

## **PERMANENT SEQUESTRATION OF CO<sub>2</sub> IN INDUSTRIAL WASTES/BYPRODUCTS**

A techno-economic investigation  
commissioned by the members of the  
**Carbon Dioxide Capture & Conversion (CO<sub>2</sub>CC) Program**

Client Private  
September 2021



### **The Carbon Dioxide Capture & Conversion (CO<sub>2</sub>CC) Program**

The **CO<sub>2</sub>CC Program** is a membership-directed consortium whose members are involved in the development, monitoring and utilization of the “state-of-the-art” in technological progress and commercial implementation of carbon dioxide capture/clean-up and conversion. By the direction of the member companies (through balloting and other interactive means), the program delivers a range of timely and insightful information and analyses which are accessible exclusively to members and protected by confidentiality agreements. The objective is to document technically and commercially viable options for CO<sub>2</sub> capture/clean-up as well as its conversion into useful products which meaningfully address the challenges posed by CO<sub>2</sub> life-cycle and overall sustainability issues.

Members receive three in-depth **CO<sub>2</sub>CC Techno-economic Reports** which are written by leading scientists and experienced industry professionals in areas selected by the membership (via ballot); weekly *CO<sub>2</sub>CC Communiqués* (delivered via e-mail) which provide the latest updates on technical breakthroughs, commercial events and exclusive development opportunities; and attendance at the CO<sub>2</sub>CC Program **Annual Meeting**.

The **Carbon Dioxide Capture & Conversion (CO<sub>2</sub>CC) Program** is available on a membership basis from The Catalyst Group Resources (TCGR). For further details, please contact Chris Dziedziak at [cdziedziak@catalystgrp.com](mailto:cdziedziak@catalystgrp.com) or +1.215.628.4447.



P.O. Box 680  
Spring House, PA 19477 U.S.A.  
ph: +1.215.628.4447  
[www.catalystgrp.com](http://www.catalystgrp.com)

## CONTENTS

<b>EXECUTIVE SUMMARY .....</b>	<b>xxxi</b>
<b>1. INTRODUCTION .....</b>	<b>1</b>
1.1 BACKGROUND CARBON CAPTURE AND SEQUESTRATION.....	1
1.2 METHODOLOGY .....	3
1.3 AUTHORS & CONTRIBUTORS .....	4
1.4 REFERENCES.....	5
<b>2. MINERAL CARBONATION .....</b>	<b>7</b>
2.1 IN-SITU AND EX-SITU MINERAL CARBON DIOXIDE SEQUESTRATION .....	7
2.1.1 Ex-situ Mineral Carbonation.....	8
2.1.2 Ex-situ Mineral Carbonation Mechanisms .....	9
2.2 EX-SITU MINERALIZATION TECHNIQUES .....	14
2.2.1 Direct Carbonation .....	15
2.2.2 Indirect Carbonation.....	19
2.3 CARBON DIOXIDE UPTAKE .....	24
2.4 RECENT LITERATURE SURVEY .....	26
2.5 CONCLUSIONS AND REMAINING HURDLES .....	26
2.6 REFERENCES.....	27
<b>3. INDUSTRIAL WASTES/BYPRODUCTS.....</b>	<b>39</b>
3.1 SOURCES OF DIFFERENT FEEDSTOCKS .....	39
3.2 SEQUESTRATION POTENTIAL AND REGIONAL AVAILABILITY .....	40
3.3 FACTORS AFFECTING CARBONATION .....	41
3.3.1 Alkalinity.....	43
3.3.2 Pre-Treatment Methods .....	43
3.3.3 Temperature and Feedstock Particle Size .....	48
3.3.4 Solid to Liquid Ratio .....	48
3.3.5 Pressure .....	48
3.4 REMAINING HURDLES AND FUTURE PERSPECTIVES .....	49
3.5 REFERENCES.....	51
<b>4. INDUSTRIAL WASTE AS A FEEDSTOCK.....</b>	<b>57</b>
4.1 IRON AND STEEL-MAKING WASTE .....	57

**PROPRIETARY -- Do Not Reproduce or Redistribute!**

This message is in red ink. If not, you have an unauthorized copy.

