandemic forced the cancellation of the event, but the parts will be repurposed for future workshops.
Conference Travel for Professional Development:

As part of my own professional development, I attended the NASPA Multicultural Institute in New Orleans, LA. Here I attended workshops on improving our campus culture for minoritized communities. I also intend to attend the ASEE national conference in June, although it will be virtual only.

Teaching Technology Supplies:

As part of my dedication to providing new and improved educational opportunities, I have recently decided to explore mastery-based and competency-based learning and grading for all my courses. In these styles, students aren’t trying to achieve a grade based on partial-credit or an ability to partially know concepts or skills; rather they earn a competency score. To facilitate this, it was necessary to create new lecture videos, example/tutorial videos, and new assignments. When the university went to remote learning, this process was accelerated, so I purchased an iPad (with stylus Apple Pencil) and a subscription to “Explain Everything,” a video recording software. I have already recorded 30+ videos as of mid-April. By the start of the summer semester in 2020, I will have recorded around 100 new videos (posted to YouTube) for two courses. By the fall, I hope to have all courses ready for this new format, with a focus on true mastery of skills and a more active learning experience.

In all the discussed areas, the Henry C. Lord Professorship is furthering my professional goals regarding student projects and experiences, professional development, student research, and hands-on educational opportunities. I believe that all the funds have been used to further Wentworth’s goals of improving the lives and educations of our students, both directly and indirectly. I am grateful for the funds, and I am sure they have a direct positive impact, for me and for the students involved.

Remaining Plans for 2020

For the remainder of 2020, I will use the remaining funds similarly to how they have already been used:

- **Senior Design Projects** (expected up to $1000): I will continue to fund projects for senior design, with the caveat that parts be returned for future use in other projects or for promotional material.

- **Student travel**: (expected up to $1000) At least two students will try to attend the rescheduled AAAS workshop that was postponed from June to September.

- **MATE ROV** (expected up to $5000, as per reallocated funds from last year): The MATE competition has been cancelled for 2020, but when the new rules are released in late 2020 for the 2021 competition, I will dedicate funds towards that as well.
• **Lending library of parts** (expected up to $500): As an extension of the purchasing of senior design materials, I am making an inventory of all parts for future project lending. I will purchase more parts (generic microcontrollers, sensors, etc.), and create a system for any student working in ECE senior design to use them for projects. This will go beyond the Tech Sandbox, in that we can more target towards needs of the ECE teams.

• **Red Hat License** (expected around $600): As the ECE server admin, it will be necessary to re-subscribe to our Red Hat license server (usually around $600).

• **Fall co-op:** If there are still enough funds available after all the above, I will also consider hiring a fall co-op student. This may prove especially important as the pandemic has slowed hiring. The ability to pay a working wage will depend on remaining funds. If the above plan comes to fruition, there will be enough to pay a full-time student above minimum wage.
Use of Funds:

(2019-2020 and 2020-present)

Expenditures (January 2019 – January 2020)

<table>
<thead>
<tr>
<th>Expenditure Category</th>
<th>Cost</th>
<th>Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Student Projects</td>
<td>$1,513.51</td>
<td>Senior design and undergraduate project parts</td>
</tr>
<tr>
<td>MATE ROV</td>
<td>$865.45</td>
<td>MATE ROV team costs (t-shirts for competition, website hosting for documentation)</td>
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<td>Conference Travel/Costs</td>
<td>$1,377.24</td>
<td>NASPA Conference attendance for professional development</td>
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<tr>
<td>Student Pay</td>
<td>$10,512.00</td>
<td>Student co-op salary (1) and stipends (4) (5 students in 2 semesters)</td>
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<tr>
<td>Student Travel</td>
<td>$1,134.99</td>
<td>Conference registration and travel costs for student presentations</td>
</tr>
<tr>
<td>Event Food</td>
<td>$17.00</td>
<td>Purchased dinner for facilitated study group</td>
</tr>
<tr>
<td>Total</td>
<td>$15,420.19</td>
<td>(Overflow to count against 2020 budget)</td>
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### Henry C. Lord Professorship 2020 Expenditures (to date)

**Total:** $4,878.58

#### Expenditure Categories

<table>
<thead>
<tr>
<th>Expenditure Category</th>
<th>Cost</th>
<th>Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Student Projects</td>
<td>$1,138.04</td>
<td>Senior design and undergraduate project parts</td>
</tr>
<tr>
<td>MATE ROV</td>
<td>$182.79</td>
<td>MATE ROV team costs (hardware, website hosting for documentation)</td>
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<td>Conference Travel/Costs</td>
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<td>Virtual ASEE National Conference</td>
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<td>Dearborn Outreach Workshop Parts (postponed)</td>
<td>$342.16</td>
<td>High school workshops (postponed due to COVID-19)</td>
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<tr>
<td>Teaching Technology Supplies</td>
<td>$638.06</td>
<td>iPad and accessories, Explain Everything software – used to record online</td>
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<td></td>
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<td>lectures for remote learning and overall course reform</td>
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<tr>
<td>Event Food/Supplies</td>
<td>$2,022.53</td>
<td>Created first annual senior design kick-off event, plan to do again in 2021</td>
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<tr>
<td><strong>Total</strong></td>
<td>$4,878.58</td>
<td>(not including $420.19 from 2019 deficit)</td>
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Anticipated spending from present through December 2020

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<th>Expenditure Category</th>
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<tbody>
<tr>
<td>Student Projects</td>
<td>$ 1,500</td>
<td>Senior design and undergraduate project parts and lending library of ECE specific parts</td>
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<td>Server license</td>
<td>$ 600</td>
<td>ECE Server Red Hat Enterprise License</td>
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<td>Conference Travel/Costs</td>
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<td>Postponed student travel through spring/summer</td>
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<tr>
<td>Fall co-op salary</td>
<td>$ 6,600</td>
<td>Minimum salary for fall co-op</td>
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Impact:
The support of the HC Lord Professorship has contributed heavily to two of my responsibilities as an instructor at Wentworth Institute of Technology. These responsibilities include my involvement in the first year engineering course ENGR1500 Introduction to Engineering Design and the Wentworth IEEE Eta Kappa Nu student chapter. The HC Lord Professorship Funds have allowed me to purchase items that can be used on student projects in Introduction to Engineering Design. These include distance sensors, temperature-humidity sensors, timers, battery chargers, LCD screen and support components. All the purchased components allow the student to produce very impressive projects. All reusable components are also maintained as inventory for future iterations of the course. The HC Lord Professorship Funds have also allowed me to purchase components to conduct Electrical Engineering workshop for Girl Scouts STEM day program at Wentworth. 56 girl scouts joined our program in 2020. The program exposed young girls to STEM fields, boosted interest and gave them hands-on experience. It could also fulfill our long-term objective of recruiting more female students into the STEM-related educational pathways and careers.

As a faculty member, I strongly encourage students to get involved with professional societies and attend student conferences. The HC Lord Funds supported five Wentworth Eta Kappa Nu student members attending 2019 IEEE-HKN Student Leadership Conference, and three of them also attended awards ceremony. Our Mu Mu Chapter achieved Key Chapter Status for 2018. In January 2020 we welcomed 11 new members, and students organized weekly problem sessions for Network Theory I, network Theory II, and digital logic. Students plan to continue weekly problem sessions in the future.
The HC Lord Professorship funds also allowed me to purchase components for the Electrical and Computer Engineering Department. This included stepping motor drivers for the Power Lab and new PIC Microcontroller boards and accessories for the microcontroller courses.
Use of Funds:

In the 2019-2020 academic year, HC Lord Funds were used for the following:

Component purchases: Total Expenses: $6987.53

- Components for the Power Lab and new PIC Microcontroller boards and accessories for the microcontroller courses: $6759.32
- Miscellaneous sensors, timers, and components for ENGR 1500 Introduction to Engineering Design student projects: $206.23
- RGB LEDs for Girl Scouts STEM day Electrical Engineering workshop: $21.98
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<th>Item</th>
<th>Vendor</th>
<th>Quan</th>
<th>Unit Price</th>
<th>Cost</th>
<th>Notes</th>
<th>Combined Cost</th>
<th>S&amp;H</th>
<th>Final Cost</th>
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<td>4-20 mA R click</td>
<td>MikroElektronika</td>
<td>11</td>
<td>$24.70</td>
<td>$271.70</td>
<td>4-20mA modules (12 &amp; 12) for PIC Explorer</td>
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<tr>
<td>4-20 mA T click</td>
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<td>CAN SPI click 5V</td>
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<td>$19.95</td>
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<td>CAN protocol modules for PIC Explorer</td>
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<td>DAC 3 Click</td>
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<td>Stepper 4 Click</td>
<td>MikroElektronika</td>
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<td>$18.05</td>
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<td>Bipolar stepping motor driver for PIC Explorer</td>
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18
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<th>Item</th>
<th>Vendor</th>
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<th>Cost</th>
<th>Notes</th>
<th>Combined Cost</th>
<th>S&amp;H</th>
<th>Final Cost</th>
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<tr>
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<td>MPLAB PICkit 4 In-Circuit Debugger</td>
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<td>4-20 mA T click</td>
<td>Mikroe</td>
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<td>$20.80</td>
<td>$291.20</td>
<td>For use in Motors Lab</td>
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<td>RS485 2 click</td>
<td>Mikroe</td>
<td>26</td>
<td>$13.50</td>
<td>$351.00</td>
<td>For use in Motors Lab</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Servo Click</td>
<td>Mikroe</td>
<td>18</td>
<td>$20.00</td>
<td>$360.00</td>
<td>For use in Motors Lab</td>
<td></td>
<td></td>
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<tr>
<td>Stepper 4 Click</td>
<td>Mikroe</td>
<td>20</td>
<td>$14.25</td>
<td>$285.00</td>
<td>For use in Motors Lab</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Miscellaneous sensors, timers, and components for student projects</td>
<td>Amazon</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>ENGR 1500 course project</td>
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<td>$0.00</td>
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<td><strong>Total</strong></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>$6987.53</td>
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</tr>
</tbody>
</table>

IEEE Eta Kappa Nu student chapter: total expenses $3467.91

- 11 student’s membership $790
- 2019 IEEE-HKN Student Leadership Conference $350
- Eta-Kappa-Nu table cover and graduation kit $2199
- Student meetings $128.91
Impact:

Since the start of the Schumann Professorship in October 2019, the funds have been devoted primarily to the development of student projects to be deployed in existing and future ECE courses, undergraduate research activities, and course development for distance learning.

Project-based learning has been an inseparable part of the courses I teach. The professorship has enabled the purchase of equipment and components that expands the inventory of the electronic labs and will be primarily utilized for the projects in ELEC3350 Analog Circuit Design and ELEC4475 Feedback and Control. The additions aim to provide students a more accessible and flexible experience in troubleshooting, an essential part of engineering education, while working on the projects. Additionally, I was able to work with a junior co-op student, Congni Shi, to design and prototype a multi-stage circuit that provides the front-end processing on an ECG signal. The findings from this project provided the framework to develop more student projects that can be either added to the project pool for Analog Circuit Design or used in a future advanced circuit course.

The Schumann Professorship also provided a senior BSEE student, Benjamin Slayton, the invaluable opportunity of conducting high-level research for his senior design project and independent studies. As part of the continuous collaboration with Professor Berggren at MIT in providing Wentworth students the research opportunities, the Professorship provided the funds for Benjamin to gain the access to the facilities at the Research Laboratory of Electronics at MIT, where he participated in designing an electron spectrometer to be integrated in a commercial SEM and the fast control of the electron optics for a gated mirror.

Without the Professorship, adapting courses for online teaching in response to Covid-19 pandemic would not have been as smooth as it has. I was able to use the funds to purchase a tablet to prepare course materials,
host virtual learning sessions, and grade assignments and exams. In addition, the Professorship has allowed me to explore affordable hardware and components for hosting remote lab sessions.

Establishing a strong industrial partnership has been the strength of Wentworth in providing high value learning experiences to our students. The Professorship has allowed me to develop a collaboration with BOSE Corporation. I was able to use the funds to invite the research director and project manager at BOSE for an on-campus presentation and to organize meetings to discuss the directions and platforms for future collaborations. The initial conversations have led to BOSE’s sponsorship of a hardware platform, BOSE Frames, to several senior design projects.
Use of Funds:

In the 2019-2020 academic year, the Schumann Professorship was used for the following expenditures:

<table>
<thead>
<tr>
<th>Category</th>
<th>Expenditure</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project-based learning</td>
<td>QUBE Servo-2</td>
<td>$11,406</td>
</tr>
<tr>
<td></td>
<td>RSR powered breadboard</td>
<td>$1,534</td>
</tr>
<tr>
<td></td>
<td>RSR solderless breadboard</td>
<td>$574</td>
</tr>
<tr>
<td></td>
<td>Electronic supplies and storage</td>
<td>$290</td>
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<tr>
<td></td>
<td>Co-op salary (2019 Fall)</td>
<td>$3,105</td>
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<tr>
<td>Undergraduate research</td>
<td>MIT visiting student fees</td>
<td>$2,779</td>
</tr>
<tr>
<td>Distance learning</td>
<td>Surface Pro</td>
<td>$1,580</td>
</tr>
<tr>
<td></td>
<td>Red Pitaya STEM Lab (portable oscilloscope, spectrum and Bode analyzer, and LCR meter)</td>
<td>$407</td>
</tr>
<tr>
<td>Industrial partnership development</td>
<td>Lunch and dinner meetings for ECE faculty and BOSE representatives.</td>
<td>$282</td>
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<tr>
<td>Professional development</td>
<td>IEEE membership</td>
<td>$208</td>
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<tr>
<td></td>
<td>Textbook (Introduction to Electrodynamics, Building Scientific Apparatus)</td>
<td>$164</td>
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<tr>
<td>Miscellaneous</td>
<td>Pizzas for learning labs of Network Theory I/II</td>
<td>$135</td>
</tr>
<tr>
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<td>Laptop stand</td>
<td>$28</td>
</tr>
<tr>
<td></td>
<td><strong>Total</strong></td>
<td><strong>$22,492</strong></td>
</tr>
</tbody>
</table>

In the next academic year, I will continue to use the Schumann Professorship to develop and deploy projects that will integrate with new and existing undergraduate- and/or graduate-level courses. I will also devote part of the funds to developing platforms and/or setups for remotely-accessible or in-home laboratory exercises and projects that will offer more flexibility to the curriculum to meet diverse learning needs.
Impact:

First and foremost, the William E. Roberts Professorship has given me the opportunity to offer applied research projects at a large scale which is often unobtainable due to budget and space constraints. Architects are trained to imagine and envision at a scale that shapes the built environment we live in but it is rare to be involved in the physical realization. The funding provided through the Professorship enables me as a design instructor to build together with students, at a one to one scale with methods and materials equivalent to what is happening in the architectural, engineering and construction industries. In my courses we can go beyond standard design research by experimenting and testing innovative materials and methods of fabrication including composites and additive manufacturing. These areas of research which are familiar in the engineering disciplines are now becoming topics within architecture due to their capacity to address material efficiency and waste reduction, customization and industrial manufacturing methods. Over the past year my course work with students has involved material research and manufacturing methods of pre-impregnated carbon fiber as a system of building that engages in additive processes of construction. Rather than beginning with a sheet good or standardized volumetric building unit the additive process allows you to add material where it performs best.

Additive processes have also included clay extrusion using our department’s 6 axis industrial robotic arm. In the spirit of other 3D printing processes, clay extrusion prints with a clay mixture that is customizable based on the application and is controlled through computational scripting and robotic movements. This process began with the developing a custom end of arm tooling needed to perform the extrusion followed by the development of a workflow from design to production. Graduate students in an advanced fabrication seminar explored additive manufacturing methods applied directly to their yearlong thesis projects.
Lastly, work at the Autodesk Build Space in South Boston has continued to provide the department with access to amazing manufacturing tools and research support for two studio groups over the past year. The Build Space is one of three Technology Centers supported by Autodesk and as their website states, “hosts teams from industry, academic, and startup communities doing forward-looking work in the areas of construction, manufacturing, and emerging technologies.” Work at Autodesk has included the fabrication of modular carbon fiber components and robotic foam cutting methods developed to manufacture modular precast concrete form work for complex geometries in collaboration with a leading precast manufacturing.
Use of Funds:

- **What have you done this past year (2019-2020) with the funding you have received?**
  
  o Over the year full scale fabrication work has included a collaboration with a local YMCA in Hyde Park where students designed and prototyped an exterior play and instructional space. The team worked with the client group to develop the design and collaborated with a precast manufacturer to develop novel manufacturing methods utilizing large scale foam cutting with industrial robots while at residency at the Autodesk Build Space.
  
  o Robotic clay extrusion methods were developed on campus through collaboration with the new Additive Manufacturing Center. End of arm tooling was designed and produced using the 3D printing equipment.
  
  o Carbon fiber manufacturing using jig systems developed by student teams were explored and tested in the spring of 2020.

- **How have the funds you received through this professorship complimented your teaching and scholarly work?**
  
  o With the funding this Professorship provides I am able pursue the teaching I do best. My teaching and research interests revolve around working at full scale to study spatial and material applications using innovative fabrication methods all of which would normally place unreasonable financial burdens on my students and myself in order to achieve measurable outcomes.
  
  o Working with students in the form of a research collaborative where group work is conducted to achieve a shared outcome has been an important aspect of my teaching and the Professorship which has given me the chance to work at a large scale necessitating intensive collaboration and partnerships.

- **What did you purchase with the funds and how was it used?**
  
  o Funding supported a graduate research assistant during the summer of 2019 for the development of the necessary end of arm tooling for robotic clay extrusion along with the all the materials and hardware needed to build the tooling.
  
  o Hardware for robotic foam cutting and industrial foam for testing.
- Materials for carbon fiber research.
- Materials for precast form making and prototyping.
- General hardware for our department’s industrial robot including end of arm tooling and hardware used to make using the equipment more efficient with students.
- Materials for mold making and casting including silicones, plaster, concrete and other required materials for production.
- Equipment for working with glass fiber reinforced concrete.

**How much total did you spend?**

The full funding of the Professorship was spent during the 2019-2020 fiscal year for a total of $10,000 to cover, research assistants, materials and equipment.

**What are your plans for the future for this professorship?**

Beyond continuing with my research in the areas of additive manufacturing and innovative material research and fabrication I hope to work across departments to collaborate with engineering faculty and students. This will provide students with the type of interdisciplinary collaboration architects experience in the profession. Real-time feedback with a more expansive team will raise the quality of the outcomes we can achieve and enrich the learning environment. I hope to build an interdisciplinary team to study additive manufacturing and to further my research in composites.

Best regards,

*Rob Trumbour*

William E. Roberts Professor

Associate Professor in Architecture
Impact:
Scholarly activity conducted under my guidance has been focused on biodiesel production. A biodiesel processor has been in various states of construction and function for several years on campus operating under my auspices. The project has focused on student design and student operation. For various reasons, including lack of funding, the project has been an on and off. The Sagan Professorship has given this project new life.

With funds from the Sagan Professorship, I was able to engage several students directly in the running of the biodiesel processor. This has allowed me to engage students in a broader way with the project, not only the students working on it directly, but also students in introductory classes can see a living project on a tour of the facility. The funds have created learning opportunities for students looking for projects, and made the facility more vibrant and visible for students whose interest it may spark.

The funds have also allowed for some improvements to the processor that required an influx of cash. Further, we were able to make necessary repairs as several components (mainly pumps) had come to the end of their operational life. Being able to make these repairs is critical in the continued operation of the facility, and would have been impossible without the Sagan Professorship. I was also planning infrastructural improvements to the facility that I have delayed pursuing as the Covid-19 pandemic has had impact on that aspect of my work.
Use of Funds:

The funding from the Sagan Professorship has allowed me to hire two student workers to advance the project. Compensating these students for their time has allowed them to engage with the project at a deeper level than other previous students who have been involved in the project. These students, one from Biomedical Engineering and one from Applied Science, have been able to participate in the production of several batches of biodiesel. They have also been able to perform a significant amount of testing on the biodiesel produced to assure quality. They have also had the opportunity to work upgrades and repairs of the processor itself.

Funds have also been spent on some replacement parts for the processor. There are also some more substantial purchases that need to be made, as our primary explosion proof pump broke shortly before quarantine, but with isolation being the norm I have deferred that purchase for later. Similarly, there are infrastructural changes I hoped to address with Facilities, but again, with current circumstances I have deferred that as well.

In total a rather limited amount of the funds ended up being used, primarily for paying the student workers. They were working on potential upgrades to the processor but that work had to be suspended.

Future plans are very much contingent on how the situation with Covid-19 develops. As the work is very much hands on, it poses significant obstacles to not be able to have hands on. If on campus activities can resume, several students have expressed continued interest in working on the project, and I would fund their ability to contribute to the extent possible. As movement restrictions are eased, I plan to better evaluate the material needs of the processor, and begin purchasing some materials for the lab. Replacement spill equipment, replacement pumps, and some testing supplies are part of this plan. Additionally, my students and I had reached out to testing facilities with hopes of being able to perform ASTM testing on samples of our fuel, which tends to be relatively expensive (~$1200 per full battery of tests). I hope to fund some of this testing, conditions permitting.
Impact:

The support of Elder professorship has been providing me with the opportunities to expand my research projects and involve undergraduate students, participate in professional development activities, and keep up with industry advancements. All these have been helping me improve my classes by discussing current Construction Industry issues and trends.

