CLEAN RESOURCES FINAL REPORT PACKAGE

Project proponents are required to submit a Final Report Package, consisting of a Final Public Report and a Final Financial Report. These reports are to be provided under separate cover at the conclusion of projects for review and approval by Alberta Innovates (AI) Clean Resources Division. Proponents will use the two templates that follow to report key results and outcomes achieved during the project and financial details. The information requested in the templates should be considered the minimum necessary to meet AI reporting requirements; proponents are highly encouraged to include other information that may provide additional value, including more detailed appendices. Proponents must work with the AI Project Advisor during preparation of the Final Report Package to en sure submissions are of the highest possible quality and thus reduce the time and effort necessary to address issues that may emerge through the review and approval process.

Final Public Report

The Final Public Report shall outline what the project achieved and provide conclusions and recommendations for further research inquiry or technology development, together with an overview of the performance of the project in terms of process, output, outcomes and impact measures. The report must delineate all project knowledge and/or technology developed and must be in sufficient detail to permit readers to use or adapt the results for research and analysis purposes and to understand how conclusions were arrived at. It is incumbent upon the proponent to ensure that the Final Public Report **is free of any confidential information or intellectual property requiring protection**. The Final Public Report will be released by Alberta Innovates after the confidentiality period has expired as described in the Investment Agreement.

Final Financial Report

The Final Financial Report shall provide complete and accurate accounting of all project expenditures and contributions over the life of the project pertaining to Alberta Innovates, the proponent, and any project partners. The Final Financial Report will not be publicly released.

CLEAN RESOURCES FINAL PUBLIC REPORT TEMPLATE

1. PROJECT INFORMATION:

Project Title:	**Multiphase characterization of Bitumen-Based Carbon Fibers (BBCF) and demonstrating its use in producing "crack-free" cement concrete**
Alberta Innovates Project Number:	AI 2516
Submission Date:	February 9, 2021
Total Project Cost:	$281,000
Alberta Innovates Funding:	$245,000
AI Project Advisor:	Dr. Paolo Bomben

2. APPLICANT INFORMATION:

Applicant (Organization):	**University of Victoria**
Address:	ECS 314, 3800 Finnerty Road, Victoria, V8W 2Y2
Applicant Representative Name:	Rishi Gupta
Title:	Associate Professor
Phone Number:	+1-250-721-7033
Email:	guptar@uvic.ca

3. PROJECT PARTNERS

Please provide an acknowledgement statement for project partners, if appropriate.

RESPOND BELOW

We would like to thank Mr. Garry Bridgens and Scott Kellar from the UVic Facilitiesy Management team for their cooperation to help obtain permission and support for the installation of smart sensing crack-free concrete bus pads. UVic Facilities management also contributed cash for the field deployment of the pavement. We would also like to thank Butler Brothers for their in-kind contribution (in terms of technical help) as well as providing concrete mix at the site. A special thanks to Wayne (Subcontractor) and his team for their cooperation during the construction of the bus pad. The technical assistance from Teijin is also acknowledged.

A. EXECUTIVE SUMMARY

Provide a high-level description of the project, including the objective, key results, learnings, outcomes and benefits.

RESPOND BELOW

The project involved the development of innovative carbon fiber reinforced concrete (CFRC) that could be utilized in the construction industry for repairs/new construction to enhance the life span of civil infrastructure. The project promoted sustainability by; 1) using asphaltene-based carbon fibers(ABCF) produced from the bitumen industry and;2) increasing the life expectancy of structures by reducing/eliminating the cracking in concrete. This allows the distribution of the embodied CO2 owing to the use of the materials over more years and further reducing the frequency of repairs or reconstruction. The project was divided into two phases, the first phase involved acquiring the carbon fibers from different industries, their characterization, and evaluation of fiber-reinforced concrete. A pool of different carbon fibers from Zoltek, Mitsubishi (Pan and Pitch based), Teijin and Asphaltene based carbon fibers (ABCF, from Dr. Chen's lab) were acquired and characterized by varying physical characteristics such as aspect ratio, modulus of elasticity, etc. were acquired. Microstructural characterization of fibers using XRD and SEM was conducted at UVIC followed by extensive casting and testing of carbon fiber composites such as cement-mortar and concrete. Although, the initial plan was to develop cement composites using ABCF fibers and compare its behavior with fibers obtained from several commercial sources, due to the limited production of ABCF fibers, they were not used for developing larger scale cement based composites specimens. The results indicated that the addition of carbon fibers exiguously improves the strength characteristics both for mortar and concrete. However, once composite undergoes the phase of micro-cracking, carbon fibers extraordinarily improve the composite behavior and induce significant post-cracking strength. The second phase of the project involved the testing of large size concrete slabs and the real-time demonstration of the carbon fiber reinforced concrete. The testing of large size carbon fiber reinforced concrete slabs indicated that the addition of fibers in concrete changes the failure mode from brittle to ductile, due to significantly increased toughness of concrete. For field demonstration, a smart sensing carbon fiber-based concrete bus pad was constructed and laid at UVIC bus exchange, in addition to two normal concrete slabs. Visual observation of the bus

pad after 28 days exhibited thin crack line growth in a concrete bus made with normal concrete while carbon fiber reinforced bus pad exhibited negligible cracking. The outcomes of the project strongly propound the use of carbon fibers in concrete with the purpose of minimizing cracking and providing significant post-crack strength to concrete. The carbon fiber reinforced concrete can be highly useful especially for the North-American subcontinent, which is generally exposed to cracking of concrete due to free-thaw cycles.

B. INTRODUCTION

Please provide a narrative introducing the project using the following sub-headings.

- **Sector introduction:** Include a high-level discussion of the sector or area that the project contributes to and provide any relevant background information or context for the project.
- **Knowledge or Technology Gaps:** Explain the knowledge or technology gap that is being addressed along with the context and scope of the technical problem.

RESPOND BELOW

1.1 Sector Introduction

The proposed product- innovative asphaltene- based CFRC provides incremental improvements on existing technologies. The construction industry has gradually started adopting sustainable construction technology and construction building materials. Fiber-reinforced concrete is one such sustainable building material as it reduces the cost of construction over the long term and provides superior performance. There are several different fiber types (more than 10 types) that are available depending upon the type of application. For example, synthetic fibers could be used for reducing shrinkage resistance and for improving the ductility of concrete while steel fibers could be used for increasing tensile and flexural strength. Market penetration for ABCF would be easy considering the demand and advantages of carbon fibers. The single most important dimension on which the Asphaltene based CFRC would outperform the competition would be the cost. It is expected that this project would allow the team to produce cost-efficient CFRC using asphaltene as a precursor.

1.2 Knowledge of Technology Gaps

Although the existing literature points towards the advantageous use of different kind of synthetic fibers, there are certain areas about the addition of carbon fibers in concrete that are yet to be explored such as:

- The optimum dosage of carbon fibers: Depending upon the desired characteristics of concrete such as increased post crack strength, amplified electrical conductivity, different dosages of carbon fibers will be applicable.

- Long term performance of Carbon Fiber Reinforced Concrete (CFRC): A well-designed concrete should be able to provide the desired service life. The addition of carbon fibers in concrete should enhance the service life of designed concrete or at least should be equivalent to normal concrete (in case it's designed to enhance electric conductivity per se).

- The behavior of Bus pads made with CFRC: Bus pads are usually small reinforced concrete slabs laid at almost all the bust stops. Due to the application of sudden brakes, its performance differs from that of concrete pavement. The addition of fibers in the concrete should be able to reduce/ eliminate cracking of the bus pad and enhance its overall service life.

C. PROJECT DESCRIPTION

Please provide a narrative describing the project using the following sub-headings.

- **Knowledge or Technology Description:** Include a discussion of the project objectives.
- **Updates to Project Objectives:** Describe any changes that have occurred compared to the original objectives of the project.
- **Performance Metrics:** Discuss the project specific metrics that will be used to measure the success of the project.

RESPOND BELOW

1.1 Knowledge or Technology Description

With the purpose of exploring the existing research gaps and extracting wealth from waste (using fibers made from bitumen), the objective of the project was focused on comparing the performance of different carbon fibers obtained from multiple sources with the ABCF for developing a 'crack-free concrete'. Further, it was also proposed that lab-based fiber reinforced concrete will be used to develop a bus pad and its long-term behavior will be evaluated. The objectives were proposed to find the suitable application of fibers from bitumen.

