FINAL OUTCOMES REPORT (REDACTED)

1.0 PROJECT INFORMATION

1. ERA PROJECT ID #	E0161580
2. CALL / ROUND	ERA / ACT 3
3. PROJECT TITLE	Carbon Reforming to Economic Additives for Transitioning into an Emission-less Era ("CREATE")
4. COMPANY NAME	Carbonova Corporation
5. PROJECT TYPE (R&D, Development, Demonstration, Implementation)	R&D
6. LOCATION (primary location the project took place by address, land description, or GPS coordinates)	New Address as of May 2023 3200 14th Ave NE Suite 1 Calgary, AB T2A 6j4
7. PROJECT START DATE	October 1, 2021
8. PROJECT COMPLETION DATE	December 31, 2024
9. TECHNOLOGY READINESS LEVEL (TRL) AT PROJECT INITIATION	5
10. TRL AT PROJECT COMPLETION	6
11. JOBS CREATED	5
12. GHG EMISSIONS REDUCED (Project-level: annual, cumulatively by 2030 and by 2050)	55,000 tCO_2eq/annum; 110,000 tonnes cumulative by 2030; 1,121,000 tonnes cumulative by 2050
13. TOTAL ERA FUNDING	$542,525
14. TOTAL PROJECT VALUE	$1,133,437
15. ERA PROJECT ADVISOR	Amanda Mitchell
16. SUBMISSION DATE	
17. KEY PROJECT CONTACT NAME AND EMAIL	Todd Pugsley, tpugsley@carbonova.com
18. QUOTE (why was ERA a pivotal funder for this project? How did ERA funding help advance on the TRL scale? Etc.)	ERA funding through the CREATE project was pivotal to Carbonova pursuing its vision of becoming an advanced materials company global in reach. The funding enabled Carbonova to prove the concrete-enhancing properties of its CNF product, which is a critical step in building our pipeline of future customers. Furthermore, in the process of producing material for product testing with its international project partners, Carbonova advanced its patented reactor technology from TRL5 to TRL6.

19. NOTABLE COMMUNICATIONS	Communications were made with ERA per the reporting schedule for Stop Light reporting, Milestone reporting and Final Report. Additionally, reporting & presentations as outlined by ACT. Further a GHGT017 presentation was made in Calgary in 2025. Additional publications and presentations are listed in sections 14 & 15 below.
20. IMAGE (please insert or link a photo capturing the technology for ERA publications)	   

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5.0 EXECUTIVE SUMMARY

The Carbon Reforming to Economic Additives for Transitioning into an Emission-less Era (CREATE) project was a collaboration between Emission Reduction Alberta (ERA) Holcim Group (Switzerland), Sika AG (France) and Carbonova Corporation. The project aimed to accelerate carbon capture and utilization (CCU) technology for large CO_2 emitters by converting waste heat and industrial CO_2 streams into valuable products. The core utilization technology is Carbonova's process that converts CO_2 into carbon nanofibers (CNF), which has a broad range of applications. The focus of this project was application as an additive in the cement industry. The project objectives were laid out in Schedule A of the Contribution Agreement (CA) between ERA and Carbonova:

1. Demonstrate the scale-up of Carbonova technology and consistency of the production.
2. Assess the technological integration of the Carbonova cycle into a cement plant using process simulators.
3. Validate the performance of Carbonova cycle solid products in field tests for composite applications against the benchmarking of products.
4. Identify and promote business opportunities for large industrial sequestration of carbon dioxide into solid carbon reinforcement additives and assess the marketing strategy in Europe.

To achieve the project objectives, a Project Plan consisting of seven work packages or milestones was created and incorporated into Schedule A of the CA. Detailed milestone descriptions are provided in section 6 of this report, but are summarized here as follows:

1. Purchase and installation of specialized lab equipment for CFN production and QA / QC.
2. Prepare safe operating procedures for the lab equipment and develop a block flow diagram and process feed specifications for integration of Carbonova's process into a LafargeHolcim cement plant in France.
3. Complete material and energy balances for cement plant integration and establish technical dispersion requirements to meet end user needs.
4. Detailed lab testing at Carbonova of dispersions and integration into cement formulations for testing of strength and electrical properties.

5. Dispersions sent to Holcim for small scale testing, one dispersed using ultrasonication and the other with mechanical dispersion only.

6. Cradle-to-gate lifecycle assessment (LCA) of use of Carbonova's CNF in cement and concrete mixtures.

7. Business model verification and techno-economic analysis based on results from milestones 1 to 6.

The results confirmed that CNFs can be effectively dispersed in aqueous solutions and integrated into Portland cement concrete, improving compressive strength at optimal loadings. This enhancement allows for Portland cement reduction, leading to about 15-20% decrease in CO_2 emissions per cubic meter of concrete, as determined by the LCA. However, the study also highlighted challenges related to dispersion stability, which require further research to improve shelf life and industrial scalability. The techno-economic analysis demonstrated that expanding production capacity would significantly reduce unit costs, making CNFs a commercially viable additive for the cement and concrete industry. The break-even analysis suggested that achieving a target price of \$5–\$10/kg would make CNFs economically attractive, paving the way for widespread industry adoption. This was set as the future goal for collaborations in concrete industry, where using CNFs in specialty concrete would be further studied to provide meaningful values, while attracting the concrete industry for co-development and investment in Carbonova's CNF technology.

Through CREATE, Carbonova has demonstrated a viable path for industrial decarbonization by transforming CO_2 emissions into a high-performance advanced carbon nanomaterial. The project's findings provide a foundation for future commercial deployment, with potential to drive sustainable innovation in the cement and concrete sectors. The results support Carbonova's value proposition of lower cost (based on the techno-economic model and breakeven analysis), and enabled GHG reductions for the customer (based on the LCA analysis), while not compromising product quality (based on experimental evidence of the strength enhancements and electrical functionality imparted by the Carbonova CNF). By combining carbon capture, material performance enhancement, and outlook for cost reduction through scaling up our technology (compared to other competitors in the carbon nanofiber and nanotube sector and our own pilot plant), CREATE has positioned Carbonova's CNFs as a potential promising solution for reducing the environmental footprint of the construction industry while maintaining material integrity and durability.

6.0 PROJECT DESCRIPTION

6.1 INTRODUCTION

CNFs are a class of advanced carbon-based nanomaterials characterized by diameters below 100 nm and lengths ranging from hundreds of nanometers to several micrometers [1]. Their unique structural properties, including high tensile strength, electrical conductivity, and thermal stability, make them valuable across various industries [2]. In recent years, CNFs have gained increasing attention as an additive in cementitious mixtures, with the potential to enhance mechanical performance, durability, and electrical properties of concrete [3]. This interest extends beyond academic research, as demonstrated by CeEntek®, a company specializing in ultra-high-performance concrete (UHPC), which incorporates CNF dispersions to refine the microstructure of its concrete [4]. This approach enables exceptionally high compressive strength while reducing dependence on traditional supplementary cementitious materials (SCMs) such as silica fume, a common component in UHPC [5].

Integrating CNFs into cementitious mixtures presents a significant opportunity to address critical challenges in the construction industry. CNFs can enhance compressive and flexural strength, and refine the microstructure of cement pastes, mortars, and concrete [6]. By improving the mechanical performance of cementitious materials, CNFs enable reductions in Portland cement usage, leading to lower material consumption and a reduction in CO_2 emissions. Their ability to influence hydration reactions and nanostructural development makes them particularly effective in reducing porosity and enhancing the density of hardened cement matrices. Beyond strength improvements, CNFs have also demonstrated potential in conductive and self-sensing concrete, opening new possibilities for electrically heated pavements, smart infrastructure, and real-time structural health monitoring.

To support these applications, the CREATE project focused on advancing the technology readiness of CNFs by developing scalable production methods, improving dispersion techniques compatible with cementitious systems, and validating performance enhancements through rigorous laboratory testing. These efforts formed the foundation of the project's technology development activities, as detailed in the following section.

6.2 BACKGROUND OF THE PROJECT

Three large construction companies, Holcim, Sika, and China Communications Constructions Company (CCCC) initiated an accelerating program, LH accelerator and called for innovation in the strategic aspects of construction industries, including:

1- Concrete 2.0 – In a continuously evolving world the need for materials with superior performance properties is required to satisfy consumer requirements and remain competitive. Cement is affected by these requirements and has to enhance its properties such as (1) weight reduction, (2) noise reduction, (3) thermal properties, (4) light reflectivity-translucency, (5) porosity, (6) conductivity, (7) strength, etc.

2- Construction waste - Rethink the design and process of making and delivering cement to reduce waste. Cement production is a highly energy intensive process that generates significant amounts of waste heat and emissions. Utilization of waste and recycling them into the value chain will enhance the profitability and sustainability of the industry.

3- CO_2 neutrality – CO_2 emissions of concrete productions is related to the energy demands and direct decomposition of limestone.

In October 2019, out of 300 applicants from all over the globe, Carbonova along with 11 other tech companies was selected to develop, test and market their revolutionary idea. With the guidance and help of these global leaders in construction, Carbonova turned these ideas into a tangible business solution.

During this one-year collaborative project, Carbonova's product performance was validated at small scale in the R&D centers of both Sika and Holcim. Business and marketing experts from Sika and Holcim identified the high potential of Carbonova technology in reducing CO_2 emissions from a cement plant while creating incremental economic value. Therefore, there was significant potential of creating an R&D consortium through the Accelerating CCU Technologies (ACT) 3 Call to further de-risk the technology and its implementation in a cement plant. ERA partnered with ACT 3 and subsequently, Carbonova was one of four Alberta-led CCUS projects funded under the partnership.

Carbonova has been uniquely placed to play an integral role in combatting the challenges highlighted by the global leaders in construction, by providing a single solution that addresses the top priorities of building industries mentioned above. In September 2020, Holcim as the first company in building industries signed the net zero pledge with science-based targets, SBTi, with Business Ambition for 1.5°C. As of November 7, 2020, 1045 companies were taking science-based climate action and were required to set detailed plans and targets. Holcim set the target of 475 kg net CO_2 per ton of cementitious material (net CO_2/t_{cement}). Building industries will require a diverse number of science-based technologies to reach this ambitious goal.

In order to reach this ambitious target Holcim has planned to reduce the clinker to cement ratio, as the majority of CO_2 footprint (65%) is from the chemical reaction that occurs when the raw material (limestone) calcinates into a clinker in the kiln. Carbonova introduced a circular economy model that uses CO_2 emissions and waste heat to produce cement enhancement additives as new materials streams to reduce the clinker to cement ratio.

6.3 PROJECT OBJECTIVES

Project objectives captured as part of the milestone tasks and deliverables. Milestones for the project including deliverables and tasks completed are presented in this section.

Milestone 1A	
Start Date	December 1, 2021
Completion Date	December 31, 2021
Milestone deliverables	*Proof of deposit for lab equipment*

Detailed milestone description:

- Purchase of lab equipment: major equipment (such as Raman Microscopy) will be purchased from a well-known provider.

Milestone 1B	
Start Date	October 1, 2021
Completion Date	March 31, 2022
Milestone deliverables	*Carbonova products in-house quality control plan and production in service* • *Project Management Plan* • *Product quality control and validation procedure* • *Purchase of lab equipment*

Detailed milestone description:

- Project Management Plan (PMP) will outline the scope, goals, budget, timeline, deliverables of a project and keep the project on track. The PMP will include the following sections: executive summary, project scope & deliverables, project schedule, project resources, risk and issue management plan, and communication management plan. The stakeholders will approve PMP before the project moves to the execution stage.

- Establish the product quality control and validation procedure for the lab experiments.

- Purchase of lab equipment: major equipment will be purchased from a well-known provider. Simple and non-traditional equipment for post-treatment (vessels and pumps) will be sized and built by third-party contractors.

