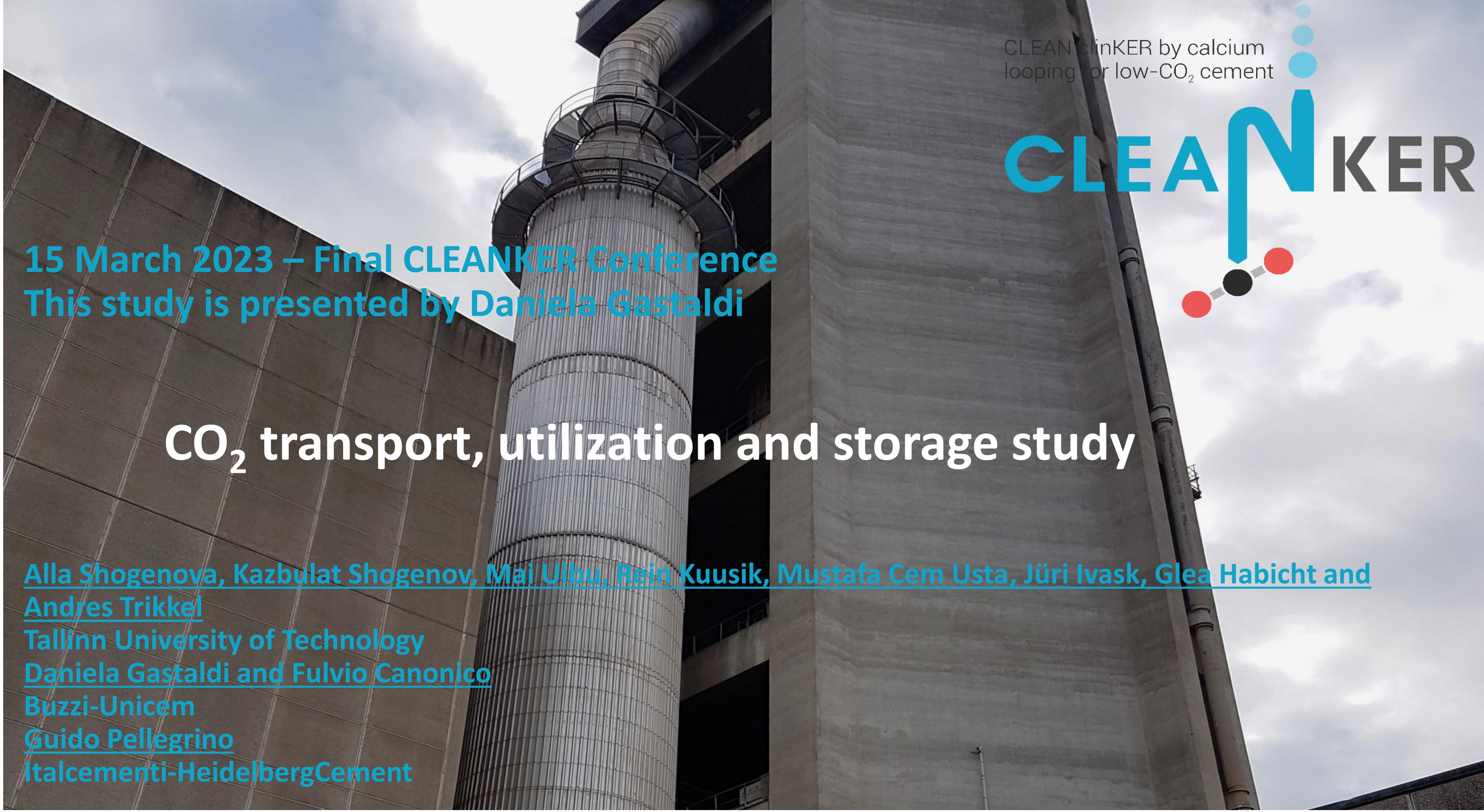

CLEAN clinKER by calcium looping for low-CO_2 cement

CLEANKER

15 March 2023 – Final CLEANKER Conference
This study is presented by Daniela Gastaldi

CO_2 transport, utilization and storage study

Alla Shogenova, Kazbulat Shogenov, Mai Uibu, Rein Kuusik, Mustafa Cem Usta, Jüri Ivask, Glea Habicht and Andres Trikkel
Tallinn University of Technology
Daniela Gastaldi and Fulvio Canonico
Buzzi-Unicem
Guido Pellegrino
Italcementi-HeidelbergCement

Content

1. WP7 study main objective – 1 slide
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7. Testing the carbonated materials for reuse in concrete - 5 slides
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10. List of publications - 2 slides
11. Acknowledgement – 1 slide

Co-funded by the Horizon 2020 Framework Programme of the European Union

Transport, utilization and storage study

Overview:

Start-End date: Full project duration

Work package leader: **Tallinn University of Technology**

Participant(s): **BUZZI UNICEM, ITC-Heidelberg Cement**

- The main objective of this study was to explore local and regional transport, utilization and storage needs, options and solutions in the vicinity of the demo system Vernasca Cement Plant in Italy, and some cement plants in the Baltic Region.

Co-funded by the Horizon 2020 Framework Programme of the European Union

CO_2 transport, utilization and storage study

Objectives:

- Developing common methodology for modelling of local and regional CCUS scenarios in Europe using international expertise;
- Modelling local and regional CCUS scenarios, relevant for cement plants owned by the end-users, in particular: a Baltic regional scenario including Kunda Cement Plant in Estonia and Slantsy Cement Plant in Russia (both of ITC-HCG); a local Italian scenario including BUZZI Vernasca Cement Plant in Italy;
- Assessing regulatory issues for transport, utilization and storage in the selected scenarios;
- Defining of suitable BUZZI and ITC-HCG cement plants for CO_2 capture in Europe, North America and Asia-Pacific region based on transport and storage opportunities of CCS clusters already well documented in the literature;

Public Deliverables:

Deliverable D 7.1. Definition of a methodology for the development of a techno-economic study for CO_2 transport, storage and utilization. 56 pp. A. Shogenova and K. Shogenov, http://www.cleanker.eu/downloads/cleanker-public-deliverables/d71-definition-of-a-methodology-for-the-development-of-a-techno-economic-study-for-co2-transport-storage-and-utilization.html

Deliverable D7.2 Techno-economic modelling of selected local and regional CCUS scenarios for Vernasca, Kunda and Slantsy cement plants.

A. Shogenova, K. Shogenov, M. Uibu and R. Kuusik. http://www.cleanker.eu/downloads/cleanker-public-deliverables/d72-techno-economic-modelling-of-selected-local-and-regional-ccus-scenarios-for-vernasca-kunda-and-slantsy-cement-plants.html

Deliverable D7.3 Regional and national regulations, gaps and recommendations for CCUS scenarios, 72 pp. Authors: A., K. Shogenov and J. Ivask. http://www.cleanker.eu/downloads/public-deliverables/d73-regional-and-national-regulations-gaps-and-recommendations-for-ccus-scenarios.html

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Techno-economic modelling of the Baltic CCUS onshore scenario

- Proposed scenario:
- ✓ 6 CO2 emission sources
- ✓ CO2 use: Mineral Carbonation Plant (CO2 + Oil Shale Ash)
- ✓ Pipeline transport (700 km)
- ✓ North-Blidene Storage site in Latvia
- ✓ Cambrian saline aquifer: Deimena Formation sandstones
- ✓ CO2 emissions and EEAP: 2019

Mineral Carbonation Plant

- 110 kg of CO$_2$ /t OSA
- 250 kg of PCC (precipitated CaCO$_3$) from one t OSA
- 0.42 Mt CO2+3.8 Mt OSA= 0.95 Mt PCC/year