In the past year, the professorship fund made it possible for me to attend several conferences/webinars, collaborate on research projects, hire undergraduate students to engage in research, and purchase books and devices for teaching and research purposes. The following section describes these activities in more detail.
Use of Funds:

• Automated Earth Moving Operations: Nowadays, with the use of 3D models in conjunction with global positioning system (GPS), construction equipment can be guided horizontally as well as vertically in real time which is not only improving production rate but also it increases jobsite safety. This research aims to identify the latest technologies introduced for automation of earthmoving operations in the construction industry and investigate their productivities. The professorship fund allowed to hire two undergraduate students as Research Assistants, and they helped with the literature search. The primary results were presented at Wentworth Showcase in March 2020 and the whole paper was expected to be presented and published at a conference at the end of June. However, due to COVID-19, there were some changes and currently the plan is to present it in August 2020.

• Best Practices for Creating Conceptual Estimates for Construction Projects: Professor John Cribbs and I are currently working on a research study regarding best practices related to conceptual estimating for construction projects. After a literature search, we designed a survey for identifying the current approaches taken by practitioners in different sectors and distributed it among a large group of professional estimators and project managers. The collected data is being processed and analyzed in the next month or so. Eventually, the outcome of this study will be shared by the industry professionals as a two-hour workshop at Advancing Preconstruction Estimating Conference in November 2020.

• Best Practices for Design Change Management Transparency Amongst All Project Stakeholders: In another collaboration with Professor John Cribbs, we are working on a research project related to design change management. We have been reaching out to different project stakeholders (i.e. owners, architects, general contractors, and subcontractors) and have been scheduling conference video calls to discuss the study, run through some formal questions and then engage in an informal working session. With these working sessions, we have been discussing the idea of design change management transparency and mapping out current and ideal workflows. Our thoughts are to provide an “Ideal State” process map for change management based on literature review, identify different teams’ current states for change management and compare against the literature review’s “Ideal State.” We will then propose changes to the ideal state to make the process scalable to current industry
application. The findings of this study will be presented at Advancing Preconstruction Estimating Conference in November 2020.

- **21st Annual Lean Construction Congress:** Each year, lean construction is being adopted by more general contractors and trade companies. Lean construction techniques and best practices should be incorporated in appropriate classes and taught to our students. Among the courses that I teach, CONM 3201: Construction Project Scheduling was one of the best places to start teaching lean and Pull Planning concept. I have been a CM-Lean (an assessment-based certificate credential issued by the Association for General Contractors) holder since 2016 and with the support of professorship, I could attend 2019 Annual Lean Construction Congress, held Oct. 14-18, 2019 in Fort Worth, TX, for the first time. This was a great opportunity to meet lean experts from all around the country and be part of this incredible knowledge-sharing event. Besides learning from the educational sessions, I came to know a few Lean experts from New England area who expressed their interests in sharing their knowledge and expertise with my students in CONM 3201 class. The arrangement was made for their participation in Fall 2020.

- In 2019, I became a member of the Lean Construction Institute (LCI) and attended two paid webinars: (1) Building a Healthy Team for Project Success: Cooperation vs. Collaboration, and (2) Visual Decision Plotter™ aka: CBA-The Lean Way.

- **NAHB Student Competition and International Builders’ Show (IBS):** Professor Monica Snow and I took 11 Construction Management and Architecture students to the annual NAHB student competition held January 20-22 at IBS 2020 in Las Vegas, NV. For the competition, students needed to apply knowledge and skills learned in their classes to a real construction company by preparing a proposal. They defended their proposal to a group of construction company executives who acted as judges. Also, the IBS included various education sessions and numerous exhibitors showcased their products. The entire group took advantage of these opportunities and the professorship fund helped cover part of the expenses.

In the past year, the professorship fund was spent on the following items:

- LCI Membership: $100.00
- LCI Conference: $2,138.89
• NAHB Conference: $1,482.39
• Student Employment: $330.00
• Books: $180.00
• Network/ Computer Devices: $1,199.87

At the end, I would like to express my gratitude and appreciation for making this fund available to me which has been having a positive impact for me and for my students. I am determined to continue utilizing this fund effectively and efficiently in advancing my professional goals and providing a better learning experience for my students.
Impact:

The Elder professorship has had a positive impact on my teaching and research. It has given me the opportunity to work on a variety of projects and my teaching abilities have improved significantly as shown in the sections below.

The funding has given me the opportunity to enhance undergraduate research at Wentworth Institute of Technology. Students have had exposure to working with graduate level instrumentation and material beyond the scope of undergraduate curriculum.
Use of Funds:

What have you done this past year (2019-2020) with the funding you have received?

During the reporting period of 2019-2020, I worked with the following students and faculty.

Students:

1) Catarina Figueiredo Mendes, 2019
2) Gabriela Kuran, 2019
3) Jerry Lu, 2020

Faculty:

1) Dr. Abigail Charest: Associate Professor, Wentworth Institute of Technology, Civil Engineering
2) Dr. Naseer Yari: Assistant Professor, Wentworth Institute of Technology, Civil Engineering
3) Dr. Hajar Jafferji, Assistant Professor, Wentworth Institute of Technology, Civil Engineering
4) Dr. Nakisa Alborz, Department Chair, Wentworth Institute of Technology, Interdisciplinary Engineering

Lab Technician:

1) Mr. William Cashel Cordon
I. Incorporation Plastic Products into Roadways

*Research with Amanda Siciliano Catarina Figueredo Mendes and Gabriela Kuran:* This research team consisted of two seniors and one junior from the civil engineering program. In 2019-2020, the students continued their research of comingling single stream waste products into beneficial uses. It was determined that plastic products originate from the same source as bitumen which is the primary constituent of asphalt, Asphalt which is the primary constituent of roadways. Ms. Siciliano, Ms. Kuran and Ms. Mendes conducted various environmental and strength testing at WIT.

Ms. Mendes and Ms. Kuran presented their research at the 10th International Conference on Environmental Engineering and Applications (ICEEA 2019) on June 26-28th, 2019. They won the best presentation award at this conference and are in the process of obtaining a journal publication as well. The manuscripts for the work done with the students are listed below.

*Figure 1: Ms. Gabriela Kuran and Catarina Mendes: Best Paper and Presentation Award in Prague Czech Republic*
Figure 2: Ms. Amanda Siciliano: Poster Presentation in Thessaloniki, Greece

**JOURNALS**


**PEER REVIEWED CONFERENCE PROCEEDINGS**


**POSTER PRESENTATION**


**Research with Dr. Nakisa Alborz:** Dr. Naksia Alborz and I undertook the task of compiling all the literature that has been done around the world on polymerized roadways. We complied work conducted by over 40 researchers into a paper and submitted it to the International Conference on Sustainable Urban Transport
and Environment. Due to the COVID-19 pandemic we were not able to present the paper, but the digital program is listed on the website as follows

PEER REVIEWED CONFERENCE PROCEEDINGS


II. Evaluating the Efficiency of Low-Cost Filtration

I competed my research with Dr. Abigail Charest to evaluate the efficiency of various low-cost water filters. The objective of this research is to identify a low-cost water filter which could be employed in areas affected by natural disasters and in developing nations. A paper was published in the New England Water Environment Association (NEWEA). Please see attached.

JOURNALS


III. Using Calcium Stearate for fly ash stabilization

Dr. Naseer Yari and I, investigated the leaching properties of Fly Ash. We are investigating various additives such as calcium stearate as potential additive which will reduce the leaching of fly ash. The paper was sent for publication and we are awaiting the comments from the reviewers.

JOURNALS


How have the funds you received through this professorship complimented your teaching and scholarly work?

The funds obtained from the Elder Professorship fund has enhanced my knowledge of sustainability and environmental remediation. Over the past few years, I have gained a better understanding of my courses and I have been able to implement them into the coursework.
How much total did you spend?

The numbers listed below are approximate amounts spent as materials are still being purchased:

1) Materials for Research: 1200$: New equipment and laboratory material
2) Student Employment: 4500$
3) Staff Employment: 1500$
4) Travel for Conferences and Meetings: 1000$

What are your plans for the future for this professorship?

My plans are to continue my research with

a. Dr. Nakisa Alborz and I are working on developing multiple grants for future research
b. I am currently working on a carbon sequestration project on making Wentworth Institute of Technology a carbon sink. Currently I am using my backyard as a carbon sink however the goal is to use the WIT front lawn as a testing site. I met with President Mark Thompson and I am awaiting his approval.
c. Identifying SARS-COV-2 in wastewater and optimizing the shape and size of the SARS-COV-2 using SEM-EDX

Attachments in Appendix A

Full Manuscripts of Published Papers

1) The incorporation of Plastic in Asphalt: A Review
2) Using Plastic bags in Roadways
3) Polymerized Roadways Around the World: A Review
4) Evaluating the Efficiency of Low-Cost Filtration
5) Using Calcium Stearate for Fly Ash Stabilization
David Blittersdorf Professorship
Abby Charest

Impact:

Assess Impact – How has the opportunity for this professorship impacted your teaching and research?

The Blittersdorf Professorship provided the resources for me to create a new vision for undergraduate research and establish graduate research in the civil engineering department. Additionally, this year the department had its first full time graduate student. The materials for the Applied Research course and the department funding for a graduate student were made a reality through the Blittersdorf Professorship.

What have you done in the past year?

-Teaching:

I was able to develop and teach a new course in Applied Research. There were seven students in the course. Prior to this year, students could volunteer to help with research projects. These students were motivated but this format did not allow for inclusive excellence. Some of our students need to work outside of class time and are unable to volunteer. As a part of the Professorship, I created a new course in Applied Research which allows any student interested in research to conduct research as a part of their coursework. I was also able to combine my teaching with internal and external campus activities. It is one of my personal priorities to connect students to professional practice I find it imperative to teach students the importance of engagement outside of the classroom by demonstrating and discussing my own experience with service. In this regard, I worked with the United States Green Building Council (USGBC) to enhance student participation. Students attended USGBC events including a Net Zero seminar and Building Tech. Additionally, two civil engineering students (Sabrina Haarstick and Abby Morin) and I attended the USGBC GreenBuild Atlanta, GA

Outcomes

- Conference: (Accepted) Abigail J. Charest, PhD, PE, Blittersdorf Endowed Professor, Wentworth Institute of Technology, Applied Research Course Aligning Teaching with Scholarship, American Society of Civil Engineers Conference, Anaheim, CA November 2020.
Research:

Over the past year, I facilitated two research groups. These groups have provided new opportunities for undergraduate research. My research includes themes of Sustainable Building and Water Quality. Over the past year, I have worked with several students to provide them with new opportunities.

Sustainable Building Research

This past spring semester I started a research project with the intent of measuring and analyzing sustainable mortar for historic preservation with the use of recycled fibers. The students conducted a literature review of reliable articles which contained research methods and conclusions regarding sustainable concrete mixes, historical preservation methods, and analyses to measure CO2 quantities. Relevant articles which related to sustainability included alternates to partially or fully replace cement, production and benefits of using recycled plastic fibers, and reduced fossil fuel processes when making cement. Relevant historical preservation articles included importance of preservation and characteristics to consider when choosing a repair mortar.

While many articles had discussed sustainability, very few were able to quantify sustainability. I began looking into how CO2 emissions were quantified in relation to production and use of mortar and found that the majority of methods used survey data from production plants and assessments of the life cycle of the products. However, almost no articles I found used laboratory experiments to quantify CO2 emissions. The undergraduate students completed a literature review paper which was submitted to the Wentworth Undergraduate Research Journal.

One article I reviewed used thermogravimetric analysis and noticed at between 550 and 750 deg C calcium carbonate began to decompose and produce CO2, using this logic the researchers were able to to compare the weight of the raw materials vs the finished mortar to quantify the CO2 being emitted. With this analysis in mind I began to develop laboratory experiments and mix designs which would be used in attempt to create a sustainable mortar with the use of 100% plastic fibers and lime as a cement replacement. Lime was chosen due to its extensive use in historical construction, production releases less CO2 emissions, and lime-based mortars are quite durable thus requiring less maintenance or replacement and lasting longer making it a more sustainable option. Potential laboratory tests include compressive and tensile strength tests, ideally a thermogravimetric analysis would also be utilized to measure CO2 emissions, and sulfate and acid resistance tests would also potentially be included to further analyze the durability of the mortar samples.
Outcomes

- Article: (Submitted) Amanda P. Siciliano, Tyler Brinson, and Abigail Charest (Ph.D., P.E.) (2020)
  Literature Review: The Impact of Limestone And Plastic Additives on Concrete, Undergraduate Research Journal, Wentworth Institute of Technology

Water Quality Research

This research was used to investigate the occurrence and physical characteristics of viruses which may impact treatment and survival in drinking water treatment. The outcomes of this research expand the current methodologies of nanoscale research by providing a time specific analysis of particle behavior. Determining the dynamic behavior of individual nanoparticles expands the current knowledge of viral transport in treatment processes, which is mainly based on size exclusion.

Previous literature in the field shows that while monitoring bacterial indicators within a water supply provides quality information about the source, viral indicators are better suited to model the fate of viral pathogens. Bacterial indicators, such as coliforms, are not considered to be suitable for adequately indicating viral presence. With the relationship between coliphages and viral pathogens recognized, ultrafiltration can be used as a reliable water treatment system in the removal of any enteric viruses. This allows for the production of high-quality potable water through affordable and accessible means.

Outcomes

  Literature Review: Ultrafiltration of Surface Water to Model Virus Removal with Bacterial and Viral Indicators, Environmental Microbiology

**Use of Funds:**

Over the past year, I have allocated and expensed funds on lab supplies and conference attendance. The funds are represented in Table 1.

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<thead>
<tr>
<th>Type</th>
<th>Description</th>
<th>Location</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lab/Instruction</td>
<td>General Supplies</td>
<td>Fisher Sci</td>
<td>$700</td>
</tr>
<tr>
<td>Conference - USBGC</td>
<td>Took two students to United States Green Building Council Conference</td>
<td>Atlanta, GA</td>
<td>$6600</td>
</tr>
<tr>
<td>Outreach – Al Akhwayan University</td>
<td>Meet with University Faculty and Administrators to discuss Project Site</td>
<td>Ifrane, Morocco</td>
<td>$3200</td>
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<tr>
<td>Graduate Student</td>
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<td>Lab Equipment</td>
<td>Autoclave</td>
<td>TOMY</td>
<td>$9300</td>
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<tr>
<td></td>
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<td>$23,400</td>
</tr>
</tbody>
</table>

**What are your future plans for this research?**

My future plans for this research include continued expansion of sustainability topics in my coursework, and innovative research. I plan to continue research within my two research groups. This fall I plan to continue the graduate assistantship and further expand the work completed in the Spring semester. As the new civil engineering graduate coordinator, I would like to expand the gains created in expanding topics of sustainability to undergraduates to include additional sustainability topics in the graduate program. I would also like to continue the work of Fall 2019 in the creation of “International Experiences on Sustainable Infrastructure” and Project Center based in Al Akhwayan University (AUI), Ifrane, Morocco. Prof. Jafferji and I traveled to AUI and we continue to work on the development of a relationship between our two campuses.
Appendix A- Gautham Das’s Work

Full Manuscripts of Published Papers
1) The incorporation of Plastic in Asphalt: A Review
2) Using Plastic bags in Roadways
3) Polymerized Roadways Around the World: A Review
4) Evaluating the Efficiency of Low-Cost Filtration
5) Using Calcium Stearate for Fly Ash Stabilization
THE INCORPORATION OF PLASTICS IN ASPHALT: A REVIEW

A. P. Siciliano, G. P. Das & H. Jafferji
Wentworth Institute of Technology, Boston, USA

ABSTRACT
As the most versatile and innovative material, plastic’s main sectors are packaging, construction, and automotive. Global plastic production is causing overflow in landfills, oceans, and the natural environment. The need to mitigate plastic pollution is imperative for the existence of various species on the planet as plastic production is to exceed 1300 million metric tons in 2050. One of the remedial methods to mitigate plastic pollution is to incorporate plastic in roadways, causing a global reduction in bitumen demand, material costs, and waste quantities. With over 2.5 and 3.2 million miles of asphalt roads in the United States and Europe, repurposing 5% of plastic waste in roadways can reduce 10-15% of global plastic pollution. This paper provides a literature review on the successful incorporation of plastic waste in roadways. By highlighting research conducted globally, this research presents an innovative solution to feasibly manage waste.
Using Plastic Bags in Roadways

Gabriela Kuran, Catarina Figueiredo Mendes, and Gautham Das

Abstract—Mass production of plastics began just six decades ago and has rapidly accelerated, creating 8.3 billion metric tons of waste, which exists mostly as disposable products that end up as trash. Incorporating plastic waste in the design of roads can be one alternative for preventing further pollution and minimizing existing plastic waste. The purpose of this research is to characterize the potential risks associated with the implementation of plastic to asphalt. Samples included the following Low-Density Polyethylene (LDPE) plastic bags, and plastic pellets. These samples were tested for the concentration of Lead (Pb), Cadmium (Cd), and Chromium (Cr). All samples were digested and analyzed using: Inductively Coupled Plasma-Atomic Emission Spectroscopy (ICP-AES) testing, Atomic Absorption Spectrometer (AA) testing, X-Ray Fluorescence Spectrometer (XRF) testing, and the Fourier Transform Infrared Spectrophotometer (FTIR). XRF results indicated that black plastic bags had 0.132% of Cr and white plastic bags had 0.01% of Cr. All the other metals in consideration were non-detect or in the parts per trillion range. The extraction results using the ICP-AES indicated Pb concentrations of 12 mg/kg which does not exceed the USEPA permissible standards. Additional testing for Manganese (Mn), Nickel (Ni), and Antimony (Sb) will be conducted in upcoming procedures.

Index Terms—Heavy metals in plastic, LDPE, plastics, sustainability.

I. INTRODUCTION

Plastics are defined as polymeric compounds with a high molecular mass and are classified by the chemical structure of a polymer’s backbone and side chains. Some advantages of plastics are that they have high thermal and electrical insulation properties while remaining low-cost, lightweight, strong, and durable corrosion-resistant materials [1]. Typically, light weight plastics are simple polymers consisting of random-length (but generally very long) chains made up of two-carbon units, as shown in Fig. 1.

From 1950 until about 2012, plastics have seen a growth in production of about 8.7 percent per year, increasing from 1.7 million tons to the nearly 300 million tons present today [2]. Among the various areas of industry that demand plastics— including transportation, construction, health care, food products, telecommunications, and consumer goods—the packaging industry is responsible for the majority of plastic demand, representing 42 percent of the demand in the United States and 40 percent in Europe [3].

From the large volume of plastics being consumed, a large quantity of end-of-life plastics are disposed of to landfills [4]. However, the disposal of plastic products in landfills has become a concern due to the continuous decrease of available space in landfills as well as the potential for plastic leaching when plastic material is deposited in an unlined landfill [5]. During the manufacturing process of plastic bags and packaging, different types of polymers are often used. These include heavy metals and additives [6]. In addition, the compounds within plastic break down very slowly due to their high molecular mass and the formation of polymers, resulting in a very slow decomposition [7], [8]. Once in landfills, these additives can potentially leach into the environment throughout their life-cycle when exposed to light, heat, or other stimulants [9], consequently representing a threat to the health of the population and environment.

The urgent need to reduce plastic presence in the environment has resulted in some countries, such as the Netherlands and India, to incorporate plastic into their roadways as a substitute of bitumen. Both plastic and bitumen—which is the major component of asphalt—originate from petroleum. Thus incorporating plastic in asphalt would serve as a possible alternative to recycling plastic. However, most countries are hesitant to incorporate plastic products into roadways as they believe that plastic breaks down into microplastics, which have the ability to adsorb various other contaminants [10].

The construction of roads required large amounts of various materials. Therefore, incorporating even small quantities of reclaimed material into the design of roadways could lead to the repurpose of significant quantities of polyethylene waste [11]. The incorporation of plastics into the design of roads has been proven by studies to add several advantageous qualities to asphalt. Some of these include increased strength, improved binding, and better surface conditions for a prolonged period of exposure to varying climate conditions, thus making tar roads suitable even during heavy traffic [12]. Thus, this alternative can prove to be an easy method to achieve sustainability within infrastructure.

Among the various types of plastic, this research primarily focuses on the recycling of Low-Density Polyethylene (LDPE) such as Plastic Bags (PB) and Plastic Pellets (PP). Due to demand within the retail industry and among consumers themselves, PBs have gained increasing popularity [13], [14]. Annually, about 500 billion to one trillion PBs are consumed worldwide; i.e., 1.4–2.7 billion per day, the equivalent of roughly one million bags used per minute [15]. In a study produced by Redford in “Sources of
plastic pellets in the aquatic environment,” plastic pellets are described as “ovoid, cylindrical or spherical pieces of polymer, between 2 and 5 mm in diameter and it is in this form that raw plastics are transported to plastic processing facilities prior to forming or molding into consumer items” [16]. According to data obtained from the shorelines, from the open ocean and from debris ingested by seabirds, there is an indication that the quantities of PP are increasing in the environment (10% by weight of strandline material) [17].

It is critical, however, to understand the potential of leaching of LDPE when incorporated with bitumen, as the recent increase in use of recycled plastic materials has been associated with the increase of human exposure to heavy metals [18]. As previously discussed, heavy metals are commonly used in plastic production and to recycle plastic materials. High levels of heavy metals were detected in some PE rubbish as well as in grocery bags, where Cr and Pb were found to exceed standards in the trash bags. Different metals were found to be within permissible standards. Moreover, no similarity was found between PBs of different colors and polymer types in the case of metal contents [19].