Milestone 2	
Start Date	April 1, 2021
Completion Date	September 30, 2022
Milestone deliverables	*Carbonova's process integration to a cement plant, safe handling procedures* • *Define process specifications of feedstock for the LafargeHolcim cement plant in France (CO_2 and waste heat)* • *Block flow diagram of the Carbonova-cement unit* • *Safety operating procedures for CNF lab testing*

Detailed milestone description:

- Carbonova is determining the process specifications for the feedstock at the LafargeHolcim cement plant in Lyon, France. Analyze the interaction between the Carbonova process and CO_2 purity achieved with the CO_2 capture process at the LafargeHolcim cement plant. Understand the impacts of the cement plant flue gases with the Carbonova process and the effects on the product quality. Develop the Carbonova process block flow diagram.

- Establish material safe handling procedures for CNFs. Perform product hazardous risk evaluation and develop safety documents for product handling during the project. Carbonova's product management team and guidance of the safety experts at Sika and LafargeHolcim will develop these safe operating procedures.

- Monitor and update pilot plant operation and product delivery schedules. Provide ongoing project management services to the project partners during the project.

Milestone 3	
Start Date	April 1, 2022
Completion Date	March 31, 2023
Milestone deliverables	*Cement plant integration design* • *Material and energy balance* • *Technical specifications for dispersion in a liquid/solvent* • *Evaluate dispersion quality of admixture*

Detailed milestone description:

- Inputs and outputs of material and energy balance using simulation software such as Aspen HYSYS or VMG.

- Analyze technical needs of end-users and define specifications for the liquid dispersion. Evaluate the compatibility of different dispersants and the different application cases of the nanofibers.

- Perform lab tests of admixture and evaluate the dispersion quality within the second medium in the R&D Center at the University of Calgary, LafargeHolcim, and Sika in France.

Milestone 4	
Start Date	September 1, 2022
Completion Date	September 3, 2023
Milestone deliverables	*CNF dispersion usage at lab scale, integration in formulations, and values assessment* • *Microstructural analysis of CNF dispersion* • *Evaluation of CNF dispersion in smart applications*

Detailed milestone description:

- Microstructural analysis of CNF dispersion
- Evaluate the CNF dispersion electrical and heat conductivity for potential smart applications
- The third phase of project management (modifying the process operation based on early feedback from Milestones 2 and 3), product delivery, and post-treatment planning.

Milestone 5 (amended)	
Start Date	September 1, 2023
Completion Date	December 31, 2024
Milestone deliverables	*CNF dispersion usage at small scale (laboratory)* • *Validation of dispersion in cement paste at low water-to-cement (w/c) ratio* • *Evaluate the effect of ultrasonication and mechanical dispersion on mechanical strength*

Detailed milestone description:

- Carbonova will provide Holcim with a CNF dispersion (using a SIKA PCE) for them to test on a small scale, in either cement paste, mortar or concrete, to validate the results seen in cement paste at low w/c ratio by University of Calgary. With these, a comparison will be drawn with Holcim results and differences can be attributed to the quality of the CNF dispersion, and/or the formulation of the mortar/concrete.
- Since it was identified that ultrasonication is an issue, two different CNF dispersions will be provided to Holcim. One with the use of ultrasound (US) as per Carbonova's formulation and one using mechanical dispersion alone.
- Holcim/University of Calgary to test for mechanical strength and electrical capabilities.

Originally, Milestone 5 focused on using CNF dispersions in concrete at an industrial level. Rather than performing a field application at an industrial level with Holcim, this milestone was carried out at laboratory scale after receiving the approval in an amended schedule submitted to ERA as discussed above.

Milestone 6	
Start Date	March 1, 2023
Completion Date	December 31, 2024
Milestone deliverables	• *LCA of CNFs*

Detailed milestone description:

- LCA definition at different system frontiers:
- Process of nanofibers
- Cement mixed with nanofibers
- Concrete mixed with nanofibers
- Mortars mixed with nanofibers
- Plastics, rubbers… etc.*
- Assess the global energy demands and carbon footprint of the integrated process.
- Analyze the yields of solid carbon materials in an integrated reforming process.

* As noted above, due to the departure of Sika from the project, the plastics, rubbers, *etc*. scope was not included in the LCA. Furthermore, the LCA within the scope of cementitious mixtures was conducted solely on concrete, due to its widespread use in the construction industry and the applicability of the findings to other cement-based materials such as paste and mortar. In fact, cement paste, and mortar have limited large scale use and are mainly used in research projects to limit the number of variables, for instance in mechanical testing evaluations. While this simplicity is appreciated in scientific research, the LCA should concern the real world applications and scenario cases, such that we have covered through analyzing concrete.

Milestone 7	
Start Date	March 1, 2023
Completion Date	December 31, 2024
Milestone deliverables	• *Business model verification and refining* • *Revise business model based on learnings from the project* • *Techno-economic analysis of Carbonova process within a cement plant*

Detailed milestone description:

- Validate and refine the business model based on all the learnings acquired from the project.
- Perform techno-economic analysis for the new CCY technology (Carbonova process) integration within a cement plant.

6.4 PERFORMANCE/SUCCESS METRICS IDENTIFIED IN THE CONTRIBUTION AGREEMENT

Success Metric	Commercialization Target	Project Target	Project Achievement	Explanation
Scaleup capacity of CNF	2,000 – 5,000 t/y	1-1.5 kg/d	0.15 kg/d	We believe the reactor is volume limited in its current design. The reason is because the bulk density is lower than expected. There appears to be an issue with heat loss near the ends of the reactor as well. Recent design modifications have increased production by 30% above the Project Achievement number.
CO_2 reduction in a cement plant	5-20% CO_2 reduction in concrete	Proof of concept in lab and field test for 5-20% CO_2 reduction of concrete	10 to 20%	Carbonova CNF enables a reduction in the amount of Portland cement required, thus lowering CO2 emissions by 10 to 20% according to LCA.
Advanced construction materials	1:1 replacement of CNF with reference additive materials	1:1 replacement of CNF with carbon black and carbon fibers	1:1 replacement achieved based on benchmarking with carbon fibers and carbon nanotubes	Benchmarking Carbonova CNF against carbon nanotubes and carbon black as additives to concreate show that CNF performance is equal to nanotubes and better than carbon black.
Business development in Europe: Partnership/investment/sales	License/product sales	Develop a commercialization and marketing plan in Europe	complete	Carbonova has developed a commercialization plan to 2050 that includes a number of production units in Europe. See Table 12 for the first 10 years of the plan.

6.5 PROJECT CHANGES

One of the project partners, namely Sika - France, dropped from the program before the end date specified in the original agreement. This created several changes to the program as is laid out in the amendment dated May 7th, 2024. Key changes included combination of original Milestones 5 & 6 into one milestone, renamed as Milestone 5 (amended). This impacted renaming Milestone 7 (original) to Milestone 6 (amended) and Milestone 8 (original) to

Milestone 7 (amended). Due to Sika's departure, LCA of plastics and rubbers was not included in Milestone 6 of the project.

The driving force behind Sika's departure from the program was the key scientist assigned to the project left the organization and wasn't replaced. This change impacted the cost of the program due to change in approach and companies responsible for said changes. The cost of the program increased to $1,133,437 from the original cost of $1,085,050.

The program did see cost overage with the total cost exceeding the budget by $45,414. This overage was mainly driven by the change is scope per the May 7th amendment. This overage was borne by Carbonova and is detailed in Section 4 – Budget further down in this report.

Milestone 5 (original) was initially planned to be executed in a field trial. However, after much consideration of the resources and previous trials, the execution method for this milestone was changed to a laboratory trial. This change was driven primarily by Sika – France's departure from the program. With their departure, Carbonova regrouped with its other partner, Holcim, and it was determined that a field trial was not warranted at this point of the R&D program, making laboratory testing the best path forward. Both Holcim and Carbonova, via University of Calgary, conducted the work completed in Milestone 5 (amended).

6.6 TECHNOLOGY RISKS

1. **CNF dispersion stability:** CNFs tend to agglomerate in aqueous solutions, creating the risk of uneven dispersion in the cementitious mixtures and reduced performance enhancements per unit mass of CNF added. The dispersion challenge was successfully overcome in this project, but the long-term stability of the dispersion will require further R&D efforts, which Carbonova is currently undertaking.

2. **CNF production scale up:** Carbonova has successfully transitioned from lab-scale to pilot-scale production. However, the next challenge is to increase the production capacity, keeping up pace with the high amount of concrete production.

7.0 PROJECT WORK COMPLETED AND OUTCOMES

7.1 METHODOLOGY

Milestone 1

The pilot plant was designed through in-house employees with expertise in design of reactors and pilot units. Moreover, Carbonova completed purchasing different quality control equipment for its R&D laboratory. The functionality of the equipment were carefully analyzed based on Carbonova's needs and different vendors were contacted to obtain quotes. The best fitting equipment in terms of functionality and price was then selected and purchased.

Milestone 2

The deliverable on defining feedstock specifications for the LafargeHolcim cement plant was led by Holcim. They compared typical CO2 composition captured at a cement plant with the CO2 specifications that had been prepared by Carbonova for their process.

Regarding waste heat, Carbonova prepared a process simulation for their process identifying flows and temperatures. To estimate how much waste heat can be obtained from a cement plant, Holcim used a well-known

European cement plant model described in a European project called CEMCAP. This was then matched with the Carbonova simulation to identify waste heat integration opportunities.

Milestone 3

AspenHYSYS® was chosen as the process simulation software for this milestone. This software is widely used in the oil and gas sector as well as in Canadian universities' chemical engineering programs. As such, Carbonova's process engineering team was familiar with the software and was able to use it effectively to build the process model.

To carry out the dispersion testing in liquid media required for this milestone, the Sika France Innovation Lab purchased a Hielscher UP400ST 400-Watt ultrasonic dispersion machine (Figure 1). A full factorial experimental design was then prepared using three parameters:

- CNF concentrations of 0.02 to 2% in water
- Sonication time from 15 to 60 minutes
- Mixing energy from 60 to 200 Watts

The stability of the aqueous mixtures was based on visually observed settling tendencies and it was found that the mixtures were not stable and tended to settle within 24 hours

Subsequently, a Sika polycarboxylate ether (PCE) superplasticizer used in the production of high-performance concrete was added to the mixture. Following an extensive study by Holcim, the following protocol was developed to complete milestone 3:

- Mixture components are combined in a 250 ml glass container
- 196.2 grams of liquid combined with 1-gram PCE and desired quantity of CNF
- Sonication probe introduced into the mixture to a depth of 2 cm
- Mixing power of 230 Watts
- The ultrasonic probe pulse is set at 80% (i.e. it emits ultrasound in pulses, with a rest time to cool the medium 20% of the time at the end of each cycle),
- A wax film seals the container to prevent any projection of nanocarbons during dispersion and the container is placed in a tray of water filled with ice cubes to limit excessive heating of the medium.

Milestone 4

Procedures for sample dispersion were established as part of Milestone 4 , building on the demonstrated dispersion success of Carbonova's CNFs facilitated by additives and application of ultrasonic energy. Essentially, Carbonova strived to optimize the ultrasonic energy and concentration of dispersants in aqueous dispersions relative to the amount of CNFs used in the mixture. This was done through defining important factors such as energy and amplitude and a long series of experiments, changing factors at various levels once at a time. The formulation of the Carbonova's proprietary dispersion method was not finalized at Sika France (due to their early retirement), with the stabilization study to be completed by the Civil Engineering Department at the University of Calgary.

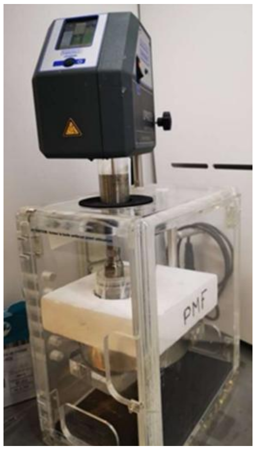

Figure 1. Hielscher UP400ST ultrasonic disperser (400 watts).

