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 the 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 the preparation of the Final Report Package to ensure 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 a 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:	**Development of smart sensing deicing surfaces using Asphaltene-based carbon fibers (ABCF)**
Alberta Innovates Project Number:	202100637
Submission Date:	August 4, 2023
Total Project Cost:	$241,016
Alberta Innovates Funding:	$170,000
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.

We would like to acknowledge the contributions of the University of Victoria Civil Engineering Department and the University of Victoria Facility Management. The support we received from Harold Engineering, Sito Concrete, McElhanney, and the Pavers in the successful completion of this project is highly appreciated. We would like to thank all our colleagues, interns and co-op students who helped us with this project. Their expertise, support, and collaboration were instrumental in achieving our goals and ensuring the project's success.

A. EXECUTIVE SUMMARY

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

Like many other countries, Canada has set a net-zero emissions target by 2050. Utilizing and storing carbon is a critical technology that can be considered a key pathway for Canadian governments and industry in reducing greenhouse gas (GHG) emissions and achieving net-zero emissions. Carbon fibers (CF)produced from Alberta bitumen utilized in concrete can be regarded as an efficient way to reduce greenhouse gas emissions while also adding self-heating capabilities to the composite.

Self-heating pavement systems can be an innovative solution to address the issue of de-icing pavements. The use of such a system can potentially reduce the number of accidents caused by snow and ice-covered roads, as well as minimize the use of labour-intensive de-icing methods that can cause infrastructural damage and harm the environment.

The project's promising approach is to develop smart electrically conductive carbon fiber-reinforced concrete with demonstrated de-icing capabilities. The use of electrically conductive fibers can allow for the generation of heat within the pavement, which can melt snow and ice. Additionally, using fiber reinforcement in concrete can increase the pavement's durability and strength.

It is worth noting that the development of self-heating pavement systems may require substantial initial investment, but the long-term benefits may outweigh the costs. Moreover, such systems may require maintenance to ensure their effectiveness, especially during extreme weather conditions.

Overall, the development of self-heating pavement systems can have significant benefits for both drivers and the environment. By reducing the need for labour-intensive de-icing methods and minimizing the use of harmful deicing salts, the system can contribute to safer and more sustainable transportation infrastructure.

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

Carbon fibers have several properties that make them suitable for pavement applications, such as high strength, durability, and electrical conductivity. By incorporating carbon fibers into the pavement, it is possible to create a conductive network that can be used to heat the pavement and melt snow and ice. This can significantly reduce the need for mechanical snow removal methods, such as ploughing or salting, which can be expensive, time-consuming, and damaging to the environment.

One potential challenge of using carbon fibers in the pavement is maintaining electrical conductivity over time. Freezing and thawing cycles can cause damage to the pavement and disrupt the conductive network, reducing its effectiveness in melting snow and ice. Further research is needed to better understand the effects of these cycles on the conductivity of carbon fiber-reinforced pavement.

Despite these challenges, the use of carbon fibers in pavements shows promise as a sustainable and environmentally friendly solution for snow and ice removal. This technology has the potential to reduce the costs associated with snow removal, while also reducing the negative impacts on the environment and infrastructure.

The electrical conductivity of a pavement reinforced with carbon fibers is important in determining its effectiveness in removing snow and ice. The percolation threshold of carbon fibers, which indicates the minimum volume percentage of fibers required to create conductive channels in the material, is a critical factor in achieving electrical conductivity. In cement composites with a low volume of carbon fibers, it is difficult to create conductive channels, resulting in an insulation zone. However, increasing the volume percentage of carbon fibers beyond the percolation threshold can effectively create conductive channels in the percolation transition zone. The saturation zone is reached when adding more fibers no longer significantly reduces the electrical resistance of the composite. Understanding the percolation behaviour of carbon fibers in the pavement is crucial in developing effective and sustainable snow removal techniques.

The research described here aims to investigate the effects of freezing and thawing cycles on the electrical resistivity of carbon fiber-reinforced cement-based composites. The study recognizes that previous research on carbon derivatives in composites has not explored the impact of freezing and thawing cycles and that such cycles can reduce the service life of the material due to cracking, surface scaling, and joint damage.

The study explores various parameters, including matrix microstructure, carbon fiber volume percentage, and specimen relative humidity, to gain a more thorough understanding of the influence of different carbon fiber concentrations on the electrical resistivity of the composite. The study results will help develop more durable and reliable carbon fiber-reinforced cement-based composites for use in sustainable snow removal techniques.

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

This project aims to develop a novel technique for de-icing pavements using smart electrically conductive fiber-reinforced concrete. This innovative technology aims to provide a more efficient and eco-friendly solution for de-icing pavements compared to traditional methods such as de-icing salts and snow removal equipment.

The proposed solution is to develop smart electrically conductive fiber-reinforced concrete that can quickly heat up and melt ice and snow on the pavement surface. The concrete will be made by embedding electrically conductive fibers in a reinforced concrete matrix. The electrically conductive fibers will be connected to a power source, allowing electricity to pass through the concrete and generate heat. The heat generated by the concrete will melt the ice and snow on the pavement surface, providing a safer and more efficient solution for de-icing pavements.

The project's main deliverable is the development of smart electrically conductive fiber-reinforced concrete that can quickly heat up and effectively de-ice pavements. This innovative material has the potential to revolutionize pavement de-icing by providing a more efficient and sustainable solution. Additionally, the project will contribute to advancing the understanding of the electrical and thermal properties of fiber-reinforced concrete and its potential applications.

The primary stakeholders of this project include the transportation industry, road maintenance agencies, and the public who rely on safe and reliable transportation during winter months. The project's results can also benefit the construction industry, material suppliers, and researchers interested in sustainable and innovative construction materials.

Performance Metrics

Project Success Metrics

Metric	Project Target
Evaluation of mechanical properties and full physical characterization of ABCF based carbon fibers and Teijin fibers	1) No. of samples to be tested: approximately 75 2) Tensile strength and Uniaxial strength: > 3 MPa 3) Electrical Resistivity of fibers: Accurate lab-based measurements of the order of 1.4 * 10^-3 Ω-cm 4) Compressive strength: > 30 MPa 5) Modulus of Elasticity: > 25 GPa 6) Modulus of rupture: > 3 MPa 7) Freeze-thaw: Lasting 200 cycles of freeze-thaw as per ASTM C666
Fracture behavior of ABCF and Teijin fiber-reinforced composites	1) Number of samples to be tested: approximately 16 2) Increase in fracture toughness in tension and flexure as compared to more than 10 % of control values
Evaluation of electrical resistivity of large size Teijin fiber-reinforced panels	1)Number of samples to be tested: approximately 9 2)Electrical resistivity :< 100 Ω-cm 3) Develop an integrated de-icing round panel 4) GHG Analysis

D. METHODOLOGY

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

RESPOND BELOW

The primary objective of this project is to develop and assess the performance of fiber-reinforced concrete containing conductive carbon fibers, with a focus on evaluating their electrical conductivity and de-icing capabilities. This specialized concrete holds significant promise for applications in regions with cold climates, where surface de-icing is a prevalent challenge. To achieve this objective, the project entails the development and testing of carbon fiber-reinforced concrete (CFRC) with varying fiber dosages of 0%, 0.5%, 1%, 2%, and 3% by volume of concrete.

The concrete was prepared by utilizing a rotary mixer, following the mixing procedure outlined in the standard guidelines of ASTM C192/C192M-1. The materials were introduced into the drum of the mixer, and the dry ingredients were mixed for 3 minutes, followed by a 2-minute wet mixing phase. In the case of samples containing carbon fibers, an additional 30 seconds of mixing was performed on the dry mixture to ensure even distribution of the fibers. Subsequently, the necessary amount of water and superplasticizer were added. To investigate the self-deicing properties and resistivity in concrete, we utilized a wooden formwork measuring 300 x 300 x 100 mm for casting the samples. We employed three different types of electrodes, including rebars, metal lath and wire mesh, positioned 30 mm from the top. To secure these electrodes in place, we used polyurethane foam. Wires were connected to the electrodes for later connection to a DC power source. Additionally, K-type thermocouple wires were strategically placed at the center and corners of the specimen to monitor temperature changes when an electrical current passed through the concrete. Our experiment analyzed material properties such as electrical resistivity, heat capacity, and thermal conductivity.

The electrical conductivity of the concrete was quantified using a 4-probe electrical resistivity testing method, which involves measuring the concrete’s resistance to electrical current flow. This test provides valuable insights into the effectiveness of the incorporated carbon fibers and helps determine the optimal fiber content for desired results. In addition to assessing electrical conductivity, the concrete’s de-icing capabilities were evaluated by monitoring the temperature rise of the composite.

In the case of both Carbon Fiber-Reinforced Mortar (CFRM) and Carbon Fiber-Reinforced Concrete (CFRC) samples, we conducted a self-heating experiment utilizing a Sky Top DC power supply with adjustable voltage and current settings. For CFRM samples, a consistent DC voltage of 30V was applied across the electrodes, and we closely monitored the resulting current flow. For CFRC samples, we increased the voltage to 60V, and temperature changes were meticulously recorded at 30-minute intervals using a FLIR camera throughout the 2-hour heating duration. Temperatures were recorded every 15 minutes during the 2-hour heating period. Furthermore, we assessed the electrical resistivity of the samples by employing an Agilent 34401A digital multimeter. Simultaneously, we utilized an infrared camera (FLIR) to capture surface temperature profiles.

The most effective concrete mixtures were identified based on a comprehensive battery of mechanical and durability tests, encompassing both destructive and non-destructive methods. The destructive tests included compression, flexure, split tension, round panel tests, and fatigue loading. Nondestructive tests covered a range of methods, including the Schmidth hammer, ultrasonic pulse velocity, resonant frequency, four-probe electrical resistivity, bulk and surface resistivity, and half-cell potential. These tests were specifically designed to assess crucial properties, including strength and durability, while pinpointing areas that may require enhancement. Once the superior mixtures were determined, they underwent further optimization, to determine the percolation threshold of carbon fibers. Within a real-world application context, these mixtures were used to construct a bus pavement reinforced with carbon fibers at the University of Victoria. This allowed for the evaluation of concrete performance in an actual operational setting, enabling the identification of additional areas for improvement.

With the help of local authorities at Saanich municipality in Victoria and BC Transit a site at the University of Victoria bus exchange was identified that included a series of three bus pads. For a real-time comparison between the performance of a carbon fiber-reinforced concrete (CFRC) bus pad and a normal concrete bus pad, this field demonstration was conducted. As part of the construction the old, deteriorated bus pads and subbase were excavated to a depth of 750 mm. A 300 mm sub-base was laid on a subgrade approved by the geotechnical engineer followed by a 150 mm base course which was compacted using vibratory rollers. Before the concreting of the bus pads, different types of electrodes and sensors were installed. The constructed bus pad consisted of 300 mm pavement quality concrete of M32 grade with 15 M steel reinforcement located at 75 mm from the bottom at 600 mm center to center. The carbon fibers were added to the concrete when the transit mixer arrived at the placing location.

In summary, this project represents a significant stride toward the development of more sustainable and efficient concrete solutions for de-icing applications. The integration of carbon fibers in concrete not only contributes to reducing the environmental impact of de-icing procedures but also offers a more resilient and effective solution for use in cold climates. It's worth noting that three different materials—10M rebar, wire mesh, and galvanized metal lath—were selected as electrodes for the self-heating test on concrete samples.

E. 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

E.1. Evaluation of mechanical properties and full physical characterization of ABCF and Teijin fibers

E.1.1. Fiber Phase

The bond behavior of fiber-reinforced concrete is a crucial factor in composite behaviour. The adhesion between the fiber and the matrix is influenced by numerous factors, including physical and chemical adhesion. To evaluate the adhesion between the fiber and the matrix, a detailed examination of the microstructural and mechanical properties of a single fiber is necessary. Past research has mainly focused on steel and polypropylene fibers, leaving a knowledge gap regarding the microstructural characteristics and pull-out behaviour of carbon fibers.

Fiber surface treatment is a well-known technique for enhancing fiber-to-cement matrix interfacial adhesion. However, the degradation of fiber surfaces during chemical treatment limits the effectiveness of this approach. Therefore, a new non-destructive surface treatment strategy is required. Our promising patented strategy for improving the microstructure of the matrix around the fiber is to coat it with supplementary cementitious materials (SCM), specifically fly ash, as shown in **Fig. 1**. The outermost material promotes hydration, resulting in a higher concentration of calcium-silicate-hydrate and a thinner interfacial zone between the fiber and the cement matrix. This approach offers a potential solution for enhancing the bond behaviour of fiber-reinforced concrete.

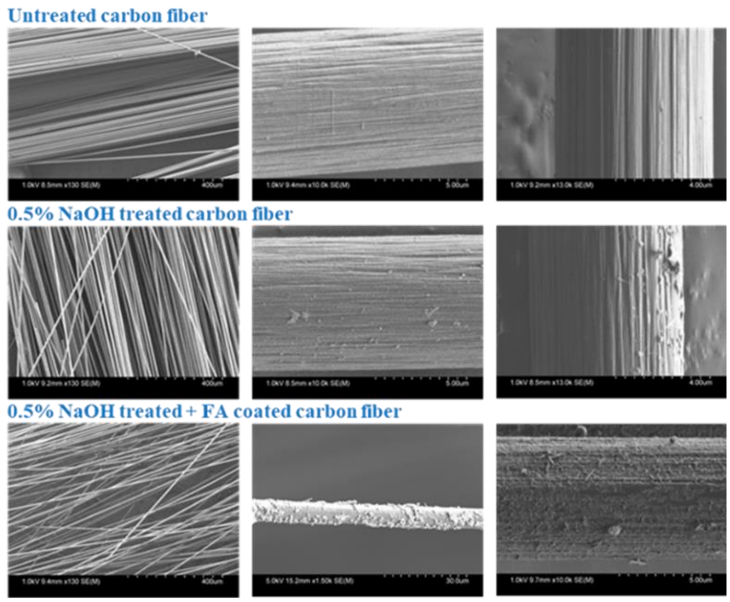


Fig. 1. SEM of treated and untreated carbon fiber

One of the primary goals of this project phase was to get a comprehensive understanding of the physical and chemical characteristics of ABCF. To do this, several microstructural tests and analysis were carried out. **Fig. 3** shows the SEM images of the ABCF. As can be seen, the Alberta carbon fiber displays significant variations in diameter ranging from 16 to 43 micrometers, with a mix of both hollow and solid cylinders observed in some fibers. The fiber's surface contains numerous small pores and appears to be much smoother than Teijin or Mitsubishi fiber. These characteristics can have significant impacts on the fiber's mechanical and physical properties and its interfacial behaviour in composite materials.

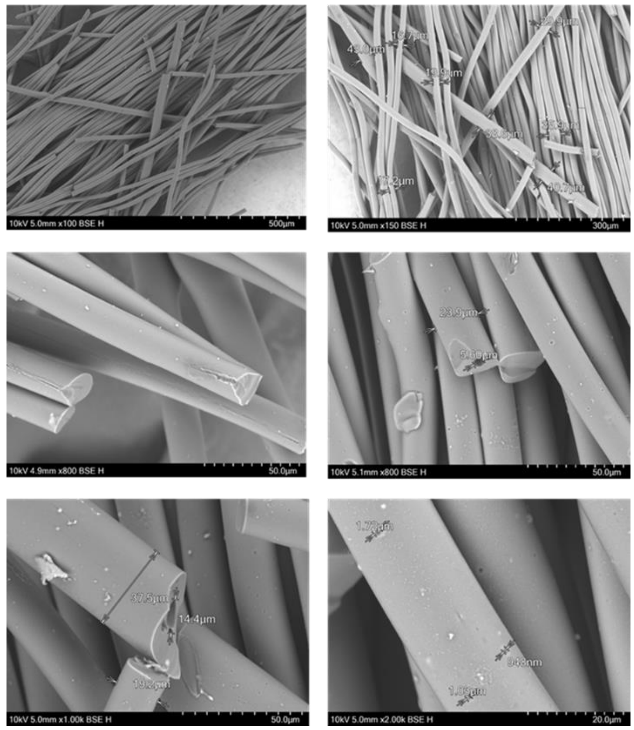


Fig. 2. SEM of ABCF

To determine the chemical components of fibers, energy dispersive X-ray (EDX) is a non-destructive analytical approach. It involves directing an electron beam onto the sample surface to cause it to emit X-rays, which are then gathered and examined to determine the types and relative amounts of elements present in the sample. Understanding the elemental makeup of fibers, locating contaminants or additions, and enhancing fiber characteristics and uses are all possible using EDX analysis. Figures 3, 4, and 5 demonstrate three different EDX approaches utilized to analyze the fibers. The elemental mapping and line scan profile of ABCF showed the presence of impurities in the form of dots on the fiber surface. These impurities had a different chemical composition compared to ABCF, as well as compared to each other. It is important to identify and understand the nature of these impurities to optimize the fiber properties and performance and identify any potential contamination sources during the manufacturing process.

