CCUS by processing globally abundant magnesium silicate minerals into cements and other construction materials – Year 2 report

CCUS Innovation 2.0

Key Knowledge Deliverable 6.2

Summary

This report summarises the work completed, including key results and deliverables. The next stages of development and the route to commercial revenue generation are also outlined. This CCUS technology uses olivine, a globally abundant magnesium silicate mineral. This is processed to form the magnesium carbonate mineral nesquehonite and an amorphous precipitated silica (APS) using a chemical digestion process. The APS forms a supplementary cementitious material (SCM) for use in low-carbon concrete. The nesquehonite is produced by a carbonation process that can use flue gases from industrial processes. This permanently sequesters CO_2, and the nesquehonite can be further processed to form hydromagnesite. This transformation produces materials that can replace various carbon intensive construction products, such as bricks, blocks and gypsum boards. The final stage in the process is to regenerate the reagents to digest the olivine, so the process is circular and does not produce any wastes. The CCUS Innovation 2.0 project has increased technological and commercial readiness of the technology, by de-risking the development of a future pilot facility, which is the next stage in commercial development.

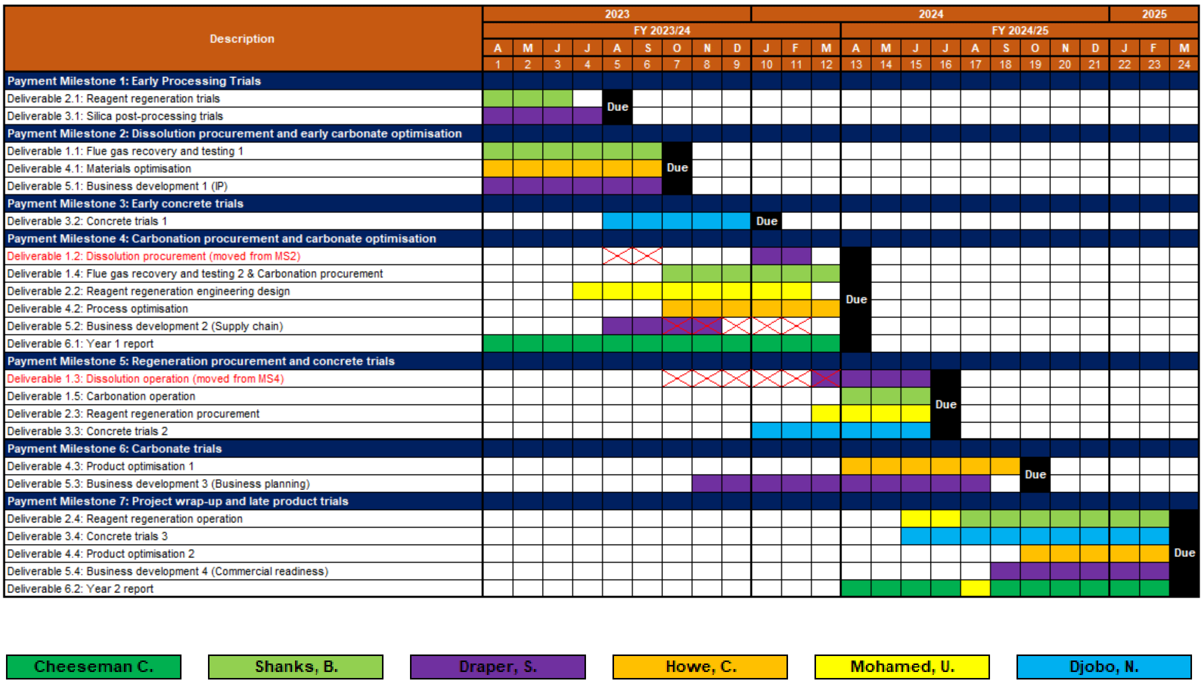
The new carbon capture utilisation and storage (CCUS) process developed is unique, because it captures CO_2 emissions directly from industrial sources, while also producing valuable low-carbon construction products. The results show that the process has significant potential to produce an effective and commercially viable silica supplementary cementitious material and hydromagnesite bound bricks, blocks and boards. The outcomes of technical work packages have directly fed into ongoing business development.

The funding provided by the NZIP Portfolio has allowed research to be completed in a well-equipped university laboratory and removed the need for an early pre-seed round, which would have been challenging to raise. By conducting extensive commercial development work throughout the two years of the project, the technology is much better placed, with stronger product-market fit. The spin-out, Seratech, and its founders, have built a strong network of potential suppliers, customers and other partners from the project.

1. Process overview

The Seratech CCUS technology uses olivine, a globally abundant magnesium silicate mineral. This is processed to form magnesium and silica using a chemical digestion. The amorphous silica is used as a supplementary cementitious material (SCM) in low-carbon concrete. The concentrated magnesium solution produced, is carbonated with flue gases from industrial processes. This permanently sequesters CO_2 by forming the magnesium carbonate mineral nesquehonite. This can be further processed to hydromagnesite and this produces materials that can replace various carbon intensive construction products, such as bricks, blocks, and gypsum boards. The final stage in the process is to regenerate the reagents used to digest the olivine, so the process is circular and does not produce any wastes. The aim of this CCUS Innovation 2.0 project is to increase technological and commercial readiness, by de-risking the development of a future pilot facility. The project GANTT chart shown in Table 1 gives an overview of the project structure. Summary results from the deliverables forms the content of this report.

Table 1. GANTT chart showing the programme of work and deliverables from the project.



