Effect of EAF slag on acidic clay

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HIRAS
Hiiltä sitovat rakennusmateriaalit suomalaisista sivuvirroista

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Introduction

- Sulfidic clay in Finland naturally occurring geological formations found almost exclusively along coastal regions, in Ostrobothnian Coast as well as Southern and Southeastern coast (Yli-Halla 2022).

Common practice

Excavation → **Transport to allocated site** → **Neutralizing** → **Landfilling and monitoring**

Environmentally and economically challenging!

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Background: Binders used in stabilization of acidic/sulfidic clay

- Nordic soft clays, including sulfidic and acid sulfate clays, are commonly stabilized by **dry deep mixing** (López Ramírez et al., 2024; Forsman et al., 2025).
- Traditional binders are mainly **lime-cement blends**, especially **50:50 and 30:70 lime/cement**, but these have a high CO_2 footprint (López Ramírez et al., 2024; Hov et al., 2022).
- Acidic/sulfidic clays may need **high binder dosages** to achieve strength and maintain alkaline conditions, increasing emissions (Forsman et al., 2025).
- Recent Finnish research and field trials, including Malminkenttä studies, focus on **low-carbon binders** to replace part of cement and lime (López Ramírez & Korkiala-Tanttu, 2023.)

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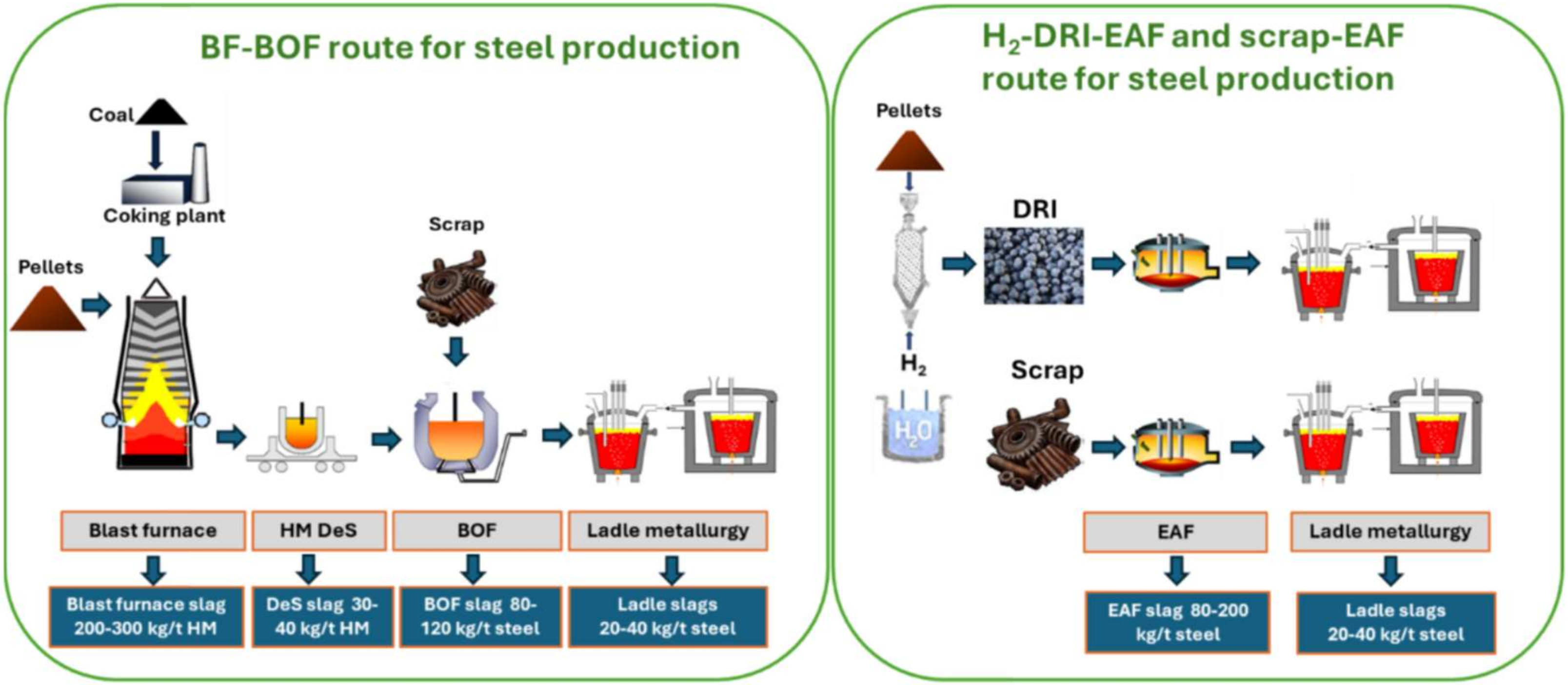
Current main binder alternatives