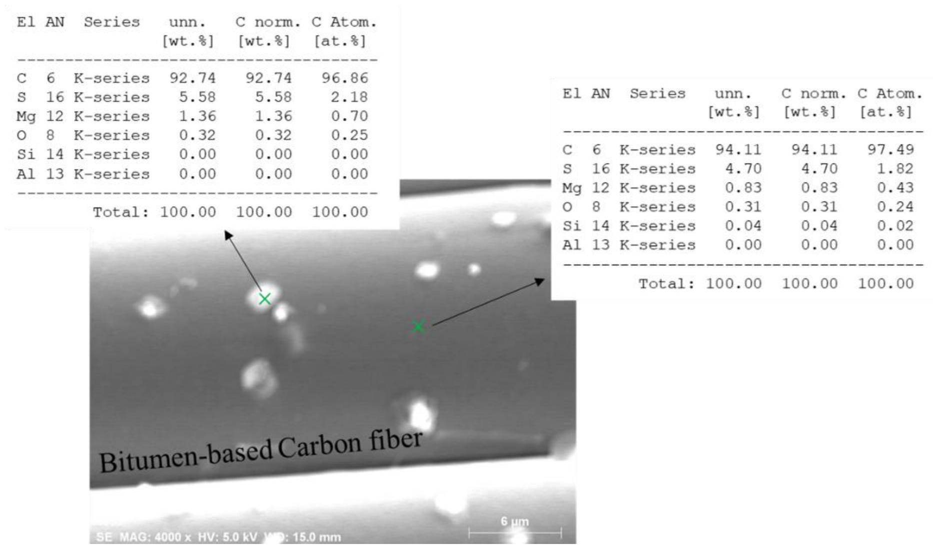


Fig. 3. Chemical composition of ABCF

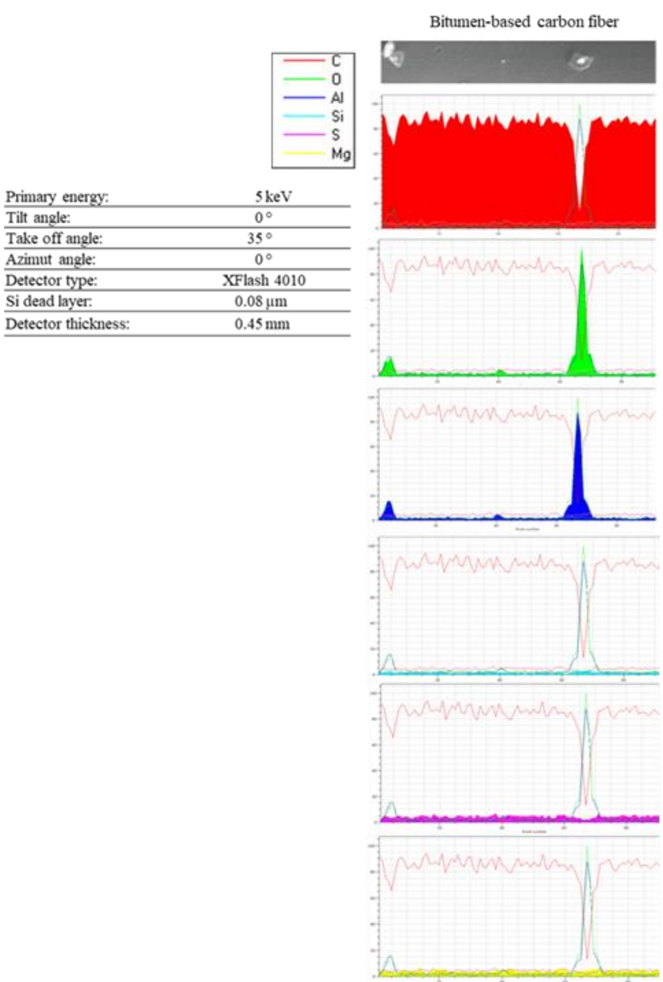


Fig. 4. Energy Dispersive X-Ray Spectroscopy (EDX), Line scan profile of ABCF

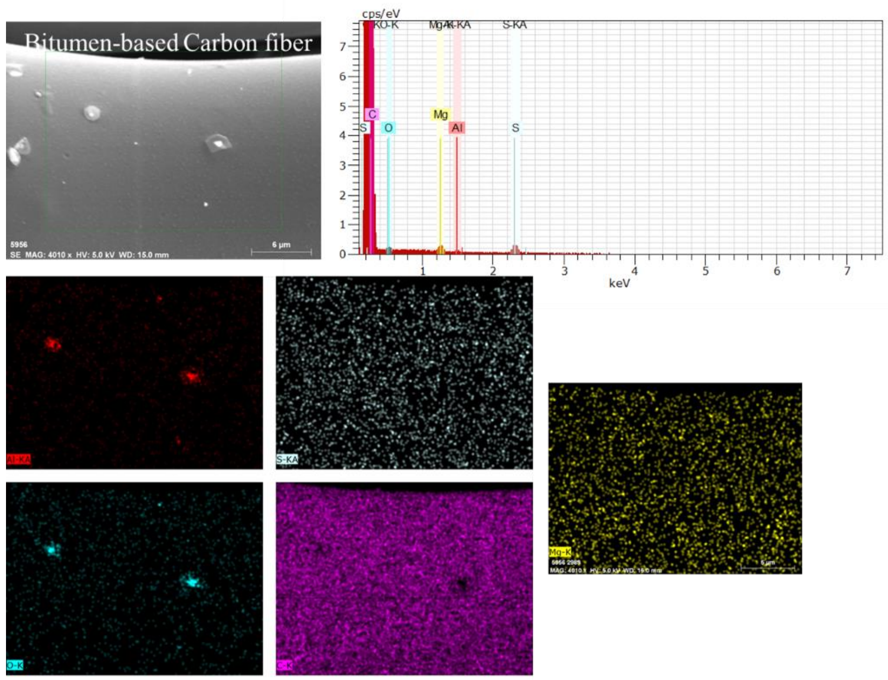


Fig. 5. Elemental map of ABCF

Measuring the bond strength between the carbon fiber and the surrounding cementitious material is necessary to evaluate the pull-out behaviour of carbon fiber in a cementitious matrix. This may be achieved by running a pull-out test on a sample, which entails pulling the carbon fiber out of the cementitious matrix at a set pace while determining the force necessary to do so.

Fig. 6 depicts the force-displacement behaviour of fibers while being pulled out, and Table 1 gives the results for maximum pull-out load (P_{max}), the standard deviation of pull-out loads (SD), displacement at maximum pull-out load (Δ_{pmax}), fiber pull-out energy (W_p), maximum fiber stress ($\sigma_{f,max}$), and equivalent bond strength (τ_{eq}). As can be shown, treated fibers have a value that is significantly lower than untreated fibers in terms of pull-out energy and bond strength (5.1 N.mm and 10381 Pa, respectively). Following the alkaline treatment, the fiber pull-out energy and bond strength both fell by 97.6% and 97.5%, respectively. According to this perspective, the alkaline treatment has a significant impact on the matrix's bonding performance, possibly because the destructive alkaline damages the micro carbon fibers. On the other hand, when treated fibers were coated with Fly Ash (FA), the negative effects were eliminated. The three failure processes that may be detected when carbon fiber is pulled out are fiber breakage, fiber pullout, and fiber debonding from the cement matrix (**Fig. 6**). Fiber breaking accounted for all failure processes when carbon fibers were treated with NaOH; nevertheless, both untreated and FA-treated fibers experienced all types of fiber breakage and fiber pullout failure. Although FA treatment is a great way to improve the bonding characteristics, it can be required to convert from an alkaline treatment to a less harmful process.

A pull-out test is a useful tool for learning more about the interfacial bonding and adhesion between the fiber and matrix as well as the general mechanical behaviour of the composite material. The performance of carbon fiber-reinforced cementitious composites for a variety of applications, such as building and infrastructure materials, must be developed and optimized using this knowledge.

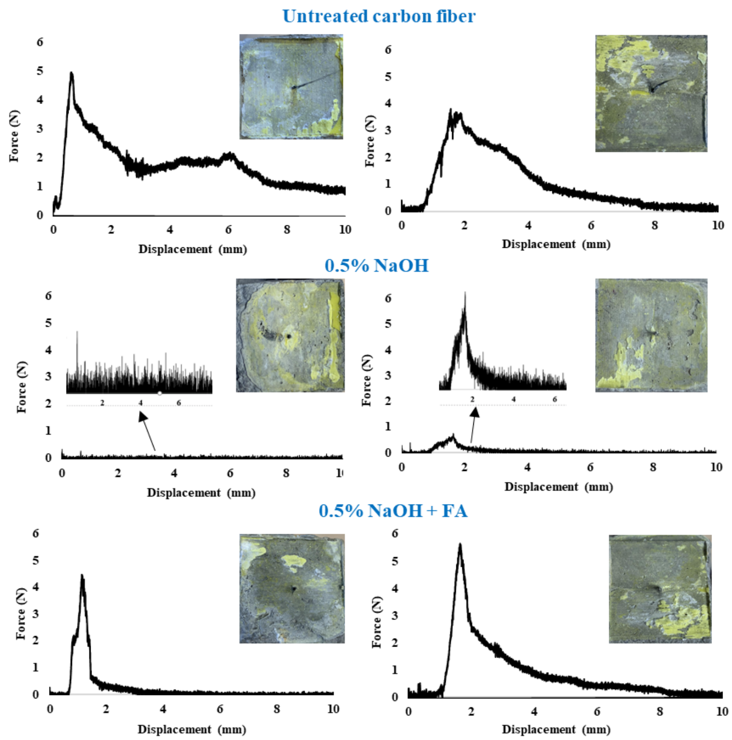


Fig. 6. Force-displacement behavior of treated and untreated carbon fibers

Table 1. Summary of fiber pull-out test results

Specimen	P_{max}	SD	Δ_{pmax}	W_p	$\sigma_{f,max}$	τ_{eq}
	N		mm	N.mm	MPa	Pa
Untreated carbon fiber	4.58	0.8	1.94	5.1	5.8	10381
5% NaOH treated carbon fiber	0.54	0.09	0.83	0.12	0.69	259
5% NaOH treated + FA coated carbon fiber	6.16	0.72	2.12	4.8	7.8	10825

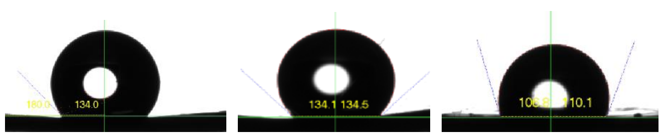
Compared to many other materials, carbon fibers have an extremely low electrical resistance, which makes them ideal electrical conductors. The high degree of graphitization and alignment of the carbon atoms inside the fiber structure are the causes of the low electrical resistance of carbon fibers. Evaluation of the electrical resistibility of treated and untreated carbon fibers was another important goal of this phase. This electrical characteristic of carbon fibers is particularly a decisive criterion in applications where electrical conductivity is sought, such as in electrical and electronic components.

Table 2 shows the changes in the electrical resistivity of fiber with different treatment methods. It has been demonstrated that applying NaOH to carbon fibers efficiently removes the fiber's sizing and lowers the fiber's electrical resistivity, but applying NaOH with fly ash to carbon fibers has a negative impact on the fiber's resistivity. This could be because fly ash, in comparison to carbon fibers, has a higher electrical resistance on its own.

Table 2. Electrical resistivity of treated and untreated fibers

Fiber	Resistivity (μohm-m)
Untreated carbon fiber	5.3
5% NaOH treated carbon fiber	2.5
5% NaOH treated + FA coated carbon fiber	6.9

The contact angle of carbon fibers in a cement matrix is an important characteristic to consider since it impacts the mechanical properties of the composite material. A high contact angle might cause the fibers and cement to have poor interfacial adhesion, which can decrease mechanical strength and durability. As a result, optimizing the contact angle by surface treatments is essential for enhancing interfacial adhesion and the overall performance of the composite material. **Fig. 7** shows changes in contact angle in both treated and untreated carbon fibers. The contact angle measurement of untreated carbon, which is shown in the image, was 134, suggesting that the fiber-matrix adhesion is extremely poor, which might be significant for carbon-fiber reinforced composites. This is mostly caused by the surface morphology and properties of the carbon fibers.



(a) (b) (c)

Fig. 7. Contact angle of a) untreated carbon fiber b) NaOH treated carbon fiber c) NaOH+ fly ash treated carbon fiber

The objectives of this phase were met by a thorough examination that included scanning electron microscopy, energy dispersive x-ray spectroscopy, contact angle measurement, fiber electrical resistivity, and pull-out testing. Nevertheless, due to the brittle nature of the Alberta Bitumen-based carbon fibers (ABCF), the tensile strength and fiber pull-out tests could not be performed since they included handling and may result in fiber breakage. One challenge we encountered was the unavailability of asphaltene-based carbon fibers in sufficient quantity to conduct the desired tests.

E.1.2. Small-scale laboratory test

Small-scale laboratory tests are a valuable tool in research and development, offering cost-effective, time-efficient, and flexible options for assessing various mix designs and testing conditions. Researchers can design and produce a range of samples with different mix designs and identify superior options before conducting full-scale testing, allowing for greater control and refinement of the cement matrix. Additionally, small-scale testing reduces the number of materials and carbon fibers needed, making it a more sustainable option.

Small-scale laboratory samples play an important role in testing and refining cement matrix compositions before using them in larger-scale samples. The cement matrix is a vital component of concrete and any changes to its composition can significantly affect the performance and durability of the concrete. Tests on fiber-reinforced cement mortar samples helps to better understand the impact of composition changes on the properties of the cement matrix and make decisions about how to optimize it for specific applications and finally improve the performance and durability of concrete structures.

The project involved preparing and evaluating more than 135 small specimens with varying amounts of CF (0, 0.5, 1, 1.5, 2, 2.5, 3, 3.5 and 4% by volume) and conducting multiple tests such as compressive strength, tensile strength, modulus of rupture, post crack analysis, and freeze and thaw tests. Compressive, tensile, and flexural testing of mortar specimens was performed on CFRC mortar at varied volumetric concentrations (**Fig. 8**). The results of mechanical tests on samples are summarized in **Fig. 9** and the fracture pattern of samples under bending is depicted in **Fig. 10**.

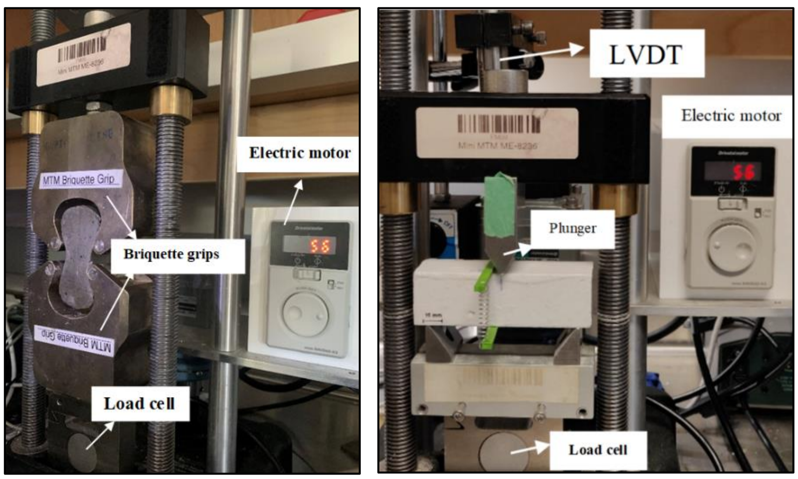


Fig. 8. Tensile and flexural strength test set-up

As can be seen in Fig. 9, as the percentage of carbon fiber by volume rises, the compressive strength drops but the tensile and flexural strengths increase. It's worth noting, though, that there appears to be significant variation in the data, particularly at the upper and lower ends of the % carbon fiber spectrum. A regression analysis of the data can be used to quantify the correlation between % carbon fiber and each category of strength. This would include fitting a mathematical model to the data that defines the relationship between the independent variable (percent of carbon fiber) and the dependent variable (strength). The choice of regression model depends on the specific characteristics of the data and the research question of interest. In this case, a second-order polynomial regression model can be used to model the relationship between the percent carbon fiber by volume and strength.

second-order polynomial regression can be written as:

$y = b_0 + b_1x + b_2x^2$

where y is the dependent variable (in this case, compressive, tensile, or flexural strength), x is the independent variable (percent of carbon fiber by volume) and b_0, b_1, and b_2 are the regression coefficients.

R-squared (R2) is a statistical measure that measures the proportion of variation in the dependent variable that is explained by the independent variable(s) in a regression model. It is a number between 0 and 1, with 0 indicating that the model explains no variability in the dependent variable and 1 indicating that the model explains all variability in the dependent variable. As can be seen in **Fig. 9**, R-squared is near to 1 in all the strength categories. This suggests that the model can explain a high amount of variance in the dependent variable (strength values) using variation in the independent variable (carbon fiber percentage).

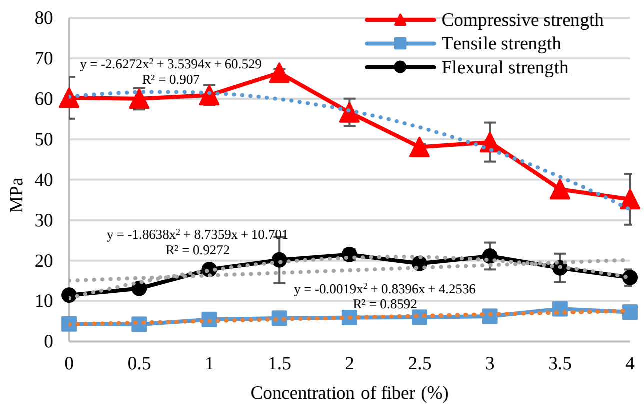


Fig. 9. Compressive, tensile, and flexural strength of CFRM

The fracture pattern of beams subjected to three-point bending tests can reveal important information about the material qualities and failure process of the beam. The fracture pattern of all tested beam are shown in **Fig. 10**. According to the fracture pattern, the fracture initiation point in the non-reinforced samples is close to the midspan, which could indicate that the matrix material is relatively homogeneous in that region. On the other hand, the fracture initiation point in the samples with higher carbon fiber volume is not exactly in the center of the beam, which could indicate that the matrix material is not uniform throughout the beam. This might be mainly because of accumulation of the carbon fibers in some areas which strengthened certain areas of the matrix more than others, resulting in local differences in strength and stiffness.