Description	2023									2024												2025		
	FY 2023/24												FY 2024/25											
	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Payment Milestone 1: Early Processing Trials																								
Deliverable 2.1: Reagent regeneration trials					Due																			
Deliverable 3.1: Silica post-processing trials																								
Payment Milestone 2: Dissolution procurement and early carbonate optimisation																								
Deliverable 1.1: Flue gas recovery and testing 1																								
Deliverable 4.1: Materials optimisation							Due																	
Deliverable 5.1: Business development 1 (IP)																								
Payment Milestone 3: Early concrete trials																								
Deliverable 3.2: Concrete trials 1										Due														
Payment Milestone 4: Carbonation procurement and carbonate optimisation																								
Deliverable 1.2: Dissolution procurement (moved from MS2)																								
Deliverable 1.4: Flue gas recovery and testing 2 & Carbonation procurement																								
Deliverable 2.2: Reagent regeneration engineering design													Due											
Deliverable 4.2: Process optimisation																								
Deliverable 5.2: Business development 2 (Supply chain)																								
Deliverable 6.1: Year 1 report																								
Payment Milestone 5: Regeneration procurement and concrete trials																								
Deliverable 1.3: Dissolution operation (moved from MS4)																								
Deliverable 1.5: Carbonation operation																Due								
Deliverable 2.3: Reagent regeneration procurement																								
Deliverable 3.3: Concrete trials 2																								
Payment Milestone 6: Carbonate trials																								
Deliverable 4.3: Product optimisation 1																			Due					
Deliverable 5.3: Business development 3 (Business planning)																								
Payment Milestone 7: Project wrap-up and late product trials																								
Deliverable 2.4: Reagent regeneration operation																								
Deliverable 3.4: Concrete trials 3																								
Deliverable 4.4: Product optimisation 2																								Due
Deliverable 5.4: Business development 4 (Commercial readiness)																								
Deliverable 6.2: Year 2 report																								

2. Work completed and key results from technical deliverables

2.1 Process related research and results

Process overview

The flow diagram in Figure 1 shows the carbon mineralisation process. A proprietary “catalyst” is dissolved in water. This releases H^+ ions, reducing the pH. The olivine reacts with the H^+ ions in an acid-base reaction, dissociating into Mg and Fe sulphates, while forming a solid insoluble ”spent catalyst”, an amorphous aqueous silica, and an alkali sulphate. This mix is then filtered to separate the spent catalyst. The remaining solution is transferred to a mixing tank where the pH is increased by adding an alkaline solution. This results in the aqueous silica and iron sulphate precipitating to produce silica gel and iron hydroxide, which are separated in a filtration unit. The magnesium sulphate solution goes through a carbonation stage by bubbling flue gas/CO_2 and adding more alkaline solution to produce nesquehonite. The alkaline solution is constantly added to maintain the optimum pH for nesquehonite formation. The nesquehonite is then filtered while the alkali sulfate rich solution is crystallised to form solid alkali sulfate. These crystals and the spent catalyst are calcined at 380°C to regenerate the catalyst, which is fed back into the agitated batch reactor to start the cycle again. The steam and alkaline gas formed are mixed with water to regenerate the alkaline solution.

Detailed mass, energy and CO_2 balance studies have been completed to understand the effect of altering the yields of the main units on the process. Pinch analysis has also completed to reduce energy demand. This involved determining achievable energy goals through thermodynamic principles and optimizing heat recovery systems, energy delivery methods, and operational parameters to meet these targets.

Techno-economic analysis showed that the total energy consumption of the process is 1070 kWh, per tonne of CO_2 sequestered. The emissions from the process mean that for every tonne of CO_2 sequestered, approximately 140 kg of CO_2 is produced. Using an energy price of 4.4p per kWh for gas, and 11.0p per kWh for electricity, processing one tonne of flue gas CO_2 costs £196.02 and potentially generates £516.44 in revenue. This equates to an EBITDA of £235.31 once the license fee and fixed costs are accounted for. This margin of 45.6% is significantly higher than the target minimum of 35% to justify the capital expenditure.

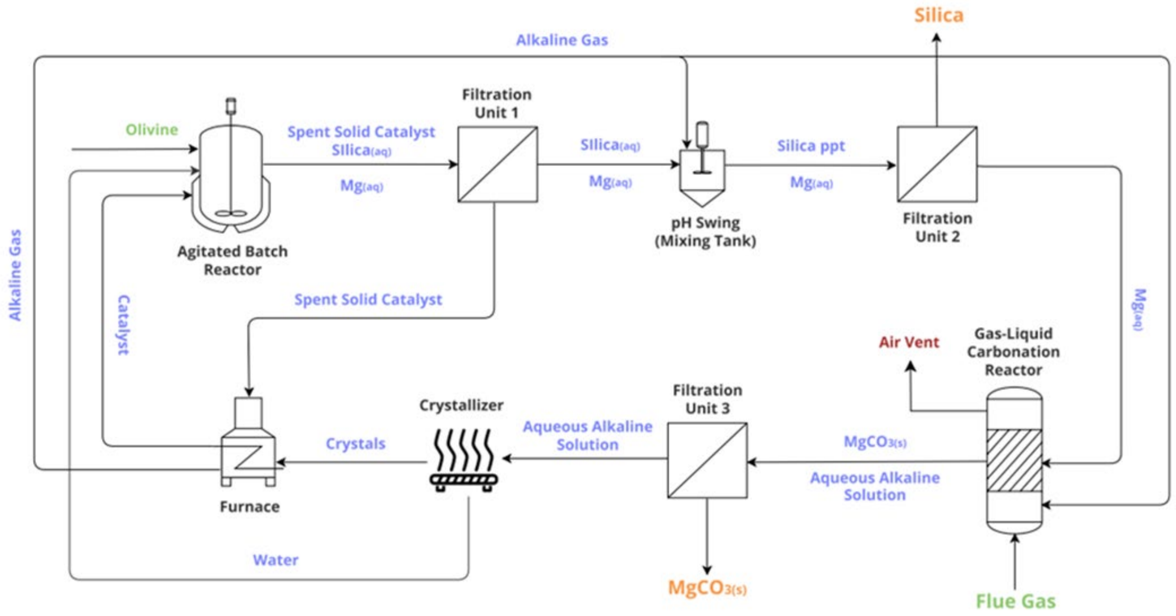


Figure 1. Schematic diagram of the olivine acid digestion and carbonation process

This work has demonstrated that the process is viable provided the overall energy consumption is below 1400 kWh per tonne of CO_2. However, this requires a 50:50 balance of energy from gas and electricity. If the process requires less than 1100 kWh per tonne of CO_2 processed, it is viable running entirely on renewable electricity.