In this study, Cd, Cr, Ni, Pb, Mn and Sb were quantified in LDPE PB and PP, using inductively coupled plasma-atomic emission spectrometry (ICP-AES), Atomic Absorption Spectrometer (AA), X-Ray Fluorescence Spectrometer (XRF), and the Fourier Transform Infrared Spectrophotometer (FTIR). All have the potential to cause serious health effects with prolonged exposure and/or ingestion and all are considered carcinogens by the Agency for Toxic Substances and Disease Registry [20].

According to the Environmental Protection Agency (EPA), serious health effects have been associated with each of these contaminants studied throughout this research. Exposure and/or ingestion to Cd can cause pulmonary irritation and kidney disease. Exposure to Cr can lead to lung cancer, bronchitis, pneumonia, and other respiratory effects. Lead poisoning can cause severe headaches, abdominal pain and various complications in the nervous system. Prolonged exposure or ingestion of Sb can lead to serious health problems such as lung disease, heart problems, severe vomiting, stomach ulcers and diarrhea [21]. Exposure to Ni can cause skin problems and increased risk of lung and nasal cancers. The health effects of Mn in humans include lethargy, increased muscle tension, tremor, and mental disturbances.

To act as stabilizers and pigments, heavy metals are added to PBs. These metal contents may vary region to region [22], [23]. When these PBs are disposed of in dumpsites, there is a potential for the spreading of toxic metals. These toxic metals will then result in contamination of nearby soil, plants, and water bodies [24]. As mentioned, heavy metals used as additives may be enfolded in PBs, meaning that they are not chemically bound within the polymer matrix. Once these metals are leached out, they spread into the surrounding environment. In the long-term, the environment will be exhausted by such contamination in addition to the growing human demand for food and drinking water [25]-[27].

The objective of this research is to evaluate the quantity of contaminants present in LDPE plastic bags and plastic pellets. To evaluate the presence of contaminants in plastic, several laboratory procedures such as an acid digestion, an extraction and XRF testing were conducted. Upon completion of this research, it is hypothesized that plastic products can be used as an alternative to bitumen in asphalt.

II. METHODS

Reams of plastic bags in multiple colors were either collected or purchased from grocery stores in Boston, Massachusetts. These samples were chosen based upon the frequent accessibility and use of plastic bags among typical American consumers. Plastic bag colors were chosen based on popularity and include: black, brown, and white. Plastic pellets were generously donated by New York-based company Domino Plastics Company and are free of dyes. All aforementioned plastics are of the low-density polyethylene variety.

For the purposes of consistency, the plastic bags were hand-cut with clean scissors into 1cm-wide strips with varying lengths averaging about 30 cm. There was no necessary preparation for the plastic pellets for any of the testing. Table I summarizes the materials tested in this research.

<table>
<thead>
<tr>
<th>Polymer Class</th>
<th>Color</th>
<th>Use</th>
<th>Sample ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDPE</td>
<td>Black</td>
<td>Grocery Bag</td>
<td>1-BI</td>
</tr>
<tr>
<td></td>
<td>Brown</td>
<td>Grocery Bag</td>
<td>1-Br</td>
</tr>
<tr>
<td></td>
<td>White</td>
<td>Grocery Bag</td>
<td>1-W</td>
</tr>
<tr>
<td></td>
<td>Black</td>
<td>Trash Bag</td>
<td>2-Bl</td>
</tr>
<tr>
<td></td>
<td>White</td>
<td>Trash Bag</td>
<td>2-W</td>
</tr>
</tbody>
</table>

A. Acid Digestion

The acid digestion procedure for this research was done in accordance to EPA 3051 and 200.2. The plastic bags (1-BI, 1-Br, 1-W) were initially sorted based on color and type of use. The plastic bags were cut to 1-cm wide and 30-cm long strips. A mixture of 5% HNO₃ and 5% HCL, known as Aqua Regia, was prepared in a flask. Approximately 1 g of plastic strips were weighed and placed into a 200 mL beaker. 100 mL of aqua regia was added to the beaker containing the plastic bags and heated on a hot plate. The mixture was heated until it reached its boiling point, based on the observed formation of bubbles. The samples were cooled, and the solid phase separated from the liquid phase. This experiment was performed in triplicate for each of the plastic bags. The liquid phase was then subjected to elemental testing using the Atomic Absorption Spectrophotometer (AAS). The analytes tested for this research were Cd, Cr, and Pb. The AAS was calibrated using stock solutions obtained from Fisher Scientific and are described in Table II.
B. Extraction

Samples tested for this experiment were 2-Bl, 2-W, 3-T. These samples were selected because the acid digestion procedure indicated lead concentration in the trash bags rather than the grocery bags. Samples were sent to an external, accredited laboratory to perform an extraction and analysis on each of the provided plastic samples. The laboratory procedure, an inductively couple plasma-atomic emission spectrometry (ICP-AES), was performed in accordance with EPA Method 200.7, Revision 4.4. 1 mL of concentrated nitric acid was added to a 50 mL aliquot of a well-mixed and preserved digestion solution sample. The sample was then heated to a high temperature, making sure not to exceed 95°C. The sample remained under heat until its volume was reduced by approximately one half. After sufficient volume reduction, the sample was set aside to cool and then gently refluxed for 15 minutes with 1 mL of 50% concentrated hydrochloric acid. Finally, the sample volume was diluted back to its original volume using deionized water and mixed well prior to analysis. Analysis using the ICP-AES method tested for the following analytes: Cd, Cr and Pb. [28]

C. XRF

The samples tested for this equipment were 2-B1, 2-W and 3-T. Testing using an X-Ray Fluorescence Spectrometer (XRF) was performed in accordance with the Background Fundamental Parameter (FP) method, patented by the instrument supplier, Shimadzu (Patent Pending: PCT/JP2013/78002, PCT/JP2013/78001). To prepare the sample, the plastic bags were trimmed and neatly folded and placed into the XRF so that the apparatus could test a layered sample of the plastic. The pellets were also tested but placed into a mylar cup for ease of containment. The XRF exposed each sample to x-rays, which in turn allowed for the sample itself to emit further x-rays due to component atoms of the sample. These x-rays produced wavelengths that were each characteristic of a specific element. Investigation of these wavelengths confirmed presence of the following analytes: Cd, Cr, Mn, and Ni. The XRF did not pick up any wavelengths for Pb. In addition to qualitative data, the XRF provided quantitative data based upon the intensity of emitted x-rays fluorescence.

D. Column Leaching

The column leaching test was performed only on the plastic pellets. The columns were filled with plastic pellets until they were tightly packed. The columns were then attached to a gravity head system as seen in Fig. 2, with one inlet tube feeding leachate from a holding tank and one outlet tube to allow for collection of the passed leachate. Based on the pore volume that was calculated to be one liter, it was determined that each time one liter of solution passed through the column, it would be tested for the selected heavy metals. The data would then be put into the Yalcin Leaching Model to predict the leaching behavior over an extended period of time. Each pore volume was tested twice to provide duplicate results. [29]

E. Environmental Modelling

“A Yalcin leaching model was formulated to capture the observed experimental leaching behavior of the contaminant exhibiting an initial increase in concentration followed by a decrease in concentration with further leaching until it reaches a low steady state concentration. The model is as follows:

\[ C(t) = C_s - C_s e^{-k_b t} + C_0 e^{-k_b t} \]

where \( k_b \) is the dissolution rate coefficient \((\text{min}^{-1})\), \( K = (S/S_0)^a \), \( S \) = Solid phase concentration \((\text{mg/g})\), \( S_0 \) = Initial solid phase concentration \((\text{mg/g})\), \( C_s \) is the effective saturation concentration \((\text{solubility})\) of contaminant \((\text{mg/L})\), \( t \) is the time \((\text{min})\), and \( a \) is a dimensionless empirical constant” (Das 2007).

III. RESULTS AND DISCUSSION

The acid digestion data revealed that only Pb was released from the plastic bags. The other analytes were in the non-detect range. The lead concentrations were in the µg/L range which were below permissible limits for soil contamination. The data is present in Table III.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Dilution</th>
<th>Replicate</th>
<th>Lead (Pb) Concentration (mg/L)</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-Bl</td>
<td>1:100</td>
<td>1</td>
<td>0.024</td>
<td>2.061</td>
<td>0.8561</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2.519</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.285</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.169</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.180</td>
<td></td>
<td>0.211</td>
<td>0.0641</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>0.101</td>
<td></td>
<td>0.108</td>
<td>0.0204</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.092</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1-Bl</td>
<td>1:1000</td>
<td>1</td>
<td>0.131</td>
<td>2.219</td>
<td>0.6821</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.217</td>
<td></td>
<td>1.577</td>
<td>0.0259</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.103</td>
<td></td>
<td>0.270</td>
<td>0.0217</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.243</td>
<td></td>
<td>0.240</td>
<td>0.0627</td>
</tr>
<tr>
<td>1-W</td>
<td>1:100</td>
<td>1</td>
<td>0.459</td>
<td>2.241</td>
<td>0.9947</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.128</td>
<td></td>
<td>0.198</td>
<td>0.0255</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.251</td>
<td></td>
<td>0.255</td>
<td>0.0211</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.342</td>
<td></td>
<td>0.342</td>
<td>0.0204</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.302</td>
<td></td>
<td>0.302</td>
<td>0.0204</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>0.325</td>
<td></td>
<td>0.325</td>
<td>0.0204</td>
</tr>
</tbody>
</table>

The extraction data proved similar to the digestion data...
where only Pb was detected by the ICP-AES as well. The extraction data is shown below in Table IV.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Analyte</th>
<th>Results</th>
<th>Reporting Limit (mg/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-W</td>
<td>Cd</td>
<td>ND</td>
<td>4.00</td>
</tr>
<tr>
<td></td>
<td>Cr</td>
<td>ND</td>
<td>8.40</td>
</tr>
<tr>
<td></td>
<td>Pb</td>
<td>&lt;12</td>
<td>12.00</td>
</tr>
<tr>
<td>2-BI</td>
<td>Cd</td>
<td>ND</td>
<td>4.40</td>
</tr>
<tr>
<td></td>
<td>Cr</td>
<td>ND</td>
<td>8.10</td>
</tr>
<tr>
<td></td>
<td>Pb</td>
<td>&lt;12</td>
<td>12.00</td>
</tr>
<tr>
<td>3-T</td>
<td>Cd</td>
<td>ND</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td>Cr</td>
<td>ND</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>Pb</td>
<td>&lt;0.49</td>
<td>0.49</td>
</tr>
</tbody>
</table>

The XRF data revealed a whole gamut of analytes, however Pb was not present in any of the samples. The results from the XRF are shown in Table V.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Analyte</th>
<th>Composition Results (%)</th>
<th>Sample ID</th>
<th>Analyte</th>
<th>Composition Results (%)</th>
<th>Sample ID</th>
<th>Analyte</th>
<th>Composition Results (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-W</td>
<td>Cd</td>
<td>-10.0</td>
<td>Cr</td>
<td>-10.0</td>
<td>Mg 0.705</td>
<td>Ti</td>
<td>-10.0</td>
<td>Al 1.053</td>
</tr>
<tr>
<td></td>
<td>Pb</td>
<td>98.49</td>
<td>Ca</td>
<td>98.49</td>
<td>Fe 1.053</td>
<td>Si</td>
<td>98.49</td>
<td>S 0.118</td>
</tr>
<tr>
<td>2-BI</td>
<td>Cu</td>
<td>-10.0</td>
<td>Zn</td>
<td>-10.0</td>
<td>Cu 0.705</td>
<td>Pb</td>
<td>-10.0</td>
<td>Sr 0.182</td>
</tr>
<tr>
<td></td>
<td>Na</td>
<td>98.49</td>
<td>Mg</td>
<td>98.49</td>
<td>Pb 0.182</td>
<td>Mn</td>
<td>98.49</td>
<td>Ca 0.091</td>
</tr>
<tr>
<td>3-T</td>
<td>Cr</td>
<td>-10.0</td>
<td>Fe</td>
<td>-10.0</td>
<td>Cr 0.091</td>
<td>Sr</td>
<td>-10.0</td>
<td>Ge 0.845</td>
</tr>
<tr>
<td></td>
<td>Pb</td>
<td>-10.0</td>
<td>Ca</td>
<td>-10.0</td>
<td>Fe 0.845</td>
<td>Mn</td>
<td>-10.0</td>
<td>Ge 0.845</td>
</tr>
</tbody>
</table>

Based on all the testing, it is hypothesized that the Pb concentrations found in a plastic bag are being sourced from the black dye and not from the plastic bag itself. The column leaching data is not presented in this paper as it is an ongoing test and will be presented at a later time.

IV. CONCLUSION

This research indicated that plastic did not release any heavy metals above permissible limits for soil. The Pb which was present in the plastic bags during the acid digestion and extraction was primarily from the dye and not from the plastic itself. This is an ongoing research project where column leaching tests are being conducted to evaluate the long-term leaching of contaminants from plastic bags and pellets. The Yalcin leaching model will be able to predict the concentration of the contaminants for hundreds of pore volumes. This data will give indication of the long-term leaching potential of plastic. Future research will be conducted to evaluate the leaching potential of plastic when placed in asphalt as a replacement for bitumen.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Research and literature review were conducted collaboratively by all three authors. Laboratory procedures were determined by Gabriela Kuran and Catarina Figueiredo Mendes under the supervision and final review of Dr. Gautham Das. Unless otherwise stated, Gabriela Kuran and Catarina Figueiredo Mendes carried out all laboratory preparation and testing. All three authors wrote the paper and reviewed it upon final submission.

REFERENCES


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Gabriela Kuran was born in Brockton, Massachusetts in August of 1997. She grew up on the Massachusetts South Shore and remained there until moving to Boston to begin her college career in September of 2015. Gabriela is currently a second-semester senior at Wentworth Institute of Technology (WIT) where she will be graduating in August of 2019. She will be graduating with a Bachelor of Science in civil engineering and a minor in environmental engineering. Gabriela has worked two internship periods during her time at WIT. Both internships were spent at CLE Engineering, Inc. in Marion, MA. Due to an acquisition during her first internship, the company is now known as Foth-CLE Engineering Group. Her work primarily involved CAD drafting on coastal and marine engineering projects such as large dredging projects on both the east and west coast of the US. Gabriela has also achieved a publication which she co-wrote with college professor Francis J. Hopcroft during her sophomore year at WIT, titled Environmental Engineering Dictionary of Technical Terms and Phrases: English to Polish and Polish to English (Boston, MA: Momentum Press 2016). Her research interests lie within sustainability, green building, and water quality.

Catarina Figueiredo Mendes was born in Brazil and migrated to the United States of America to attend school at Wentworth Institute of Technology in pursuit of a civil engineering degree in 2015. Catarina is expected to graduate in the summer of 2019, which a Bachelor of Science in civil engineering.

During her junior year as a civil engineering major at Wentworth Institute of Technology, Catarina has worked in structural engineering roles at DESMAN Parking Specialists, and site/civil engineering roles at the Department of Public Works of the City of Cambridge. Her interests in sustainability pushed her to obtain her LEED Green Associate certification. Her excellence in academics has earned her a membership with the Phi Theta Kapp student society. Catarina’s interests include sustainability, sustainable buildings, ground and soil remediation and water quality.

Gautham P. Das has served as associate professor of civil and environmental engineering at Wentworth Institute of Technology (WIT) in Boston, Massachusetts since August 2008. Dr. Das received a doctorate from the University of North Carolina at Charlotte. Dr. Das is currently an elder endowed professor at WIT.

Prior to starting his teaching career, Dr. Das worked for environmental consulting firms in North Carolina and Boston. His expertise lies in water resources, hydraulic engineering and environmental remediation. He is active in the Water Environment Federation, the New England Water Environment Association and the American Society for Engineering Education.

He has authored numerous technical papers on various civil and environmental engineering subjects that have been presented at technical conferences and appeared in the Proceedings of those conferences.
Polymerized Roadways Around the World: A Review
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ABSTRACT: As the most versatile and innovative material, plastics main sectors are packaging, construction, and automotive. Global plastic production is causing overflow in landfills, oceans, and the natural environment. The need to mitigate plastic pollution is imperative for the existence of various species on the planet as plastic production is to exceed 1300 million metric tons in 2050. One of the remedial methods to mitigate plastic pollution is to incorporate plastic in roadways, causing a global reduction in bitumen demand, material costs, and waste quantities. With over 2.5 and 3.2 million miles of asphalt roads in the United States and Europe, repurposing 5% of plastic waste in roadways can reduce 10-15% of global plastic pollution. This paper provides a literature review by highlighting the research conducted globally on the successful incorporation of plastic waste in roadways.

1 INTRODUCTION

Plastic is one of the most versatile and innovative materials. Created by Leo Henricus Baekeland in 1907, the first plastic, known as Bakelite, was a synthetic polymer made from phenol and formaldehyde (Baekeland 1909). Since plastics creation, this material has composed innumerable products because of its favorable qualities. This polymeric compound has long hydrocarbon structures, making it extremely durable and easy to manufacture. Due to these long polycyclic and polymeric compounds, plastic takes a long time to degrade and decompose. Utilized in packaging and construction, plastic serves as a sterile, lightweight, and easy way to package and transport goods (Plastics Europe 2018). Research published in 2015 estimates that of the 6300 million metric tons produced, only 9% was recycled with 12% incinerated and 79% collecting in landfills or the environment (Geyer et al. 2017). Due to this issue, plastic disposal is of high importance.

Different solutions, such as improving product circularity, using conversion technology, and creating trackable smart bins, have been proposed to reduce waste quantities (Keller 2019). Incorporating plastics within public infrastructure can mitigate its pollution while promoting recycling. In fact, some cities are recognizing the importance of improving plastic recycling efforts. In 2017, the city of Boston released an ordinance regarding the cutback of plastic bags with the goal of jumpstarting the city’s new zero waste initiative (O’Malley & Wu 2017; City of Boston 2019). It was estimated 393 kilotons(kt) of carbon came from managing municipal solid waste in 2017 (City of Boston 2019). Later that same year, China announced a new policy ban that will stop the county’s import of plastic waste. As the leading global importer of plastic waste, at almost 106 million metric tons collected since 1992, this policy is expected to offset an estimated 111 million metric tons of waste by 2030 (Brooks et al. 2018).

One solution to repurpose soaring plastic waste quantities is its incorporation within construction materials. With over 2.5 and 3.2 million miles of paved asphalt roads in the United States and Europe, repurposing plastic into asphalted roadways could drastically improve public infrastructure (NAPA & EAPA 2011). Infrastructure affects a country’s foundation and ability to have a prosperous economy. In the American Society of Civil Engineer’s 2017 Infrastructure Report Card, America’s cumulative infra-structure received a grade of D+, while the roadways received a grade of D (Infrastructure Report Card 2017). It is estimated that for every 5 miles of highway pavement, 1 mile requires maintenance and
rehabilitation, causing a suggested annual 6.9 billion hours and $160 billion in wasted time and fuel (Infrastructure Report Card 2017). If plastic waste is used in roadways as a replacement to bitumen, global plastic pollution and cost will drastically decrease while road quality, public safety, and nation-wide resilience will increase.

While the idea of incorporating plastic into construction products may seem innovative, it is not a new concept. In fact, plastic incorporation within highways has already been experimented in countries such as India, Australia, Britain, Netherlands, and Indonesia (Economist 2018). In India, plastic is used to fill potholes and incorporated into asphalt mixtures, where test roads have shown promising results. In Australia, Netherlands, and Indonesia, test stretches have been completed in small scale tests. Within the Netherlands, a bike track was made from prefabricated, modular sections that incorporated recycled plastic within asphalt. In Britain, plastic mixes roads show promising results by not needing as much resurfacing maintenance as traditional roadways. All these test models show the feasibility of incorporating plastics into roadways, with many declaring these construction projects to be of national importance (Lombardo 2018).

2 PLASTIC TYPES & COMMON USES

When reviewing plastic’s composition, this polymeric material is made of elements such as carbon, hydrogen, and nitrogen, and has a high molecular weight that can copy the properties of natural materials (American Chemistry Council 2005). Two different types of plastics, thermoplastics and thermosets, devise numerous products used across various sectors. Thermoplastics, or plastics that can melt when heated or harden when cooled, show adaptable characteristics that allow for reworking. Thermosets, or plastics that experience a change in molecular structure, cannot be altered after achieving final form. Common thermoplastics include Polyethylene (PE), Polypropylene (PP), Polyethylene Terephthalate (PET) and Polystyrene Chloride (PVC) and Polystyrene (PS). Common thermosets include Polyurethane (PUR), epoxy resins, and silicone. The most commonly used plastics include PP, PE, and PET, as these materials predominantly devise food packaging, plastic bags, and water bottles (Plastics Europe 2018).

When plastic debris ends up in oceans rather than landfills, these products often turn into microplastics. Microplastics are defined as plastic particles between 1 and 1000 micrometers that easily pollute natural environments because of their small nature (GESAMP 2015). It is anticipated that these plastics are a result of fragmentation from larger plastic waste, or physical degradation from weathering (Barnes et al. 2009). As a result, larger quantities of primary and secondary microplastics pose threats to the marine wildlife. The physical characteristics of plastic determine pollutant impact, a detrimental concern to the marine ecology. Among many characteristics, density and chemical structure determine the fate of microplastics. Density and its relativity to seawater decides buoyancy and final location, while chemical structure dictates how a microplastic will eventually oxidize and degrade (Andrady 2017). Despite being practically invisible to the naked eye, microplastics show the growing necessity to better manage plastic waste.