1.2 Updates to Project Objectives

There has been no change in the proposed objectives however, a new dimension in evaluating the long-term behavior of lab-based crack-free concrete, has been worked out. A novel piezo-electric, non-destructive structural health monitoring system has been developed. The piezo patches were embedded in the plain concrete bus pad as well as the carbon fiber reinforced bus pad. The piezo patches are periodically excited and data is acquired. The data is further used in conjunction with the data from strain gauges, temperature and humidity sensors to overall evaluate the performance of the plain concrete bus pad and carbon fiber reinforced bus pad. ABCF could not be used in the project due to limited quantities and instead Teijin fibres were used to obtain learnings that could inform the use of ABCF in the future.

1.3 Performance Metrics

The following project metrics were explored:

1. Tensile strength and modulus of rupture
2. Bond strength/Fiber pull out strength
3. Compressive strength f'c, modulus of elasticity E, and modulus of rupture fr
4. Pavement thickness- the results from the round panels (large specimens) will provide information about the two-dimensional behavior of carbon fiber-reinforced concrete. This will be utilized to consider the possibility of having a lower thickness in applications that utilize carbon fibers, and
5. Evaluation of field performance.

Please provide a narrative describing the methodology and facilities that were used to execute and complete the project. Use subheadings as appropriate.

RESPOND BELOW

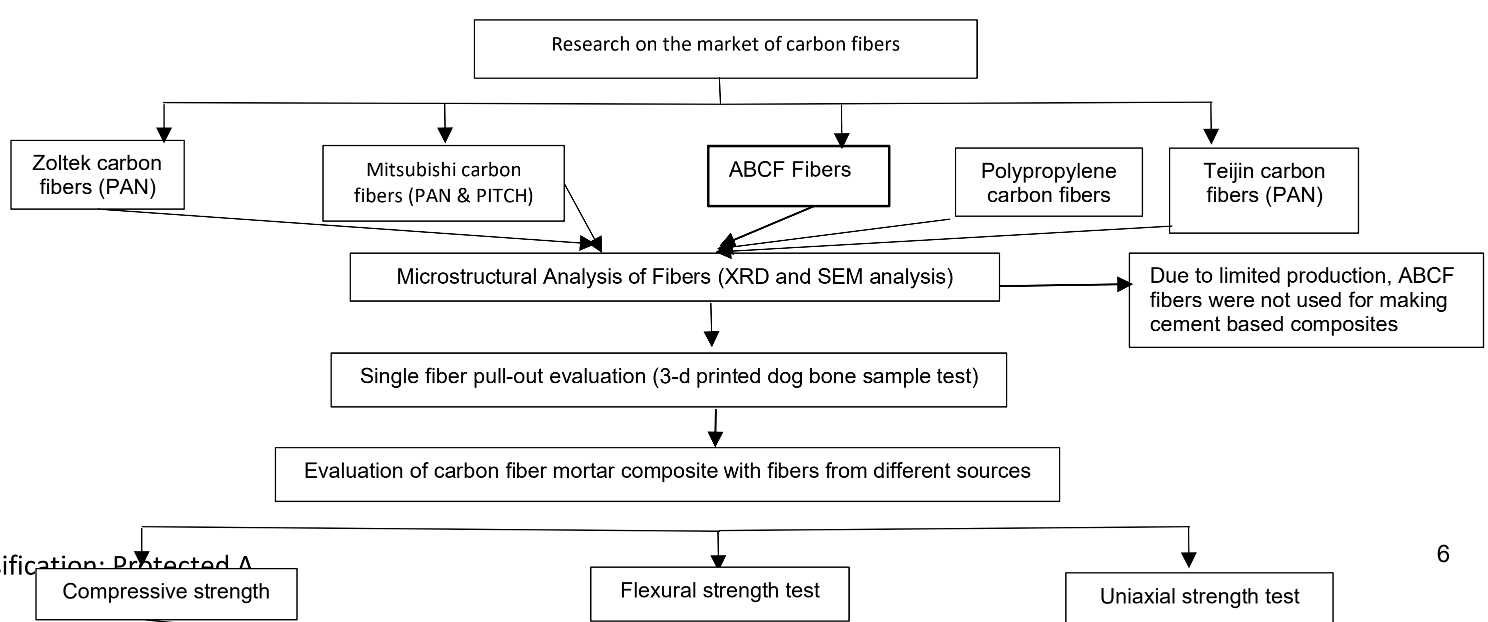
1.1 Facilities used for the project:

The work to accomplish the objectives was done at the Facility for Innovative Materials(FIMIM) laboratory at the University of Victoria(UVIC). Following are the details of various instruments used for achieving the project objectives:

1) The microstructural analysis of fibers procured from different sources was done at 'Advanced Microscopy Facility at UVIC. A Hitachi S-4800 FE Scanning electron microscope was used for high-resolution imaging of fibers.
2) 3-D printing facility of UVIC was utilized for the fabrication of plates for dog bone samples to simulate the single fiber pull-out test.
3) A machine "Tinius Olsen" with a very low loading capacity, was specifically procured to test the single fiber pull-out test.
4) The carbon fiber reinforced mortar composite behavior was evaluated using a small compressive testing machine available in FIMIM.
5) The medium size samples such as the beam were tested using MTI available in the Materials lab at UVIC.
6) For testing the large-size slabs, a new 50-ton Press was procured. Larger size circular molds of dia 80 cm and 100 mm thick were designed in the Material lab itself. Furthermore, a special three-point support system was also fabricated at UVIC to test the large size circular samples.

1.2 Project Methodology

The entire project methodology is presented in the flow chart below:



D. PROJECT RESULTS

Please provide a narrative describing the key results using the project's milestones as sub-headings.

- Describe the importance of the key results.
- Include a discussion of the project specific metrics and variances between expected and actual performance.

RESPOND BELOW

The details of key results obtained from accomplishing each milestone are detailed below:
1) *Acquisition of fibers (Accomplished)*

- A small quantity of sample ashphaltene based carbon fibers (ABCF) was acquired from Dr. Chen's lab at the University of Alberta at the start of this project. The ABCF was then characterized and evaluated for their possible use in concrete. It was found that the sample fibers needed to be larger in diameter or less brittle for them to be feasible for their use in concrete.
- Four different fiber types of varying lengths, varying material characteristics and from different sources were acquired; 1) Polypropylene fibers (lengths 6 mm, 13mm, 19 mm) acquired from Euclid chemicals; 2) Pitch-based carbon fibers (length 6mm) acquired from Mitsubishi chemicals; 3) PAN-based carbon fibers (lengths 6 mm and 12 mm) acquired from Mitsubishi, Zoltek and Teijin chemicals respectively.
- The fibers were acquired in small quantities initially for testing lab-based samples. From the testing results, it was found that Teijin fibers (of length 12 mm) outperformed all other fibers in enhancing mechanical behavior of concrete and inducing crack free characteristics in concrete.
- A small quantity (1 Kg) of Teijin fibers with 18 mm length were acquired thereafter. This was done to further corroborate the previously drawn conclusions and evaluate whether the concrete behavior further improves. It was found that carbon fibers obtained from Teijin (length 18 mm) yielded significant improvement in the mechanical behavior of fiber-reinforced concrete.
- As a result, a full batch of carbon fibers (60 Kg) were ordered from Teijin for developing a crack-free fiber reinforced concrete for a concrete bus pad, to be constructed at Transit BC bus loop at UVic located in the City of Saanich.
- Sufficient quantities of ABCF were unavailable to continue their use in the project.

The characteristics of all the carbon fibers are given in Table 1 in Appendix 1.
2) *Characterization of ABCF and other fibers (Accomplished):*

- All the acquired fibers were characterized using Scanning Electron Microscope (SEM) and X-ray Diffraction (XRD), specifically to verify the precise filament diameter, fiber morphology, and fiber composition. Fig. 1, Firg. 2, Fig. 3 gives the EDX results of pitch based, pan based and asphaltene based carbon fibers.
- The results indicated that pitch-based carbon fibers had 94 % carbon content, 98 % carbon content for PAN-based carbon fibers, and 81 % carbon content for ABCF. Further, traces of Sulphur, titanium, and vanadium were also found in the ABCF.