Flue gas recovery and testing

Carbonation in the Seratech process is a liquid-gas reaction between activated Mg and the CO_2 present in a flue gas. The activated Mg solution can contain residual Fe. This does not influence the rate of CO_2 sequestration and does not change the type of magnesium carbonate ($MgCO_3$) formed. The $MgCO_3$ product has properties independent of the Fe content in the starting olivine.

Four gas compositions were used in laboratory scale trials. These were compressed air, pure CO_2, and two simulated flue gas streams. The rate at which CO_2 mineralises is determined by the rate CO_2 dissolves in the Mg solution. Carbonation has been investigated at three different CO_2 concentrations, 0.4, 15 and 100%. Trials using 0.4% (400 ppm, atmospheric concentration) did not produce any precipitation after 10 days of carbonation. Further research therefore focussed on using pure CO_2 and simulated flue gases. The rate of carbon mineralisation has been investigated at different magnesium concentrations. The concentrations studied were 0.1, 0.2, 0.3, 0.4 and 0.5 mol/L and pure CO_2 was used in these studies. Increasing the concentration of Mg in the solution increased the carbonation rate. At high concentrations the amount of precipitate formed thickens the slurry and reduces efficiency, reducing carbonation. Initial rate measurements for a 2.0 M Mg solution gave a value of 158 kg/m^3/hr, and this is ~ 50 times the rate of sequestration in direct air capture, for a given volume. The observation that the capture efficiency is unaffected by the concentration of the CO_2 suggests that utilising multiple passes would capture significant proportions of CO_2. These numbers represent sub-optimised equipment with no pressurisation.

The magnesium carbonate produced has been characterised. The chemical species present in the flue gas do not have a direct impact on the morphology of the carbonate produced. Carbonate particles from simulated flue gas are consistently larger, owing to a longer reaction time. Slower growth crystals are larger, and a long residence time allows for mechanisms such as Ostwald ripening to coarsen particles. X-ray diffraction showed that despite high concentration of SOx and NOx in the simulated flue gas, the only insoluble phase present in the carbonate product was the magnesium carbonate nesquehonite. Magnesium sulphate salts are present due to partially incomplete reactions, and alkali sulphate can precipitate out of solution by drying. However, both are easily removed by washing.

Dissolution equipment procurement and operation

The dissolution stage in the process uses acids to digest olivine, releasing Mg and silica. The activated Mg solution can contain residual Fe. Co-precipitation of Fe and silica produces the silica supplementary cementitious material (SCM). Research has specified and obtained the equipment required to operate dissolution and separation at increased scale. Additionally, preliminary work was conducted to ensure that the reaction products are of appropriate purity and reaction efficiencies are acceptable at increased volumes.

Operating dissolution at increased volumes appeared to take longer than at lower volumes. The increased size of the glass beaker and an insufficiently powered hotplate may have caused a decrease in temperature and therefore reaction rate. Additionally, dissolution using a commercial version of the catalyst was slower than using the catalyst material and the reaction was stopped after three and a half hours. After dissolution is complete, the solid spent catalyst crystals are removed by filtration. The supernatant contains the $(Mg,Fe)SO_4$ and silica species.

Flue gas recovery and carbonation

A cylindrical continuous carbonation reactor has been developed. This allows 3L of $MgSO_4$ solution to react with different CO_2 containing gases. To start the experiment, alkali solution and $MgSO_4$ pumps are switched on while simultaneously opening the exit and inlet gas flowrate valves. As the first residence time passes the exit flow was collected and disposed of because the exit stream had a variable output flow residence time. The first residence time batch was used to achieve a continuous equilibrium, with the exit flow having the same residence time. Samples were taken at different intervals to see the effect of residence time on conversion. Samples were taken from 5 holes on top of the reactor during the second residence time. The inlet and outlet flows were stopped after the second residence time. The samples collected were filtered using a syringe filter and diluted by a factor of 10. The solution collected in the beaker for the duration of the second residence time was then left for an hour in the beaker before being vacuum filtered, dried at 60*C and in a furnace. The filter cake is then weighed and characterized using XRD, TG and SEM. Titration tests were conducted to estimate how much magnesium ion is in the solution to estimate the conversion at different residence times.

In the carbon sequestration part of the process, CO_2 is permanently sequestered in the mineral nesquehonite ($MgCO_3.3H_2O$). This can be used to form bricks, blocks and board products.

These have potential to replace more carbon intensive construction products, such as concrete bricks, concrete blocks, and gypsum boards.

There have been several studies that have investigated CO_2 sequestration via carbonation by bubbling CO_2 through $Mg(OH)_2$ solutions. This work has investigated carbonation of the $MgSO_4$ solution produced in this process. The overall carbonation reaction is:

$MgSO_4 + CO_2$ + alkaline solution + $2\ H_2O \rightarrow MgCO_3.3H_2O$ + alkali sulfate

A series of experiments have been completed to investigate key variables that influence this reaction. These are the effect of pH, CO_2 and alkaline solution injection periods, and the stoichiometric alkaline solution/$MgSO_4$ ratio. The aim was to optimise the production of the magnesium carbonate mineral nesquehonite ($MgCO_3{\cdot}3H_2O$).