Milestone 5

For tests conducted on cementitious mixtures at Sika and Holcim (Milestones 4 & 5), CNF aqueous dispersions were prepared according to Carbonova's optimized dispersion method and shipped to Europe for incorporation in cementitious mixtures. The tests conducted on cementitious mixtures at Sika and Holcim complied with the British and European (BS-EN) standard testing methods.

For tests conducted at the University of Calgary (Milestone 5), aqueous dispersion was also prepared according to Carbonova's proprietary dispersion method, albeit at the university facilities and immediately before incorporation in cementitious mixtures of different water-cement ratios (w/c) and concentrations of CNFs. The tests conducted at the University of Calgary complied with the ASTM standard testing methods. Based on BS-EN and ASTM, typically a minimum of three samples are tested for compressive strength of cementitious mixtures at any age and the average value is reported.

For tests conducted on cementitious mixtures at Sika and Holcim (Milestones 4 & 5), CNF aqueous dispersions were prepared according to Carbonova's proprietary dispersion method and shipped to Europe for incorporation in cementitious mixtures. The tests conducted on cementitious mixtures at Sika and Holcim complied with the British and European (BS-EN) standard testing methods.

For tests conducted at the University of Calgary (Milestone 5), aqueous dispersion was prepared at the university facilities and immediately incorporated in cementitious mixtures of different water-cement ratios (w/c) and concentrations of CNFs. The tests conducted at the University of Calgary complied with the ASTM standard testing methods.

Milestone 6

To achieve objectives of Milestone 6, the direct environmental impacts of the production of Carbonova's CNFs from CO_2 and the indirect impacts of incorporating CNF into concrete were independently evaluated by Solas Energy Consulting. Two scenarios were considered for the indirect environmental benefits of CNF considering Portland cement reduction. The first involved decreasing Portland cement content with changes in mix design involving higher w/c. The second assumed replacing 50 wt% of Portland cement with ground granulated blast furnace slag (GBFS), compared to a baseline mix with 30 wt% GBFS. To maintain functional equivalency, all scenarios ensured comparable compressive strength between CNF-enhanced and conventional concrete.

Concrete was chosen for indirect environmental impact assessment rather than mortar or cement paste because it is the primary end-use product of Portland cement, with the highest global production and emissions footprint. While mortar and paste are useful for evaluating fundamental material properties (as was the case in this project under Milestone 5), their environmental impact in real-world applications depends on specific use cases, making standardized assumptions about mix design and material substitution more challenging. In contrast, concrete's large-scale production and well-established mix designs allow for a more direct and meaningful assessment of environmental benefits. Additionally, since the strength-enhancing effects of CNFs observed in mortar tests are expected to translate to concrete, the environmental impact improvements are similarly transferable, making concrete the most relevant and practical choice for analysis.

It is important to note that the LCA was based on a cradle-to-gate framework as per the original project proposal. The corresponding LCA boundaries and summary of potential environmental impacts considered in this study are shown in Figure **2** and Table 1, respectively. Given the high carbon intensity of Portland cement plants and the utilization and hence abatement potential of CO_2 by Carbonova's process, the main emphasis was on the GHG emissions impact category. Air emissions (PM_{10}, NO_x, SO_x, VOCs) associated with Carbonova's process block were also considered. Soil impacts were not considered since those impacts are anticipated to be negligible. Water impacts were also not considered. The Carbonova process generates water as a byproduct and this water has the potential to be treated and re-used in either the Carbonova process or the co-located cement plant. This would beneficially reduce freshwater usage. Alternatively, the water byproduct would be stored in holding tanks for third-party pickup and proper disposal in accordance with government regulations.

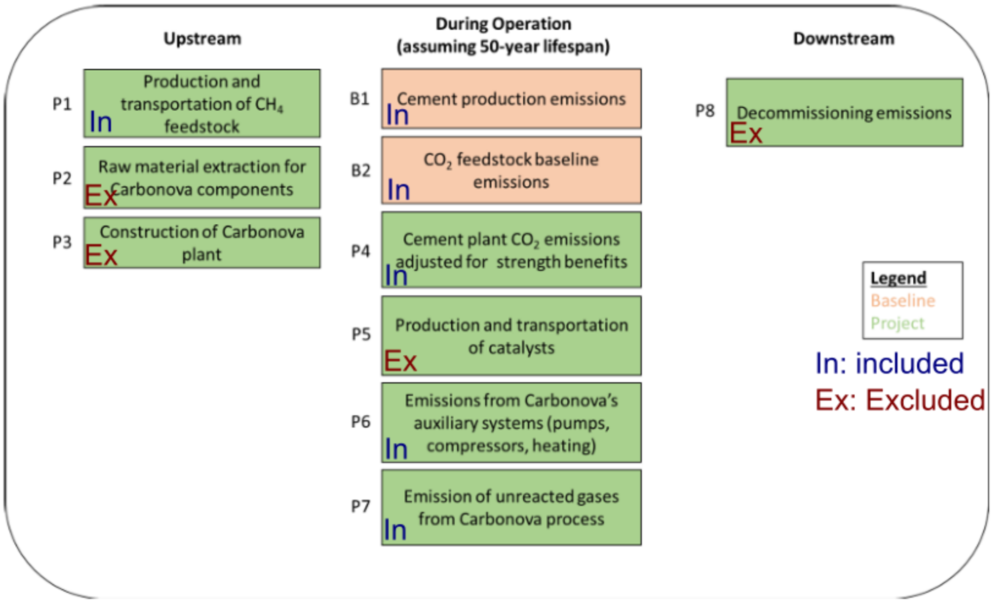

Figure 2. Project and baseline activity boundaries.

Table 1. Summary of inputs and potential environmental impacts associated with Carbonova's project.

Input	**Environmental Impact Area**			
X = included	**GHGs**	**Air**	**Water**	**Soil and Land**
B1	X			
B2	X			
P1	X			
P4	X			
P6	X			
P7	X	X		

Milestone 7

For Milestone 7, a techno-economic analysis was conducted to evaluate the feasibility of producing CNFs in a modular production facility integrated with a Portland cement plant. The analysis compared a concrete mixture incorporating 0.6 wt% CNF with a business-as-usual baseline mixture without CNFs, both having a 28-day compressive strength of 35 MPa. The required annual CNF production capacity was determined based on the cement content in these mixtures and the corresponding volume of concrete that can be produced annually. This provided insights into the yearly production target necessary to meet market demand.

To assess the economic viability of the proposed production plan, an economies of scale analysis was conducted to evaluate how the unit cost of CNFs decreases with increasing production capacity. This analysis was coupled with a break-even analysis to identify the production volume at which the operation becomes cost-effective. Together, these assessments provided a comprehensive understanding of the scalability, pricing dynamics, and economic feasibility of integrating CNF production into the concrete supply chain.

The business model was re-evaluated considering the findings from the technoeconomic analysis to determine whether any modifications are required. This evaluation focused on incorporating insights from project learnings, including production scalability, cost dynamics, market feasibility, and potential adjustments to align the business strategy with emerging opportunities and challenges.

7.2 TECHNOLOGY DEVELOPMENT

Figure **3** shows the pilot plant located at Carbonova's facility in Calgary, Alberta. During CREATE project (Milestone 1), Carbonova completed the construction and commissioning of its pilot plant. This pilot plant is being used to produce samples for testing in the products of different Canadian and international partners. The completion and commissioning of the pilot plant was performed on time and budget by Carbonova's third-party contractor, and all the necessary operating and safety procedures were developed and put in effect before production began. As of 2023, Carbonova's trained personnel have been operating the plant. A product inventory has been developed for product shipment to our partners.

Figure 3. Carbonova's pilot plant.

As part of the market development plan, Carbonova expanded its product quality control capacity by purchasing a Raman Spectroscopy/microscopy (see Figure **4**), allowing Carbonova to create CNFs with specifications required for different applications including cementitious mixtures in the construction industry.

Figure 4. Raman spectrometer procured by Carbonova's Product Development team.

Table 2 indicates the process specification for CO_2 feedstock gas. The specification for the feedstock gas was completed as a part of technology development during Milestone 2 of the CREATE project. It should be noted that these specifications are meant to represent “guidelines” as not all of them have been thoroughly tested. Moreover, a block flow diagram was prepared for Carbonova’s process, assisting with future potential integrations with Portland cement plants (see Figure 5). The numbers presented in the block flow diagram are based on preliminary mass balance with 90% conversion of CO_2 to CNFs. The waste heat amounts do not account for the heat loss to the environment.

Table 2. Process specifications for CO_2 feed gas.

Component	Optimal Concentration	Explanation
CO_2	> 99mol%	This target purity is based on not only the needs of the Carbonova process, but also on the feasibility and cost of purifying CO_2 in a cement plant, and the other potential uses of captured CO_2. Many CO_2 capture technologies can achieve a higher purity than 99.0%, and low-purity CO_2 streams can be further purified with a CPU (CO_2 Purification Unit), which would likely be necessary if the CO_2 is intended for ship transport. Many applications for CO_2 such as medicine or food and beverage have purity requirements equal to or higher than 99.0% (e.g., the European Commission regulates CO_2 for use in food to 99% minimum). Purifying CO_2 above 99.0% would not only benefit the Carbonova process but also expand the potential customer market if the CO_2 is sold elsewhere. Low-purity CO_2 has a much more limited range of applications (mostly EOR for oil production).
N_2/ Other inerts	< 1mol%	Nitrogen and other inert gases are not directly harmful to our process, but they do have a negative effect by diluting the reactants and accumulating in the process because of recycling. Our dry-reforming process is different than conventional steam-reforming because we recycle some of the gases, which means that any inert will accumulate in the system and reach higher levels than the concentrations in the feed.
CH_4, Hydrocarbons	< 100ppm	Low-molecular-weight hydrocarbons are not a concern for our catalysts or our overall process, and of course methane is the other main feedstock besides CO2. However, heavier hydrocarbons could form deposits in the process.
NH_3, Amines	< 100ppm	NH3 and amines are not a major concern for our catalysts or our overall process. However, the exact limits have not been tested yet.
NOx	< 100ppm	NOx is not as dangerous to our catalysts as SOx or sulfur compounds. We may be able to tolerate low NOx levels in the feedstock, but the exact limits have not been tested yet.
SOx, Sulphur Compounds	< 5ppm	SOx and other sulfur compounds are the most dangerous impurities for our catalysts. SOx compounds can be reduced to H2S which will poison the catalyst, eventually requiring replacement. Both the CO2 feed and the natural gas will likely require a dedicated sulfur removal process before they are used in the main Carbonova process, to protect the catalysts.

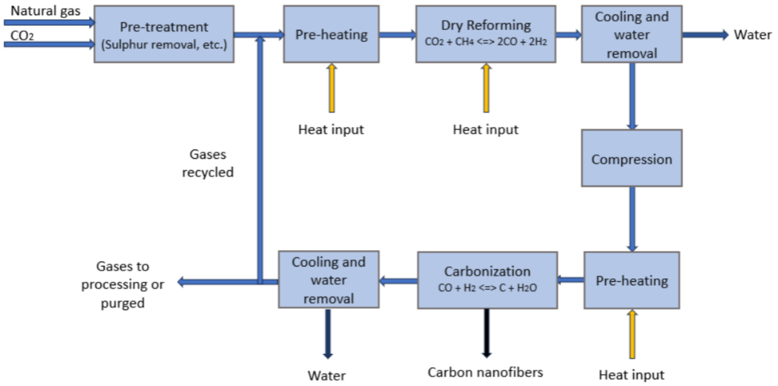

Figure 5. Block flow diagram of Carbonova's process.

Safety during production was advanced through development of safety operating procedures. This included completion of REACH (Registration, Evaluation, Authorization, and Restriction of Chemicals) certification, which is a regulation in the European Union that requires manufacturers to make sure their products are safe and to provide detailed information on the substances they contain, and the safety data sheet for Carbonova's CNFs. The technical team periodically updates/improves the safety data sheet and procedures through safety meeting.

