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**
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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

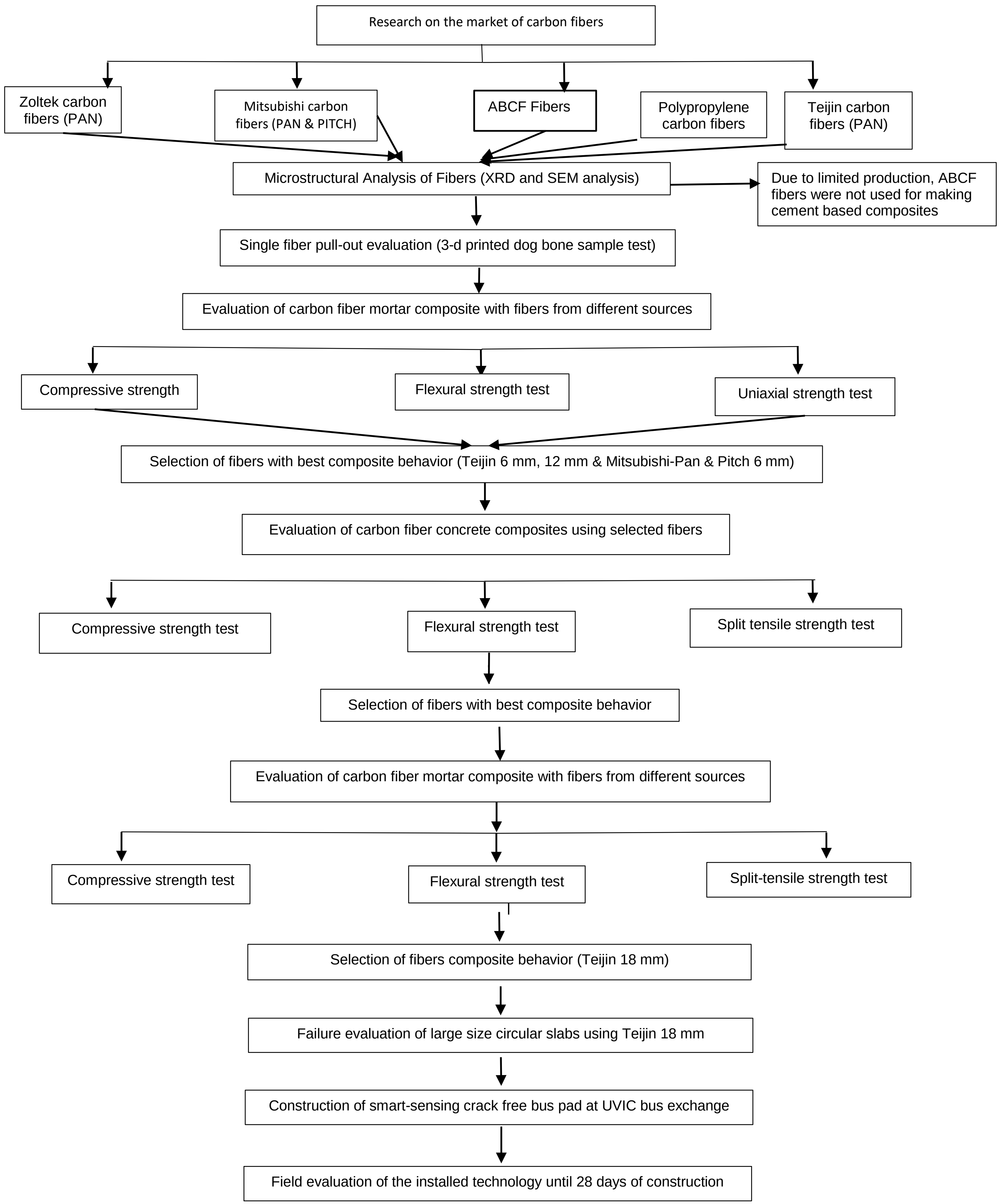
1.1 Facilities used for the project:

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:



Research on the market of carbon fibers
Zoltek carbon fibers (PAN)
Mitsubishi carbon fibers (PAN & PITCH)
ABCF Fibers
Polypropylene carbon fibers
Teijin carbon fibers (PAN)
Microstructural Analysis of Fibers (XRD and SEM analysis)
Due to limited production, ABCF fibers were not used for making cement based composites
Single fiber pull-out evaluation (3-d printed dog bone sample test)
Evaluation of carbon fiber mortar composite with fibers from different sources
Compressive strength
Flexural strength test
Uniaxial strength test
Selection of fibers with best composite behavior (Teijin 6 mm, 12 mm & Mitsubishi-Pan & Pitch 6 mm)
Evaluation of carbon fiber concrete composites using selected fibers
Compressive strength test
Flexural strength test
Split tensile strength test
Selection of fibers with best composite behavior
Evaluation of carbon fiber mortar composite with fibers from different sources
Compressive strength test
Flexural strength test
Split-tensile strength test
Selection of fibers composite behavior (Teijin 18 mm)
Failure evaluation of large size circular slabs using Teijin 18 mm
Construction of smart-sensing crack free bus pad at UVIC bus exchange
Field evaluation of the installed technology until 28 days of construction

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.

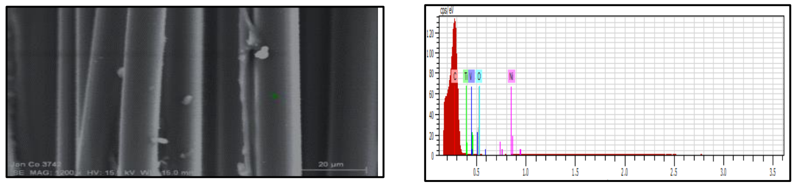


Fig. 1 EDX results of Pitch based carbon fibers

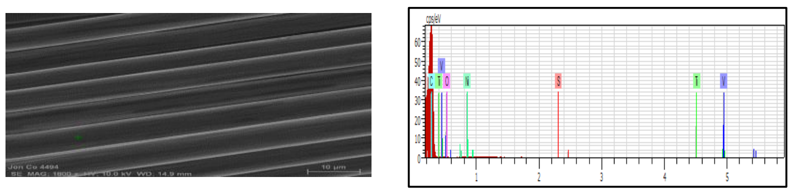


Fig. 1 EDX results of PAN based carbon fibers

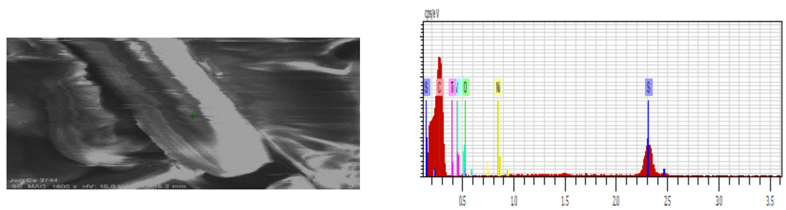


Fig. 3 EDX results of Ashphaltene based carbon fibers

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.

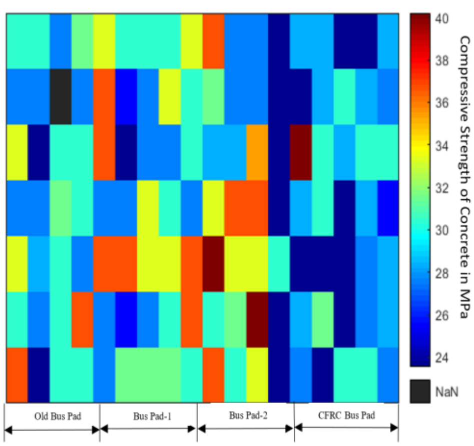


Fig. 4 Schmidt Hammer Test

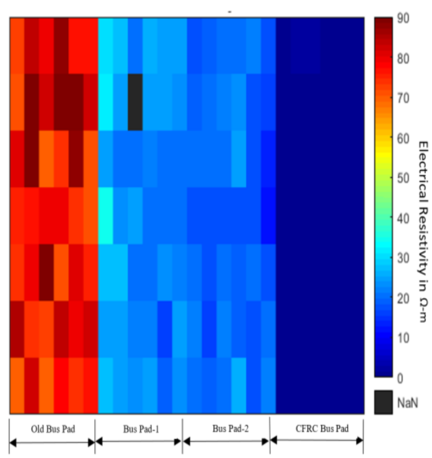


Fig. 5 Electrical Resistivity Test

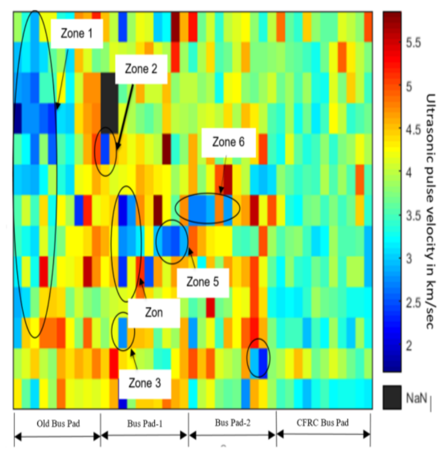


Fig. 6 Ultrasonic Pulse Velocity Test

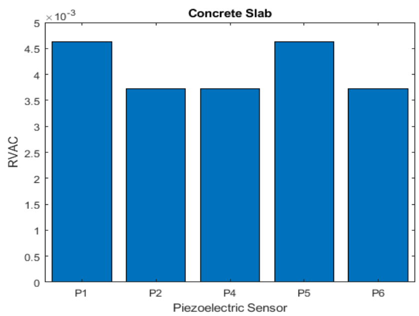


Figure 7a: Relative Voltage Attenuation Coefficient (RVAC) for signals recorded in concrete bus pad by piezoelectric sensors (P1, P2, P4, P5, and P6) when piezoelectric actuator (P3) was excited.

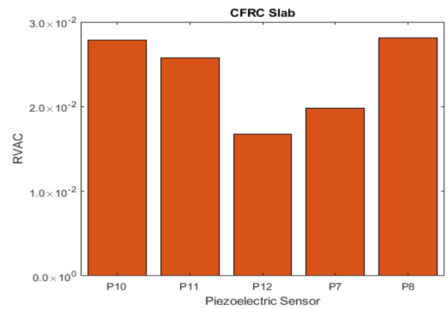


Figure 7b: Relative Voltage Attenuation Coefficient (RVAC) for signals recorded in CFRC bus pad by piezoelectric sensors (P7, P8, P10, P11, and P12) when piezoelectric actuator (P9) was excited.

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 CO_2 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 CO_2 eq in 1990 to 183 Mt CO_2 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 CO_2 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.

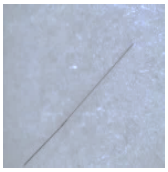
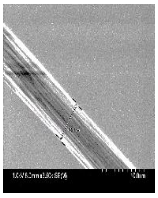
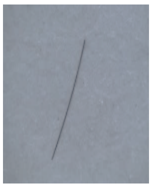
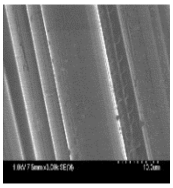
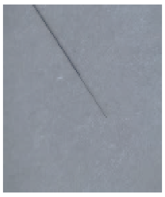
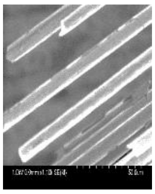
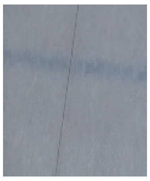
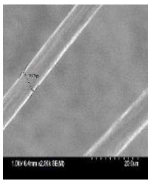
Overall, the project outcomes strongly suggest the inclusion of carbon fibers in concrete can improve its behavior. The inclusion of carbon fiber in the construction sector can be highly beneficial for Alberta which is a huge source of oil and asphaltene. Considering carbon fibers produced from processing 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.

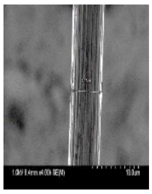
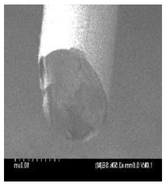
References:

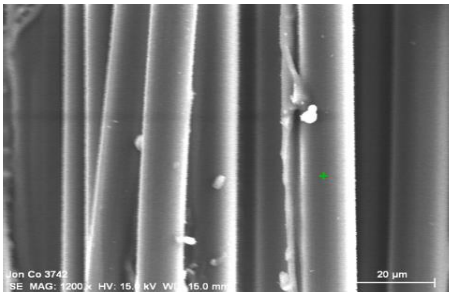
1) ACI Committee 440. "State-of-the-art report on fiber reinforced plastic (FRP) reinforcement for concrete structures." American Concrete Institute, 1996.
2) ASTM C1550-20, Standard Test Method for Flexural Toughness of Fiber Reinforced Concrete (Using Centrally Loaded Round Panel), ASTM International, West Conshohocken, PA, 2020
3) ASTM C666 / C666M-15, Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing, ASTM International, West Conshohocken, PA, 2015.
4) Available online: https://www.concretealberta.ca/about

Appendix 1

Table 1-1 Details of acquired fibers and their characteristics

Source	**Type**	**Length^{+} (mm)**	**Filament Diameter^{++} (µm)**	**Filament Diameter^{+} (µm)**	**Specific Gravity^{+}**	**Tensile Modulus^{+} (GPa)**	**Tensile Strength^{+} (GPa)**	**Optical Microscopic View^{++} (x45 zoom)**	**Scanning Electron Microscopy photos^{++}**
Euclid	Virgin monofilament polypropylene (PSI 150)	6 &19		~25	0.91	-	-		
	Virgin monofilament polypropylene (Multimix 80)	13		~30	0.91	-	-		
Mitsubishi	PAN (PU6-1) (Chopped fiber)	6	6.5	6	1.8	234	4.8		
	Pitch (K223SE) (Chopped fiber)	6	11	11	2	186	2.34		
Zoltek	PAN (PX35-45) (Chopped fiber)	6	7.2	7.2	1.81	242	4.14		
	PAN (PX35-65) (Chopped fiber)	6	7.2	7.2	1.81	242	4.14		

Teijin	PAN (Chopped fiber)	6, 12, 18	6.85-7.2	7	1.9	227	4.89		
ABCF	Asphaltene	Strand	10	-	-	-	-		



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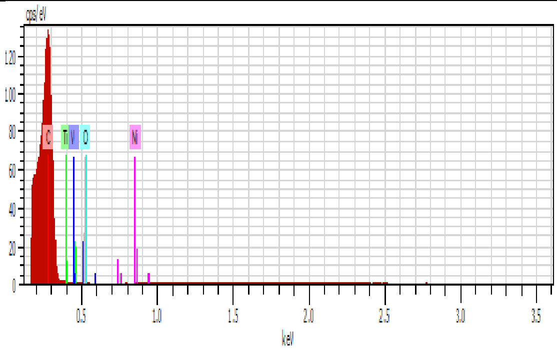
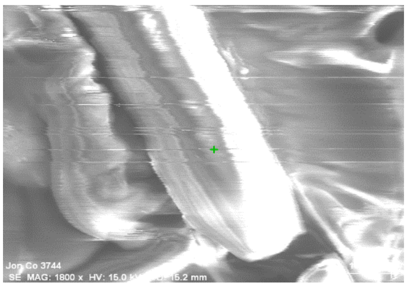
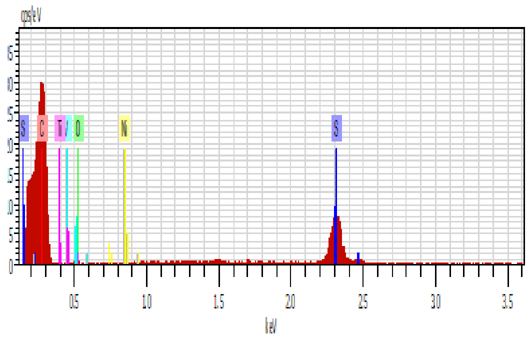


b)

Fig. 1-1 EDX results of Pitch based carbon fiber

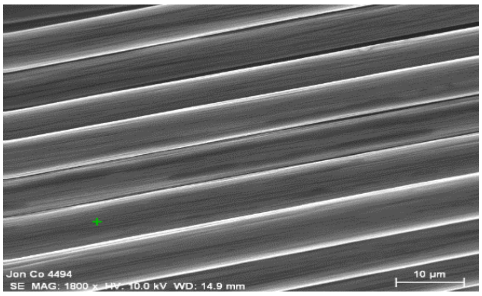


a)

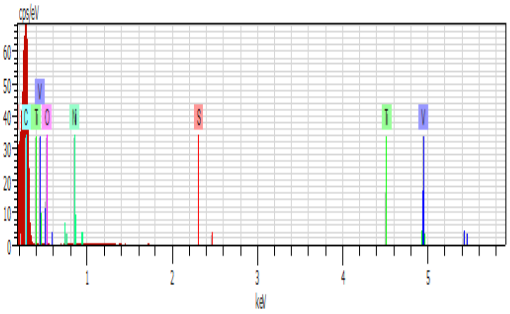


b)

Fig. 1-2 EDX results of Asphaltene based carbon fiber



a)



b)

Fig. 1-3 EDX results of PAN based carbon fiber

Appendix 2

Table 2-1 Fiber Nomenclature and Mix design details

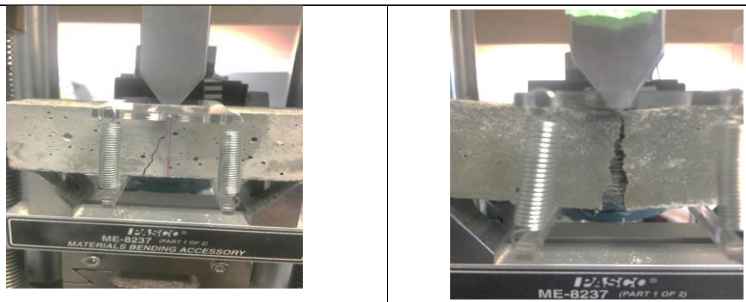
Fiber	**Design mix details**					
Compound	Qty. of Cement		Qty. of sand		Water	
	Kg/m^3	Vol (%)	Kg/m^3	Vol (%)	Kg/m^3	Vol (%)
Control sample (Co)	712.00	23.00	1188.00	47.00	281.00	28.00
Carbon 45 from PAN(C45-1)	712.00	23.00	1188.00	47.00	281.00	28.00
Carbon 45 from PAN(C45-2)	712.00	23.00	1188.00	47.00	281.00	28.00
Carbon 65 from PAN(C65-1)	712.00	23.00	1188.00	47.00	281.00	28.00
Carbon 65 from PAN(C65-2)	712.00	23.00	1188.00	47.00	281.00	28.00
Polypropylene (Py-1)	712.00	23.00	1188.00	47.00	281.00	28.00
Polypropylene (Py-2)	712.00	23.00	1188.00	47.00	281.00	28.00
Polypropylene (Py-3)	712.00	23.00	1188.00	47.00	281.00	28.00
Polypropylene (Py-4)	712.00	23.00	1188.00	47.00	281.00	28.00
Polypropylene (Py-5)	712.00	23.00	1188.00	47.00	281.00	28.00
Polypropylene (Py-6)	712.00	23.00	1188.00	47.00	281.00	28.00
Carbon from PAN(Cpa-1)	712.00	23.00	1188.00	47.00	281.00	28.00
Carbon from PAN(Cpa-2)	712.00	23.00	1188.00	47.00	281.00	28.00
Carbon from PAN(Cpa-3)	712.00	23.00	1188.00	47.00	281.00	28.00
Carbon from PAN(Cpa-4)	712.00	23.00	1188.00	47.00	281.00	28.00
Carbon from PITCH(Cpi-1)	712.00	23.00	1188.00	47.00	281.00	28.00
Carbon from PITCH(Cpi-2)	712.00	23.00	1188.00	47.00	281.00	28.00
Carbon from PITCH(Cpi-3)	712.00	23.00	1188.00	47.00	281.00	28.00
Carbon from PITCH(Cpi-4)	712.00	23.00	1188.00	47.00	281.00	28.00
Carbon from PITCH(Cpi-5)	712.00	23.00	1188.00	47.00	281.00	28.00
Carbon from PITCH(Cpi-6)	712.00	23.00	1188.00	47.00	281.00	28.00
Carbon from PITCH(Cpi-7)	712.00	23.00	1188.00	47.00	281.00	28.00
Carbon from PITCH(Cpi-8)	712.00	23.00	1188.00	47.00	281.00	28.00
Carbon from PITCH(Cpi-9)	712.00	23.00	1188.00	47.00	281.00	28.00
Carbon from PITCH(Cpi-10)	712.00	23.00	1188.00	47.00	281.00	28.00
Carbon from PITCH(Cpi-11)	712.00	23.00	1188.00	47.00	281.00	28.00
Carbon from PITCH(Cpi-12)	712.00	23.00	1188.00	47.00	281.00	28.00
Carbon from PITCH(Cpi-13)	712.00	23.00	1188.00	47.00	281.00	28.00
Carbon from PITCH(Cpi-14)	712.00	23.00	1188.00	47.00	281.00	28.00