- Blast furnace slag based binders → CEM III/A and CEM III/B
- Gypsum-lime-cement blends → Terra GTC
- Lime kiln dust/cement blends →Terra Green
- Fly ash based cement binders →E65
- Emerging low carbon binders → Alkali-activated fly ash, slag geopolymers, CSAB (Calcium Sulfoaluminate Belite), Reactive MgO

with lower CO_2 emissions compared with conventional lime-cement binders.

- Source: Forsman et al.; 2025; López Ramírez et al., 2024; Hov et al., 2022; argent et al., 2016; Consoli et al., 2019; Hay et al., 2021

Production of slag, BF vs EAF



Transition away from the conventional Blast Furnace-Basic Oxygen Furnace (BF-BOF) route to H2-DRI with subsequent melting of DRI in an electric arc furnace (EAF) (Kallio et al., 2025)

The material change

- The Hydrogen-based Direct Reduced Iron (H_2-DRI) pathway is primarily a Carbon Direct Avoidance (CDA) strategy. It utilizes fossil-free reductants and renewable or clean energy to process virgin iron ore. (Kallio et al., 2025)
- Coal-reliant Blast Furnace route is phasing out to meet climate targets.
- The solid-state hydrogen direct reduction (H_2-DRI) processes that replace blast furnaces do not inherently produce slag!
- Subsequent electric smelting yields "EAF steel slags" → vastly different mineralogical properties, chemical behaviour, and unknown cementitious performance (Ehrenberg, 2025).

Research goal

This research aims to study

- if EAF slag could be used in stabilization of soft acidic clay
- the optimal proportion of EAF slag to be added
- whether EAF slag can replace the conventional binders in mass stabilization
- if any other binder (lime, geopolymer,..) can replace the cement activator role in clay-EAF blends

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Materials - Clay

- Clay samples from Malminkenttä-Helsinki and Heikkilänkangas-Oulu

Malmi clay. The clay had largely been oxidized. Pictures: Heli Kivisaari-GTK

Excavated soil in Heikkilänkangas-Oulu. unoxidized clay (left-Photograph-Veikko Pekkala) and oxidized clay (middle and right-Photograph Heli Kivisaari)

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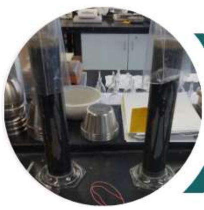
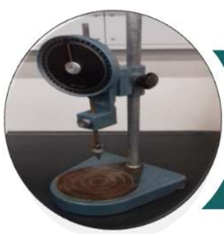
Characterization Tests

01 **Specific Gravity**
Determines how heavy soil particle is compared to water

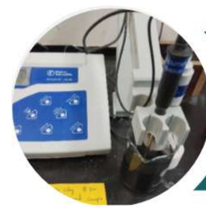


02 **Particle Size Distribution**
Determine the grain size distribution of soil particles



03 **Atterberg Limits**
Determine the consistency limits (PL, LL) of soil

04 **Organic Content**
Determines the amount of organic matter present in soil



05 **Ph test**
Determines the amount H^+ or OH^- ions

06 **Oxidation rate test**
Evaluates the potential for sulfide oxidation and associated acidity