4.1.1 Steel Slag.....	57
4.1.2 Blast Furnace Slag.....	57
4.1.3 Basic Oxygen and Electric Arc Furnaces.....	58
4.1.4 Ladle Furnace.....	58
4.1.5 Reaction Mechanism .....	60
4.1.6 Lab-scale Application .....	63
4.1.7 Life Cycle and Techno-Economic Assessment.....	73
4.1.8 Summary .....	74
4.2 RED MUD.....	79
4.2.1 Availability and Composition .....	79
4.2.2 Reaction Mechanism .....	80
4.2.3 Lab-scale Implementation .....	80
4.2.4 Summary .....	85
4.3 PAPER MILL WASTE .....	85
4.3.1 Availability and Composition .....	85
4.3.2 Lab-Scale Implementation .....	86
4.3.3 Summary .....	87
4.4 CEMENT KILN DUST .....	87
4.4.1 Lab Scale Implementation.....	88
4.4.2 Techno-Economic Assessment .....	90
4.4.3 Summary .....	90
4.5 DESALINATION BRINE .....	91
4.5.1 Summary .....	92
4.6 FLY ASH .....	92
4.6.1 Reaction Mechanism .....	93
4.6.2 Lab-scale Implementation .....	94
4.6.3 Utilization of Carbonated Fly Ash .....	100
4.6.4 Lifecycle and Techno-Economic Assessment.....	102
4.6.5 Summary .....	103
4.7 CONCRETE/BUILDING MATERIALS .....	103
4.7.1 Availability and Composition .....	104
4.7.2 Techno-Economic Assessment .....	105

**PROPRIETARY -- Do Not Reproduce or Redistribute!**

This message is in red ink. If not, you have an unauthorized copy.

4.7.3	Summary .....	106
4.8	MINE TAILINGS.....	106
4.8.1	Nickel Tailings .....	106
4.8.2	Summary .....	108
4.9	REMAINING HURDLES AND FUTURE PERSPECTIVES.....	109
4.10	REFERENCES .....	109
<b>5.</b>	<b>CURRENT AND POTENTIAL INDUSTRIAL APPLICATIONS OF MC PROCESSES .....</b>	<b>125</b>
5.1	CEMENT INDUSTRIAL WASTE .....	126
5.1.1	Calera Process .....	126
5.1.2	CO <sub>2</sub> -SUICOM .....	127
5.1.3	Integration of a Pilot-scale Serpentinite MC Process with an Industrial Lime Kiln.....	128
5.1.4	Chemical Looping and Mineralization.....	128
5.2	STEEL INDUSTRIAL WASTE.....	129
5.2.1	Steelmaking Slag to Calcium Carbonate Using Indirect MC.....	129
5.2.2	Aqueous MC using Basic Oxygen Furnace .....	129
5.3	OTHER INDUSTRIES LARGE SCALE IMPLEMENTATION .....	130
5.3.1	Phosphogypsum Utilization .....	130
5.3.2	Fly Ash .....	132
5.3.3	Mine Tailings .....	133
5.4	INDUSTRIAL SCALE PROCESS MODELING .....	134
5.4.1	Modeling a Pilot-scale Aqueous MC Reactor Using Computational Fluid Dynamics .....	135
5.4.2	Economic Feasibility of Large-scale Mineral Carbonation.....	135
5.5	EXPERTS' OUTLOOK ON MC .....	136
5.6	REMAINING HURDLES AND FUTURE PERSPECTIVES.....	139
5.7	REFERENCES .....	139
<b>6.</b>	<b>INDEX .....</b>	<b>143</b>