Carbon from PITCH(Cpi-15)	712.00	23.00	1188.00	47.00	281.00	28.00
Carbon from PAN(Cpa-5)	712.00	23.00	1188.00	47.00	281.00	28.00
Carbon from PAN(Cpa-6)	712.00	23.00	1188.00	47.00	281.00	28.00
Carbon from PAN(Cpa-7)	712.00	23.00	1188.00	47.00	281.00	28.00
Carbon from PAN(Cpa-8)	712.00	23.00	1188.00	47.00	281.00	28.00

Table 2-2 Mechanical characteristics of fiber reinforced mortar and Post crack strength analysis

Fiber	Physical properties of fibers				Strength Characteristics				Flexural toughness characteristics of Matrix			
Compound	**Length**	**Dia**	**Tensile Strength**	**Modulus**	**Concentration**	**Compressive Strength (Mpa)**	**Tensile Strength (MPa)**	**Flexural Strength (Mpa)**	**First Crack Deflection**	**Collapse displacement**	**Ductility**	**Post crack strength (Mpa)**
C-1	0.00	0.00	0.00	0.00	0.00	56.80	3.75	10.57	0.00	0.00	0.00	0.00
C45-1	6.00	7.20	4.14	242.00	0.50	62.00	4.39	10.25	0.09	1.87	1.78	2.20
C-45-2	6.00	7.20	4.14	242.00	1.00	52.00	4.76	10.76	1.67	2.83	1.16	2.40
C-65-1	6.00	7.20	4.14	242.00	0.50	49.50	4.11	12.50	0.16	1.03	0.87	3.10
C-65-2	6.00	7.20	4.14	242.00	1.00	47.50	3.98	13.10	0.88	3.82	2.94	2.65
Py-1	6.00	30.00	3.20	120.00	0.50	47.60	3.89	8.57	0.18	1.39	1.21	1.93
Py-2	6.00	30.00	3.20	120.00	1.00	50.00	3.93	7.69	0.21	1.99	1.78	2.81
Py-3	13.00	30.00	3.20	120.00	0.50	52.00	4.21	10.75	0.24	1.31	1.07	4.24
Py-4	13.00	30.00	3.20	120.00	1.00	50.40	3.66	8.38	0.65	2.64	1.99	4.35
Py-5	19.00	30.00	3.20	120.00	0.50	45.60	3.52	7.35	0.37	2.26	1.89	6.95
Py-6	19.00	30.00	3.20	120.00	1.00	50.00	3.13	6.71	0.26	1.86	1.60	3.43
Cpa-1	6.00	6.00	4.80	234.00	0.50	54.80	4.11	11.43	0.53	4.29	3.76	2.10
Cpa-2	6.00	6.00	4.80	234.00	1.00	54.40	5.36	11.40	0.16	1.50	1.34	2.20
Cpa-3	6.00	6.00	4.80	234.00	2.00	35.66	5.20	12.10	0.15	1.87	1.72	2.90
Cpa-4	6.00	6.00	4.80	234.00	3.00	41.38	5.30	11.90	1.93	2.74	0.81	2.61
Cpi-1	6.00	11.00	2.34	186.00	0.50	59.20	5.45	12.65	1.87	3.00	1.13	5.10
Cpi-2	6.00	11.00	2.34	186.00	1.00	54.80	4.37	11.43	0.53	4.29	3.76	4.89
Cpi-3	6.00	11.00	2.34	186.00	2.00	41.70	5.15	13.10	0.52	2.46	1.94	5.40
Cpi-4	6.00	11.00	2.34	186.00	3.00	49.70	5.12	13.20	1.00	2.78	1.78	6.50

Cpi-5	6.00	11.00	2.34	186.00	10.00	21.46	5.05	13.20	0.09	3.34	3.25	6.40
Cpi-6	6.00	7.00	4.89	227.00	0.50	57.80	4.80	13.10	0.31	3.76	3.45	5.32
Cpi-7	6.00	7.00	4.89	227.00	1.00	51.00	4.45	12.10	0.20	4.85	4.65	5.10
Cpi-8	6.00	7.00	4.89	227.00	2.00	36.54	5.33	13.40	0.36	2.75	2.39	5.54
Cpi-9	6.00	7.00	4.89	227.00	3.00	31.68	5.60	1.30	0.89	4.63	3.74	8.75
Cpi-10	12.00	7.00	4.89	227.00	0.50	58.10	4.85	1.20	0.89	4.12	3.23	6.30
Cpi-11	12.00	7.00	4.89	227.00	1.00	52.00	4.65	12.60	0.50	1.48	0.98	7.20
Cpi-12	12.00	7.00	4.89	227.00	2.00	34.40	5.50	13.20	0.70	2.44	1.74	8.23
Cpi-13	12.00	7.00	4.89	227.00	3.00	44.40	5.20	13.20	1.36	3.13	1.77	12.30
Cpi-14	6.00	7.00	4.89	227.00	0.50	52.40	5.43	11.56	0.71	3.86	3.15	3.35
Cpi-15	6.00	7.00	4.89	227.00	1.00	63.20	4.06	12.56	0.68	4.15	3.47	3.95
Cpa-5	6.00	6.00	4.80	234.00	0.50	57.20	4.57	11.10	0.68	3.84	3.16	3.45
Cpa-6	6.00	6.00	4.80	234.00	1.00	64.80	4.31	11.39	1.50	4.00	2.50	4.00
Cpa-7	12.00	6.00	4.80	234.00	0.50	62.80	5.04	10.04	0.49	3.92	3.43	3.68
Cpa-8	12.00	6.00	4.80	234.00	1.00	54.40	4.67	12.94	0.59	3.75	3.16	3.65



(a) (b)

Fig 2-1 Three-point flexural testing of carbon fiber reinforced mortar beams

(a) (b)

Fig 2-2 Direct tensile test on carbon fiber reinforced dog bone samples

(a)

Fig. 2-3 Testing CF reinforced cubes under compression

Appendix 3

Table 3-1 Mix Design details for medium size and large size samples

Specimen	% of fiber by volume	**Gravel**		**Sand**		**Cement**		**Fly ash**		water		WRA	AEA
		Kg/m^3	Vol (%)	Kg/m^3	Vol (%)	Kg/m^3	Vol (%)	Kg/m^3	Vol (%)	Kg/m3	Vol (%)	gram/m3	Gram/m3
COC	×	1055	42.2	815	32.5	276	8.9	60	2	148	14.8	1883	123
1P13C	1	1055	42.2	815	32.5	276	8.9	60	2	148	14.8	1883	123
2P13C	2	1055	42.2	815	32.5	276	8.9	60	2	148	14.8	1883	123
1PAM6C	1	1055	42.2	815	32.5	276	8.9	60	2	148	14.8	1883	123
1PIM6C	1	1055	42.2	815	32.5	276	8.9	60	2	148	14.8	1883	123
1PAM6C	2	1055	42.2	815	32.5	276	8.9	60	2	148	14.8	1883	123
1PIM6C	2	1055	42.2	815	32.5	276	8.9	60	2	148	14.8	1883	123
1PIT6C	1	1055	42.2	815	32.5	276	8.9	60	2	148	14.8	1883	123
1PIT6C	2	1055	42.2	815	32.5	276	8.9	60	2	148	14.8	1883	123
1PIT12C	1	1055	42.2	815	32.5	276	8.9	60	2	148	14.8	1883	123
1PIT12C	2	1055	42.2	815	32.5	276	8.9	60	2	148	14.8	1883	123
1PIT18C	1	1055	42.2	815	32.5	276	8.9	60	2	148	14.8	1883	123
1PIT18C	2	1055	42.2	815	32.5	276	8.9	60	2	148	14.8	1883	123

Table 3-2 Test results of flexural testing of medium size beams

Specimen	Load (KN)	Modulus of Rupture (Mpa)	Mean	Standard Deviation
CO1	6258	3.28545	3.23995	0.475186584
CO2	7030	3.69075		
CO3	5226	2.74365		
T0.5S1	8016	4.2084	5.3095	1.078824074
T0.5S2	12123	6.364575		
T0.5S3	10201	5.355525		
T1S1	14844	7.7931	6.8404	0.834158312
T1S2	12356	6.4869		
T1S3	11888	6.2412		
T2S1	7210	3.78525	3.689175	0.340291134
T2S2	7564	3.9711		
T2S3	6307	3.311175		
PAN1S1	18100	9.5025	5.8191	4.804287822
PAN1S2	908	0.4767		
PAN1S3	4068	2.1357		
Pitch1S1	3968	2.0832	2.2987125	0.3047807
Pitch1S2	4789	2.514225		
Pitch1S3	NA	NA		
PP1S1	2685	1.409625	1.791825	0.831540505
PP1S2	2324	1.2201		
PP1S3	5230	2.74575		
PP2S1	4977	2.612925	2.3744	0.804243511
PP2S2	2815	1.477875		
PP2S3	5776	3.0324		

Table 3-3 Physical charcateristics of samples subjected to freeze thaw cycles

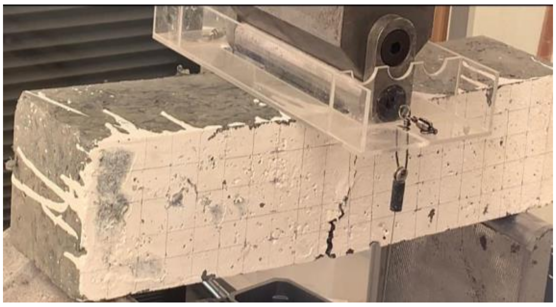
Specimen	Mass	Length (m)	Depth (m)	Width (m)
Pitch1	7.16	0.404	0.077	0.102
PP1	6.78	0.404	0.076	0.102
PP2	6.97	0.405	0.075	0.101
Pan 1	7.5	0.405	0.077	0.101
Pitch2	7.09	0.405	0.077	0.1
CO2	7.7	0.405	0.076	0.1
Pan2	7.24	0.406	0.076	0.102
PP3	6.87	0.404	0.075	0.1
PP4	6.97	0.404	0.077	0.1014
Pan3	7.3	0.404	0.077	0.101
PP5	6.94	0.406	0.077	0.102
CO1	7.58	0.405	0.077	0.1
PP6	7.07	0.405	0.077	0.101
Pitch3	7.2	0.405	0.077	0.102

Table 3-4 Resonant Frequency test results of samples subjected to free-thaw cycles

Name	Transverse f (Hz)	Longitudinal f (Hz)	Torsional f (Hz)	E (Pascals) (T)	E (Pascals)(L)	G (Pascals)
Pitch1	3506	4882	1997	1.39E+11	3.45E+10	266.41
PP1	1953	4572	1953	4.34E+10	2.95E+10	267.07
PP2	1953	4794	1953	4.69E+10	3.42E+10	267.07
Pan 1	2308	5282	2263	6.55E+10	4.36E+10	267.07
Pitch2	2041	4971	2041	4.87E+10	3.68E+10	267.07
CO2	2441	5637	2441	7.89E+10	5.22E+10	267.07
Pan2	2263	5282	2263	6.29E+10	4.23E+10	267.73
PP3	1997	4838	1997	4.89E+10	3.48E+10	266.41
PP4	1955	4794	1997	4.31E+10	3.31E+10	266.41
Pan3	2308	5371	2308	6.32E+10	4.38E+10	266.41
PP5	1997	4838	1997	4.58E+10	3.39E+10	268.39
CO1	2397	5726	3196	7.20E+10	5.23E+10	267.07
PP6	2086	4971	2086	5.05E+10	3.65E+10	267.07
Pitch3	3506	4882	1997	1.42E+11	3.51E+10	267.07

a) Casting of medium size specimens

b) Preparation of Beam samples for testing



c) Three-point flexure test

d) Stitching action of fibers

Figure 3-1 Casting and Testing of carbon fiber reinforced specimens

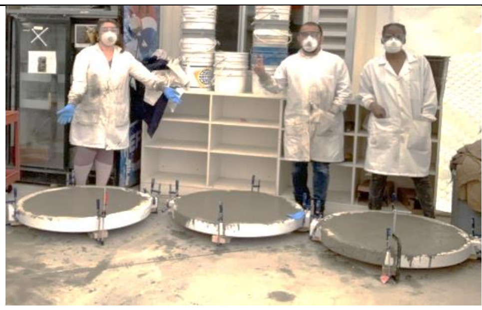
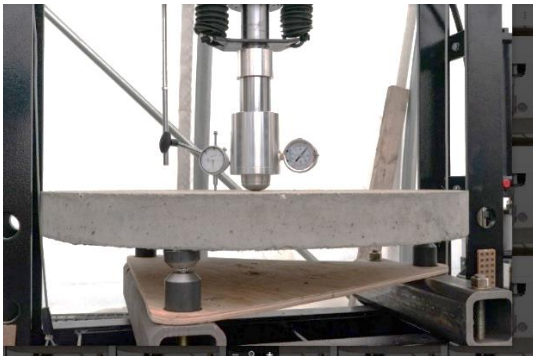
 a) Large size round panel molds prepared at UViC	 b) Casting of large size round panels
 c) curing of large size round panels	 d) Automation of 50 tonne Press for round panel testing
 e) A three-point support system designed and developed at UViC	 f) Testing of 1st circular panels with the entire group

Fig. 3-2 Round panel sample preparation and instrumentation for testing

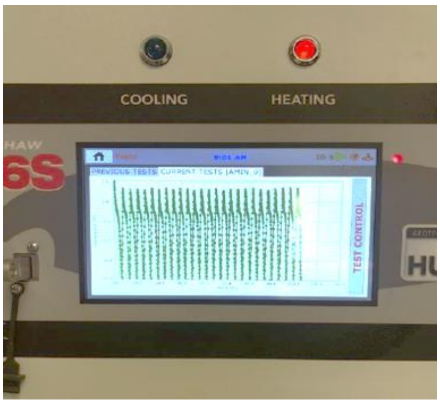
a) Control samples exhibiting a brittle failure and zero post crack strength

b) Carbon fiber reinforced samples exhibiting significant post cracking behavior

c) Triangular cracking in carbon fiber reinforced concrete

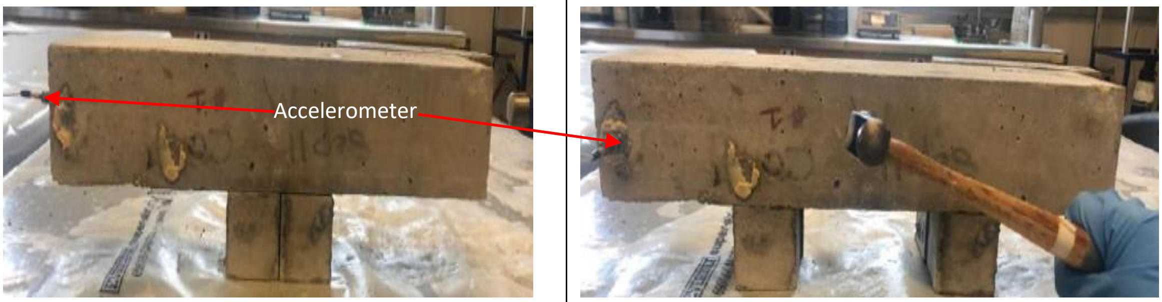
Fig. 3-3 Testing of Carbon fiber reinforced round panels

a) Carbon fiber reinforced concrete samples kept in Freeze thaw chamber



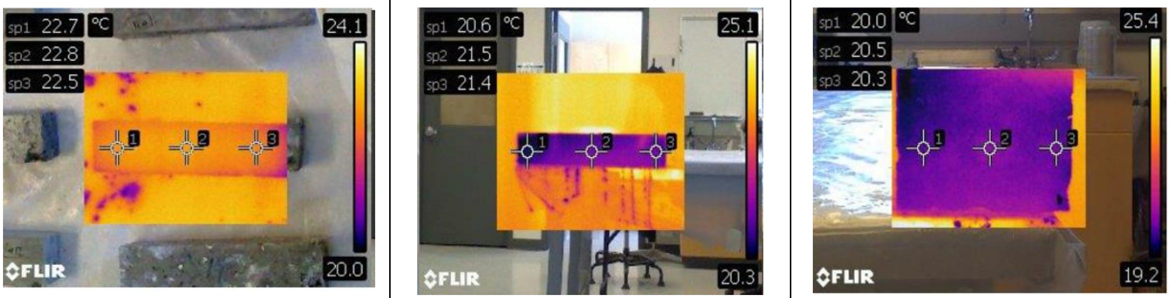
b) Freeze-thaw chamber controller

Fig. 3-4 Carbon fiber reinforced concrete samples subjected to continous free-thaw cycles



a) b)

Fig. 3-5 Resonant Frequency test to evaluate the dynamic modulus of carbon fiber reinforced concrete subjected to freeze-thaw cycles



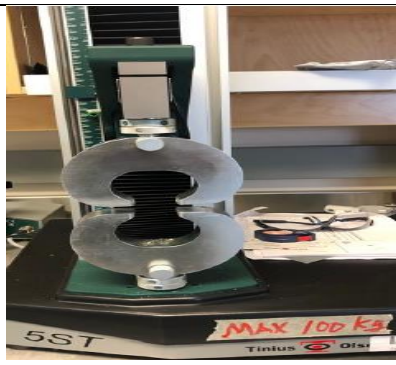
a) b) c)

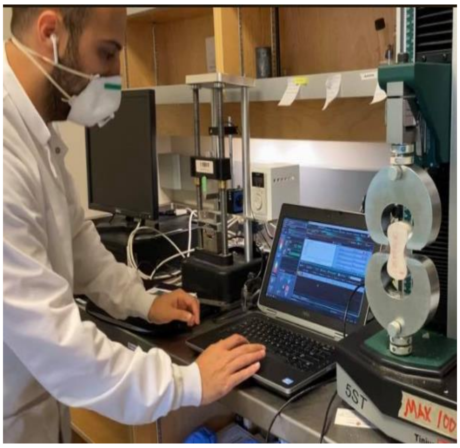
Fig. 3-6 Infra-red thermography of samples subjected to freeze-thaw cycles