In 2015, it was estimated that of 6300 million metric tons produced, only 9% had been recycled, with 12% being incinerated and 79% collecting in either landfills or the environment (Geyer et al. 2017). The materials being recycled are predominantly PP and PE and come from the packaging and building and construction sectors (Plastics Europe 2018). To improve the circular life cycle of plastic, some end of life alternatives includes mechanical reuse, product re-pair, or energy recovery. Mechanical reuse and product repair show promising results that allow plastic to be converted. In Europe, it is estimated that of the 51.2 million metric tons collected for conversion demand, the packing (39.7%), building and construction (19.8%), automotive (10.1%), and electrical and electronic (6.2%) sectors compose more than 75% of re-cycled materials (Plastics Europe 2018). Although plastic
recycling has increased by almost 80% in the last ten years, there is still more progress to be made to reduce plastic pollution (Plastics Europe 2018). It is possible that by incorporating plastics within asphalt in roadways, recycling quantities can be further increased.

3 ASPHALT PROCESSES & MIX DESIGN

Asphalt, also known as bitumen, is a derivative of petroleum crude oil. This viscous material is made of carbon, hydrogen, and oxygen, and tends to have a low molecular weight. This material is often found in reservoirs that require extraction from the ground. To upgrade product quality, the thick fluid requires extreme heat through the refining process. Typically, bitumen can be created into intricate chemical mixtures that can produce different characteristics, an ability that makes it useful in the construction industry where specific properties are required (NAPA & EAPA 2011). Approximately 85% of all bitumen is used as a binder in asphalt for highways, roads, parking lots, and foot paths (Afework et al. 2018). In 2007, it was estimated that approximately 1.6 trillion metric tons of asphalt were produced worldwide in a single year (NAPA & EAPA 2011). In the United States, it is suggested that 2,500 asphalt mixing sites produce a combined 350 million tons of asphalt pavement every year (NAPA 2011).

To create asphalt, aggregates are combined with bitumen to create Hot Mix Asphalt (HMA). This asphalt is mixed at high temperatures, typically ranging from 150° C to 175° C, at hot mixing plants. Because of high production temperatures, the asphalt has homogeneity between the various mixture components thus creating good workability. However, these high temperatures also produce greenhouse gas (GHG) emissions such as carbon dioxide, sulfur dioxide, volatile organic compounds (D’Angelo et al. 2008). These mixes are often used for roads and highways and over an extended service lifespan, it is assumed that the asphalt will meet the needs of varying traffic loads and environmental conditions.

Traditional asphalt mix designs incorporate aggregates and bitumen, innovative mix designs can include materials like limestone, fly ash and Portland cement as a filler for both coarse and fine aggregates (Tiwari & Rao 2017, Celauro et al. 2019; Costa et al. 2017). Worm pipe stone is silicate of magnesium often called as ophite has been recommended to be used in asphalt as an additional aggregate and filler (Vila-Cortavitarte et al. 2018). Overall, a well-made mix design is typically rated for resistance to deformation, moisture, fatigue, skid, and cracking.

HMA process of making asphalt is the most commonly used method however due to the various GHG emissions various other environmentally friendly methods has been explored. Warm Mix Asphalt (WMA) represents a new technology in which asphalt mixes are created at temperatures about 10-75° C lower than traditional mixtures (Mallick & El-Korchi 2017). This lower temperature is possible due to lowered viscosity of the asphalt binder, which can occur through modification to the traditional mix designs through additives. As a result, these mixes improve workability and compaction while reducing permeability (D’Angelo et al. 2008). Some additional benefits of WMA include reduced emissions, fuel usage, and worker exposure. This new method has evident environmental components, as there is a reduction in consumed natural resources, energy usage and production of carbon dioxide, resulting in a fuel savings of 20-35% (D’Angelo et al. 2008). With WMA, paving can be completed in temperatures lower than traditional asphalt, allowing for quicker pavement periods. Research indicates that WMA should be an allowable alternative to HMA.

While incorporating plastic into the mix design, there are two different processes used for modifying bitumen mixtures with plastic: wet and dry. The dry process varies the aggregates while the wet process varies the bitumen. The wet process involves mixing shredded plastics directly with bitumen at high temperatures. This blended mixture allows the asphalt to withstand varying temperatures and high moisture conditions as compared to traditional mix designs. However, this method often requires additional equipment and resting time, as
cooling is needed to avoid air pockets (Gawande et al. 2012). One study that used the wet process was able to conclude that 6% of plastic improved the bitumen mixture (Tiwari & Rao 2017).

However, some studies have identified the dry process as the preferred method as it was more economical, less GHG emissions and improved binding properties (Moghaddam et al. 2013; Appiah et al. 2017). In the dry process, aggregates are chosen, based on qualities such as adsorption, soundness, and porosity, and coated with a softened plastic. This coating improves the nature of the aggregate by decreasing porosity. Vasudevan et al. 2018 found that it was feasible to incorporate higher percentages of plastic waste (up to 10% of bitumen replaced) through the dry method. Vila-Cortavitarte et al. 2018 modified the dry process by adding unheated plastic to heated aggregates for 30 seconds before adding fine aggregates and bitumen. The dry process is often selected for its simplicity and product homogeneity (Usman & Masirin 2019). Regardless of the process, both the wet and dry methods show that improved resistance to permanent deformation and fatigue resistance is possible with polymerized asphalt mixtures (Costa et al. 2017).

4 ASPHALT PROCESSES & MIX DESIGN

To create these modified mixtures, a variety of plastics have proven effective when combined with bitumen. Research in Malaysia compared waste and virgin plastics and discovered that, when blended to form a modified bitumen mixture, waste polymer mixtures too showed improved physical properties (Kalantar et al. 2012). Some of the most common waste plastics combined with asphalt include PE, covering Low Density Polyethylene (LDPE), High Density Polyethylene (HDPE) and Cross-Linked Polyethylene (PEX), PET, PP, and PS. These types of plastics derive from products such as plastic bags, wrappers, films, water bottles, electrical cables and hangers. Other materials, such as cold-in place recycled foam asphalt, crumbed rubber, and stabilized bottom ashes, have also been researched in asphalt mixtures (Kim et al. 2009; Khan et al. 2016; Topini et al. 2018).

To be incorporated into asphalt mixtures, plastics are cut or shredded into strips, typically ranging from 1 to 4 mm (Vasudevan et al. 2012; Nkanga et al. 2017; Kalpana & Suresh 2018; Tiwari & Rao 2017; Appiah et al. 2017; Jan et al. 2017; Moghaddam et al. 2013). One study even shredded PET into strips of 0.78 mm by 10 mm to create a fiber-like materials (Usman & Masirin 2019). In other research, plastic was ground into flakes or pelletized before addition to the asphalt mixture (Costa et al. 2017; Melbouci et al. 2014; Celauro et al. 2019; Vila-Cortavitarte et al. 2018).

While the mixing process involved does alter the amount of plastic incorporated, many of these mixes included proportions of plastic, by weight of bitumen, within 0% to 15% (Nkanga et al. 2017; Kalpana & Suresh 2018; Tiwari & Rao 2017; Khan et al. 2016). Some studies used even finer proportions of plastic, within 0% to 3% of waste material, by weight of bitumen (Appiah et al. 2017; Usman & Masirin 2019; Vila-Cortavitarte et al. 2018). However, Vasudevan et al. 2012 used larger increments, varying plastic in 5% increments from 5-20% plastic, by weight of bitumen.

After these modified plastic asphalt mixtures are created, a variety of tests are conducted to assess the properties. To better understand bitumen, it is important to know the safety, age hardening, and temperature susceptibility of the material (Mallick & El-Korchi 2017). Tests, such as penetration (ASTM D5), specific gravity (ASTM D70), and ring and ball softening point (NA 2617), can provide information about binder properties such as penetration grade, mass ratio, and softening point (Mallick & El-Korchi 2017; Melbouci et al. 2014; Jan et al. 2017).

To evaluate waste plastic characteristics, analysis includes water adsorption (ASTM D570), strain (ASTM C1557), specific gravity (ASTM D792), grading curve (EN 993-1), and particle density (EN 1097-6) (Usman & Masirin 2019; Costa et al. 2017). These tests, when
conducted on waste plastic, provide a more in depth understanding of material performance, size, and density. When using the wet method, the characteristics of plastic-coated aggregate can be evaluated through moisture adsorption (AASHTO T96), soundness (AASHTO T96), aggregate impact (AASHTO T 96), and Los Angeles abrasion (AASHTO T96) (Vasudevan et al. 2012). These tests assess the aggregate’s resistance to weathering, toughness, and abrasion.

After understanding the different materials involved, it is crucial to assess the overall modified plastic asphalt mixture. One of the most popular tests is the Marshall Stability (ASTM D1559; EN 12697- 34), which provides information on asphalt stability, indicating the modified pavement’s capacity to withstand load (Vasudevan et al. 2012; Melbouci et al. 2014; Nkanga et al. 2017; Moghaddam et al. 2013; Jan et al. 2017). Other common tests include bitumen extraction (ASTM D2172), indirect tensile (ASTM D4123 or EN 12697-23), rutting resistance (EN 12697-22), fatigue resistance (EN 12697-24), and stiffness modulus (EN 12697-26) (Vasudevan et al. 2012; Nkanga et al. 2017; Usman & Masirin 2019; Costa et al. 2017; Celauro et al. 2019; Vila-Cortavitarte et al. 2018; Moghaddam et al. 2013). These tests present data regarding the mixture’s bonding nature, material quality, deformation, and bearing capabilities. One study even used Fourier transform infra-red (FTIR) technology to examine chemical changes occurring during the mixing of waste plastic with asphalt (Appiah et al. 2017).

This plethora of tests helps to analyze the properties of the bitumen, plastic, and the combined plastic asphalt. Findings from a host of research indicates that not only will incorporating waste plastic into asphalt help reduce plastic pollution, but also improve characteristics and performance. Bettered characteristics of plastic modified mixtures include water repellence, material binding, and decreased density (Jan et al. 2017; Appiah et al. 2017; Vasudevan et al. 2012; Costa et al. 2017). Improved physical properties include durability, fatigue resistance, performance life, deformation resistance, and strength (Tiwari & Rao 2017; Nkanga et al. 2017; Moghaddam et al. 2013; Usman & Masirin 2019; Celauro et al. 2019; Rahman & Wahab 2013; Jan et al. 2017; Melbouci et al. 2014).

5 CASE STUDIES

To further validate this literature review, two publications are used as case studies in evaluating the incorporation of asphalt within roadways. In Malaysia and India, research has been completed regarding this successful means of reducing plastic pollution. In Malaysia, green pavement was synthesized by incorporating PET from plastic water bottles within bitumen mixtures. In India, the dry method was utilized to incorporate a variety of waste plastics in an eco-friendly method. This source shows the successful evaluation and implementation of plastic roads.

According to research published by Rahman and Wahab in Malaysia in 2013, PET can be used as a partial fine aggregate replacement. This PET, used in the form of recycled plastic pellets, was tested in 5% increments, by weight of the asphalt mixture, from 5% to 25%, while bitumen content was varied from 4% to 6%, by weight of the asphalt. A density-voids and resilient modulus analysis indicated that 5% of mass of the asphalt mixture was the optimum bitumen content. In combination with an 80/100 penetration grade bitumen, the bitumen and aggregate were compacted through a Marshall Compactor, and the replacement pellets were added to the mix.

The samples were subjected to tests, such as Re-peated Load Axial Test (RLAT) and Indirect Tensile Stiffness Modulus Test (ITSM), to determine permanent deformation and stiffness. Testing results, as shown in Figure 1, indicate that the stiffness of recycled asphalt mixtures tends to be lower than that of unmodified asphalt mixtures. However, ITSM results show that the 20% PET asphalt mixture displayed remarkable deformation recovery even after 1800 loading cycles. As a result, it is possible that recycled PET, when used in asphalt,
can improve asphalt properties, resist road failures, decrease bitumen quantities, and reduce road construction costs.

Research published by Vasudevan in India in 2012 shows that waste plastic is being disposed of in an ecofriendly way through its application to flexible pavements. This procedure takes advantage of the softening points of plastic, and heats rather than burns the material to avoid producing toxic gases. Known as the dry process, this method releases no carbon dioxide emissions, helping to avoid greenhouse gas emissions. It is estimated that for every 1 km, at least 1 metric ton of waste plastic is used, reducing carbon dioxide emission by at least 3 metric tons.

Waste plastics are shredded between 2.5mm and 4.36 mm and heated to 170°C. Shredded plastic waste is sprayed over the stone aggregate and then mixed with bitumen. This spraying method allowed for a higher percentage of plastic waste to be used without concern over material separation, producing a higher quality aggregate. The hot plastic-coated aggregate is evaluated for binding properties such as moisture absorption (AAHSTO T96), soundness (AAHSTO T96), aggregate impact (AAHSTO T96), and Los Angeles abrasion (AAHSTO T96). Results indicate that the modified asphalt experiences significant strength improvement, with enhanced properties from the plastic polymer coating.

To characterize physical properties, the modified mix was subjected to additional tests such as Marshall Stability (ASTM D1559-1979), bitumen extraction (ASTM D2172) and stripping value (IS: 6241-1971). The Marshall value improved as the plastic coating filled and blended the aggregate with the bitumen. The Marshall Stability test upgraded by 50% to 60%, in comparison with the unmodified sample. Results also displayed that, when plastic coated aggregate was used, the required quantity of bitumen reduced by 0.5% of the total weight. This 0.5% reduction in total weight decreases the overall quantity of bitumen by 10%. The extraction test showed that removal of bitumen after the plastic coating was more difficult in comparison to the plain bitumen coated aggregate, indicating a successful blend of materials. In fact, the modified extraction was only able to be extracted after the sample was refluxed in an industrial solvent, decalin.

A field study analyzed six different sites to evaluate the performance of five plastic roads in comparison to one plain bitumen road. These sites were evaluated for deflection (IRC: 8101997), unevenness (IRC: SP16-2004), field density, skid resistance (ASTM E 303-83), texture depth (BS 598 Part 105), and surface condition. Results, as shown in Figure 2, indicate that these plastic roads, which were laid between 2002 and 2006 and surveyed between May 2007 and May 2008, performed much better than traditional asphalt roads.

The Benkelman Beam test, used to understand deflection, indicated that the bitumen
layer of the traditional road lost its visco-elastic properties after extended exposure to the atmosphere. However, the modified plastic road experienced no changes to the visco-elastic behavior within the same bitumen layer due to enhanced binding properties. Unevenness, measured using MERLIN equipment, was drastically different between the two roads.

<table>
<thead>
<tr>
<th>Road</th>
<th>Year</th>
<th>Unevenness (mm/km)</th>
<th>Skid Number</th>
<th>Texture Depth (mm)</th>
<th>Field Density (kg/m^3)</th>
<th>Rebound Deflection (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jambulingam Street</td>
<td>2002</td>
<td>2700</td>
<td>41</td>
<td>0.63</td>
<td>2.55</td>
<td>0.85</td>
</tr>
<tr>
<td>Veerabadra Street</td>
<td>2003</td>
<td>3785</td>
<td>45</td>
<td>0.7</td>
<td>2.62</td>
<td>0.6</td>
</tr>
<tr>
<td>Vandiyur Road</td>
<td>2004</td>
<td>3005</td>
<td>41</td>
<td>0.66</td>
<td>2.75</td>
<td>0.84</td>
</tr>
<tr>
<td>Vilachery Road</td>
<td>2005</td>
<td>3891</td>
<td>45</td>
<td>0.5</td>
<td>2.89</td>
<td>0.86</td>
</tr>
<tr>
<td>Canteen Road TCE</td>
<td>2006</td>
<td>3100</td>
<td>45</td>
<td>0.65</td>
<td>2.33</td>
<td>0.86</td>
</tr>
<tr>
<td>Plain Bitumen Road^a</td>
<td>2002</td>
<td>5200</td>
<td>67</td>
<td>0.83</td>
<td>2.86</td>
<td>1.55</td>
</tr>
<tr>
<td>Tolerance Value^b</td>
<td>4000</td>
<td>&lt;65</td>
<td></td>
<td>0.6-0.8</td>
<td></td>
<td>0.5-1</td>
</tr>
</tbody>
</table>

^a Reference road Constructed with plain bitumen
^b Theoretical value for the effective performance of a good road

Figure 2. Summary of Field Study Results Analyzing Six Different Sites in India to Evaluate Performance of Plastic Roads (Sites 1-5) Compared with Plain Asphalt Road (Site 6). Adapted from Vasudevan et al. (2012). Copyright 2012 by Construction and Building Materials.

The plain bitumen road resulted in unacceptable levels of unevenness due to poor binding, disentangling of materials, and oxidation due to aging, while the plastic road showed continued uniformity due to strong bonding, helpful changes in bitumen structure, and increased stability. When analyzing field density over 7 years, the traditional road experienced a decreased performance of 19% while the plastic road experienced a reduction of 9% to 10%. Skid resistance and texture depth also improved for the plastic road in comparison to the traditional road. The surface condition survey showed that the plastic roads experienced no potholes, cracking, rutting, or flaws within the road.

Both case studies prove the feasibility and importance of modifying traditional bitumen mixes with plastic. By repurposing waste plastic through Vasudevan’s patented dry process, flexible and sustainable pavement can be made through an ecofriendly method. As a result, this sustainable construction will reduce bitumen quantities, repurpose waste plastics, produce less greenhouse gas emissions, and reduce pavement costs.

6 CONCLUSION

As plastic production continues to increase exponentially, alternative methods to mitigate plastic pollution are imperative. Based on the literature review presented in this paper, findings suggest that the incorporation of plastic within roadways can serve as a remedial method to alleviate plastic’s detrimental effects to the environment. Not only will this addition repurpose waste products, but also reduce bitumen amounts, improve roadway characteristics, lower construction costs, diminish greenhouse gas emissions, and promote a circular economy. Further research and field tests are suggested to verify the findings in this paper. It has been estimated that if 5% plastic waste is used to replace bitumen in roadways, there will be a 10% to 15% decrease in global plastic pollution.

7 REFERENCES
practice. CRC Press.

INNOVATION

Evaluating the efficiency of low-cost ultrafiltration

On the road to a sustainable infrastructure: Part 2—integrating sustainability in planning, design, and construction

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*On the cover: Muddy River (the Fens) in Boston is the water source for the experiments described in “Evaluating the efficiency of low-cost ultrafiltration”

Page 74: Measurement unit conversions and abbreviations*
Evaluating the efficiency of low-cost ultrafiltration

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ABSTRACT | Low-cost ultrafiltration is frequently incorporated into water purification systems to treat potable water. For this project, we applied water quality criteria to evaluate the efficiency of a low-cost ultrafiltration product. Treatment was assessed by comparing influent and effluent biochemical oxygen demand (BOD), turbidity, coliforms, and concentrations of heavy metals, including arsenic, lead, and selenium. For the experiments was obtained from the Muddy River in Boston. Results indicated a significant decrease in the level of contamination after ultrafiltration. Fecal coliforms reduced from >500 to 0 CFU/100 mL; Turbidity reduced from over 6.8 to 0.6 nephelometric turbidity units (NTU); and BOD levels dropped from 20.0 to 6.0 mg/L. Because of the low heavy metal concentration in the unfiltered water, further testing was discontinued. Although further testing is recommended, the tested low-cost ultrafiltration method showed potential for providing potable drinking water.

KEYWORDS | Membrane filtration, ultrafiltration, indicators, coliforms, BOD, turbidity, and heavy metals

INTRODUCTION

Contaminated drinking water is a leading cause of over 1.6 million child deaths each year (Wardlaw et al., 2012). Drinking water is often contaminated by waterborne pathogens, such as cholera, that are the leading causes of gastrointestinal diseases. Also, the increase in population is causing an exponential increase in the use of polluted water.

Deaths from waterborne disease include deaths due to cholera. The World Health Organization (WHO) estimates between 3 million to 5 million cholera cases and 25,000 to 100,000 deaths occur every year; of which only a fraction is officially reported. In 2013, three years after a major cholera outbreak began in October 2010, 120,000 cases and 2,120 deaths were reported worldwide, with 44 percent of cases reported in Africa and 45 percent in Haiti alone (where between October 2010 and December 2012, 6,567,924 cases were reported with 8,351 deaths) (WHO; 2013 and 2014). Cholera outbreaks can occur during emergencies, such as earthquakes and flood events, or in refugee settings when water supply, sanitation, and hygiene infrastructure is compromised.

These issues demonstrate the need for robust, selective, and economical purification techniques. Membrane filtration is one of the most promising purification technologies to emerge in the past decade. Membrane development started in the 1930s with the first reverse osmosis membranes for desalination. Since then, membrane technology has seen tremendous growth in development, creating a new and extensive market for membrane filtration applications. A wide range of membrane filters have been created, from nanofiltration (NF, good for softening and dechlorination through ultrafiltration (UF, good for virus removal) to microfiltration (MF, good for suspended solids removal) (Kreissel et al., 2012).