Revenues

- avoided EEAP 40 Euro/t CO$_2$
- 3 €/t OSA for OSA disposal
- 50 €/t PCC

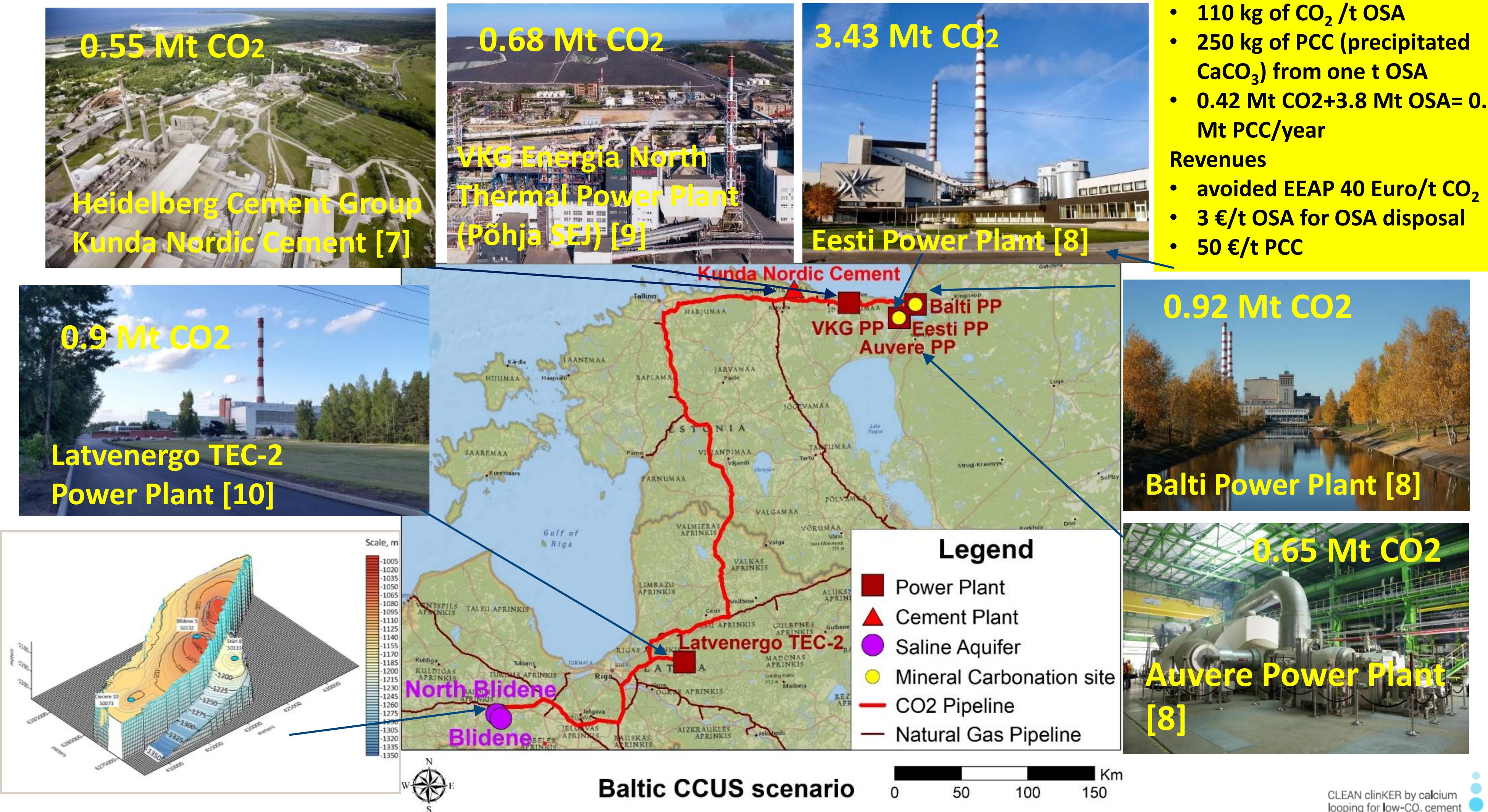
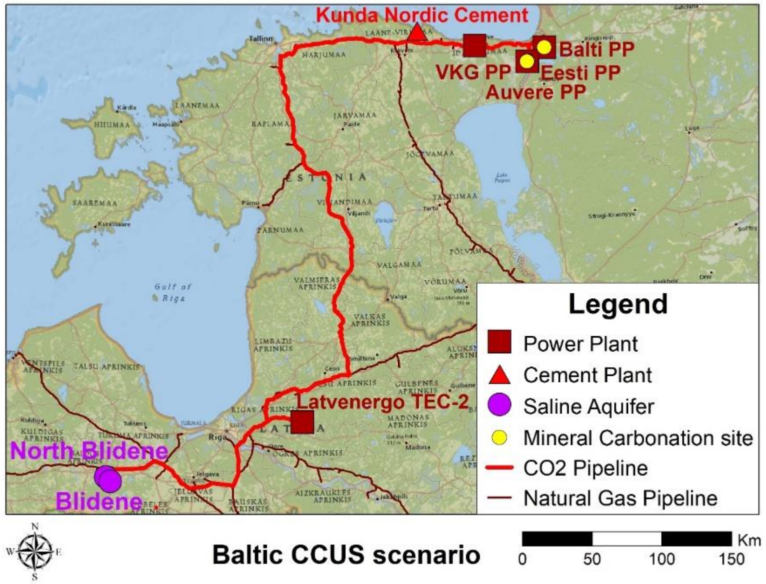


Fig 2. Baltic CCUS scenario.CO2 emissions produced in 2019 are shown in yellow colour (Shogenova et al, 2021)

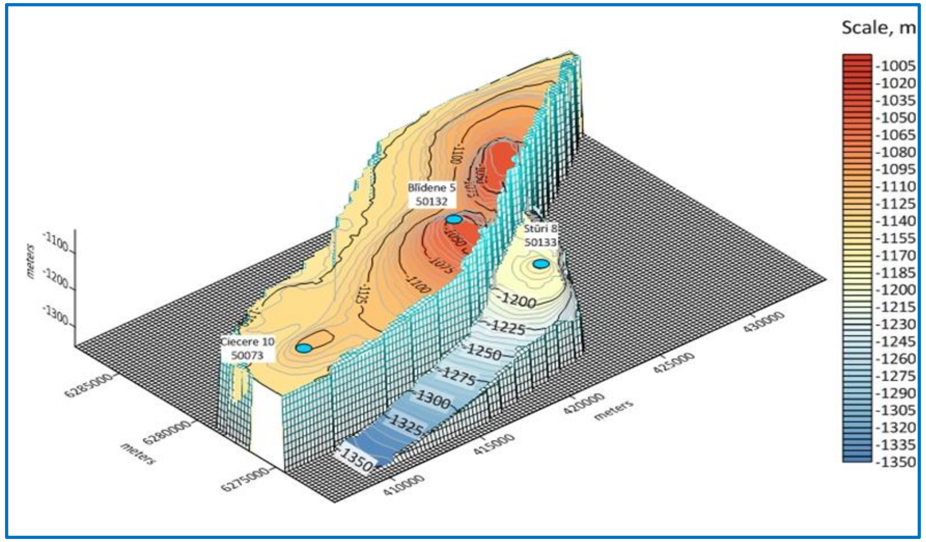
Co-funded by the Horizon 2020 Framework Programme of the European Union

Techno-economic modelling of the Baltic CCUS onshore scenario

- **Annually 6.8 Mt CO_2 could be captured, transported and injected, including 6 Mt CO_2 avoided using transport and storage and 0.42 Mt avoided using MC of Estonian OSA.**
- **During 30 years nearly 204 Mt CO_2 will be captured, used and stored**
- **CCUS scenario includes CO2 use of 0.47 Mt CO_2 produced at Eesti PP and using 3.8 Mt of fresh OSA produced during combustion of OS at three Eesti Energia power plants.**
- **6.4 Mt of captured and compressed CO_2 will be transported annually for onshore CO_2 storage site in Latvia (North Blidene) via pipelines. CO_2 will be injected into the 50 m thick Cambrian Series 3 Deimena Formation reservoir sandstones at the depth of 1035-1150 m.**
- **The total average transport and storage cost of the scenario is 18.4 €/tCO_2 injected.**
- **The cost depends on the transport distance, and it is the most expensive for the Eesti Energia PPs.**
- **The lowest T&S cost of 5.54 €/tCO_2 injected will have Latvenergo TEC2 PP with closest location to the storage site.**
- **At the present EEAP* (2021-2023) of about 90-100 €/t CO_2 the full chain CCUS and post-closure monitoring scenario is beneficial to all participated plants.**



Baltic CCUS scenario



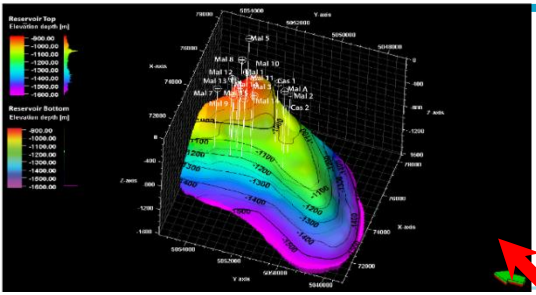
* EEAP – European Emission Allowance Price