Appendix 4

Table 4-1 Test results from fiber pull-out test

		Pmax	SD	Δpmax	Wp	σf,max	τav	τeq
	Day	N		mm	N.mm	MPa	MPa	MPa
S	7	308	9.1	3.1	925	392.4	3.9	0.943
S	14	382	12.1	3.7	915	486.6	4.9	0.932
S	28	358	0.7	3.5	1050	456.1	4.6	1.070
S	56	346	71.1	3.6	1053	440.8	4.4	1.073
SI	7	106	29.1	3.6	255	353.3	1.9	0.374
SI	14	115	38.5	3.1	245	383.3	2.1	0.360
SI	28	122	25.4	3.5	277	406.7	2.2	0.407
SI	56	140	15	4.18	453	466.7	2.5	0.665
PA0.5	7	31	12.1	0.8	16	158.0	0.8	0.033
PA0.5	14	43	21.9	0.8	14	219.2	1.1	0.029
PA0.5	28	-	-	-	-	-	-	-
PA0.5	56	76	-	0.7	15	387.4	1.9	0.031
PA0.8	7	65	-	-	-	-	-	-
PA0.8	14	73	33.23	0.7	36	145.4	1.2	0.046
PA0.8	28	135	-	0.7	36	268.9	2.1	0.046
PA0.8	56	143	-	0.8	38	284.9	2.3	0.048
PA1	7	139	16.9	1.1	36	177.1	1.8	0.037
PA1	14	144	-	0.8	44	183.4	1.8	0.045
PA1	28	155	-	0.8	47	197.5	2.0	0.048
PA1	56	160	-	0.9	54	203.8	2.0	0.055
PI0.5	7	81	10.2	0.6	27	412.8	2.1	0.055
PI0.5	14	100	-	0.7	48	509.7	2.5	0.098
PI0.5	28	111	-	0.7	50	565.7	2.8	0.102
PI0.5	56	-	-	-	-	-	-	-
PI0.8	7	98	35.3	0.7	36	195.2	1.6	0.046
PI0.8	14	110	-	0.7	42	219.1	1.8	0.054
PI0.8	28	-	-	-	-	-	-	-
P0.8	56	127	-	0.8	55	253.0	2.0	0.070
PI1	7	100	-	0.7	28	127.4	1.3	0.029
PI1	14	104	-	0.7	36	132.5	1.3	0.037
PI1	28	156	108.5	0.5	55	198.7	2.0	0.056
PI1	56	165	22	0.7	62	210.2	2.1	0.063

 a) Dog bone samples embedded with 3-d printed plates for simulating a single-fiber pull-out	 b) Newly purchased grips for Tinius Olsen for testing dog bones



c) Single fiber pull-out test

Fig. 4-1 Dog bone test for single fiber pull-out using Tinius Olsen

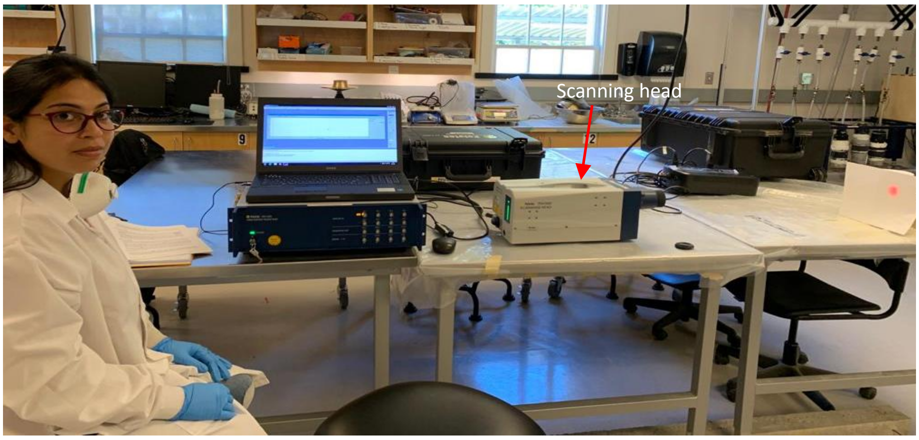


Fig. 4-2 Setting up Laser Scanning Vibrometer for evaluating Fiber reinforced concrete

Appendix 5

a) Bus pad 1

b) Bus pad 2

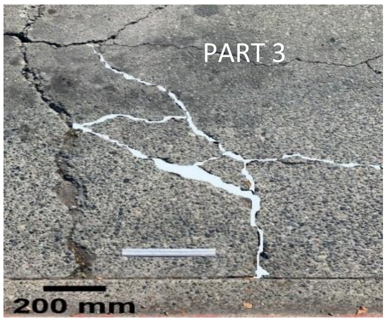
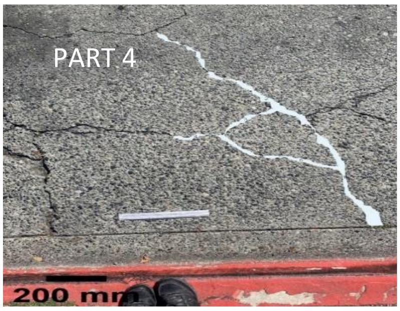
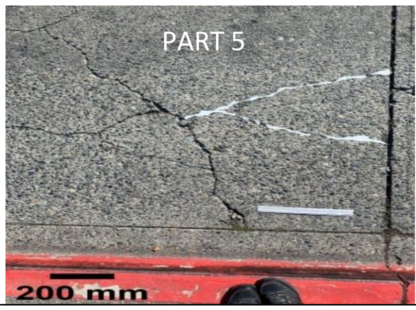
c) Bus Pad 3

Fig. 5-1 Existing bus pads (to be replaced)

Table 5-1 Crack analysis of bus pad 1 using Image J

Slab No.	**Crack Area**	**Slab Section**
slab 1-part 1	16201.536	
slab 1-part 1	20667.747	
slab 1-part 1	13369.454	
slab 1-part 1	7137.031	
slab 1-part 1	12063.993	
slab 1-part 1	4986.86	
slab 1-part 1	2475.768	
slab 1-Part 2	4290.274	
slab 1-Part 2	12185.536	
slab 1-Part 2	3282.793	
slab 1-Part 2	1686.783	
slab 1-Part 2	8460.848	
slab 1-part 3.jpg	28478.823	
slab 1-part 3.jpg	8118.479	
slab 1-part 3.jpg	5744.324	
slab 1-part 3.jpg	1095.339	
Total crack Area	150245.88 (mm^2)	

Table 5-2 Crack analysis of bus pad 2 using Image J

Slab #	Area (mm²)	Slab section
Slab 2 part1	12701.689	
Slab 2 part1	21482.176	
Slab 2 part1	3039.4	
Slab 2 part1	35414.634	
Slab 2 part1	6637.899	
Slab 2 part1	4013.133	
Slab 2 part1	7283.302	
Slab 2 part1	12701.689	
slab 2- part 2	11572.65	
slab 2- part 2	2697.436	
slab 2- part 2	19097.436	
slab 2 part 3	22672.22	
slab 2 part 3	1352.131	
slab 2 part 3	7832.426	
slab 2 part 3	4407.241	
slab 2 part 3	7882.089	
slab 2 part 3	4492.15	
Slab 2 part 4	13609.523	
Slab 2 part 4	9105.48	
Slab 2 part 4	3342.658	
Slab 2 part 4	4419.512	
Slab 2 part 4	3476.805	
slab 2-part 5	8092.21	
slab 2-part 5	6406.995	

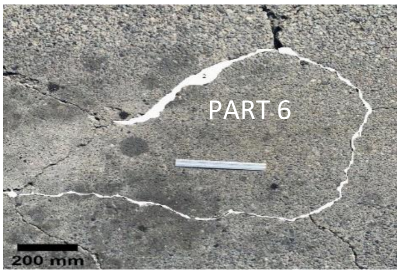
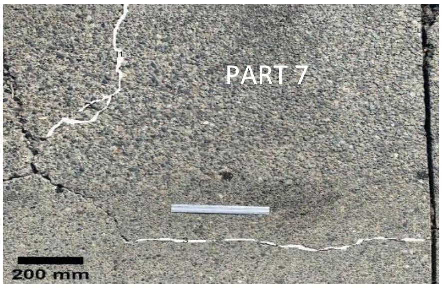
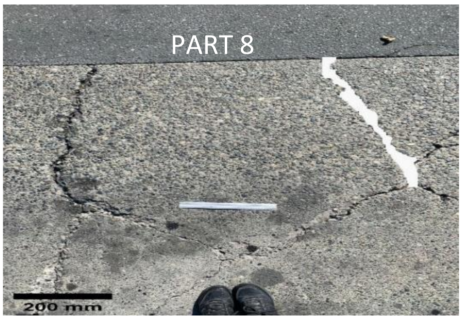
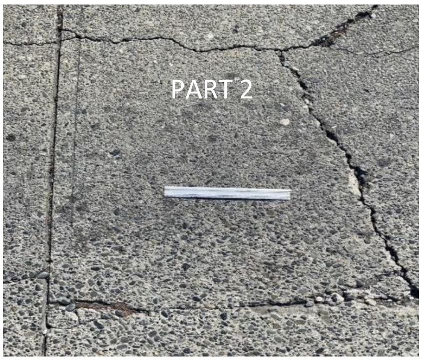
slab 2- part 6	11078.766	
slab 2- part 6	19090.018	
slab 2- part 6	7655.123	
slab 2-part 7	8548.818	
slab 2-part 7	1151.39	
slab 2-part 7	7625.668	
slab 2-part 8	12913.114	
Total Area	301795.781	

Table 5-3 Crack analysis of bus pad 3 using Image J

Slab No.	Area (mm^2)	Slab section
slab 3-part 1.jpg	29357.907	
slab 3-part 1.jpg	18478.002	
slab 3-part 1.jpg	7563.747	
slab 3-part 1.jpg	1891.928	

		
slab 3-part 2.jpg	4293.066	
slab 3-part 2.jpg	310.51	
slab 3-part 2.jpg	12738.77	
slab 3-part 3.jpg	5073.763	
slab 3-part 3.jpg	21495.516	
Total crack Area	101203.209	

Design of rigid pavement based on AASHTO guide for design of pavement structures 1993: Design Equation (Rigid Pavement)

The basic design equation is as follows:

$$\log_{10} W_{18} = Z_R \times S_0 + 7.35 \times \log_{10}(D+1) - 0.06 + \frac{\log_{10}\left(\frac{\Delta PSI}{4.5-1.5}\right)}{1+\frac{1.624\times10^{7}}{(D+1)^{8.46}}} + (4.22 - 0.32p_t) \times \log_{10}\left[\frac{(S_c^{'})(C_d)(D^{0.75}-1.132}{215.63\,(J)\left(D^{0.75}-\frac{18.42}{\left(\frac{E_c}{k}\right)^{0.25}}\right)}\right]$$

W_{18} = predicted number of 80 kN (18,000 lb.) ESALs (Equivalent Single Axle Loads)

Z_R = standard normal deviate

S_0 = combined standard error of the traffic prediction and performance prediction

D = slab depth (inches)

p_t = terminal serviceability index

ΔPSI = difference between the initial design serviceability index, po, and the design terminal serviceability index, pt

$S_c^{'}$ = modulus of rupture of PCC (flexural strength)

C_d = drainage coefficient

J = load transfer coefficient (value depends upon the load transfer efficiency)

E_c = Elastic modulus of PCC

k = modulus of subgrade reaction

Design procedure

Step 1 – Reliability

Step 2 – Overall standard deviation

Step 3 – Cumulative Equivalent Single Axle Load

Step 4 – Effective Roadbed Soil Resilient Modulus

Step 5 – Resilient Moduli of Pavement Layers

Step 6 – Serviceability Loss

Step 7 – Modulus of Subgrade Reaction

Step 8 – Drainage Coefficient

Step 9 – Construction Materials Properties

Step 10 – Minimum Thickness

Step 1 – Reliability

Two reliability levels were selected: R = 85%, R = 90%

- A reliability level (R) is selected depending on the functional classification of the road and whether the road is in urban or rural area. The reliability is the chance that pavement will last for the design period without failure. A larger reliability value will ensure better performance, but it will require larger layer thicknesses.

Functional Classification	Recommended Level of Reliability	
	Urban	Rural
Interstate and other freeways	85–99.9	80–99.9
Principal arterials	80–99	75–95
Collectors	80–95	75–95
Local	50–80	50–80

Step 2-deviation factor

It is suggested that standard deviations of 0.45 be used for flexible pavements and 0.35 for rigid pavements

Assume: 0.35

Step 3: Cumulative equivalent single axel load

The predicted loading is simply the predicted number of 80 kN (18,000 lb.) ESALs that the pavement will experience over its design lifetime.

ESAL calculation for bus pad

$ESAL_i = N_i * F_{Ei} * \ f_d * AADT_i * 365 * G_{RNi}$

1 day

1 year

nth year

i = type of vehicle : bus

F_E = Load equivalent factor

f_d = Design lane factor (Number of lanes : 1)

AADT = average annual daily traffic

$$G_{RN} = Growth\ rate = \frac{[(1+r)^n - 1]}{r} = \frac{(1+0.02)^{25} - 1}{0.02} = 32$$

Assumptions

AADT = average annual daily traffic = 700 buses per day (20% 3 axle and 80 % 2 axle)

Growth rate = 2%

f_d = Design lane factor = 1 (100% 0f traffic is for design lane)

2 Axle

F_E = Load equivalent factor = (19 kips is not related to thickness) = 1.29

$ESAL_{2axel}$= 2×1.29×700×0.7×365×1×32 = 14,765,856

3 Axle

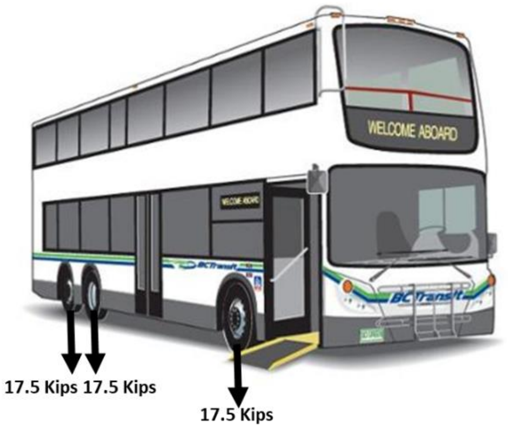
F_E = Load equivalent factor = (17.5 kips is not related to thickness) = 0.9

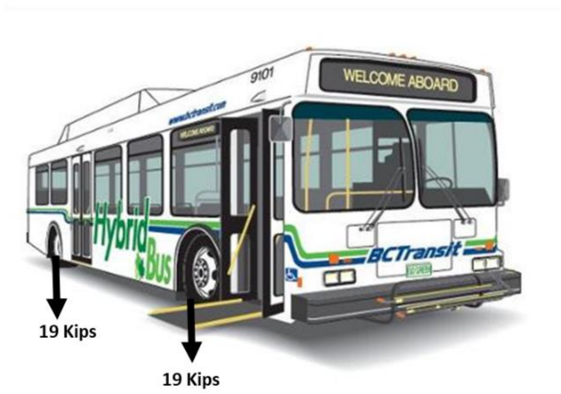
$ESAL_{3axel}$= (3×0.9×700×0.3×365×1×32 = 6,622,560

Total ESAL= 21,388,416 (80 KN or 18 kips)

2 Bus types in British Columbia according to Transit

Name of Bus	AXIS	Weight in kg	Weight in KN	Load each axel (Kips)	Average (KN)	ESAL (empty)	Average (KN)
Enviro500H	3	24200	237	17.6	17.5	2.96	
Enviro500	3	23,700 - 24,200	232-237	17.3-17.6		2.9 – 2.96	
Trident	2	23100	226	25.4	19	2.82	
XN40 Xcelsior	2	12,920-19,290	126-189	14.1-21.2		1.57	
LFS	2	17,805 - 19,400	174-190	19.5-21.3		2.36	
DE40LF Hybrid	2	18,415	180	20.2		2.25	
D40LF	2	12,383 - 18,200	121-178	13.6-20		1.51-2.22	
35’ Vicinity	2	16500	161	18.1		2	
30’ Vicinity	2	13700	134	15		1.67	



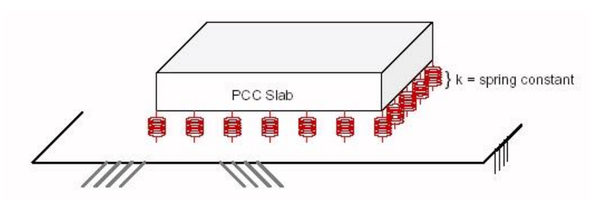


Step 4 & 5 : Modulus of Subgrade Reaction

The modulus of subgrade reaction (k) is used as a primary input for rigid pavement design. It estimates the support of the layers below a rigid pavement surface course (the PCC slab). The k-value can be determined by field tests or by correlation with other tests.

The modulus of subgrade reaction (k) is used as a primary input for rigid pavement design. It estimates the support of the layers below a rigid pavement surface course (the PCC slab). The k-value can be determined by field tests or by correlation with other tests. There is no direct laboratory procedure for determining k-value.

The modulus of subgrade reaction came about because work done by Westergaard during the 1920s developed the k-value as a spring constant to model the support beneath the slab



Modulus of subgrade reaction (k).

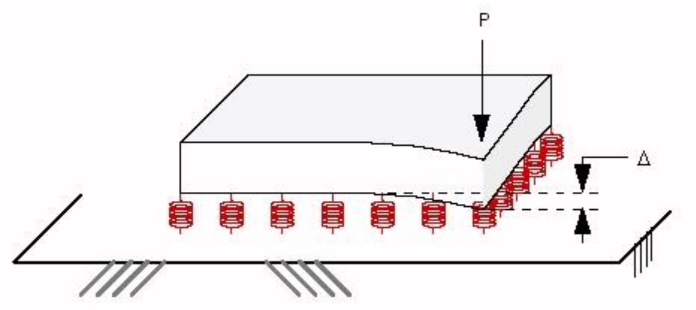
The reactive pressure to resist a load is thus proportional to the spring deflection (which is a representation of slab deflection) and k (Figure 2):

$$P = k\Delta$$

where: P = reactive pressure to support deflected slab

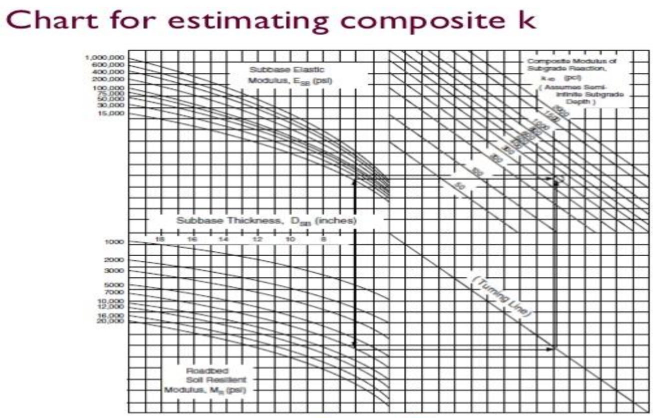
k = spring constant = modulus of subgrade reaction

Δ = slab deflection



Relation of load, deflection and modulus of subgrade reaction (k).

The value of k is in terms of MPa/m (pounds per square inch per inch of deflection, or pounds per cubic inch – pci) and ranges from about 13.5 MPa/m (50 pci) for weak support, to over 270 MPa/m (1000 pci) for strong support. Typically, the modulus of subgrade reaction is estimated from other strength/stiffness tests, however, in situ values can be measured using the plate bearing test. For exact calculation, the chart below can be used, however subbase elastic modulus, subbase thickness and roadbed resilient modulus is needed



Assume k: 600 psi

Step 6: Serviceability Loss

- The serviceability loss is the difference between the initial serviceability index (po) and the terminal serviceability index (pt). The typical Po value for a new pavement is 4.6 or 4.5. The recommended values of pt are 3.0, 2.5 or 2.0 for major roads, intermediate roads and secondary roads, respectively

$$\Delta PSI = p_o - p_t$$

Assume: $p_0 = 4.5$ *and* $p_t = 2.5$ *then* $\Delta PSI = 4.5 - 2.5 = 2$

1.3. Load transfer coefficient (J Factor). This accounts for load transfer efficiency. Essentially, the lower the J Factor the better the load transfer. Typical J factor values are as shown below.

Table 3. J factor according to AASHTO

Condition	J Factor
Undoweled PCC on crushed aggregate surfacing	3.8
Doweled PCC on crushed aggregate surfacing	3.2
Doweled PCC on HMA (without widened outside lane) and tied PCC shoulders	2.7
CRCP with HMA shoulders	2.9 – 3.2
CRCP with tied PCC shoulders	2.3 – 2.9

<u>Step 7: Drainage coefficient</u>

Assume = 0.8

<u>Step 8. Load transfer coefficient (J Factor)</u>

This accounts for load transfer efficiency. Essentially, the lower the J Factor the better the load transfer. Typical J factor values are as shown below.