UF (50 to 50 nm) has been established for removing microbiological contaminants in drinking water, but because of their size, enteric viruses (20 to 160 nm) may not be as effectively removed compared to bacteria (Elhadidy et al., 2012). The UF system tested purports to effectively remove microorganisms to log reduction values of 4 to 7. The low cost to produce and easy maintenance have made UF promising for treating drinking water because the systems can be setup virtually anywhere with no electricity or fuel required, for example, the tested unit operates from 6 to 13 ft (to a m) of water head for the inlet feed. These units have been especially popular in disaster situations and more impoverished developing countries. This low-cost UF product was used to test the effectiveness of microorganism removal in this research. UF shows promise for virus removal not only based on size exclusion but also because of other mechanisms such as adsorption and electrostatic repulsion (Kreissel et al., 2012).

Pathogens are excreted in the feces of infected humans and animals and may directly or indirectly contaminate water intended for human consumption (Figueiras et al., 2010). Hundreds of different enteric microorganisms are known to infect humans, and more than 160 of them are known waterborne pathogens (Figueiras et al., 2010; Reynolds et al., 2009). Pathogens capable of causing waterborne illness include viruses, bacteria, and protozoa. The impact of waterborne pathogens in humans is often acute gastrointestinal disease. Immunosuppressed subpopulations are more likely to be infected and experience morbidity and mortality resulting from waterborne illness (Reynolds et al., 2009). While testing for all enteric pathogens in drinking water would be ideal, time and financial constraints make it impractical. Therefore, indicator organisms are used to assess the potential presence of pathogenic microorganisms (Yates, 2007).

There are many different indicator organisms, and no one indicator is appropriate for every water system. Factors including detection methodology and survival rates influence an indicator system’s validity. An indicator’s most important attribute is a strong quantitative relationship between the indicator concentration and the degree of public health risk; therefore, a strong correlation between the indicator concentration and pathogen levels is vital (Yates, 2007). Bonde (1966) first described the ideal qualities of an indicator. Organisms, surrogates, and physical models are used to establish potential risk from fecal contamination in drinking water. Bacterial groups, such as coliforms, are commonly used to indicate the microbial quality of water, and their detection is included in drinking water regulations. Fecal coliforms and Escherichia coli (E. coli) are used as indicators of fecal contamination in regulations by EPA, the Council of European Communities (CEC), and WHO. Two commonly tested viral surrogates are the bacteriophages MS2 and PhiX174 because they are small, laboratory workers, are 27 to 32 nm in diameter and contrast in structure. MS2 has an outer diameter of 27 nm while PhiX174 has an outer diameter of 35 nm due to 12 extruding protein spikes (McKenna et al., 1991). Another method of testing UF’s effectiveness at virus removal is measuring the passing of nanoparticles through a membrane and correlating the size of the nanoparticle to a virus. For example, Pang et al. (2009) observed the ability of protein-coated nanoparticles to model MS2. MF and UF can filter out contaminants based on particle size; they also can retain macromolecules or high-molecular-weight compounds as well as colloidal and apparatus (Arnal et al., 2004). Because UF and MF membranes filter out particles based on size, they are classified as porous membranes. MF pore sizes typically range from 0.1 to 10 µm while UF pore sizes typically range from 0.01 to 0.05 µm (Koyuncu et al., 2005).

The use of low-pressure membrane systems using UF and MF is increasing for water treatment. The global market for MF and UF is projected to reach a component annual growth rate of 30 percent and 5.7 percent, respectively over the next five years (Koyuncu et al., 2005). Membrane technology offers many advantages, such as its modular nature, scale flexibility (small to very large), quality of the product water, small environmental footprint, and, in most cases, low energy usage (Fane et al., 2012).

Fane et al. state that MF membranes typically have a high permeability (>5000 m3/h•bar) and can operate at a low pressure, from 1.5 to 30 psi (10 to 210 bar). MF membranes can be fabricated from both polymeric and inorganic materials with either symmetric or asymmetric structures, while UF membranes usually have an asymmetric structure to maximize membrane permeability. UF membranes are commonly selected by their molecular weight cutoff (MWCO), defined as the molecular weight of a particle in the solution to be treated in which 90 percent of the particles of that weight will be rejected (removed) by the membrane. UF membranes typically have a MWCO of 1 to 300 kilodaltons (kDa)—one dalton is defined as 1/12 the mass of an unbound neutral atom of carbon 12 or approximately the mass of one hydrogen atom. A membrane with a larger MWCO indicates lower rejection (a lower removal rate) and larger pore size (Fane et al., 2012).

In this study, a commercially available UF unit was used to filter water from the Muddy River in Boston. The UF unit uses 6 to 13 ft (2 to 4 m) of water pressure as the driving force to push water through the membrane system while leaving particles on the opposite side of the membrane without further operation. This apparatus is used to generate a maximum 185 gal (700 l) of clean drinking water per hour. The tested device uses an outside-to-inside polyamide membrane (PVDF). This low-pressure membrane has a nominal pore size of 0.04 µm, which characterizes it as a UF membrane. The test used the membrane UF technology to remove contaminants and pathogens including...
bacteria and viruses, and the unit significantly removed dirt and turbidity without the use of chemicals. This unit is designed to be a low-cost method to provide potable water to areas affected by natural disasters and developing countries without access to electricity. According to the manufacturer’s data, the hollow fiber membrane filters out pathogens including bacteria, protozoa, cysts, helminths, total coliforms, and E. coli to a log reduction value >4. The data sheets also state that the membrane will lower the turbidity to <0.1 NTU and remove all total suspended solids.

This research evaluated the efficacy of a low-cost membrane water filtration system for use in developing countries by comparing water quality parameters pre- and post-filtration.

MATERIALS AND METHODS

The samples of water used in all testing criteria were taken from the Muddy River in Boston. Two gal (7.5 L) was withdrawn from each of four locations along the river including the end of the river where it is dammed prior to the Charles River. These sampling locations were based on the recommendations from a consulting firm working with the researchers. The locations are shown in Figure 1. Initial testing of water quality at all locations showed location 2 as the most polluted. An additional 1 gal (3.8 L) was taken from location 2 for the filtration assessment. The filtered sample was then tested for water quality parameters such as biochemical oxygen demand (BOD), turbidity, coliforms, and concentrations of heavy metals.

To evaluate the efficiency of the UF unit for coliform removal, Muddy River samples were tested for colony-forming units (CFUs) before measurements were taken. The turbidity was determined for the four sampling locations and the filtered samples. All tests were done in triplicate. To test the metal contents of the samples, an atomic absorption spectrophotometer (AAS) was used. As the concentration of heavy metals in the Muddy River was unknown, the AAS was calibrated for the concentration shown in Table 1 (Santos et al., 2005 and Emmanuelle et al., 2010). The flame atomic absorption method measures the change in energy state of the flame when it interacts with the atoms from the sample and correlates that visible change to the metal content. Each of the four Muddy River locations was tested for selenium, lead, and arsenic prior to filtration, and location 2 was tested after filtration.

To evaluate the efficiency of the UF unit for coliform removal, Muddy River samples were tested for total coliforms, fecal coliforms, and E. coli. The vacuum filtration method was used to determine the total and fecal coliforms (EPA Method 510a). The testing procedure for all samples consisted of filtering the sample through a filter membrane 47 mm diameter, 0.45 µm ± 0.02 µm pore size using a suction pump. The filter membrane was then placed in agar plates with pads that had a total-colliform indicator broth poured over them and were incubated at 30°C and 95°F (35°C) for 24 hours for fecal coliforms and 95°F (37°C) for total coliforms. Testing was done on two unfiltered Muddy River water sample types: i) undiluted and ii) 5:1 diluted using 10 percent distilled water to 10 percent unfiltered water.

RESULTS AND DISCUSSION

Treatment was assessed by comparing influent and effluent BOD, turbidity, coliforms, and concentrations of heavy metals including arsenic, lead, and selenium. Results indicated a significant decrease in contamination after ultrafiltration.

BOD Testing Results

The BOD levels of the four locations without filtration ranged between 4.5 to 20 mg/L, whereas the filtered sample ranged from 0.9 to 0.45 mg/L, as shown in Tables 2 and 3. These results indicate that before filtration the river had a high level of oxygen-reducing biological matter, which consistently consumed the oxygen within the sample while the filtered sample did not have the same quantity of oxygen-reducing biological matter, as shown in Figures 2 and 3. Oxygen consumption in the filtered samples was low, though greater removal would be desirable (BOD is normally used as a drinking water parameter). The higher BOD in the stream at location 2 could be attributed to a sewer outfall, which is about 1,500 ft (460 m) away.

Coliform Testing Results

Unfiltered (undiluted and diluted) and filtered samples were tested for colony-forming units (CFUs) for total coliforms, fecal coliforms, and E. coli. The CFU counts are included in Tables 4a and 4b (see next page). Approximately 1,000 total coliform colonies were observed after a 22-hour incubation period for the unfiltered water both for undiluted and for a dilution of 30 percent distilled water and 10 percent unfiltered Muddy River water. At an average of 16 total coliform colonies observed in the filtered water from location 2, the UF unit tested effectively removed 85.5 percent of the total coliforms. This is a log reduction value of less than 1 compared to the cited log reduction value of greater than 4 log removal from the product literature. No fecal coliforms were observed in the filtered samples.

Table 1. Constituents and properties

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Chemical Symbol</th>
<th>Common Oxidation State(s)</th>
<th>Common Aqueous Metal Complexes</th>
<th>AAS Stock Solution Used in Preparation (1000 mg/L)</th>
<th>Concentration Range Tested (mg/L)</th>
<th>Drinking Water Standards (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arsenic</td>
<td>As</td>
<td>–3, 0, +3, +5</td>
<td>AsO3, AsO4</td>
<td>AsO4</td>
<td>0.00 to 100.0</td>
<td>0.0100</td>
</tr>
<tr>
<td>Lead</td>
<td>Pb</td>
<td>2</td>
<td>Pb2+</td>
<td>Pb(NO3)2</td>
<td>0.00 to 100.0</td>
<td>0.0015</td>
</tr>
<tr>
<td>Selenium</td>
<td>Se</td>
<td>–2, +2, +4, +6</td>
<td>SeO2, SeO4</td>
<td>SeO4</td>
<td>0.00 to 100.0</td>
<td>0.0050</td>
</tr>
</tbody>
</table>

Table 2. Unfiltered Muddy River water—Biological Oxygen Demand (BOD)

<table>
<thead>
<tr>
<th>Location</th>
<th>Day 1</th>
<th>Day 2</th>
<th>Day 3</th>
<th>Day 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.50</td>
<td>12.75</td>
<td>12.75</td>
<td>12.75</td>
</tr>
<tr>
<td>2</td>
<td>10.50</td>
<td>15.00</td>
<td>15.75</td>
<td>20.25</td>
</tr>
<tr>
<td>3</td>
<td>5.25</td>
<td>15.00</td>
<td>16.50</td>
<td>12.75</td>
</tr>
<tr>
<td>4</td>
<td>5.25</td>
<td>12.75</td>
<td>15.75</td>
<td>13.50</td>
</tr>
</tbody>
</table>

Table 3. Filtered Muddy River water—Biological Oxygen Demand (BOD)

<table>
<thead>
<tr>
<th>Location</th>
<th>Day 1</th>
<th>Day 2</th>
<th>Day 3</th>
<th>Day 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.90</td>
<td>2.55</td>
<td>2.55</td>
<td>2.55</td>
</tr>
<tr>
<td>2</td>
<td>2.10</td>
<td>3.00</td>
<td>3.15</td>
<td>4.05</td>
</tr>
<tr>
<td>3</td>
<td>1.05</td>
<td>3.00</td>
<td>3.30</td>
<td>2.55</td>
</tr>
<tr>
<td>4</td>
<td>1.05</td>
<td>2.55</td>
<td>3.15</td>
<td>2.70</td>
</tr>
</tbody>
</table>
so the tested unit appeared effective at removing detectable fecal coliforms, as shown in Table 4a. unfiltered Muddy river water—

<table>
<thead>
<tr>
<th>Test</th>
<th>Location</th>
<th>Turbidity (NTU)</th>
<th>Coliforms (CFU)</th>
<th>E. coli (Colony)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>17</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Figures 4a and 4b. Filtered Muddy River water—

<table>
<thead>
<tr>
<th>Test 1</th>
<th>Location</th>
<th>Turbidity (NTU)</th>
<th>Coliforms (CFU)</th>
<th>E. coli (Colony)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.41</td>
<td>0.2</td>
<td>0.27</td>
<td>0.32</td>
</tr>
</tbody>
</table>

**Metal Testing**

EPA permissible limits for each metal tested were 0.05 mg/L for lead, 0.01 mg/L for arsenic, and 0.05 mg/L for selenium (EPA, 2009). The filtered water was below all three detection limits for possible potable drinking water, but each of the four filtered samples was below the limits, as well. Since the unfiltered heavy metal concentration was below permissible limits, this testing does not conclusively assess filter removal of metal content; however, the filtered results were lower than the unfiltered results, as shown in Table 8.

**CONCLUSION**

Based on this research, the tested UF unit treated the Muddy River to near-potable water standards. The BOD levels, turbidity, and coliform counts in the filtered samples from this test came close to United Nations standards for drinking water and were also permissible to National Primary Drinking Water Regulations (NPDWRs) as prescribed by 40 CFR 111:208 and as promulgated by EPA (EPA, 2009); however, further confirmatory research is indicated. The next steps will be to conduct challenge tests using spiked (heavy metal) samples of unfiltered water. Also, viruses were not tested in this research, and we recommend the efficacy of virus removal be further evaluated in future testing.

**ABOUT THE AUTHORS**

- Dr. Gautam P. Das received a doctorate from the University of North Carolina at Charlotte. Prior to starting his teaching career, Dr. Das worked for environmental consulting firms in New England and is a professional engineer in Massachusetts. Her expertise is in water resources, hydraulic engineering, and environmental remediation. She is active in the Water Environment Federation and NEWEA.

**REFERENCES**


**AAS Results**

<table>
<thead>
<tr>
<th>Location</th>
<th>Metal Content (mg/L)</th>
<th>Se</th>
<th>As</th>
<th>Pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0003</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0.0038</td>
<td>0.0065</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>0.0002</td>
<td>0.004</td>
<td>0.0001</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.0052</td>
<td>0.005</td>
<td>0.0001</td>
<td></td>
</tr>
</tbody>
</table>

| Filtered water | ND | 0.0008 |

**Turbidity Testing Results**

The turbidity for the Muddy River locations prior to filtration averaged between 5.02 and 7.25 NTU, as shown in Table 6. These values indicate a high level of turbidity for the Muddy River water—

<table>
<thead>
<tr>
<th>Test 2</th>
<th>Location</th>
<th>Test 3</th>
<th>Test 4</th>
<th>Average (NTU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.41</td>
<td>0.2</td>
<td>0.27</td>
<td>0.32</td>
</tr>
<tr>
<td>2</td>
<td>0.0038</td>
<td>0.0065</td>
<td>0</td>
<td>0.0001</td>
</tr>
<tr>
<td>3</td>
<td>0.0002</td>
<td>0.004</td>
<td>0.0001</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.0052</td>
<td>0.005</td>
<td>0.0001</td>
<td></td>
</tr>
</tbody>
</table>

Leading innovation.  
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Alewife Reservation Stormwater Wetland—
Provides water quality improvement and unique recreational and educational open space for the community.
Using Calcium Stearate as a Modifier for fly ash stabilization

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Abstract – Heavy metal leaching from improperly disposed fly ash remains a concern to human health and the environment as a result of their toxicity. The objective of this paper is to evaluate the performance of calcium stearate to encapsulate heavy metals in fly ash to prevent chemical leaching. To assess the ability of the additive to solidify heavy metals, batch leaching tests and column leaching tests were performed. The methodology involved testing fly ash with various amounts of additive. The fly ash with the additive was evaluated by measuring the concentration of heavy metals such as Chromium, Lead and Cadmium that leached from the fly ash. Batch leaching results indicated that the concentration of chromium was 65 $\mu g/L$ for fly ash alone. However, with 1% calcium stearate the concentration dropped to 45.5 $\mu g/L$. Column leaching results revealed that the concentration of cadmium was 166 $\mu g/L$ for 3% calcium stearate. On the other hand, with 1% calcium stearate the concentration fell to 93.4 $\mu g/L$. Further testing revealed that 1% calcium stearate reduced the amount of heavy metal leaching from fly ash. It
is hypothesized that the calcium stearate attacks the transition metals rendering the metal essentially inactive due to the free lime hydration.

**Keywords** – Heavy metal leaching, Fly ash, Water-repellant

I. INTRODUCTION

Fly ash is a common by-product of the coal combustion process that has been studied for reuse in the construction industry for many years. Yao et al. (2014) explains that the world generates approximately 750 million tons of coal based fly ash each year. Coal fly ash is hazardous both to human health and the environment if disposed of improperly. The global demand of coal is projected to increase thus increasing the amount of fly ash produced each year. However, less than 25% of the total quantity of fly ash produced in the world has been recycled (Zentar et al., 2012). If this continues, there would be no choice but to continue improperly disposing of fly ash. The issue is the presence of trace metals in the fly ash which leach out of the combined materials and cause detrimental effects to the environment as well as humans. Hence, the removal or solidification of these metals is of utmost importance attempting to recycle fly ash and creating a sustainable final product. Water dissolution, phosphation and adding sodium carbonate have been reviewed and tested as possible methods to remove these metals, but not all elements have become effectively stabilized (Aubert et al., 2006). In terms of solidification, most solutions lead to mixing the by-product with cement, which has been proven effective, but fails to control the leaching of various metals. Yao et al. (2014) states currently, 20% of coal fired fly ash is used in concrete production with it also being used in road base construction, and soil amendment. More recently, a form of organic modification that uses organosilanes to irreversibly bond with fly ash has been introduced as water repellant technology (Daniels et al., 2009). With this idea in mind,
CALSAN™ 50, a product made by BASF which is a calcium stearate dispersion in water was believed to be a suitable replacement (BASF 2009). The objectives of this paper are to (1) review previous work regarding the use of waterproofing substances as an option for the solidification of fly ash, (2) evaluate the performance of calcium stearate through chemical leaching testing in various conditions and (3) provide commentary on whether this is a viable option for attenuation of fly ash metals.

II. BACKGROUND

Many methods have been tested to explore the possibility of recycling fly ash in order to reduce the volume of waste while providing a comparable and safe alternative to landfills. Among these methods are: the inclusion of slag, alkali-activation, metakaolin, Portland cement and nano-silica (Rashad, 2014). For this experiment, the process of encapsulation will be explored as an option to mitigate leaching levels to EPA regulatory standards.

In order to begin comprehending how to prevent fly ash from leaching into the ground, a basic understanding of what fly ash is must be acquired. As stated previously, fly ash is a common by-product of the coal combustion process. Depending on how the coal is processed, a wide range of properties could be seen when analyzing different ashes. Cho et al. (2005) states coal fly ash is extremely varied in its mineral makeup, and its characteristics depend heavily on the kind of coal used, and the way in which it was burned as well as several other factors. On average, fly ash occurs as fine particles with a spherical shape and an average size of less than twenty micrometers, has low to medium bulk density and a high surface area for its small size. The pH values range from 1.2 to 12.5, but the trend is usually towards alkalinity.

The common heavy metals found in fly ash include: Chromium, Lead, Cadmium, Nickel, Barium, Strontium, Vanadium and Zinc (Yao et al., 2015). Since there are hazardous metals in fly ash a method must be created in order to encapsulate the contaminants eliminating the chance for leaching to occur.
There have been many tests performed in order to determine the best method of containing the toxic metals that are present in fly ash. The leaching of toxic metals from fly ash is the primary inhibitor to the widespread use of fly ash in construction projects. Van der Sloot speaks how leaching is a function of the surface exposed to the leaching fluid. The ratio of the particle surface area to the volume occupied by the particles, the average particle size, and internal pore structures in the material all control the surface area where dissolution from the solid to the liquid can occur. Smaller particle sizes produce larger surface area, allowing for increased contact between the solid material and the leaching fluid, resulting in increased contact between leaching fluid and leachable constituents (Van der Sloot, et al. 1997).

Kerkhoff shows that fly ash can be used as liming material on acid soils or acid mine soils or alkali soils for improving the pH of the soils depending on nature of soil and ash. Increases in pH induced by alkaline fly ash addition is a desirable property and could be used for detoxifying elements like Cd, Al and Mn. Due to fine nature of fly ash, it improves the WHC of sandy soils removing the compaction of clay soils. It improves the physical and chemical properties of soil as well as biological properties of problematic soils. Application of fly ash, particularly unweathered ones, show a tendency of accumulating elements like B, Mo, Se and Al, whose toxic levels are responsible for a bad influence on animal and human health, (Kerkhoff 2001).

Cinquepalmi et al. investigated the use of fly ash as an artificial aggregate in Portland cement mortars and found that the release of each metal increased with increasing amount of artificial aggregate in the mortar specimens. Also, it was found that pH has a great influence on the leachability of heavy metals from the cement mixture. The greatest effect was shown at pH levels below 6-8 and as the pH rose, the release of metals decreased to a point where the amount of artificial aggregate in the mixture had nearly no effect at all (Cinquepalmi et al., 2008).
The ionic strength of the leaching fluid also influences solubility and leaching behavior. Ionic strength is the relationship of the concentration of ions in solution and the charges of those ions. Ionic strength impacts reaction rates as well as the solubility of ionic species, with solubility generally increasing as ionic strength increases, (Lowenbach, 1978).