Preparation: Irfan Haque-Aalto

Clay characteristics - Oulu

Property	Test	Result	Remarks
Specific Gravity	Pycnometer	2,69	
Particle Size Distribution	hydrometer	Clay Silt	
Liquid Limit	Fall Cone Test	80,47 %	
Plastic Limit	Plastic Limit Test	30,80 %	
Classification Based on Atteberg limits	Liquid Limit & Plastic Limit Test	Clay, Very High Plastic	
Orgenic Content	Determination of Loss on Ignition	4 %	
PH	Determination of PH	6,89	Unoxidized Sample from Bucket 17
		7,04	Unoxidized Sample from Bucket 17
		4,44	Natural / Wet Oxidization from Bucket 17
		5,03	Natural / Wet Oxidization from Bucket 17
		6,81	Air Dried Oxidization from Buckt 17
		6,9	Air Dried Oxidization from Buckt 17
		6,05	Oven Dried Oxidization from Bucket 17
		5,99	Oven Dried Oxidization from Bucket 17
		5,21	Unoxidized Sample from Bucket 12
		4,99	Unoxidized Sample from Bucket 12
		3,63	Natural / Wet Oxidization from Bucket 12
		3,46	Natural / Wet Oxidization from Bucket 12
		6,96	Unoxidized Sample from Bucket 20
		7,12	Unoxidized Sample from Bucket 20
		3,77	Natural / Wet Oxidization from Bucket 20
		3,85	Natural / Wet Oxidization from Bucket 20

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Clay characteristics - Malmi

Properties	Results
Clay content (%)	71.00
Classification	Soft clay
Average water content (%)	75.15
Liquid limit (%)	82.00
Plastic limit (%)	28.07
Plasticity index	53.93
Liquidity index	0.87
Average unit weight (kN/m³)	15.16
Average density (g/cm³)	1.50
Sensitivity	18.10
Undrained shear strength (kPa)	11.60
Average natural pH	5.70

From Hanafi et al., 2024

Comparison

Particle size distribution suggest that the soil is **Clay-Silt**

On Casagrande plasticity chart, the soil lies in the **very high plastic** region

Oulu clay has **higher organic matter**

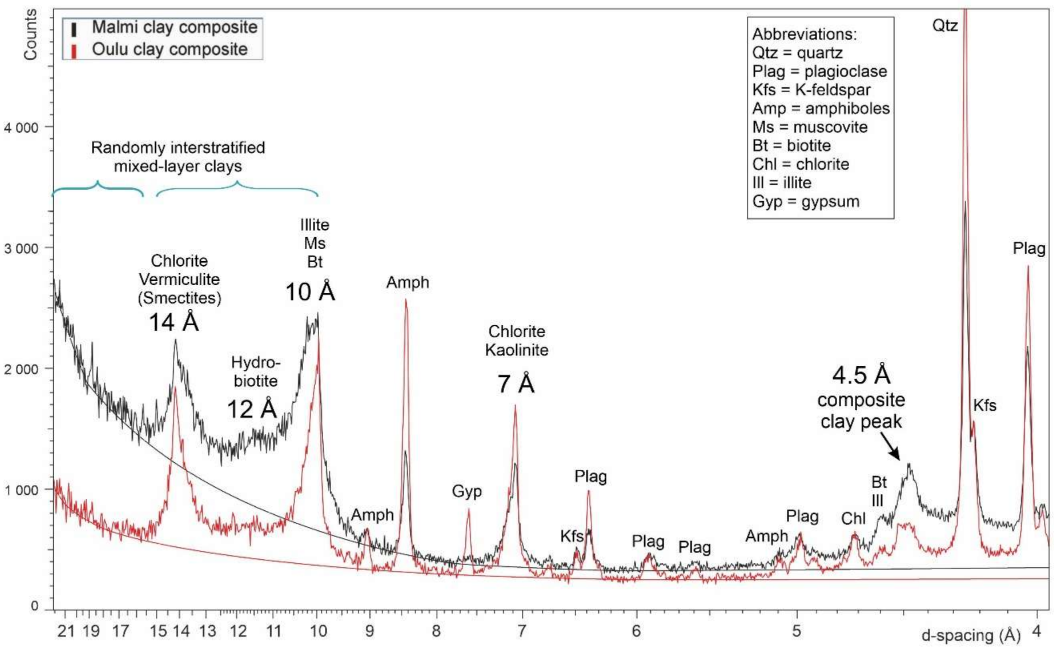
Geotechnical Characterization and Comparison with Malmi clay