<u>Condition</u>	<u>J Factor</u>
Undoweled PCC on crushed aggregate surfacing	3.8
Doweled PCC on crushed aggregate surfacing	3.2
Doweled PCC on HMA (without widened outside lane) and tied PCC shoulders	2.7
CRCP with HMA shoulders	2.9 – 3.2
CRCP with tied PCC shoulders	2.3 – 2.9

Shoulder	Asphalt		Tied PCC	
Load transfer device	Yes	No	Yes	No
Pavement type				
Plain jointed and jointed reinforced	3.2	3.8–4.4	2.5–3.1	3.6–4.2
CRCP	2.9–3.2	NA	2.3–2.9	NA

Assume J = 2.3

Step 9: construction materials properties

PCC elastic modulus. If no value is known, the PCC elastic modulus (Ec) can be estimated from relationships such as the following:

$$E_c = 57{,}000\sqrt{f'_c}$$

Fc= 35 Mpa or 5076 psi then

Ec=57000$\sqrt{5076}$ = 4,106,856 psi

PCC S'_c = 650 psi (4.5 MPa)

Step 10: minimum thickness

- Minimum Thickness (in.) (AASHTO, 1993)

Traffic, ESAL's	Asphalt Concrete	Aggregate Base
Less than 50,000	1.0 (or surface treatment)	4
50,001–150,000	2.0	4
150,001–500,000	2.5	4
500,001–2,000,000	3.0	6
2,000,001–7,000,000	3.5	6
Greater than 7,000,000	4.0	6

Inputs:

Reliability: 0.85 and 90

Overall standard deviation: Z_R = 0.35

Cumulative Equivalent Single Axle Load, Total ESAL: 21,388,416

Effective Roadbed Soil Resilient Modulus and Resilient Moduli of Pavement Layers: modulus of subgrade reaction = k = 600 psi

Serviceability Loss (p_0= 4.5 and p_t=2.5 then ΔPSI=4.5-2.5=2)

Drainage Coefficient = C_d = 0.6

Construction Materials Properties (Ec=4,061,024 psi, S'_c = 650 psi)

J = 2.3

Output:

Depth of pavement = 8 inches

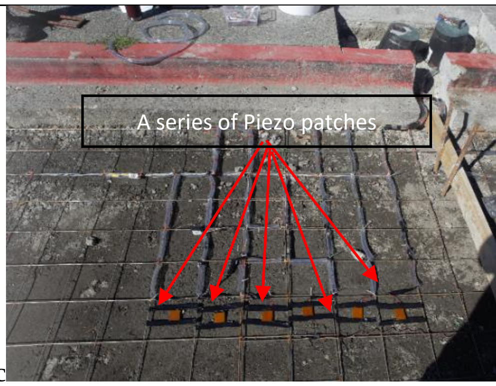
MATLAB Code for solving the depth of pavement

```
clc; clear; close all;
W18= 2.1*10^7;
Zr= 0.35;
So= 0.32;
PSI= 2;
Pt= 2.5;
Sc= 650;
Cd = 0.6;
J= 2.3;
Ec= 4.1* 10^6;
```

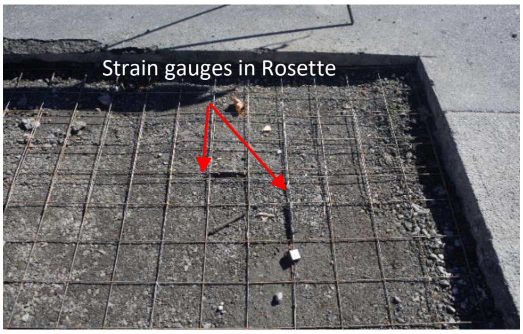
```
k= 600;
lhs=log10(W18);
disp("lhs is "); disp(lhs);

for D=4:0.1:10
       rhs = (Zr * So) + (7.35 * log10(D+1)) - (0.06) + (log10(PSI/(4.5-1.5)) / (1.0 + (1.624*10^7 /(D+1)^8.46)))
+ ((4.22-0.32*Pt)* log10((Sc * Cd*(D^0.75 - 1.132))/(215.63*J*(D^0.75 - (18.42 / (Ec/k)^0.25))))) ;
    disp("D= "); disp(D);
    disp("rhs= "); disp(rhs);
    if (rhs-lhs < 0.1)
       disp("Depth of pavement is ");
       disp(D)
       rhs
   end
end
```

a) Excavated Site laid with wire mesh

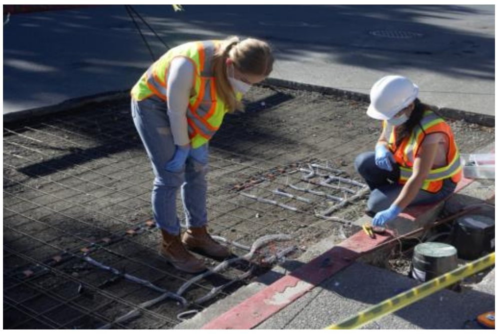
dc



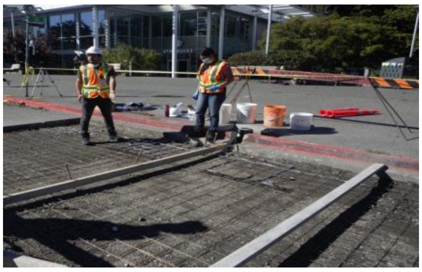
b) Installed Piezo patches before concrete pour



c) Installed strain gauges, thermocouples and temperature sensors



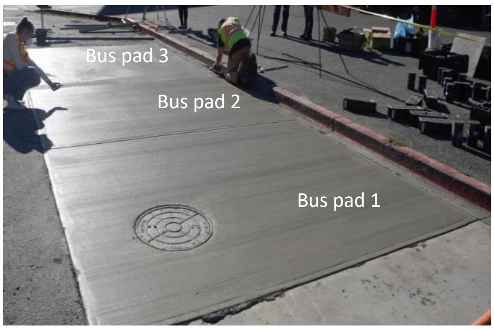
d) Installation of the entire sensing module



e) Joints for three bus pads

f) Concrete pour from truck directly mixed with fibers

g) On-site testing of concrete



h) Final shape of three bus pads

i) Entire FIMIM group participated in the construction of Smart sensing carbon fiber reinforced bus pad

Fig. 5-2 Construction of Smart sensing carbon fiber reinforced bus pad at UViC Bus Loop

Literature Review

Report (Appendix 6)

Project: *Multiphase characterization of Bitumen-Based Carbon Fibers (BBCF) and demonstrating its use in producing "crack-free" cement concrete*

Agreement Number: AI 2516

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1.0 Introduction

The construction activity of 20^{th} century is driven by the use of a combination of materials such as cement, aggregates and steel known as Reinforced concrete [1,2]. The majority of infrastructure including buildings, bridges, power plants, dams etc. across the globe have been successfully developed using reinforced concrete. As a result, the demand for more efficient and improved performance of reinforced concrete is essential to cope with the future demands of construction. The hidden goal behind the demand is further to reduce the cost during, as well as post construction of the infrastructure.

Despite being the most popular and commonly used construction material, concrete has numerous undesirable characteristics such as brittleness, presence of micro cracks, large drying shrinkage, low bonding strength in repair applications, low chemical resistance, inability to bear tensile stresses etc.[3–5]. These shortcomings lower the long-term performance of concrete and sometimes result in severe failures of poorly designed structures. In order to exploit high compressive strength and parry the frailty of concrete, strong and ductile materials such as steel bars are usually integrated in design. These materials are placed in the apprehended zones of tensile stress and preventing concrete to fail in tension.

Under load, micro cracks begin to develop in the interfacial transition zone (ITZ) between aggregates and cement paste throughout the paste. This process continues until these micro cracks meet other micro cracks and coalesce into macro-cracks[6]. A fully developed macro crack will considerably reduce the load carrying capacity of concrete. In the absence of steel reinforcement, a sudden failure of concrete is expected. However, even the presence of tensile reinforcements such as conventional steel rebars, the crack arrest mechanism is not effective. Alongside the use of steel reinforcements, the tensile characteristics of concrete can be improved by randomly dispersing discrete fibers to the mixture. [5]This type of concrete developed with discontinuous randomly distributed fibers is knows as 'Fiber reinforced concrete'(FRC). FRC is a potential material as it effectively overcomes the brittleness of concrete and makes it more versatile. Conventionally, a modest increase in concrete strength could be achieved, the principal focus of addition of fibers is to control the cracking of concrete. It further extends to post cracking as fibers are expected reduce the rate of increasing crack width by bridging across the cracks. This is also known as post-cracking ductility to FRC [7]. In some cases, fibers can be utilized for carrying load in non-structural applications. **Fig. 1** shows different phases of multiscale crack growth in fiber reinforced concrete [8]. In the absence of proper reinforcements for taking the tensile loads, this kind of multiscale crack propagation can take place in any matrix. This can be prevented by using fibers of different sizes dispersed throughout the concrete. Fibers can be considered as the pro-active crack fighters that significantly enhances the overall performance of concrete.

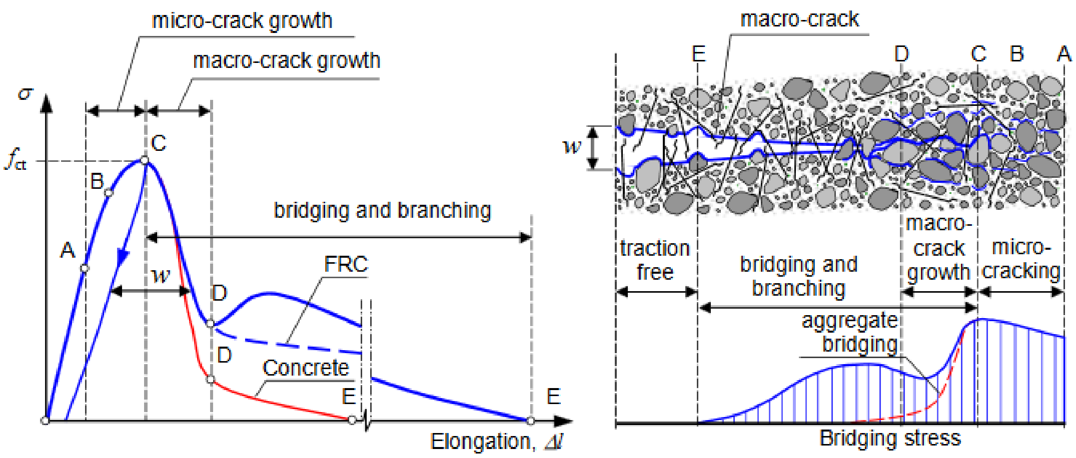

Fig. 1 crack development stages in FRC and the relation to the stress strain response[8]

Fibers have been used to impart tensile strength in relatively weaker materials since ancient times. For example 57 m high hill of Aqar Quf (near Baghdad) was built with straw reinforced sunbaked bricks[9]. The earliest patent on fiber-reinforced concrete was by A. Beard, USA, 1874 and followed by numerous others by G. Martin-1974, Zitkevic-1939, G. constantinesco etc. In the words of krenchel (1974)[10], *" If, as in the case of the fiber-reinforced mortar, it one day proves possible to achieve an apparent elongation at rupture for ordinary concrete that is ten or more times the value normally achieved, it will be found that, for example, many of the structures for which pre-stressed concrete is now used can be produced more simply and economically in ordinary, reinforced concrete with a certain percentage of fibers added as secondary reinforcement for crack distribution. Moreover, the risks of corrosion of the principal reinforcement will be so reduced that it should be possible to use considerably less concrete cover than is normal to-day. Particularly in the case of reinforced concrete water tanks, sea-bed structures and similar, this should be of great economic importance"*

The fiber reinforced composites are developed in such a way the discontinuous phase(fibers) remain embedded in continuous phase(matrix). Fibers are generally discontinuous with more suitable (uni-directional, bi-directional or random) orientation. As matrix depend upon the materials used, it can be brittle or ductile. The matrix type defines weather the inclusion of fibers will modify the strength or toughness. Conventionally, the short fibers are used to influence strength in a ductile matrix and long fibers are used in brittle matrix to influence its toughness. Following are the primary factors that influence the overall performance of the composite: a) Physical properties of fibers and matrix; b) Quality of bond between the fibers and the matrix; c) Amount of fibers and their distribution

1.1 Fibre-Cement-Mortar-Concrete Composites

Unpredictable and sudden fracture of construction materials is undesirable. This is usually the case in brittle materials concrete. That is the prime reason of the inclusion of steel reinforcements in concrete to develop a ductile composite thereby preventing sudden failure. To impart the ability of carrying and transferring tensile loads without rupture, has led to the use of fibers in concrete already reinforced with steel. This is generally accomplished by bridging the tensile cracks within concrete with the help of randomly distributed fibers. Numerous types of fibers have been tested for developing different type of concretes. For example, ACI 318 allows the inclusion of steel fibers for shear reinforcement, as a replacement to stirrups.

The characteristics and the performance of fiber-based composite primarily depends upon the micro-macro structure of the composite. A fiber base cementitious composite will have three main components a) A cementitious matrix (either a combination of cement-sand-water or cement-sand-coarse aggregates-water); b) Randomly distributed fibers (e.g. steel, carbon, glass etc.); c) Interfacial transition zone (ITZ) of fiber-matrix (bond between the fiber and matrix)

a) Cementitious Matrix: It is further divided into cement mortar and cement concrete. The cement mortar consists of cement, water and sand. Fiber cement mortars are generally used for cladding purposes or sometimes for grouting (for patch repairs). Fibers volume in cement mortars generally vary between 5-15 percent. On the other hand, cement concrete consists of cement, sand, water and coarse aggregates. For developing fiber reinforced concrete, a volume of fibers less than 2 % are generally added. It is to be noted that fibers in mortar act as primary reinforcement and the in concrete as secondary reinforcements.
b) Fibers: Fibers used for developing FRC can be evaluated in two categories; 1) Shape of fibers; 2) Their orientation in matrix. Single fibers can be monofilament based e.g. Steel fibers or fiber assemblies (bundles of fibers, with a diameter less than 10 µm) e.g. Synthetic fibers like carbon fibers etc. It is to be note that monofilament fibers used in FRC composites are usually cylindrical in nature and in most cases, they are bent or deformed. On the other hand, the bundled fibers are expected to keep the bundle intact inside the matrix. Further, the orientation of fibers depend upon the two different type of fiber reinforcing arrays :1) Continuous reinforcement, wherein the fibers are mixed in the matrix with the help of

filament winding or lay up of layer of fiber mats; 2) Discrete short fibers, where in the fibers are simply added by spraying or mixing.

2) Interfacial Transition zone between fiber and matrix: In FRC, ITZ's depend upon the type of fiber and the production technology. ITZ's in FRC basically define the overall quality of bond between the fiber and the matrix. 544.8R-16: Report on Indirect Method to Obtain Stress-Strain Response of Fiber-Reinforced Concrete (FRC) he microstructure of composite consists of hydration products such as CSH and crystals of CH. In case of fresh mix, the fibers are usually surrounded by entrapped water with unpacked cement particles. This results in the porous ITZ between fiber and the matrix, as hydration proceeds. It should be noted that the entire surface area of monofilament fibers are in contact with the surrounding material which is not the case for bundled fibers as only exterior most fibers develop bond with the surrounding matrix.

Another important underlying characteristic that dominates the overall FRC composite the interaction involving the transfer of tensile forces between the fibers and the surrounding matrix[11]. This interaction can be termed as a 'bond' between the fibre and the matrix. Hence, a better bond will result in a ductile matrix and a poor bond will create voids, resulting in a brittle failure. The interactivity between the fibre and the surrounding matrix primarily depend upon three basic factors: 1) Adhesion (physical & chemical); 2) friction; 3) Mechanical anchorage

Adhesion and frictional bonding between the fibre and the matrix is driven by the ITZ's as well as the fibre properties. It is usually weak and of significance only when the surface area is large (e.g. Synthetic fibers). Furthermore, highly refined and low porosity mixes can easily induce better adhesion or frictional bonding between the fibers and the matrix. During loading, this type of bond activates first and decides the pull resistance. For straight fibers with no deformation, this bond is of highest significance. On the other hand, mixes where water cement ratio is higher or the diameter of fibers are greater than 0.1 mm, adhesion or frictional forces become insignificant to provide a reinforcing action for load transfer between the fibre and the matrix. In such a case, mechanical interlocked created by deforming the geometry of the fibre is utilized along with the transverse tensile strength of concrete. Various factors such as fibre geometry, fibre embedded length, fibre orientations, matrix strength etc. significantly influence the fibre matrix bond behavior.

In case of steel fibers only, mechanically deformed geometries are available and the pre-deformation of fibers is done to induce the mechanical anchorage characteristics[12,13]. Different types of deformation such as hooks, paddles, button on the both ends of fibre or along the length of fibers as indented, crimped, & polygon twisted fibers etc. Straight steel fibers primarily depend upon the physiochemical bond unlike the deformed fibers dependent on mechanical anchorage.

2.0 Types of Fibers

Fibers are used in numerous structural applications such as elevated slab, concrete overlays, beam-column joints, pavements etc. A twofold mechanism enables the fibers protect the structural integrity :1) by stitching action, keeping cracks/joints intact; 2) by load transfer from one side to the other. A diverse range of fibers with different, physical & chemical characteristics, cross-sectional shape, geometry, effective diameter and aspect ratio are available. Depending upon the fibers used, the behavior of the cracked and uncracked concrete can be modified.

From cement composite point of view, fibers can be classified into two major categories: 1) structural or macro fibers; 2) non-structural or microfibers. Macro fibers are stiff that can help in load transfer as well as providing the crack arrest property to the mix. In a cement matrix, their length is greater than the maximum size of aggregate (at least 2 times) and their cross section dia is greater than that of cement grains (less than 50 µm). Generally, the length of macro fibers goes up to 38 mm. Invariably, macro-fibers are effective in post cracking stage (point C in Fig.1). Because of longer lengths, they can provide load-transfer mechanism between larger cracks and preventing from further widening. It is to be noted that macro fibers do not participate in the early stage of crack development (**Fig. 3**).

On the other hand, the microfibers are less stiff and only participate providing the post-crack ductility. Microfibers have same diameter as that of cement grains and their length is lesser than the maximum aggregate size. By virtue of their size, microfibers can easily bridge the tensile stress across the ITZ's, thereby preventing the micro cracks from taking place (**Fig. 3**). This micro-scale reinforcement action of microfibers makes them most effective for influencing the matrix behavior before even the micro cracks take place (point A of **Fig.1**).