Becker, et al., (2013) determined that after several experiments using the Environmental Protection Agency’s testing guidelines for fly ash leaching, fly ash leached toxic metals at levels exceeding the regulatory limits. It was noted that pH levels can directly affect the rate and amount of leached metals, and each batch test conducted should be adjusted to accurately reflect site specific conditions. There is typically a non-linear relationship between leachate metal concentrations and fly ash content, thus requiring full testing be done to better estimate the amount of leached material. Additionally, column leach testing was found to not accurately represent long term leaching risks, and therefore should not be conducted with that purpose in mind.

Singh, et al., compared the chloride resistivity of nanoparticles to fly ash and concluded that in general, fly ash does not prevent chloride permeability as well as silica nanoparticles. A silica nanoparticle content of 3% was shown to improve chloride ion resistance up to nearly 40% when compared to plain cement. Adding fly ash alone reduces the strength of the concrete compared to not adding any, but adding the fly ash and a small amount of silica increases the compressive strength of the concrete. Park et al, (2006) found that adding small amounts of silica, 4% by weight, increased strength in concrete bricks up to nearly 20.8MPa. Commercial bricks made with natural sands had compressive strengths of around 11.9MPa. Most notably, it was found that the silica helped reduce the leaching of the hazardous substances from the solidified ash.

“It was observed that the efficiency of nanoparticles such as nano-silicon oxide depends on their morphology and genesis, as well as on the application of super plasticizer and additional treatment options such as thermal treatment and ultra-sonification. The method studied here is capable of manufacturing the wide range of
nanoparticles with engineered parameters such as particle size, porosity and surface conditions. It was demonstrated that all synthesized nano-silicon oxides improve the early compressive strength of Portland cement mortars, but at later stages of hardening, strength was adversely effected by these additives. The major problem of nano-silicon oxide application and such strength loss is related to the agglomeration of nanoparticles at the final drying stage. High-temperature treatment affects the performance of these additives and should be avoided. Further research is required to modify the sol-gel method in order to avoid the formation of agglomerates and to achieve better dispersion of developed nano silicon oxides” (Drexler 1991).

(Malhotra 1988) explains that “Concrete containing Class F fly ash exhibited higher long-term resistance to chloride-ion penetration compared to Class C fly ash concrete. The best long-term performance was recorded for both of the 53 percent and the 67 percent Class F fly ash and 70 percent of Class C fly ash concrete mixtures as they were found to be relatively impermeable to chloride ions in accordance with ASTM C 1202. Except for control mixture C-4, the differences in the Coulomb values of the high-volume fly ash mixtures are not significant. All fly ash concrete mixtures showed excelling performance with respect to chloride-ion penetration resistance.”

Al-Saadoun, et al., (1993) determined that fly ash blends of cement typically outperform plain cement in corrosion resistance of reinforcing steel. Fly ash blends significantly affected the initiation time for corrosion and in some cases tripled the time required for corrosion to begin. Notably, lignite fly ash performed best when compared to bituminous and sub-bituminous fly ash. Since the corrosion of steel is an electrochemical process, it was shown that having a 25% fly ash mixture can increase the electrical resistivity of cement threefold.

Fly ash has a tendency of not acting as a pozzolanic material until at least one week after being mixed. Fraay, et al., (1989) determined that fly ash created as a byproduct of bituminous coal (class F) contains crystalline inclusions which is primarily comprised of alumina silica glass. This crystalline structure is the cause for the
delayed hydration when mixed with Portland cement. The pozzolanic reaction is explained by the dependency of breaking down the glass on the alkalinity of the pore water. High alkalinity in conjunction with the precipitation of reaction by-products can inhibit the breaking down phase, ultimately delaying the pozzolanic reaction from the fly ash. Additionally, the pH and temperature of the pore water can affect the reactivity of the fly ash as well as the solubility of the glass. In most cases lower pH levels create a less reactive fly ash which, in turn, delays the pozzolanic state from occurring. Cao., (2010) determined that by influencing the micro-gradation of cement the delayed pozzolanic reaction of fly ash could be counteracted and early strength could be improved. Since fly ash slows the early strength generated by concrete, slag was incorporated into the design to improve early strength. Since slag on its own can produce harmful air voids, the fly ash will be used to counteract this by filling the air voids. Cao found that the optimal fly ash to slag ratio was 4:1 and performed best when an activator was used. When the activator content was at 2%, the day one compressive strength and flexural strength was approximately 21% and 10% higher, respectively, when compared to concrete with just fly ash. These numbers rose when the activator was increased to 3%. Activator significantly speeds up the hydration process and increases early strength in cement with fly ash and slag additives. This same method could potentially be used in speeding up the hydration of fly ash cement mixes to help move the pozzolanic reaction along.

Rashad reviewed many experiments which tested various admixtures to fly ash and the effect that occurred. One experiment studied the compressive strength with various amount of fly ash added to Portland cement. From the experiment, it was found that a ratio of 60 percent fly ash to 40 percent Portland cement yielded the best results for mechanical performance. This is good to keep in mind because for the proposed experiment a comparable product must be made in terms of strength and not just reduced leachability (Rashad, 2014).
Most of these procedures were completed using one or more of the following testing methods: batch, column or block. For the purposes of this paper it was found sufficient that batch testing and column testing be performed.

“Batch extraction tests typically involve mixing a sample of waste or other fill material with a specific amount of leaching solution without renewal of the leaching solution. The mixing is performed over a short period with aim of trying to reach equilibrium with some type of rotary agitation. The mixing is followed by filtration and analysis of the filtered liquid phase” (Washington State Department of Ecology 2003).

“A column leaching procedure is used to classify a waste as hazardous or not, and to determine the effectiveness of a waste treatment process. A column leaching procedure using a leaching fluid being pumped into a sample material in a column. One should then use a tube coming out of the sample column and into an effluent to sample the extracts” (Washington State Department of Ecology 2003).

By using the calcium stearate technology, an effective way of encapsulating heavy metals within a cement matrix is expected.

III. MATERIALS AND METHODS

The fly ash studied was donated from Headwaters Resources and came from Brayton Point. Headwaters Resources lists the material density at 2.38 grams per centimeter cubed.

The calcium stearate (Calsan™ 50) was procured from BASF Corporation in New Jersey. It is a part of the metal stearate family and is used primarily as a coating lubricant.

The columns used for the column leaching tests had dimensions of 4.5 inches in diameter by nine inches in height for a total volume of 143.14 cubic inches. They were connected to a gravity head system to conduct the column tests.
A spectrophotometer was used to determine the amount of light that a sample of the leachate could absorb. The intensity of light that reaches the detector would then be used to measure the quantity of heavy metals that have leached into solution.

The batch leaching was performed using varying fly ash and calcium stearate mixtures and adding the leachate of nitric acid and distilled water at a pH of 4.2 to 4.4. The pH was set at this level to mimic the worst-case scenario and cause the most leaching to occur from the fly ash mixtures. The amount of leachate was kept at a constant 50 mL and the liquid to solid ratio was altered using various amount of fly ash and calcium stearate mixtures. After creating ratios of 100:1, 50:1 and 10:1, each with a different quantity of calcium stearate (0%, 1%, 2% and 3% by weight), the mixtures were shaken for 48 hours. Once the shaking was complete, the leachate was extracted from the surface with pipettes. Ten mL of the solution was mixed with cadmium, chromium, and lead reagents in a test tube and shaken for three minutes each to ensure a complete mixture. Each test tube was then placed in the spectrophotometer to measure the amount of heavy metal leaching that occurred. This process was repeated twice for duplicate testing.

The column leaching test was performed by first mixing the fly ash and calcium stearate mixtures with a specified amount of water to achieve optimum moisture content and maximum dry density. Once this was complete, the columns were then filled with each mixture in five equal lifts, compacting each with approximately 25 drops of a compaction hammer. The columns were then attached to a gravity head system as seen in Figure 1, with one inlet tube feeding leachate from a holding tank and one outlet tube to allow for collection of the passed leachate. Based on the pore volume that was calculated to be one liter (Source needed), it was determined that each time one liter of solution passed through the column, it would be tested for the selected heavy metals. The data would then be input into the Yalcin Leaching Model in order to predict the
leaching behavior for an extended period of time. Each pore volume was tested twice to provide duplicate results.

“A Yalcin leaching model was formulated to capture the observed experimental leaching behavior of the contaminant exhibiting an initial increase in concentration followed by a decrease in concentration with further leaching until it reaches a low steady state concentration. The model is as follows

\[ C(t) = C_s - C_s e^{-K_kbt} + C_0 e^{-K_kbt} \]

Where \( k_b \) is the dissolution rate coefficient \((\text{min}^{-1})\), \( K = (S/S_0)^a \), \( S \)=Solid phase concentration \((\text{mg/g})\), \( S_0 \)=Initial solid phase concentration \((\text{mg/g})\), \( C_s \) is the effective saturation concentration \((\text{solubility})\) of contaminant \((\text{mg/L})\), \( t \) is the time \((\text{min})\), and \( a \) is a dimensionless empirical constant” (Das 2007).

IV. RESULTS AND DISCUSSION

Tables 1 through 3 show the results of the batch leaching tests that were conducted on each L:S ratio containing 0-3% calcium stearate. For each metal, a general trend could be seen that the 1% calcium stearate mixture produces a constant

Table 1 – Batch Leaching Average Concentration of Chromium

<table>
<thead>
<tr>
<th>Metal</th>
<th>Concentration (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chromium</td>
<td>100</td>
</tr>
<tr>
<td>Iron</td>
<td>50</td>
</tr>
<tr>
<td>Zinc</td>
<td>20</td>
</tr>
</tbody>
</table>

Figure 1- Gravity Head Column Leaching
when compared to the plain fly ash solution, most notably for chromium. The same results could be seen in
graphical representation in Figures 2 through 4. The same general trend could be seen in this instance as well.

<table>
<thead>
<tr>
<th>L:S Ratio</th>
<th>Calcium Stearate (% by weight)</th>
<th>Average Concentration (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100:1</td>
<td>0</td>
<td>0.065</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>0.0455</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.0475</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.0495</td>
</tr>
<tr>
<td>50:1</td>
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<td>0.0685</td>
</tr>
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<td></td>
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</tr>
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<td>0.0585</td>
</tr>
<tr>
<td></td>
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<td>0.051</td>
</tr>
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</tr>
<tr>
<td></td>
<td>1</td>
<td>0.0495</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.0835</td>
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<tr>
<td></td>
<td>3</td>
<td>0.0925</td>
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</tbody>
</table>

Cadmium
<table>
<thead>
<tr>
<th>L:S Ratio</th>
<th>Calcium Stearate (% by weight)</th>
<th>Average Concentration (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.069</td>
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<td></td>
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<tr>
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<td>0.0805</td>
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<tr>
<td></td>
<td>3</td>
<td>0.1425</td>
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</table>

*Table 2 - Batch Leaching Average Concentration of Cadmium*

*Table 3 - Batch Leaching Average Concentration of Lead*
<table>
<thead>
<tr>
<th>L:S Ratio</th>
<th>Calcium Stearate (% by weight)</th>
<th>Average Concentration (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100:1</td>
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<td>0.1495</td>
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<tr>
<td>50:1</td>
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<td>0.1775</td>
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<td>0.1765</td>
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<tr>
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<tr>
<td></td>
<td>3</td>
<td>0.3275</td>
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</table>
Figure 2 – Batch Leaching Average Concentration of Chromium

Figure 3 – Batch Leaching Average Cadmium Concentration of Fly Ash
Table 4 shows the results of the column leaching tests based on the average values from each pore volume collected. These values vary widely due to the lack of information for the succeeding pore volumes which
could not be collected due to time restraints. From the information gathered, as seen in Figures 5-16, it has been shown that the data collected will fit the predicted concentrations, but more data would be needed to create more accurate results.

*Table 4 - Column Leaching Average Heavy Metal Concentrations*

<table>
<thead>
<tr>
<th>Heavy Metal</th>
<th>Column Leaching Data</th>
<th>Calcium Stearate (% by weight)</th>
<th>Average Concentration PV1 (µg/L)</th>
<th>Average Concentration PV2 (µg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chromium</td>
<td></td>
<td>0</td>
<td>197</td>
<td>259.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>540.5</td>
<td>143.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>478.5</td>
<td>144</td>
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<tr>
<td></td>
<td></td>
<td>3</td>
<td>514.5</td>
<td>153</td>
</tr>
<tr>
<td>Cadmium</td>
<td></td>
<td>0</td>
<td>78.4</td>
<td>60.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>93.4</td>
<td>63.25</td>
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<td>3</td>
<td>166</td>
<td>137.8</td>
</tr>
<tr>
<td>Lead</td>
<td></td>
<td>0</td>
<td>189</td>
<td>138.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>222</td>
<td>141</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>309</td>
<td>310</td>
</tr>
</tbody>
</table>
Figure 4 - Yalcin Leaching Model (0% C.S. - Chromium)
Figure 5 - Yalcin Leaching Model (1% C.S. - Chromium)
Figure 6 - Yalcin Leaching Model (2% C.S. - Chromium)
Figure 7 - Yalcin Leaching Model (3% C.S. - Chromium)
Figure 8 - Yalcin Leaching Model (0% C.S. - Cadmium)
Figure 9 - Yalcin Leaching Model (1% C.S. - Cadmium)
Figure 10 - Yalcin Leaching Model (2% C.S. - Cadmium)
Figure 11 - Yalcin Leaching Model (3% C.S. - Cadmium)
Figure 12 - Yalcin Leaching Model (0% C.S. - Lead)
Figure 13 - Yalcin Leaching Model (1% C.S. - Lead)
Figure 14 - Yalcin Leaching Model (2% C.S. - Lead)
After final review of all the compiled data, the batch leaching and column leaching data generally indicate that by adding 1% calcium stearate to fly ash, the overall concentration of leached heavy metals, Chromium, Cadmium, and Lead, was reduced by the greatest amount when compared to the 0%, 2% and 3% mixtures. At higher concentrations of calcium stearate, a trend of increasing concentrations of leached metals was observed in both testing methods.

The Yalcin leaching model was used as a numerical modeling method rather than an analytical method due to time constraints and the limited pore volumes that were able to be obtained. This does not discredit the data obtained, instead it shows that the recorded results follow a predicted trend. This trend could become more
accurately depicted if subsequent pore volumes were collected and tested allowing for precise analytical modeling to predict leaching behavior for months or even years in the future.

Since calcium stearate is a molecule consisting of a central calcium ion with two stearate groups attached, it could be considered a scavenger additive. The stearate group is essentially a long-chain carbon molecule, making it similar in nature to polymer chains. Using the chain, calcium stearate will attack the transition metals, found in the form of metal chlorides by the following reaction

\[
\text{Ca(O}_2\text{C}_{18}\text{H}_{37})_2 + \text{MCl}_2 \rightarrow \text{CaCl}_2 + \text{MSt}_2 
\]

where Ca(O\text{C}_{18}\text{H}_{37})_2 is the calcium stearate, MCl_2 is the metal chlorides (Cr, Cd and Pb), CaCl_2 is calcium chloride and MSt_2 which is the new metal stearate chain (Equistar n.d.). The calcium chloride is an inactive chemical and the new metal stearate is the heavy metal that combines with the long stearate chains, effectively encapsulating the contaminant.

During chemical bonding, there is only a certain amount of bonds that could be made and electrons that could be transferred. This being the case, it was determined that the 1% calcium stearate addition provided the optimum conditions in terms of bonds available. When additional quantities of calcium stearate were added, there was an excess of electrons that were available to bond creating poorer performance of the additive.

Due to limited data, future research to be conducted will include triplicate testing for both the column and batch leaching tests. Furthermore, numerous additional pore volumes would be collected to more accurately predict the contaminant leaching behavior using the Yalcin leaching model. Other options include testing for more heavy metals or using different leaching models such as the Van Genuchten leaching model.
V. ACKNOWLEDGMENTS

For the donation of fly ash, Stephen Berlo from Headwaters Resources is to be acknowledged as well as Wentworth Institute of Technology for the use of labs and testing materials.

REFERENCES


Appendix B-
Abby Charest’s Work
Evaluating the efficiency of low-cost ultrafiltration

GAUTHAM P. DAS, Associate Professor, Department of Civil Engineering and Technology, Wentworth Institute of Technology, Boston, Massachusetts
ABIGAIL CHAREST, Assistant Professor, Department of Civil Engineering and Technology, Wentworth Institute of Technology, Boston, Massachusetts

ABSTRACT | Low-cost ultrafiltration is frequently incorporated into water purification systems to treat potable water. For this project, we applied water quality criteria to evaluate the efficiency of a low-cost ultrafiltration product. The treatment was assessed by comparing influent and effluent biochemical oxygen demand (BOD), turbidity, coliforms, and concentrations of heavy metals, including arsenic, lead, and selenium. Water for the experiments was obtained from the Muddy River in Boston. Results indicated a significant decrease in the level of contamination after ultrafiltration. Fecal coliforms reduced from >500 to 0 CFU/100 mL; Turbidity reduced from over 6.8 to 0.6 nephelometric turbidity units (NTU); and BOD levels dropped from 20.0 to 6.0 mg/L. Because of the low heavy metal concentration in the unfiltered water, further testing was discontinued. Although further testing is recommended, the tested low-cost ultrafiltration method showed potential for providing potable drinking water.

KEYWORDS | Membrane filtration, ultrafiltration, indicators, coliforms, BOD, turbidity, and heavy metals

INTRODUCTION
Contaminated drinking water is a leading cause of over 1.6 million child deaths each year (Wordlaw et al., 2009). Drinking water is often contaminated by waterborne pathogens, such as cholera, that are the leading causes of gastrointestinal diseases. Also, the increase in population is causing an exponential increase in the use of polluted water.

Deaths from waterborne disease include deaths due to cholera. The World Health Organization (WHO) estimates between 3 million to 5 million cholera cases and 100,000 to 120,000 deaths occur every year, of which only a fraction is officially reported. In 2013, three years after a major cholera outbreak began in October 2010, 129,064 cases and 2,102 deaths were reported worldwide, with 44 percent of cases reported in Africa and 45 percent in Haiti alone (where between October 2010 and December 2013, 896,794 cases were reported with 8,531 deaths) (WHO, 2013 and 2014). Cholera outbreaks can occur during emergencies, such as earthquakes and flood events, or in refugee settings when water supply, sanitation, and hygiene infrastructure is compromised.

These issues demonstrate the need for robust, selective, and economical purification techniques. Membrane filtration is one of the most promising purification technologies to emerge in the past decade. Membrane development started in the 1960s with the first reverse osmosis membranes for desalination. Since then, membrane technology has seen tremendous growth in development, creating a new and extensive market for membrane filtration applications. A wide range of membrane filters have been created, from nanofiltration (NF, good for softening and decoloring) through ultrafiltration (UF, good for virus removal) to microfiltration (MF, good for suspended solids removal) (Kreissel et al., 2012).

UF (10 to 50 nm) has been established for removing microbiological contaminants in drinking water, but because of their size, enteric viruses (20 to 160 nm) may not be as effectively removed compared to bacteria (Elhaddidy et al., 2013). The UF system tested purports to effectively remove microorganisms to log reduction values of 4 to 7. The cost to produce and easy maintenance have made UF promising for treating drinking water because the systems can be
set up virtually anywhere with no electricity or fuel required; for example, the tested unit operates from 6 to 13 ft (2 to 4 m) of water head for the inlet feed. These units have been especially popular in disaster situations and more impoverished developing countries. This low-cost UF product was used to test the effectiveness of microorganism removal in this research. UF shows promise for virus removal not only based on size exclusion but also because of other mechanisms such as adsorption and electrostatic repulsion (Kreissel et al., 2012).

Pathogens are excreted in the feces of infected humans and animals and may directly or indirectly contaminate water intended for human consumption (Figueras et al., 2010). Hundreds of different enteric microorganisms are known to infect humans, and more than 140 of them are known waterborne pathogens (Figueras et al., 2010; Reynolds et al., 2008). Pathogens capable of causing waterborne illness include viruses, bacteria, and protozoa. The impact of waterborne pathogens in humans is often acute gastrointestinal disease. Immunocompromised host populations are more likely to be infected and experience morbidity and mortality resulting from waterborne illness (Reynolds et al., 2008). While testing for all enteric pathogens in drinking water would be ideal, time and financial constraints make it impractical. Therefore, indicator organisms are used to assess the potential presence of pathogenic microorganisms (Yates, 2007).

There are many different indicator organisms, and no one indicator is appropriate for every water system. Factors including detection methodology and survival rates influence an indicator system’s validity. An indicator’s most important attribute is its strong quantitative relationship between the indicator concentration and the degree of public health risk; therefore, a strong correlation between the indicator concentration and pathogen levels is vital (Yates, 2007). Bondé (1866) first described the ideal qualities of an indicator.

Organisms, surrogates, and physical models are used to establish potential risk from fecal contamination in drinking water. Bacterial groups, such as total coliforms, are commonly used to indicate the microbiological quality of water, and their detection is included in drinking water regulations. Fecal coliforms and Escherichia coli (E. coli) are used as indicators of fecal contamination in regulations by EPA, the Council of European Communities (CEC), and WHO. Two commonly tested viral surrogates are the bacteriophages MS2 and ϕX174 because they are safe for laboratory workers, are 27 to 34 nm in size, and contrast in structure. MS2 has an outer diameter of 27 nm while ϕX174 has an outer diameter of 33 nm due to 12 extruding protein spikes (McKenna et al., 1992). Another method of testing UF’s effectiveness at virus removal is measuring the passing of nanoparticles through a membrane and correlating the size of the nanoparticle to a virus. For example, Pang et al. (2009) observed the ability of protein-coated nanoparticles to model MS2.