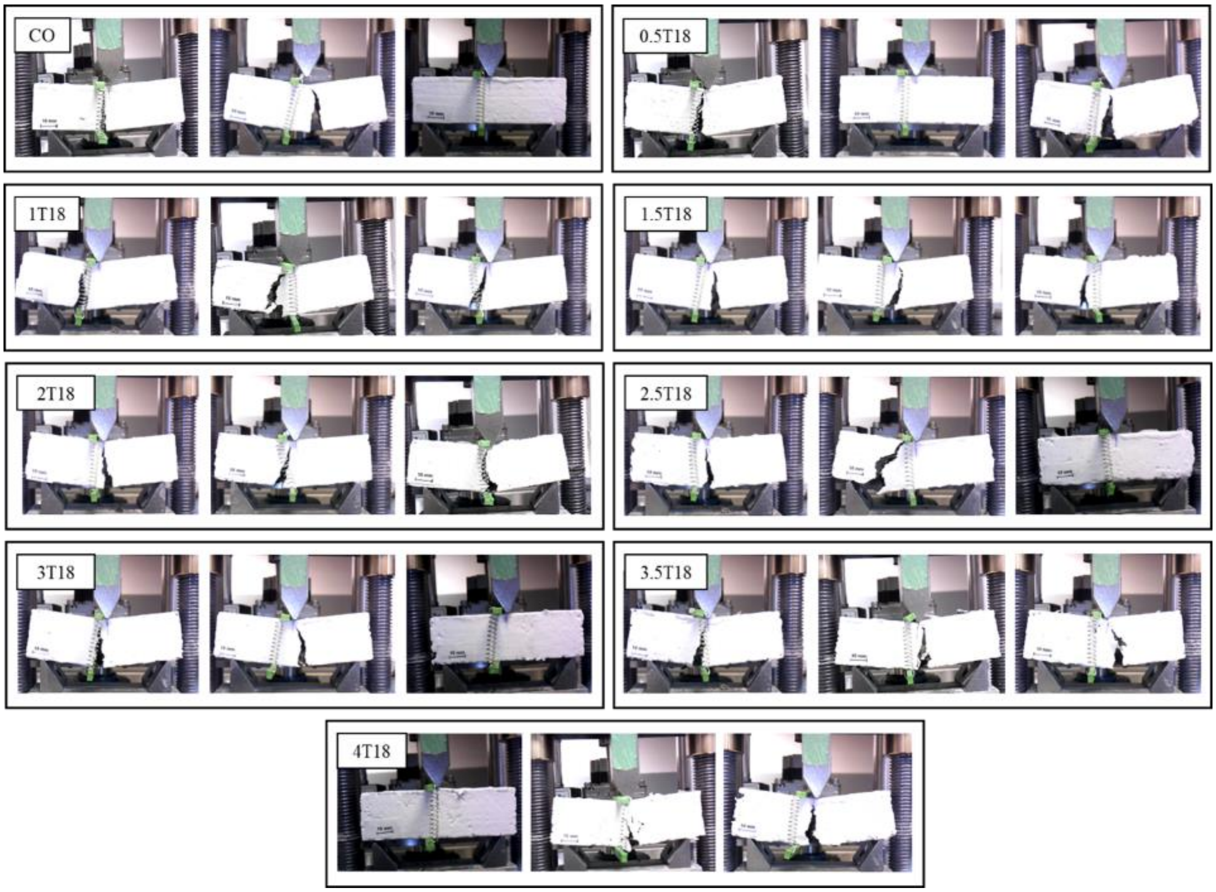


Fig. 10. Fracture pattern of cement mortar samples under bending test

The Modulus of Rupture (MR) of a material is a measure of its flexural strength. It indicates the maximum stress that a material can withstand before failing under the bending test. As per **table-3** the MR of the Control (CO) sample in the present study was 11.4 MPa, which was lower than the MR of all the carbon fiber-reinforced samples. The MR was generally increased as the amount of carbon fiber rose, showing that the addition of carbon fibers improved the material's flexural strength. The displacement at maximum load (Δpmax) was also higher for the carbon fiber-reinforced samples compared to the CO sample. This means that the fiber-reinforced samples were able to deform more before failing under bending.

The indices I_5 and I_{10} provide information on the amount of energy absorbed by the material during loading. As the percentage of carbon fiber in the concrete mix increases, the values of both I_5 and I_{10} also tend to increase. This indicates that the addition of carbon fibers increases the energy absorption capacity of the concrete. The I_5 and I_{10} values also show a trend of increasing with increasing bending load (P_{max}).

Table 3. Flexural behaviour of CFRM beam under bending test

Code	P_{max}	Δ_{pmax}	MR	MR (average)	SD (MR)	$E_{initial}$	I_5	I_{10}	I_5 (average)	I_{10} (average)
	N	mm	MPa	MPa		N.mm				
CO	2120	0.13	10.60	11.44	0.73	270.1	1.47	1.47	1.16	1.16
CO	2384	0.46	11.92			729.7	1.00	1.00		
CO	2360	0.30	11.80			253.2	1.00	1.00		
0.5T18	2788	0.25	13.94	13.15	0.76	325.5	1.98	2.84	1.72	2.24
0.5T18	2615	0.26	13.08			351.8	1.79	2.20		
0.5T18	2485	0.26	12.43			345.6	1.39	1.68		
1T18	3344	0.31	16.72	17.80	0.97	498.4	1.93	2.19	1.81	1.97
1T18	3615	0.40	18.08			520.4	1.89	1.95		
1T18	3720	0.33	18.60			530.5	1.63	1.77		
1.5T18	2883	0.54	14.42	20.17	5.71	604.2	2.59	2.73	2.59	2.74
1.5T18	4048	0.86	20.24			868.0	3.23	3.33		
1.5T18	5168	0.36	25.84			1144.6	1.94	2.16		
2T18	4140	0.44	20.70	21.49	1.39	791.2	2.05	2.40	1.80	1.97
2T18	4620	0.50	23.10			1082.1	1.90	1.93		
2T18	4136	0.37	20.68			921.0	1.44	1.59		
2.5T18	3753	0.15	18.77	19.32	0.48	273.1	2.50	3.10	2.38	2.93
2.5T18	3923	0.40	19.62			635.4	1.90	2.12		
2.5T18	3916	0.29	19.58			605.9	2.73	3.58		
3T18	3864	0.36	19.32	21.99	4.80	805.4	2.89	3.64	2.16	2.56
3T18	3825	0.74	19.13			2169.0	2.08	2.39		
3T18	5507	0.68	27.54			1696.7	1.53	1.65		
3.5T18	3905	0.45	19.53	18.19	3.53	1095.4	2.51	3.02	2.45	2.99
3.5T18	4172	0.61	20.86			1038.6	1.91	2.08		
3.5T18	2838	0.66	14.19			1009.1	2.92	3.85		
4T18	3023	0.56	15.12	15.80	2.01	907.7	2.47	3.06	2.91	3.85
4T18	2845	0.87	14.23							
4T18	3612	0.53	18.06			846.9	3.35	4.64		

E.1.3. Freeze-thaw test

The freeze-thaw test is commonly used to assess the durability of cement-based composites. Under controlled settings, this test determines the durability of cement mortar to repeated cycles of freezing and thawing. The freeze-thaw cycles can cause damage to the cement mortar through the expansion and contraction of water within the material, which can lead to the formation of micro-cracks and breakage of carbon fiber. The crack will then widen resulting in a loss of material strength and, in the case of conductive concrete, can disrupt the electrical network if the expanded fracture disrupts the passage of electric current. A more porous composite will also have a higher electrical resistivity due to the deterioration of disruption of the electrical path in the material.

The electrical resistivity of samples at different FT cycles is shown in Fig. 11. The results show that as the amount of carbon fiber in the cement mortar increases, so does the electrical conductance. This is predicted since carbon fiber is a conductive substance, and adding more of it to the mixture should enhance the conductivity of the resultant composite material. Nevertheless, there seems to be a critical threshold percentage of carbon fiber beyond which the conductivity exhibits limited variation. This threshold appears to be approximately 0.5-1.5% for zero freeze-thaw (0 FT) cycles and increases to approximately 2-2.5% for higher freeze-thaw (FT) cycles. Surprisingly, even with a higher proportion of carbon fiber, the conductivity values remain consistently steady at and above this identified threshold.

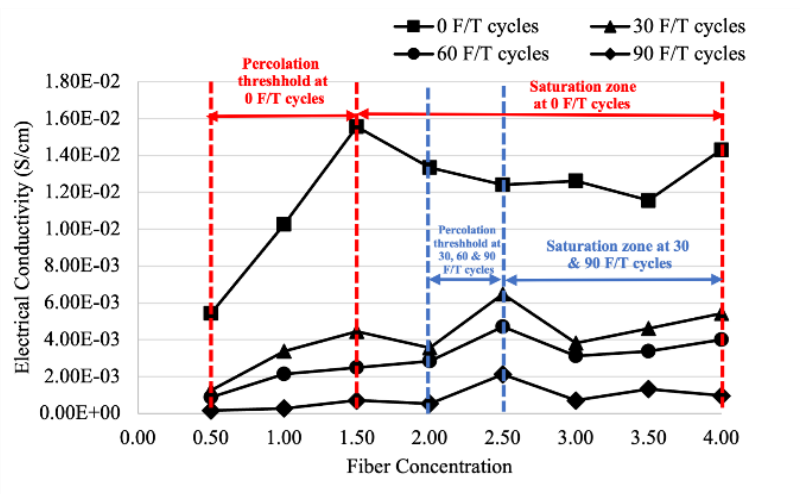


Fig. 11. Electrical conductivity of samples at different FT cycles

The project goals have been met successfully, except for the preparation of ABCF reinforced cement mortar samples due to the unavailability of fiber.

E.2. Fracture behaviour of ABCF and Teijin fiber-reinforced composites

Fracture behaviour is an important aspect of the structural safety of concrete, especially in large-scale structures. Fresh concrete's characteristics have a significant impact on its ability to resist fracture, and the addition of carbon fibers has been shown to enhance its fracture toughness. The flexural behaviour of carbon fiber-reinforced concrete has been extensively studied over the past few decades, but there has been relatively little research on the fracture behaviour of such samples under a three-point bending fracture test. It is important to investigate the effects of fiber addition in concrete samples with varying concentrations to understand the fracture behaviour of carbon fiber-reinforced cementitious composites.

Fracture analysis of carbon fiber-reinforced cementitious composites can provide valuable insights into the behaviour of these materials under loading, which can inform the development of safer and more durable concrete structures. By examining the fracture patterns and mechanisms of these materials, researchers can identify potential weaknesses and areas for improvement in their design and composition.

The results of the fracture test on notched Carbon Fiber Reinforced Mortar (CFRM) specimens are summarized in **Table 4** and the Force-Crack Mouth Opening Displacement CMOD behaviour is shown in **Fig. 12**. Based on the results provided, the addition of carbon fibers to the cement mortar matrix has a significant impact on the fracture behaviour of the notched beam and as the percentage of carbon fiber increases, the fracture properties of composites improve. Specimens with a higher percentage of carbon fiber (3.5T18 and 4T18) have significantly higher toughness and energy absorption capacity than specimens with lower percentages of carbon fiber (CO, 0.5T18). This is because carbon fibers are able to provide additional reinforcement to the material, which allows it to better resist crack propagation and failure under load. In addition, it can be observed that the maximum load is also affected by the percentage of carbon fiber. As the percentage of carbon fiber increases, the maximum load capacity of the material also increases, indicating that the addition of carbon fibers also improves the overall strength of the composite.

However, it is important to note that the results obtained from notched tests may not necessarily be representative of the material's behaviour under other loading conditions. Therefore, further testing may be required to fully understand the mechanical properties of the carbon fiber-reinforced cement mortar material.

Table 4. Fracture behaviour of notched CFRM beam under bending test

Sample	Fmax (N)	$CMOD_{max}$ (mm)	Pre-Crack Energy (N.mm)	Toughness (N.mm)
CO	717.50	1.18	284.33	56.28
0.5T18	877.00	1.65	241.59	3571.84
1T18	1628.00	2.76	1458.96	13180.16
1.5T18	1677.67	2.01	619.34	9302.33
2T18	2245.50	1.73	1540.51	7192.37
2.5T18	2475.33	2.72	2497.67	11594.50
3T18	2577.33	2.40	2338.66	12408.32
3.5T18	2582.67	6.85	11393.38	64236.45
4T18	2836.33	8.62	19045.81	82329.55

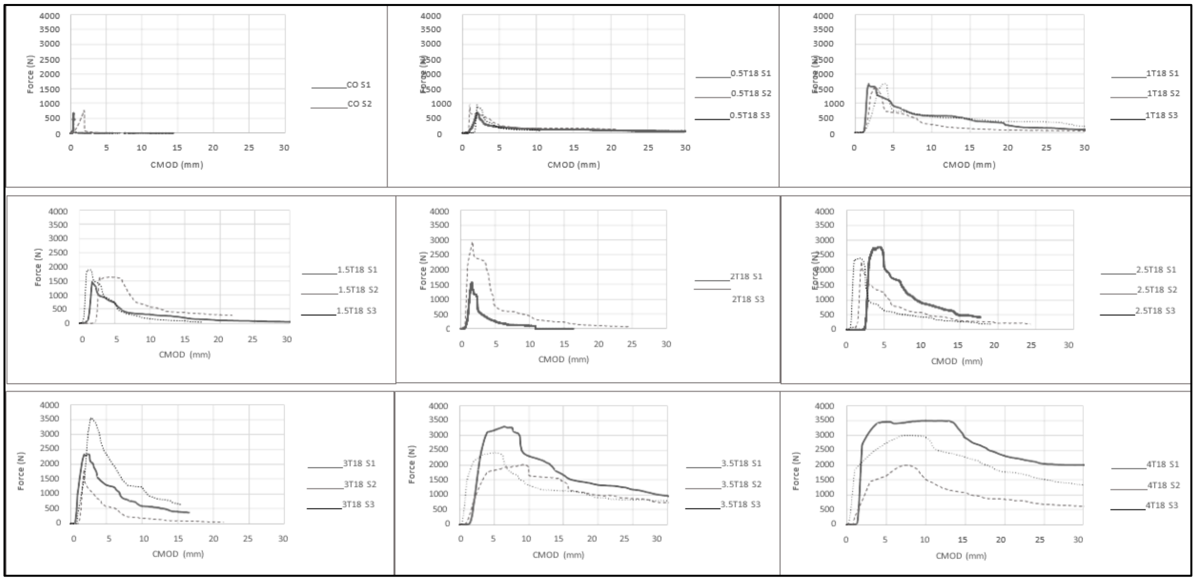


Fig. 12. Fracture behavior of carbon fiber-reinforced mortar

Table 5. Mix design and compressive strength of concrete samples

Sample	Gravel (kg/m^3)	Sand (kg/m^3)	Cement (kg/m^3)	Fly ash (kg/m^3)	Water (kg/m^3)	CF (kg/m^3)	fc (MPa)	SD
CO	1055	815	276	60	148	0	46.7	2.6
0.5T18	1055	815	276	60	148	9	31.1	1.2
1T18	1055	815	276	60	148	18	16.7	1.3
2T18	1055	815	276	60	148	36	7.5	1.6

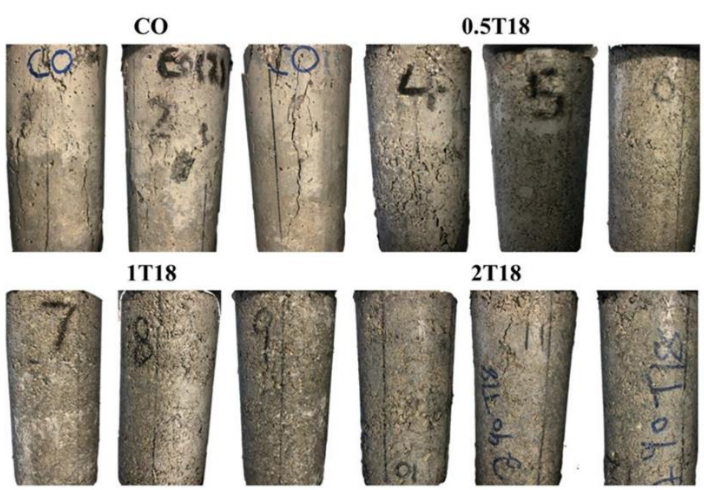


Fig. 13. Fracture pattern of concrete samples after compression test

Fig 14. illustrates the effect of using fiber in concrete samples. It is observed that by increasing the amount of fiber, the flexural strength of the concrete beams decreases, and the post-crack absorbed energy increases. The inclusion of carbon fibers can disturb the uniformity of the concrete mixture. As the quantity of carbon fiber is raised, it can lead to a less even dispersion of aggregates and cement paste, potentially compromising the overall structural integrity of the concrete. This non-uniform distribution may lead to vulnerable points within the concrete, ultimately reducing its flexural strength. Conversely, the increased capacity to absorb energy after cracking is a consequence of the characteristics of carbon fibers, such as their ability to enhance the concrete's resistance to crack propagation and their capacity to bridge cracks. These attributes contribute to the concrete's improved ability to withstand the propagation of cracks and absorb energy, even in the presence of pre-existing cracks.

According to the detailed results in Table 6, the concrete containing 0.5% fiber had the optimum strength and toughness values with a marginal reduction in flexural strength and a considerable improvement in toughness (163% improvement compared to the CO sample).