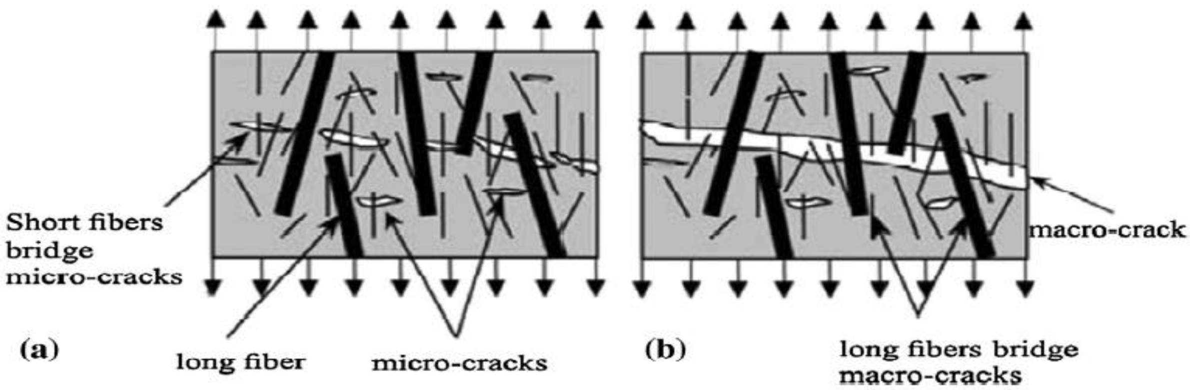

Fig. 3 Simplified tensile reinforcement contribution of micro and macro fibers at different stages of crack propagation[14]

As per ASTM C1116, Standard Specification for Fiber reinforced concrete, fibers are categorized in 4 major categories based on their parent material as:

1) Metallic
2) Glass
3) Synthetic
4) Natural

As per ACI 544, 1996[15], some definitions, parameters, and features are used to characterize different type of fibers:

- Aspect ratio, which is the ratio of length to diameter of a fiber;
- Bundled fibers, which usually are strands consisting of several hundreds or thousands of filaments of microfibers
- Chopped strand, which contains fibers chopped to various lengths
- Collated, which refers to fibers bundled together either by cross-linking or by chemical means
- Fibrillated, referring to continuous networks of fiber, in which the individual fibers have branching fibrils,
- Filament, which is a continuous fiber, i.e., one with aspect ratio approaching infinity;
- Monofilament, a large diameter continuous fiber, generally with a diameter greater than 100 μm
- Multifilament, a yarn consisting of many continuous filaments or strands

All the above stated are independent of the type of parent material of fibers, i.e., polymeric, metallic, glass etc. and depend on the geometry. The details are given in **Table 1**

Table 1:Characteristics of fibers used for reinforcing cement matrix[11]

Type of fibre	**Diameter [μm]**	**Specific gravity [g/cm3]**	**Tensile strength [MPa]**	**Elastic modulus [GPa]**	**Ultimate elongation [%]**
Metallic					
Steel	5-1000	7.85	200-2600	195-210	0.5-5
Glass					
E glass	8.0-15.0	2.54	2000-4000	72	3.0-4.8
AR glass	8.0-20.0	2.7	1500-3700	80	2.5-3.6
Synthetic					
Acrylic (PAN)	5.0-17.0	1.18	200-1000	14.6-19.6	7.5-50
Aramid (e.g., Kevlar)	10.0-12.0	1.4-1.5	2000-3500	62-130	2.0-4.6

Carbon (low modulus)	7.0-18.0	1.6-1.7	800-1100	38-43	2.1-2.5
Carbon (high modulus)	7.0-18.0	1.7-1.9	1500-4000	200-800	1.3-1.8
Nylon (polyamide)	20-25	1.16	965	5.17	20
Polyester (e.g., PET)	10.0-8.0	1.34-1.39	280-1200	10.0-18.0	10.0-50.0
Polyethylene (PE)	25-1000	0.96	80-600	5	12-100
Polyethylene (HPPE)		0.97	4100-3000	80-150	2.9-4.1
Polypropylene (PP)	10-200	0.90-0.91	310-760	3.5-4.9	6.0-15.0
Polyvinyl acetate (PVA)	3.0-8.0	1.2-2.5	800-3600	20-80	4.0-12.0
Natural - organic					
Cellulose (wood)	15-125	1.5	300-2000	10.0-50.0	20
Coconut	100-400	1.12-1.15	120-200	19.0-25.0	10.0-25.0
Bamboo	50-400	1.5	350-50	33.0-40.0	
Jute	100-200	1.02-1.04	250-350	25.0-32.0	1.5-1.9
Natural - inorganic					
Asbestos	0.02-25	2.55	200-1800	164	2.0-3.0
Wollaston	25-40	2.87-3.09	2700-4100	303-530	

2.1Metallic Fibers Steel fibers are most commonly used in concrete[3,16–21] for building regular civil and industrial structures, airports, highways, impact resistant structures etc.[22]. The prime reason behind that its inclusion in the matrix has multi-fold benefits in terms of increased toughness & ductility, flexural, & tensile strength of concrete and nonetheless crack controlling properties by increasing the critical cracking resistance[12,23–25]. Other than the physical characteristics of steel fiber, quantitative parameters such as fiber volume, fraction, dimensions & matrix properties overall influence the performance[7,26].

Generally steel fibers are produced from carbon steel, however, in case of corrosive environments, steels fibers can also be produced from stainless steel[11]. As per [11], five different methods of steel manufacturing are given as below:

- Type I: Cold -drawn wire
- Type II: Cut sheet
- Type III: Melt Extracted
- Type IV: Mill-cut
- Type V: Modified cold-drawn wire

The different categories of steel fibers are shown in **Fig. 4**

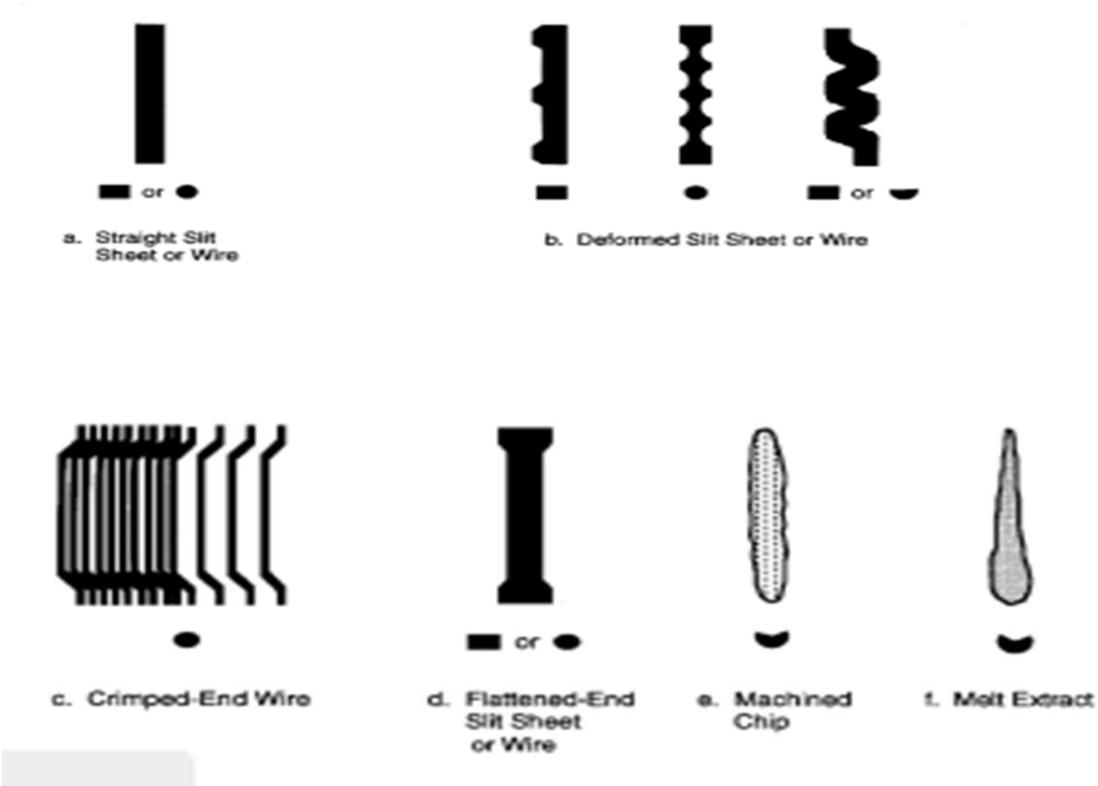

Fig. 4 Various type of steel fibers[11]

According to [11], the minimum yielding strength of 345 MPa for use in concrete is required and the ability to be bent around a 0.125 -inch diameter pin to an angles of 90 degrees at a temperature not greater than 15 degrees. This is primarily to make sure that fibers don't break during handling. **Table 1** gives the range of mechanical properties as given by the Portland cement association (PCA).

Fig.5 gives the commonly used and available steel fibers[11]. The tensile strength of steel fiber reinforced concrete depends upon the interfacial bond between the fiber and cement matrix. Weaker bond will result in the forced pull-out of the fiber and as a result, fiber will not be able arrest the propagating cracks. On the other hand, if the bond is too strong, the fiber will break before it could aid in providing post crack ductility. In-between the fiber and the matrix, two types bond can exist: 1) a physiochemical bond(by adhesion & frictional ITZ)); 2) Mechanical bond (by anchor effect of interlocked fibers)[11]. The first type of bond is prevalent in undeformed fibers. However, the preformed fibers develop a mechanical interlock and significantly improves the tensile strength of concrete[27]. Hence, the property of being able to be molded into different shapes (malleability) without affecting the material characteristics such as stiffness, makes steel most suitable for concrete.

Fig. 5 gives the details of various geometries of steel fibers that are used for making Steel fiber reinforced concrete

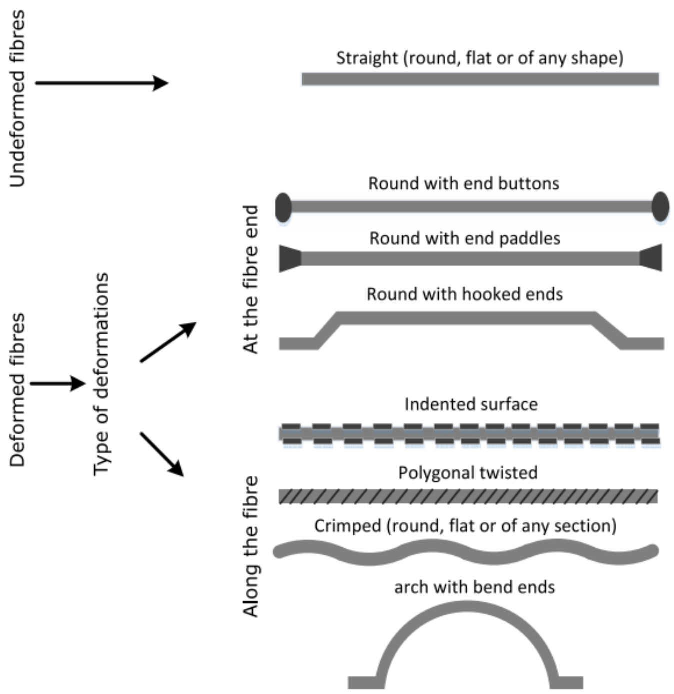

Fig.5 Different type of steel fibers categorized according to their geometric shape[28]

Numerous factors such as 1) Fiber geometry; 2) Fiber embedded length; 3) matrix strength affect the bond behavior of steel fiber reinforced concrete. Despite all the exceptional characteristics, its susceptibility to corrode and a consequent loss of cross-section and strength, steel fibers may not be as promising for aggressive environments such as marine conditions. The post-crack strength of steel fiber reinforced concrete gets significantly affected as a result of long-term corrosion exposure[29]. Interestingly, when the steel fiber reinforced concrete samples were exposed to corrosive environment for short periods, an increase in the post peak residual strength was reported[29]. This is primarily because of improved fiber-matrix bond as a result of increased volume of steel fibers inside concrete. This phenomenon was also confirmed by [30] where in concrete reinforced with hooked steel fibers, was exposed to short corrosion exposure. As a result of short-term corrosion, roughening of steel fibers and increased pull-out strength was reported. In another study[31], a discordance in literature with regards to the loss of residual strength in steel fiber reinforced concrete and corrosion exposure in lab & field conditions primarily, has been accentuated. Both chloride-induced as well as carbonation-induced corrosion exposure are discussed. The literature suggests that crack width of the order of 0.5 mm or above could significantly lower the performance of steel fiber reinforced concrete.

However, the crack widths below 0.2 mm is rendered safe and is further expounded that such concrete will not undergo any loss in residual strength. The vulnerability of carbon steel fibers to corrosion exposure has led to the manufacturing of stainless steel and brass made fibers. Few studies reported that stainless steel fiber reinforced concrete exhibited negligible loss of residual strength and no sign of corrosion was seen even after 2000 cycles of salt exposure[32]. Another study reported the use of chopped, steel fibers, brass coated steel fibers and stainless-steel fibers subjected to corrosion exposure. Brass coated fibers were found to significantly enhance the flexural strength and indirect tensile strength[33]. The stainless-steel fibers and brass coated fibers can be expensive and hence are not very popular. Steel fibers coated with a compound of zinc phosphate mixed in concrete, were also tested for corrosion exposure. A mere 4% loss in flexural strength of concrete was reported when compared to 26 % loss for non-coated fibers. Another disadvantage of steel fiber is their higher specific gravity that significantly increases the unit weight of concrete. This further prevents steel fibers for light weight construction applications. The higher specific gravity further results in the increases weight of the steel fibers to be used for a mix in comparison to other fibers, resulting in higher costs.

2.2 Synthetic Fibers

Synthetic fibers are developed from various organic polymers found in petroleum and textile products. In the draft European Standard prEN 14889-2:2004[34], the following definition is provided for polymer fibers: *"Polymer fibers are straight or deformed pieces of extruded orientated and cut material which are suitable to be homogeneously mixed into concrete or mortar".* Polymer is defined as: *"basic fiber material based on polyolefin (e.g. polypropylene or polyethylene), polyester, nylon, PVA, acrylic and aramids etc. and blends of them".* In the same text, polymer fibers are classified as:

- Class I; intended primarily to improve the short-term plastic properties of mortar and/or concrete by controlling plastic shrinkage, settlement cracks, and reducing bleeding, but not adversely affecting the long-term properties.
- Class II; intended primarily to improve the durability of mortar and/or concrete by improving abrasion and impact resistance and by reducing damage caused by cycles of freezing and thawing.
- Class III; fibres which primarily increase the residual strength of mortar and/or concrete.
- Class IV; fibres which are primarily used to improve the fire resistance of mortar and/or concrete.

Table 2 enlists the properties of the most used synthetic fibers as per PCA. Synthetic fibers are basically lab manufactured and totally different from steel or glass. Owing to their diversified physical, chemical and dimensional properties, different type of synthetic fibers have been tested for fiber reinforced concrete such as polypropylene (PP)[4,6,35–49] , Polyvinyl Alcohol (PVA)[50–58], polyolefin(PO)[59–64], Carbon[5,65–71], Polythene (PE)[72,73], Polyester[74–80], Acrylic[81–84], Nylon[85–97] and Aramid[98–106] etc.[13,107–118]. These can be mono-filament, micro-filament or fibrillated (**Fig. 6**). **Table** 1 gives the durability characteristics of different fibers

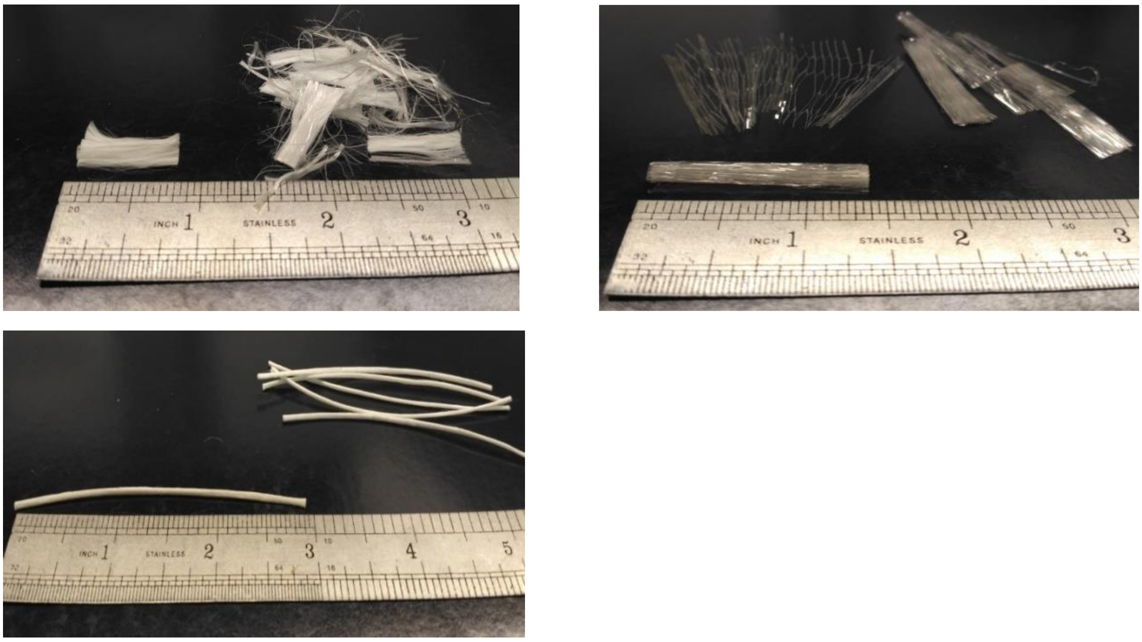

Fig. 5 Synthetic fibers (monofilament, fibrillated & macro fibers)[119]

Table 2: Durability of synthetic fibers [107,110,120]

	Environmental Durability		**Thermal resistance**	
Fibre type	**Alkali resistance**	**Water resistance**	Behavior at high temperature	**Temp. at which all st. is lost ©**
Aramid	Good	Good	Progressive loss in tensile st. at 200C or higher.	400-500
Nylon	Good	Good	Progressive loss in tensile st. at 100C or higher.	180-200
Polyethylene	Good	Good	Progressive loss in tensile st. at 100C or higher.	100-130
Polypropylene	Good	Good to fair	Progressive loss in tensile st. at 100C or higher.	120-150

Poly (vinyl alcohol)	Good	Good	Progressive loss in tensile st. at 100C or higher.	200-240
Pitch-based carbon	Good	Good	Gradual dec. in tensile st. at 300-350C.	500-600
PAN-based carbon	Good	Good	Gradual dec. in tensile st. at 300-350C.	500-600

2.2.1 Polypropylene Fibers

These fibers are most used in fiber reinforced concrete (Fig. 7). These fibers are readily available, cheap, hydrophobic and chemically stable. These fibers undergo very less strain at ultimate loads and have high strength (**Table 1**). The influence of short and discontinuous PP fibers on different characteristics of concrete has been extensively reported[35,40,43]. Although the tensile strength and modulus of elasticity of PP fibers is much less than those of steel fibers yet they induce significant ductility and toughness into the concrete matrix.

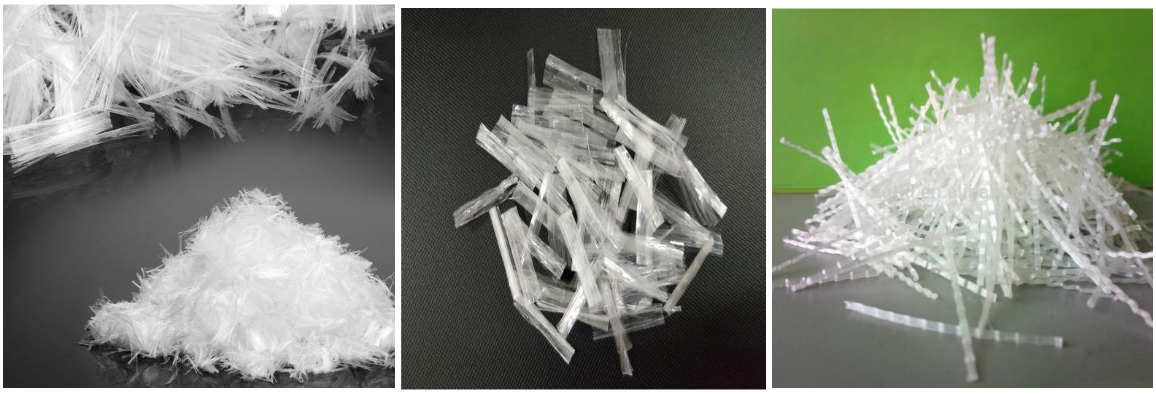

Fig. 7 Different type of polypropylene fibres[121]

In concrete, fibrillated PP fibers and monofilament PP fibers are commonly used. Fibrillated fibers are basically microfibers (low diameter, high aspect ratio). This makes them most suitable for restricting plastic shrinkage cracking in fresh concrete[48]. At the same time, monofilament fibers are macro fibers whose shape can also be modified for better bond characteristics. Different shapes of monofilament PP fibers such as straight, crimped, hooked, button end, twisted, sinusoidal etc. have been tested extensively in concrete[49]. Both the crimped and sinusoidal fibers outperformed in terms of increase in mechanical properties. Monofilament fibers develop both adhesion with the matrix and mechanically lock itself owing to its random geometry. This aids in the better bonding of fiber-matrix. One of the major issues of using PP fibers in concrete is its hydrophobic nature with very high contact angles. Therefore, when large volumes of concrete are to be prepared with higher fiber concentration, achieving the desired workability could be an issue. Some researchers have reported a loss of slump at volumes greater 1%, depending upon fiber dimensions and mix design[122]. Further, the hydrophobic nature of PP fibers results in poor fiber-matrix bond significantly affecting the mechanical properties of FRC. In a new development, by using specific chemical compounds on the surface of PP fibers before extrusion, the chemical bond of a macro PP fibers has been significantly improved as given in **Table 3**.