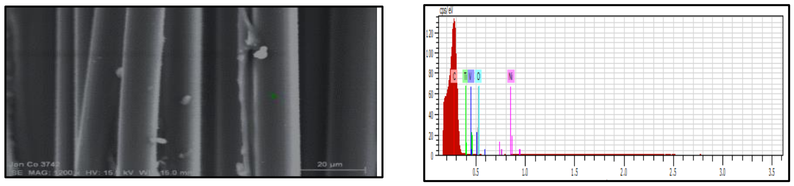


Fig. 1 EDX results of Pitch based carbon fibers

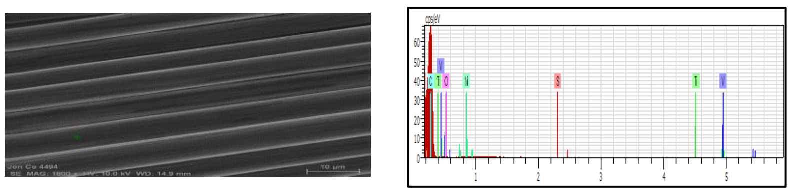


Fig. 1 EDX results of PAN based carbon fibers

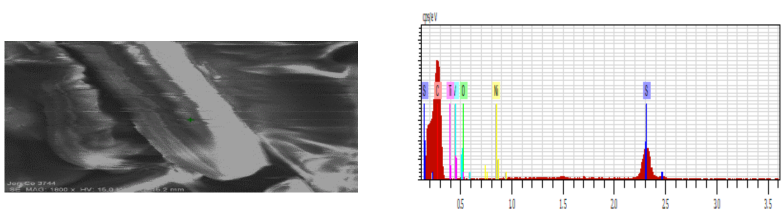


Fig. 3 EDX results of Ashphaltene based carbon fibers

The details of the fiber characterization including the images and results in a graphical format are given in Appendix 1.

3) *Small-size fiber reinforced mortar samples (Accomplished)*

- A mix design developed in the PI's Facility for Innovative Materials and Infrastructure Monitoring (FIM), as per ACI 544-1[1] was modified based on several iterations over the years to make it applicable to locally available materials. This base mix was used as a control for developing all fiber reinforced cement mortar and concrete samples. The details of materials of the mix are given in the table, shown in Appendix 2.
- With an objective to evaluate the overall behavior of carbon fiber reinforced mortar, three different kinds of samples including mortar cubes of size (50 X 50 X 50 mm), dog bones (overall length of 78 mm and critical length of 25.4 X 25.4 mm) and mortar beams (30 X 30 X 100 mm) were considered.
- A volumetric concentration of 0.5 % and 1 % were considered initially for all the cement mortar samples. Further, to evaluate the mechanical behavior at higher concentrations, cement mortar samples with 2%, 3%, 10 %, samples were also developed. It should be noted that 3 samples for each type were cast to maintain repeatability.
- The scope of this task was large and involved the casting of a total of 63 carbon fiber reinforced cement mortar cubes using the acquired fibers of different material types, dimensions, and sources. These cubes were tested using a compressive testing machine and the 28-day compressive strength was recorded.

- A total of 63 carbon fiber reinforced cement mortar dog bones were also cast and tested under uniaxial tension. The respective 28-day tensile strength of the dog bones was recorded.
- A total of 63 carbon fiber reinforced cement mortar beams were cast and tested under flexure. A 3-point loading test was conducted, and the 28-day flexural strength of the beams was recorded.

The relevant figures and the results are given in Appendix 2.

4) *Medium-size and large-size fiber reinforced concrete samples (Accomplished)*

- Development of medium size and large size specimens was done according to the standard mix design used in FIMIM (as per ACI 544-1)[1].
- After the testing of fiber reinforcement mortar was complete, the testing was further extended to fiber reinforced concrete with an attempt to evaluate the overall mechanical and durability behavior of concrete.
- Initially, a total number of 27 cubes (of size 150 mm X 150 mm X 150 mm), 15 beams (of size 100 mm X 100 mm X 400 mm), and 27 cylinders (of dia 75 mm and 200 mm deep) were cast and tested for compression, flexure and tension respectively using fiber volume concentrations of 0.5, and 1 %. Later, using Teijin fibers of 18 mm length, a series of 9 beams, 9 cylinders, and 9 cubes were cast and tested using 0.5%, 1%, and 2 % fiber volume concentrations.
- In an attempt to evaluate the durability of the fiber-reinforced concrete beams, a series of 18 beams were cast and subjected series of continuous cycles of freeze-thaw. Further, the dynamic modulus of fiber reinforced concrete was evaluated using a resonant frequency test.
- A set of 9 large fiber reinforced concrete round panels (800 m diameter and 100 m thick) were cast using Teijin fiber of 18 mm length and 0.5 %, 1 %, and 2 % fiber volume concentrations. The samples were tested using an in-house developed supports and a bench press of capacity 50 ton.

The details of various tasks conducted under this milestone are given in Appendix 3.

5) *Fiber mechanical and bond properties in cement matrix (Accomplished)*

- In order to determine the interaction of fiber and the cement matrix surrounding it, pull-out strength tests were conducted.
- 3-d printed plates were developed in-house of 1 mm thickness and with a central hole to prepare the dog bone specimens. 5mm-long twisted carbon fiber bunches with 3 different diameters (0.5, 0.8, and 1 mm) were placed through the hole. The mortar was placed in the dog bone sample to fill half of its height, the plate was placed in the middle of the mold and the rest of the mortar was placed.
- Initially, the tests were conducted using a conventional tensile testing machine with a relatively larger load capacity and loading rate. These values did not have a high resolution. Hence, special equipment (a tensile testing machine- Tinius Olsen with a capacity of 200 N) acquired for this project was used to conduct the fiber- pull-out tests. This was primarily done to record the entire process of fiber pull-out with greater accuracy.
- A total of 24 new samples were cast and tested using Tinius Olsen and the fiber pull-out strength was recorded. It should be noted that 8 of the total 24 samples were coated with fly ash (an industrial waste from thermal power plants) in an attempt to further improve the bond between the fiber and the cement matrix.

The details of testing and the test results are included in Appendix 4.

6) *Design of FRC pavements (Accomplished)*

- In order to demonstrate the use of carbon fiber reinforced concrete for bus pads, various municipalities (including the City of Saanich, City of Victoria, City of Langford, City of Oak Bay, and Facilities Management at UVic) were contacted. For this, several municipalities have shown interest including UVic Facilities Management. Considering the limited researcher mobility during the pandemic and to have a more controlled demonstration site, the bus pad at UVic (in District of Saanich) was considered for this project. A site-visit at the bus loop that frequents heavy bus traffic was conducted on June 17th, 2020, along with the relevant authorities from UVic and a local contractor.
- At UVic bus exchange, a group of three adjacently laid, deteriorated concrete bus pads were identified and permission to replace them was sought from the local authorities. It was decided that out of three, two bus pads will be replaced with normal concrete and the third one will be replaced with lab-developed crack-free concrete.
- After the permission was given, a complete survey of the bus loop was conducted, and pictures of the existing cracked bus pad were taken. For the bus pads to be replaced, a crack width analysis was done using the pictures to evaluate the width of cracks, using the software Image J.
- The site work started on September 25th including the excavation of the existing bus pads, removal of debris, and embedding the steel-wire mesh. Thereafter, the FIMIM research group installed and configured a series of sensors across the entire bus pad. The different types of sensors used are wireless temperature sensors, humidity sensors, thermocouples, strain gauges. In addition, a newly developed NDT by the FIMIM group utilizing the piezoelectric phenomenon to study the changes or material deformations was also installed at the site. This included a series of 12 piezo patches located at a strategic distance were also installed across the bus pad.
- Special permission was sought by local authorities to install a local monitoring station on the sidewalk near the bus pad. All the wires and cables coming from the sensors were routed in this station. This was done to acquire data from any changes taking place inside the bus pad after its construction.
- On September 26, a local contractor was hired who brought concrete (5 m^3) into the mixing truck. Firstly, concrete was poured into the two bus pads with normal concrete. Thereafter, a large number of fibers (0.55 % of total concrete) were added to the truck in steps of 5 kg each and the mixing was done at the site. This was followed up by pouring the fiber reinforced concrete in the third bus pad and screeding of all the bus pads.
- For quality assurance, the FIMIM group filled cylinders, cubes, beams, large size circular panels with the normal as well as the fiber-reinforced concrete mixed on the site. These samples were later tested in the lab and results were correlated with the previously acquired lab-based samples. The details and figures are given in Appendix 5.
- The data from embedded temperature and humidity sensors, strain gauges, and piezo patches were acquired at regular intervals. Also, after 28 days of construction, permission from BC transit was sought to block the bus

pad from any traffic for 5 days. During these 5 days, the entire FIMIM team conducted a series of tests such as Schmidt hammer, Ultrasonic Pulse Velocity, Electrical resistivity on the constructed bus pads. Piezo patches were also excited for the very first time after 28 days of construction. The details of testing are included in Appendix 8. Fig. 4 Fig. 5 and Fig. 6 show the results obtained from the testing of bus pads using Schmidt hammer, electrical resistivity, and Ultrasonic pulse velocity. Fig. 7 a and b give the results obtained from exciting the piezo patches.