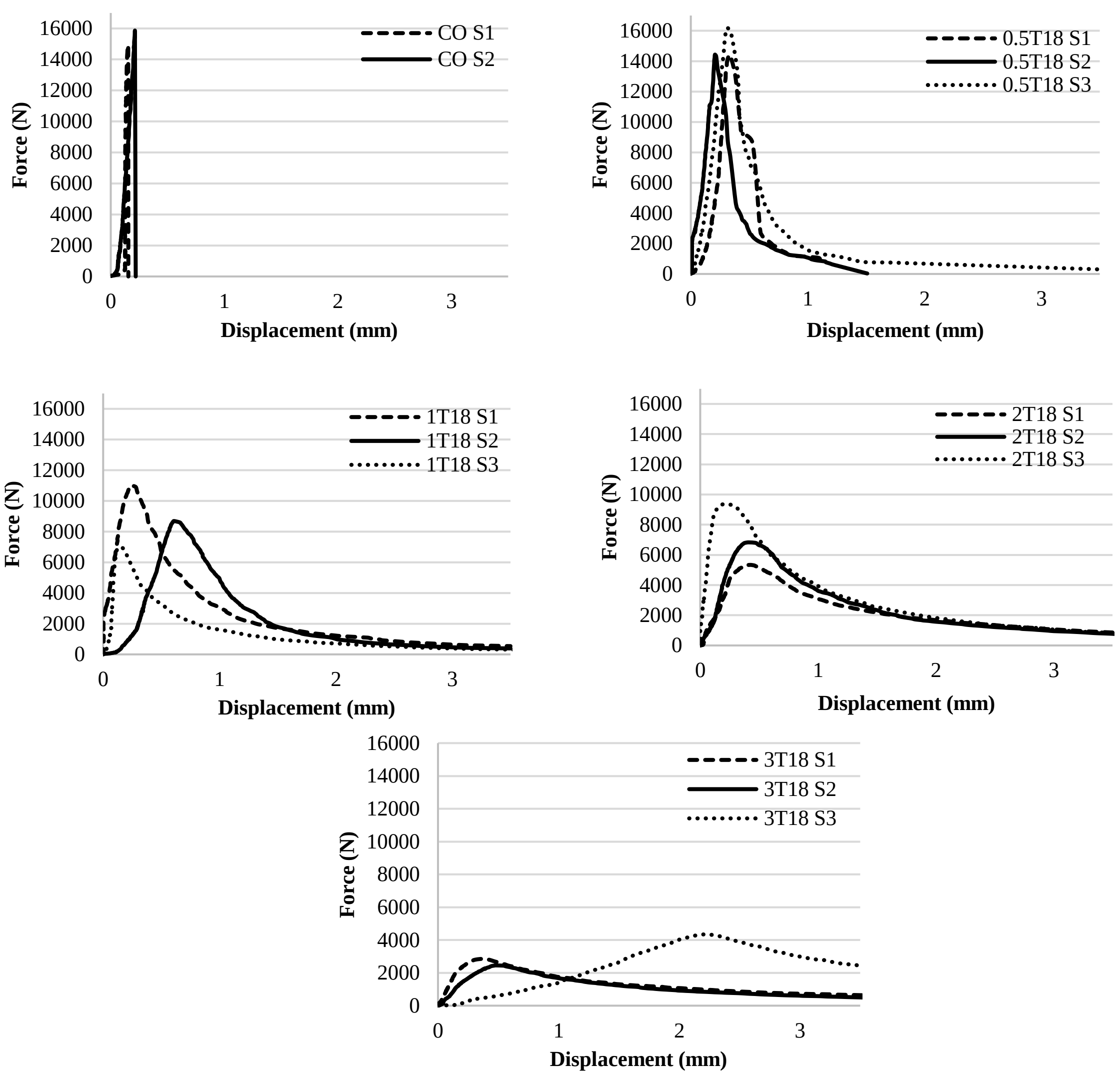


Fig. 14. Force-Displacement behaviour of carbon fiber-reinforced concrete samples

Table 6. Flexural properties of carbon fiber-reinforced concrete samples

Code	MR (average)	$E_{initial}$(average)	I_5 (average)
CO	9.24	765.5	1
0.5T18	8.65	2010.7	2.9
1T18	5.91	2180.5	3.9
2T18	3.65	1805	5.8
3T18	1.59	826.5	6.5

E.2.2. Evaluation of electrical resistivity of large-size Teijin fiber-reinforced concrete

A composite's electrical resistance is an indicator of its capacity to resist the flow of electrical current through it. It can be influenced by factors including the composite's composition, dimensions, and temperature. The 4-probe electrical resistivity test is a commonly employed technique for evaluating electrical resistance. Four probes are used in this procedure to measure the material's resistance. One pair of probes is used to pass current, while the other pair is used to monitor voltage on a different set of electrodes. The advantage of this method is that contact resistance concerns are not a factor, making it more reliable than other techniques.

Using Ohm's law, resistance can be calculated as follows:

$R=\frac{V}{I}$

where R is the electrical resistance (ohm), I is the value of the input electrical current (ampere), and V is the value of electrical voltage (volt)

The electrical resistivity of the material was calculated using the following equation:

$\rho=k\times R$

k is the geometry-independent property and an inherent characteristic of a material which can be calculated using the following equation:

$k=\frac{A}{L}$

Where A is the cross-sectional area perpendicular to the current and L is the height of the sample.

The bulk resistivity technique, also known as the uniaxial approach, involves placing two electrodes on the surface of the concrete and placing a wet sponge in between them. The following equation can be used to determine the geometrical factor in this method:

$\rho=\frac{A}{L}\times R$

The electrical resistivity test setup and the resistivity results are shown in **Figs 15-18**. According to **Fig. 18**, as the CF percentage increases, the bulk electrical resistivity decreases significantly, indicating an improvement in the electrical conductivity of the composite material. The surface resistivity also decreases as the CF percentage increases, but the trend is not as significant as in the bulk resistivity measurements. In the case of the 4-probe test, electrical resistance measurements were only detected for the 0.5% CF and 1% CF samples, while no measurements were detected for the 2% CF and 3% CF samples. This suggests that the electrical conductivity of the composite material significantly improved beyond the threshold of 1% CF, and hence the resistivity was beyond the detectable range of the probe.

Fig. 15. Four-probe surface electrical resistivity of (a) CO (b) 3T18 sample

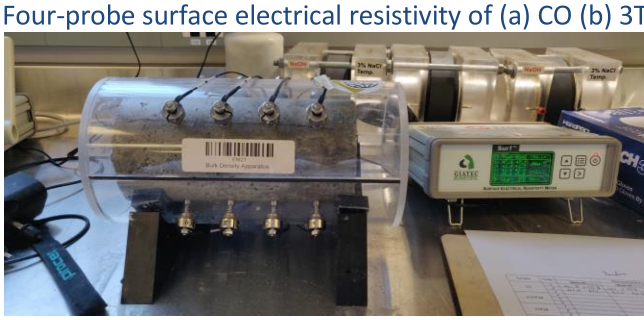


Fig. 16. Surface resistivity of concrete cylinder

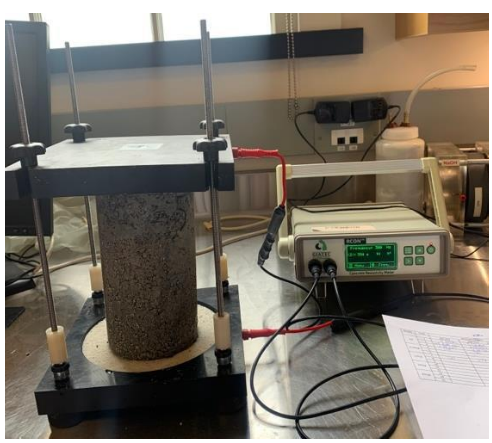


Fig. 17. Bulk 1electrical resistivity of concrete cylinder

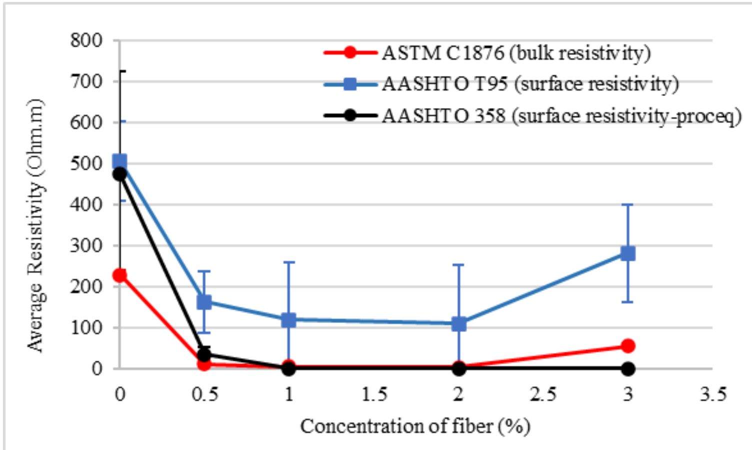


Fig. 18. Electrical resistivity of CFRC using different measurement methods

The freeze-thaw (FT) tests were conducted in a Humboldt HC-3186S4F freeze-thaw chamber (**Fig. 19**). In one FT cycle, the temperature of the specimens was reduced from +4.4 °C to -17.8 °C and then raised from -17.8 °C to 4.4 °C in around 3.5 hours. Within a single FT cycle, the time spent freezing and thawing is generally equal. After every 30 cycles of FT, the machine was stopped, and non-destructive evaluation (NDE) techniques were used to analyze the behaviour of the samples. All tests were performed on specimens at room temperature in the saturated surface dry (SSD) condition, and the testing was completed after 300 cycles. The non-destructive test performed on beams were the mass loss test, ultrasonic pulse velocity (UPV) test and Resonant frequency (RF) test (**Fig. 20**).

Fig. 19. Freeze-thaw test on beams

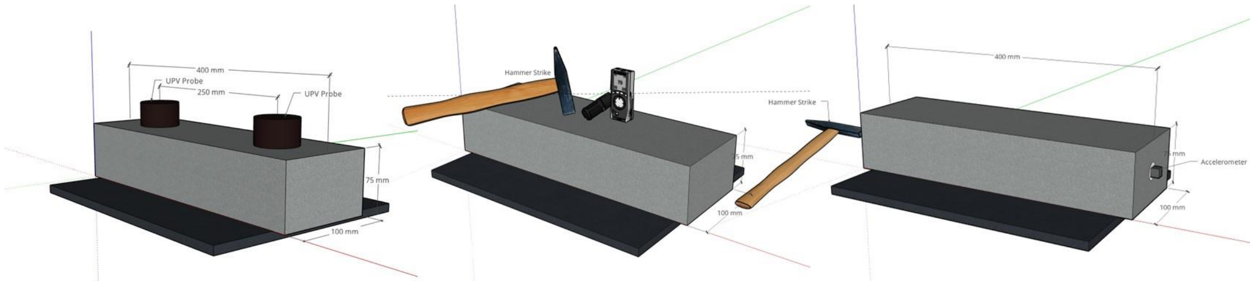


Fig. 20. NDE on beam a) UPV, b) RF and c) HP tests

Fig. 21 shows the surface condition of representative samples of various mixtures after 300 FT cycles, and **Fig. 22** shows the mass loss of the samples after each FT cycle. According to **Fig. 22**, the mass loss curves have two basic stages: a slow decline and a quick drop. Up to 60 cycles of FT, the changes in the mass loss were moderate and consistent across all samples; however, beyond 60 FT cycles, the rate of scaling was demonstrated to increase, particularly for samples with larger fiber volumes. The major cause of the transition from a gradual shift to a quick change is concrete cracks that form and grow because of repeated FT cycles. When there are extra expanding components, such as water, in both the initial pores of the concrete and newly developed cracks, stress greater than the tensile strength of the material occurs, causing cracks. More carbon fibers in addition to more and wider cracks make samples more porous, which will result in more water being contained inside the samples. When the pores and new micro cracks link with one another and create a route in concrete that allows water to move through the sample readily, the mass loss increases significantly. It was also seen that the results of mass loss are aligned with the visual observation. Samples with 3% fibers not only became noticeably deteriorated on the surface at 300 FT cycles but also underwent a mass loss of more than 1%. This is while no bulk damage was observed in specimens with 0% and 0.5% in the long term, as seen by the almost constant mass with FT cycles.

Fig. 21. Surface condition of samples at 300 FT cycles

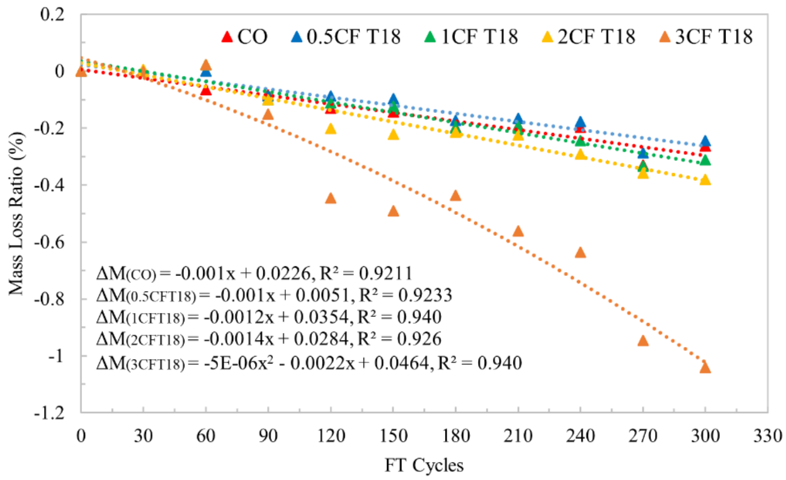


Fig. 22. Mass loss of samples

The propagation velocity of ultrasonic longitudinal stress waves (P-wave) through concrete in the UPV test can be related to composite components used in concrete, such as cement, aggregate, fiber type, aggregate-cement ratio, and water-cement ratio. Because the only difference between the five groups of samples is the amount of CF, the presence of fibers can be considered as the only cause of differences in UPV at each FT cycle. **Fig. 23** shows that adding CF to concrete lowered the velocity and makes the matrix more porous. The five sets of concrete specimens (CO, 0.5CFT18, 1CFT18, 2CFT18, and 3CFT18) had initial ultrasonic velocities of 6657, 6623, 5105, 4227 and 3329 m/s respectively. For CO and 0.5CFT18 samples, the change in velocity was more gradual, but for the other three groups, the fall in velocity was more abrupt as the number of FT cycles increased. For each set of specimens, the fitting curves with the highest coefficient of determination (R2) are presented as dashed lines. It is demonstrated that the polynomial fitting has the maximum reliability proposing that the equations can be used to predict UPV variations over time. **Fig. 24** shows the relation between the dynamic modulus of elasticity and FT cycles. As can be observed, the variations in the dynamic modulus of elasticity of the five groups of concrete specimens that underwent FT cycles exhibited patterns that were comparable to those of the ultrasonic pulse velocity under FT cycles. Polynomial fitting, which demonstrated a satisfactory reliability threshold, was the best-fitting curve that described the variability of DMOE. As shown in Figure 24 in CO and 0.5CFT18, the DMOE of frozen-thawed concrete showed a slow declining stage and a quickly declining stage. The main reason is that during the early stages of the freeze-thaw cycle, degradation occurs mostly on the concrete surface due to the dense pore structure in CO and 0.5CFT18, and the relative dynamic elasticity modulus gradually declines. On the other hand, the damage to the samples is further aggravated. by the addition of CF above 0.5%, which also results in additional pores being created inside the concrete. Due to the increased porosity of such concrete, water can enter the interior and cause microcracks beginning with the early FT cycles, significantly decreasing the dynamic elasticity modulus.

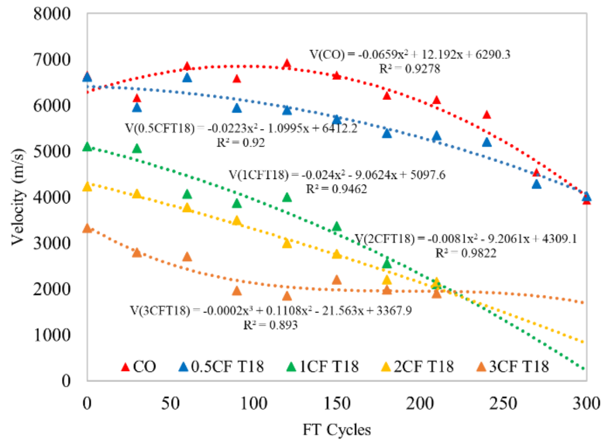


Fig. 23. Ultrasonic pulse velocity of samples at different FT cycles

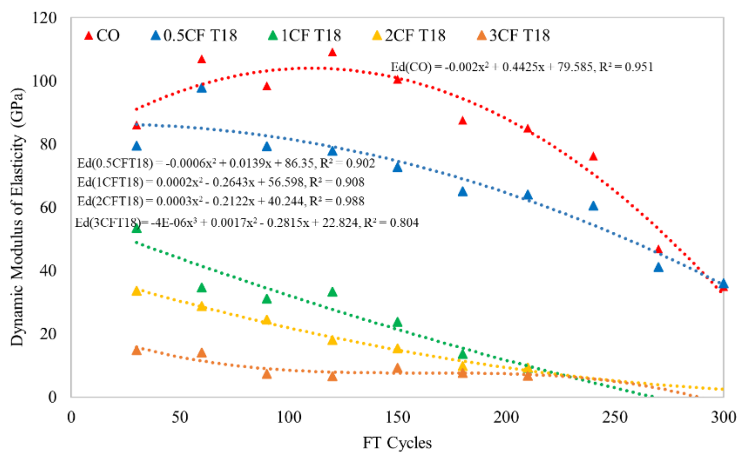


Fig. 24. Dynamic modulus of elasticity derived from Ultrasonic pulse velocity test

Fig. 25hows the relative dynamic modulus of elasticity values (DMOE) and the dynamic modulus of elasticity for all samples at various FT cycles derived from the RF test. Samples with 0.5 % CF had comparable results to non-reinforced ones. According to Fig. 2(a), there is a definite trend showing that the dynamic modulus decreases exponentially as fibers concentration increases. All samples with 1, 2, and 3 % of CF failed before 60 FT cycles, however those with 0.5% fiber were able to endure 300 FT with a minimal decline in DMOE. Although CO and 0.5PAT18 greatly outperformed other samples in both UPV and RFT tests, the findings of the comparison between the two test results were inconsistent in terms of the trend for DMOE. It is demonstrated that in the UPV test, the DMOE decreases proportionally as the FT cycle increases, however, in the RF test, the DMOE difference was only negligible until 300 FT cycles in both CO and 0.5PAT18 samples. It was also shown that the DMOE results did not have similar magnitudes. In comparison to RFT results, it was claimed that UPV exhibited substantially higher values in three primary vibration modes (longitudinal, transverse, and torsional).