Table 3: Performance improvement of chemical bond macro fiber relative to a reference fiber

Polypropylene fiber	**ASTM C1399/C1399MM Average residual strength psi (Mpa)**	**ASTM C1609/C1609M equivalent flexural strength ratio, %**	**ASTM C1550energy absorption, in-lb(J)**	**Pull-out Load, lbf (N)**
Dosage, lb./yd^2 (kg/m^2)	5(3)	5(3)	9(5.3)	Single fiber
Reference	176(1.2)	27	3248(367)	14.4(64)
Chemical Bond	240(1.7)	36	4283(464)	20(93)
Performance Improvement, %	37	33	32	45

2.2.2 Nylon Fibers

Nylon fiber is a standard name for a family of polymers, used for various applications. According to PCA2015, these fibers are developed from a nylon polymer and are converted into oriented, crystalline fiber structure by stretching, extrusion and heating[reference]. In concrete, nylon fibers have been used as secondary reinforcements for preventing temperature related shrinkage in concrete[123]. Although, the nylon fibers don't form any chemical bond with the matrix yet they are able to impart ductility to concrete as that of PP fibers owing the scarring of fibers and the consequent development of friction during pull-out[97]. In a more recent published work, it was reported all nylon fibers failed by pull-out in compression where in flexure, only 70% of fibers failed by pull-out[90]. As nylon fibers are available and used both in micro as well as macro size, their ability to modify the characteristics of concrete is similar to inherent properties of FRC. In one the reported work, both micro-macro monofilament nylon fibers were used for developing FRC. It was reported that micro-fibers significantly affected the pre crack stage characteristics of concrete such as plastic shrinkage etc. On the other hand, the macro fibers impacted the post crack stage by increasing the post crack strength of concrete[85].

Few studies have been reported wherein the use of recycled nylon fibers made from waste nylon products such as fishing nets etc.[95,124]. One of the characteristics of nylon fibers is that they are hydrophilic in nature and they tend to absorb water. This is one of the issues in using high concentration of nylon fibers in concrete as this tends to interfere with the workability of concrete mix. This further limit their scope of being utilized at very low concentrations especially for the short fibers. As already stated, the nylon fibers exhibit similar structural characteristics as that of PP fibers, therefore the choice of fibers bottle down to the cost. PP fibers are much cheaper than nylon fibers making them less desirable in practical purposes.

2.2.3 Polyvinyl Alcohol Fibers

The ban on the use of asbestos fibers in concrete in 80's led to the research in the use high strength PVA fibers for FRC[51]. These fibers contain flexible hydroxyl; groups with an ability to form hydrogen bonds with between different molecules and within the single molecule itself. This makes PVA fibers highly suitable for FRC as it results in improved aggregate-matrix & fiber-matrix bond strength. Furthermore, the present ether oxygen functional groups act as weak base which can interact with electropositive materials such as C-S-H or magnesium. This makes PVA fibers more compatible in cement matrix environment and resulting in improved chemical bonding between the PVA fibers and the matrix[2,55,125]. PVA fibers are hydrophilic and yet they do not absorb much water. The compatibility of PVA fibers and cement matrix by virtue of its inherent characteristics and chemical composition negates the necessity pre-deforming the fibers for improving the bond. As a result, the PVA fibers are produced in monofilament form only for both micro & macro fibers. Owing to their strong fibre-matrix bond, the PVA fibers tend to fail by rupture and not by pull-out[126]. PVA fibers significantly increase the post crack toughness and provide great post crack ductility to the matrix but their addition mildly increase the flexural or tensile strengths[57]. This may be because of their low modulus of elasticity.

2.2.4 Polyester Fibers

These fibers belong to the thermoplastic group of polymers and fall in two categories, 1) Polyethylene Terephthalate (PET) and Poly-1, 4—cyclohexylene-Dimethylene Terephthalate (PCDT). PET is more ductile and silent, has more strength & stiffness than PCDT. PET is a common plastic used for making bottles. These are hydrophobic and temperature sensitive fibers. They are non-biodegradable and are the by-product of the textile industry. In concrete, they are added in very low volumes with sole purpose of reducing drying and plastic shrinkage cracking of fresh concrete[127]. Their very low modulus of elasticity prevents them from participating in mechanical characteristics of concrete. Their bond with concrete is only mechanical through adhesion. They do significantly improve the abrasion resistance of concrete and is therefore more popular in pavement constructions.

2.2.5 Carbon Fibers

Thomas Edison was one of early researchers who used carbon fibers as filaments in the electric bulb, which was soon replaced by tungsten. As carbon fibers gained popularity for their ability withstand vibration and their consequent use in US war ships, the prospects of their use for various structural applications broadened significantly. Fibers containing more than 92 % of carbon are termed as carbon fibers. These fibers are heat treated with temperature ranging from 1000-1500 ^{0}C. resulting in 2-dimensional polycrystalline structure and in non-graphitic stage. As carbon fibers are developed from the pyrolysis of synthetic fibers (precursor fibers), a diverse range of mechanical, physical & chemical properties of carbon fibers can easily be achieved. The three most used precursor of carbon fibers are polyacrylonitrile (PAN), pitch and rayon. PAN fibers are also called high modulus or high strength fibers. The modulus is almost double to that of steel. Pitch fibers are developed from coal and petroleum products and are categorized as 1) general purpose fibers; 2) high performance fibers. It is to be noted that fibre characteristics depend upon the pitch at which they are produced. General purpose fibers are low modulus and low strength fibers owing their non-oriented fibre structure. On the other hand, the oriented structure obtained from mesophase pitch material [39], high performance fibers have high tensile strength and high modulus of elasticity. Both pitch and PAN based carbon fibers have varying properties primarily because of different precursor matter, varying degrees of heat treatment, stretching and oxidation[11]. The **table 4** below gives the properties of carbon fibers

Table 4 : Properties of Carbon Fibers[120]

Property	**PAN Type1**	**PAN Type2**	**Pitch**
Diameter (micro-m)	7.0-9.7	7.6-8.6	18
Density(kg/m^3)	1950	1750	1600
Mod. of elasticity (GPa)	390	250	30-32
Tensile st. (MPa)	2200	2700	600-750
Elongation of break (%)	0.5	1	2.0-2.4
Coefficient of thermal expansion (*10^-6 /C)	(-0.5) to (-1.2) [parallel] and 7 to 12 radial	(-0.1) to (-0.5) [parallel] and 7 to 12 radial	NA

Carbon fibers are chemically inert, and they do not form any chemical bond with the surrounding matrix. The resulting bond between the carbon fibre and the surrounding matrix is purely mechanical due to friction developed at the interface. This further defines the failure pattern of carbon fibers. High modulus fibers, therefore, will fail in pull-out and low modulus fibers will fail by rupture. However, fibre failure also depends upon the strength of the surrounding matrix. In contrast to this, pitch-based carbon fibers were found to fail by pull-out mechanism than rupture in cement mortar specimen. However, the failure shifted from pull-out to rupture when the pitch based fibers were modified with latex[71].

2.2.6 Polyethylene Fibers (PE)

These fibers are produced from the commonly used plastic for packaging. The characteristics of PE fibers are somewhat similar to those of the PP fibers being low in strength and low in modulus[113,128,128]. This trend has been changed with the development of ultra-high-density polyethylene with greater stiffness and strength. High strength and higher stiffness are proportional to the fibre density, its molecular weight and the degree of molecular alignment. This possibility of variation in the inherent characteristic of fibers during manufacturing along with their chemical stability, makes them most suitable for numerous applications such a different fabric, ropes, & yarns. Even though plenty of research has been reported wherein the use of PE fibers have used to reinforcement cement concrete composites, yet there is lacuna in the current state of the art about low performance FRC made with PE fibers. Furthermore, these fibers aren't very popular despite being readily available and of low cost. This has been overcome with high strength PE (HSPE) fibers.

2.2.7 Aramid Fibre

"Aromatic Polyamide" known as aramid fibers, high strength, and high modulus fibers, making them most suitable for structural applications. The chemical structure of aramid fibers consists of rigid molecular chains along the fibre axis. This enables the use of covalent bonds along the polymer chains making them high strength fibers so much so that their modulus is even greater than that of steel wires[129,130].. These are generally used for making high strength ropes and yarns, bullet proof vests etc. For various matrix-reinforcing applications, Kevlar and technora fibers are most commonly used. Kevlar fibers are produced by dry and wet spinning of aromatic polyamide where spinning is absent in the production of technora fibers. Different production methodologies make fibers differentiate themselves particularly, their chemical characteristics despite being made from the same parent material. The earliest work [131] on the use of aramid fibers reported impressive results of Kevlar-cement composites in terms of mechanical properties, durability & fire resistance characteristics. In other work[132], it was reported that aramids are excellent for concrete. With fibers in concrete up to a volume of 2 %, an improvement of the order of 40-90% in tensile strengths was observed. It was also reported that the residual strength and fracture toughness significantly increased for low crack openings[97,133]. In another study[134], different types, geometries, volumetric concentrations, diameters and different length of aramid fibers were tested in cement mortar. It was found that workability was inversely proportional, to fibre length and concentration. No significant changes in compressive strength found with short aramid fibers but longer fibers exhibited modest variations. The study suggested that aramid fibers significantly contribute in the pre crack strength development. In contrast to above study, aramid fibers in concrete mix with variations of 0.5, 1 and 1.5 % was used and the variation in compressive strength was studied[102]. It was found that low volumes at 0.5 % slightly increases the compressive strength whereas at 1 % & 1.5%, the compressive strength exhibited declivity.

2.2.8 Acrylic Fibers

These fibers are named after a polymer containing at least 85 % of acrylonitrile [11] and, the actual name is Polyacrylonitrile(PAN). The development of acrylic fibers also took place during 80's in search of alternatives for banned asbestos fibers. These fibers are basically a product of the textile industry with tensile strength ranging between 24 to 340 MPa. Furthermore, their poor resistance to alkali and acids prevented their wide usage in cement concrete composites. Later, higher tensile strength acrylic fibers (ranging up to 600 MPa) were also developed but they were hydrophilic. These fibers have the capacity to absorb 2.5 % of water by weight that could be problematic in fresh concrete[11].

High strength acrylic fibers with their lengths varying from 6-24 mm, diameter varying from 18-1054 mm and elastic modulus up to 19.5 GPA were used in concrete[135]. It was found that acrylic fibers develop a superior bond with the fibre matrix owing to their irregular cross-sectional shape. A positive impact on reduced drying shrinkage at higher volumes was reported. Although the compressive strength decreases slightly, but the flexural tough significantly improved. Another study[136] explored the feasibility of using acrylic fibers as a reinforcing material in cement paste, mortars and concrete. The study employed two different type of acrylic fibers SEKRIL900 & SEKRIL130. The properties of these are given in **Table 5.** It was reported that SEKRIL 900 exhibited better bond between the fibre-matrix than SEKRIL130. Further, the fracture & deformation behavior also followed the same sense. This could primarily be attributed to the longer length of the fibers.

The summary of manufacturing of fibers is given in **Table 6.**

Table 5: Description of raw material in the manufacturing process of fibers

Property	28 days	Aged
Density	1900-2500 kg/m3	1900-2500 kg/m3
Impact strength	935-25.4 Nmm/mm2	3.5-5.0 Nmm/mm2
Compressive strength	48-83 MPa	70-83 Mpa
First crack	6.0-10.0 MPa	7-11 Mpa
Ultimate strength	17.0-28.0 MPa	9-14 Mpa
Modulus of elasticity	10.0-20.0 GPa	17-24 GPa
First crack	4.8-7.0 MPa	4.8-8 Mpa
Tensile		
Ultimate strength	7.0-11.0 MPa	5-8 Mpa
Modulus of elasticity	0.6-1.2 %	0.03-0.06 %
Interlaminar	2.8-5.5 MPa	2.8-5.5 Mpa
In plane	7.0-11.0 MPa	5-7.6 Mpa
Coefficient of thermal expansion	11-16 x $10^{-6°C\text{^}-1}$	11-16 x $10^{-6°C\text{^}-1}$

Table 6: Description of raw material in the manufacturing process of fibers

Fibre type	Remarks
Mineral	Asbestos, basalt and brucite are considered the most popular group of mineral fibers. They come from deep in the Earth's crust and can be found in cracks in solid rock. The most used raw materials are silicates [35], which can be manufactured by electro thermal methods [36,37].
Polyester	Polyester fibers, manufactured from the polymerization of ethylene, are one of the most widely used synthetic fibers in the textile sector [38]. Polyester is a thermoplastic polymer which can be remelted and remolded. Therefore, it is considered an easily recyclable material. Its structure is a combination of crystalline and nanocrystalline regions [39]
Polyacrylonitrile (PAN)	Polyacrylonitrile fibers or PAN fibers as they are commonly known, are the result of the acrylonitrile polymerization process in the presence of a catalyst peroxide [40,41]. Its use is linked to composite structures for military and commercial aircraft [42]
Carbon	PAN fibers are considered the first precursor of the carbon fibers [43]. Carbon fibers exhibit higher specific strength, fatigue resistance and stiffness than any other type of reinforcement fibers. However, they have other interesting properties such as good electrical and thermal conductivity [44–46]
Glass	Glass fibre, also called fiberglass, is considered a mineral fibre as its manufacturing process involves limestone, kaolin clay, fluorspar, dolomite and other minerals [47]

Steel	Steel fibers are short discontinuous strips of manufactured steel. Their manufacturing process includes different types of arrangements including the use of materials such as carbon and phosphorous [48]
Aramid	Aramid fibers are considered man-made high-performance fibers. Aramid fiber's first commercial applications appeared in the early 1960s and its main application is reinforcement of composites. Continuous fibre reinforcement polymers (CFRP) or aramid fibre reinforcement polymers (ARFP) are used in sports goods, aircraft, ballistic protection or structural applications, among others [49,50]
Coconut	This 100% natural product is obtained from the outer shell of the coconut fruit. Their walls are composed by lignin, a complex woody chemical [51]

2.3 Glass Based Fibers

Glass fibers are developed by a process where in the molten glass (derived from naturally occurring minerals or glass) comes out as filaments out of the heated platinum tank[11]. As soon as the filaments come out of the heating tanks, they are impregnated with "sizing" imparting a surface texture and reducing the contact angle. This is done to protect the filament from abrasion and modify the interfacial characteristics of the glass fibers. Normally 204 filaments can be drawn out at concomitantly followed by their solidification. Thereafter, the fibers can be given any shape such as short fibers, long fibers, a spool of fibers or could shaped into a mat (**Fig.7**).

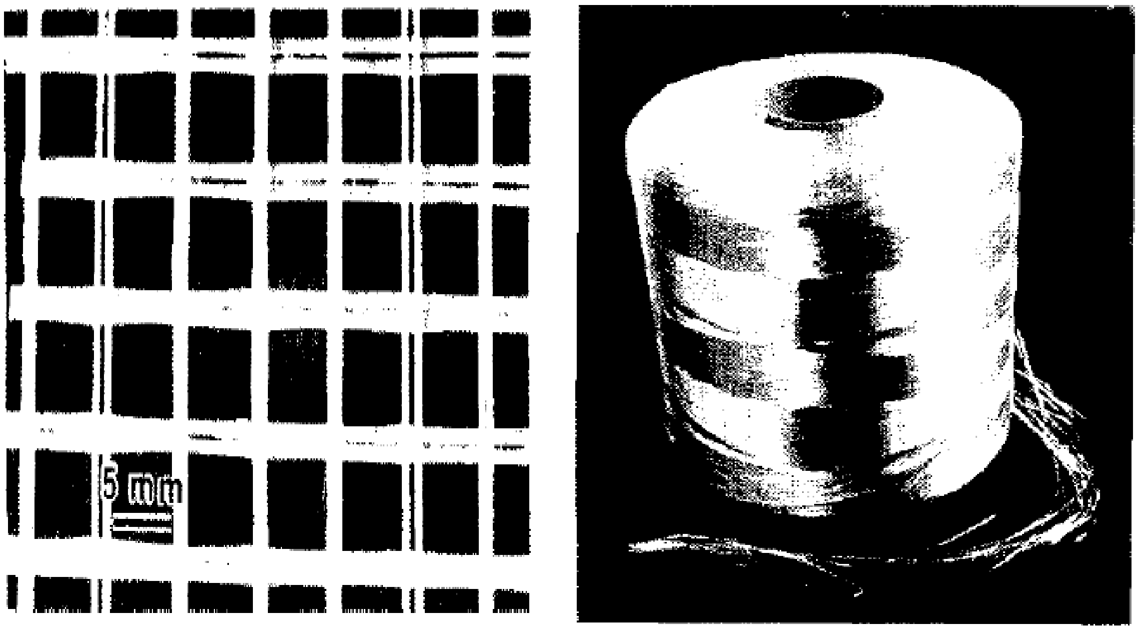

Fig. 7 Woven mat & continuous roving form of glass fibers[11]

The typical structure of glass is shown in **Fig. 8** and **Table 1** gives the physical characteristics of the glass. The most used glass for reinforcing concrete is silica glass and basalt glass. Both these fibers have similar characteristics owing to same parent material. There is however, a slightly different in their chemical constituents resulting from different production processes. The constituents of basalt glass include iron, potassium, magnesium and sodium oxides. On the other hand, the silica glass contains silica majorly and some levels of boron dioxide[137,138].

$$-\underset{|}{\overset{|}{\mathrm{Si}}}-\mathrm{O}-\underset{|}{\overset{|}{\mathrm{Si}}} \quad +\mathrm{O}\bar{\mathrm{H}} \rightarrow \underset{|}{\overset{|}{\mathrm{Si}}}-\mathrm{OH}+\mathrm{SiO}^{-}\,(\text{in-solution})$$

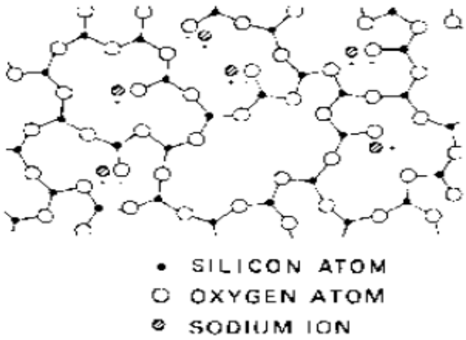

Fig. 8 Schematic structure of glass[139]

In glass fibre (silica & basalt) cement composites, three different type of deteriorating mechanisms[140] play major roles:

1) Chemical attack: One of the problems with glass fibers (E-type) is poor alkali resistivity of fibers. The pH of a fresh concrete is around 13 i.e., highly alkaline. It has been reported that E-glass fibers degrade much faster in the alkaline environment of concrete[11,141–144]. This is primarily because of the breaking Si-O-Si bonds in glass network by readily available OH^{-1} ions. The degradation of glass results in the loss of weight and strength, followed by the reduction in the loss of cross-section. This was observed for e-glass in a cement matrix [145]. A study reported the durability of both silica glass and basalt glass exposed to acid alkali and salt solutions[146]. It was found that degradation was so severe that fibers lost their strength after exposure to acid and alkali solutions. However, fibers exhibited better performance as no loss of strength was reported.
2) Mechanical attack: As per the study[147], the growth of hydration products in the paste surrounding glass fibers results in the embrittlement in the early curing stage of composite. This occurs even faster than the chemical attack resulting in the loss of filament length.

3) Delayed Fracture: It has been theorized[148–150] that even before the chemical attack, fracture can begin as a result of pre-exiting flaws. In general, stress concentration take place around the flaws in glass. These are production flaws as they take place at the time of manufacturing. With the development of hydration products, the glass may come under load. As a result, the pre-existing flaws begin to grow and propagate, ultimately evolving into a failure. This type of failure is referred to as static fatigue failure.

The problem of low alkali resistivity prevented the use of e-glass in GRC and was overcome by using glass in cement matrix with low alkalinity but it led to the development of AR-glass fibers[143,151–153]. AR fibers are coated with specific alkali resistant glass polymer resins as done for GFRP bars[67,154–156]. **Tables 7 & 8** enlists the characteristics of glass fibers. The AR glass is most commonly used for thin sheet panels used for exetererior façade purposes[11], where heavy load carrying members are required. Hence, their use in reinforcing concrete mix is very uncommon. It has been reported that the use of AR fibres result in the uneven distribution in the mix and often result in fibre damage during mixing[11]. **Table 9** gives the specification of AR glass fibres for their use in concrete mixing.