Co-funded by the Horizon 2020 Framework Programme of the European Union

Shogenova, A. and Shogenov, K. and Uibu, M. and Kuusik, R. and Simmer, K. and Canonico, F., *Techno-economic Modelling of the Baltic CCUS Onshore Scenario for the Cement Industry Supported by CLEANKER Project* (April 1, 2021). Available at SSRN: http://dx.doi.org/10.2139/ssrn.3817710

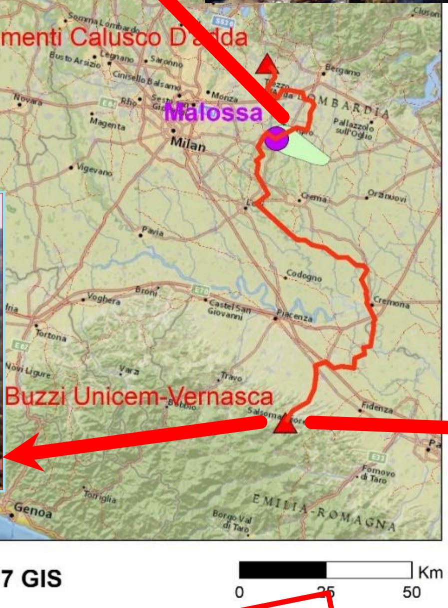
NORTH-ITALIAN CCUS SCENARIO FOR THE CEMENT INDUSTRY

- The objective of this research - a techno-economic assessment of the CO2 transport and storage scenario in the vicinity of the demo plant at Vernasca Cement Plant (CP) and estimate the feasibility of the full value chain Carbon Capture and Storage (CCS) scenario.
- Techno-economic modelling of the CCS scenario for the Northern Italy includes the two largest cement plants with a total of 1.2 Mt CO_2 emissions produced in 2020.
  - It is possible to capture, transport and store annually **23 Mt CO_2 during 20 years** of the project into the Malossa structure in **Sergano Gravel conglomerate Formation** (average depth 1240 m and thickness 200 m) considering the optimistic CO_2 storage capacity of the Sergano Gravel Reservoir Formation (24 Mt).
- Considering 5% of additional emissions produced during CCS operations, only 21.8 Mt of CO_2 could be avoided during 20 years of the project.




Heidelber Cement Italcementi plant
Cementeria di Calusco d'Adda

One of the largest cement plants in Europe




Buzzi Unicem Vernasca Cement plant


CO_2 capture pilot cement plant opened in October 2020 at Vernasca Cement plant

Buzzi Unicem is the second largest industry player in the country

Table 1: Clinker and cement produced in 2018 and CO2 produced in 2018–2020 by cement plants

Cement Plant	Company	Location	Clinker (kt)	Cement (kt)	CO_2 emissions (kt/yr)		
					2018	2019	2020
Vernasca	Buzzi Unicem	Emilia Romagna	575.5	786.1	445.4	504.9	521.8
Italcementi Calusco D'adda		Bergamo	1097	955	903.6	818.9	688.2

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Total costs for CO_2 transport and geological storage for 20 years project

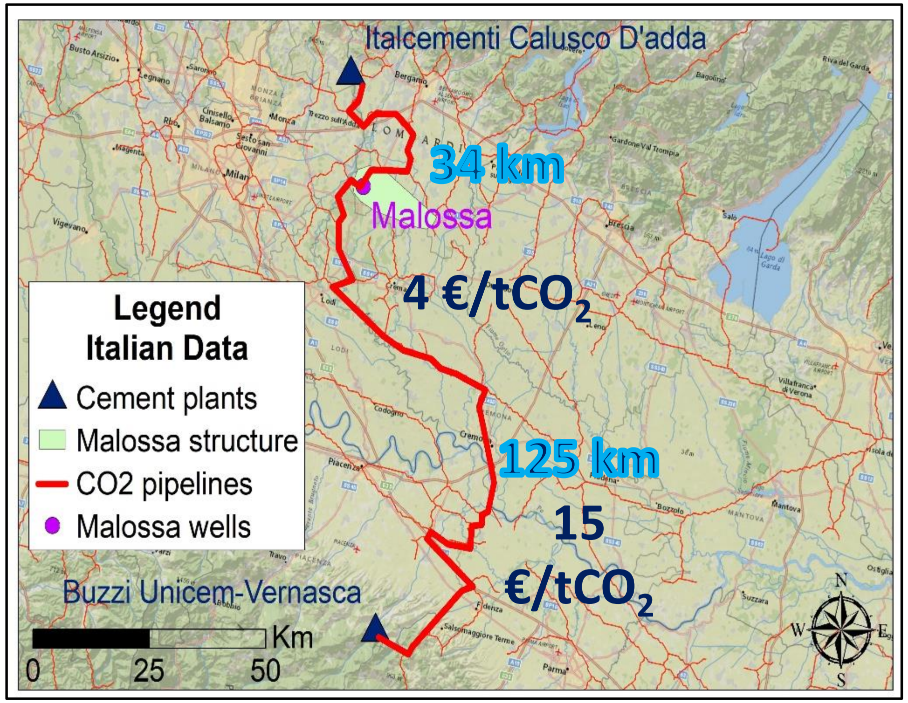
- **The total transport, storage and monitoring cost:**
- **15 €/tCO_2 avoided** for **Vernasca CP ,**
- **4 €/tCO_2 avoided for Italcementi Calusco D'adda CP.**
- This difference is explained by about **4 times shorter** pipeline distance and not needed **booster** for recompression for this plant compared to **Vernasca with 125 km pipeline and needed recompression.**

Table. Total costs for CO_2 transport and storage for 20 years project in the Lombardy Region

Company	Buzzi Unicem	Heidelberg Cement	Total costs/(average per t CO_2) for 2 Italian cement plants
Plant			
Parameters	Vernasca	Italcementi Calusco D'adda	
CO_2 injected per year, Mt	0.50	0.65	1.15
Total pipeline CAPEX, M€	34.96	6.87	41.83
Total CAPEX for all wells, M€	5.71	5.71	11.41
2Booster CAPEX, M€	3.53	-	3.53
Storage facilities CAPEX, M€	0.05	0.05	0.09
BEC (for pipeline, wells and storage facilities), M€	44.24	12.62	56.86
Decommissioning cost (DC) 25% from TPC, M€	11.06	3.15	14.21
Interest (1.5%) for 2 years of constrycyion	1.33	0.38	1.71
FOM (annual fixed O&M cost) M€	0.61	0.18	0.79
TPC (Total Plant Cost), M€	57.23	16.34	73.56
CAPEX, €/tCO_2 injected	10.46	2.28	5.81
OPEX total (40% from BEC), M€	17.70	5.05	22.74
OPEX, €/tCO_2 injected	2.86	0.62	1.58
MVEX (annual monitoring and verification cost), M€	0.50	0.56	1.06
MVEX, €/tCO_2 injected	1.01	0.85	0.92
COSTtotal, €/tCO_2 injected	14.32	3.75	8.31
COSTtotal, €/tCO2 avoided	15.1	3.95	8.74