PROPERTY		OULU CLAY	MALMI CLAY
Specific Gravity, kg/m^3		2.69	2.8
Particle Size Distribution	D_{50}, mm	0.007	0.001
	Clay Content, %	22.7	65.2
Consistency Limits	Plastic Limit, %	30.8	28.2
	Liquid Limit, %	80.4	55.2
	Plastic Index, %	49.6	27
Organic Content, %		4.1	0.9

Reference to: Irfan Haque and Lopez Ramírez et al., 2024

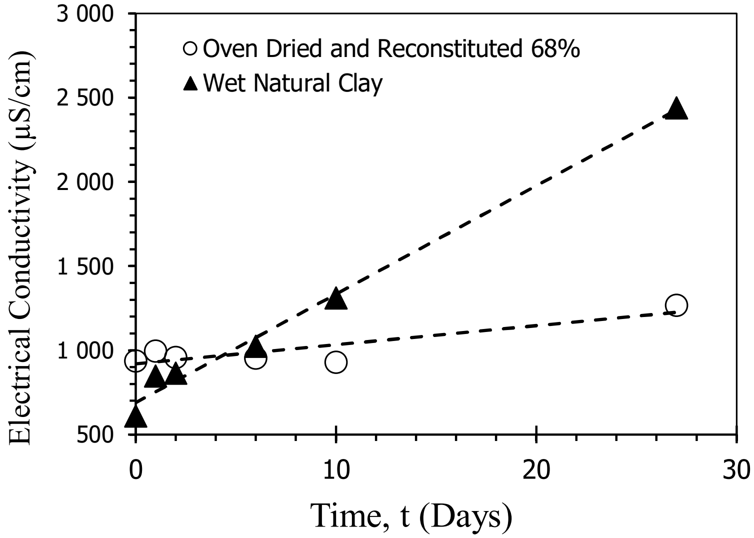
XRD on Clay

- Distinctly higher clay mineral content in Malmi clay when compared to the Oulu clay sample.
- Consistent with the observed higher initial water content of the Malmi clay.
- The key clay phases in both Malmi and Oulu clays are illite, chlorite, and mixed-layer clays covering the d-spacing range 10–14 Å.

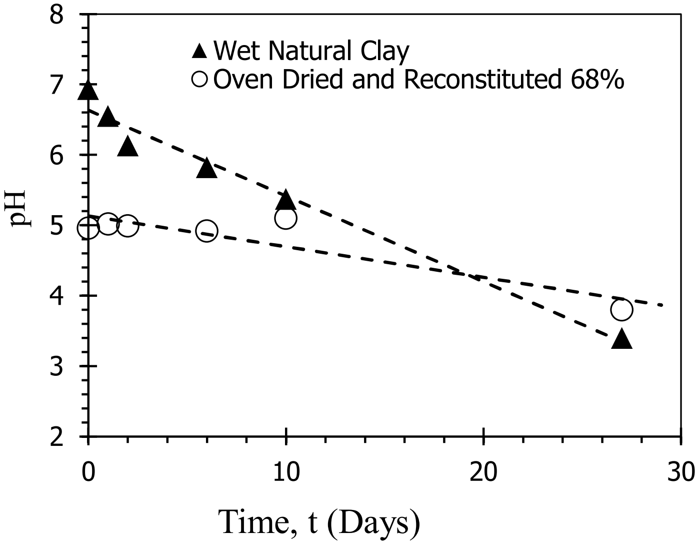


XRD powder patterns of Malmi and Oulu clay composite samples overlain for comparison. By: Pasi Heikkilä- GTK