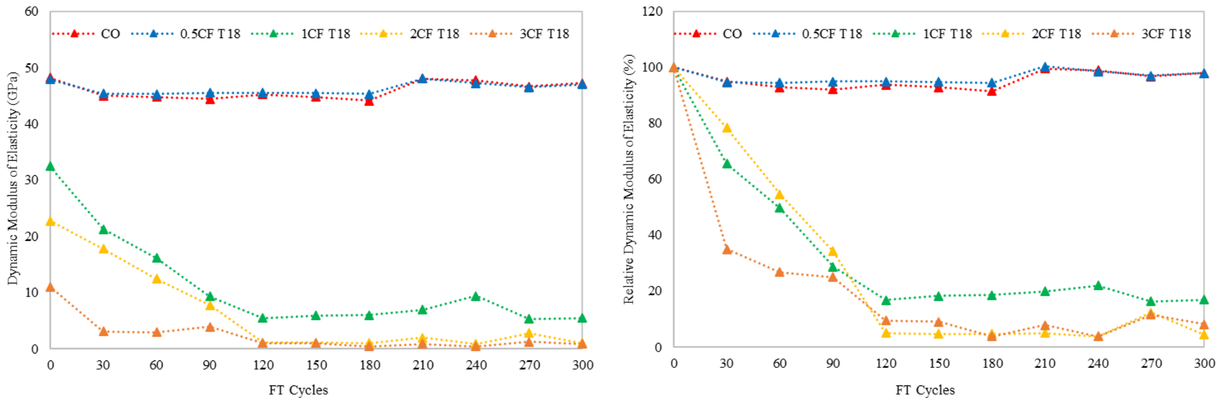


Fig. 25. a) dynamic modulus of elasticity and b) relative dynamic modulus of elasticity derived from resonant frequency test

E 2.3. Crack analysis of Tejin fiber-reinforced concrete

Fracture mechanics is a field of mechanics that studies the behavior of materials under the conditions of crack propagation. Concrete is prone to cracking and fracture, especially under loading conditions that cause tensile stress. In the case of a concrete beam, fracture mechanics can be used to analyze and predict the behavior of cracks in the beam. This analysis is important in determining the structural integrity of the beam and ensuring its safe operation.

The current experimental work seeks to better understand the fracture behavior of fiber-reinforced concrete beams under cyclic loads caused by different carbon fiber amounts. **Fig. 26** shows the cyclic test set-up. The variable amplitude fatigue loading was applied incrementally to investigate the progressive damage, as depicted in Figure 27(a). Figure 27(b) depicts a typical CMOD vs. time chart obtained from the clip gauge data acquisition (DAQ). The experimental data from the testing, including the load, CMOD and mid-span vertical displacement, are analyzed. As can be seen in **Fig. 28** samples with different amounts of carbon fibers failed under different loading cycles. The summary of the results is shown in **Table 7**. The data in the table suggest that the addition of carbon fiber to concrete can have a significant effect on the mechanical behavior of the concrete samples under cyclic loading conditions. Specifically, the addition of a moderate amount of carbon fiber (around 1-2% by volume) appears to improve the composite material's resistance to fatigue and cyclic loading, potentially increasing its durability and lifespan in certain applications.

In particular, the sample with 1% carbon fiber exhibited the highest number of cycles to failure in the cyclic loading test, suggesting that this was the optimal fiber content for improving the composite material's performance in this test. This contrasts with the static three-point bending test, where the sample with 1% fiber did not perform as well as 0.5CFT18 samples. This highlights the fact that the effects of fiber reinforcement on composite properties and behavior can be complex and may depend on multiple factors, including the specific loading conditions and the distribution of fiber within the material. It is clear, however, that in the case of cyclic loading, the addition of carbon fibers can have a significant positive impact on the mechanical behavior of the composites.

Additionally, the data suggest that while the final longitudinal displacement of the fiber-reinforced samples may be like that of the unreinforced samples, the displacement occurred at a much higher load in the fiber-reinforced samples (**Fig. 28**). This suggests that the addition of fiber may improve the material's ductility and resistance to crack propagation, potentially resulting in a more resilient material.

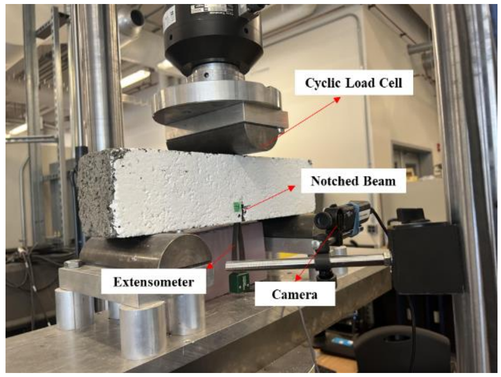


Fig. 26. Cyclic test on concrete beams

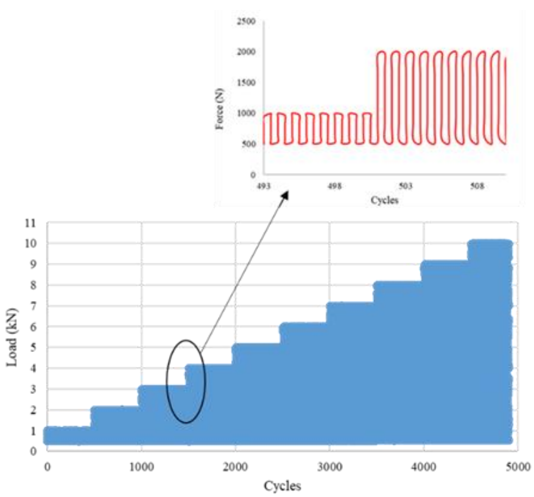


Figure 27(a). Variable amplitude fatigue loading

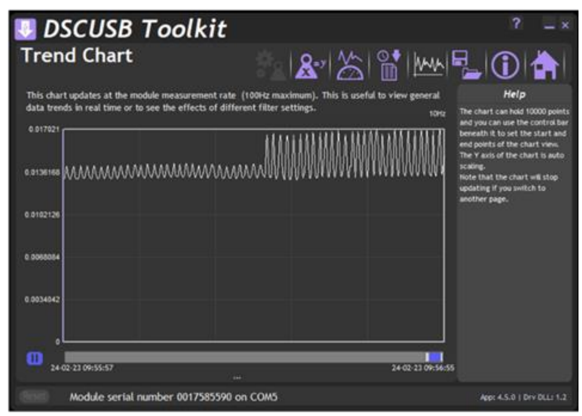


Figure 27(b). Typical CMOD vs. time chart

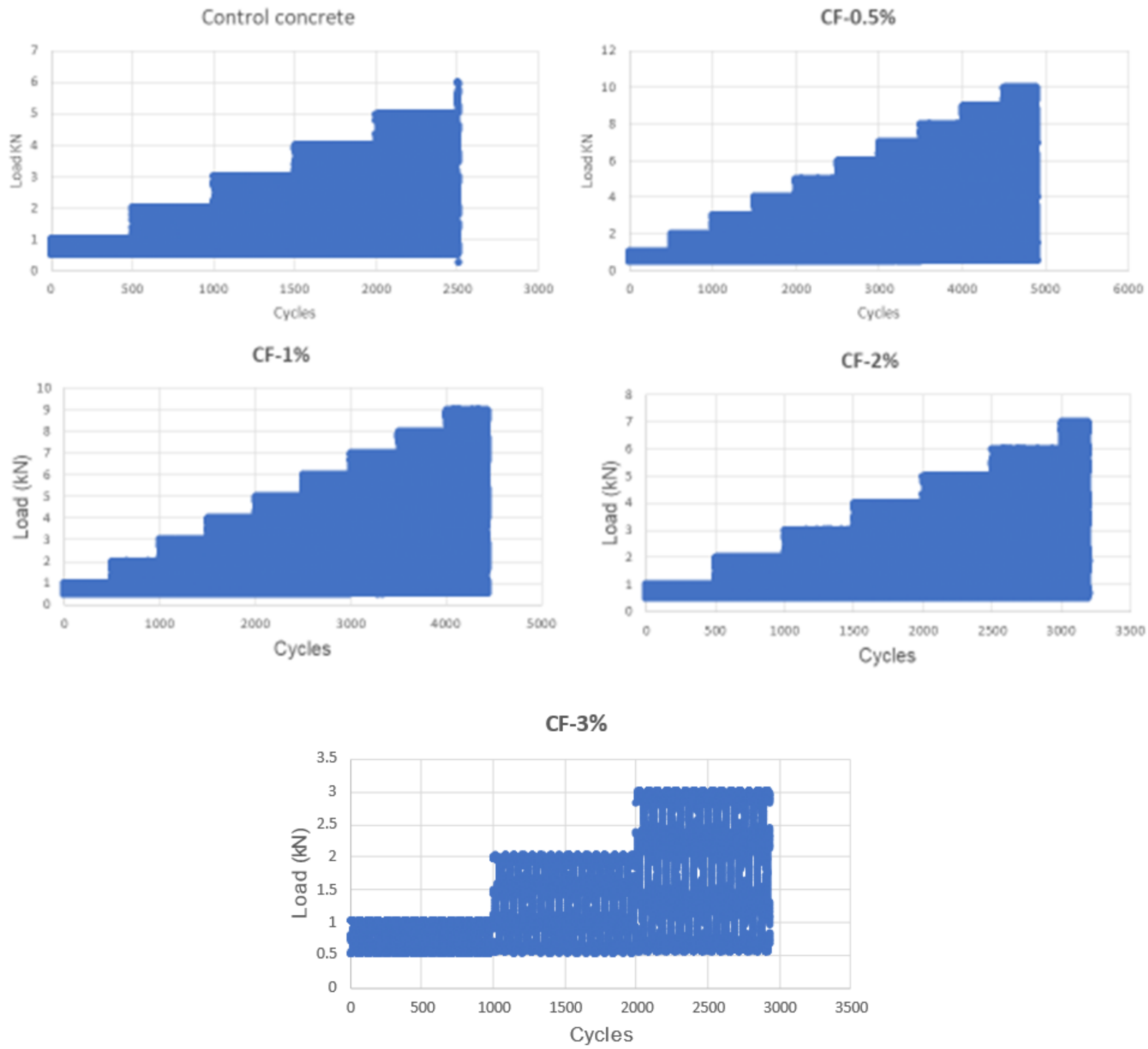


Fig. 28. Behavior of concrete samples under cyclic loading

Table 7. The behaviour of concrete samples under cyclic loading

	Force	**Displacement**	**Cycle**	**CMOD**
	KN	mm		mm
CO	5.0053	0.68	2072	0.027
0.5CFT18	7.6776	0.63	3534	0.038
1CFT18	8.5132	0.78	3917	0.047
2CFT18	5.6750	0.86	2447	0.232
3CFT18	3.6626	0.72	2665	0.742

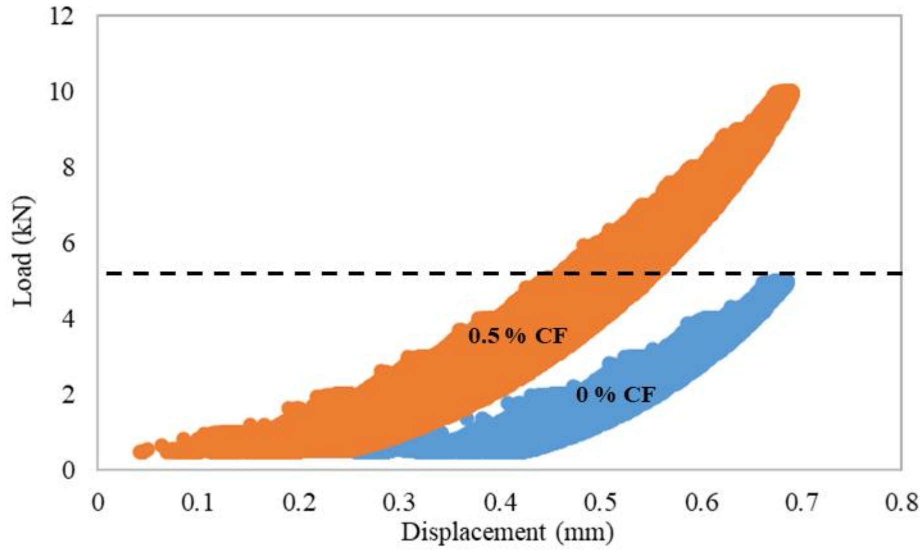
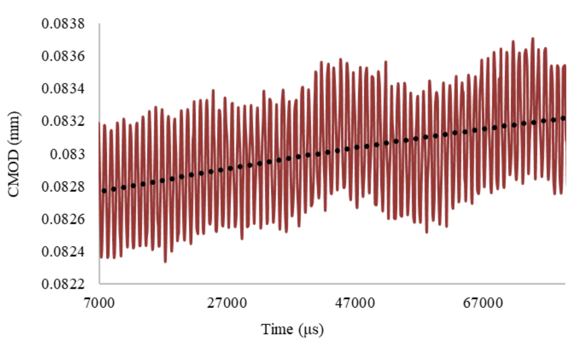
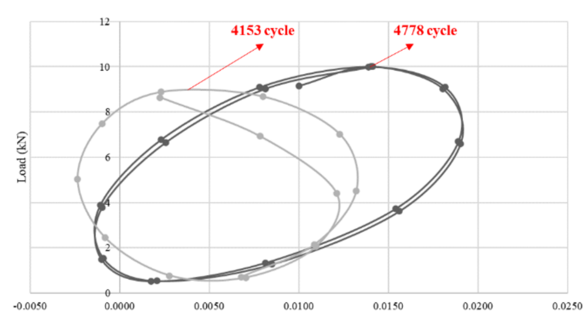


Fig. 29. Load-displacement curves of samples under cyclic loading

Fig. 30 (a) shows the changes in CMOD with time and load. Fig. 30 (b) shows the load-CMOD behaviour of 0.5CFT18 at 4153 cycles and 4778 cycles in which the beam failed. Using regression analysis, it is evident that the slope of the curve is shallower at lower cycles, and as the load approaches its failure point, the slope becomes steeper. The application of a linear regression model to the data, which was collected from the elliptical curve for 4153 cycles, reveals a lesser slope for the regression line in comparison to the slope of the regression curve for the 4778 cycles, where it becomes steeper. This indicates that initially, there is a slower rate of microcrack formation and propagation. However, as the samples approach their failure load, a noticeable change in slope occurs. It is important to note that this same failure mechanism was observed consistently across all samples.





(a) (b)

Fig. 30. a) Load-CMOD and b) CMOD-time relation in 0.5CFT18

The dissipated energy during each cycle of loading is also an important parameter for characterizing the fatigue behavior of a composite material. In general, the amount of dissipated energy increases with an increase in the amplitude of fatigue load cycles. This is because higher amplitude load cycles result in a greater amount of damage to the material, leading to more energy being dissipated. However, it is also important to note that the relationship between dissipated energy and the load value is not necessarily linear. As the load increases, there may be a point at which the concrete sample begins to experience sudden failure, resulting in a sudden release of energy. This can be seen in the sudden spikes in the dissipated energy plot shown in **Fig. 31**, which occur at different amplitudes of load cycles at different samples. This sudden release of energy was observed in all samples.

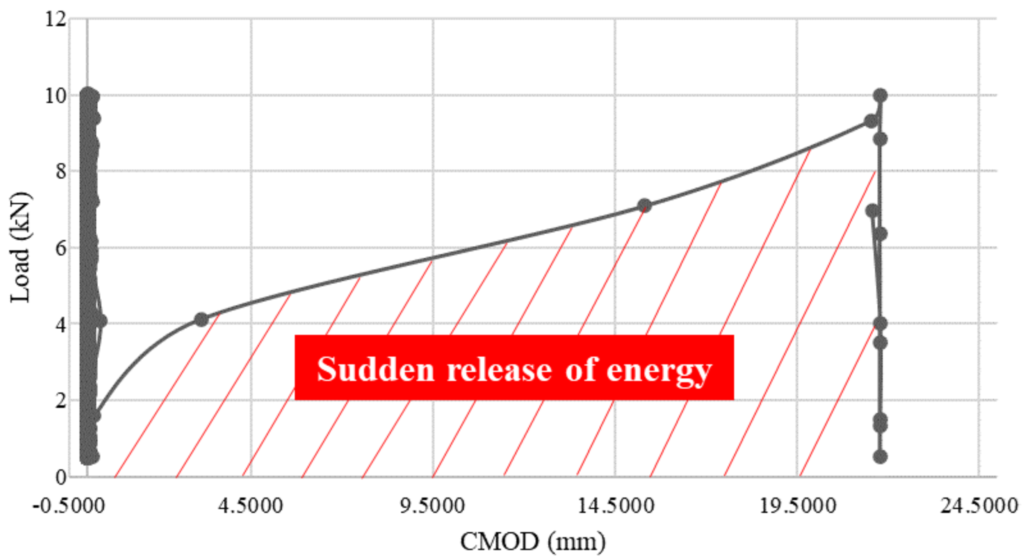


Fig. 31. Sudden release of energy in 0.5CFT18 under cyclic loading

The results of the fatigue test are under analysis and the outcomes will be reflected in a paper in a related journal. Initial analysis of the fracture test indicates the following:

1. The behavior varied with different carbon fiber dosages, with 0.5% exhibiting the highest fatigue resistance and ultimate strength.
2. The reduced ductility of CF fibers keeps the post-crack load capacity low, increasing concrete brittleness. This makes it more susceptible to sudden failure during cyclic loading instead of gradual crack propagation, impacting energy absorption

E. 3. Evaluation of electrical resistivity of large-size Teijin fiber-reinforced panels

E.3.1. Casting large-size circular slabs of diameter 80 cm and 10 cm thickness

The study involved preparing and testing 15 concrete slabs of different sizes with varying amounts of carbon fiber (0%, 0.5%, 1%, 2%, and 3%). The slabs were tested under single-point loading using a 500

KN pneumatic/hydraulic press, as shown in **Fig. 32**. The results of the tests are presented in **Table 8**. According to the data, the CO and 0.5CFT18 samples had the highest peak loads, with values of 31835.71 N and 30078.79 N, respectively. In contrast, the 3% carbon fiber reinforced concrete samples had the lowest peak load of 5907.99 N. While the displacement at which the samples failed was comparable for all samples except 3CFT18, the post-crack behaviour and energy absorption of the CFRC samples differed significantly from that of the CO samples. The 0.5% CF samples were able to absorb the highest amount of energy, with a value of 229.52 J, compared to the other samples. Additionally, both the 0.5CFT18 and 1CFT18 samples experienced very high deflection, almost two times greater than the CO sample. However, the samples with 3% CF performed unsatisfactorily, even worse than the unreinforced samples.