Conclusions

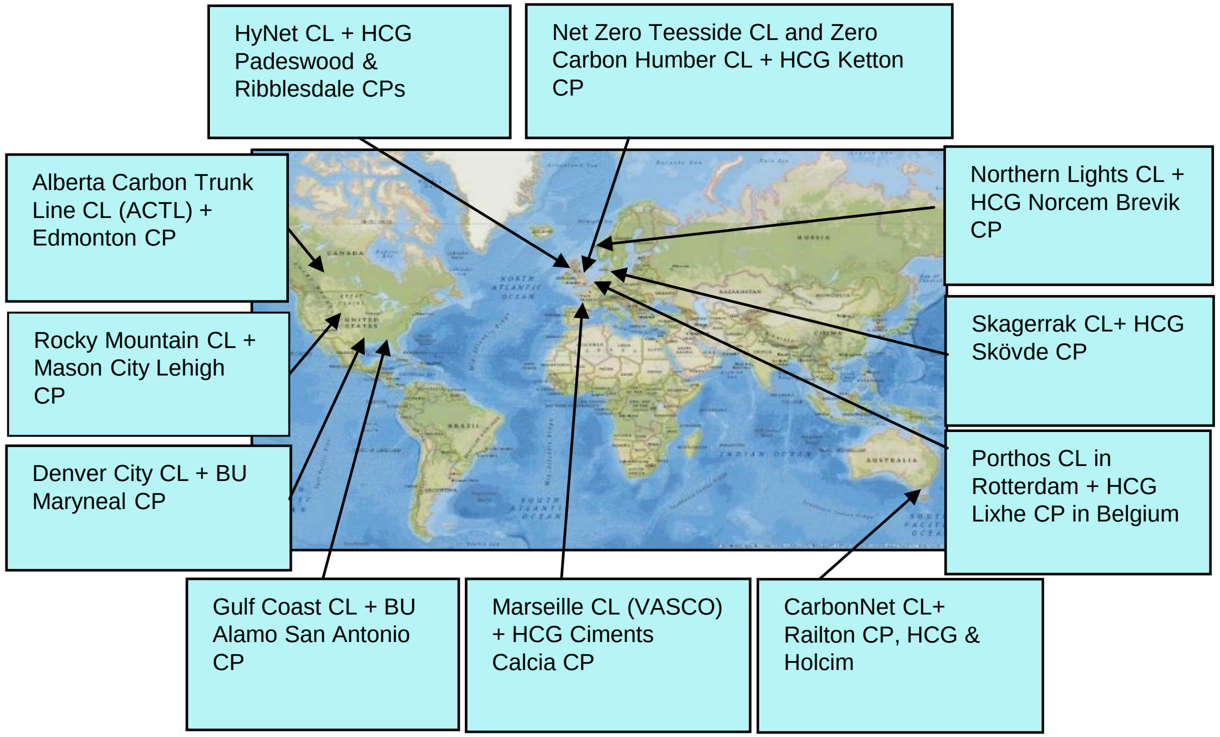
- The total costs for the CCS scenario will depend on the final costs of Ca-looping CO_2 capture at the Vernasca CP at the end of the CLEANKER project.
- Although the reference Ca-looping capture cost is 58 €/t CO_2 avoided, it will be cheaper for the CLEANKER demo system at BUV CP.
- The **maximum** total CCS cost for Vernasca CP with the transport and storage into the Malossa site could be 73 €/t CO_2 avoided, the **maximum** CCS cost for HCICD CP is 62 €/t CO_2.
- These costs are already feasible and beneficial now considering EEAP **90-100 €/t CO_2** reached in EU ETS in 2021-2023.



Shogenova, A.; Shogenov K.; Mariani, M.; Gastaldi, D.; Pellegrino, G. (2022). North Italian CCS Scenario for the Cement Industry. Chemical Engineering Transactions, 96, 115–120. DOI: 10.3303/CET2296020.

Integration of Buzzi and Heidelberg cement plants into the first operating and planned CCUS cluster projects worldwide

- Technical and geological parameters of the 12 large CCUS cluster projects worldwide were included into the CLEANKER ArcGIS Database and integrated with 12 HCG and BU CPs prospective for CLEANKER Ca-looping technology exploitation.
- CO_2 transport distance from the CP to the CO_2 storage site and maturity of the projects permitted to propose priority for the possible CPs integration (recommendations sent to HeidelbergCement in 2020).
- The **HCG Norcem Brevik CP** is the first worldwide CP already included into the Longship project with Northern Lights infrastructure for CO2 storage.
- The second world candidate CP for integration into the cluster project is **HCG Edmonton CP** located at the **170 km** from the Clive DOF of the **ACTL** project in Alberta State in Canada. The CO_2 capture pilot is already developing now at the Edmonton CP.
- Among three CPs proposed for UK clusters, the **Padeswood CP** has the closest location to offshore storage site (about **60 km onshore and offshore**).
- **In December 2020 CLEANKER WP7 sent an abstract to HeidelbergCement with proposed cement plants to be included into the CCUS clusters.**
- **In 2021 HeidelbergCement's British subsidiary Hanson UK has became a partner in the HyNet North West consortium with Padeswood cement plant.**
- All the proposed CPs are producing clinker and cement and suitable for exploitation study of the CLEANKER project Ca-looping capture technology.


HyNet CL + HCG Padeswood & Ribblesdale CPs

Net Zero Teesside CL and Zero Carbon Humber CL + HCG Ketton CP

Alberta Carbon Trunk Line CL (ACTL) + Edmonton CP

Northern Lights CL + HCG Norcem Brevik CP

Rocky Mountain CL + Mason City Lehigh CP

Skagerrak CL+ HCG Skövde CP

Denver City CL + BU Maryneal CP

Porthos CL in Rotterdam + HCG Lixhe CP in Belgium

Gulf Coast CL + BU Alamo San Antonio CP

Marseille CL (VASCO) + HCG Ciments Calcia CP

CarbonNet CL+ Railton CP, HCG & Holcim

Fig.1. 12 CCUS Cluster Projects (CL) with Cement Plants (CP) proposed for Buzzi Unicem and HeiselbergCement

Results and recommendations from this study was sent to HeidelbergCement Group in December 2020

Shogenova, A., Shogenov, K. and Ivask, J.,Habicht, G.,Gastaldi, D., Pellegrino, G., *Integration of Buzzi and Heidelberg Cement Plants Into the First Operating and Planned CCUS Cluster Projects Worldwide, Using CLEANKER Project GIS Database.*
SSRN: https://ssrn.com/abstract=3813982 or http://dx.doi.org/10.2139/ssrn.3813982

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Integration of Buzzi and Heidelberg cement plants into the first operating and planned CCUS cluster projects worldwide - Task 7.4

Abstract sent to HeidelbergCement (07.12.2020):

- **Abstract:**
- **Integration of Buzzi and Heidelberg cement plants into the first operating and planned CCUS cluster projects worldwide, using CLEANKER project GIS database – recommendations for exploitation study**
- *Alla Shogenova[a], Kazbulat Shogenov[a], Jüri Ivask[a], Guido Pellegrino[c], Daniela Gastaldi[b] and Glea Habicht[a]*

Table 1. The most prospective clusters and cement plants for exploitation study

Country	Cluster Name	Website	Main project partners	Storage sites, Offshore/ Onshore	Pipeline/ Ship/ Onshore/ Offshore, km	Cement Plant, Heidelberg/ Buzzi (H/B)	Development Phase
Canada	**Alberta Carbon Trunk Line**	https://actl.ca/	Enhance Energy Inc.; Wolf Carbon Solutions Inc.; Nutrien Inc.; Nortwest Redwater Partnership	Depleted oil fields, Onshore	P, On /240	EdmontonLehigh Hanson, Canada (H)	Operating
The Netherlands	**PORTHOS**	https://www.rotterdamccus.nl/	EBN, Gasuine and the Port of Rotterdam Authority	Depleted Gas fields, Offshore	P, On/ 21; P, Off/33	Maastricht (H)	Development
UK	**HyNet**	https://hynet.co.uk/	Cadent, Progressive Energy, CF Fertilisers, Essar, Peel and the University of Chester	Depleted Gas fields, Offshore	P, On/ 27+31; P, Off/ 33; Ship	Padeswood Works & Ribblesdale Works, Hanson UK (H)	Development
UK	**Zero Carbon Humber**	https://www.zerocarbonhumber.co.uk/	Drax Group; Equinor; National Grid Ventures; Phillips 66 Ltd; px Group; SSE Thermal; Saltend Cogeneration; VPI-Immingham LLP; etc	Depleted Gas fields, Offshore	P, Off /160; 250	Ketton Works, Hanson UK (H)	Development
Denmark and Sweden	**SKAGERRAK**	link	GEUS, SINTEFF, NORDICCS partners, Maersk, INEOS Oil & Gas Denmark and Wintershall Dea	Saline aquifer, Offshore	P/On, 110; S/700	Skövde (H)	Development

The best-known CCUS clusters in the world: 3 UK clusters studied by the Cleanker project

HeidelbergCement is a partner of HyNet!

- **From Press Release 2.03. 2021:**
- "HeidelbergCement's British subsidiary Hanson UK has become a partner in the HyNet North West consortium
- HyNet North West covers the largest concentration of advanced manufacturing and chemical production in the UK, including Hanson's Padeswood cement plant
- As a first step, a feasibility study will be conducted to provide a clear design basis and cost estimate for a capture facility at the Padeswood plant, and connection to the proposed HyNet North West CO2 network and storage system.
- The project will reduce regional CO2 emissions by up to 10 million tonnes every year by 2030 – including up to 800,000 tonnes from the Hanson plant in Padeswood. This is the equivalent of taking four million cars off the road."
- Padeswood CP is located at 8 km onshore to the River Dee and 50 km offshore to the Hamilton gas field.