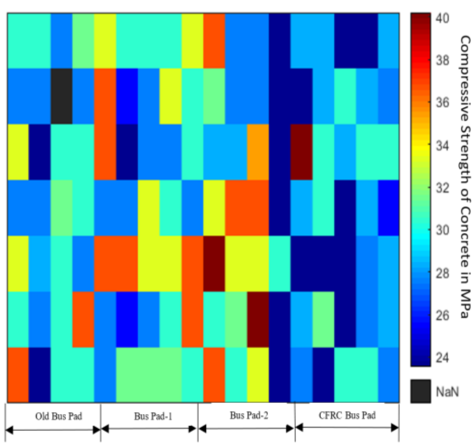


Fig. 4 Schmidt Hammer Test

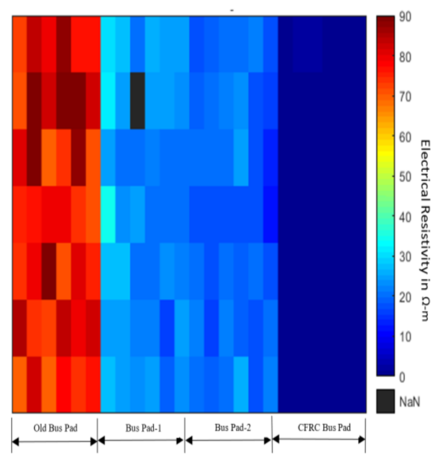


Fig. 5 Electrical Resistivity Test

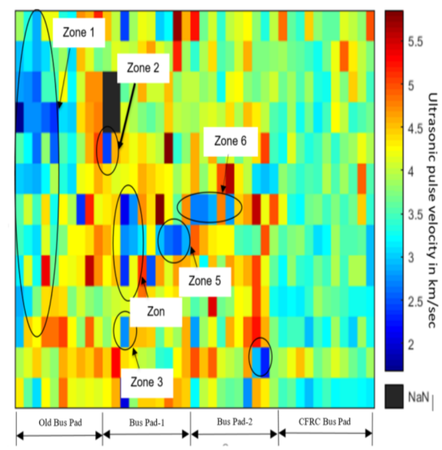


Fig. 6 Ultrasonic Pulse Velocity Test

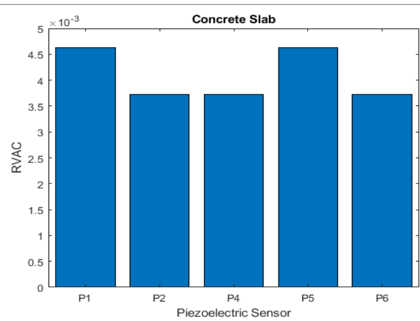


Figure 7a: Relative Voltage Attenuation Coefficient (RVAC) for signals recorded in concrete bus pad by piezoelectric sensors (P1, P2, P4, P5, and P6) when piezoelectric actuator (P3) was excited.

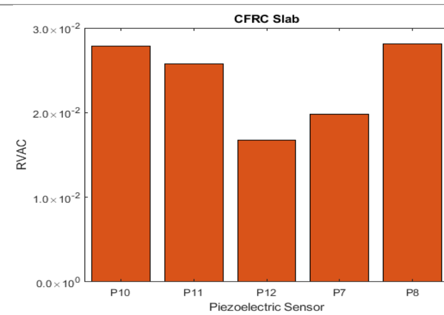


Figure 7b: Relative Voltage Attenuation Coefficient (RVAC) for signals recorded in CFRC bus pad by piezoelectric sensors (P7, P8, P10, P11, and P12) when piezoelectric actuator (P9) was excited.

B) Other Additional Activities:

The details of various other tasks that were completed that are not directly related to milestones as per the investment agreement are enumerated below:

- As per the suggestions recorded in one of the meetings with Dr. Axel Meissen, a detailed literature review on developments in fiber reinforced concrete was conducted. This is included in Appendix 6 (and is made available as a separate attachment to maintain brevity in this report). The details are given in Appendix 6.
- An optical method used for measuring the displacement dynamically, aiding in non-contact strain measurements was explored and a fitting algorithm was tailored. The developed method will help in lab-scale testing of beams and circular round panels.
- Three Coop students namely Bruce Wang, Zeridah Atwine, and Kara Labelle were recruited from January to May, June to August and October to December respectively. A Ph.D. student Sreekumari Raghavan has been working in parallel for the last 18+ months to explore the use of piezo patches for structural health monitoring. She helped acquire the necessary equipment including an oscilloscope and a waveform generator. All of this has been used in this project.
- With the objective of wireless data transmission, a Raspberry Pi tool kit was procured. This Raspberry pi will eventually be integrated with our existing data acquisition system installed at bus pad.
- A full-fledged round panel test program was developed including the procurement of a 50 Ton Pneumatic/Hydraulic Shop Press. The press has been installed in Materials Laboratory, UVic. Three-point support as per ASTM C15550[2] was developed at UVic specifically for testing the circular panels. In addition to that, large wooden circular molds (800 mm diameter and 100 mm thick) were developed at UVic. designing a three-point support system and fabricating the circular molds for casting specimens was done in UVic's machine shop.
- To study fiber dispersion in concrete, an optical method using Infrared thermography was explored. Concrete made with different concentrations of fibers was monitored and the results were recorded. Infra-red thermography was also used to check the dispersion of carbon fibers placed in the constructed bus pads.
- The recently acquire Teijin fibers were characterized using a microscope. Single fiber strands were separated from the bunch and the individual measurements were taken. This was done to prepare the samples for a single fiber pull-out test using Tinius Olsen.
- A detailed mix design was prepared for constructing the bus pad. A small algorithm to find out the depth of the pavement was also developed.
- A total of three deteriorated and fully cracked bus pads (Bus Pad-1, Bus-Pad-2, and CFRC Bus Pad) at UVic bus exchange were replaced. Two of them were replaced with normal concrete and the remaining were replaced with carbon fiber reinforced concrete. A series of sensors such as temperature, humidity sensors, thermocouples, strain gauges, and piezo patches were embedded along with the steel wire mesh, inside the concrete bus pad. It should be noted that all the sensing modules were installed in Bus Pad-2 and CFRC Bus Pad for comparative purposes. The layout of the bus pad and the details about the location of sensors are included in Appendix 8.
- A concrete mix of target strength 40MPa was ordered and placed into bus pads 1 and 2. In the case of carbon fiber reinforced bus pad, approximately 0.55 % by volume, of carbon fibers were added to the mix and then placed into the bus pad.

- For developing a smart sensing bus pad, a series of sensors such as thermocouples, strain gauges, temperature and humidity sensors, etc. were procured. These sensors were embedded inside the pavement and are currently used to evaluate the performance of both the normal concrete and carbon fiber reinforced concrete pavement. The details are included in Appendix 5.
- With an objective of long-term monitoring of bus pads, a structural health monitoring technique involves embedding the piezoelectric patches in concrete at the time of construction. These piezoelectric patches will be later utilized to take concrete signatures at different intervals and be linked with induced damage such as progressive cracking. In this regard, a preliminary laboratory investigation was conducted in which two piezoelectric patches were surface bonded to a plexiglass sheet at some distance apart with an epoxy resin. Figure7-1(in **Appendix 7**) shows the experimental set-up of piezoelectric patches. One piezoelectric patch acting as an actuator was excited by giving a high voltage high-frequency sinusoidal signal to create stress waves within the structure. The sinusoidal signal is generated by a function generator at a specific frequency, followed by an amplification using a high voltage amplifier, and eventually fed to the actuator. The other piezoelectric patch acting as a sensor received these stress waves and converted them to an electrical sinusoidal signal. The electrical signal was further analyzed in an Oscilloscope. The changes in input and output electrical signal signature indicate the presence of cracks, voids, or any other defects within the material. It is a non-destructive evaluation technique for monitoring the structure. The details are given in Appendix 7

E. KEY LEARNINGS

Please provide a narrative that discusses the key learnings from the project.