Table 7: Properties of single filaments of glass[157]

Characteristic	**E glass**	**AR glass**
Density (kg/m3)	2540	2780
Tensile strength (MPa)	3500	2500
Modulus of elasticity (GPa)	72.5	70
Elongation at break (%)	4.8	3.6

Table 8: Chemical constituents of glass

Column1	**E glass**	**AR glass**
SiO2	52.40%	71%
K20 + Na2O	0.5	11
B2O3	10.4	
Al2O3	14.4	18
Mg0	5.2	
CaO	16.6	
ZrO2		16
Li2O		1

Table 9: Property requirements of AR glass fibre as per ASTM C1666[11]

Property	Specification Value	Method of Test
Zirconia content (ZrO_2)	16% min	X-ray fluorescence
Density	2.68_+ 0.3 g/cm [167.0_+19 lb/ft]	ASTM D3800
Tensile Strength	1.0-1.7 GPa	ASTM D2256
	[145*10-246*10psi]	ISO 3341, JISR 3420
Range of Filament Diameters	8-30pm	ASTM D578
	[31*10-118*10in.]	ISO1888, JISR 3420
Roving tox	_+10%of	ASTM D1577
	manufacturer's nominal	ISO 1889, JISR 3420
Strand length	_+3mm[_+0.118in.] of manufacturer's nominal	Caliper-Average of 20 measurements Physical count
End count	_+20% of manufacture's nominal	
Loss on ignition	<3%	ASTM D4963, ISO 1887 JISR 3420
Strength retention	Minimum value after 96_+1h in water at 80 _+ 1C [176_+2F] _>250 Mpa [36 250 psi] for water dispensable strands _>350MPa [50 750 psi]	EN 14649

On the similar lines because of poor alkali resistivity and related degradations, AR basalt fibers were developed. These fibers were exposed to acid, alkali and salt solutions as a measure to evaluate their durability, it was found that strength reductions were found related to acid exposure only[158]. Several attempts have been made in surface modification of the basalt fibre to make them suitable for concrete applications[159]

2.4 Natural Fibers

In a push towards sustainable construction, the scope of natural fibers as reinforcements in concrete have been explored significantly in the last four decades. The company that started developing asbestos fibers in 1917 (James Hardie Industries) started exploring cellulose as an alternative as early as 1940. In Europe, cape industries started developing boards with 5 % of cellulose fibers along with high concentration of minerals, for fire resisting use[160,161]. As the health concerns with the use of asbestos fibers increased, resulting in the banning of asbestos cement production, companies started to look for alternatives (**Table 10**). The result was the development of 'cellcern" containing a mixture of cellulose and other fibers.

Table 10: Comparison of the properties of fibers for possible asbestos alternatives[162]

Fibre	Alkali resistivity	Temperature Resistivity	Process ability	Strength	Toughness	Price
Wood pulp (Chem)	High	High	High	High	High	Low
Wood pulp (mech)	Medium	Medium	Medium	Medium	Low	Low
polypropylene	High	Low	Low	Low	Low	Medium
PVA	High	Low	Low	High	High	Medium
Kevlar	High	Medium	Medium	High	High	High
Steel	High	High	Low	Low	Low	Medium
Glass	Low	High	Low	Low	Low	Medium
Mineral fibre	Low	High	Low	Low	Low	Low
Carbon	High	High	Low	High	High	High

For reinforcement purposes, natural fibers can be generalized as cellulosic fibers, produced within the organic tissue of plants. Only those fibers that can exhibit significant strength and dimensional characteristics are concerned for reinforcing applications As per[163], natural fibers can be divided into 4 major categories(**Table 11**):

1) Stem or blast fibers are obtained by clearing the stalks of plants of unwanted materials using a combined action of moisture and bacteria(retting). This is followed by drying and then the textile fibers can be spun into a yarn. They are commonly used as full length bundled or strands of fibers. Jute and flax fibers are fall in this category.
2) Leafy fibers are obtained by crushing and scrapping of leaves to extract fibers out. This followed by drying. The cellular tissues and gummy substance are separated during leaf processing. This makes them harder, stiffer and coarser in nature. Sisal, henequen & abaca fall in this category of fibers. Sisal, however, is the commonly used fibers.
3) Surface fibers are the single cell fibers obtained from the surface of stems, fruits and seeds of plants. Cotton and coconut fibers fall in this category. Coir fibers are commonly used for reinforcing in cement composites[161,163]. Coconut fibers are obtained from the husk

surrounding the nut by soaking them in water, beating with spikes in order to separate long, coarse fibers.

4) Wood (cellulose) fibers are most suitable for long term performance in cement matrix as they are short and strong. The parent wood (bamboo or sugarcane) is processed and by using mechanical treatment, good quality cellulose fibers can be extracted from the pulp.

Table 11 gives the properties of these fibers[161–163]

Plant fibre	Tensile strength (MPa)	Young's modulus (GPa)	Specific modulus (GPa)	Failure strain (%)	Length of ultimate l (mm)	Diameter of ultimate (mm)	Aspect ratio, l/d	Microfilm, θ (degree)	Density (kg/m3)	Moisture content (eq.) (%)
Cotton	300-700	6.0-10	4-6.5	6.0-8	20-64	11.5-17	###	20-30	###	8.5
Kapok	93	4	13	1	8.0-32	15-35	724	_	311-384	10.9
Bamboo	575	27	18	_	2.7	10.0-40	###	_	###	_
Flax	500-900	50-70	34-48	1.3-3.3	27-36	17.8-21.6	###	5	1400-1500	12
Hemp	310-750	30-60	20-41	2.0-4	8.3-14	17-23	549	6.2	1400-1500	12
Jute	200-450	20-55	14-39	2.0-3	1.9-3.2	15.9-20.7	157	8.1	1300-1500	12
Kenaf	295-1191	22-60	_	_	2.0-61	17.7-21.9	119	_	1220-1400	17
Ramie	915	23	15	4	60-250	28.1-35	###	_	###	8.5
Abaca	12	41	_	3	4.6-5.2	17-21.4	257	_	###	14
Banana	529-914	27-32	20-24	1.0-3	2-3.8	_	_	11.0-12	1300-1350	_
Pineapple	413-1627	60-82	42-57	0-1.6	_	20-80	_	6.0-14	1440-1560	_
Sisal	80-840	9.0-22	6.0-15	2.0-14	1.8-3.1	18.3-23.7	115	10.0-22	1300-1500	11
Coir	106-175	6	5.2	15-40	0.9-1.2	16.2-19.5	64	39-49	1150-1250	13

In general, natural fibers such as hardwood, softwood, jute, hemp, sisal banana, palm, coconut, kenaf, ramie, pineapple, maguey, lechuguilla, caruua, flax, wheat, barley, sugar cane etc. are some of the fibers that have been used for reinforcing cementitious composites[11]. **Table 11** gives the detail of some selected fibers. Since natural fibers come from different species of plants, a great variation in their characteristics can be seen. **Table 12** gives the compositions of most common natural fibers.

Table 12 : Constituents of natural fibers[11]

Name of the fibers	Cellulose(wt.%)	Lignin (wt.%)	Hemicellulos-lose (wt.%)	Pectin (wt.%)	Wax (wt.%)	Microfibrillar/spiral angle (degree)	Moisture content (wt.%)
Bast fibers							
Jute	61-71.5	12.0-13.0	13.6-20.4	0.2	0.5	8.0	12.6
Flax	71	2.2	18.6-20.6	2.3	1.7	10.0	10.0
Hemp	70.2-74.4	3.7-5.7	17.9-22.4	0.9	0.8	6.2	10.8
Ramie	68.6-76.2	0.6-0.7	13.1-16.7	1.9	0.3	7.5	8.0
Leaf fibres							
Sisal	67-78	8.0-11.0	10.0-14.2	10.0	2.0	20.0	11.0
Pineapple leaf fibre	70-82	5.0-12	_	_	_	14.0	11.8
Seed fibers							
Cotton	82.7	0.7-1.6	5.70	_	0.6	_	33-34

The most pertinent issues about using natural fibers is their susceptibility to degrade in alkali rich environment resulting in the mineralization of fibers[164,165]. The water absorption capacity of natural fibers is high that can easily result in volumetric instability in the matrix[166].

3.0 Closing Remarks

The use of fibers as a local reinforcement in cement-concrete mix can significantly enhance its mechanical characteristics and overall long-term performance. The pre-deformed metallic fibers significantly induce ductility and increases the strength of the composite by virtue of mechanical bonding (deformed geometry) and by adhesion through interfacial friction. However, their vulnerability to corrode and conversely, the use of coated fibers being costly, makes them unsuitable in the marine/aggressive condition. Low cost, chemical stability and other recent advancements have brought synthetic fibers on the top of the list for reinforcing cement composites. Although their stiffness is not comparable with that of steel but their capacity to control the mechanisms of like plastic shrinkage or thermal cracking etc., is impeccable. Glass fibers have high modulus and high strength are most suitable to be used on the outer portion as reinforcement such as GFRP wraps or thin glass sheets. Their susceptibility to degrade under highly alkaline environment makes them not a very good choice to be used as short fibers inside concrete matrix. Natural fibers seem promising and a great potential for making construction practice more sustainable. They are still being explored and tested. As of now, their degradation in alkali environments and their high-water absorption characterizes have limited their scope as reinforcing fibers in concrete matrix.

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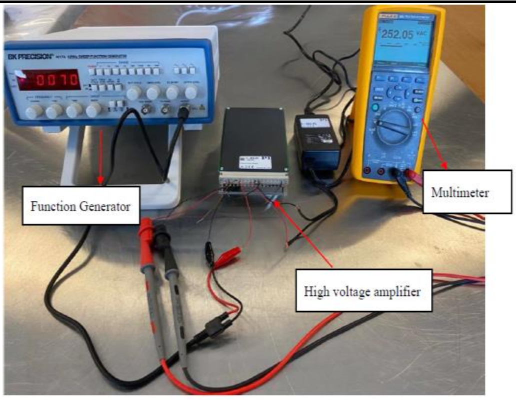
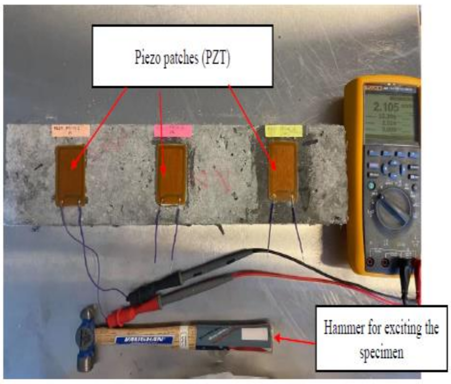
Appendix 7



a)



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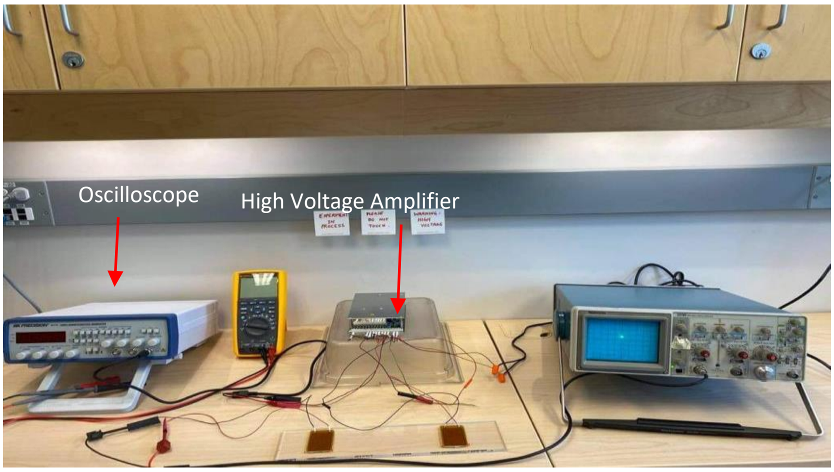


c)

Fig. 1 In-house developed structural health monitoring technique using Piezoelectric patches

Appendix 8

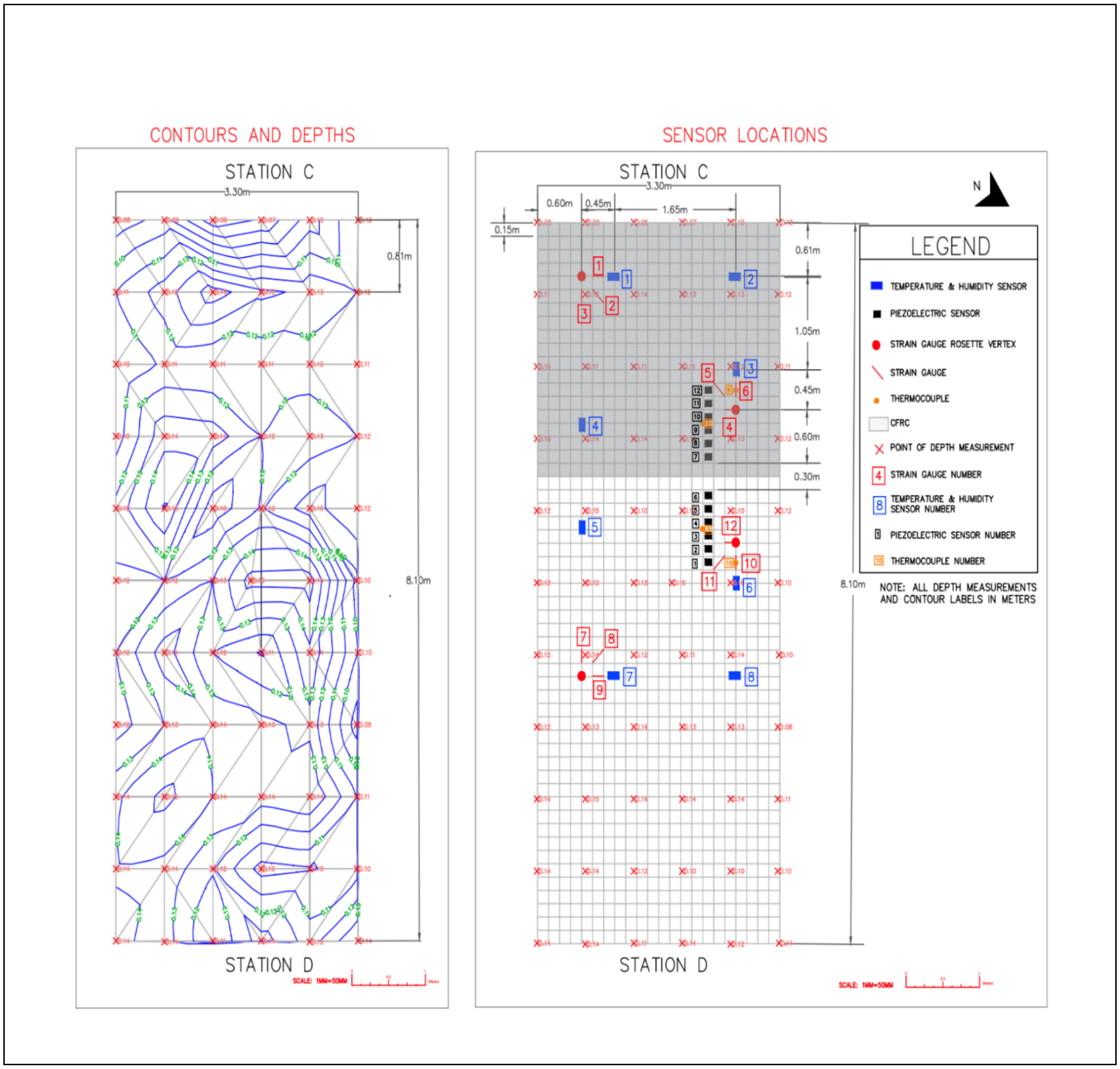


Fig. 1 Lay-out of the bus pad and details of sensor location

 a) Integrated wireless temperature and humidity sensor	 b) Thermocoupl es	 c) Strain Gauges	 d) Thermocouple data logger

Fig. 2 Different type of sensors embedded inside concrete

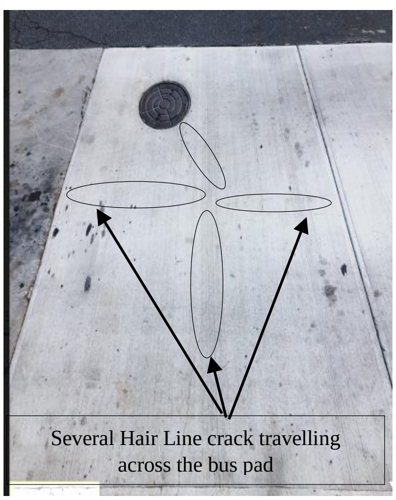
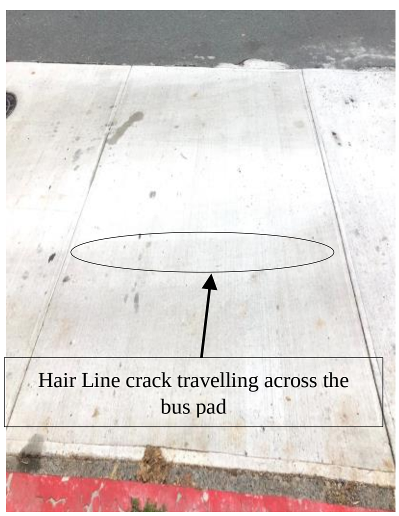
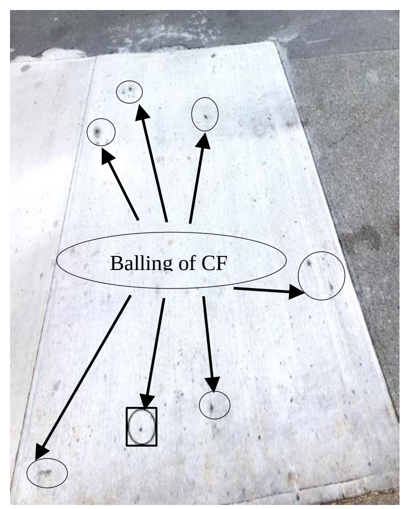
Bus Pad-1	Bus Pad-2	CFRC Bus Pad
		