During Milestone 3 of the CREATE project, the effect of impurities, particularly nitrogen, on Carbonova's process and product quality was extensively researched. Several tests were conducted with nitrogen in the pilot plant and showed no significant impact on the conversion ratios or product quality.

Carbonova analyzed the technical requirements of its end-user partners in this project and developed an aqueous dispersion method at the University of Calgary. The dispersions were then used in cementitious mixtures including cement paste and mortar to evaluate the compressive strength, electrical conductivity, and microstructure of the final product. These experiments were performed at the labs of Sika and Holcim in Switzerland and France, respectively as well as at the University of Calgary.

7.3 PROJECT ACHIEVEMENTS, RESULTS, AND ANALYSIS

Milestones 1 & 2

The main accomplishment during Milestones 1 & 2 reporting period was the completion of multiple runs of the Pilot Plant and successful production of CNF material for use in subsequent milestones. A representative image of CNF is shown in Figure 6.

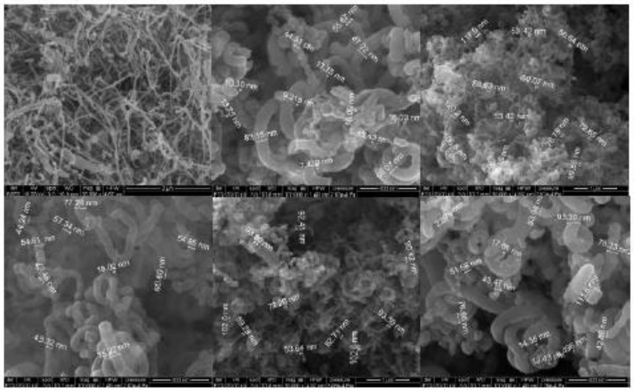

Figure 6 - Scanning Electron Microscopy (SEM) images of CNF product.

*Milestone **3***

Milestone 3 accomplishments include establishing a methodology for dispersing the CNFs using ultrasonic irradiation. Moreover, the quality of aqueous dispersion through ultrasonic irradiation and mechanical mixing was compared. The other accomplishment in Milestone 3 was related to simulation of Carbonova's process in the chemical engineering simulation software AspenHYSYS® and evaluating input/output of materials and energy. Key process variables such as composition (mass and mole fractions, mass and molar flows), temperature, pressure, and heat flows for all process streams were obtained from the simulation.

Milestone 4

The key accomplishments and learnings during Milestone 4 reporting period (Sep 1st, 2022 – Sept 30th, 2023) were presented at the ACT 3 Knowledge Sharing Workshop (Paris, October 4-5, 2023) including the microstructural analysis of CNF dispersion performed by Sika and Carbonova.

Procedures for sample dispersion were established, and Laser Scanning Confocal Microscopy was employed to demonstrate successful dispersion of Carbonova's CNFs following the incorporation of additives and application of ultrasonic energy. Moreover, the water content of cement pastes incorporating CNFs were adjusted to find the tolerance and avoid rising of CNFs to the surface.**Error! Reference source not found.** Figure 7 shows the Hielscher UP400ST ultrasonic disperser (400 watts) acquired by Sika France for the development of the current methodology. Figure 8 showcases images of samples (both with and without additives) along with their Confocal micrographs to show evidence of successful dispersion. During this milestone, the compressive strength and electrical heating of cementitious mixtures incorporating Carbonova's CNFs were tested, and experimental values were recorded

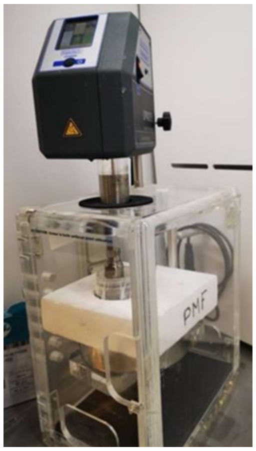

Figure 7 - Hielscher UP400ST ultrasonic disperser (400 watts).

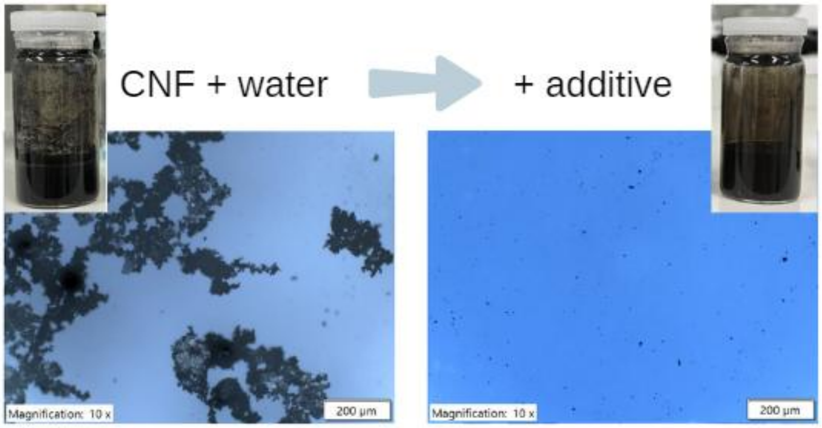

Figure 8 - Confocal microscopy images of CNF samples, a) CNF dispersed in water, b) the same sample after adding dispersant and ultrasonic irradiation.

Milestone 5

I. Dispersion analysis

The dispersion of CNFs in both fresh cement paste (fluid state within the first day of hydration) and hardened cement paste (solid state after strength development, with CNFs embedded within the matrix) was evaluated using visual inspection and scanning electron microscopy (SEM) at the University of Calgary. For the fresh specimens, fluid samples were collected three hours after water was added, while the visual assessment of dispersion in hardened cement paste was performed on samples cured for 28 days.

Error! Reference source not found. 9 a and b illustrate the internal surfaces of fractured hardened cement paste containing poorly dispersed and well-dispersed CNFs, respectively. In the poorly dispersed sample, where mechanical mixing was the sole method for disentangling CNFs, significant air entrapment and localized CNF agglomerates are evident. These issues, including poor CNF dispersion and entrapped air bubbles, can compromise the mechanical strength of the material and should be avoided. In contrast, Carbonova's optimized dispersion technique employing ultrasonic irradiation, markedly improved the uniform distribution of CNFs throughout the hardened cement paste matrix, demonstrating its effectiveness in enhancing material performance. The dispersion considerations would add to the energy use and may have negative implication on the practicability of using CNFs. Yet, it ensures that CNFs in fact help improving the performance of cementitious mixtures. Carbonova is using this as a practical lesson to further improve the efficiency of its dispersion methods.

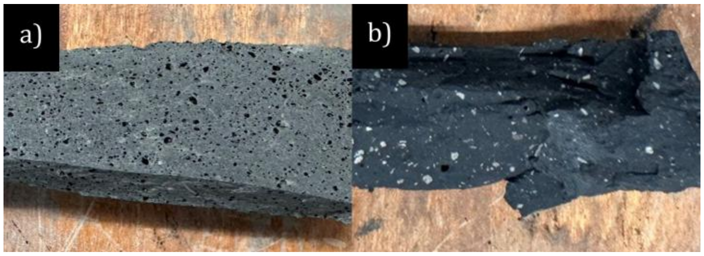

Figure 9 - Visual inspection of CNF dispersion in fractured inner surfaces of cement paste, a) cement paste with non-dispersed CNFs, and b) cement paste with well-dispersed CNFs.

II. Compressive strength

During Milestone 5 reporting period, the effect of CNF dispersions on the compressive strength of hardened cement pastes and mortars at different w/c ratios from 0.25 up to 0.485 and different ages was explored. **Error! Reference source not found.** Figure 10 shows Holcim results on mortars with w/c of 0.25, 0.30, and 0.40 while incorporating CNF concentrations up to 0.4 wt%. Based on Holcim results, use of 0.2 wt% CNFs in mortars with w/c of 0.25 and 0.30 resulted in a slight increase in 1- and 7-day compressive strength of cement mortar. However, incorporating CNFs in mortars with a w/c of 0.40 resulted in significant loss of compressive strength.

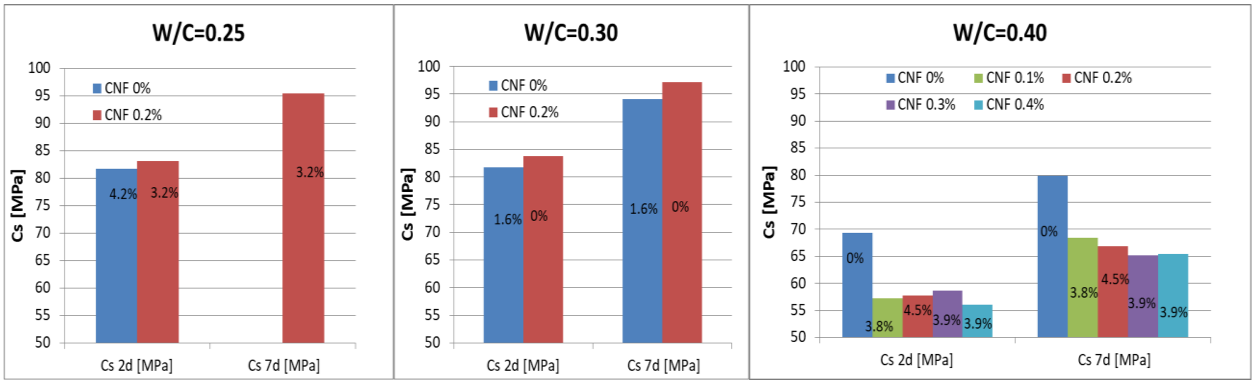

Figure 10 - Holcim results for compressive strength of cement mortar incorporating CNF dispersions at w/c = 0.25 (left), w/c = 0.30 (middle), and w/c = 0.40 (right).

The compressive strength of cement pastes and mortars incorporating different concentrations of CNFs was also explored at the University of Calgary (Figures 11 and 12). **Error! Reference source not found.** shows that cement pastes incorporating CNFs up to 0.5 wt% had a compressive strength 20-30% higher than the reference with no CNFs addition. The positive effect of CNFs on the 28-day compressive strength was observed for both w/c of 0.25 and 0.42.

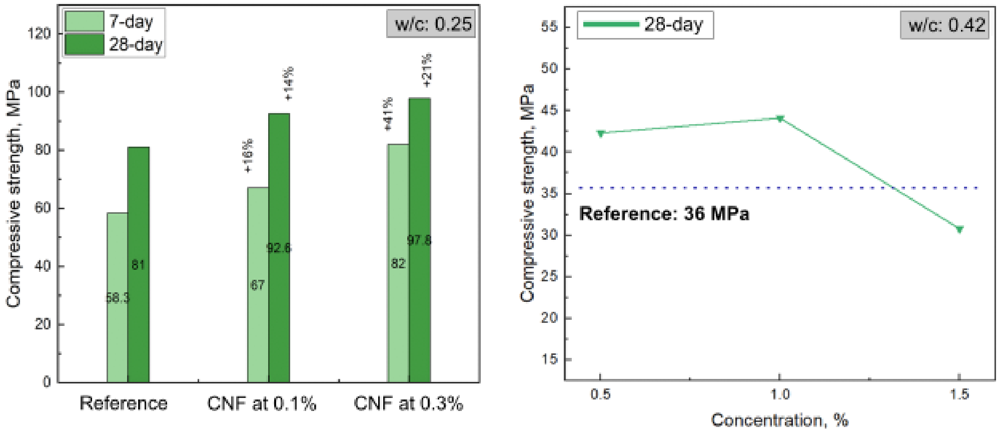

Figure 11 - University of Calgary results for compressive strength of cement paste incorporating different concentrations of CNFs at w/c of 0.25 (left) and 0.42 (right).