The optimal pH for the reaction was found to be 9.5. A 15-minute injection period to a 0.2 M $MgSO_4$ solution resulted in rapid supersaturation and efficient nucleation. Increasing in $MgSO_4$ concentration from 0.2 M to 0.5 M improved the percentage completion of the reaction.

Adjusting the alkaline solution /$MgSO_4$ ratio influenced both the reaction rate and product morphology. Using excess alkaline solution resulted in higher reaction completion rate but this introduced challenges during subsequent process stages. The highest percentage completion was 97.1%.

Experiments using an experimental $MgSO_4$ solution derived from chemical digestion of olivine resulted in reduced carbonation efficiency. This was because of interference from other ions present in the solution. XRD and SEM analyses confirmed the formation of some sodium carbonate rather than nesquehonite, indicating that impurities can significantly influence the carbonation reaction. Previous steps in the process need to be optimized to prevent disruption of the carbonation process for maximum efficiency.

The work completed highlighted the importance of controlling pH, the CO_2 injection period, and the reactant ratios to produce effective CO_2 sequestration using $MgSO_4$ solutions.

Reagent regeneration

The reagent regeneration is where the catalyst used in the process is regenerated so it can be reused in the batch reactor to react with more olivine. This consists of two stages. Crystallization separates the dissolved alkali sulfate from the solution and forms solid crystals. The second stage reacts alkali sulfate crystals with the spent catalyst. Two different methods have been used for the crystallization process. The first was evaporative crystallization in which the pressure of the solution was reduced to ~100 mbar. This reduces the boiling temperature of water to ~50°C. An alternative method used anti-solvent crystallization. The antisolvent was mixed with alkali sulfate solution. This reduces the solubility, leading to supersaturation and subsequent crystallization of alkali sulfate.

Evaporative crystallization used a rotary evaporator. The process was run for 6 hours, but very little water was evaporated. This was because of the high solvation energy of the alkali sulfate solution. The results showed that as the amount of anti-solvent increased, more alkali sulfate crystals were recovered. The highest recovery rate was 99%. However, this is associated with increased energy to recover the anti-solvent.

Process optimisation

Work has integrated the process stages optimized in previous deliverables. Key stages involve dissolution, pH swing, carbonation, crystallization and regeneration. This has provided a deeper understanding of the issues involved in process integration and operation, and this will facilitate future scale-up to a pilot plant facility. Understanding potential problems will reduce risks and ensure an effective transition to larger-scale production.

Two sets of cycles were conducted of the entire process. Learning outcomes were gained from the first set of cycles, and these were used to optimize the process in a second set of cycles. After analyzing several cycles of dissolution, pH swing, carbonation, and crystallization, important process optimization requirements were identified.

There is an optimum time for the dissolution reaction that is required to minimize the buildup of olivine. Excessive reaction time also results in silica gelling with spent catalyst and this needs to be avoided. A filtration unit is required after dissolving the catalyst. This is crucial for removing solid impurities that can inhibit the olivine reaction. Washing the silica SCM prevents the loss of residual magnesium and sulfate ions. Using twice the stoichiometric alkaline solution requirement during carbonation enhances the process efficiency. Washing the silica increases the nesquehonite yield and improves the carbonation efficiency by reducing the formation of other sulfate phases in the final product. Using a ball mill to reduce the particle size of the spent catalyst and alkali sulfate mixture improves the regeneration stage. Implementing these key processing changes in a second optimisation trial resulted in increased production efficiencies and yield and are key learning outcomes that will be implemented in subsequent pilot plant design and operation.

1.2. Amorphous precipitated silica (APS) and hydromagnesite product development and testing

a) Amorphous precipitated silica (APS) performance as a supplementary cementitious material (SCM)

Research has investigated the effect of a range of thermal, mechanical, and chemical treatments on the as-produced amorphous precipitated silica (APS) SCM, with the aim of controlling mix rheology, reaction kinetics, and to provide basic indicators of the performance in concrete. The workability of composite cements containing the APS SCM was significantly reduced compared to the control CEM I system. Superplasticisers can be used to compensate this effect.

X-ray diffraction of composite binders showed that there is significant consumption of portlandite, an indicator of pozzolanic activity. The composite APS SCM binders had increased compressive strengths compared to CEM I, indicating the pozzolanic effect of the APS. Replacement levels of up to 40% APS SCM are viable, and these samples had high compressive strengths. Thermal treatment of the APS SCM also improves the reactivity exhibited in the R3 pozzolanicity test by ~150%. Both air cooling and water quenching are effective in thermally activating the APS SCM. Air cooling is likely to be preferable from an energy perspective.

The Seratech process can produce APS SCMs with different purity levels, depending on the raw materials used. Work has assessed the inherent characteristics of high- and low-grade APS samples. The performance of the resulting concretes was benchmarked against Portland cement concrete and blended cement concrete containing coal fly ash, a conventional widely used SCM.

The work demonstrated that the APS SCM has higher pozzolanic activity than fly ash. This high reactivity causes rapid sulfate depletion, and this inhibits dissolution of the silicate phase, tricalcium silicate (C_3S), adversely influencing the setting behaviour of paste samples. High-grade APS is more reactive than low-grade APS, and the lower compressive strengths observed were due to problems with mixing the APS, rather than reduced reactivity.