Oxidation response in sulfidic Oulu clay



Oxidation Induced Ions Mobilization



Oxidation acidification of Oulu clay

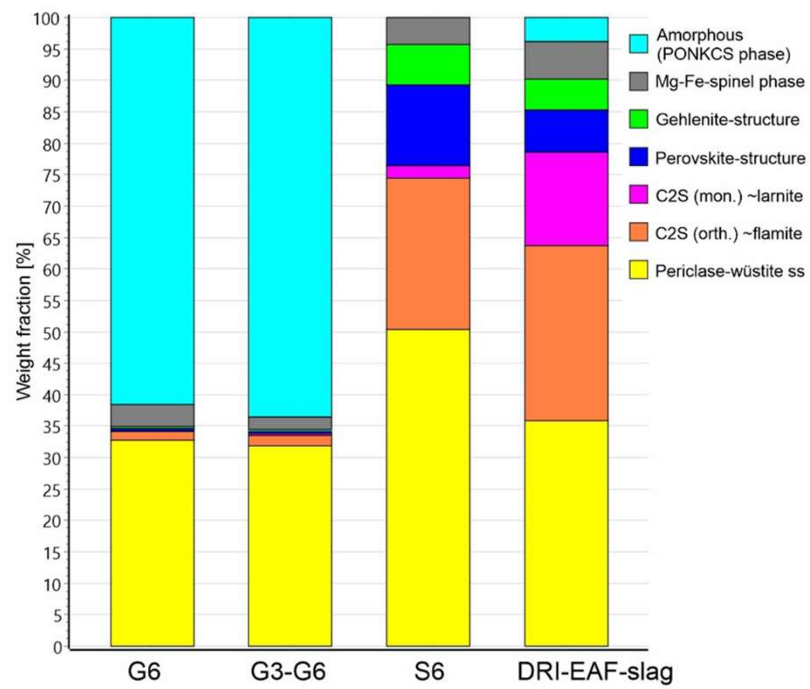
By: Irfan Haque

Material - Electric Arc Furnace Slag

- Direct Reduced Iron (DRI) Electric Arc Furnace (EAF) slag samples from pilot-scale electric arc furnace in Luulaja, Sweden. Both XRD results of unmodified, air-cooled (S6, DRI-EAF slag) as well as chemically modified and granulated slag samples are included. Modified G3-G6 combination was used further, ground to particle size <250 Micrometers.

Granulated EAF

EAF after grinding



Phase compositions of modified, granulated (G) and unmodified, air-cooled (S, DRI-EAF-slag) samples by XRD Rietveld method. (By Pasi Heikkilä- GTK)

UCS sample preparation

- The dry binder components (cement and EAF) were pre-mixed and then added to the clay at a dosage of 100 kg/m^3, a typical rate for Finnish soft clays (Ramírez and Korkiala-Tanttu, 2023).
- The mixtures were moulded in cylindrical plastic moulds (50 mm diameter × 100 mm height) and sealed in nylon bags.
- After 24 h, the samples were demoulded and stored in sealed conditions at 6 ± 1 °C to simulate field conditions in Finland.

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Unconfined compressive strength

	UCS 7-days (kPa)	UCS 28-days (kPa)	Binder used	Binder amount per clay
Malmi Ref (100kg/m³)	424,0	1053,7	CEMIIIB	100 kg of binder per m3 of clay
Oulu Ref (150kg/m³)	50,4	587,5	CEMIIIB	150 kg of binder per m3 of clay
Oulu Ref (100kg/m³)	44,8	65,3	CEMIIIB	100 kg of binder per m3 of clay
Oulu + 30% slag (100kg/m³)	15,3	27,7	CEMIIIB: EAF G3-G6 Slag (70:30)	100 kg of binder per m3 of clay
Oulu + 50% slag (100kg/m³)	14,0	31,2	CEMIIIB: EAF G3-G6 Slag (50:50)	100 kg of binder per m3 of clay
Oulu Ref (200kg/m³)	840,1	1823,3	CEMIIIB	200 kg of binder per m3 of clay
Oulu + 10% slag (200kg/m³)	NA	3041,7	CEMIIIB: EAF G3-G6 Slag (90:10)	200 kg of binder per m3 of clay
Oulu + 20% slag (200kg/m³)	822,3	1645,2	CEMIIIB: EAF G3-G6 Slag (80:20)	200 kg of binder per m3 of clay
Oulu + 30% slag (200kg/m³)	951,1	1887,1	CEMIIIB: EAF G3-G6 Slag (70:30)	200 kg of binder per m3 of clay