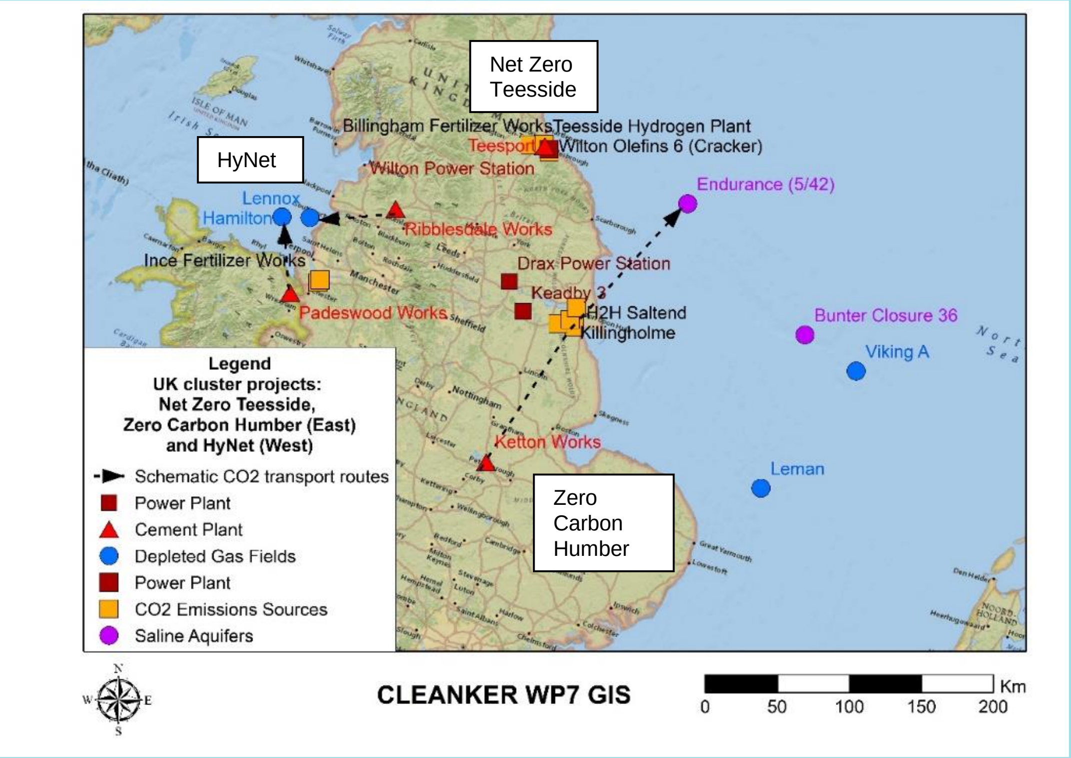

Fig. 7. Three CCUS cluster projects in UK.
HyNet North West cluster can integrate two CPs: Padeswood Works and Ribblesdale Works, Hanson UK.
Zero Carbon Humber can include HCG Ketton Works, Hanson UK CP with CO_2 storage in Endurance SA (in cooperation with Teesside cluster).

2.03. 2021: HeidelbergCement's British subsidiary Hanson UK has become a partner in the HyNet North West consortium with Padeswood Cement Plant (one the recommended plants by CLEANKER WP7)

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Operating North-America cluster projects

- **Alberta Carbon Trunk Line (ACTL) project in Canada** has the world's largest capacity pipeline for CO_2 from human activity.
- Agrium Fertilizer Facility and North West Redwater Refinery, producing in 2018 about **0.3 and 1.3 Mt CO_2** correspondingly will transport captured CO_2 emissions using **240 km of 16 inches pipeline to CO_2-EOR and storage site in Clive field in Alberta**, which includes Leduc Formation and Nisku reservoirs at the depth of 1900 m.
- **The CO_2 pipeline with annual capacity of 14.6 Mt CO_2 will be open access to all CO_2 producers in Alberta's Industrial Heartland and central Alberta.**
- HCG's North American subsidiary Lehigh Cement in November 2019 announced a feasibility study of a full-scale CCS project.
- The plant located at 170 km to the **Clive storage site**. Integration of the Lehigh Hanson CP in Edmonton into the ACTL project will increase its annual capacity from **1.6 to 2.4** Mt CO_2.

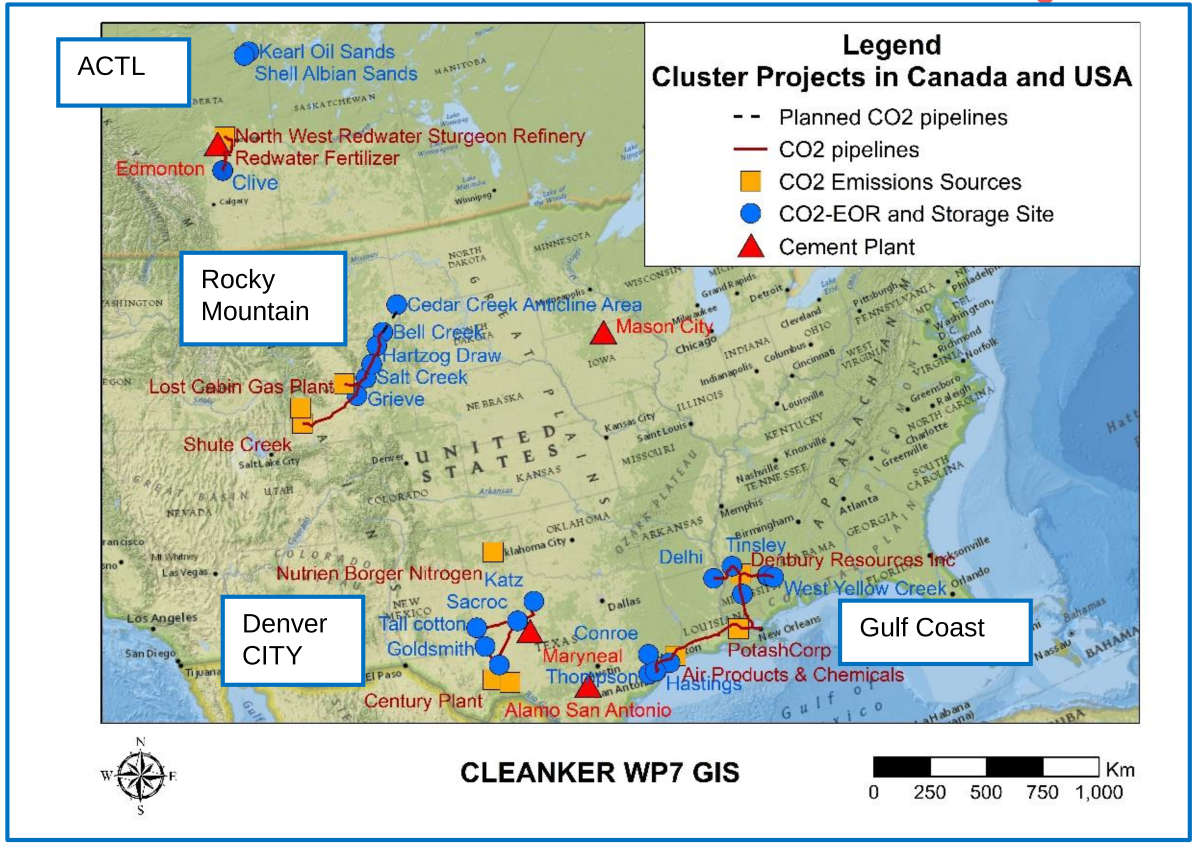

Fig. 1. North American Cluster projects: (1) ACTL project in Canada with HCG Edmonton CP included; 2) Rocky Mountain project with HCG Mason City Lehigh Portland CP proposed; 3) Denver CITY Cluster project in Texas with BU Maryneal CP; 4) The Gulf Coast cluster with BU Alamo San Antonio CP.

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CO_2 transport, utilization and storage study

The most recent results from BUZZI UNICEM Vernasca Cement Plant

CO_2 UTILIZATION

Objective: Demonstrating mineral carbonation of CaO-rich waste ash from Estonia and concrete demolition waste (CDW) from cement plants with CO_2 captured from the demo system in Vernasca BUZZI plant.