Research has investigated how the APS produced from the acid digestion of olivine can be used as a supplementary cementitious material (SCM) in concrete. Cement was replaced with up to 40 wt.% of the olivine-derived APS. The gypsum addition was adjusted to improve performance. The work investigated how APS reacts with cement phases, and how this influenced concrete strength.

The results showed that olivine derived APS is highly reactive. It reacts rapidly in a blended cement system. It has high surface area, and this accelerates concrete setting and significantly increases concrete strength. Compressive strengths of concrete containing APS were >50 MPa after 90 days. This is marginally lower than normal concrete. However, it was found that adding a small amount of gypsum (up to 3-4 wt.%) improved the early strength. The high specific surface area of APS increases the water demand of blended cements and concrete. A maximum water-to-cement ratio of 0.63 could be used without affecting the compressive strength of blended cement mortars. This was for a 20 wt.% cement replacement. At higher cement replacement the concrete strength was significantly reduced.

The work has demonstrated that APS derived from olivine is a promising SCM for use in concrete. This can have comparable performance to normal concrete, but with significantly reduced embodied carbon. The gypsum content in the concrete containing APS needs to be adjusted for optimum performance. The high surface area of APS also influences the water demand and this needs to be controlled.

The durability of concrete incorporating APS) derived from olivine has been investigated. Four concrete mixes were prepared including a control mix made of normal concrete (CO), a fly ash-blended mix (CFA), a blended APS concrete mix (C20), and a ternary blend with APS and limestone (CLS). The mixes were tested for workability, compressive strength, water absorption, sorptivity, electrical resistivity, chloride permeability and carbonation.

The results showed that APS improves the durability of concrete, by reducing permeability and enhancing the pore structure. Although APS-containing mixes exhibit lower initial slump, they have comparable or superior long-term performance. APS-based concrete (C20) had similar compressive strength to normal concrete, with improved durability related properties such as low water absorption and higher electrical resistivity, indicating reduced pore connectivity. The CLS mix also showed enhanced durability, though this was slightly less than C20. The study demonstrated that the APS derived from olivine is a promising SCM for producing durable, low-carbon concrete, that is suitable for general construction. External characterisation, testing and validation of the APS as an SCM as originally intended was not possible within this research project. This was because of the limited capacity to produce APS in a laboratory and the larger quantities than expected that are required for complete commercial SCM testing.

b) Hydromagnesite bound construction products

Olivine ($(Fe,Mg)_2.SiO_4$) can contain both Fe and Mg. There is scope for the iron to be removed if necessary. Different iron removal methods were investigated and the impact of Fe on the magnesium carbonate products formed was evaluated. It was found that the presence of Fe at the levels found did not influence the use of the magnesium carbonates produced for use in construction products, either chemically or physically.

Nesquehonite ($MgCO_3.3H_2O$) is the metastable form magnesium carbonate produced in the Seratech process. The nesquehonite produced must remain stable until it is used. When water is added the phase transformation from nesquehonite to hydromagnesite ($Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$) occurs and this produces a strength gain within the construction products. Therefore, it is important to control the stability of powdered nesquehonite.

There is also potential to mitigate the CO_2 release that occurs during the nesquehonite to hydromagnesite phase transformation using a small percentage of alternate binders and this was also investigated. It was found that removal of the Fe was essential to maintain nesquehonite reactivity, although higher Fe contents did seem to produce improved magnesium carbonate products. The inclusion of additional binders in the nesquehonite at low percentages, such as CaO, MgO and $Ca(OH)_2$ allows CO_2 released in the phase transformation to be sequestered.

The workability of the nesquehonite needs to be optimised to reduce the water demand. Ball milling was used to change the specific surface area and particle size. In addition, the reaction conditions were changed to alter nesquehonite particle size and morphology. It was found that milling, even with the use of stearic acid as a milling aid, had no significant impact on the workability of the magnesium carbonate.

The carbon mineralisation process produces metastable nesquehonite, ($MgCO_3.3H_2O$). Over time, nesquehonite decays to hydromagnesite, ($Mg_5(CO_3)_4(OH_2).4H_2O$) through a dissolution and reprecipitation reaction. This transition can be accelerated through the addition of water and elevating the temperature to ~60 °C. The morphological changes that accompany this transition are responsible for the setting mechanism used in product formation.

Both block and boards have been successfully produced. A water to binder ratio of 0.6 gave the best performance. Curing at 60 °C produced the best materials, although more testing is required at intermediate temperatures to determine the optimum curing temperature. Time at elevated temperature for curing had minimal impact on 28-day compressive strength data and a strong relationship between exists between the degree of transformation from nesquehonite to hydromagnesite and compressive strength.

The nesquehonite transition to hydromagnesite, HM, ($Mg_5(CO_3)_4(OH_2).4H_2O$) is through a dissolution and reprecipitation reaction:

$$5MgCO_3.3H_2O \rightarrow Mg_5(CO_3)_4(OH_2).4H_2O + CO_2 + 10H_2O$$

The morphological changes that accompany this transition are responsible for the setting mechanism in HM bound materials developed and investigated in this work.

The strength of HM bound board and brick products has been optimised. The effect of varying the curing temperature on strength and the chemical and physical effects of water on HM bound materials were investigated. The water to binder ratio was optimised for board production and the influence of aggregate addition on strength reported.

Using a curing temperature outside the 50 to 60 ºC range did not improve the compressive strength of HM bound samples. This temperature range is optimal for the NQ to HM transition. Exposure of HM samples to water did not adversely influence the samples formed. These have comparable water absorption to commercial sintered clay bricks. Cyclic water exposure also had no impact on the dry strengths of the magnesium carbonate (HM) bricks. The wet strength of magnesium carbonate bricks was lower than the dry strengths, but this is still greater than the minimum strength required for use as bricks.