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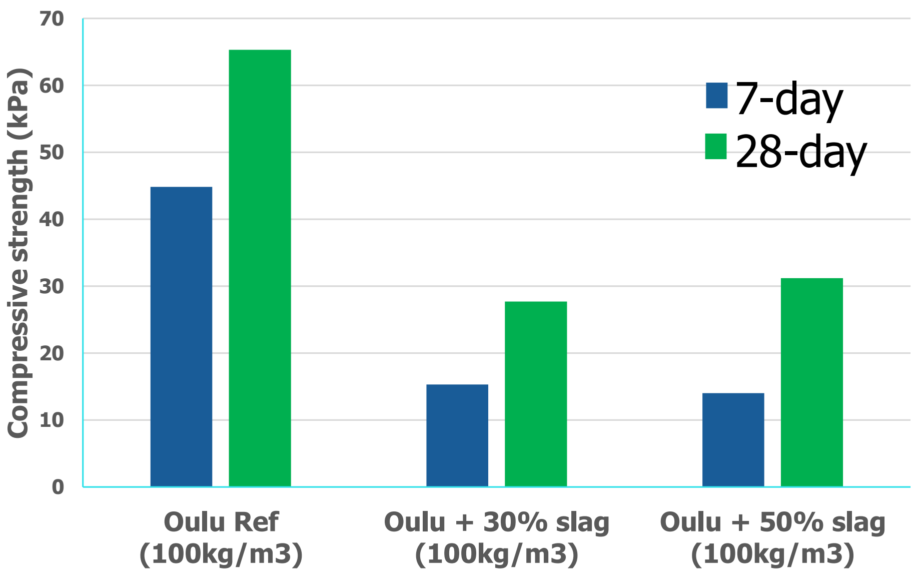
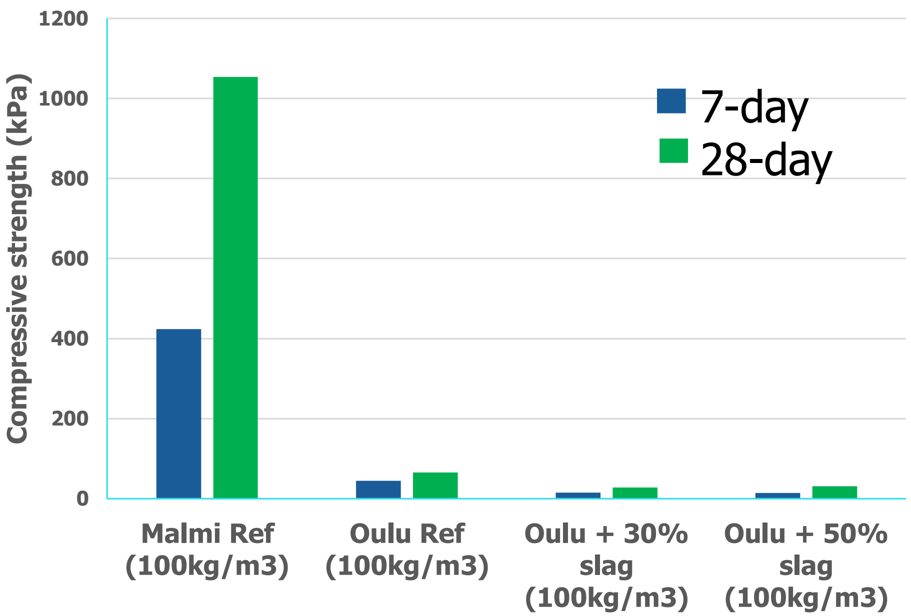
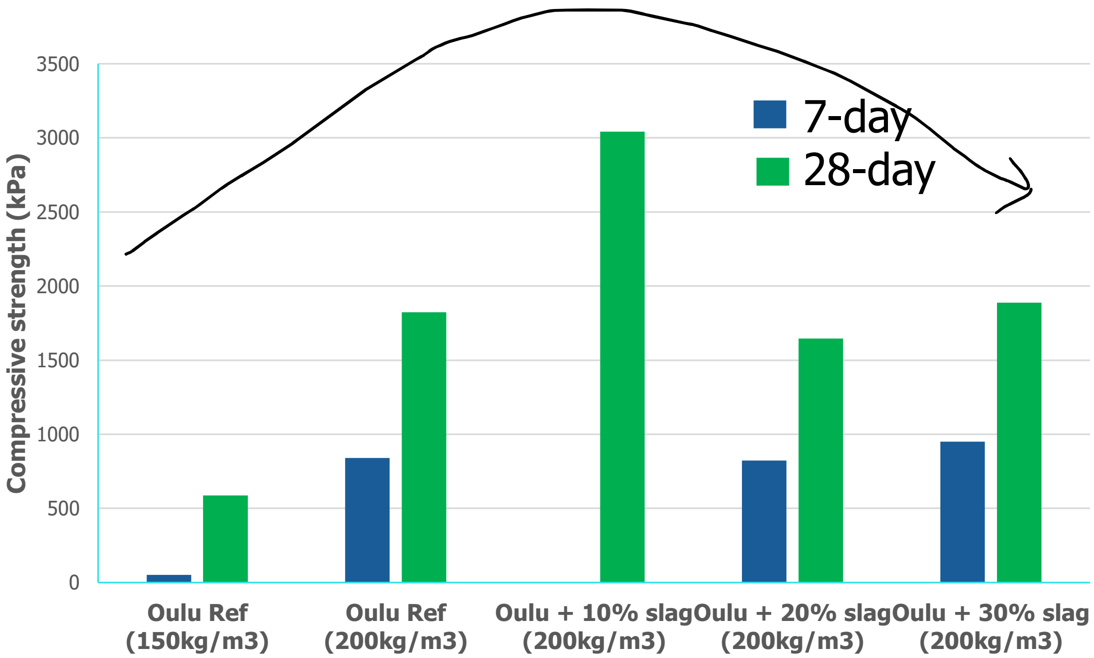
Results