Fig. 3 Visual assessment of bus pads at 28th day

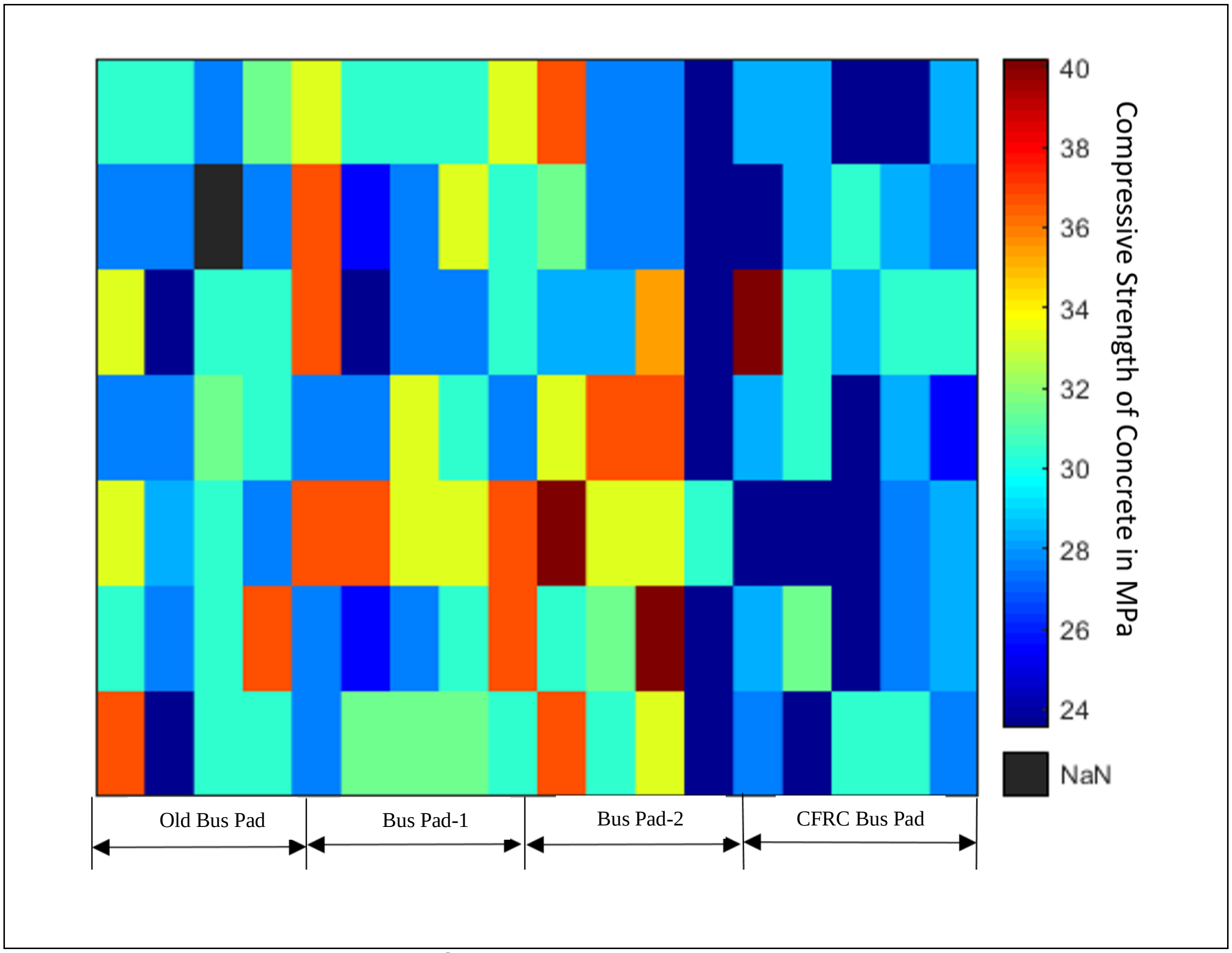


Fig.4 28th Day Schmidt Hammer testing data

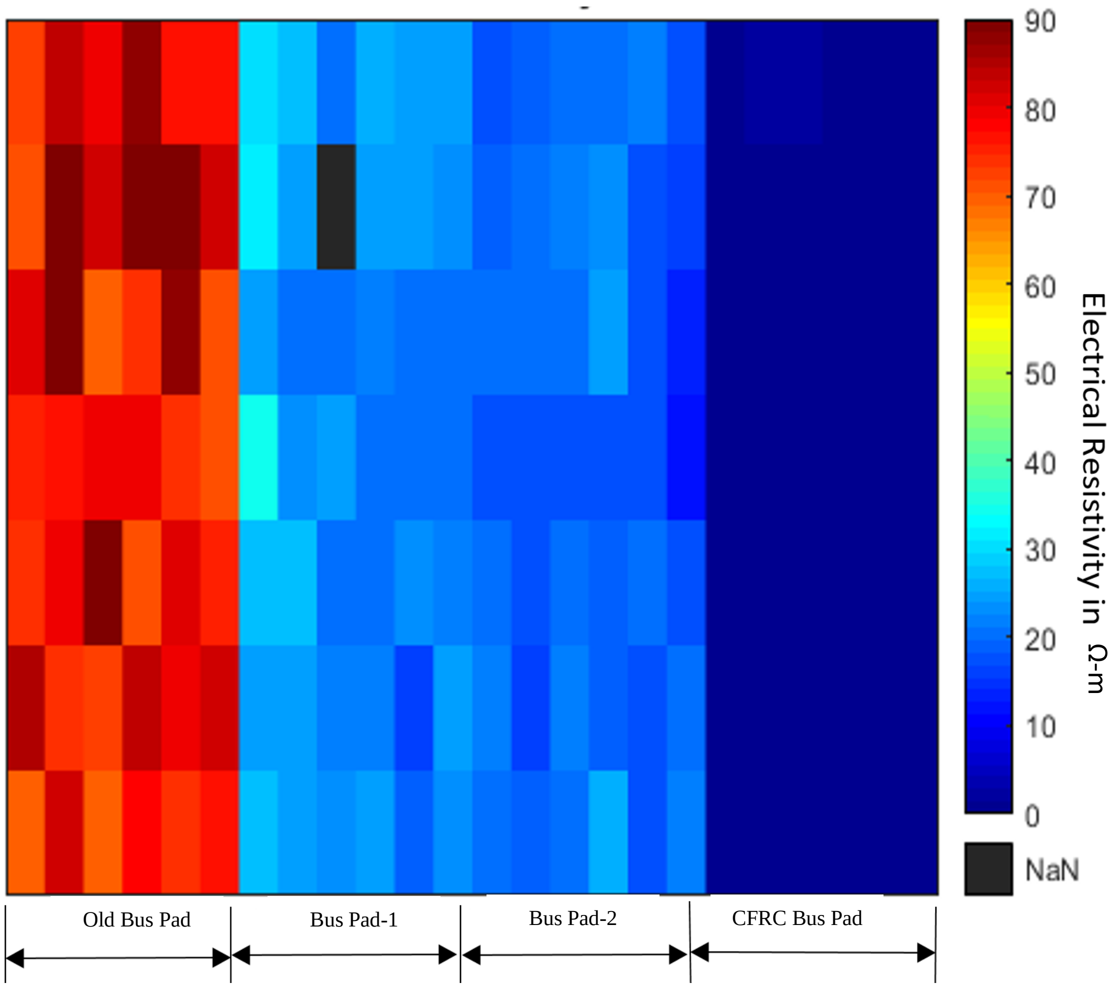


Fig.5 28th Day Electrical Resistivity testing data

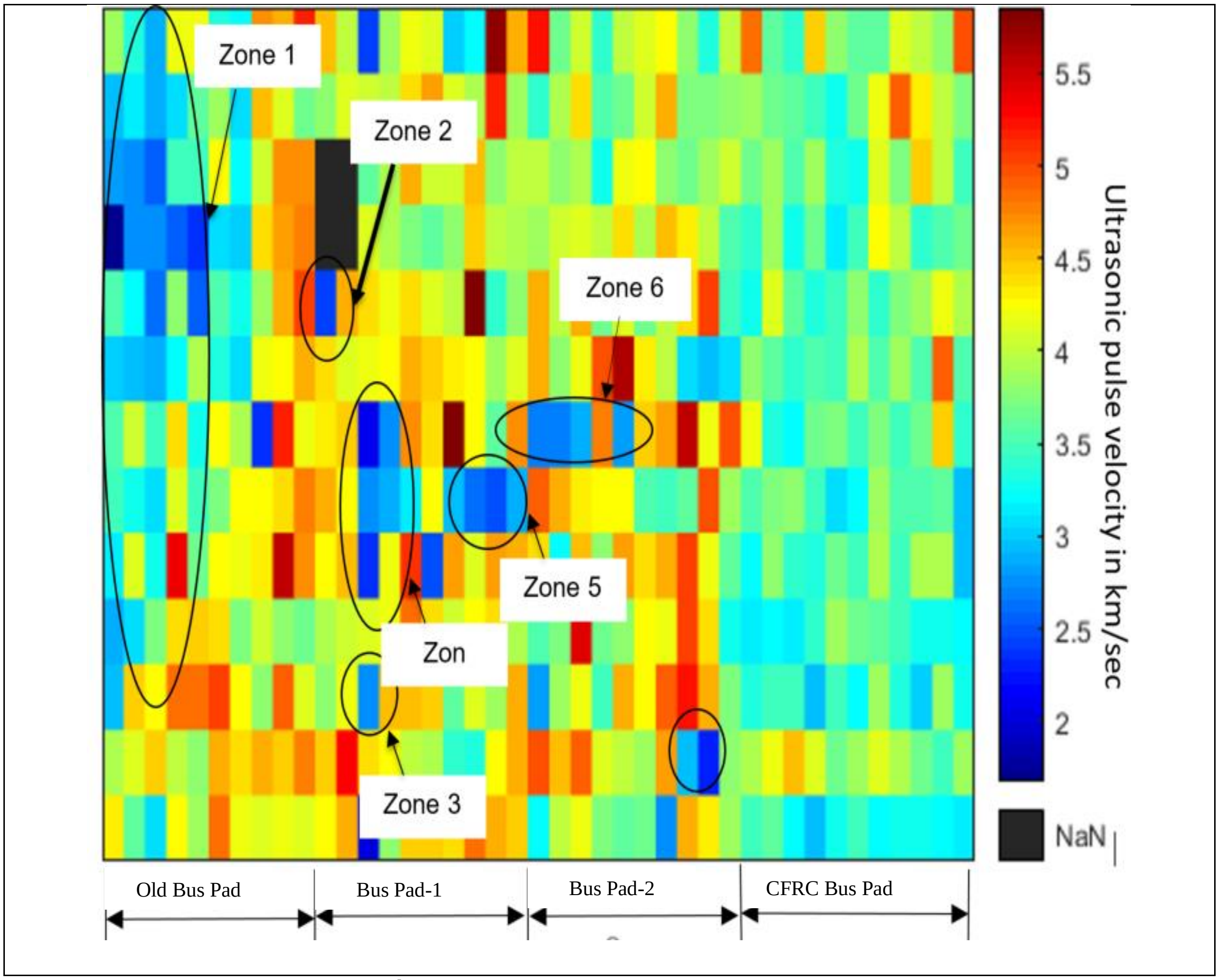
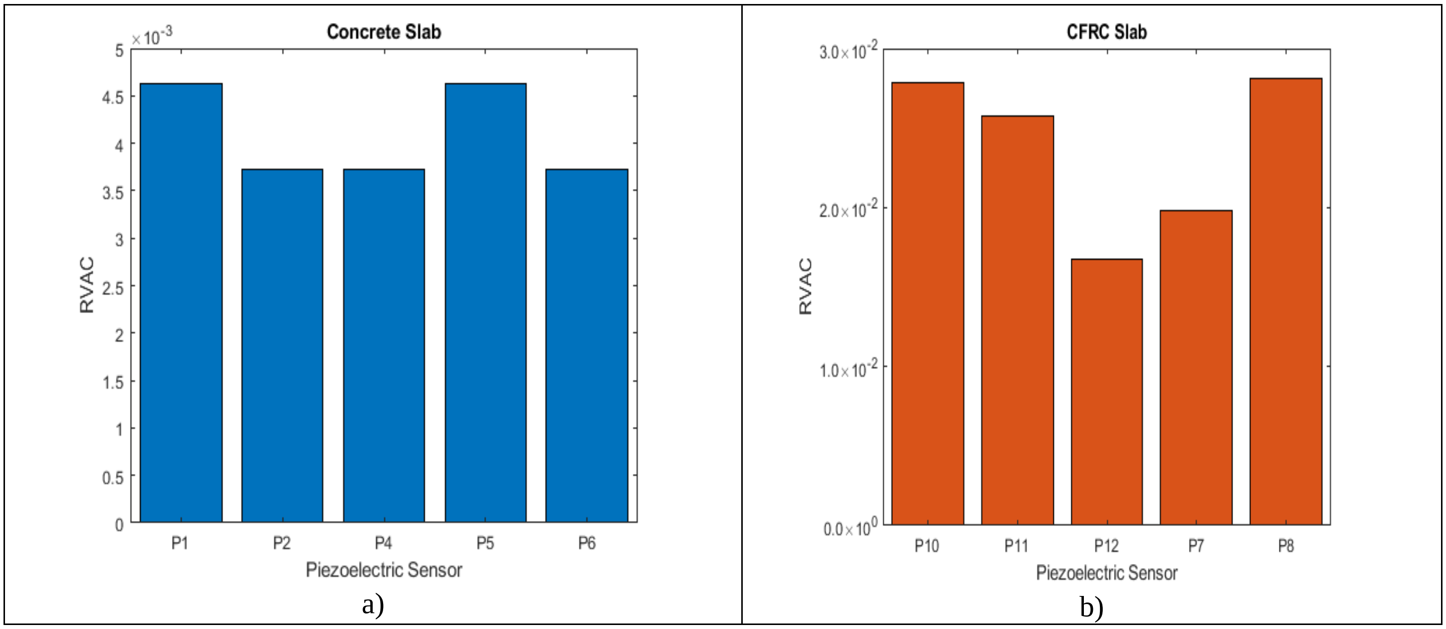


Fig.6 28th Day Ultrasonic Pulse Velocity testing data



a) b)

Figure 7 a: 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 7 b: 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.

Table 1 Data acquired from embedded temperature sensor in normal concrete bus pad and CFRC bus pad

Temperature Data		Bus Pad -2				CFRC Bus Pad				
Day of testing	Date of Reading	TH1	TH 2	TH 3	TH 4	TH 5	TH 6	TH 7	TH 8	Ambient Reading
1	09-29-20	No recording	No recording	No recording	No recording	19.5	19.6	20	19.6	23.2
2	09-30-20	No recording	No recording	No recording	No recording	19.6	19.2	19.5	19.3	18.3
3	10-01-20	No recording	No recording	No recording	No recording	18.5	18.8	19	19.2	19.7
4	10-02-20	No recording	No recording	No recording	No recording	17.8	18	18.2	18.2	18.2
5	10-05-20	No recording	No recording	No recording	No recording	16.1	15.6	16.3	16.1	16.3
6	10-06-20	No recording	No recording	No recording	No recording	16.6	16.5	16.7	17	17.7
7	10-08-20	No recording	No recording	No recording	No recording	17	16.6	16.9	17.1	17
8	10-09-20	No recording	No recording	No recording	No recording	16.9	16.8	17.1	17.1	16
9	10-13-20	No recording	No recording	No recording	No recording	14.1	13.9	14.3	14.4	12.7
10	10-15-20	No recording	No recording	No recording	No recording	13.3	13	13.6	13.7	12.6
11	10-16-20	No recording	No recording	No recording	No recording	15.2	14.9	15.1	15.4	15
12	10-19-20	No recording	No recording	No recording	No recording	13.8	13.6	14	14	No Reading
13	10-20-20	No recording	No recording	No recording	No recording	10.9	10.8	11.5	11.5	No reading
14	10-22-20	No recording	No recording	No recording	No recording	11.1	10.5	11.2	11.2	No reading
15	10-23-20	No recording	No recording	No recording	No recording	9.6	9.7	10.1	10.2	No reading
16	10-26-20	No recording	No recording	No recording	No recording	7.5	8.1	8.1	8.03	No reading
17	10-27-20	No recording	No recording	No recording	No recording	10.9	10.9	10.9	11.3	No reading

Table 2 Data acquired from embedded humidity sensor in normal concrete bus pad and CFRC bus pad

Humidity Data		Bus Pad-2				CFRC Bus Pad				
Day of testing	Date of Reading	H1	H 2	H 3	H 4	H 5	H 6	H 7	H 8	Ambient Reading
1	09-29-20	No recording	No recording	No recording	No recording	100	100	100	100	61.8
2	09-30-20	No recording	No recording	No recording	No recording	100	100	99.5	100	97.6
3	10-01-20	No recording	No recording	No recording	No recording	100	100	100	100	97.8
4	10-02-20	No recording	No recording	No recording	No recording	100	100	100	100	100
5	10-05-20	No recording	No recording	No recording	No recording	100	100	100	100	99.9
6	10-06-20	No recording	No recording	No recording	No recording	100	100	100	100	96.8
7	10-08-20	No recording	No recording	No recording	No recording	100	100	100	100	97
8	10-09-20	No recording	No recording	No recording	No recording	100	100	100	100	97
9	10-13-20	No recording	No recording	No recording	No recording	100	100	100	100	98.8
10	10-15-20	No recording	No recording	No recording	No recording	100	100	100	100	98.9
11	10-16-20	No recording	No recording	No recording	No recording	100	100	100	100	98.8
12	10-19-20	No recording	No recording	No recording	No recording	100	100	100	100	No reading
13	10-20-20	No recording	No recording	No recording	No recording	100	100	100	100	No reading
14	10-22-20	No recording	No recording	No recording	No recording	100	100	100	100	No reading
15	10-23-20	No recording	No recording	No recording	No recording	100	100	100	100	No reading
16	10-26-20	No recording	No recording	No recording	No recording	100	100	100	100	No reading
17	10-27-20	No recording	No recording	No recording	No recording	100	100	100	100	No reading

Table 3 Data acquire from embedded thermocouples in Bus Pad-2 and CFRC Bus Pad

Thermocouple data			Bus Pad-2		CFRC Bus Pad		
Day of testing	Date of Reading	Time of Reading	TC 3	TC 10	TC 6	TC 9	Ambient Temperature
1	09-29-20	10:50am	19.7	19.4	21.1	20.7	
	09-29-20	2:08pm					21.2
2	09-30-20	11:30am	19.7	20.2	19.6	25.2	18.5
3	10-02-20	11:15am	19.3	18	18.2	25.1	19.4
4	10-05-20	11:20am	16.7	16.6	17.1	16.9	16.5
5	10-16-20	2:10 PM	14.4	14.7	14.5	14	14.2
6	10-19-20	2:20 PM	13.7	13.6	13.3	13	12.5
7	10-26-20	10:00 AM	8.9	9.1	8.4	8.3	8
8	11-1-20	11:20AM	8.6	9	7.8	7.7	8.5

Table 4 Average strain readings from embedded strain gauges in Bus Pad-2 and CFRC Bus Pad

Strain Gauge Data		Bus Pad-2						CFRC Bus Pad					
Day of testing	Date of Reading	SG 1	SG 2	SG 3	SG 4	SG 5	SG 6	SG 7	SG 8	SG 9	SG 10	SG 11	SG 12
1	09-29-20	0.693153	0.693153	0.693153	0.693153	0.693153	0.693153	0.693153	0.693153	0.693153	0.693153	0.693153	0.693153
2	09-30-20	0.693153	0.693153	0.693153	0.693153	0.029460667	0.000437056	0.693153	0.693153	0.693153	0.693153	0.057814111	0.693153
3	10-02-20	0.681696	0.681696	0.681696	0.460088333	0.693153	0.686466	0.693153	0.693153	0.693153	1.12222E-05	0.686466	-0.037220389
4	10-05-20	0.693153	0.693153	0.000241944	0.000552556	-0.000115111	0.000372167	0.693153	0.053817889	-0.001324778	-0.000193667	-0.0001195	0.000023
5	10-13-20	0.0022189	0.02224625										
6	10-16-20	0.000770575	0.002763267	0.045495267	0.686466	0.0011465	0.686466	0.693153	0.693153	-6.53333E-06	0.0004158	-7.235E-05	0.0471007
7	10-19-20	0.0000645	0.000448	0.000033	0.686466	0.693153	-0.0002004	0.686466	0.686466	0.00000125	0.686466	0.000037	0.063030775
8	10-26-20	9.07333E-05	0.45238035	0.03635936	0.686466	0.0001478	0.005983659	0.686466	0.686466	-0.00002485	-0.00014765	0.023126533	-0.00043155
9	11-1-20	-0.0027481	0.693153	0.2688221	-0.037892133	-0.0085874	0.68624062	-0.001659071	0.693153	0.091755571	0.00685595	0.0007865	-0.001618414

Table 5 Details of testing of concrete samples cast on –site.

Sample Nomenclature	Sample Details	ASTM standards	Number of Samples	Type of test	Average values	
					Control	CFRC
C-1, C-2, C-3, CF-1, CF-2, CF-3	Cylinders of size 4-inch(100 mm) diameter and 8-inch (200 mm) length	ASTM C39	6	Compressive strength test	16.83 MPa	15.50 MPa
F-1, F-2, F-3, F_{CF}-1, F_{CF}-2, F_{CF}-3	Medium size beams of size 400 X 400 X 100 mm	ASTM C78	6	Flexural strength test	4.18 MPa	5.3 MPa
R-1, R_{CF}-1	Round panels of size 800 mm diameter and 100 mm thickness	ASTM C1550	4	Round Panel Test	20.7 KN	20.7 KN