The effect of milling the magnesium carbonate and using magnesium carbonate aggregates on properties was evaluated. The impact of freeze-thaw testing on magnesium carbonate brick samples was also assessed using British Standard EN 772-18:2011.

Brick samples containing magnesium carbonate aggregate had reduced compressive strength compared to those made using sand. This was because of increased water demand and consequent changes in the microstructure. Milling the nesquehonite increased the compressive strength of samples. The milling increased the surface area, and this promoted more effective dissolution and reprecipitation, producing a higher density matrix. Freeze thaw cycling resulted in microcracking, and this caused a gradual decline in compressive strength of block samples. Wet-dry cycling resulted in minimal strength degradation.

The effect of water to binder (w/b) ratio, aggregate volume and fibre inclusion on the properties of hydromagnesite board samples was assessed. An inverse relationship was found between the water to binder ratio and the flexural strength. At low water to binder ratios, increasing the aggregate to binder ratio reduced the flexural strength. The inclusion of short glass fibres and long typha fibres demonstrated potential to improve the mechanical properties of board samples.

The conclusion from the work on hydromagnesite products are that they have potential to compete with concrete bricks and blocks. The work on producing hydromagnesite boards to potentially compete with gypsum boards is still at a preliminary stage and further work is necessary. Initial results are encouraging. Given the relative quantities of the APS and nesquehonite formed by the Seratech process developing applications for the nesquehonite is important for the success of the technology. The work completed in this project has indicated significant potential, and this will be the focus of ongoing future research and development.

3. Business development and commercial revenue generation

The CCUS2.0 project included essential commercialisation elements in Work Package 5 (Business Development). Funding was allocated to conduct key activities including the production of a clear, practical business plan for an Imperial spin-out, design of a pilot plant, and identifying investors to provide the funding to carry the programme forward and engage customers for the proposed products.

Seratech has been established as a spin-out company from Imperial through which the technology will be commercialised. As part of the spin-out agreement, Seratech has agreed with Imperial an exclusive license for the IP developed.

This section of the Report provides background information on the business development of Seratech, and plans for growth.

Business Plan

Seratech will be a for-profit manufacturing business that will buy in low-cost feedstock, transform this through a low-energy, low-cost process into two ultra-low carbon cementitious materials. It will sell these to businesses that need lower cost ultra-low carbon cement. The silica product will be sold as a supplementary cementitious material (SCM) to suppliers of ready-mix concrete and the magnesium carbonate (MagCarb) will be targeted towards manufacturers of concrete products, such a blocks and paving.

Global Potential

Seratech products have massive global market potential. Concrete, for which cement is the most critical ingredient, is the most prevalent man-made product on the planet central to construction across the developing world. Initial focus would be on the European cement market of $23 Billion. Of this, about $10 Billion is ready-mix concrete with a further $4 Billion opportunity in concrete products. We will operate on a manufacturing and direct-sales model, supplying ready-mix suppliers and concrete product manufacturers with low-carbon cementitious materials essential for their production processes. We already have potential access to around $8 million in annual recurring revenue through signed Letters of Intent with key industry players, including Lignacite, Cornish Concrete Products, and Marshalls who would use the materials to make their products. We have also confirmed CO_2 supply agreements with DAC operators such as NeoCarbon, AirHive, and MissionZero as an alternative to using CO_2 emissions from industry.

Once the technology is de-risked and proven at scale, we ultimately expect to license the technology world-wide, to achieve more rapid market penetration and greater impact on reducing global CO_2 emissions from construction.

Business Plan Summary

Raising the initial funds to develop a Pilot Plant to provide potential customers with material to trial and prove that Seratech Cement is a viable replacement for traditional Portland Cement.

Building our Technical Expertise to achieving the full potential of the innovative Seratech processes. Initially investing in R&D to explore wider applications and better products. The construction industry is cautious about introducing innovation. Communication is crucial to demonstrate that Seratech Cement is a direct replacement for traditional Portland Cement for making ready-mix concrete and concrete products without requiring changes in regulations, production practices or skills required.

An industrial-scale production facility will follow on from the Pilot, once potential customers have proven for themselves the value to them of having a lower cost, lower carbon cement, and that supply can be relied upon. Building a team to add skills and experience in production, sales and delivery to meet potential demand. Recruitment will be a priority.

Longer-term, investment in R&D will remain a priority to ensure the potential of Seratech as a long-term business is achieved, broadening IP and patents ensuring that ultra-low carbon construction materials are increasingly economic and available.

International expansion to maximise global emissions reduction. Many countries that use significant quantities of cement have sources of our raw materials, and we believe our product will be of value to them.

Detailed Business Plan

The detailed Business Plan for Seratech has already been developed, setting out a route to market for the technology and building a viable business. This business plan incorporates an Executive Summary, Business Description and Business Model, The Technology, Supply and Product Markets, Licensee Business Model and Techno-Economic Analysis, Seratech

Financial Forecasting, Business Development and Growth, Technology and IP Development, Team, SWOT Analysis. A copy of this Business Plan was provided in Deliverable D5.3.

Plans for scaling up the Seratech business

Phase 1: Pilot for initial product trials in Industry. This will have a capacity of ~1000 tonne product/year (2025/26)

Industry trial with existing partners:

- First sales to partners
- Products go into high-profile projects with existing partners
- Modest profits allowing inwards investment
- Raise investment for Phase 2

Phase 2: Production Pilot with a capacity of 50,0000 tonne products/year (2027/28).