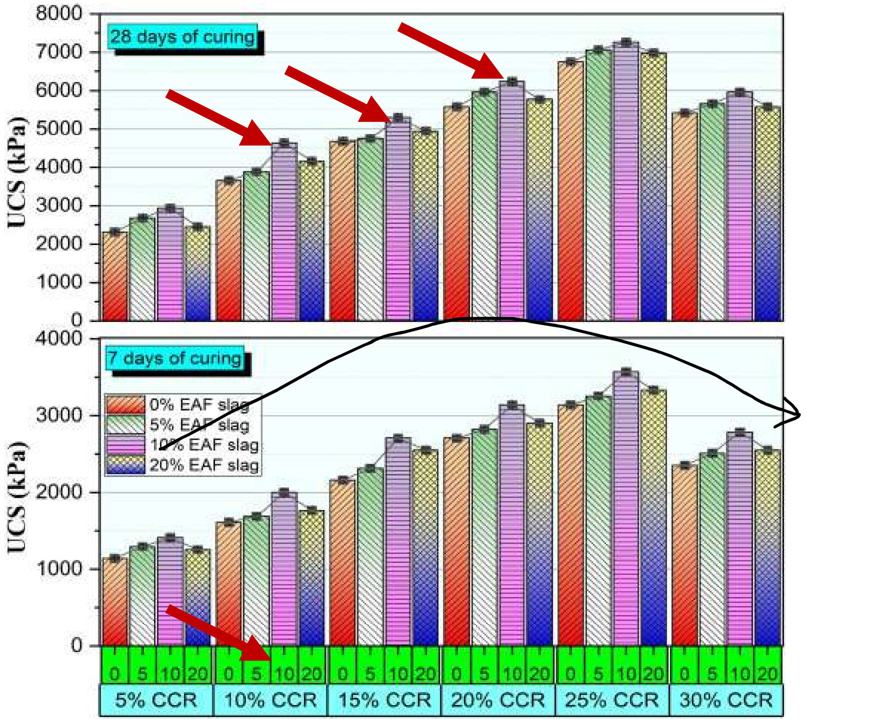

Compressive strength (kPa)
70
60
50
40
30
20
10
0
7-day
28-day
Oulu Ref (100kg/m3)
Oulu + 30% slag (100kg/m3)
Oulu + 50% slag (100kg/m3)