Following this improvement, CNFs were also incorporated in standard cement mortar (w/c = 0.485) at the University of Calgary to examine the scalability of the work and as a benchmark to compare with Holcim results. **Error! Reference source not found.** shows that mortar incorporating 0.6 wt% CNFs had a compressive strength 13-18% higher than the reference mortar at varying ages from 1 day to 28 days. The increase in compressive strength of hardened mortars was lower than what was observed in paste, yet more significant than the effect observed by Holcim **Error! Reference source not found.**in Figure 10. The increase in compressive strength due to the addition of CNFs was leveraged to increase Portland cement replacement with GBFS from 30% to 50% without compromising the compressive strength of mortar. This would further signify the effect of CNF dispersion as an eco-friendly admixture in cementitious mixtures.

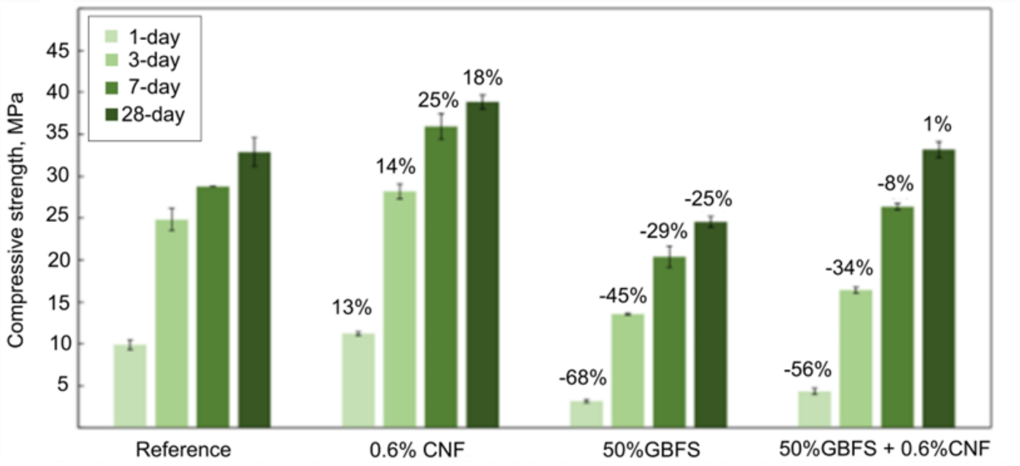

Figure 12 - Compressive strength results of mortar at ages of 1, 3, 7, and 28 days. CNFs and GBFS were used separately and together to find their synergic effect.

The disparity between the results obtained at the University of Calgary (**Error! Reference source not found.**Figure 11 and Figure 12**Error! Reference source not found.**) and those achieved by Holcim (Figure 10**Error! Reference source not found.**) can be primarily attributed to differences in materials, mixing methods, CNF concentration, and—most critically—the time elapsed between preparing the CNF dispersion and casting the cementitious mixtures. At

Carbonova, cementitious mixtures were cast immediately after preparing the CNF dispersion, ensuring optimal dispersion and maximizing their contribution to compressive strength. In contrast, the logistical delays associated with transporting materials from North America to Europe and the additional time required for planning and casting at Holcim resulted in a significant degradation of CNF dispersion stability over at least 1–2 months.

As illustrated in Figure 13**Error! Reference source not found.**, the dispersion stability of Carbonova's CNFs in aqueous solutions with Sika ViscoCrete 2100 as a dispersant can degrade by an average of 75% within eight days. This highlights the critical role of minimizing the time between CNF dispersion preparation and its integration into cementitious mixtures to maintain optimal performance. Moreover, the presented results indicate necessity of R&D on stability of CNF dispersions to improve the shelf life of the product, where such improvement is demanded by the customers. While Carbonova continues the research to enhance the shelf life of its dispersion products, alternative strategies, such as incorporating on-site industrial dispersion facilities at the CNF-cement production plant, can be explored as part of future techno-economic plans. Engineering economic cash flow analysis will be employed to evaluate the financial feasibility of these alternatives and guide decision-making for potential collaborations.

Despite these challenges, even with prolonged delays and low CNF concentrations, Holcim still observed slight improvements in compressive strength of hardened mortar at low w/c ratios. The results from both University of Calgary and Holcim underscore the strong potential of CNFs to enhance mechanical performance of cementitious mixture — provided that proper preparation, dispersion stability, and mixing protocols are maintained.

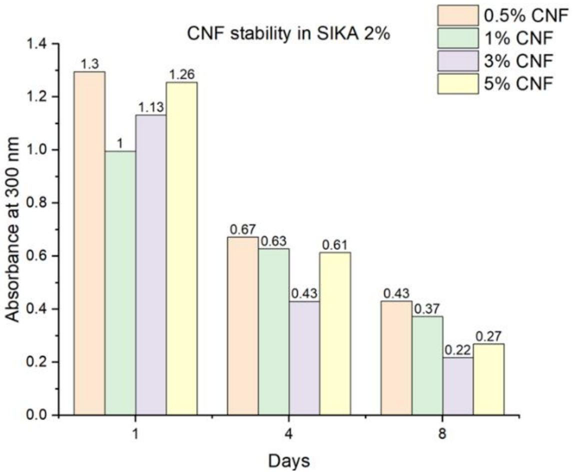

Figure 13 - UV-Vis absorbance of CNF-ViscoCrete 2100 dispersions in water at various times after dispersion preparation.

<u>Milestone 6</u>

I. LCA

A block flow diagram of the Carbonova process was presented previously in Figure 4. As shown in the diagram, the process consists of two reactors in series. In the first reactor CO_2 and methane are converted into synthesis gas (mixture of carbon monoxide and hydrogen) via dry reforming of methane (DRM) according to the gas-phase reaction:

(Eq. 1). $CO_2 + CH_4$ --> $2CO + 2H_2$ ΔHR = +247.4 kJ/mol (endothermic)

In the carbonization (CNZ) reactor the syngas is converted into the CNF product according to Eq. 2. The CNF is a solid carbon material, i.e. 1 kg CNF equates to 1 kg carbon:

(Eq. 2). $2CO + 2H_2 \dashrightarrow 2H_2O + 2C(s)$ $\Delta HR = -131.3$ kJ/mol (exothermic)

The net reaction combining DRM and CNZ indicates that for every kilogram of carbon produced, 1.8 kg of CO_2 are consumed:

(Eq. 3). $CO_2 + CH_4 \dashrightarrow 2H_2O + 2C(s)$ $\Delta HR = -15.2$ kJ/mol (net exothermic)

The exothermic heat of reaction released in the CNZ reactor is used to preheat the incoming DRM feed. Heat integration between the exo- and endothermic reactor stages significantly lowers the energy intensity of CNF production, setting Carbonova apart from its competitors. Our process simulation described above predicts energy intensity of less than 20 kWh/kg CNF (70 MJ/kg) for the fully heat-integrated Carbonova process. This compares with Carbonova's competitors' processes in terms of energy intensities.

II. Using CNFs in concrete: Scenario 1

The functional unit in this scenario is one cubic meter of air-entrained Portland cement concrete with a 28-day compressive strength of 45 MPa (see Table 3 for the mix designs). Compressive strength results for mortars incorporating Carbonova's CNF dispersions (Section 7.1.5, Milestone 5) indicate a 20–30% improvement in the compressive strength of concrete is achievable. This enhancement allows concrete mixtures to gain the same compressive strength with a reduced Portland cement content. For instance, a base concrete mix typically requires 440 kg of Portland cement per cubic meter to achieve a 28-day compressive strength of 45 MPa (Baseline condition, or B1, in Figure 2). In comparison, a concrete mix containing 380 kg of Portland cement per cubic meter, usually exhibiting a 28-day compressive strength of 35 MPa, can also reach 45 MPa if 0.6 wt% (2.3 kg) CNF is added (Project condition, or P4, in Figure 2). In this case, the mass of CO_2 sequestered for 2.3 kg of CNF would be 4.5kg CO_{2eq} and the electrical energy used to produce this amount of CNF would be:

$$2.3 \text{ kg CNF} \times 14 \text{ kW·h/kg CNF} = 32.2 \text{ kW·h} = 116 \text{ MJ}$$

Considering the emissions intensity of Alberta's current electricity grid, a net total of 6.2 kg CO_2eq is released into the atmosphere for production of 2.3 kg of Carbonova's CNF used in 1 cubic meter of concrete (for clarity this the sum of sequestered CO_2 as a reactant in Carbonova's process (scope 1) plus the CO_2 emissions associated with the electricity consumption (scope 2)).

Table 3. Mix design of the base and project concrete in Scenario 1.

Mixture ID	Component, kg/m^3						
	Portland cement	Water	Superplasticizer	Air entraining agent	Coarse aggregate	Fine aggregate	CNF
Base	440	151.6	4.4	0.2	800	838	–
Project	380	152	3.8	0.15	800	889	2.3

II. Using CNFs in concrete: Scenario 2

The functional unit in this scenario is a cubic meter of Portland cement concrete with a 28-day compressive strength of 35 MPa. The environmental impacts of two concrete mixtures (see **Error! Reference source not found.** for the mix designs) are evaluated to assess the benefits of incorporating Carbonova's CNFs alongside an increased GBFS replacement rate. In the base concrete, 30 wt% of the Portland cement is replaced with GBFS. This mixture contains 260 kg of Portland cement and 120 kg of GBFS per cubic meter, achieving a 28-day compressive strength of 35 MPa without any CNF addition.

In the project concrete, the replacement level of Portland cement with GBFS is increased to 50 wt%, facilitated by the incorporation of 0.6 wt% CNF to offset the reduction in cement content. This mixture includes 190 kg of Portland cement, 190 kg of GBFS, and 2.3 kg of CNFs per cubic meter. CNFs enhance the microstructural properties of the mixture, supporting compressive strength development and enabling the project concrete to achieve the same 28-day compressive strength of 35 MPa as the base concrete. In this case (similar to Scenario 1), the net CO_2 emissions for production of 2.3 kg of CNF would be 6.2 kg CO_2eq (for CNF production energy requirements refer to Scenario 1).

Replacing Portland cement with GBFS significantly reduces the total GHG emission impacts of concrete, given that the global warming potential (GWP) of GBFS is considerably lower than that of Portland cement. GBFS emits approximately 147.0 kg CO_2eq per tonne, as reported by the Environmental Product Declaration (EPD) certified by ASTM International, compared to Portland cement's 765 kg CO_2eq per tonne, as cited by the Cement Association of Canada.

Table 4 - Mix design of the base and project concrete in Scenario 2.

Mixture ID	Component, kg/m^3							
	Portland cement	GBFS	Water	Air entraining agent	Coarse aggregate	Fine aggregate	Superplasticizer	CNF
Base	260	120	160	0.17	930	940	1	–
Project	190	190	160	0.2	930	940	1	2.3

- **GHG emissions calculation for Base (B1) and Project (P4) concrete in Scenario 1**

1. GHG related to Portland cement production for base concrete (B1):

The basis or functional unit for this calculation is 1 m^3 of concrete, which, as noted above, requires 440 kg of Portland cement. It therefore follows that:

GHG emissions of 1 m^3 concrete = Portland cement GWP per kg x mass of Portland cement in concrete

$$765\ \frac{\text{kg CO}_2\text{eq}}{\text{tonne}} \times \frac{1\ \text{tonne}}{1000\ \text{kg}} \times \frac{440\ \text{kg}}{1\ \text{m}^3} = 336.6\ \frac{\text{kg CO}_2\text{eq}}{\text{m}^3_{\text{concrete}}}$$

2. GHG related to Portland cement production for project concrete (P4):

In this case, the addition of 0.6 wt% CNF to the concrete (the project case), reduces the amount of Portland cement required in 1 m^3 of concrete to 380 kg:

$$765\ \frac{\text{kg CO}_2\text{eq}}{\text{tonne}} \times \frac{1\ \text{tonne}}{1000\ \text{kg}} \times \frac{380\ \text{kg}}{1\ \text{m}^3} = 290.7\ \frac{\text{kg CO}_2\text{eq}}{\text{m}^3_{\text{concrete}}}$$

Reducing Portland cement content results in an indirect saving of approximately:

$$336.6 - 290.7 = 45.9 \text{ kg } CO_2eq/m^3 \text{ concrete}$$

When considering both the emissions of CNF production and the indirect emissions saved through cement reduction (**Error! Reference source not found.**), the total savings can reach approximately 39.7 kg CO_2eq per cubic meter of concrete. This represents an estimated 12% reduction in total GHG emissions compared to the base concrete.