## FIGURES

Figure 2.1	Bjerrum plot of carbonate speciation versus pH in aqueous solution .....	11
Figure 2.2	Reaction pathways of different carbon species .....	12
Figure 2.3	Recent publications on industrial waste carbonation against total publications on mineral carbonation generated from Scopus .....	26
Figure 3.1	a) different wastes contribution b) reduction potential by county .....	41
Figure 3.2	Estimates of the regional CO <sub>2</sub> reduction potential using industrial alkaline waste .....	42
Figure 3.3	The difference in uptake based on increasing the pressure .....	49
Figure 3.4	Summary of the MC parameters available in the literature .....	50
Figure 4.1	Tertiary diagram showing the composition of different industrial wastes .....	59
Figure 4.2	Average industrial wastes produced per ton of produced steel .....	59
Figure 4.3	Surface of the a steel slag as received (a) and slags after passivation (b) .....	64
Figure 4.4	Effect of pressure on extent of carbonation .....	65
Figure 4.5	SEM analysis of the solid products before (a) and after (b) carbonation .....	66
Figure 4.6	A schematic diagram of the autoclave and the slag-containing cell for the ternary system of CO <sub>2</sub> -Slag-Water .....	67
Figure 4.7	SEM analysis of the calcium and magnesium contained solid products .....	68
Figure 4.8	SEM analysis of the (NH <sub>4</sub> ) <sub>2</sub> MgCO <sub>3</sub> .4H <sub>2</sub> O (a), CaCO <sub>3</sub> and SiO <sub>2</sub> (b) solid products obtained from the leaching process .....	69
Figure 4.9	A schematic diagram of an integrated system combining indirect mineral carbonation with electrochemical cell for CO <sub>2</sub> sequestration .....	70
Figure 4.10	Calcite products recovered from indirect pressure swing mineral carbonation ...	72
Figure 4.11	SEM images of red mud samples before (a) and after (b) aqueous mineral carbonation .....	82
Figure 4.12	Mineral Carbonation of mechanically pretreated red mud .....	83
Figure 4.13	Fly ash samples before(a) and after(b) carbonation .....	96
Figure 4.14	Process flow diagram of the integrated absorption-mineralization (IAM) process .....	98
Figure 4.15	SEM images with elemental mapping of:the cross-section (a) and the surface (b) of solid products obtained at the end of the carbonation .....	99
Figure 4.16	A schematic diagram for the proposed cement manufacturing utilizing aqueous MC .....	105
Figure 4.17	An integrated process for mineral carbonation with mine extraction site for sustainable mine tailings management .....	108

Figure 5.1	Maturity of several carbon capture technologies and their deployment level 1 .....	125
Figure 5.2	3D diagram of retrofitting of Fortera's technology into a cement plant in the US.....	127
Figure 5.3	Difference between conventional cement process and CO <sub>2</sub> -SUICOM.....	127
Figure 5.4	Process flow diagram of serpentine carbonation process.....	128
Figure 5.5	Process diagram of the pilot plant design in Alto University.....	130
Figure 5.6	a) Side view and b) inner cross section of the MC reactor used in the pilot plant.....	131
Figure 5.7	a) a schematic diagram of the pilot plant b) pilot plant at the Puguang natural gas purification plant.....	132
Figure 5.8	A schematic diagram for the joint process between Sinochem Chongqing Fuling Chemical and Chinese Academy of Sciences .....	133
Figure 5.9	Process flow diagram of the proposed MC process CO <sub>2</sub> capture and mineralization. Inset shows the actual testing at the plant .....	134
Figure 5.10	A schematic diagram of Aqueous MC pilot plant.....	136
Figure 5.11	Cost versus efficiency for different MC processes .....	137

## TABLES

Table 2.1	Global Carbon Dioxide Storage Capacity of Several Storage Options .....	8
Table 2.2	Carbon Dioxide Uptake Capacity of Different Natural Rocks.....	9
Table 2.3	Summary of the Uptake of Different Feedstocks Using Different Methods.....	25
Table 3.1	Industrial Waste/Byproducts Production Capacity Per Year with Their Composition.....	39
Table 3.2	Summary of the Physical Pretreatment Methods .....	46
Table 3.3	Summary of the Chemical Pretreatment .....	47
Table 4.1	Recent Literature for Mineral Carbonation of Different Steelmaking Waste/Byproducts .....	75
Table 4.2	Recent Literature for Mineral Carbonation of Red Mud.....	84
Table 4.3	Composition of Different Deinking Sludge Generated from Pulp Ash .....	86
Table 4.4	Calcium Oxide Content in Different CKD Samples .....	88
Table 4.5	Recent Literature for Mineral Carbonation of Fly Ash.....	101