- Describe the project learnings and importance of those learnings within the project scope. Use milestones as headings, if appropriate.
- Discuss the broader impacts of the learnings to the industry and beyond; this may include changes to regulations, policies, and approval and permitting processes

RESPOND BELOW

The details of key findings recorded for each task under milestone 1, 2, 3, 4, and 5 are given below:

Milestone 1, Acquisition of fibers

- A small quantity of sample ashphaltene based carbon fibers (ABCF) was acquired from Dr. Chen's lab at the University of Alberta at the start of this project. The ABCF was then characterized and evaluated for their possible use in concrete. It was found that the sample fibers needed to be larger in diameter or less brittle for them to be feasible for their use in concrete.
- Fibers of different material characteristics and lengths were procured from 5 different sources named as 1) Polypropylene fibers (lengths 6 mm, 13mm, 19 mm) acquired from Euclid chemicals; 2) Pitch-based carbon fibers (length 6mm) acquired from Mitsubishi chemicals; 3) PAN-based carbon fibers (lengths 6 mm and 12

mm) acquired from Mitsubishi, Zoltek and Teijin chemicals respectively; and 4) ABCF from University of Alberta. Initially, a small quantities of fibers was procured for evaluating the composite behavior.

- From the fiber-mortar composite and fiber-concrete composite behavior, it was found that all carbon fibers mildly improve the strength characteristics of the composite and significantly modify the post crack strength characteristics of the composite. Teijin based carbon fibers with 12 mm length exhibited the highest value of post crack strength.
- This was followed by the 1 kg procurement of 18 mm Teijin based carbon fibers. Further testing revealed that 18 mm length improves the composite behavior significantly with the highest values of post crack strength. This was followed by the bulk procurement of Teijin carbon fibers of the order of 60 kg.

Milestone 2 Characterization of fibers(Accomplished)

- SEM and XRD analysis was performed on ABCF and all other kinds of fibers to verify the precise filament diameter, fiber morphology, and fiber composition. This was done by using Hitachi S-4800 FESEM available in 'Advanced Microscopy Facility' at UVIc. Energy Dispersive X-Ray Spectroscopy (EDX) was conducted to estimate fiber chemical components.
- The presence of carbon©, Nickel (Ni), Titanium(Ti), Vanadium(V), and Sulphur(S) was reported. The results indicated that two commercially available carbon fibers have a higher content of carbon (a94% in Pitch-based and 98 % in PAN-based carbon fibers), as compared to asphaltene fibers (81 % carbon).
- This is attributed to the fact that ABCF fibers were not graphitized (i.e. subjected to high temperatures in an inert atmosphere) during production. Furthermore, 6 % of Sulphur was observed in ABCF fibers. All carbon fibers showed traces of Nickel, however, only traces of Titanium and Vanadium was observed in ABCF.

The details of the fibers are enclosed in the Appendix1

Milestone 3, Small-size fiber reinforced mortar samples (Accomplished)

- Initially, the experimental work started with utilizing fiber dosage ranging from 0.5 % to 1 %. The fiber-mortar mix was found to be workable for the specified range. Furthermore, it was found that at $V_f = 1$ %, fiber balling had started taking place affecting the workability of the mix mildly.
- A 5-10% increase in the compressive strength of carbon fiber reinforced concrete as compared to control, with almost no insignificant changes in the tensile strength and flexural strength. The results were based on fiber volume concentrations ranging from 0.5 to 1 %. This led the researchers to explore other fiber dosages.
- In an attempt to evaluate the upper limit of fiber concentration in the matrix, the mortar samples were tested for 2%, 3%, and 10 % fiber volume concentration (V_f).
- The results exhibited that when $V_f > 2$ %, the workability of the mix significantly reduces. This is primarily a phenomenon of static electricity that causes short fibers to attract each other, thereby causing them to clump together into balls. Also, the workability is lost due to the additional friction within the mix that must be overcome. In addition to negligible workability, the mix with higher fiber concentration exhibited poor fiber dispersion.

- It was concluded that fiber volume concentrations higher than 2 %, would significantly impact the uniform distribution of fibers throughout the matrix. This finding helped in finalizing the upper bound for fiber dosage (at least at the lab-scale).
- The results indicated that the addition of carbon fibers in the cement matrix insignificantly contributes to the mechanical characteristics of the matrix such as compressive strength, tensile strength, and flexural strength.
- For all the fiber-reinforced mortar samples, a strain-softening behavior was exhibited in all the stress-strain curves. This is primarily due to the relatively shorter length of fibers, the poor bond strength between the fibers and the matrix, poor dispersion of fibers in the matrix.
- From the flexural testing, it was found that fiber-reinforced mortars at higher V_f exhibited promising post crack strength, improved characteristics in the strain at peak stress and energy absorption.
- The results further indicated that carbon fiber reinforced mortar can carry more stress after matrix cracking thereby modifying the overall post cracking behavior of the matrix.
- During the testing, it was also observed that cement mortar samples exhibited sudden failure, whereas the fiber-reinforced mortar samples exhibited a more gradual failure (like a ductile failure). Further, the sample fiber lengths 12 mm exhibited more resistance to cracking than the samples with 6 mm lengths of fibers.
- Teijin fibers with a length of 12 mm length, exhibited the highest post crack strength. This further indicates a significant amount of frictional forces at the fiber-cement interface attributing to increased fiber length.
- The results differentiate the carbon fiber and plain cement mortar samples. It is concluded that the damage is directly proportional to the relative strength of the mortar matrix and the fiber itself. This could be attributed to the fact the microcrack propagation in plain concrete is different from plain cement mortar samples than composites. This is reinforced from the visual inspection of the failed specimens that suggested a fracture of fiber than complete pull-out.
- It was also observed that the global cracks developed in carbon fiber reinforced mortar samples were all in the loading direction. This is primarily in the case of fibers in a mortar, where the cracking initiates from the interfacial transition zones, and thereafter, it propagates across the mortar region connecting. This is usually not the case in the case of plain cement mortar samples wherein crack initiates from the surface mortar and then propagate into the mortar along the loading direction.

Lessons Learned

- The addition of synthetic fibers of a minimum length of 12 mm is ideal for cement mortar composites as they significantly improve their mechanical behavior. Further, the volumetric fraction of fibers is to be limited to 2 % in order to induce better workability and relatively uniform fiber dispersion.
- The pre-coating of fibers can be considered to improve the fiber-matrix bond that is a prime factor for improving the mechanical behavior of the composite.
- Out of all the acquired fibers, Teijin fibers with a length of 12 mm yielded the best results. These results were further motivated for procuring Teijin fibers of length 18 mm and for the construction of a bus pad.

Milestone 4, Medium-size and large-size fiber reinforced mortar samples (Accomplished)

- The compressive strength test results indicate that there is almost a 10-15 % increase in the compressive strength of concrete with V_f ranging from 0.5 to 1 %. However, a fiber content greater than that results in a decrease in the compressive strength of concrete.
- All the acquired PAN-based fibers from different sources exhibited better strength values than those of Pitch based fibers. This is generally due to the isotropic nature of the polymer chains in the fiber.
- The decreasing strength values with increasing fiber volume fraction could be a result of increased porosity and inhomogeneity in terms of dispersion of fibers. This further becomes worse as carbon fibers tend to agglomerate in the mix.
- From the Flexural strength test, it was found that certain carbon fiber reinforced concrete samples had greater flexural strength than the control specimens. The flexure strength for control samples was recorded as 3.4 MPa, the PAN and Pitch-based carbon fibers exhibited flexural strength ranging from 2.4 to 3.0 MPa, for all volume concentration of fibers. On the contrary, the flexural strength recorded for Teijin fibers was recorded as 7 MPa, at 1 % volume concentration. Apart from greater flexural strength, it was also observed that at peak load, the control samples exhibited a brittle failure by simply breaking into two. On the other hand, carbon fiber reinforced concrete samples exhibited significant post crack strength (post-peak load).
- The scope of this project was further expanded to include freeze-thaw testing according to ASTM C 666[3]. All the fiber reinforced concrete samples exhibited significant damage after 120 cycles of freeze-thaw. The dynamic modulus of control samples dropped more than 15 % whereas the dynamic modulus of both PAN and PITCH samples dropped by less than 5 %. This suggests that the fibers significantly held the matrix together from severe cracking induced by cycles of freeze and thaw.
- In an attempt to capture the pure bending behavior of carbon fiber reinforced concrete, the testing of large circular statically determinate specimens was conducted. It was observed that while the control specimens cracked immediately into two pieces at the peak load, the round panels with fibers V=0.5%, 1% underwent cracking gradually. From the visual observations, three different crack lines originating right from the center point developed as the load increased and cracks widened to the maximum until load reduced to negligible.
- The peak load for control samples and fiber-reinforced samples somewhat similar but their deflections recorded in the case of fiber-reinforced round panels was much greater than those of control samples.