Table 5. Projected GHG savings due to addition of 0.6 wt% CNF in concrete according to Scenario 1, kg CO2eq/m^3concrete. Note that a negative value indicates an increase in CO2 emissions associated with electricity consumption from the Alberta grid.

Direct	Indirect	Total
-6.2	45.9	39.7

- **Scenario 1 energy inputs**

In terms of the underlying energy inputs to the project concrete (P4), an EU document prepared by the Politecnico Milano and shared to the CREATE project by Holcim (CEMCAP report, see Methodology section, milestone 2), reports the thermal energy intensity of modern Portland cement production to be approximately 3 MJ/kg cement, mainly used to heat the rotating cement kiln (the kiln is also the major source of CO_2). At 440 kg cement per m^3 concrete, this equates to 1,320 MJ/m3 of concrete:

Thermal energy input = 3 MJ / kg cement x 440 kg cement / m^3 concrete = 1,320 MJ / m^3

On top of this, 97 kWh /tonne of cement in electrical power is also required. The 116 MJ of energy input required to produce the 2.3 kg of CNF in the project is more than offset by the energy reduction associated with the 60 kg reduction (from 440 to 380kg) in required Portland cement:

Energy savings = (440 – 380) kg cement x 3 MJ / kg cement = 180 MJ energy savings

It should be pointed out that incremental energy requirements to mix the CNF into the cement paste will be minimal compared with the overall energy requirements of the concrete production process.

- **GHG emissions calculation for Base (B1) and Project (P4) concrete in Scenario 2**

1. **Base concrete (260 kg Portland cement and 120 kg GBFS):**

$$\textbf{Portland cement: } 765\ \frac{\text{kg CO}_2\text{eq}}{\text{tonne}} \times \frac{1 \text{ tonne}}{1000 \text{ kg}} \times \frac{260 \text{ kg}}{1 \text{ m}^3} = 198.9\ \frac{\text{kg CO}_2\text{eq}}{\text{m}^3_{\text{concrete}}}$$

$$\textbf{GBFS: } 147\ \frac{\text{kg CO}_2\text{eq}}{\text{tonne}} \times \frac{1 \text{ tonne}}{1000 \text{ kg}} \times \frac{120 \text{ kg}}{1 \text{ m}^3} = 17.64\ \frac{\text{kg CO}_2\text{eq}}{\text{m}^3_{\text{concrete}}}$$

$$\textbf{Total: } 198.9 + 17.64 = 216.5\ \frac{\text{kg CO}_2\text{eq}}{\text{m}^3_{\text{concrete}}}$$

2. Project concrete (190 kg Portland cement, 190 kg GBFS, and 0.6 wt% CNF):

$$\textbf{Portland cement: } 765\ \frac{\text{kg CO}_2\text{eq}}{\text{tonne}} \times \frac{1\ \text{tonne}}{1000\ \text{kg}} \times \frac{190\ \text{kg}}{1\ \text{m}^3} = 145.35\ \frac{\text{kg CO}_2\text{eq}}{\text{m}^3_{\text{concrete}}}$$

$$\textbf{GBFS: } 147\ \frac{\text{kg CO}_2\text{eq}}{\text{tonne}} \times \frac{1\ \text{tonne}}{1000\ \text{kg}} \times \frac{190\ \text{kg}}{1\ \text{m}^3} = 27.93\ \frac{\text{kg CO}_2\text{eq}}{\text{m}^3_{\text{concrete}}}$$

$$\textbf{Total: } 145.35 + 27.93 = 173.3\ \frac{\text{kg CO}_2\text{eq}}{\text{m}^3_{\text{concrete}}}$$

- **Scenario 2 GHG emission savings**

Replacing Portland cement by GBFS, combined with the contribution of CNFs, results in an indirect saving of approximately:

$$216.5 – 173.3 = 43.2\ \text{kg CO}_2\text{eq}$$

When considering both the direct emissions from CNF production and the indirect emissions saved through cement reduction (**Error! Reference source not found.**), the total savings can reach approximately 37.0 kg CO_2eq per cubic meter of concrete. This represents an estimated 17% reduction in total GHG emissions compared to the base concrete.

Table 5. Projected GHG savings due to addition of 0.6 wt% CNF in concrete according to Scenario 2, kg CO_2eq/m^3concrete. Note that a negative value indicates an increase in CO2 emissions associated with electricity consumption from the Alberta grid.

Direct	Indirect	Total
-6.2	43.2	37.0

It is important to note that GBFS is widely used in concrete production as a SCM, with global consumption steadily increasing due to its potential to reduce Portland cement usage. Therefore, it becomes crucial to explore the use of alternative low-grade SCMs, such as natural pozzolans, calcined clays, or reclaimed fly ash. Additionally, the synergistic effects of incorporating Carbonova’s CNFs with these low-grade SCMs could unlock new pathways for sustainable concrete production. By enhancing the microstructure and mechanical properties of concrete, CNFs may enable higher replacement levels of Portland cement with these alternative materials, offering a more balanced and impactful approach to reducing the overall carbon footprint of concrete at scale.

- **Scenario 2 Energy Inputs**

The energy reduction associated with less Portland cement usage in Scenario 2 is slightly more than for Scenario 1 and hence the conclusion is the same that the energy required to produce the 2.3 kg CNF is more than offset by the energy savings associated by reduced cement requirement.

The current LCA presented in this report employs a cradle-to-gate boundary, focusing on the environmental impacts of CNF and CNF-enhanced concrete up to the production stage. Carbonova is actively expanding its understanding of the durability of CNF-enhanced concrete to enable future cradle-to-grave or cradle-to-cradle analyses. Preliminary findings suggest that Carbonova's CNFs could enhance concrete durability in harsh conditions, owing to improvements in microstructure and their hydrophobic properties. This durability improvement would represent an additional positive environmental impact of CNFs in concrete products, which can be quantified in future studies. Furthermore, suitability of using demolished CNF-enhanced concrete as recycled aggregate for new concrete production requires further investigation.

- **Air Impacts (Criteria Air Contaminants, CAC)**

Error! Reference source not found. shows the criteria contaminants associated with the production of the 2.3 kg CNF used in 1 m^3 of the project concrete. This table does not include the air emission impacts for the Portland cement production.

Table 6. Criteria contaminants related to the production of 2.3 kg of CNF used in 1 m^3 of concrete based on Solas report.

Impact Areas	Project Condition Impact [kg CAC/m^3 concrete]			
	PM 2.5	NOx	SOx	VOC
P6 – Emissions from Carbonova's auxiliary systems	1.25E-04	1.24E-03	1.03E-05	1.06E-04

Error! Reference source not found. also shows the criteria contaminants related to the production of Portland cement for the amount of cement used in 1 m^3 of base (B1) and project (P4) concrete in Scenario 1. The source of the data in **Error! Reference source not found.** is the 2024 annual data provided on the National Pollutant Release Inventory website for the Exshaw, AB Portland cement plant.

Table 7. Criteria contaminants related to the production of the amount of Portland cement used in base and project concrete (440 and 390 kg/m^3 concrete).

Impact Areas	Project Condition Impact [kg CAC/m^3 concrete]			
	PM 2.5	NOx	SOx	VOC
B1 – Emissions from Portland cement plant	1.95E-3	0.6	0.29	2.58E-03
P4 – Emissions from Portland cement plant	1.73E-3	0.54	0.25	2.29E-03

As can be inferred from comparing **Error! Reference source not found.** and **Error! Reference source not found.**, criteria contaminants related to Portland cement used in 1 m^3 concrete are all at least one order of magnitude higher than the 2.3 kg CNF used in the project concrete. Considering that using CNF results in a reduction in the amount of Portland cement used in concrete, it can be concluded that using CNFs would in fact reduce the criteria contaminants associated with the production of concrete.

The detailed technical analysis presented has synthesized data to show the clear GHG reduction benefits of incorporating Carbonova CNF into Portland cement concrete mixtures. In the two scenarios presented, CNF reduces the amount Portland cement required while maintaining concrete compressive strength and enabling increased usage of lower GHG intensity supplementary cementitious materials such ground blast furnace slag. The incremental energy required to produce the CNF if more than offset by the energy reduction associated with less Portland cement usage.

These findings confirm and reinforce the original premise of the business model and circular economy opportunity proposed by Carbonova whereby a Carbonova plant is co-located at a Portland cement plant to utilize the CO_2 emissions and waste heat from the plant to manufacture CNFs that are then blended into Portland cement concrete products. Analysis of the economics and competitiveness of the Carbonova model is part of Milestone 7 deliverables, discussed further in the next section.

Milestone 7

I. Technology integration

CNFs are highly sought after across various industries due to their exceptional properties, including high specific strength, electrical conductivity, and thermal conductivity. Carbonova's CNFs exhibit outstanding mechanical performance and are produced through an eco-friendly process that utilizes CO_2 and CH4 emissions as raw materials, effectively converting GHGs into valuable products. Moreover, Carbonova's production process is modular, enabling seamless integration with industrial facilities that emit heat and GHGs, such as Portland cement plants.

Reducing CO_2 emissions from cement and concrete production is a critical global challenge that demands innovative solutions. Cement and concrete producers face increasing pressure to adopt sustainable practices and carbon reduction technologies while maintaining the performance and durability of their products. To maintain performance (mainly compressive strength), a high amount of Portland cement is often used in the concrete mix design. Incorporating Carbonova's CNFs into concrete mixtures presents a compelling opportunity to enhance compressive strength development while reducing dependence on Portland cement. For example, should the data observed in mortar be also observed in concrete, an air-entrained concrete mixture with a 28-day compressive strength of 35 MPa that requires 260 kg Portland cement and 120 kg GBFS per cubic meter can be designed with only 190 kg of Portland cement, 190 kg of GBFS (50 wt% replacement), and 2.3 kg of CNF per cubic meter. This innovative mix not only achieves the desired performance metrics but also aligns sustainability goals by significantly lowering cement content.

Integrating Carbonova's CNF production technology with a Portland cement plant, therefore, creates a unique opportunity to address these challenges. By combining cement manufacturing with CNF production, this approach tackles environmental concerns and contributes to a more sustainable and efficient construction industry (as described in Milestone 6). This solution enables significant reductions in the carbon footprint of cement and concrete without compromising industry standards.

Recognizing cement and concrete industry as a high-value opportunity, Carbonova has prioritized collaboration with industry leaders to explore the integration of its CNFs into cementitious materials. To this end, Carbonova partnered with Holcim and Sika to evaluate the technical feasibility and potential benefits of using its material. Holcim and Sika have investigated innovative, high-potential applications of CNFs, aiming to reduce the environmental impact of construction. Research has shown that incorporating carbon-based nanomaterials can enhance the mechanical performance of cementitious matrices, enabling a reduction in Portland cement content in mortar and concrete while maintaining or improving overall strength and durability. These technological insights provide a strong foundation for assessing the techno-economic feasibility and scalability of integrating CNFs into the cement and concrete supply chain.

CO_2 emissions from cement plants are abundantly available and can serve as feedstock for CNF production, provided that the emissions are effectively captured. Moreover, to estimate the potential for heat recovery to support the CNF production process, the conventional cement plant model described in the European project CEMCAP has been utilized. According to this model, the primary source of recoverable heat in a cement plant is the gas flow from the chiller. This gas, composed primarily of 78% N_2 and 21% O_2, flows at a rate of 40 kg/s at a temperature of 285°C.

For a temperature drop of 80°C in a heat exchanger and 40 kg/s flowrate, approximately 3.2 MW of thermal energy could be recovered (using Cp air = 1 kJ/kg°K). Since the maximum temperature available is 285°C, this heat can be used for a preheating step in the Carbonova process, which will have a positive impact on thermal efficiency in Carbonova's process.