This will involve:

- Increased sales to Pilot partners
- Using existing network of Founders and NEDs to win new customers
- Working with infrastructure clients and asset owners to guarantee offtake for new customers
- Business becomes profitable

Phase 3: EU Scale-up of production with a capacity of $2x10^6$ tonne products/year (2029+)

- Continued expansion in the UK and EU through European arms of UK customers
- Increased sales team to acquire new customers
- New European customers prioritised where there are multi-national opportunities
- Substantial profits and reinvestment possible

Competitor Technologies

It is important to understand competitor technologies where businesses are seeking to provide substitutes or replacements for traditional cement. This is such a large potential market that others have been developing potential solutions. Competitors identified include:

- AACMs (alkali activated cementitious materials) using industrial wastes, such as GGBS, and an alkali activator, such as sodium hydroxide. Examples include Cemfree, Material Evolution and brands from major cement producers, such as EcoPact by Holcim.
- Fortera produce a cement based on an alternative, calcium carbonate, chemistry.
- Celitement produce a cement from lime and a source of silica.

These technologies typically rely on materials such as slag from steel blast furnaces which are in limited and diminishing supply, or lime, which is a carbon intensive to produce. Using activators, alternative raw materials and/or new manufacturing approaches typically increase the costs of the competitive products.

Seratech does not rely on feedstocks with unreliable sources and rising costs. Therefore, we believe that Seratech has a unique technical approach to the challenge of decarbonising concrete and has a significant chance of successful commercialisation.

Business Development Partnerships

Business partnerships are particularly focussed on those required for the Pilot facility that represents the next commercialisation stage of the technology. This includes suppliers and customers with whom we would conduct early industrial trials to verify the performance of cement replacement and cementitious materials. These relationships sometimes bridge across several categories depending on the nature of the relationship. Olivine Suppliers include Sibelco, Grecian Magnesite, LKAB, and Breedon. CO_2 suppliers for the Pilot facility and beyond include CRH, Sigmaroc, NeoCarbon, AirHive, MissionZero. Product customers include SigmaRoc, Lignacite, Cornish Concrete Products, and Marshalls. Other Stakeholders/Influencers include AKTII, British Land, Laing O'Rourke, Carmody Grourke

Some of these partnerships may also offer routes to investments though Corporate Venture Capital (CVC) arms, or through operating companies. Relationships with "funds only" investors, such as venture capital firms, are covered entirely in the "Investment Progress" section of this report below.

Pilot and Investment Progress

The technology developed in this project will be commercialised by Seratech ltd. Seratech is seeking initial seed funding of £4.00 M raised from one or more VCs. The primary objective of the seed round is to de-risk the scale up of the process from lab to industrial. To achieve this, approximately £2M will be spent on building the Pilot facility designed by the subcontractor, Xytel, as part of D2.2.

The Pilot will have a capacity of ~1000 tonnes of cementitious materials per year, which will be used in industrial-scale trials with future customers. The remainder of the funds will be used to run the Pilot for 18-24 months, establish a lab independent from Imperial to continue R&D work, and continue to build commercial traction and pre-agree offtake for subsequent productions facilities.

A successful Pilot will de-risk the technology sufficiently to enable a ~£20 M Series A round to build a larger commercial facility with capacity of ~25,000 tonnes per year.

Investor Data Room

A comprehensive data room has been prepared for investors, with the structures and files as detailed below:

1. Corporate Documents and ICL Spin-out

2. Finances
    a. 10-year financial forecasts (1 year granularity)
    b. 2-year financial forecasts (1 month granularity)

3. Team Structure
    a. Consultancy agreements
    b. Team presentation: detailing current team, future hires and business structure (prepared for D5.4)

4. Technical
    a. Product technical presentation
    b. Process technical presentation
    c. Techno-economic assessment spreadsheet (prepared for D5.2)
    d. Techno-economic presentation: detailing assessment process, assumptions and sensitivity analysis

5. Intellectual Property
    a. Patent licensed from Imperial and IP Pipeline document (prepared for D5.1)

6. Market Analysis
    a. Letters of intent (obtained throughout WP5)
    b. Competitors presentation: giving a high-level assessment of different approaches to cement/concrete decarbonisation, relative merits and drawbacks, and how this technology compares (prepared for D5.3)
    c. GTM Strategy presentation: detailing a three-stage scaling strategy, with distinct approaches on how customers will be won and retained during each stage (prepared for D5.3 and refined)
    d. Market Analysis presentation: detailing sectors of the concrete market and analysing customer behaviour, requirements and priorities across the UK, Europe and US

7. One Pager summarising the spin-out, technology, market and fundraising round

8. Pitch Deck summarising the fundraising round for prospective investors (prepared for D5.4).

Investor Approach and Progress to Date

Many different potential investors have been contacted (123 to date, in total) as part of the fundraising process, and a list was provided in D5.4. The majority of these are VC firms specialising in early-stage businesses with a focus one or more of the following verticals: ClimateTech, DeepTech, PropTech or ConTech. The list also contains some CVCs (eg CEMEX Ventures) and strategic industrial investors who may be long term suppliers (eg Sibelco) or customers (eg SigmaRoc) of the spin out.

At time of writing this report there are five major investors intent on making an investment on agreement of terms. Due to confidentiality, further details of these interactions cannot be disclosed at this time.

In addition, because of external factors, fundraising may not be completed before the end of the project on 31 March 2025, but is expected to close shortly after.

Team Development

Seratech has been holding formal Board Meetings six time per year since the start of the CCUS2.0 Project. The founding four Board Directors are:

Sam Draper - CEO, Barney Shanks - CTO, Dr Mike Cook – Chairman, Mike Eberlin - Non-Executive Director.