Lessons learned

- The fiber addition in concrete will significantly enhance the toughness and the post crack performance of concrete as observed from the flexural and the round panel tests.
- The addition of fibers in concrete can, therefore, significantly eliminate/ reduce cracking for their real-time application use.
- Greater fiber lengths (> 12mm) can be useful in providing a dual pull-out and fiber fracture mechanism overall enhancing the damage resistance of the composite.
- This application of carbon fiber reinforced concrete will be highly useful for constructing bus pads where breaking loads induce a significant amount of cracking in concrete.

Milestone 5, Fiber mechanical and bond properties in cement matrix (Accomplished)

- Different failure modes were recorded during the pull-out test. In synthetic macro and microfiber samples, the failure mode was a complete pull-out of fiber from the cement matrix, while in carbon fibers, fiber fracture and fiber pull-out were the two failure modes observed during the pull-out test. The complete pull-out failure is an indication of weaker bonding between fiber and matrix compared to the strength of the matrix or fiber, which is a desirable failure mode to prevent sudden brittle failure in structures
- Failure pattern of fibers was investigated using pull-out force versus slip curves. In carbon fibers, after fiber reached the peak load, a sudden drop in the pull-out load occurred which was mainly due to the rapid debonding of fiber and matrix around the fiber. In synthetic fibers, the increase in slip after peak load was followed by a gradual decrease in pull-out load until anchorage of the fiber was straightened. In synthetic macro fiber samples, the decrease rate was much more significant than in synthetic microfiber samples but still smoother than carbon fibers. It is noteworthy to mention that all types of carbon fibers reached their peak load in less than 1 mm of slip, while this amount was much higher in other fiber types.
- Peak load and fiber pull-out differed significantly according to the fiber type. The highest average pull-out force of 358 N was obtained for S while this amount was 122, 155, and 156 N for synthetic macro fibers, PAN, and Pitch with the same diameter at 28 days respectively. For both S and SI samples, maximum load occurred at approximately 3.5 mm of slip, while for PA1 and PI1, the slip at maximum load was 0.8 and 0.5 mm respectively which is the main reason for the much lower pull-out energy absorption capacity of carbon fibers compared to synthetic micro and macro fiber-based samples. Further, the lower values of carbon fiber attribute to their smooth filament without any crimping or shape deformations.

Lessons learned

- During the preparation and testing of CF, several samples were damaged or broken due to the sensitivity and vulnerability of fibers to any kind of impact. These impacts were produced during sample handling, pre-test preparation, testing, and due to the matrix to matrix adherence of the two parts of the dog-bone sample.
- Average bond strength was investigated in all four fiber types. The results showed that after SF, CF and SI showed comparable results and in some samples such as PI0.5, the bond strength value of CF was even higher than SI. The effect of fiber bundle diameter on bond strength didn't show a clear trend.

Milestone 6, Design of FRC pavements (Accomplished)

- The design thickness proposed by the sub contractor that meets the requirements of the local authorities was used for this project. Nevertheless, the FIMIM team has prepared a detailed design of the concrete bus pad as per the AASHTO guide for the design of pavement structures, 1993. This design exercise was completed so a design example is readily available for any future projects where fibers may be proposed. The design primarily involves the calculation of the depth of the pavement using a general formula provided by AASHTO 1993. The depth of pavement depends upon various parameters such as traffic load, subgrade quality, reinforcement details, environmental effects, time constraints, etc. It should be noted that the design procedure involved the use of peak values of modulus of rupture. From the lab test results of the incorporation of carbon fibers in concrete, a 10% increase in the modulus of rupture was assumed for fiber reinficed concrete. The overall depth of pavement turned out to be 8". Due to field constraints, the bus pad design prepared by the local contractor was used and the actual depth of pavement ranged between 5”-6”, for all bus pads. The design details are included in Appendix 5.

- A survey of the preexisting cracked bus pads was done and the pictures were analyzed using Image J. A total crack area of 301795 mm^2, 150245 mm^2, and 101203 mm^2 was observed. It should be noted that the calculated crack areas for individual bus pads is very high and represents a highly deteriorated concrete.
- To understand the dispersion of fibers in the concrete mix (one of the goals of this project), three cylinders (size 200 mm depth and 100 mm dia) were filled with the concrete that was placed into the CFRC bus pad. The samples were then taken to the lab and concrete was washed away and fibers were retained. Thereafter the percentage of fibers in each cylinder was evaluated. This was done to confirm that the design fiber volume is being dispersed in the concrete. It was found that the fiber concentration in the cylinder exhibited a range from 0.55 to 0.61 %. This manual test confirms that fibers were very well dispersed in the entire mix. Visual observations were also made during the dispensing of the concrete through the chute in the ready-mix truck. Uniform fiber mixing was observed in the chute with no visual fiber balling. During finishing, some fiber minor clumps of fibers were observed at the surface.
- From the visual observation, it was observed that the bus pads developed with normal concrete exhibited thin hairline cracks within 15 days since casting, whereas the carbon fiber reinforced concrete bus pad has not exhibited any crack even after three months of construction.
- The data from embedded temperature and humidity sensors, strain gauges, and piezo patches were acquired at regular intervals. Also, after 28 days of construction, permission from BC transit was sought to block the bus pad from any traffic for 5 days. During these 5 days, the entire FIMIM team conducted a series of tests such as Schmidt hammer, Ultrasonic Pulse Velocity, Electrical resistivity on the constructed bus pads. Piezo patches were also excited for the very first time after 28 days of construction. The details of testing are included in Appendix 8.
- It should be noted that wireless temperature and humidity sensors embedded in carbon fiber reinforced pavement have not been able to relay the data successfully. The possible reason for the presence of well-dispersed carbon fibers interfering with the Bluetooth signals.
- From the electrical resistivity test data, it was observed that the CFRC bus pad exhibited negligible electrical resistivity. This is primarily due to the incorporation of electrically conductive carbon fibers. The electrically conductive values for normal concrete bus pads range from 20-30 Ω-m. However, the electrical resistivity of the old bus pad was found to be very high ranging from 60 to 90 Ω-m. This is primarily due to the presence of water in the freshly made concrete which increases the electrical conductivity.
- The recorded ultrasonic pulse velocity data indicated wave velocities above 3.5 Km/sec for CFRC as well as plain concrete bus pad. This indicated the fresh state of the concrete bus pad. It should be noted that recorded wave velocities for the old bus pad were very low below 3 Km/sec suggesting deteriorated concrete.
- Schmidt hammer test data indicated lower values of compressive strength of the CFRC bus pad averaging around 28 MPa. However, for the concrete bus pad (control), the recorded compressive strength was about 34 MPa. It should be noted that the average compressive strength of both control and CFRC cylinders when

tested in the lab were 16.83 MPa and 15.50 MPa respectively (noted in Table 5, Appendix 8), indicating similar strengths for both mixes but lower than that recorded by Schmidt hammer. The difference between the values can be primarily attributed to the fact that Schmidt hammer data exhibits an error of around 20 % as Schmidt hammer primarily correlates the surface hardness of concrete with its compressive strength. Due to the presence of fibers in CFRC, the surface hardness may not be comparable with that of plain concrete.