Deliverables:

- **Deliverable D7.5. Design and full specifications of the pilot facility for mineralization tests in Vernasca (**submitted in **M25).** Fulvio Canonico , Mai Uibu, Rein Kuusik, 13 pp, Public: http://www.cleanker.eu/downloads/cleanker-public-deliverables/d75-design-and-full-specifications-of-the-pilot-facility-for-mineralization-tests-in-vernasca.html
- **Deliverables 7.6**. **Final report with results of the mineralization tests at Vernasca (ready to submit)**. Daniela Gastaldi, Francesco Magli, Fulvio Canonico
- **Deliverable 7.7**. **Results from casting concrete containing CaLooped CO_2 trapped in the Vernasca demo system** Daniela Gastaldi, Fulvio Canonico

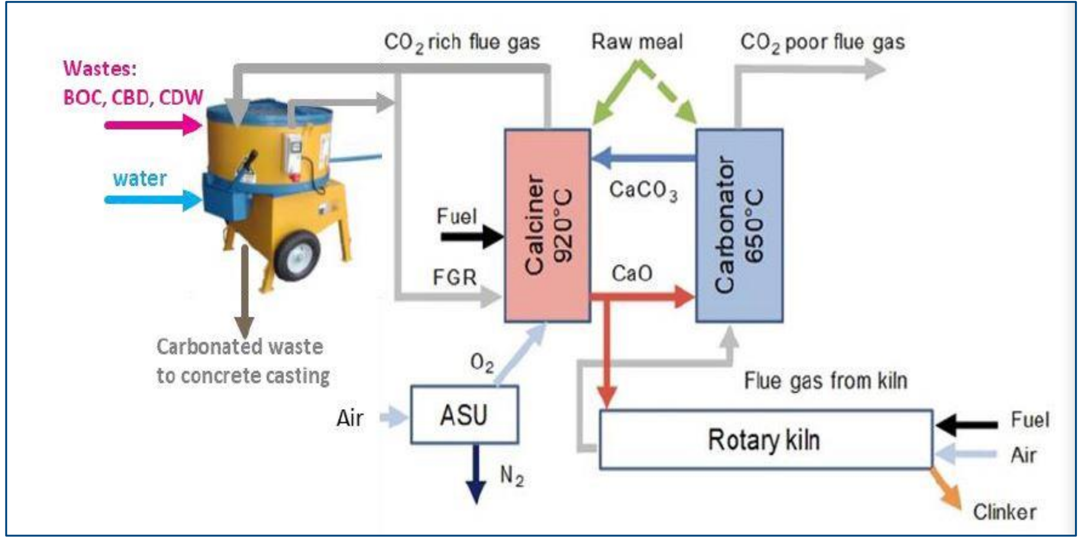
Co-funded by the Horizon 2020 Framework Programme of the European Union

Mineral trapping of CO_2 from the demo system

- One of the objectives of the Horizon 2020 project CLEANKER is the construction of a CO_2 mineralization reactor that will capture CO_2 emitted by the CaL system.

- CO_2 mineralization consists in the capture of carbon dioxide gas by means of mineral phases: CO_2 is bound in the form of thermodynamically stable carbonate minerals, which, by eliminating the greenhouse effect of CO_2 allows environmentally safe disposal or recycling of CO_2.

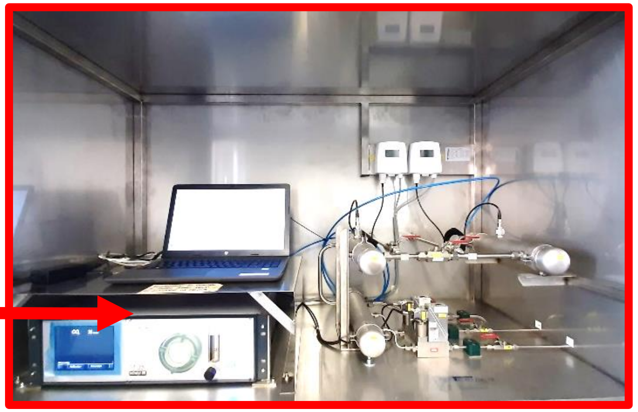
- The lab-scale experiment was perfomed @ TUT in a 46 L reactor with the aim to:
  - Test different materials and select the most performing in terms of CO_2 capture ability;
  - Establish the best test condition (gas flow, CO_2 concentration, wet/dry route);
  - Supply full specification for the realization of the pilot facility



Burnt oil shale (BOS) ashes resulted to be the best material, thanks to the high content of free lime:

- $CaO + H_2O \rightarrow Ca(OH)_2$
- $Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$

Mineral trapping of CO_2 from the demo system



Upper part (off-line test):
- Flowmeters
- Mixing chambers
- RH/T probes
- CO2 analyzer
- PC

Bottom part (in-situ test):
- Cooler
- Suction pump

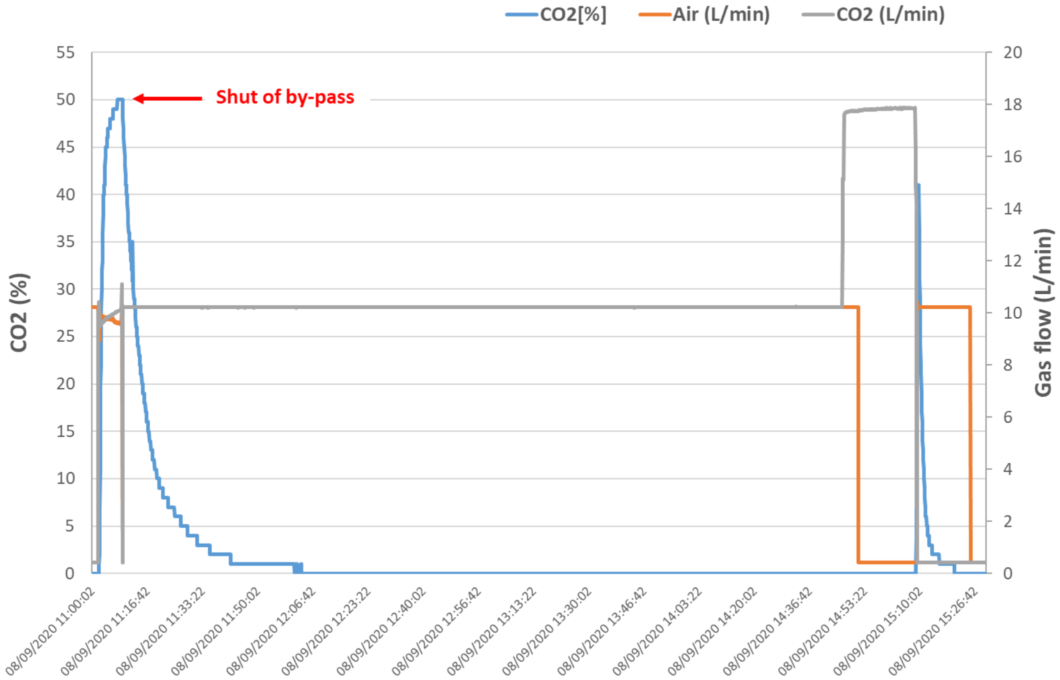
200 L concrete mixer as reactor

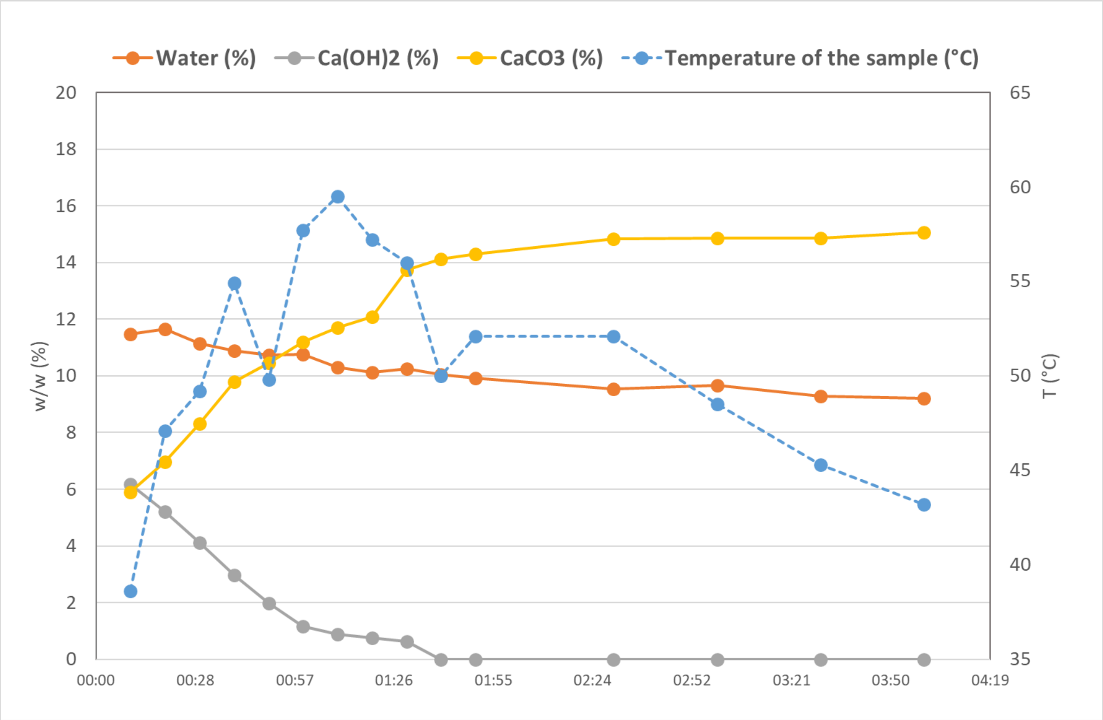
Co-funded by the Horizon 2020 Framework Programme of the European Union