MF and UF can filter out contaminants based on particle size; they also can retain macromolecules or high-molecular-weight compounds as well as colloidal and suspended matter (Arnal et al., 2004). Because UF and MF membranes filter out particles based on size, they are classified as porous membranes. MF pore sizes typically range from 0.1 to 10 μm while UF pore sizes typically range from 0.01 to 0.05 μm (Koyuncu et al., 2015).

The use of low-pressure membrane systems using UF and MF is increasing for water treatment. The global market for MF and UF is projected to rise at a compound annual growth rate of 10 percent and 5.7 percent, respectively over the next five years (Koyuncu et al., 2015). Membrane technology offers many advantages, such as its modular nature, scale flexibility (small to very large), quality of the product water, small environmental footprint, and, in most cases, low energy usage (Fane et al., 2011).

Fane et al. state that MF membranes typically have a high permeability (>5000 m−2 h−1 bar−1) and can operate at a low pressure, from 1.5 to 30 psi (0.1 to 2.0 bar). MF membranes can be fabricated from both polymeric and inorganic materials with either symmetric or asymmetric structures, while UF membranes usually have an asymmetric structure to maximize membrane permeability. UF membranes are commonly selected by their molecular weight cutoff (MWCO), defined as the molecular weight of a particle in the solution to be treated in which 90 percent of the particles of that weight will be rejected (removed) by the membrane. UF membranes typically have a MWCO of 1 to 300 kilodaltons (kDa)—one dalton is defined as 1/2 the mass of an unbound neutral atom of carbon 12 or approximately the mass of one hydrogen atom. A membrane with a larger MWCO indicates lower rejection (a lower removal rate) and larger pore size (Fane et al., 2011).

In this study, a commercially available UF unit was used to filter water from the Muddy River in Boston. The UF unit uses 6 to 13 ft (2 to 4 m) of water head pressure as the driving force to push water through the membrane system while leaving particles on the opposite side of the membrane without further operation. This apparatus is purported to produce a maximum 185 gpm (700 l) of clean drinking water per hour. The tested device uses an outside-to-inside polyvinylidene fluoride (PVDF) hollow fiber UF membrane. The membrane has a nominal pore size of 0.04 μm, which characterizes it as a UF membrane.

The test used the membrane UF technology to remove contaminants and pathogens including
bacteria and viruses, and the unit significantly removed dirt and turbidity without the use of chemicals. This unit is designed to be a low-cost method to provide potable water to areas affected by natural disasters and developing countries without access to electricity. According to the manufacturer’s data, the hollow fiber membrane filters out pathogens including bacteria, protozoa, cysts, helminths, total coliforms, and E. coli to a log reduction value >4. The data sheets also state that the membrane will lower the turbidity to <0.1 NTU and remove all total suspended solids.

This research evaluated the efficacy of a low-cost membrane water filtration system for use in developing countries by comparing water quality parameters pre- and post-filtration.

**MATERIALS AND METHODS**

The samples of water used in all testing criteria were taken from the Muddy River in Boston. Two gal (7.5 l) was withdrawn from each of four locations along the river including the end of the river where it is dammed prior to the Charles River. These sampling locations were based on the recommendations from a consulting firm working with the researchers. The locations are shown in Figure 1.

Initial testing of water quality at all locations showed location 2 as the most polluted. An additional 10 gal (38 l) was taken from location 2 for the filtration assessment. The filtered sample was then tested for water quality parameters such as biochemical oxygen demand (BOD), turbidity, coliforms, and concentrations of heavy metals.

The BOD was determined from the manufacturer’s recommended method using a commercially available dissolved oxygen (DO) meter. Muddy River samples were tested as oxidized effluents with anticipated BOD values ranging from 10 to 50 mg/L and as polluted rivers with anticipated BOD values from 2 to 6 mg/L.

A commercial turbidity meter was used to test the samples’ turbidity of filtered and unfiltered Muddy River water. The meter was calibrated each time before measurements were taken. The turbidity was determined for the four sampling locations and the filtered samples. All tests were done in triplicate.

To test the metal contents of the samples, an atomic adsorption spectrophotometer (AAS) was used. As the concentration of heavy metals in the Muddy River was unknown, the AAS was calibrated for the concentration shown in Table 1 (Santos et al., 2005 and Emmanuelle et al., 2012). The flame atomic absorption method measures the change in energy state of the flame when it interacts with the atoms from the sample and correlates that visible change to the metal content. Each of the four Muddy River locations was tested for selenium, lead, and arsenic prior to filtration, and location 2 was tested after filtration.

To evaluate the efficiency of the UF unit for coliform removal, Muddy River samples were tested for total coliforms, fecal coliforms, and E. coli.
vacuum filtration method was used to determine the total and fecal coliforms (EPA Method 1604). The testing procedure for all samples consisted of filtering the sample through a filter membrane 47 mm diameter, 0.45 μm ± 0.02 μm pore size using a suction pump. The filter membrane was then placed in agar plates with pads that had a total/e-coliform indicator broth poured over them and were incubated at 114°F (46°C) for 24 hours for fecal coliforms and 95°F (35°C) for total coliforms. Testing was done on two unfiltered Muddy River water sample types: 1) undiluted and 2) diluted using 90 percent distilled water to 10 percent unfiltered water.

RESULTS AND DISCUSSION
Treatment was assessed by comparing influent and effluent BOD, turbidity, coliforms, and concentrations of heavy metals including arsenic, lead, and selenium. Results indicated a significant decrease in contamination after ultrafiltration.

BOD Testing Results
The BOD levels of the four locations without filtration ranged between 4.5 to 20 mg/L, whereas the filtered sample ranged from 0.9 to 4.05 mg/L, as shown in Tables 2 and 3.

These results indicate that before filtration the river had a high level of oxygen-reducing biological matter, which consistently consumed the oxygen within the sample while the filtered sample did not have the same quantity of oxygen-reducing biological matter, as shown in Figures 2 and 3. Oxygen consumption in the filtered samples was low, though greater removal would be desirable. (BOD is not normally used as a drinking water parameter.) The higher BOD in the stream at location 2 could be attributed to a sewer outfall, which is about 1,500 ft (460 m) away.

Coliform Testing Results
Unfiltered (undiluted and diluted) and filtered samples were tested for colony-forming units (CFUs) for total coliforms, fecal coliforms, and E. coli. The CFU counts are included in Tables 4a and 4b (see next page). Approximately 1,000 total coliform colonies were observed after a 24-hour incubation period for the unfiltered water both for undiluted and for a dilution of 90 percent distilled water and 10 percent unfiltered Muddy River water.

At an average of 14 total coliform colonies observed in the filtered water from location 2, the UF unit tested effectively removed 81.5 percent of the total coliforms. This is a log reduction value of less than 1 compared to the cited log reduction value of greater than 4 log removal from the product literature. No fecal coliforms were observed in the filtered samples.
so the tested unit appeared effective at removing detectable fecal coliforms, as shown in Table 5 and Figures 4a and 4b.

Table 4a. Unfiltered Muddy River water—undiluted samples

<table>
<thead>
<tr>
<th>Location</th>
<th>Total Coliforms (CFU)</th>
<th>Fecal Coliforms (CFU)</th>
<th>E. coli Colonies (CFU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>&gt;500</td>
<td>&gt;500</td>
<td>&gt;500</td>
</tr>
<tr>
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<td>&gt;500</td>
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<td>4</td>
<td>&gt;500</td>
<td>&gt;500</td>
<td>&gt;500</td>
</tr>
</tbody>
</table>

Table 4b. Unfiltered Muddy River water—diluted samples

<table>
<thead>
<tr>
<th>Location</th>
<th>Total Coliforms (CFU)</th>
<th>Fecal Coliforms (CFU)</th>
<th>E. coli Colonies (CFU)</th>
</tr>
</thead>
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<tr>
<td>1</td>
<td>139</td>
<td>64</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>76</td>
<td>93</td>
<td>7</td>
</tr>
<tr>
<td>3</td>
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<td>81</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>104</td>
<td>58</td>
<td>1</td>
</tr>
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</table>

Table 5. Filtered Muddy River water from Location 2—undiluted samples

<table>
<thead>
<tr>
<th>Day</th>
<th>Total Coliforms (CFU)</th>
<th>Fecal Coliforms (CFU)</th>
<th>E. coli Colonies (CFU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>17</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 6. Unfiltered Muddy River water

<table>
<thead>
<tr>
<th>Location</th>
<th>Test 1 (NTU)</th>
<th>Test 2 (NTU)</th>
<th>Average (NTU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.81</td>
<td>5.79</td>
<td>5.30</td>
</tr>
<tr>
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<td>6.15</td>
<td>7.46</td>
<td>6.81</td>
</tr>
<tr>
<td>3</td>
<td>6.08</td>
<td>8.41</td>
<td>7.25</td>
</tr>
<tr>
<td>4</td>
<td>5.74</td>
<td>4.29</td>
<td>5.02</td>
</tr>
</tbody>
</table>

Table 7. Filtered Muddy River water from Location 2

<table>
<thead>
<tr>
<th>Sample</th>
<th>Test 1 (NTU)</th>
<th>Test 2 (NTU)</th>
<th>Test 3 (NTU)</th>
<th>Test 4 (NTU)</th>
<th>Average (NTU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.41</td>
<td>0.2</td>
<td>0.27</td>
<td>0.32</td>
<td>0.60</td>
</tr>
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</table>

Metal Testing

EPA permissible limits for each metal tested are 0.015 mg/L for lead, 0.01 mg/L for arsenic, and 0.05 mg/L for selenium (EPA, 2009). The filtered water was below all three detection limits for potable drinking water, but each of the four unfiltered samples was below the limits, as well. Since the unfiltered heavy metal concentration was below permissible limits, this testing does not conclusively assess filter removal of metal content; however, the filtered results were lower than the unfiltered results, as shown in Table 8.

Table 8. AAS Results

<table>
<thead>
<tr>
<th>Location</th>
<th>Se</th>
<th>As</th>
<th>Pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ND</td>
<td>0.003</td>
<td>0.0005</td>
</tr>
<tr>
<td>2</td>
<td>0.0038</td>
<td>0.0065</td>
<td>ND</td>
</tr>
<tr>
<td>3</td>
<td>0.0002</td>
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</tr>
<tr>
<td>4</td>
<td>0.0052</td>
<td>0.005</td>
<td>0.0001</td>
</tr>
<tr>
<td>Filtered water</td>
<td>ND</td>
<td>0.0008</td>
<td>ND</td>
</tr>
</tbody>
</table>

Turbidity Testing Results

The turbidity for the Muddy River locations prior to filtration averaged between 5.92 and 7.25 NTU, as shown in Table 6. These values indicate a high level of suspended solids within the samples. The filtered water, shown in Table 7, measured an average of 0.6 NTU indicating that most suspended solids were removed during filtration.
CONCLUSION
Based on this research, the tested UF unit treated the Muddy River to near-potable water standards. The BOD levels, turbidity, and coliform counts in the filtered samples from this test came close to United Nations standards for drinking water and were also proximate to National Primary Drinking Water Regulations (NPDWRS) as prescribed by 40 CFR 141.208 and as promulgated by EPA (EPA, 2009); however, further confirmatory research is indicated. The next steps will be to conduct challenge tests using spiked (heavy metals) samples of unfiltered water. Also, viruses were not tested in this research, and we recommend the efficacy of virus removal be further evaluated in future testing.

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- Dr. Abigail Charest received a doctorate from the Worcester Polytechnic Institute. Prior to starting her teaching career, Dr. Charest worked for environmental consulting firms in New England and is a professional engineer in Massachusetts. Her expertise is in water resources, hydraulic engineering, and environmental remediation. She is active in the Water Environment Federation and NEWEA.

REFERENCES
Literature review: The impact of limestone and plastic additives on concrete

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Abstract

Even though concrete is one of the most universal construction materials, projections indicate that 5-9% of global greenhouse gas emissions result from the cement industry. This research summarizes available information regarding concrete mix designs that incorporate additives, repurpose waste plastic, and reduce carbon emissions. Some of the explored additives include limestone, a carbonate sedimentary rock, and plastic waste, a globally abundant product. The resulting concrete mixture will be “greener” since the lower cement required will lower carbon dioxide emissions. Both the inclusion of limestone and plastic attempt to create a more sustainable mixture, with limestone promoting hydration and plastic promoting recycling. The summarized literature compares the compressive and tensile strength of mixes with varying proportions of limestone, plastic fibers and cement. The inclusion of plastic fibers acts as a secondary layer of reinforcement and helps to reduce plastic shrinkage and settlement. Additional properties of limestone are examined such as slump, shrinkage, hydration, and packing density. The carbonization process is also examined with the goal of understanding how different methods evaluate carbon dioxide emissions. Literature review suggests limestone in concrete mixtures increases healing and physical strength, while decreasing alkali-silica reactions and drying shrinkage.

Keywords: Concrete; Sustainability; Plastic; Plastic Fibers; Limestone

1. Concrete in Construction

With the hopes of making the future a better and more sustainable place, the United Nations created 17 Sustainable Development Goals (SDGs) that are a call to action for all countries to achieve by 2030. These goals tackle relevant initiatives such as improving industry and infrastructure, encouraging responsible material consumption and production, decreasing carbon dioxide emissions and addressing climate change. Despite carbon dioxide emission intensity from cement production increasing by 0.3% annually from 2014 to 2017, a 0.7% annual decrease is necessary to achieve the aforementioned SDGs by 2030 [1]. In 2018, cement was the third largest contributor to annual global fossil emissions at 4% or 1.6 gigatonnes (Gt) of [2]. This critical time period calls even more attention to the existing statistics for the construction industry. It is anticipated that global construction will continue to increase, with a suggested 230 billion square meters of new floor area added by 2060 [3]. Substituting alternatives to Portland cement (PC) serves as a simple low-carbon solution, while options for meeting sustainability goals can also include regenerative design.

2. Material Replacements: Plastic & Limestone
To combat the emissions side effect of the concrete carbonation process, material replacements are used. In some concrete mixtures, supplementary cementitious materials (SCMs) are used in place of Portland cement. SCMs are either industrial byproducts or naturally occurring materials that mimic cementitious behavior when they are hydrated [4, 5]. Examples of SCMs are fly ash, silica fume, ground-granulated blast furnace slag (GGBFS), and limestone (LS) [5]. By using fly ash, the cement paste density increases which allows the water-to-cement (w/c) ratio to decrease. Silica fume is used as a PC replacement, yet it requires a higher w/c ratio and as a result, additional water reducing agents [5]. Slag cement works with PC to increase strength and reduce permeability [6]. The incorporation of coal ash as a replacement to PC can reduce at least 5.89 million tonnes of carbon dioxide emissions by 2035 [4].

2.1. Plastic

The 2018 Chinese import ban is suggested to displace 111 million metric tons of plastic waste by 2030, with 89% of exports containing polymer groups from single use food packaging sources [7]. In the United States, it is estimated that 35.4 million tons of plastics were generated in 2017, representing approximately 13.2% of total municipal solid waste (MSW) generation [8]. Only 3 million tons of plastic, or 8.4% of MSW, was recycled and 5.6 million tons of plastic, or 16.4% of MSW, was combusted for energy recovery, with landfills receiving 26.8 million tons of plastic, or 19.2% of MSW [8].

PlasticsEurope Market Research Group estimates that plastic production reached a global height of 360 million tonnes in 2018, with packaging compromising the largest production sector of 39.9%. Polypropylene, a resin that is used in the production of food packaging and microwave containers, accounts for 19.3% of plastics demand, while low density polyethylene (LDPE), a material that makes up reusable bags and packaging film, results in a 17.5% of plastics demand. Even though recycled plastic waste has doubled since 2006, 25% is still being sent to landfill sites. Switzerland, Austria, and the Netherlands send 100% of their plastic post-consumer waste to either recycling or energy recovery locations [9].

In recognition of the growing quantity of waste, the inclusion of plastic into different construction materials has been a growing interest. Because the incorporation of plastic fibers within concrete will improve mechanical performance, reinforcing waste plastic has been a rising topic of research since 2009 [10].

2.2. Limestone

Limestone is a naturally occurring rock that is found in abundance throughout the world. Thousands of years ago, the Romans used LS powder in their concrete structures which are still standing today. LS is one of the most available materials, accounting for approximately 5% of the Earth’s crust [11]. When PC is mixed with this natural material, the carbon footprint of the PC is reduced [12]. Although Portland-limestone cement (PLC) has been heavily researched, the following section aims to examine its properties. By varying amounts of LS, an optimal ratio that improves sustainability without compromising strength can be determined in PLC.

When used in appropriate quantities, LS improves workability, reduces carbon footprint and does not compromise strength [13, 14, 15]. It is an accepted admixture used in concrete mixtures throughout the
world, where it has even become part of European, Canadian, and British Standards [16]. European standards allow for a range between 6-20% LS addition, Canadian standards allow for up to 5% addition, and British standards allow no more than 20% addition [16]. These standards have increased the grounds for more sustainable concrete mixes and aid in the reduction of carbon dioxide emissions.

Due to its natural widespread availability, LS does not need to be transported long distances to be used. This reduction in greenhouse gas (GHG) emissions from transportation devices is another sustainable advantage that LS has over other SCMs. When used in concrete mixtures, LS reduces the environmental impact from the PC hydration process, the resulting emissions of , and has versatility when used for historical restoration purposes. The increased workability and lack of compromised strength are also benefits that increase its preferability across the industry [5, 17, 18].

3. Impact Due to Supplementary Cementitious Materials

3.1. Plastic

Similar to how the addition of SMCs in PC-based concrete has an effect on its strength, plastic fibers also have an impact on compressive and split tensile strength. Plastic has been shown to be a viable replacement material for sand in concrete mixtures. It is estimated that a 10% replacement of sand with plastic fibers has the potential to save 820 million tons of sand annually, which accounts for approximately 5% of the global use [19]. A large amount of research being has utilized standard compressive and split tensile testing.

3.1.1. Compressive Strength

A reduction in sand has an impact on the compressive strength of concrete. Research from the University of Salento in Italy concluded that the addition of 5% plastic by weight replacement of sand to a concrete mixture slightly reduced compressive strength, which is attributed to the decreased adhesive strength between the PC and the plastic compared to the sand [10, 20, 21, 22]. Similar research replaced sand with 10%, 15%, and 20% plastic fibers. This research found that compared to the control, the varying plastic addition mixes performed worse under compression testing, with the compressive strength decreasing approximately 5 MPa after 10 days of curing [22]. The decrease in compressive strength increases based on the increase of plastic percentage and curing age [22]. While strength decreases, it has been shown that the addition of plastic fibers reduces the severity of a concrete compressive failure and slightly increases the ductility of the concrete [21, 23]. When plastic was subjected to gamma irradiation, results found that it could partly retrieve some of the strength lost with substituting PC, leading to samples with improved compressive strength [24].

3.1.2. Split Tensile & Flexural

The split tensile test is used to measure tensile strength, which is relevant since concrete is weak in tension. Failure results show the weakest point and is indicative of the overall quality of a mix. The majority of research that has been considered concludes that plastic, which replaces sand in any form or quantity, results in little to no change in tensile strength when amounts less than 5% by volume of sand are replaced, yet the tensile strength drops when higher percent volumes are added [21, 22, 25, 26, 27].
The split tensile strength decreased at higher volumes. The severity of the concrete’s failure decreases with the addition of plastic fibers, compared to a non-fiber reinforced concrete cylinder, since plastic fibers can absorb post-failure energy [20, 23]. Similar to compressive strength, the split tensile failures have been linked to the decreased adhesion between the PC and the plastic fibers, compared to the PC and the sand [10, 20, 21, 22]. While sand replacement has been frequently analysed, plastic replacement does not stop with sand. Research has been conducted where the PC binder is being replaced with 0%-0.6% plastic fibers. This experiment concluded that the flexural strength of the concrete increased by 16.5% with a 0.6% optimal PC replacement compared to the control sample [28].

Due to the compilation of physical strength research that has been reviewed, it can be concluded that the addition of plastic fibers as a sand replacement may be better suited for concrete that is not subject to heavy loads [19, 25, 29]. However, the inclusion of waste plastics in concrete could have potential benefits in precast concrete applications where early strength is necessary [27, 29, 30].

3.2. Limestone

SCMs are commonly used to improve the workability and environmental impacts of the carbonization process of PC, as well as impacting strength. The effectiveness of LS as an SCM has been heavily researched as a PC replacement material due to its availability and effectiveness. LS has an effect on slump (ASTM C143), shrinkage, hydration, packing density, compressive strength and split-tensile strength of concrete mixtures. Although PLC has been heavily researched, the following section aims to compile information regarding its properties. An optimal ratio of PC to LS can be determined to improve sustainability without compromising strength or workability.

3.2.1. Compressive Strength

Research from the Structural Engineering Department of the Ain Shams University in Cairo, Egypt concluded that PC with LS substitution decreased the compressive strength of concrete [14]. However, their research also concluded that this decrease is negligible until the replacement reached 10% LS [14]. This finding is supported by research done by El-Moussaoui et al. [31] which states that, with a consistent w/c ratio, the compressive strength of the concrete decreased with the increase of LS content [13, 31, 32]. The reason for the reduced strength beyond the optimal 5-10% replacement is due to the fine LS particles filling the voids created from the PC and aggregate, which compacts the mixture. However, once the voids are filled, the LS begins to take the place of the stronger PC as an aggregate. When this happens, the stiffness and integrity of the concrete begins to be compromised [13, 15, 33].