- The embedded piezo patches were also excited and the data was recorded. In the concrete bus pad, piezoelectric patch P3 was actuated and remaining patches P1, P2, P4, P5, and P6 in the array acted as sensors. In the CFRC bus pad, piezoelectric patch P9 was actuated and remaining patches P7, P8, P10, P11, and P12 in the array acted as sensors. Relative Voltage Attenuation Coefficient (RVAC) was calculated by taking the ratio of peak to peak amplitude across the sensor to the amplitude across the actuator. The data suggested that attenuation of wave signals in CFRC was much lesser than that of plain concrete. This could be attributed to the fact that during hydration of concrete, micro-cracks due to the shrinkage develop inside the concrete. The presence of carbon fibers induces the stitching effect when shrinkage cracks intend to build and hence the microstructure of the CFRC concrete will remain intact enabling the efficient travel of the mechanical wave. In plain concrete, there are no fibers present to hold the packing of microstructure, and shrinkage cracking could easily distort it. As a result, several microvoids are formed inside concrete inducing a damping effect for transient elastic waves triggered by piezo patches and causing significant attenuation of the signal. It should be noted that several cracks were also seen after 15 days of construction on the surface of the plain concrete bus pad.
- The data presented in the report was acquired between August and December 2020. From the visual observation and the testing data, it indicates that the plain concrete bus pad has developed cracks (within 7 days of casting) while the CFRC bus pad continues to maintain its structural integrity. It is clear that even though the compressive strength of the CFRC concrete was less than 20 MPa (with an average thickness of 5”), due to the addition of carbon fibers, cracks have not developed in these placements indicating shrinkage, high impact and flexural toughness. As of mid January (2021), the cracks in the plain concrete bus pads have widened significantly. It is expected that these cracks will continue to widen under the action of aggressive environmental forces such as freeze-thaw etc. and the plain concrete bus pads will require to be replaced in the near future. On the other hand, the CFRC based bus pad has exhibited no cracking which indicated the durability and longer service life of the bus pad. The FIMIM team will continue to evaluate the assessment of the condition of bus pads for another year until the end of December 2021.

F. OUTCOMES AND IMPACTS

Please provide a narrative outlining the project's outcomes. Please use sub-headings as appropriate.

- **Project Outcomes and Impacts:** Describe how the outcomes of the project have impacted the technology or knowledge gap identified.
- **Clean Energy Metrics:** Describe how the project outcomes impact the Clean Energy Metrics as described in the *Work Plan, Budget and Metrics* workbook. Discuss any changes or updates to these metrics and the driving forces behind the change. Include any mitigation strategies that might be needed if the changes result in negative impacts.
- **Program Specific Metrics:** Describe how the project outcomes impact the Program Metrics as described in the *Work Plan, Budget and Metrics* workbook. Discuss any changes or updates to these metrics and the driving forces behind the change. Include any mitigation strategies that might be needed if the changes result in negative impacts.
- **Project Outputs:** List of all obtained patents, published books, journal articles, conference presentations, student theses, etc., based on work conducted during the project. As appropriate, include attachments.

RESPOND BELOW

1.1 Project Outcomes and Impacts:

The prime goal of incorporating carbon fibers in concrete was to improve the structural integrity by keeping the cracks unyielding and by utilizing the fiber action to distribute the busload throughout the concrete slabs, specifically in concrete bus pads where dowel bars are seldom used. From the visual inspection of the bus pad, it was found that the CFRC bus pad is intact without any cracks of even micro-level whereas the normal concrete bus pads have developed thin hairline cracks. From the lab-based test results and the site investigations, the optimum percentage of Teijin fibers of length for developing better concrete composite ranges between 0.25 to 1 %. The project outcomes can have the following impacts:

1) The load transfer efficiency of fiber-reinforced composites will be improved.
2) The differential displacement of fiber-reinforced composites will be greatly reduced, resulting in the improved mechanical behavior of the composite.
3) Higher resistance to free-thaw will significantly improve the resistance of the composite to deterioration in extreme weather conditions.
4) The addition of fibers induces a characteristic in the composite known as "Crack arrester" i.e., Lesser stress at crack tips, reduced crack width, slow crack progression will significantly improve the resistance to ingress of chlorides, CO_2, and many other aggressive chemical agents that adversely affects the integrity of the structure.
5) The thickness of fiber reinforced concrete composites can be reduced as a result of fiber action and will significantly reduce costs in major projects.
6) The brittle nature of a composite like concrete that evinces its design limitation can be easily overcome by the inclusion of carbon fibers by changing the mode of fracture.

1.2 Clean resources metrics:

No clean resources metrics were defined at the start of the project because it pre-dates the formation of the metrics. The project outcomes indicate the efficacious impact of the incorporation of carbon fibers in concrete composites, remarkably improving the mechanical behavior, service life of the fiber-reinforced concrete structures. Hence, the use of carbon fibers has a great potential in reducing the repair and retrofitting and as a result, mitigating CO_2 emissions.

1.3 Program-specific metrics:

Under the innovative hydrocarbons product program, this project helped me realize a few metrics. The number of end-users that may utilize the developed products has been increased. The local contractor on this project has been trained first hand to use the carbon fibers in concrete. Also, the ready-mix producer and their ready-mix truck were used to demonstrate the use of commercial equipment for mixing and placing carbon fiber reinforced concrete. Also, a unique product and process have been developed to produce carbon fiber reinforced concrete. The findings could be applied to the use of asphaltene based carbon fibers from Alberta when they start being produced at a commercial scale.

1.4 Project success metrics:

The following project success metrics were identified previously:

- Tensile strength and modulus of rupture- this project metric has been met as various types of carbon fibers have been characterized.
- Bond strength/Fiber pull out strength- this project metric has been met as various types of carbon fibers have been analyzed.
- Compressive strength f'c, modulus of elasticity E, and modulus of rupture fr- this project metric has been met as various types of mortars and concrete with carbon fibers have been tested and analyzed.
- Pavement thickness- the results from the round panels (large specimens) will provide information about the two-dimensional behavior of carbon fiber-reinforced concrete. This will be utilized to consider the possibility of having a lower thickness in applications that utilize carbon fibers.
- Evaluation of field performance- This metric is anticipated to be met after the completion of the last project milestone.

1.5 Project Outputs

The project work has resulted in two conference publications, one journal publication is under review, three publications are under editing.

G. BENEFITS

Please provide a narrative outline the project's benefits. Please use the subheadings of Economic, Environmental, Social and Building Innovation Capacity.

- **Economic:** Describe the project's economic benefits such as job creation, sales, improved efficiencies, development of new commercial opportunities or economic sectors, attraction of new investment, and increased exports.
- **Environmental:** Describe the project's contribution to reducing GHG emissions (direct or indirect) and improving environmental systems (atmospheric, terrestrial, aquatic, biotic, etc.) compared to the industry benchmark. Discuss benefits, impacts and/or trade-offs.
- **Social:** Describe the project's social benefits such as augmentation of recreational value, safeguarded investments, strengthened stakeholder involvement, and entrepreneurship opportunities of value for the province.
- **Building Innovation Capacity:** Describe the project's contribution to the training of highly qualified and skilled personnel (HQSP) in Alberta, their retention, and the attraction of HQSP from outside the province. Discuss the research infrastructure used or developed to complete the project.

RESPOND BELOW

1.1 Economic Benefits

The Project execution directly involved the employment of 5 coop undergraduate students, 1 Ph.D. student, 3 postdoctoral fellows. The successful execution indication of the utilization of carbon fibers in the construction industry. There are more than 200 small and large companies in Alberta associated with concrete production. The concrete production industry in Alberta is worth $3.63 billion by gross revenue per year [4] The concrete production figure is about 4765,000m^3 per year and it is increasing every year. It should be noted that the concrete producers employ over 10, 000 people currently. 93.3 % of companies expect to maintain or increase their number of employees over the years. The current project proposes an optimum dosage of fibers ranging from 0.2 to 1 % for best composite behavior. A 1 % dosage of fiber in concrete produced in Alberta, would require 85770 tons of fibers per year. Multiple facilities to cater to the production of a large number of fibers would require to employ at least 5000 personnel and the overall revenue will be more than $1 billion.

1.2 Environmental Benefits

The project outcomes suggest that the incorporation of carbon fibers in concrete would significantly reduce the cost of construction, repair, and maintenance and reduced cement requirements. As result, its usage induces sustainability in construction and reduces the impact on the surrounding environment.

Two baseline indicators can be chosen for the proposed technology's impact on GHG emission reduction. 1) GHG emission contribution by the concrete industry and 2) GHG emission contribution by bitumen combustion.

1) GHG emission contribution by the concrete industry: The GHG emission by the concrete industry is approximately 1 ton of CO2 per 1 ton of cement production. Although the proposed technology can not directly reduce cement production, the direct reduction of CO2 would be negligible. However, since the proposed ABCF based cement

concrete could be used as a repair material, it would help extend the service life of existing structures. Furthermore, the innovative material could also be used as a new building material to construct sustainable and long-lasting structures. Both of these would lead to a reduction in GHG emissions.

2) GHG emission contribution by bitumen combustion: The use of carbon fibers in cement concrete would allow the reduction of GHG emission from the bitumen combustion. In 2016, the oil and gas sector was the largest source of GHG emissions, accounting for 26% of total national emissions in Canada [1]. Emissions of GHGs from the oil and gas sector have increased 70% from 107 Mt CO2 eq in 1990 to 183 Mt CO2 eq in 2016. This increase is mostly attributable to the increased production of crude oil and the expansion of the oil sands industry. On the other hand, due to the combustion of bitumen related products, the GHG emission led to 25% (173 Mt CO2 eq) of total national emissions in 2016.