Mineral trapping of CO_2 from the demo system

«Off-line» test – experimental conditions:

- 40 kg of BOS + 8 kg water (w/s = 0.2)
- CO_2 = 50%
- Gas flow 20 L/min





«Off-line» test - results:

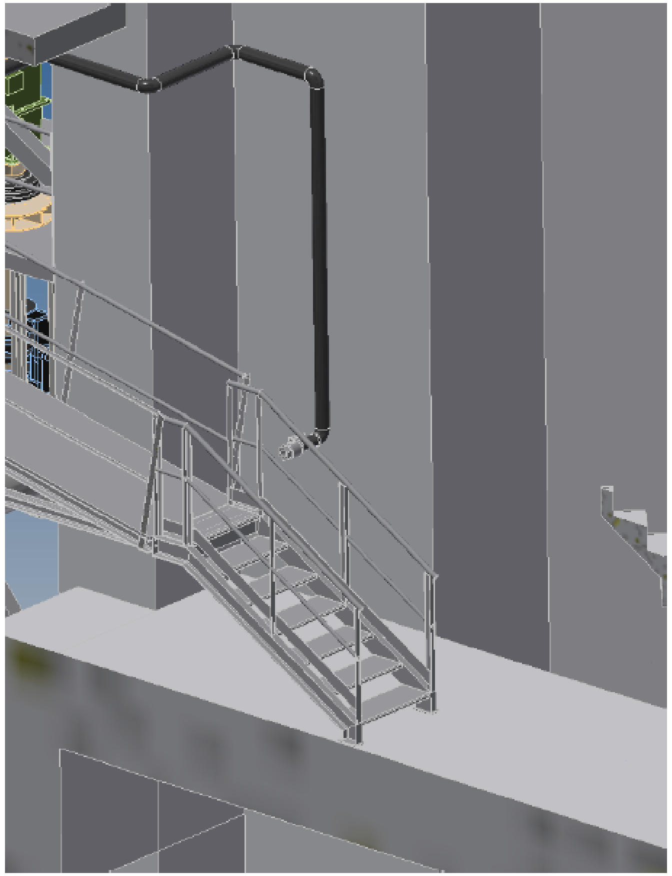
- CO_2 saturation of BOS after 2 hours
- Increase in temperature up to 60°C (CaO hydration)
- 1 kg of BOS stores 50 g of CO_2

Co-funded by the Horizon 2020 Framework Programme of the European Union

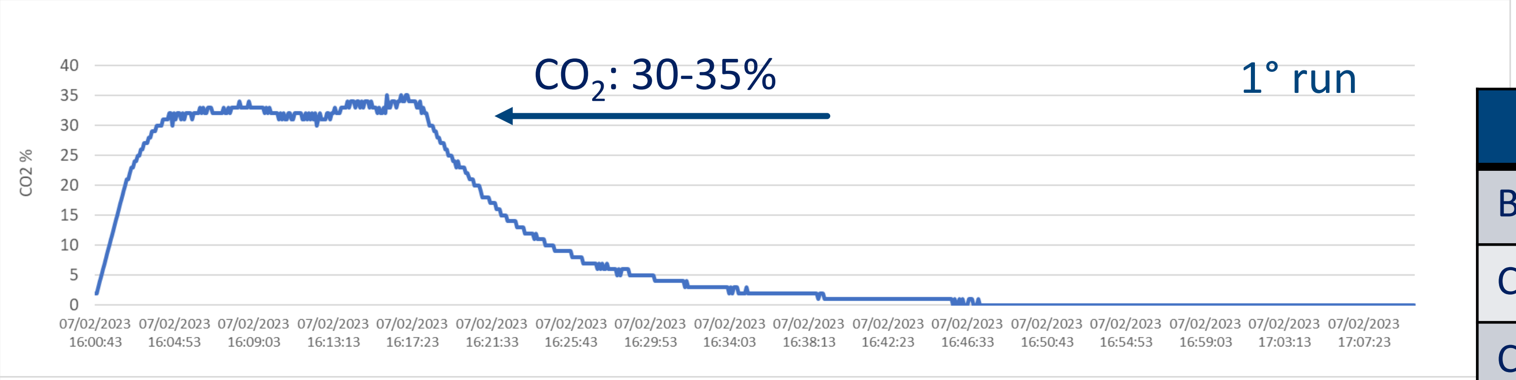
Mineral trapping of CO_2 from the demo system

For in situ test the mineralizing system was installed on the 4° floor of the preheater tower in Vernasca plant

Three runs of mineralization were carried (40 kg + 8 kg water each) – gas flow 60L/min