3.2.2. Split Tensile

Split tensile strength is an important parameter when discussing the strength of concrete. Concrete failures, even under compression, are due to tensile failure. The replacement of various amounts of PC will have an impact on the tensile strength of the mix as seen in the compressive strength [14, 32, 34]. Research conducted by Alexandria University in Egypt [14] found that the addition of LS powder influences both compressive and tensile strength at 28 days. While compressive strength was reduced with the inclusion of LS, split tensile strength was reduced of a greater magnitude, with a steep decline in testing results of approximately 0.30 MPa observed with mixtures containing 5% - 10% LS content.
compared to the control [14]. See Figure 1 for further detail. This notion is supported by research which describes the split tensile strength of PLC. Once the 5%-10% LS replacement of PC is achieved, further addition of LS powder decreases flexural strength [34].

Figure 1. Limestone cement concrete splitting tensile strength at 28 days [14]

3.2.3. Slump

The workability of concrete is an essential part of its effectiveness as a construction material. Slump testing following the ASTM C143 procedure is used as a preemptive means of checking that the correct w/c ratio has been implemented in the concrete mix. The w/c ratio and the amount of aggregate used can have a profound impact on the workability of the concrete mixture. PC alone has low workability compared to PC that is supplemented with various amounts of SCMs [35].

LS supplementation has been shown to improve workability in many cases. When working with an optimized concrete that contains 5% LS, the workability can increase compared to the same cement mixture without the LS addition [15, 35]. LS can accomplish this when it is finely ground by filling the gaps between the clinker particles, reducing the water demand and densifying the structure of the hardened cement paste [13, 35, 36]. In a study from the Laboratoire de Recherche de Génie Civil (LRGC) [15], slump tests were compared between a control concrete sample and LS concrete sample. When the w/c ratio is held constant and the aggregate content is increased, the workability is slightly decreased. However, when a portion of the cement is replaced with LS powder and both the w/c ratio remains constant and the aggregate content is increased, the resulting workability increases [15].

3.2.4. Shrinkage

Shrinkage in concrete is a result of the loss of capillary water during the curing process. Shrinkage can lead to cracking, external deflection, and an increase in tensile stress and strain, before the concrete is subjected to any external load [37]. This greatly weakens the concrete and shortens the lifespan of the structure. Cement content, water content, aggregate type, aggregate content, chemical composition, temperature, and humidity all play a role in shrinkage.

Dimensional variations, such as shrinkage, were evaluated by the group from LRGC [15]. In their research, they studied the known relationship between increased PC amounts and increased shrinkage, to
that of increased PLC and shrinkage. Shrinkage measures were carried out on 7x7x28 cm prismatic samples. Shrinkage in micrometers was measured using a digital dial. Results showed that shrinkage decreased for samples with low contents of filler (limestone). While 15% of filler content will return close to the control samples shrinkage measurements, any filler content above 5% showed increased shrinkage [15]. Multiple research findings indicate that any percentage replacement higher than 15% will increase shrinkage past the control value [15, 18, 37]. Based on the size of the particle filler, it is possible that a higher quantity of filler will be required, resulting in a more optimal mixture [38].

3.2.5. Hydration

The hardening of a concrete mixture is known as the hydration process. Driven by water and the chemical reaction with the PC binder, hydration is the process of these two bonding together with the inert aggregate to form a hardened concrete. This is an exothermic reaction and relates to shrinkage if the reaction becomes too hot, for example in high strength concrete on a hot day. Hydration can occur at varying rates based on the chemical reaction between the binder, water, and most importantly, the w/c ratio.

It is well known that LS as calcium carbonate in various amounts has an effect on the hydration process of PC mixtures. It has been shown that the addition of LS in any amount will variably decrease the hydration time for a concrete mixture. Compared to a control sample, a concrete mixture with LS in a 1:1 ratio against PC had a higher heat development over the span of approximately 900 minutes [18]. This extra heat causes the hydration process to speed up and shortens the amount of time available to work with the material. Increasing the rate of hydration also leads to the potential for increased cracking. The accelerated hydration process also reduces the workability of the product. It is shown that calcium carbonate has an accelerating effect on calcium trisilicate and cement hydration, and leads to the precipitation of some calcium carbon silicate hydrate [37, 39, 40].

3.2.6. Packing Density

LS is softer than PC, which allows the fine LS particles to grind preferentially and concrete samples to be made with an improved particle size distribution. The LS itself requires less processing energy to produce. These filler particles fill the gaps created by the PC and aggregate which compacts the mix [15, 38].

4. Sustainability & Carbon Emissions

It is important to consider a variety of different data with the vast quantity and quality of resources available for measuring carbon emissions. Different initiatives have been launched, such as the “Getting the Numbers Right ” program by the World Business Council for Sustainable Development (WBCSD), a global organization which combines CEOs from all over to promote sustainability. WBCSD collects relevant cement data from different parts of the world. However, some organizations that use this or the UN Framework Convention of Climate Change (UNFCC), an agreement that attempts to stabilize GHGs, have seen outdated numbers. The Global Carbon Project aims to annually publish and maintain carbon models for estimating accurate emission databases [41].
The Global Carbon Project, an organization established in an attempt to quantify global greenhouse gas emissions with accurate data, published startling results in 2019. The report indicates that global fossil carbon dioxide emissions have steadily increased by almost 27 Gt throughout the last five decades, with little promise of slowing down soon [2]. Projections in 2018 indicate that the United States has the highest annual fossil carbon dioxide emissions per capita of 16.6 tonnes/person. Overall, China annually contributes the highest emission totals with 10.06 Gt or 27.5% while the United States is the second highest contributor at 5.42 Gt or 14.8% [2].

Talaei [42], who performed a case study in Canada, uses a bottom up energy model and scenario analysis to assess greenhouse gas emissions from the cement industry. Through the Long-range Energy Alternative Planning model, 20 different scenarios were created with the goal of reducing greenhouse gas emissions with analyzed factors such as cost of energy saved, GHG reduction potential and carbon abatement. Results indicate that 70% of emissions can be reduced without negative cost to the industry through strategies such as implementing energy management systems, fuel switching, and indirect firing for clinkers, resulting in mitigated carbon dioxide emissions of 27 million tonnes by 2030 and 59 million tonnes by 2050 [42].

In other studies, the Green Concrete Life-Cycle Assessment Tool is used to understand unit processes involved with the creation of concrete [43]. This tool uses factors of energy consumption related to material production such as lead and carbon dioxide emissions, electricity and fuel, and material usage. The user can input different characteristics specific to the concrete mix design including anticipated volume quantities, materials used, and method of aggregate transportation. Results show that global warming potential and carbon dioxide emissions are reduced when creating cement mixes that reduce Portland cement content, and that using dichotomous earth in areas where the product is abundant (Western US, China, Turkey) serves as a mix design advantage [43].

Research published by Flower [44], used an Australian Greenhouse Office Factors and Methods workbook to calculate carbon dioxide emissions from multiple energy sources throughout Melbourne, Australia. Data collected from a life cycle analysis reviews two coarse aggregate quarries, one fine aggregate quarry, six concrete batching plants, and other sources. Results indicate that Portland cement is the main source of carbon dioxide emissions within a concrete mixture, responsible for 74% to 81% of total emissions [44].

5. Carbonation

Carbonation occurs within concrete because of the reaction of calcium hydroxide with the carbon dioxide of the cement paste. This reaction, which creates calcium carbonate, is often concerning because of its pH, which is known for corroding steel reinforcement bar, and its harmful greenhouse gas emissions [45]. As a result, improving the resistance of concrete carbonation is a widely researched topic.

Some methods used to evaluate carbonation profiles include Thermogravimetric Analysis (TGA), chemical analysis, gammadensimetry, pH change, Energy Dispersive X-Ray Fluorescence Spectrometer (EDX), Fourier-Transform Infrared Spectroscopy (FTIR), and Laser Diffraction Particle Size Analyzer [45, 46]. TGA finds that using the temperature range of 530-950 °C is the best way to measure
decomposition due to carbonation, in conjunction with a chemical analysis correcting factor that accounts for tracer cement materials [45, 46].

When experimenting with concrete mix designs, a variety of different additives and SCMs are explored. Research in Brazil [47], that created concrete samples of varying strengths to be crushed and used as recycled concrete aggregates (RCA) in new samples of 32.5 MPa concrete, used compression and carbonation testing to understand the durability of concrete with recycled aggregates. Results indicate that after accelerated carbonation, which took place in conditions of 1% and 70% relative humidity (RH) across 147 days, it was found that concrete with RCA from 18 MPa and higher porosity resulted in a carbonation depth equal to 50% of reference mixes, while concrete with RCA from 37 and 50 MPa and equal or higher porosities resulted in similar carbonation depth to reference mixes [47].

Other anticipated influences on carbonation results include aggregate replacement content and type, material size and microcracking. Using aggregate replacement from RCA is one option that displayed carbonation depth results similar to the reference concrete samples [47].

Limestone powder has a fineness which creates nuclei locations for calcium carbonate precipitation, and it is of comparative size with cement particles. Thus, PLC mixtures result in high carbon reactivity and early strength gain [46]. The use of finer materials promotes higher carbonation reactivity and early strength, while the occurrence of microcracking along the carbonation front causes cement degradation, decreased mechanical strength and increased permeability [46, 47, 48].

When considering the effect of the addition of SCMs on carbonation, such as silica fume and low/high calcium fly ash, results indicate that carbonation depth decreases when SCMs replace aggregates and carbonation depth increases when SCMs replace cement [49]. Other research considers the effects on carbonation due to the inclusion of limestone in concrete. One study found that despite the inclusion of 40% calcium carbonate, 15% limestone additives, and 25% carbonation induced calcium carbonate, results indicate that PLC can be used to effectively replace Portland cement, especially for precast concrete products where early strength is necessary [46]. Portland limestone concrete mixes that are designed on the basis of equal strength, rather than equal w/c ratio and exposed to continuous moist curing, show comparable carbonation resistance with control mixes. However, the inclusion of SCMs such as fly ash, limestone, and slag tend to create concrete mixes that carbonate at higher rates than control groups [16]. When limestone was used as an embedding agent and subjected to carbonation from brine, no evidence of degradation or permeability was present in the concrete [50].

However, research conducted in Italy [51], that aims to explore the w/c ratio, cement content, curing time, and other performances of the effect of ground limestone (15/30% replacement to PC) in concrete, show opposing results indicating that mechanical properties (compressive strength) and resistance to penetration are reduced with the increase of limestone [51].

With the growing interest of plastics, this material has also been evaluated for its effect on carbonation. Concrete, that was made with 10% replacement of sand by volume with graded polyethylene terephthalate (PET) plastic, was tested for carbonation at 4% and 55-65% RH [52]. Results indicate that while plastic concrete mix had a higher initial carbonation rate at 14 and 28 days, the results from 180-
day testing indicate that an acceptable carbonation depth was only 0.5 mm deeper, or 5% higher than the reference concrete [52].

6. Conclusion

Based on the compiled research, it can be concluded that introducing certain amounts of supplementary cementitious materials into Portland-limestone cement mixes can have countless benefits. Limestone and recycled plastic fibers have been shown to improve the sustainability of concrete, without comprising strength or workability, by reducing the carbon dioxide emissions and providing a use for recycled plastic. It is anticipated that a small percentage (0.5% by weight) of plastic is desired, as large percentages can create oxygen that hinder binding abilities. The inclusion of waste plastics in concrete could have potential benefits in precast concrete applications where early strength is necessary [27, 29, 30]. Meanwhile, a percentage (5-10% by weight) of limestone is desired, as it fills voids that hinder compacting abilities. Results indicate that Portland cement is the main source of carbon dioxide within a concrete mixture, responsible for 74% to 81% of total emissions [44]. When combined in the aforementioned proportions, Portland-limestone cement mixtures will have comparable qualities to a control sample. These proposed proportions fill the voids between research that solely tested limestone or solely tested plastic fibers and verifies results from combined mixtures.

7. Acknowledgements

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9. References


Abstract

The presence of harmful bacteria and viruses within surface water indicate a violation of public health and should be addressed. Sources of fecal contamination include wastewater treatment plants, animal and human feces, stormwater runoff, and septic systems [1]. Ultrafiltration has become a viable treatment process in areas that lack clean water because it does not require a power source or usage of chemicals [2]. This review investigates the efficacy of an ultrafiltration unit for the removal of viral contamination in surface water. Coliforms and coliphages were analyzed as possible indicators to detect this contamination. Although coliforms are commonly used and useful bacteria indicators, this review finds that coliphages tend to be a more accurate indicator for viral pathogens. Current literature suggests that the ultrafiltration for the removal of viral contamination in surface water is feasible. The use of coliphages as viral indicators for the measurement of removal was found to be more appropriate than the use of coliforms.
Literature Review: Ultrafiltration of Surface Water to Model Virus Removal with Bacterial and Viral Indicators

*Keywords: ultrafiltration, fecal contamination, coliphage, coliform, surface water*

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Abstract

The presence of harmful bacteria and viruses within surface water indicate a violation of public health and should be addressed. Sources of fecal contamination include wastewater treatment plants, animal and human feces, stormwater runoff, and septic systems [1]. Ultrafiltration has become a viable treatment process in areas that lack clean water because it does not require a power source or usage of chemicals [2]. This review investigates the efficacy of an ultrafiltration unit for the removal of viral contamination in surface water. Coliforms and coliphages were analyzed as possible indicators to detect this contamination. Although coliforms are commonly used and useful bacteria indicators, this review finds that coliphages tend to be a more accurate indicator for viral pathogens. Current literature suggests that the ultrafiltration for the removal of viral contamination in surface water is feasible. The use of coliphages as viral indicators for the measurement of removal was found to be more appropriate than the use of coliforms.

Introduction

In untreated environmental systems, waterborne diseases can be prevalent and lead to potential illnesses. Indicator organisms are utilized to determine the presence of viruses that pose a threat to human health. In the past, bacterial indicators such as *E. coli* and total coliform bacteria were used in determining the quality of the water [1]. However, current literature suggests that coliphages are a more reliable indicator of viral pathogens due to their ability to indicate the removal of viruses in a system [3]. With nearly one billion people worldwide without access to clean water sources, ultrafiltration could become a necessary tool to provide safe drinking water [4]. The use of coliphages as viral indicators may allow for the detection of viral pathogens and their removal through ultrafiltration technology.

Coliforms

There are several nonpathogenic bacteria that are common in the human intestine and other warm-blooded animals. These bacteria include total coliform bacteria, fecal coliform bacteria, *E. coli*, and enterococci. Since the concentrations of pathogens from fecal contamination are typically small in water and difficult to detect, indicator organisms, such as coliforms, are used to observe the presence of pathogens. These indicators grow in the presence of fecal contamination and are easier to detect than a small pathogenic presence [1,5,6]. Testing for total coliforms and fecal coliforms provides water quality information for the bacterial condition of the water source. If there is a large concentration of coliforms, this suggests poor water quality. Coliforms are considered reliable when monitoring the presence of certain bacteria, although they are not commonly recognized to be apposite viral indicators [1].

In a study done in Buenos Aires, Argentina by Barrios et al. (2018), tested wastewater from wastewater treatment plants of bovine and equine slaughterhouses, poultry, swine farms, and domestic sewage. It was found that F-specific RNA bacteriophages (F-RNAPh) were highly present in the domestic and food-industrial wastes. F-RNAPh had a significant correlation with human pathogens, including norovirus GII, human polyomavirus, and human adenovirus. Coliforms were not found as frequently as the coliphages and did not have a significant correlation with viral pathogens [1]. This study suggests that the bacterial indicator is not an adequate indicator to detect viral pathogens as the coliphages.

Another study by Plummer et al. (2014) compared coliforms and coliphages as indicator organisms in wastewater and drinking water systems directly [7]. Wastewater and drinking water samples were collected from 4 different regions of the US during a 24-month period. Coliforms and male-specific coliphages were observed in these samples and their frequencies of detection were measured. Frequency of detection is an important factor when evaluating the efficacy of a potential indicator. Coliforms and *E. coli* were detected frequently in many of the wastewater samples which contained high concentrations of fecal contamination, however, they did not correlate with enteroviruses as much as coliphages [7]. This study suggests that coliforms such as *E. Coli* are useful as bacterial indicators of fecal contamination, but that the coliphages were more useful to detect viral pathogens.

Although bacterial indicators are often used for general monitoring of water quality, they are not considered to be satisfactory indicators of viral contamination [3,6,8]. This is due to their structure, size, and survival characteristics [1]. Virus cells are typically much smaller than bacteria cells which makes it difficult for bacteria to indicate pathogens.
that are magnitudes out of range [9]. Viruses can also endure longer than bacteria in the natural environment [6]. In the experiments to be conducted, this edifies the hypothesis that coliphages will be more effective as a viral indicator.

**Coliphages**

Somatic coliphages and male specific coliphages (also known as F-specific bacteriophages) are types of bacteriophages that are commonly found in human feces due to their ability to infect *E. coli* [10]. Due to the similar characteristics of bacteriophages and viral pathogens, bacteriophages have been used to model the fate of viral pathogens when introduced into a treatment system. If coliphages are removed from a water source, then it can be assumed that the same removal process can eliminate viral pathogens [3,9].

Dias *et al.* (2017) studied the relationship of coliphages and viral pathogens. The phages studied were somatic coliphages, F-RNA coliphages, and human-specific phages. The pathogens were human adenovirus and norovirus. Samples were collected every 2 weeks for a year, at each stage of 4 full-scale water treatment plants in Southern England. Coliphages were counted using the double-layer agar method and viral pathogens were counted using molecular methods. The findings of this study are that phages, especially somatic coliphages, are better indicators of the fate of viral pathogens than fecal coliforms. It was also concluded that while both correlates with each other, phages do not appear to show the presence of viral pathogens. Plummer *et al.* (2014) suggests that coliphages could be studied along with bacterial indicators to help detect fecal contamination. By quantifying both viral and bacterial indicators within an environmental system, it could potentially provide additional information about the contamination or detect fecal contamination that bacterial indicators initially missed.

Temperature and climate are factors that can potentially alter results of coliphage quantification. Both coliphages and viral pathogens have been found to survive longer in colder temperatures and decay more rapidly in warmer temperatures [11](US Environmental Protection Agency, 2017). Arredondo-Hernandez *et al.* (2017) looked at 3 types of F-RNA coliphages to see their correlation with human adenoviruses in Mexican water systems. Quantification was done by qPCR and RT-qPCR. Contrary to Dias, *et al.* (2017), the study found that F-RNA coliphages accurately determined points of water contamination. All the F-RNA coliphages correlated the presence of human adenoviruses. The differences in these results may be attributed to the various temperate conditions in the sampling locations of the two studies.

**Ultrafiltration**

Ultrafiltration is a type of membrane filtration process that uses hydrostatic pressure to push water through a semipermeable membrane that has a pore size of approximately 0.01 microns. Ultrafiltration can filter out suspended solids, bacteria, viruses, endotoxins, and various types of pathogens to produce water with high purity levels and low silt density levels [12]. When compared to conventional treatment, membrane filters such as ultrafiltration (UF) can produce a similar result in a more compact unit [13]. The Sky Hydrant GEM is an ultrafiltration unit that produces sustainable portable water to communities in developing countries [2]. Currently there is no available literature regarding research implementing a Sky Hydrant GEM in applying ultrafiltration technology to create potable water.

When comparing various membrane filtration units, their effectiveness is largely dependent on the filter pore sizes. Microfiltration units have a pore size of 0.2 µm whereas ultrafiltration units have a pore size of 0.05 µm. When analyzed next to ultrafiltration, microfiltration showed a low removal capacity for *E. coli* and fecal coliforms. Sixty-two percent of microfiltration effluent samples contained fecal coliforms with a maximum value of 610 CFU/100 ml, compared with 25% of ultrafiltration effluent samples containing fecal coliforms, with a maximum value of 5 CFU/100 ml [12]. This proves that pore sizes influence the effectiveness of membrane technologies in the removal of fecal bacteria.

Ultrafiltration units prove to be advantageous in that they are automated, compact, consistent, and non-pollutant. [13]. An alternative membrane filter that would produce higher quality water would be reverse osmosis (RO). However, in exchange for higher quality, there is an increase in cost which makes RO a less affordable option. RO membranes provide a finer filter membrane in removing contaminants and bacteria which can prove to be more effective in producing potable water [14].
Multiple researchers have agreed that membrane filter technology has the potential of becoming a viable water treatment system for drinking water [13,14]. While monitoring the bacteriological quality of the water, results from secondary clarification and microfiltration systems show that *E. coli* was present. However, using membrane filtration presented a total absence of *E. coli* [11]. Ultrafiltration of surface water with PAN (polyacrylonitrile) membranes resulted in the successful production of drinking water. This resulted in the reduction of turbidity to 0.1 NTU, completely removing iron, manganese, aluminum, and coliform bacteria [13]. As a result, membrane technology, such as ultrafiltration, produces a high-quality clarified effluent and does not require the addition of chemical reagents, which aid in avoiding the production of harmful byproducts [12].

**Conclusion**

Previous literature in the field shows that while monitoring bacterial indicators within a water supply provides quality information about the source, viral indicators are better suited to model the fate of viral pathogens. Bacterial indicators, such as coliforms, are not considered to be suitable for adequately indicating viral presence [6,7,8]. With the relationship between coliphages and viral pathogens recognized, ultrafiltration can be used as a reliable water treatment system in the removal of any enteric viruses. This allows for the production of high-quality potable water through affordable and accessible means.
Bibliography