1.3 Social Benefits

This project aims at developing a crack-free concrete system that is durable and stronger. Since the applications for this material include infrastructure for the public such as bus pads, sidewalks, bridge decks, etc, the crack-free nature of this material can have a positive impact on the public using the infrastructure making them feel safer. The higher resistance to cracking of this material can leave the municipalities and transit operators (infrastructure owners) with more confidence in their infrastructure and give them a higher ROI due to the extended life of the infrastructure.

1.4 Building Innovation Capacity:

The project has trained 3- post-doctoral fellows, 5 Coop students, and a Ph.D. student. In addition to that, the lab manager and two technologists of the Civil engineering department at UVic were also involved and trained. Engineers and technologists at the concrete ready-mix plant (Butler Brothers) were also involved in the project work. Overall, more than 10 HQSP’s were trained in this project. The knowledge gained in this project is applicable in AB and the learnings can be disseminated to the Alberta community through Alberta Innovates.

To execute different tasks of the project, various instruments, such as Tinius Olsen, 50-ton Press, fabrication of large-sized circular panels, and a three-point support system, were procured.

H. RECOMMENDATIONS AND NEXT STEPS

Please provide a narrative outlining the next steps and recommendations for further development of the technology developed or knowledge generated from this project. If appropriate, include a description of potential follow-up projects. Please consider the following in the narrative:

- Describe the long-term plan for commercialization of the technology developed or implementation of the knowledge generated.
- Based on the project learnings, describe the related actions to be undertaken over the next two years to continue advancing the innovation.
- Describe the potential partnerships being developed to advance the development and learnings from this project.

RESPOND BELOW

Please provide a narrative outlining how the knowledge gained from the project was or will be disseminated and the impact it may have on the industry.

RESPOND BELOW

The current project has successfully demonstrated the potential of incorporating carbon fibers in concrete and it is evident that the post-crack behavior of the composite significantly improves from brittleness to ductility. During the research work, it was seen that the increase in the length of the fiber from 6 mm to 18 mm significantly improves the post-crack behavior of the composite. The future work may involve researching the fiber of longer lengths and irregular cross-section shape. Furthermore, in this study, the used carbon fibers had negligible lateral stiffness due to which there was not much contribution to the uniaxial strength or the flexural behavior of the composite. This could also become a part of the future study where carbon fibers with higher lateral stiffness could be used. The influence of the incorporation of carbon fibers in concrete has shown great promise in improving the overall mechanical behavior of concrete and it has come out that carbon fibers should be included in all types of concrete construction for longer service life with reduced repair and maintenance work. this project has exploited the physical characteristics of carbon fibers such as modulus of elasticity, filament diameter, and aspect ratio. a follow-up project has already been submitted to Alberta innovates, that not only exploits the physical characteristics of carbon fibers but also the electrical properties as well. the follow-up project explored the utilization of already embedded carbon fibers inside concrete for electric conduction and therefore, self-heating of pavements. for the next two years, the focus will be on developing smart sensing, crack-free, self-healing concrete pavements which will be a game-changer for regions like Alberta.

For knowledge dissemination, interested stakeholders such as the Butler brothers- a local ready mixed concrete producer, a contractor, government officials from BC Transit, and Facilities management of UVIC were actively involved during the construction of the concrete bus pad. Furthermore, the knowledge produced during the research and construction of the crack-free concrete bus pad has been presented in technical conferences. Multiple research papers are written that are currently either under review in internal journals or in the editing phase.

Please provide a narrative outlining the project conclusions.

- Ensure this summarizes the project objective, key components, results, learnings, outcomes, benefits and next steps.

RESPOND BELOW

I. CONCLUSIONS

The focus of the construction industry has completely changed since the last decade towards sustainability and automation. The successful implementation of the project is an incremental addition to the sustainability goals of the construction industry. The project aimed to investigate the potential of utilizing carbon fibers as an additive in concrete to make it a "crack-free" and more durable construction material. Generally, concrete is a mix of cement, sand, and coarse aggregates, considered a highly brittle composite which considerably limits its potential for several construction applications. Furthermore, this characteristic makes concrete more vulnerable to rapid deterioration due to various causes such as fatigue, corrosion, freeze-thaw, etc. This reduces the overall service life of a concrete structure and increases the repair and maintenance costs significantly. From a load-displacement curve (recorded when a specimen is loaded during a test) perspective, failure of concrete is considered at the first yielding point (first crack). The essence of this project was to utilize carbon fibers for maintaining the composite integrity beyond the first crack (improving the post-crack performance) and therefore modifying the brittleness of the overall composite. The entire project was divided into 5 Milestones. In the 1st milestone, fibers were acquired from different sources such as Mitsubishi, Zoltek, Euclid, Teijin, and the University of Alberta. In the 2nd milestone, SEM and XRD analysis of all the procured fibers was done to evaluate their surface characteristics. In the 3rd milestone, different fiber volume fractions V_f ranging from 0.5 to 10 % were used to cast fiber-mortar samples and their mechanical behavior was evaluated. In the 4th milestone, carbon fibers with V_f ranging from 0.5 to 2 % were used to cast medium-size and large-size concrete samples, and their mechanical behavior was evaluated. In the 5th milestone, a real-time demonstration of the carbon fiber-reinforced composite was completed through the construction of a smart sensing crack-free bus pad at UVic bus exchange. Following are the key learnings from the project work:

- ABCF fibers were found to have a slightly lower carbon content and it is hypothesized that this is because of the non-graphitization of fibers at the production stage. For all other fibers, PITCH based fibers exhibited 94 % carbon content and PAN-based fibers exhibited 98 % carbon content
- Fibers of different lengths ranging from 6 mm to 18 mm were used to evaluate the effect of length on the composite behavior. It was found that by increasing the length of fibers, the post crack performance of the overall matrix was improved significantly.

- The pre-coating of fibers can be considered to improve the fiber-matrix bond that is a prime factor for improving the mechanical behavior of the composite. Dr. Gupta's surface coating technology can be a possible solution.
- Amongst all the commercially available fibers used in the study, Teijin fibers of 18 mm length yielded the best results.
- The fiber addition in concrete will significantly enhance the toughness (which is a measure of ductility) and the post crack strength performance of the concrete as observed from flexural and round panel tests.
- With the Volume fraction V_f ranging between 0.5 to 1, compressive strength, tensile strength, and flexural strength increase marginally by 10-15 %. However, beyond this range of volume fraction, it begins to decrease (this is expected).
- The agglomeration of carbon fibers in the concrete mix increases significantly at a higher dosage of carbon fibers required the increasing the percentage of admixtures.
- Due to the extremely small diameter, the carbon fibers reduces the workability mix with increasing dosage.
- Greater fiber lengths (> 12mm) can be useful in providing a dual pull-out and fiber fracture mechanism overall enhancing the damage resistance of the composite.
- Coating of fibers using sustainable construction materials improves the failure mechanism by inducing both fiber-pullout and fiber fracture.
- In synthetic macro and microfiber samples, the failure mode is a complete pull-out of fiber from the cement matrix, while in carbon fibers, fiber fracture and fiber pull-out were the two failure modes observed during the pull-out test.
- The incorporation of carbon fibers can significantly reduce freeze-thaw related damage in concrete as it tends to hold the matrix together.
- Carbon fiber-reinforced composite has better load transfer efficiency and exhibits the uniform distribution of the overall load. This can be instrumental in achieving reduced differential displacements.
- Carbon fibers maintain the structural integrity of the concrete composite by stitching action and therefore, their participation is largely active only during active cracking.

Overall, the project outcomes strongly suggest the inclusion of carbon fibers in concrete can improve its behavior. The inclusion of carbon fiber in the construction sector can be highly beneficial for Alberta which is a huge source of oil and asphaltene. Considering carbon fibers produced from processing bitumen, their utilization in concrete can significantly generate large employment opportunities and promote sustainability. The focus of this project was to utilize the physical properties of carbon fibers to improve the behavior of concrete. In the next proposed project, the focus will be on exploiting the physical as well as electrical characteristics of carbon fibers with a dual objective : 1) to improve the overall mechanical behavior of concrete; 2) to make concrete conducive to induce self-heating characteristics during field implementation.

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