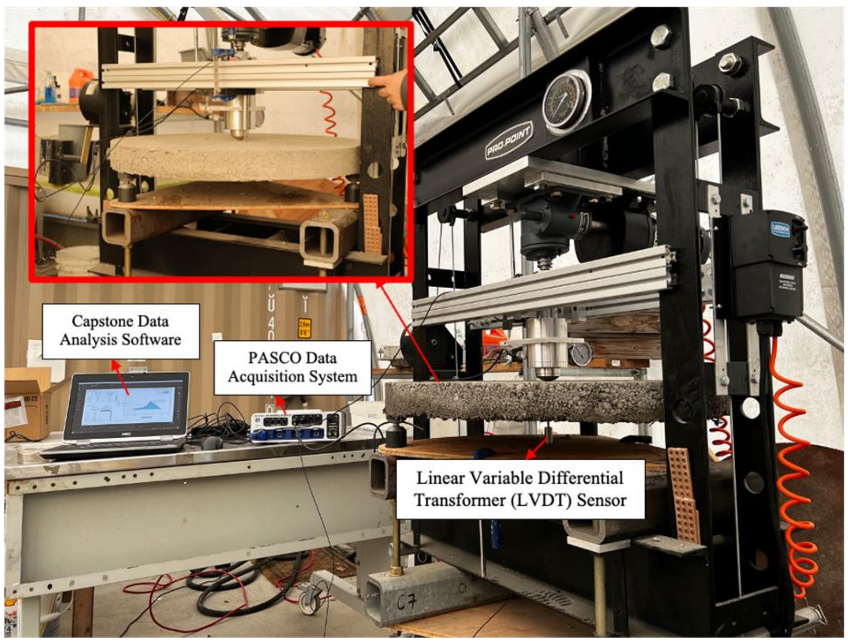


Fig. 32. Round panel test set up

Table 8. Behavior of concrete round panels

					Residual energy				Residual load			
	Peak load	**Δpeak**	**Δmax**	**MOR**	**5 mm**	**10 mm**	**15 mm**	**20 mm**	**5 mm**	**10 mm**	**15 mm**	**20 mm**
	N	mm	mm	MPa	J	J	J	J	N	N	N	N
CO	31835.71	6.84	15.33	6.13	45.66	96.89	191.80	191.80	14035.84	9424.44	25548.05	
0.5CFT18	30078.79	3.62	26.22	5.79	47.60	93.79	151.41	229.52	11729.52	6806.45	4066.07	2809.82
1CFT18	19047.74	6.50	34.27	3.67	35.55	80.22	113.19	192.55	14113.79	9184.57	5703.86	3986.22
2CFT18	13896.41	5.00	28.77	2.67	35.55	71.64	118.55	136.85	12258.40	6280.34	4282.17	3137.08
3CFT18	5907.99	2.30	22.60	1.14	22.34	40.31	51.10	58.74	4094.60	2564.78	1815.69	1247.07

E3.2. Evaluation of electrical resistivity and self-heating technology

For CFRM samples, the self-heating experiment was carried out at two humidity levels, ambient-dry and Saturated surface dry. A Sky Top power DC power supply with adjustable voltage and current input was utilized to apply a constant 30 DC voltage across the copper electrodes while measuring the relative current (**Fig. 33**). The initial temperature and the temperature after 3 minutes of heating in the middle of the beam were recorded. The electrical resistivity of samples was measured using an Agilent 34401A digital multimeter. While the samples were being heated, an infrared camera (FLIR) was employed to assess the surface temperature profile.

As can be seen from Fig. 11 and **Fig. 34**, there is a direct relationship between the amount of carbon fiber used in the composite material and its electrical conductivity. This finding suggests that the conductivity of the CFRM can be tailored by adjusting the amount of carbon fiber added. However, as it was mentioned earlier, Fig. 11 also shows that there is a threshold at around 0.5%-1.5% carbon fiber, beyond which the conductivity does not change significantly.

The self-heating results of CFRMs are promising, as the addition of 1.5% carbon fiber led to a temperature increase of around 20 °C in certain spots of the sample. However, it is important to note that the observed temperature increase may not be representative of the material's overall performance since the presence of a very hot spot can be the reason for a non-uniform distribution of fiber in the cement mortar.

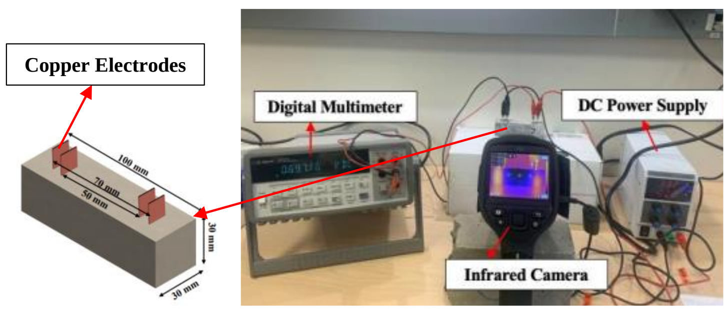


Fig. 33. Self-heating test setup on carbon fiber-reinforced mortar

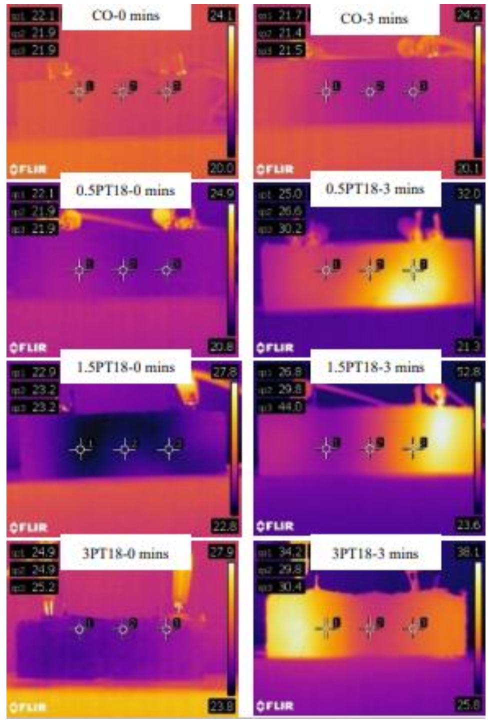


Fig. 34. FLIR images of CFRMs before and after self-heating test

For the self-heating test on concrete samples, three materials were selected to serve as electrodes, 10M rebar, a wire mesh, and a galvanized metal lath. Electrode configurations were created as shown in **Fig. 35** (All dimensions are in mm). The diagonal hatching in the figures below represents the wooden formwork used for the casting of the samples. The dotted hatching shown in the top view in the figures below represents the polyurethane foam used in the casting process (**Fig. 36**). A PVC frame (3.75 cm in height) was constructed and placed on the specimen. A 60 DC voltage was applied through the electrodes and the temperature change was measured every 30 minutes.
The test results **(table-9)** show that the temperature change observed in the concrete samples varied depending on the type of electrode used. The wire mesh electrode induced the lowest temperature change, with a maximum temperature increase of 2.05°C for the 0.5CFT18 sample and only 0.50°C for the 1CFT18 sample. The metal lath electrodes (horizontal) produced temperature changes that were higher than the wire mesh but lower than the rebar electrode. The rebar electrode and metal lath (vertical) induced the highest temperature change. The temperature increase was 4.20°C for the 0.5CFT18 sample and 2.97°C for the 1CFT18 sample when rebar was used as the electrode. The highest temperature change was for metal lath placed vertically with a temperature increase of 6.10 °C. This suggests that the electrodes placed in an acceptable space far from each other, especially the ones with plate shape were the most effective at inducing self-heating in the concrete samples.

The specific heat, thermal conductivity, and thermal resistivity values of the electrode materials can offer information on how well they perform. For instance, even though the wire mesh electrode had the highest specific heat and thermal conductivity values, it caused the lowest temperature change in the concrete samples. This is primarily because, within a mesh, there is a low probability for carbon to conduct electricity and generate heat in the concrete and its surface, resulting in only the wire mesh getting heated up. Overall, the test results indicate that the vertical metal lath and rebar electrodes were the most effective at inducing self-heating in the concrete samples, while the wire mesh electrode was the least effective.

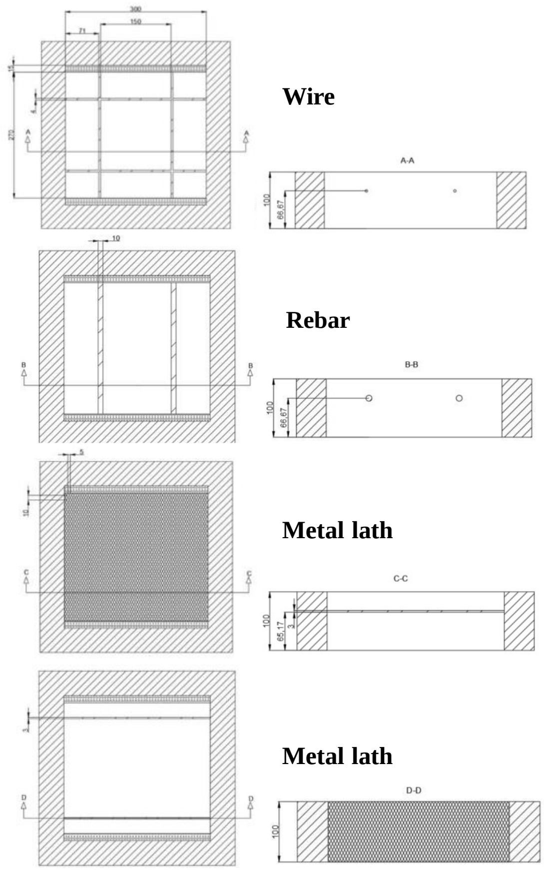


Fig. 35. Electrodes use for self-heating test

Fig. 36. Preparation of sample

Table 9. Summary of self-heating test results

	Electrode Type	Voltage	Current	Duration	Temperature change	Specific Heat	Thermal Conductivity	Thermal Resistivity
		v	A	s	°C	J/Kg°C	W/mK	mK/W
0.5CFT18	Rebar	60.00	0.34	7200.00	4.20	1835.50	22.83	0.05
	Wire mesh	0.50	5.00	7200.00	2.05	1529.00	25.48	0.51

1CFT18	Metal lath (H)	60.00	0.16	7200.00	3.60	22.00	0.30	2.70
	Metal lath (V)	60.00	0.04	7200.00	6.10	630.00	7.87	0.13
	Rebar	60.00	0.22	7200.00	2.97	1691.33	24.18	0.05
	Wire mesh	0.50	5.00	7200.00	0.50	2083.50	34.73	0.03

E 3.3. Analysis of Greenhouse gas (GHG) emissions

Life cycle assessment (LCA) is a technique of quantitatively evaluating the environmental effects of a system over the course of its full life cycle, from raw material extraction to ultimate disposal. This section involves calculating the quantity of CO_2 emissions for a 100 m^2 area (for CO and 0.5CFT18 mix designs) based on embodied and operational LCA. The pavement thickness is 12 cm. **Tables 10 and 11** show the results of the analysis for embodied CO_2. The results show that the CO_2 gas emissions for the construction of both CO and CFRC are essentially equal. The total CO_2 emission was, however, reduced by 17.4% in CFRC pavements due to its higher performance in durability parameters and the lower number of maintenance requirements for CFRC. The incorporation of CF (carbon fibers) offers several advantages for concrete, including enhanced properties such as improved crack control, increased flexural strength, enhanced overall strength and durability, reduced susceptibility to shrinkage cracking, and heightened resistance to fatigue. These improvements not only lead to a reduction in overall maintenance costs but also contribute to an extended service life of the concrete structures.

Table 10. Life cycle assessment results of control pavement

Materials	Unit Carbon (Kg CO_2/ton)	Materials used every m^3 (kg)	Total used in 15 m^3 (kg)	Total CO_2 (kg)
Cement	940.5	276.0	4140.0	3893.7
Gravel	10.0	1055.0	15825.0	158.3
Sand	8.0	815.0	12225.0	97.8
Steel	720.0	2.3	34.2	24.6
Fuel	8kg/1km			4400.0
			Total	8574.3
		Repair (30-year service life)		
Concrete repair	571.0			571.0
Fuel	8kg/1km			4000.0
			Total	4571.0
		Total Global Warming Potential (CO2 emission): 13145 kg		

Table 11. Life cycle assessment results of carbon-fiber reinforced pavement

Materials	Unit Carbon (Kg CO_2/ton)	Materials used every m^3 (kg)	Total used in 15 m^3 (kg)	Total CO_2 (kg)
Cement	940.5	276.0	4140.0	3893.7
Gravel	10.0	1055.0	15825.0	158.3
Sand	8.0	815.0	12225.0	97.8
Steel	720.0	2.3	34.2	24.6
Carbon fibers	15400	10.0	150.0	2310
Fuel	8kg/1km			4400.0
			Total	10884.4
		Repair (30-year service life)		
Concrete repair	571.0			285.5
Fuel	8kg/1km			2000.0
			Total	2285.5
		Total Global Warming Potential (CO2 emission): 13170 kg		

Analysis Software: Athena Pavement LCA
Athena Pavement LCA is a free LCA-based software tool that assesses the environmental impact of pavement designs in Canada and the United States. LCA analysis was performed on pavements using Athena software and the inputs are shown in **Table. 12**.

Table 12. Inputs in Athena pavement LCA software

Project location	**AB**	**BC**
Real Inflation rate	5.90%	5.90%
Real discount rate	4.50%	4.50%
Distance of RMC plant to site	30 Km	8 Km
Distance of stockpile to site	30 Km	30 Km
Distance of equipment depot to site	25 Km	25 Km
Slab length	28.5 m	28.5 m

Slab width	3.5 m	3.5 m
Slab thickness	12 cm	12 cm
Grade of concrete	40 MPa	40 MPa
Cement type	GU	GU
Carbon fibers	0.5%	0.5%
10M diameter bars. 600 mm c/c	0.57 MT	0.57 MT
Base course	150 mm crushed aggregate	150 mm crushed aggregate
Subbase on subgrade	300 mm-crushed aggregates	300 mm-crushed aggregates
Initial construction cost-Control Concrete	$95,000	$95,000
Initial construction cost-CFRC	$100.00	$100.00
Number of 2 Axle -6 tire Buses & trucks-daily	1,200	1,200
Number of Light duty vehicles-daily	9,520	9,520
Annual daily traffic growth factor	5%	5%

Tables 13 and 14 and **Figs 37-38** contain a summary of the Athena pavement results. The software calculated CO_2 emissions of 9058 kg for CFRC pavement, which is close to the 10859 kgs in **Table 11**, the difference is due to some criteria being removed in the boundary system. In contrast, 13656 kgs of CO_2 emissions were calculated for CO samples in the Athena analysis, as compared to 13145 kgs of CO_2 manually computed in **Table 10**. The software indicates that CFRC pavement emits 33% less carbon dioxide than CO pavement in the embodied LCA phase**.**

Table 13. Life cycle assessment summary results of control pavement from Athena pavement LCA for the Alberta location

Name	Unit	Site Preparation		Manufacturing		Construction		Maintenance		Embodied Effects
		Equipment	Transport	Material	Transport	Equipment	Transport	Materials and Equipment	Transport	Total
Global Warming Potential	kg CO2 eq	9.88	252.08	3,767.10	26.10	519.26	1,047.58	7,479.84	554.84	13,656.69
Acidification Potential	kg SO2 eq	0.10	2.43	15.64	0.28	4.99	10.08	49.87	5.68	89.06
HH Particulate	kg PM2.5 eq	0.01	0.13	1.98	0.01	0.28	0.56	8.21	0.30	11.48
Eutrophication Potential	kg N eq	0.01	0.15	2.53	0.02	0.31	0.63	8.61	0.35	12.61
Ozone Depletion Potential	kg CFC-11 eq	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.02
Smog Potential	kg O3 eq	3	77	240	9	158	318	445	180	1,429
Total Primary Energy	MJ	144	3,676	36,572	378	7,572	15,275	135,268	8,058	206,943
Non-Renewable Energy	MJ	144	3,674	33,906	378	7,569	15,269	134,083	8,054	203,078
Fossil Fuel Consumption	MJ	144	3,669	31,925	378	7,557	15,246	133,891	8,042	200,852

Table 14. Life cycle assessment summary results of carbon-fiber reinforced pavement from Athena pavement LCA for the Alberta location

Name	Unit	Site Preparation		Manufacturing		Construction		Maintenance		Embodied Effects
		Equipment	Transport	Material	Transport	Equipment	Transport	Materials and Equipment	Transport	Total
Global Warming Potential	kg CO2 eq	9.88	252.08	3,763.62	26.10	519.38	1,047.86	3,209.55	229.59	9,058.05
Acidification Potential	kg SO2 eq	0.10	2.43	15.62	0.28	4.99	10.08	21.71	2.36	57.57
HH Particulate	kg PM2.5 eq	0.01	0.13	1.99	0.01	0.28	0.56	3.58	0.12	6.68
Eutrophication Potential	kg N eq	0.01	0.15	2.51	0.02	0.31	0.63	3.78	0.15	7.55
Ozone Depletion Potential	kg CFC-11 eq	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.01
Smog Potential	kg O3 eq	3	77	240	9	158	318	190	75	1,069
Total Primary Energy	MJ	144	3,676	36,470	378	7,573	15,279	59,251	3,333	126,106
Non-Renewable Energy	MJ	144	3,674	33,804	378	7,570	15,273	58,819	3,332	122,994
Fossil Fuel Consumption	MJ	144	3,669	31,815	378	7,559	15,250	58,807	3,327	120,948