As the Carbonova process is still under development, this thermal integration example is presented as a preliminary concept. If integration were to occur, the additional positive environmental impact of utilizing heat from the cement plant could be quantified more precisely and incorporated into the LCA analysis, enhancing the overall assessment of the process's sustainability.

Partnerships with the concrete industry are not only essential for product development but also for scaling production capabilities. By aligning with market demands and maintaining a consistent supply to partners, Carbonova can foster confidence in its solutions. Furthermore, successful product development could encourage the cement and concrete industry to invest in scaling up Carbonova's technology, driven by its dual benefits of solving environmental challenges and enhancing the quality and innovation of concrete products. This could lead to significant breakthroughs in novel concrete applications. Carbonova continues to work with our partners in this program.

We are in discussion around the next steps for product development and evaluation. In addition, Carbonova is working with other partners such as landscape paver manufacturers to help bring more sustainable solutions to their applications. Carbonova has a blend of large, multinationals and smaller, specialty key customers.

Tailoring CNF solutions to specific applications while engaging directly with industry stakeholders increases the likelihood of adoption. Carbonova has completed a screening process on specialty applications within the concrete market. Applications of interest for future work are dry-cast pavers, 3D concrete printing, specialty grouts, eclectically heated concrete panels, and viscosity modifying admixtures.

• LESSONS LEARNED

8.1 CHALLENGES

- **Dispersion Stability:** Maintaining CNF dispersion stability in aqueous solutions remains a challenge, as degradation over time affects performance in cementitious applications.

- **Dispersion of CFNs in Cement Materials:** Ensuring dispersion methods for incorporation of CFNs in cement pastes realize optimal dispersion of fibres to reduce the occurrence of agglomerations and air pockets in the cement matrix, which can contribute to issues with product integrity and mechanical strength.

- **Scaling up production:** While CNFs have demonstrated technical benefits, achieving cost-effective large-scale production is necessary for widespread adoption in the construction industry, and getting costs down from current price $35/kg to the break-even price ~$10/kg.

- **Supply chain and logistics:** Ensuring the timely transportation and storage of CNFs, particularly for international partners, is crucial to maintaining product quality and effectiveness. Alternatively, for future partnership in-place dispersion facilities need to be considered as an alternative method.

- **Market adoption barriers:** Despite environmental and performance benefits, regulatory approvals, industry conservatism, and cost considerations may slow CNF adoption in concrete applications.

- **CFNs remaining in solution under high water content applications:** Shelf-life of the CNF dispersion is important for commercialization in industrial applications.

8.2 PRACTICAL LEARNINGS

The main practical learning during CREATE project was developing business and market strategy in cement and concrete industry. Partnerships with major industry players like Holcim and Sika provided critical market insights. Engaging stakeholders early ensures alignment with industry needs and improves the commercialization pathway.

8.3 ORGANIZATIONAL LEARNINGS

The organizational learnings are in line with practical learnings, explicitly explained in section 8.2.

8.4 HIGHLIGHTS

- Successful CNF production and scale up

- Performance enhancement of cementitious mixtures incorporating CNFs

- Massive GHG emission reduction potential

- Market insights that were developed by working closely with our collaboration partners. The most critical insights were the need for dispersions that have 3-month shelf-life stability and more thorough understanding of the cost drivers.

- Techno-economic analysis and recognizing target price for CNFs

9.0 GHG BENEFITS

Based on the LCA results in Section 7.3, Carbonova estimates reducing 55,000 tCO_2eq/year in direct (CNF production) and indirect (Portland cement replacement) emissions through capturing just 12% of a major cement plant such as Lafarge Exshaw (about 2% of the Portland cement industry in Canada). This amount will be realized as the CNF production as Carbonova increases to 10,000 t/year close to 2030, dedicating only 2,500 tonnes of its annual product to the cement and concrete industry.

Moreover, the GHG reduction could grow with the adoption of eco-friendly methane feedstock in Carbonova's process and capturing higher shares of market through making positive customer references in the cement and concrete industry. To ensure this plan's feasibility, Carbonova is researching alternative SCMs compatible with its CNF product and improving the mechanical performance of cementitious mixtures to enable further Portland cement reductions.

9.1 PROJECT BASELINE EMISSIONS

Please refer to the detailed LCA results presented under Milestone 6.

9.2 PROJECT EMISSIONS

Please refer to the detailed LCA results presented under Milestone 6.

9.3 EMISSIONS REDUCTION IMPACT

Key assumptions:

- 12% market penetration in Alberta (i.e., Carbonova CNFs are utilized in 12% of the Portland cement produced) corresponding to a 55,000 tCO2eq/year reduction in direct (CNF production) and indirect (Portland cement replacement) emissions
- Baseline CO2e emissions correspond to the sum of the 2023 GHG emissions from the two largest cement plants in AB (Lafarge – Exshaw and Heidelberg – Edmonton) as reported at Canadian Environmental Sustainability Indicators - Canada.ca (1,800,000 tonnes per year in 2023)
- Baseline emissions assumed to increase at a rate of 1.5% per year

Using these assumptions, the cumulative reduction in CO2 by 2050 in AB due to incorporation of Carbonova CNF with Portland cement in concrete products will be 1,121,000 tonnes. Carbonova considers this to be a conservative estimate because once the Carbonova technology is commercially demonstrated and de-risked and the benefits of the CNF in concrete begin to accrue at commercial scale, the market pull for the CNF product will increase, leading to even greater benefits accruing in Alberta.

Year	Baseline Emissions @Year (tCO_2e)	Project Emissions @Year (tCO_2e)	Estimated Annual Production (if applicable)*	Unit of Production	Emissions Reduction @Year** (tCO_2e)
2023	1,803,000	0	0	tonnes/yr	0
2024	1,830,045	0	0	tonnes/yr	0
2025	1,857,496	0	0	tonnes/yr	0
2026	1,885,358	0	0	tonnes/yr	0
2027	1,913,638	0	25	tonnes/yr	0
2028	1,942,343	(27,500)	1,025	tonnes/yr	27,500
2029	1,971,478	(27,500)	1,025	tonnes/yr	55,000
2030	2,001,050	(55,000)	1,025	tonnes/yr	110,000
2031-2040	21,739,936	(550,000)	14,025	tonnes/yr	660,000
2041-2050	25,227,762	(550,000)	24,025	tonnes/yr	1,121,000

**CNF production in AB (see table 14.10)*

*** cumulative emissions reduction@ year*

10.0 ENVIRONMENTAL, ECONOMIC, AND SOCIAL IMPACTS

10.1 ENVIRONMENTAL IMPACTS

Please refer to the GHG reductions described in Section 9.

10.2 PROJECTED ECONOMIC IMPACT

Over the course of this project 8 jobs were maintained, and 5 new direct jobs were created. Fabrication of pilot plant equipment was all done locally with the associated economic benefits to those companies contracted by Carbonova to do the work.

The current project was able to achieve scale-up to pilot scale and generate material for customer testing. As we scale up along with our customers, the next logical step on the path to Carbonova's planned commercial rollout will be field or commercial demonstration (i.e., not full commercial scale, but final technology de-risking at a suitable intermediate demonstration scale).

The results of this work provide justification, in Carbonova's opinion, for the next step in Carbonova's commercial rollout plant, specifically a 25 tonne/yr commercial demonstration unit (CDU) to be designed and constructed in Calgary. Pre-FEED has been completed for the CDU and an RFQ was issued for FEED. Carbonova anticipates the CDU will be commissioned in Q3 2026. Twenty-four new direct and indirect jobs will be created, along with 11 maintained jobs, with an additional 19 new direct and indirect non-residential construction jobs for the construction period only — all located in Calgary, Alberta only.

The estimated economic impacts of the CDU project using recently reported 2021 total multipliers include output growth increases at $29.1 million for Alberta; GDP growth of $12.1 million; and labour income increases of $4.4 million. These benefits would result in broadening the tax base and further diversification of the economy in basic chemical manufacturing, advanced manufacturing innovation, and competitiveness in the global marketplace as international uptake of Carbonova technology grows.

10.3 RESULTED INNOVATION CAPACITY

During the CREATE project, Carbonova collaborated with the Civil Engineering Department at the University of Calgary by outsourcing its research program. The research was conducted by two civil engineering interns, both of whom have close ties to Carbonova. Following the project, Carbonova offered a part-time position to one of these interns, who is now developing market entry strategies for cement and concrete materials. This individual also leads R&D efforts focused on advancing innovations in construction materials at Carbonova. Sharing the learnings from the project will aid in innovation through various industries. Carbonova has already presented portions of the work from the project at 3 conferences such as GHG-17 and Canadian Society of Civil Engineers. Carbonova has issued papers in conjunction with the results from the project in Journal of Building Engineering as well as additional publications. See section 4.1 for details.

• 10.4 SOCIAL IMPACT AND EDI OUTCOMES

***Workforce Development and Job Growth for HQPs* -** By integrating circular economy principles and advanced manufacturing technologies, the technology commercialization will create a range of new job opportunities across various skill levels, improving the competitiveness of the Albertan workforce in an evolving global market. During this project Carbonova's workforce increased from 8 to 15 all which had an impact on the project.

***Diversity, Equity, and Inclusion (DEI*) -** Positive impacts on DEI initiatives within the Alberta basic chemical manufacturing sector would be realized. Carbonova is led by Dr. Mina Zarabian, a woman, engineer, and immigrant to Canada, who is an inspiring role model in SME leadership. Approximately, 1/3 of Carbonova's workforce is female. In addition to its Canadian workforce, Carbonova has a workforce which is comprised of employees with a place of origin being Iran, Sri Lanka, America, and India. An inclusive environment and diverse hiring practices would set a precedent for inclusivity and creating a more equitable, dynamic sector.

***Health and Safety* -** Advanced CNF composites would enhance the durability and performance of products across a variety of industries, increasing service life, reducing failure rates, minimizing accident risk, and improving overall operations, safer industrial practices, and environmental health.

***Industry Knowledge* -** It is expected that Carbonova's CNF product will outperform carbon black and competitors' CNF on cost and carbon footprint, while exhibiting similar performance compared with carbon nanotubes (CNT).

***Strengthening Chemical Manufacturing in Alberta* -** The project would introduce innovative materials that advance chemical technologies through utilization of captured industrial CO_2, driving the development of tailored solutions, enhancing market position, and setting new industry standards that establish Alberta leadership in sustainable practices, assuring environmental goals would be achieved, while driving economic growth and innovation.

11.0 SCIENTIFIC ACHIEVEMENTS

The following are some novel scientific findings during CREATE project:

- Dispersion of CNFs in cementitious mixtures was analyzed through analyzing SEM images of fresh cement pastes incorporating Carbonova CNFs. This was among the first instances where positioning of CNFs on cement particles was observed. This analysis, together with rheology assessment of cementitious mixtures led to further understanding the interaction of Portland cement phases with CNFs.

- Previous research focused on the hydration kinetics of cementitious mixtures incorporating CNFs was inconclusive, some stating CNFs would result in acceleration and others indicating it would lead to deceleration of hydration reactions. Our studies clearly indicated that CNFs lead to acceleration while the dispersant used for dispersing them results in retardation of hydration reactions. The extent to which CNF dispersions results in acceleration or deceleration depends on the relative amount of CNFs compared to the dispersant, and the surface adsorption capability of CNFs.

- CNFs resulted in improved compressive strength at early and late ages. Our studies indicated that this could effectively increase the substitution level of Portland cement with different SCMs. Carbonova is currently undertaking further research to find the best combination of CNFs and SCMs for Portland cement replacement and further reduction of GHG emissions associated with concrete production.