Compressive strength (kPa)
1200
1000
800
600
400
200
0
7-day
28-day
Malmi Ref (100kg/m3)
Oulu Ref (100kg/m3)
Oulu + 30% slag (100kg/m3)
Oulu + 50% slag (100kg/m3)

Results



UCS results of Oulu clay combined with CEMIII/B and different percentage EAF granulate modified slag replacement



UCS of clay stabilized with Calcium carbide residue (CCR) and EAF replacement after 7, 28 days curing (Mahmoudi et al, 2026)

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Effect of binder content

- Cement and granulated modified EAF slag synergistically stabilize sulfidic soft clay well with 10% EAF slag replacement
- At higher binder content (eg: 200kg/m^3) pH is suitable enough for dissociation of ions from EAF slag
- In the highly alkaline environment created by cement, soluble silicate and aluminate species released from cement, EAF slag, and, to a lesser extent clay, react with Ca^{2+} ions to produce C-S-H and C-A-S-H and create long term strength gain through pozzolanic reaction (Mahmoudi et al, 2026).
- Higher EAF slag levels (>10%) show lower strength, likely due to reducing cohesion, increasing voids, and weakening chemical binding in sulfuric soil.

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Conclusion and next steps

- Better strength gain of EAF slag added samples in higher content of cement would imply that if we can provide a liming agent with the EAF slag, the strength gain could still occur.
- Triaxial testing for better understanding of saturated in-situ behavior
- Assessing the environmental aspects and leaching properties

Hiiltä sitovat rakennusmateriaalit suomalaisista sivuvirroista (HIRAS)

Carbon-sequestering building materials from Finnish side streams (HIRAS)

HIRAS
Hiiltä sitovat rakennusmateriaalit suomalaisista sivuvirroista

- Projektin aikataulu:
  - 09/2025 – 05/2028
- Konsortio:
  - Aalto yliopisto, koordinoija
  - Geologian tutkimuskeskus (GTK)
  - Savonia
  - Oulun yliopisto

- Project schedule:
  - 09/2025 – 05/2028
- Consortium:
  - Aalto University, coordinator
  - Geological Survey of Finland
  - Savonia University of Applied Sciences
  - University of Oulu

Aalto University School of Engineering
GTK
UNIVERSITY OF OULU
SAVONIA

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Hankesuunnitelman esittely, keskeinen sisältö ja tavoitteet

Project plan, key content and objectives

- Tutkimusprojektin tavoitteena on edistää Suomen tavoitteita siirtymisessä hiilineutraaliin ja kiertotalousvetoiseen yhteiskuntaan.
- Hankkeen tavoitteena on kehittää uusia rakennustuotteita, kuten hiilinegatiivisia keinotekoisia kiviaineksia ja vähäpäästöisiä komposiittimateriaaleja pääasiassa infrastruktuurin kehittämiseen hyödyntäen epätavanomaisia mutta runsaita suomalaisia sivuvirtoja.
- Tutkittavia sivuvirtoja ovat mm. biohiili, rakennustyömaiden ylijäämämaat, talteen otettu hiilidioksidi, terästeollisuuden kuonat ja kaivosten rikastushiekat.
- Projektissa myös testataan suunniteltujen kovettuneiden komposiittien kestävyysominaisuuksia kolmella eri paikkakunnalla Suomessa.

- The research project aims to promote Finland's goals in the transition to a carbon-neutral and circular economy driven society.
- The project aims to develop novel building products, like negative emission artificial aggregates and low emission cementitious materials mainly for infrastructure development utilising relatively unconventional yet abundant Finnish side streams.
- Some side streams include surplus earthworks from construction sites, biochar from organic wastes, CO_2 from anticipated direct air capture units, industrial slags and mine tailings.
- HIRAS will test the durability characteristics of these unique envisioned cementitious composites in three geographically different Finnish locations.

Kiitos

Photograph by: Esa Kapila / Aalto University

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