Note: Y-axis on logarithmic scale

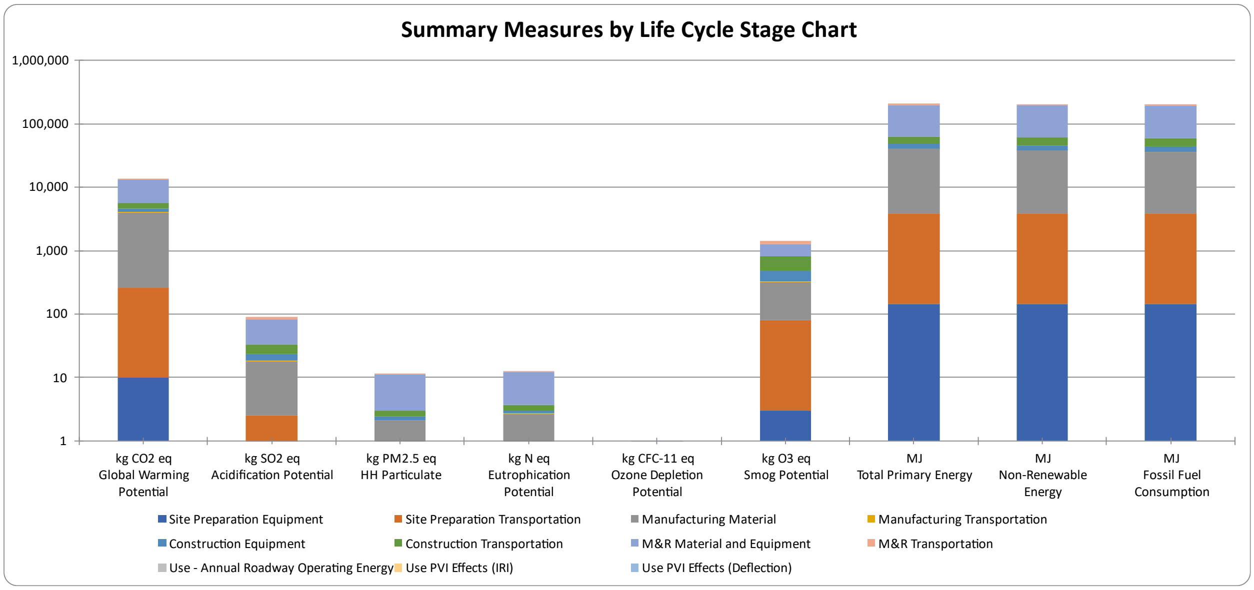


Figure 37. Summary of LCA analysis of Control pavement derived from Athena pavement LCA software for Alberta location

Note: Y-axis on logarithmic scale

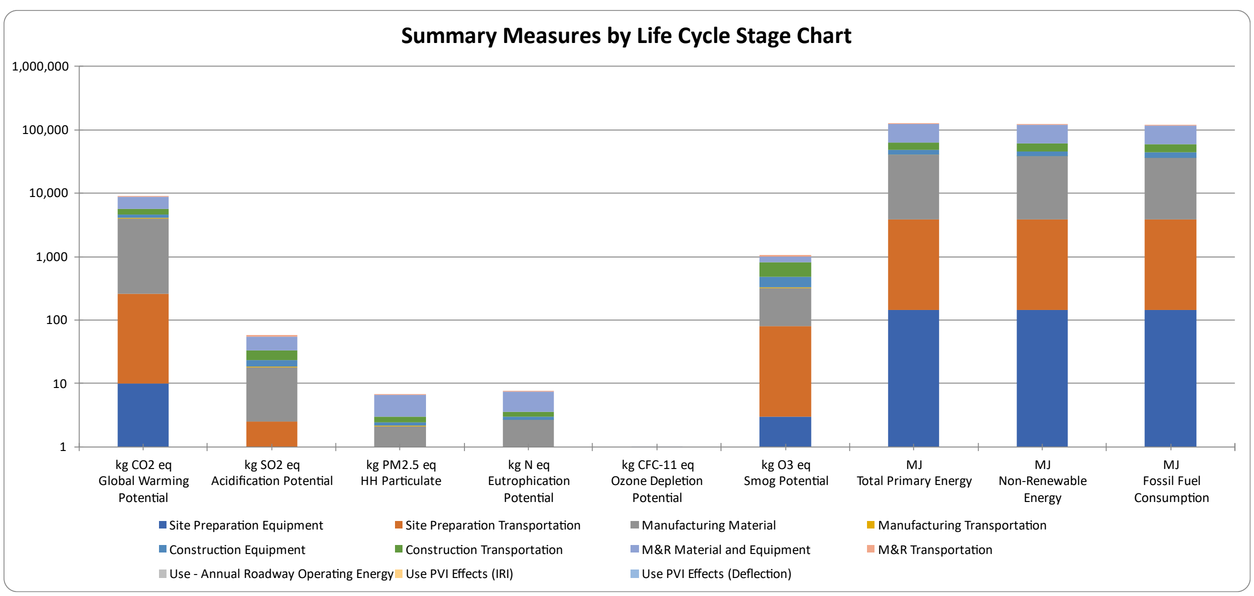


Figure 38. Summary of LCA analysis of CFRC pavement derived from Athena pavement LCA software for Alberta location

E 3.4. Self-deicing: Operational CO2

One of the key considerations when evaluating the performance of self-heating pavement is the amount of energy required to heat the pavement. This is important because energy consumption will impact the cost and environmental sustainability of the technology. Additionally, the amount of carbon dioxide (CO_2) emissions associated with the electricity used to power the heating system is an important parameter that must be considered. The amount of energy required to heat will depend on several factors, including the size of the pavement area, the desired temperature, and the thermal properties of the materials used. In general, carbon fiber-reinforced concrete pavement requires less energy to heat compared to traditional pavement heating systems due to the higher electrical conductivity. However, the energy consumption can still be significant, especially for large pavement areas or when higher temperatures are required.

When fossil fuels are utilized to provide the energy to heat the pavement, the quantity of CO2 emissions related to the electricity used can be determined using the fuel source's carbon intensity. The carbon intensity, which varies based on the kind of fossil fuel used, is a measurement of the quantity of CO2 emitted per unit of energy generated. According to the Canada Energy regulator, the greenhouse gas intensity of Alberta's electricity grid, measured as the GHGs emitted in the generation of the province's electric power, was 590 grams of CO_2e per kilowatt-hour (g CO_2e per kWh) electricity generated in 2020.Based on the self-heating test on concrete samples (as per table-6) the total operational CO_2 for heating the pavement per sq. meter to gain a temperature rise of 25^0C has been calculated, as provided in **Table-15**. The total operational CO_2 for heating the pavement per sq. meter is between 1.2-1.5 Kg-hr/m2 for rebar and wire mesh electrode types, with 0.5-1.0% carbon fibers.

Table 15. Total operational CO2 for heating the pavement per sq. meter

	Electrode Type	Voltage (V)	Current (I)	Temperature change (T)	Specific Heat	Time duration (t)	Heat dissipated (Q=I*V*t)	Power (watts) Q/t	Total operational CO2 for heating the pavement per sq. meter
		volts	Ampere	°C	J/Kg°C	seconds	Joules	(Joules/sec)	Kg-hr/m2
0.5CFT18	Rebar	60	0.34	25	1835.5	40489	825975	20.4	1.504
	Wire mesh	0.5	5	25	1529	275220	688050	2.5	1.253
	Metal lath (H)	60	0.16	25	22	1031	9900	9.6	0.018
	Metal lath (V)	60	0.04	25	630	118125	283500	2.4	0.516
1CFT18	Rebar	60	0.22	25	1691.33	57659	761098.5	13.2	1.386
	Wire mesh	0.5	5	25	2083.5	375030	937575	2.5	1.707

Environmental Impacts of Snow Ploughing and Existing Salt Management Practices

The Code of Practice for the Environmental Management of Road Salts (the Code) was developed in 2004 to assist municipal and provincial road organizations to manage their de-icing salt operations, to reduce environmental harm and maintain road safety. As per the Canada Salt group limited, approximately 5 million tonnes of salt are estimated to be used for ice or snow removal on pavements, roads, parking lots, and sidewalks in Canada. Although salt remains the cheapest way to de-ice pavements and sidewalks[54], the scale of the damage from each salt truck is disturbing.

The heavy use of road salts can lead to damage to vegetation, organisms in the soil, birds, and other wildlife. Almost all chloride ions from road salts eventually find their way into waterways which can harm freshwater plants, fish and other organisms that are not adapted to living in saline waters[55]. Way back in 1975, Transport Canada estimated that de-icing salts were causing $200 in damage per car, per year, the equivalent of $854 in 2017. Salt was a key contributor to the deadly 2006 collapse of the De La Concorde bridge in Laval, killing six people. Also, Toronto's Gardiner Expressway concrete has severe spalling of concrete due to rapid rebar corrosion caused due to de-icing salts.

Greenhouse gas calculations for snow removal from pavements (Reference values taken from Snow ploughing forum)

1. One backhoe pusher with a 12 ft shovel would plough three inches (75 mm) of snow at 90 minutes per acre (4045 m^2)
2. Furthermore, filling up one Caterpillar 730 dump truck with a capacity of 16.8 CuM with one backhoe loader with a 12 ft shovel would take 60 minutes. Hence, it would take 19.5 hours to lift three inches (75 mm) of snow per acre (4045 m^2).
3. Total time taken to plough and lift 1 acre of 3 inches of snow would require 21.5 hours. Hence, in one hour, an area of 192 sq. meters can be covered.
4. One backhoe would consume around 2 gallons of fuel per hour. Around 8 Kg of CO_2 is produced from burning a gallon of gasoline.
5. For 192 sq. meters, 2 gallons of fuel is consumed per hour, which generates 16 Kg of CO_2 e. Hence, 1 sq. meter of road area would generate **0.08 Kg of CO2e** emissions for ploughing and dumping snow.

Greenhouse gas calculation for a de-icing salt truck

Assumptions:

For de-icing the pavement in Edmonton, Alberta, we have assumed that the salt is sourced from NSC Minerals, Brooks, Alberta located 450 km from Edmonton. Each Caterpillar 730 dump truck would carry around 30 MT of salt[58]. Furthermore, the salt will have to be transported from the storage facility in Edmonton to the pavement location at Sherwood Park and Highway 21 in Edmonton, Alberta for a distance of around 50 km (Total approximate travel distance-500 km).

The calculation of CO2e emissions below has been referred to the Green freight math from the environmental and defence fund.

1. Determine the total amount of MT-Kms. Multiply 500 km times 30 MT, which gives us a total of 15,000 MT-Kms.

2. Get the weight-based truck emissions factor for a freight truck. The average freight truck in Canada emits 8 Kg of CO2 per ton-km.
3. Multiply this emissions factor by the total MT-Kms (8 X 15,000), which gives us a total of 120,000 Kg of CO2.
4. Approximately 25 Kg of salt is used for 1000 sq. meters of road area. Hence 30 MT would cover 1200,000 sq. meters of road area.
5. As 120,000 Kgs of CO2 would be generated from 1200,000 sq. meters of road area. 1 sq. meter would generate **0.1 Kg of CO2e** emissions.

Greenhouse gas calculation for dumping snow to a dump site (Reference values taken from Snow ploughing forum)
Assume a Caterpillar 730 dump truck with a heaped dump capacity of 16.8 CuM is used to dump snow to a dump site 25 Km from Sherwood Park and Highway 21 in Edmonton, Alberta.

1. One Caterpillar 730 dump truck with a capacity of 16.8 CuM can transport 8.064 MT of snow (density of snow 480 Kgs/CuM)
2. The total amount of MT-Kms. Multiply 25 km times 8.064 MT, which gives us a total of 201.6 MT-Kms.
6. The average freight truck in Canada emits 8 Kg of CO2 per ton-km, which gives us a total of 1612.8 Kg of CO2, for each dump truck.
3. Assuming three inches (75 mm) of snow, around 224 sq. meters of area could be covered by 1 dump truck.
4. As 1612.8 Kgs of CO2 would be generated from 224 sq. meters of road area. 1 sq. meter would generate **7.2 Kg of CO2e** emissions to dumping the snow to a desired location.

Total Greenhouse gas generated in ploughing snow, sprinkling dicing salts and dumping snow to a dump site will generate around 7.38 Kgs of CO2e emissions per sq. meter. On the other hand, the total operational CO_2 for heating the pavement per sq. meter is around 1.2-1.5 Kg-hr/m2 for rebar and wire mesh electrode types, with 0.5-1.0% carbon fibers.

Based on the LCA calculations conducted, the following conclusions can be made:

1. Carbon dioxide emissions from CFRC bus pad pavement were 33% lower than those from the control concrete bus pad pavement. Enhancing the durability of pavements and eliminating the use of de-icing salts improves the maintenance regime of CFRC pavements. Additionally, the increase in the life span of the road and the increase in the period between mandatory surface overlays, when compared with existing asphalt and conventional concrete pavements, reduces the overall environmental impact.
2. Furthermore, snow ploughing, sprinkling de-icing salts and lifting snow to a dump site will generate high CO2 equivalent emissions per sq. meter as compared to electricity consumed for de-icing. Winter maintenance using de-icing salts has the largest relative environmental impact on the overall life cycle of a road, including fresh and marine water eutrophication and eco-toxicity. Thus, a self-de-icing pavement can protect the environment from the long-term devastating effects of road salts.
3. The addition of carbon fibers in concrete has proved to enhance mechanical properties, and durability, thereby creating safer roads, improving road user safety, and providing reliable performance in all weather conditions. Furthermore, minimizing the impact of winter

maintenance via the elimination of the use of de-icing salts can have a major impact on the overall life cycle performance of roads, especially in locations with adverse weather conditions.

Project Specific Metrics

Metric	Project Target
Evaluation of mechanical properties and full physical characterization of ABCF based carbon fibers and Teijin fibers	1) No. of samples to be tested: approximately 75 2) Tensile strength and Uniaxial strength: > 3 MPa 3) Electrical Resistivity of fibers: Accurate lab-based measurements of the order of 1.4 * 10^-3 Ω-cm 4) Compressive strength: > 30 MPa 5) Modulus of Elasticity: > 25 GPa 6) Modulus of rupture: > 3 MPa 7) Freeze-thaw: Lasting 200 cycles of freeze-thaw as per ASTM C666
Fracture behavior of ABCF and Teijin fiber-reinforced composites	1) Number of samples to be tested: approximately 16 2) Increase in fracture toughness in tension and flexure as compared to more than 10 % of control values
Evaluation of electrical resistivity of large size Teijin fiber-reinforced panels	1)Number of samples to be tested: approximately 9 2)Electrical resistivity :< 100 Ω-cm 3) Develop an integrated de-icing round panel 4) GHG Analysis

We conducted extensive testing on over 75 concrete specimens, each featuring varying carbon fiber dosages ranging from 0% to 3% by volume. These specimens encompassed a variety of configurations, including cylinders for evaluating compressive strength, uniaxial tension, and resistivity; beams for assessing flexural properties; notched beams to study static flexure and toughness; additional notched beams to investigate concrete fatigue under cyclic loading; beams for freeze-thaw testing; round panels for analyzing yield line theory; and concrete panels for self-heating assessments.

The results of our tests revealed that CFRC exhibited a compressive strength exceeding 30 MPa, while the splitting tensile strength fell within the range of 3.1-3.3 MPa. Electrical resistivity of CF was between 0.025 to 0.5 $*10^{-3}$ Ω-cm. Furthermore, the modulus of rupture ranged between 5.5-6.5 MPa, and the modulus of elasticity fell within the range of 26-27 GPa. In freeze-thaw testing conducted in accordance with ASTM C666, the specimens endured 300 cycles.

Our study evaluated the fatigue fracture behavior of Carbon Fiber-Reinforced Concrete (CFRC) in flexural applications, considering carbon fiber dosages of 0.5%, 1%, 2%, and 3% by volume. For each batch, we cast three beams measuring 100*100*400 mm, including the control mix, totaling 15 beams subjected to cyclic loading to assess CFRC's fracture behavior.

We also conducted self-heating and electrical resistivity tests on 15 samples featuring 0.5% and 1.0% CF, utilizing various types of electrodes, and incorporating mixes with silica fumes and graphite coatings. The observed electrical resistivity values were consistently below 100 Ohms-cm. It's worth noting that these tests were performed on concrete panels measuring 300*300*100 mm instead of round panels to allow for equidistant placement of electrodes with respect to the specimen's geometry. Additionally, a comprehensive greenhouse gas (GHG) analysis has been included in the Milestone-3 report.

F. 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

Evaluation of mechanical properties and full physical characterization of ABCF and Teijin fibers

Evaluation of the mechanical properties and physical characterization of ABCF and Teijin fibers was important for the development of a self-deicing surface or pavement. The experiments conducted revealed an optimized carbon fiber dosage range of 0.5-1.0%. The presence of carbon fibers significantly enhanced the concrete's resistance to bending and cracking under both static and dynamic loads, particularly enhancing its flexural strength. Furthermore, these experiments demonstrated that carbon fibers effectively increased the concrete's resistance to splitting forces, reducing its susceptibility to cracking and enhancing overall durability.

A notable alteration was observed in the electrical resistivity of the concrete, indicating improved conductivity, especially at dosages around 1.0%. This becomes particularly relevant for self-deicing surfaces which have the potential to greatly improve the safety and efficiency of transportation systems in regions with cold climates such as Alberta.Carbon fiber-reinforced concrete also exhibited superior resistance to damage caused by freeze-thaw cycles, a critical characteristic for structures in cold climates. The study identified an optimum fiber dosage of 0.5%, which demonstrated the best performance in terms of dynamic modulus of elasticity and mass loss while preserving the concrete's structural integrity under repeated freezing and thawing cycles.

In summary, this study underscored the influence of carbon fibers on various mechanical properties of concrete, including compressive strength, flexural strength, post-crack behavior, energy absorption, and dynamic modulus of elasticity. It emphasized the importance of carefully selecting the carbon fiber content to strike a balance between mechanical performance and durability, with 0.5% carbon fiber content emerging as the most optimal choice in this regard. Given the physical characteristics of ABCF fibers in comparison to Teijin fibers, it's feasible to achieve a comparable enhancement of mechanical properties of concrete.

Fracture behavior of ABCF and Teijin fiber-reinforced composites

The study investigated the impact of varying carbon fiber dosages (0.5%, 1%, 2%, and 3% by volume) on the fatigue behavior of concrete. The cyclic loading experiments conducted on CFRC beams yielded valuable insights into their fatigue response under bending conditions, holding significant implications for the design of structures exposed to cyclic loads. The experimental approach included the analysis of load versus vertical displacement and load versus CMOD for both control concrete beams and CFRC beams. This research focuses on assessing the fatigue life of CFRC by determining the number of loading cycles necessary for the initiation and subsequent propagation of cracks, ultimately resulting in failure. The results obtained sheds light on the mechanical behavior, crack resistance, and fatigue performance of CFRC. An optimal carbon fiber dosage of 0.5% is identified, striking a balance between static load-bearing capacity and fatigue resistance. These findings provide valuable insights for designing structures subjected to cyclic loads, ensuring durability, safety, and reliability.