This project has also resulted in several conference presentations and three publications in scientific journal articles or conference proceedings. These are listed in the Communications Plan section of this report and discussed in the Innovation Capacity section previously

12.0 POST-PROJECT STEPS

12.1 NEXT STEPS AND FOLLOW-UP PROJECTS

Carbonova's path forward in the construction market is focused on several key customers.

- Cement Company #1 – An NDA has been signed with the Cement Company #1's Innovation Hub. It is one of the key Centers for Excellence and Innovation within the parent company. The use of SCM for sustainability improvement is just one key area Cement Company #1 has interest in working with Carbonova. Also, discussions have begun around the key specialty areas identified by Carbonova. The impact of Carbonova's CNF on set time is of interest in the use of 3D printing.

- Cement Company #2 – Cement Company #2 has reengaged post the CREATE project work. Their interests are aligned with the specialty applications identified by Carbonova as target applications in the construction sector. Scope of Work details are now being drafted between the organizations.

- Cement Company #3 – Although Cement Company #3 exited the CREATE project mid-way, work has continued between the Carbonova and Cement Company #3. Proprietary work with CNFs for other Cement Company #3 materials in the construction market is on-going.

- Paver Company #1 is a BC-based manufacturer of dry cast landscape pavers. We have an NDA in place with Paver Company #1 and sampling of CNFs to Paver Company #1 has begun.

- NDAs have been signed with several other ready mix and concrete producers. Project work is being scoped with these customers. This was all achieved due to the results generated by this CREATE program.

12.2 PARTNERSHIPS

Please see preceding section.

13.0 OVERALL CONCLUSIONS

The CREATE project has demonstrated the feasibility and benefits of Carbonova's carbon nanofibers (CNFs) for enhancing the sustainability and performance of cementitious materials. Over the course of the project, key milestones were achieved in developing CNF production, optimizing dispersion techniques, and assessing the environmental impact of CNF incorporation in concrete. The research findings confirm that CNFs can improve the mechanical properties of cementitious mixtures, allowing for a reduction in Portland cement content without compromising structural integrity. This advancement presents a significant opportunity to reduce greenhouse gas (GHG) emissions in the concrete industry.

The integration of Carbonova's CNF technology with the cement industry was explored through experimental work and techno-economic assessments. Results indicate that CNFs contribute to increased compressive strength and improved microstructural properties in cementitious matrices, which can support the adoption of higher supplementary cementitious material (SCM) replacement rates. This shift has the potential to significantly decrease the carbon footprint of concrete production, aligning with industry goals for emissions reduction.

The project also identified challenges, particularly in the dispersion stability of CNFs in aqueous solutions. Further research and industrial collaborations are required to refine dispersion methods to ensure long-term stability and ease of use in concrete applications. Additionally, while preliminary life cycle assessments (LCA) suggest that the environmental benefits of CNF-enhanced concrete outweigh the energy inputs for CNF production, additional cradle-to-grave studies are necessary to fully quantify the long-term impacts.

Collaboration with major industry partners such as Holcim and Sika provided valuable insights into market needs and application strategies. Carbonova's engagement with these stakeholders has helped lay the foundation for future partnerships and commercialization pathways. The economic feasibility of scaling CNF production was assessed, indicating that cost reductions through production scaling will be critical for widespread industry adoption.

Moving forward, Carbonova will continue to explore partnerships for co-developing novel solutions in construction materials as identified in 12.1 above. Efforts will focus on further optimization of CNF formulations, developing scalable manufacturing processes, and conducting additional field trials. The successful outcomes of CREATE reinforce Carbonova's potential to contribute to a low-carbon future by transforming industrial CO2 emissions into high-value materials that enhance the durability and sustainability of infrastructure.

14.0 COMMERCIALIZATION AND TECHNOLOGY TRANSFER PLAN

14.1 PROJECT COMMERCIALIZATION ADVANCEMENTS

Carbonova is planning its first-of-a-kind commercial demonstration unit (CDU) to be sited in Calgary. To date, the company has completed the pre-FEED study in collaboration with a local EPC firm. The current plan is to launch FEED in Q2 2025 with a final investment decision in Q3 at which point construction of the CDU will begin. Commissioning and start-up of the CDU is presently estimated for Q2 2026.

Following successful completion of the CDU project, Carbonova will immediately move into the design and construction of its first commercial unit, a 1000 tonne/yr CNF plant located in Alberta. Based on the results of the CREATE project, co-location of that plant at a cement production facility could be very attractive due to the ample supply of CO2 and waste heat in combination with the circular economic and GHG abatement benefits for the operator of the cement plant.

14.2 PROJECT TECHNOLOGY ADVANCEMENTS

Carbonova's core technology is its carbonization reactor, which takes the synthesis gas (a combination of carbon monoxide and hydrogen) product from the dry methane reforming reactor and converts it to solid carbon product. Over the course of this project, our pilot scale carbonization reactor was successfully scaled by doubling its diameter. As a result, production from the pilot increased by a factor of 4, allowing Carbonova to produce larger volumes of our nanofiber product for testing by customers and partners, including Holcim, Sika, and the U of Calgary as part of the CREATE project.

This advancement in technology and production has led to a rapid expansion of our customer pipeline. This growth in the customer pipeline is critically important to small-to-medium enterprise like Carbonova as we go to market to seek the next round of investment in the company.

14.3 PROJECT TRL ADVANCEMENTS

Over the course of the CREATE project, the technology has advanced from TRL 5 to TLR6 based on the AB Innovates definition, i.e., system/subsystem model or prototype demonstration in a simulated environment. Once the above-mentioned CDU project is complete in 2026, Carbonova's technology will be at TRL8 (actual technology completed and qualified through tests and demonstrations) and ready for commercial deployment in accordance with Carbonova's commercial rollout plan.

14.4 MARKET AND END-USERS

Due to regulatory constraints, technical challenges in CNF dispersion, and the current production method at Carbonova, a revised approach will be adopted moving forward.

Figure 14 illustrates the relationship between a co-located Carbonova CNF plant, a cement plant, concrete batching plants, and end users of the concrete. The CREATE project primarily focused on developing CNF for blended cement products intended for concrete production.

In this revised model, CNF dispersions will be prepared at Carbonova plants co-located with cement plants and then separately transported to concrete batching plants for use in specialty applications requiring CNFs. This strategy ensures that CNFs remain a low-dose additive in concrete, minimizing regulatory hurdles while providing greater flexibility in targeting high-value specialty applications. The wasted heat and CO_2 emissions of cement production will still be used in production of CNFs.

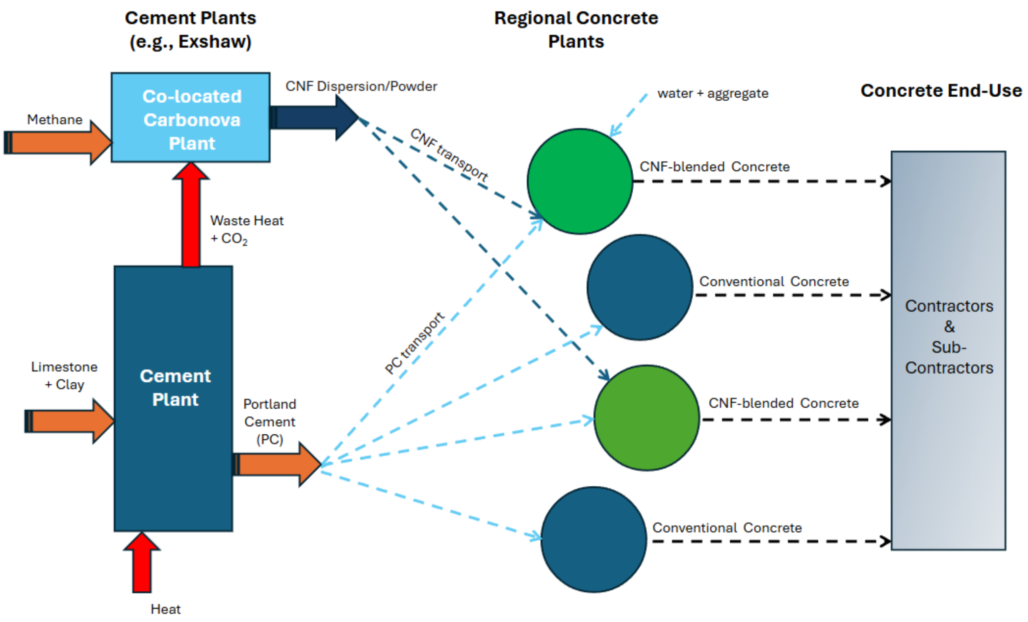

Figure 14 - Relation between cement plant, Carbonova's CNF plant, concrete batching plant and the end users of concrete.

14.5 TECHNOLOGY PROTECTION

Carbonova's Intellectual Property (IP) strategy involves a combination of patents, trade secrets and know-how that protects our freedom to operate and our competitive advantage. Carbonova's process to produce carbon nanofibers from CO2 and methane and the core carbonization reactor technology have both been patented. The former is the subject of WO2020154799A1 ("Apparatus and Method for Producing Carbon Nanofibers from Light Hydrocarbons"), granted in Canada and Japan and under examination in several other countries. The latter is the subject of WO2023197077A1 ("A Reactor for Converting Gaseous Carbon-containing Reactants to Solid Carbon Product and Associated Methods"), currently under examination.

15.0 COMMUNICATIONS PLAN

15.1 KNOWLEDGE SHARING DURING PROJECT

Conference Presentations:

- Annual presentation at the ACT3 Knowledge Sharing workshop, held in September each year of the project.
- Teymouri, A. Haji Hossein, R. Khoshnazar, Early-age Properties of Cement Pastes Incorporating Aqueous Dispersions of Carbon Nanofibers, presented at the Canadian Society for Civil Engineers (CSCE) Annual Conf. Moncton, N.B., May 24-27, 2023.
- M. Zarabian, T. Pugsley, M. Bianchini, H.J. Guzman, The Carbonova Process: Utilizing Captured Industrial CO2 by Conversion into Valuable Advanced Carbon Nanomaterials, presented at GHGT-17, Calgary, AB, October 20-24, 2024.

Publications in Scientific Journal Articles and Conference Proceedings:

- Zarabian, Mina and Pugsley, Todd and Bianchini, Michael and Guzman, Hector J., The Carbonova Process: Utilizing Captured Industrial CO2 by Conversion into Valuable Advanced Carbon Nanomaterials (December 17, 2024). Proceedings of the 17th Greenhouse Gas Control Technologies Conference (GHGT-17) 20-24 October 2024, Available at SSRN: https://ssrn.com/abstract=5063644 or http://dx.doi.org/10.2139/ssrn.5063644.

- Teymouri, A. Haji Hossein, A**.** Khoshnazar, R. (2023) A Review on Carbon Nanofiber Production and Application in Cementitious Mixtures, *Journal of Building Engineering*, 84, 108519. https://doi.org/10.1016/j.jobe.2024.108519

- Haji Hossein, A. Mostafa, M.M. Teymouri, A. Guzman, H.J. Khoshnazar, R., Pugsley, T. (TBD) Rheological Properties and Early-age Hydration of Cement Paste Incorporating Pristine and Pre-dispersed Carbon Nanofibers, submitted to ACS Applied Nano Materials.

16.0 LITERATURE REVIEWED

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17.0 DEFINITIONS

Definitions

- **PCE:** Polycarboxylate ether, a polymer-based concrete high-range water reducer (Type F) and a CNF-compatible dispersant
- **Cement paste:** a mixture of Portland cement, SCMs, admixtures and water.
- **Cement mortar:** a mixture of Portland cement, SCMs, admixtures, water, and sand.
- **Concrete:** a mixture of Portland cement, SCMs, admixtures, water, sand, and gravel.

Table of Acronyms

Acronym	Full Name
CNF	Carbon nanofiber
CCU	Carbon capture and utilization
CDU	Commercial demonstration unit
GHG	Greenhouse gas
LCA	Life cycle assessment
SCM	Supplementary cementitious materials
UHPC	Ultra-high-performance concrete
w/c	Water-to-cement ratio