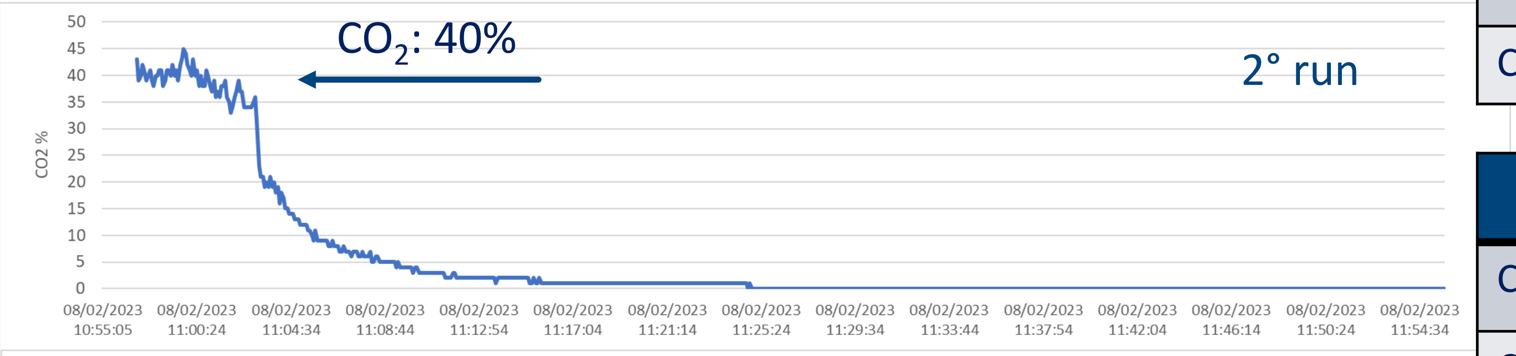


Mineral trapping of CO_2 from the demo system



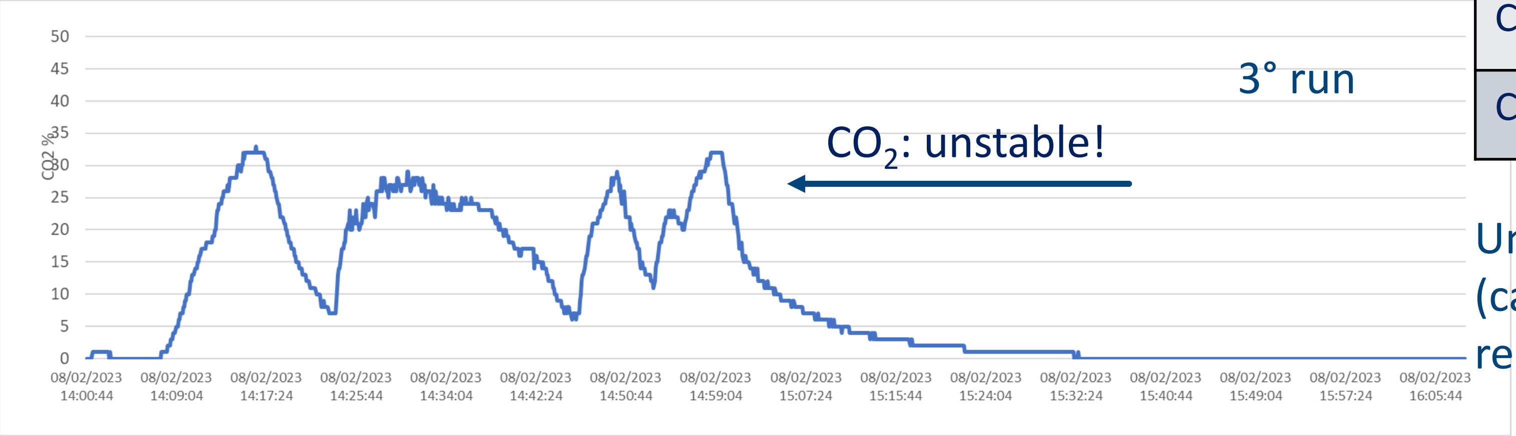
CO_2: 30-35%

1° run



CO_2: 40%

2° run



3° run

CO_2: unstable!

	$Ca(OH)_2$	$CaCO_3$
BOS (original material)	9,7	4,8
Carbonated-BOS 1° batch	5,0	9,2
Carbonated-BOS 2° batch	4,5	10,7
Carbonated-BOS 3° batch	7,2	6,1

	g CO_2 in 1kg of BOS	
Carbonated-BOS 1° batch	19,6	👍
Carbonated-BOS 2° batch	26,2	👍
Carbonated-BOS 3° batch	6,0	👎

Unconstant CO_2 concentration in the gas stream (caused by dust glogging of the pipes) significantly reduces the efficiency of the process!!!

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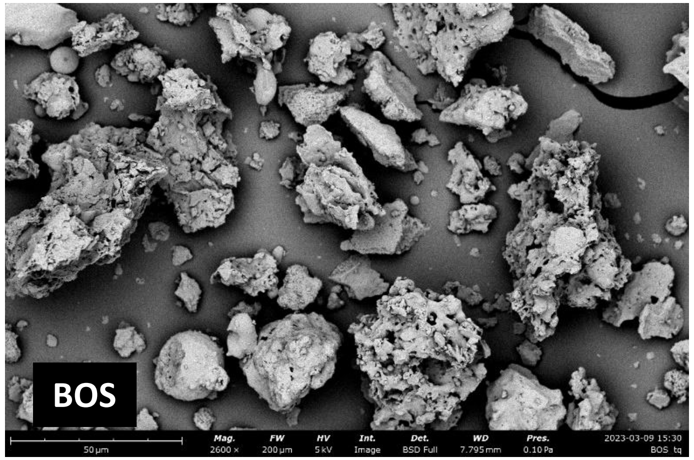
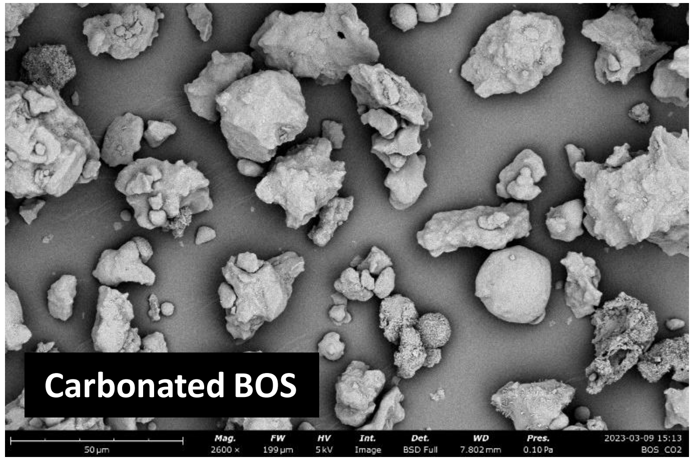
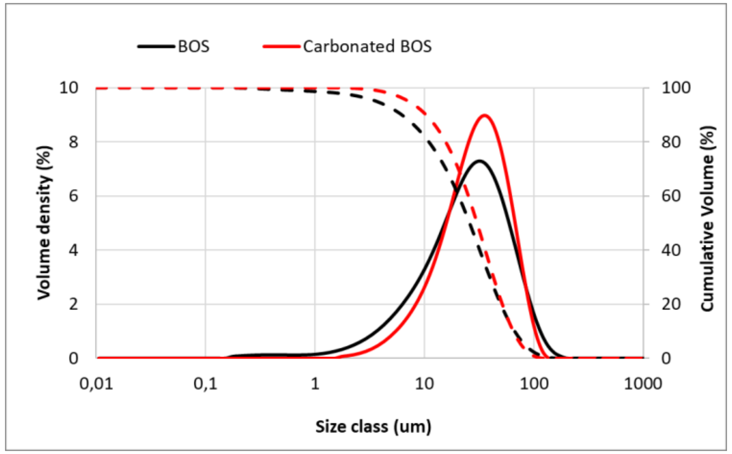
Mineral trapping of CO_2 from the demo system

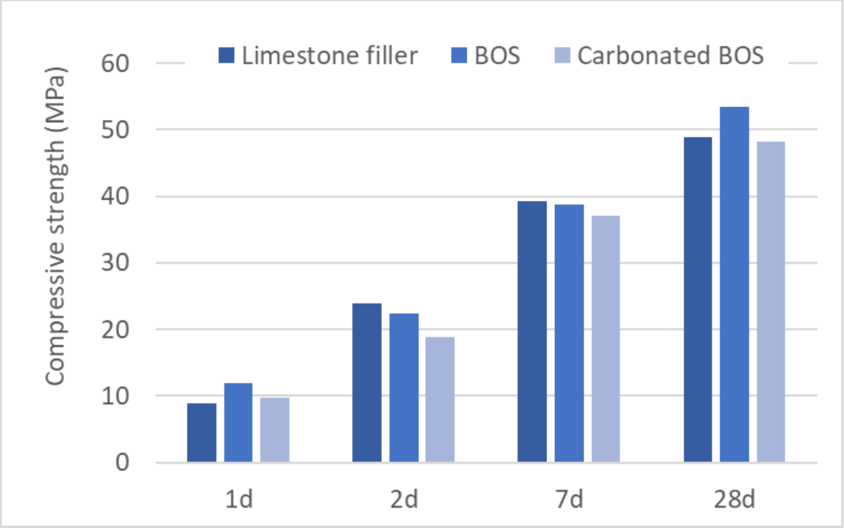






- Electron microscopy on carbonated BOS shows rounded particles due to the deposition of carbonation product on the surface of ashes → lower surface and larger particle size!

- Test on mortars (UNI EN 196-1) based on CEM II/A-LL with 8% addition of BOS (only 1° and 2° batches were used)
- Limestone filler used as reference
- Loss of flexural and compressive strength



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Casting of concrete containing CaLooped CO_2

Concrete specifications (4 m^3):
CEM II/A-LL (340 kg/m^3)   w/c: 0.59   Strength class: C30/37   Slump class: S5   Max d: 32 mm

2 m^3 (half load) of ordinary concrete (according to specifications) were poured in a first hole

60 kg of carbonate BOS were added to the remaining 2 m^3 of concrete, homogeneized for 5 minutes and poured in the second hole

Casting of concrete containing CaLooped CO_2

260 mm

200 mm

The addition of carbonated BOS results in the lost of 1 class of consistency (S5→ S4)!!!

Workability can be adjusted through increasing the amount of superplasticizer (1/3 more in laboratory tests)

N/mm²	Reference concrete	Carbonated BOS concrete
1 day	6,3	6,7
2 days	22,6	25,1
7 days	37,3	35,7
28 days		

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Casting of concrete containing CaLooped CO_2

Conclusions

- BOS ashes can be successfully used as mineralizers for CO_2 storage
- The efficiency of mineralization process is strictly related to the CO_2 concentration in the gas stream
- During the in-situ test performed in Vernasca, 20-25g of CO_2 per kg of BOS were stored
- The use of carbonated BOS in mortar and concrete allows a CO_2 reduction of 4 kg of CO_2/m3 of concrete leads to a loss of workability that can be easily managed using additives, while strength performances are preserved

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