Evaluation of electrical resistivity of large size Teijin fiber-reinforced panels

Numerous correlations have been established, affirming the direct link between concrete's transport parameters and its durability. The movement of ions through the concrete microstructure plays a pivotal role in determining concrete's long-term durability. Herein lies the significance of electrical resistivity, as it characterizes concrete's ability to impede the migration of charged ions within its microstructure. Thus, the data on electrical resistivity serves as an indicator of concrete's susceptibility to deterioration. Lower values signify a heightened risk of ion transfer, which, in turn, increases the likelihood of rebar corrosion. In our assessment of CFRC, electrical resistivity was evaluated through the Wenner probe technique. Notably, the electrical resistivity values observed for carbon fiber-reinforced concrete were exceedingly low. Given carbon fibers inherent electrical conductivity, they significantly diminish the overall composite's electrical resistivity. The consistently low electrical resistivity values can be attributed to the effective formation of a fiber network throughout the concrete. However, it is imperative to recognize that using electrical resistivity as a sole measure of durability for carbon fiber-reinforced concrete may not be entirely suitable. Our experiments demonstrated that carbon fibers achieved a percolation threshold (the minimum number of fibers required to infuse efficient electric current inside concrete) within the range of 0.5-1.0% dosage.

Based on the findings from our research and experiments conducted, the following key learnings from this project provides valuable insights into the development of CFRC for self-deicing applications, offering cost-effective, environmentally friendly, and durable solutions for cold-climate regions like Alberta. The learnings from the use of carbon fiber reinforced concrete (CFRC) have broad and far-reaching impacts on various industries and can influence regulations, policies, and approval processes in several ways:

1. Construction and Infrastructure Development:

- Enhanced Durability: The improved fracture resistance and durability of CFRC can lead to longer-lasting infrastructure, reducing maintenance and repair costs.

- Reduced Environmental Impact: The potential to reduce the carbon footprint by choosing more durable CFRC mixes aligns with sustainability goals in construction.

2. Transportation and Cold-Climate Regions:
   - De-icing Solutions: CFRC's ability to generate heat for de-icing pavements can revolutionize snow and ice removal in cold climates, improving safety and reducing the need for chemical de-icers.
   - Improved Safety: Safer Road conditions in winter can significantly reduce accidents and injuries.

3. Environmental and Sustainability Considerations:
   - Reduced Carbon Emissions: The choice of more durable CFRC mixes can contribute to a reduction in CO2 emissions associated with frequent repairs and replacements.
   - Regulations and Incentives: Governments may incentivize the use of CFRC or other sustainable construction materials through policies and regulations.

4. Regulations and Standards:
   - Updating Building Codes: The success of CFRC may prompt updates to building codes and standards to incorporate and regulate the use of carbon fibers in concrete.
   - Safety Standards: Safety standards for road construction and maintenance may evolve to include or prioritize materials like CFRC that enhance safety in cold climates.

5. Approval and Permitting Processes:
   - Material Approvals: Regulatory bodies and agencies may need to adapt their approval and permitting processes to accommodate new materials like CFRC.
   - Performance-Based Approaches: A shift toward performance-based assessments may become more prevalent, focusing on the durability and safety benefits of materials rather than strictly adhering to traditional specifications.

G. 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

Project Outcomes and Impacts

Conventional techniques for snow and ice removal from pavements typically involve the use of deicing salts and mechanical methods, which come with environmental implications. Driven by concerns related to economics, safety, and the environment, extensive research has been dedicated to discovering cleaner and more sustainable approaches to safely clear ice and snow from pavement surfaces. This study investigates into the feasibility of implementing electrically conductive concrete manufactured with carbon fibers as an innovative substitute for traditional practices. By examining carbon fiber percolation across various cementitious mixtures, we determined the optimal carbon fiber dosage to attain the desired electrical conductivity were between 0.5-1.0% by volume. To evaluate the heating performance, particularly in terms of energy consumption, we conducted experiments using prototype slabs measuring 300 x 300 x 100 mm. The findings revealed that this technology could effectively contribute to the removal of ice and snow from pavement surfaces, offering a viable alternative to conventional methods, provided that the carbon fiber meets the necessary physical characteristics and mixing proportions, with the application of due precautions.

Clean Resources Metrics

Metric	Project Target
Investment in 4 Core Strategic Technology Areas	$170,000
TRL advancement	3 to 5
New products/services created	1
Collaborators	1 - Working with a ready mix producer
Publications	Publish articles
Patents & Records of Invention filed	1

Currently, we find ourselves at a Technology Readiness Level (TRL) of 4, conducting process validation within a laboratory setting. Furthermore, we advanced our efforts by showcasing our technology in a practical bus loop scenario at the University of Victoria. This opportunity enabled us to engage in collaborative discussions regarding our technology with various key stakeholders, including the UVic facilities management team, BC Transit Road development team, McElhanney's designers, Sparker Construction as the contractor, and Trio Readymix, the supplier of ready-mix concrete.

In the summer of 2022, the University of Victoria initiated significant renovations to enhance the transit experience for both students and residents in the surrounding areas at its bus exchange. As a component of our field demonstration project, which involved a real-time performance comparison between a carbon fiber-reinforced concrete (CFRC) bus pad and a standard concrete bus pad, we partnered with the local authorities of Saanich municipality and BC Transit in Victoria to construct and closely monitor two bus pads.

These bus pads were constructed using 300 mm pavement-quality concrete of M32 grade, and we collaborated with Trio Readymix Victoria for the concrete supply and the incorporation of carbon fibers. The project's findings have been disseminated through the presentation of two papers at both national and international conferences. Additionally, based on the test results, we are currently in the process of preparing two more papers for publication, which are specific to this project.

Currently, we have not submitted any patent applications or records of invention.

Based on the field demonstration test results of a concrete bus pad , we recommend the utilization of Carbon Fiber-Reinforced Concrete (CFRC) for various applications, including concrete pavements, hard standings, airport pavements, bridge decks, offshore structures, and other projects where specific concrete properties are sought after. These properties encompass crack control, increased flexural strength, improved overall durability, reduced shrinkage cracking, and enhanced fatigue resistance.

One challenge we encountered was the unavailability of asphaltene-based carbon fibers from the relevant team. However, we successfully developed the composite using PAN-based carbon fibers, which have yielded promising test results.

Project Outputs

Published Journal Articles:

- Monazami, M., Sharma, A., & Gupta, R. (2022). Evaluating Performance of Carbon Fiber-Reinforced Pavement with embedded sensors using Destructive and Non-Destructive Testing. Case Studies in Construction Materials, e01460.

- Monazami, M., & Gupta, R. (2022). Monazami, M., & Gupta, R. (2022). Investigation of mechanical behavior and fracture energy of fiber-reinforced concrete beams and panels. Cement and Concrete Composites, 133, 104656.

- Monazami, M., & Gupta, R. (2022). Effect of Curing Age on Pull-Out Response of Carbon, Steel, and Synthetic Fiber Embedded in Cementitious Mortar Matrix. Journal of Materials in Civil Engineering, 34(10), 04022275.

- Monazami, M., & Gupta, R. (2021). Influence of Polypropylene, Carbon and Hybrid Coated Fiber on the Interfacial Microstructure Development of Cementitious Composites. Fibers, 9(11), 65.

Conference Articles:

The project's results will be presented at two national and international conferences in the coming months. Two papers have been prepared for these two conferences and have been submitted; the papers are now being reviewed. Further information about the two papers may be found below:

- Monazami, M., & Gupta, R. (2022). Comparative study of alkali treated, and fly ash-alkali treated carbon fibers (will be presented in 2023 Canadian Society for Civil Engineering conference)

- Monazami, M., Pereira C. & Gupta, R. (2022). Use of non-destructive evaluation techniques to assess condition of carbon fiber-reinforced concrete pavements (will be presented in Rilem Week 2023 conference)

Papers being prepared

- Monazami, M., & Gupta, R. (2022). Analyzing bond-deterioration during freeze-thaw exposure in electrically conductive carbon fiber-reinforced concrete using non-destructive method
- Pereira C., Monazami, M., & Gupta, R. (2023). Experimental investigation of the fracture behaviour of carbon fiber-reinforced concrete under variable amplitude flexural fatigue loading for enhanced durability and structural performance

H. 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

Discussion of Benefits

This project's holistic approach yields several benefits that span economic efficiency, environmental responsibility, societal well-being, and innovation capacity, making it an impactful endeavor for infrastructure improvement. The project's benefits can be summarized under the categories of Economic, Environmental, Social, and Building Innovation Capacity:

Economic Benefits:

Sales: This technology holds the potential for acceptance and adoption in the snow-covered northern regions of Canada, where traditional snow removal techniques encounter significant challenges.

Cost Reduction: The use of smart electrically conductive fiber-reinforced concrete (CFRC) for de-icing pavements can potentially reduce costs associated with traditional de-icing methods like salts and snow removal equipment. CFRC's enhanced durability can lead to reduced maintenance requirements and, in turn, cost savings.

Improved Efficiency: CFRC's superior performance in durability parameters can extend the lifespan of pavements. Longer-lasting pavements reduce the frequency of repairs and replacements, ultimately saving substantial maintenance and construction costs.

New commercial opportunities: This technology will open up new markets for the adoption of carbon fibers and ABCF in concrete for pavement self-deicing, catering to various government agencies, road contractors, and ready-mix suppliers.

Environmental Benefits: Environmental Impact: By lowering the number of maintenance interventions required, CFRC pavements contribute to a reduction in environmental impact. This results in a more sustainable and cost-effective solution for pavement management.

Lower Carbon Emissions: Life cycle analysis indicates that CFRC pavements can reduce CO2 emissions compared to conventional pavements. The lower maintenance requirements and increased durability of CFRC contribute to a reduction in carbon emissions during the pavement's life cycle. As per the calculations presented in this report, for a 100 m2 pavement area, the CO2 emissions were 9058 kg for the CFRC pavement, whereas they were 13656 kg for a control concrete pavement. This data reveals that the CFRC pavement exhibits 33% lesser carbon dioxide emissions than conventional concrete.

Reduced Chemical Usage: CFRC's ability to efficiently de-ice pavements reduces the need for chemical de-icing agents, which can have harmful environmental effects. This technology offers a more eco-friendly alternative by minimizing chemical usage.

Resource Efficiency: CFRC's improved resistance to freeze-thaw cycles reduces the need for frequent repairs and reconstructions. This leads to resource conservation and minimizes the environmental impact associated with construction materials.

Social Benefits:

Safer Pavements: CFRC's de-icing capabilities enhance pavement safety by reducing the risk of ice accumulation. This, in turn, improves road safety for motorists, cyclists, and pedestrians, reducing accidents and injuries.

Longer-Lasting Infrastructure: CFRC pavements have the potential to remain in good condition for an extended period. This translates to smoother and more reliable transportation networks, benefiting the community by reducing disruptions and inconveniences caused by maintenance work.

Innovation and Knowledge Sharing: The project's focus on developing and testing CFRC technology enhances innovation capacity within the construction and infrastructure sectors. Knowledge gained from this research can be shared and applied in Alberta and other regions with similar climate challenges, promoting industry-wide advancements.

Building Innovation Capacity:

Technological Advancements: The project's findings on CFRC's microstructure, mechanical properties, and durability characteristics contribute to technological advancements in concrete materials. This newfound knowledge has the potential to spur further research and innovation in Canadian provinces, particularly those in Northern regions with severe winter conditions that significantly affect concrete durability.

Real-World Application: The next phase of implementing CFRC in Alberta's harsh environmental conditions will provide valuable insights into its practical performance. This real-world application will enhance the capacity to develop and refine innovative solutions for infrastructure challenges.

Collaborative Learning: The cooperation between researchers, industry stakeholders, government funding agencies such as NSERC, and provincial funding agencies like BC Innovates & Alberta Innovates throughout this project promotes the exchange of knowledge and the development of capabilities. This collaborative strategy enhances the capacity to tackle intricate infrastructure challenges, particularly those related to alternative pavement deicing techniques, which have been central to this research.

In summary, the project's benefits extend across economic, environmental, social, and innovation capacity aspects. It offers a cost-effective and environmentally friendly alternative for de-icing pavements, enhances pavement durability, reduces carbon emissions, improves road safety, and contributes to the advancement of construction technologies. The transition to real-world application in Alberta will further validate and expand the project's positive impact.

I. 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

The long-term plan for commercialization of the self-deicing technology or implementation of knowledge generated during the project would depend on the successful production and availability of Alberta bitumen carbon fiber (ABCF) and the field demonstration of the technology in an area in Alberta. The development of ABCF with acceptable properties is critical to the success of the self-deicing technology. The production process for ABCF would need to be refined and optimized to ensure that it can be used in the pavement industry.

On the other hand, the self-deicing technology would need to be tested and validated in various settings and locations to evaluate its efficacy for de-icing purposes. This would involve testing the technology under a range of weather conditions, as well as assessing its durability and maintenance requirements. The outcomes of these tests would be critical in determining the feasibility and commercial potential of the technology.

Overall, the long-term plan for commercialization of the self-deicing technology would involve a combination of research and development, testing and validation, and commercialization strategies. The success of the technology would depend on the ability to refine and optimize the production process for ABCF, validate the technology's efficacy in various settings, and bring it to market in a way that maximizes its potential for commercial success.

J. KNOWLEDGE DISSEMINATION

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

To have the greatest possible influence on the industry, the information developed through the project will be communicated through a variety of ways. The sharing of information is essential for ensuring that the project's advantages are recognized by a larger population and for encouraging the adoption of innovative technologies.

Peer-reviewed articles published in academic journals will be one of the main ways the knowledge will be spread. The study findings will be presented concisely, highlighting the major accomplishments of the project such as the development of self-deicing technology and the mechanical and fracture behaviour of concrete samples reinforced with carbon fibers. This will make it possible for more researchers and business professionals to build on the project's findings and speed up the development of self-deicing technology.

In addition to academic journals, the project's findings will be shared at several international and national conferences. Researchers and business experts will have the chance to learn about the study outcomes, ask questions, and share their personal experiences and thoughts. The researchers can encourage interest in ABCF production and self-deicing technology by interacting with industry stakeholders, which will promote its acceptance and increase investment. In general, the project's knowledge transfer will play a crucial role in encouraging the industry to adopt this innovative technology.

K. CONCLUSIONS

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

The objective of this project was to develop a novel technique for de-icing pavements using smart electrically conductive fiber-reinforced concrete. This innovative technology aims to provide a more efficient and eco-friendly solution for de-icing pavements compared to traditional methods such as de-icing salts and snow removal equipment. To choose the optimum mix, a thorough investigation of microstructure, mechanical and durability properties of fibers, cement mortar and cement concrete was performed, and the summary of the results can be found as follows:

- As per the microstructural analysis of the fibers, Alberta carbon fiber exhibits noticeable fluctuations in diameter ranging between 16 and 43 micrometers, with a blend of both empty and solid cylinders identified in certain fibers. Additionally, the fiber's surface contains numerous minute pores and seems smoother than other carbon fibers. These attributes may greatly affect the fiber's mechanical and physical features as well as its interaction with other materials in composite materials. Therefore, it is advisable to refine the carbon fibers prior to utilizing them in concrete applications.
- To improve the interfacial transition zone, NaOH treatment and fly ash surface coating were employed to assess the changes in the matrix microstructure and fiber pull-out behaviour. The results showed that although fly ash treatment is a great way to improve the bonding characteristics, it is required to convert from an alkaline treatment to a less destructive process.
- During the static flexural tests on concrete beams, it was observed that by increasing the amount of fiber, the flexural strength of the concrete beams decreases, and the post-crack absorbed energy increases. Concrete containing 0.5% fiber had the optimum strength and toughness values with a marginal reduction in flexural strength and a considerable improvement in toughness (163% improvement compared to CO sample).
- During the electrical resistivity test on concrete samples, it was observed that as the CF percentage increases, the bulk electrical resistivity decreases significantly, indicating an improvement in the electrical conductivity of the composite material. The surface resistivity also decreased as the CF percentage increased, but the trend was not as significant as in the bulk resistivity measurements.
- During the freeze-thaw cyclic test on concrete samples, a definite trend showing that the dynamic modulus decreases exponentially as fibers concentration increases were observed. All samples with 1, 2, and 3 % of CF failed before 60 FT cycles, however those with 0.5% fiber were able to endure 300 FT with a minimal decline in dynamic modulus of elasticity.
- Large-sized round panel testing results revealed that both the 0.5CFT18 and 1CFT18 samples experienced very high load as well a significant deflection before failure (almost two times greater than the CO sample). However, the samples with 3% CF performed unsatisfactorily, even worse than the unreinforced samples.
- During the cyclic bending tests on concrete samples, the beams reinforced with 1% carbon fiber tolerated the highest number of loading cycles to failure, suggesting that 1% was the optimal fiber content for improving the composite material's performance in this test. This contrasted with the static three-point bending test, where the sample with 1% fiber did not perform as well as 0.5CFT18 samples.
- The self-heating test on CFRMs showed promising results, as the addition of 1.5% carbon fiber led to a temperature increase of around 20 °C in certain spots of the sample. However, it is important to note that the high-temperature increase may not be representative of the material's overall

performance since the presence of a very hot spot especially near to the electrodes can be the reason for a non-uniform distribution of fiber in the cement mortar.

- Comparing different electrode types to get the optimum outcome from the self-heating test, it was observed that the vertical metal lath and rebar electrode were the most effective at inducing self-heating in the concrete samples (with the highest temperature rise), while the wire mesh electrode was the least effective.
- During the life cycle analysis of the CO and CFRC pavement, the results show that the CO_2 gas emissions for the construction of both CO and CFRC are essentially equal. The total CO_2 emission was, however, reduced by 17.4% in CFRC pavements due to its higher performance in durability parameters and the lower number of maintenance requirements for CFRC.

The project's next step would be to implement the developed approach in the field preferably in Alberta. The smart electrically conductive fiber-reinforced concrete's (CFRC) characteristics and behavior have been well understood through laboratory studies. The performance of CFRC needs to be assessed in practical environments since Alberta's harsh environmental conditions may differ greatly from controlled laboratory conditions.