Sam Draper CEO and Co-founder: Sam Draper studied Engineering at the University of Cambridge, before moving to Imperial College London in 2017 to undertake a PhD in the field of low carbon cement chemistry. During this time, he co-founded Seratech with Barney Shanks. In his current role as CEO of Seratech, Sam leads the business development as the company looks to scale their solution, working closely with numerous parties throughout the cement and concrete value chains. Sam regularly gives presentations and takes part in panel discussions to increase awareness of the challenges facing the construction industry and potential solutions.

Barney Shanks CTO and Co-founder: Barney Shanks studied Chemistry at the University of Surrey, before moving to Imperial College London in 2018 to undertake a PhD exploring the processing of magnesium silicate mineral into cementitious materials. During this time, he co-founded Seratech with Sam Draper. In his current role as CTO of Seratech, Barney leads the technical development and optimisation of new products and processes and to ensure these fit within existing markets to be commercially viable. He manages the company's IP portfolio and pipeline, and engagement with key research collaborators, such as Imperial College London.

Dr Mike Cook FREng Chairman: Mike Cook spent 45 years in the construction industry successfully delivering large innovative engineering design projects to tight commercial time schedules. He is a Fellow of the Royal Academy of Engineering, won the prestigious Institution of Structural Engineers' Gold Medal in 2020 and is a former Vice President of the Institution. In his role at Seratech, Mike ensures that the business and technology is highly visible and well understood in the relevant industry sectors, and that potential partners and investors are keen to engage in subsequent commercialisation. He will also provide strong links into the professional institutions and consulting practices so that the future specifiers of newly available materials are prepared to take up the opportunities for low carbon products.

Mike Eberlin Non-Executive Director and Business Advisor: Mike Eberlin has over 30 years of experience in the building materials sector. Mainly as the MD/CEO of cement and lime companies both in the UK and in NZ working for three of the four cement majors. He has raised capital and run smaller sustainable material start-ups. More recently Mike was the CEO of Tarmac's Cement and Lime business as well as Chair of the UK Cement Association and a member of the Cembureau board. Mike provides advice and support to Seratech to ensure its products and services are positioned correctly within the cement and CO_2 industries to maximise chance of success and growth. He plays an active role in building long-term business strategy and making the business investment ready.

A further position, Investor Director, will be filled by the lead investor of the Seed round. The remaining one or two positions will be filled after Seed completion, with expertise as required.

A Non-Executive Director will be recruited with expertise in building high-growth, innovative start-ups, building executive teams including mentoring and professional development of the C-suite or development of intellectual property strategies.

Summary of Commercialisation Outcomes and Funding Impact

The outcomes of the technical work packages have directly fed into the four WP5 Deliverables on business development as detailed below:

D5.1: Business Development 1 (IP) used results from the preliminary investigations in WPs 1-4 to begin building a 20-year IP strategy for the spin-out to maximise its potential and resilience through product and market diversification and ensuring strong product-market fit. This strategy has been refined throughout the Project as further experimental data has been obtained.

D5.2: Business Development 2 (Supply Chain) built a comprehensive Techno-Economic Assessment (TEA) model for the business using process data (eg estimates of energy requirements) from WPs 1 and 2, and materials performance data from WPs 3 and 4 (to estimate the market value of the cementitious materials produced).

D5.3: Business Development 3 (Business Planning) collated much of the earlier work to form a coherent 10 business plan for the spin-out. Continued understanding of the process (WPs 1 and 2) helped to assess capex requirements for financial planning. An ever-increasing bank of performance data for the products (WPs 3 and 4) was also crucial to engage in more detailed conversations with potential customers and other stakeholders in the cement and concrete value chains to fully assess the markets and identify the most promising early sectors.

D5.4: Business Development 4 (Commercial Readiness) continued the work in D5.3 in terms of using credible data as a basis for ongoing conversations with potential suppliers, customers and other partners. The data room technical presentations are built from the findings of WPs 1-4 and have been essential to engage with potential investors and demonstrate R&D progress. The benefits of this are two-fold, not only de-risking the technology but also showing the credibility of the team and making the spin-out a much more investable prospect.

1. Conclusions

Work on this CCUS2.0 Project during year 2 has significantly accelerated the route to market for this technology that permanently sequesters CO_2 using the magnesium silicate mineral olivine and produces cementitious materials. Four technical Work Packages (WPs 1-4) have improved understanding of the underlying chemistry of the process and optimised the performance of the two cementitious materials (silica and magnesium carbonate) that are produced. The outcomes of these technical work packages have directly fed into the WP5 deliverables related to business development.

The funding provided by the NZIP Portfolio has allowed research to be developed completed in a well-equipped laboratory and removed the need for an early pre-seed round, which would have been challenging to raise. By conducting extensive commercial development work throughout the two years of the project, the technology is much better placed, with stronger product-market fit. The spin-out, and its founders, have built a strong network of potential suppliers, customers and other partners.

Overall, support of this project has drastically increased the likelihood that the spin-out will succeed. If this is the case, it has potential to replace a significant proportion of UK cement, reduce dependence on the import of alternative cementitious materials, and add hundreds of millions of pounds to the UK economy. This will provide DESNZ with a significant return on the money invested through this grant.

Olivine is a globally available mineral with significant potential to contribute to carbon sequestration. The amorphous precipitated silica extracted from olivine has potential to be used as a supplementary cementitious material that can produce low-carbon cement. This is now widely regarded as a world leading development in delivering carbon negative concrete and infrastructure. Carbon sequestration occurs through the production of nesquehonite. The research completed to date shows that this can be used to manufacture hydromagnesite blocks and boards. This is critically important because of the relative amounts of silica and magnesium produced. Scope for additional innovation and IP is significant, and there is every potential for Seratech to become a world leading UK low-carbon company.