

ESTEP 2025 Annual Event

28-30 October 2025
Udine (ITALY)

How decarbonisation, digitisation
and circular solutions forge the
sustainable European steel future?

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SLAG2BUILD

State of the Art in Dry Granulation of Ladle Furnace Slag



DIGIMET



DANIEMI AUTOMATION



**UNIVERSITÀ
DEGLI STUDI
DI UDINE**
HIC SUNT FUTURA

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SLAG2BUILD



Fig.3 Representation of LF slag before and after cooling, **a** hot LF slag in the ladle, **b** LF slag after cooling



**Ordinary Portland
cement replacement**



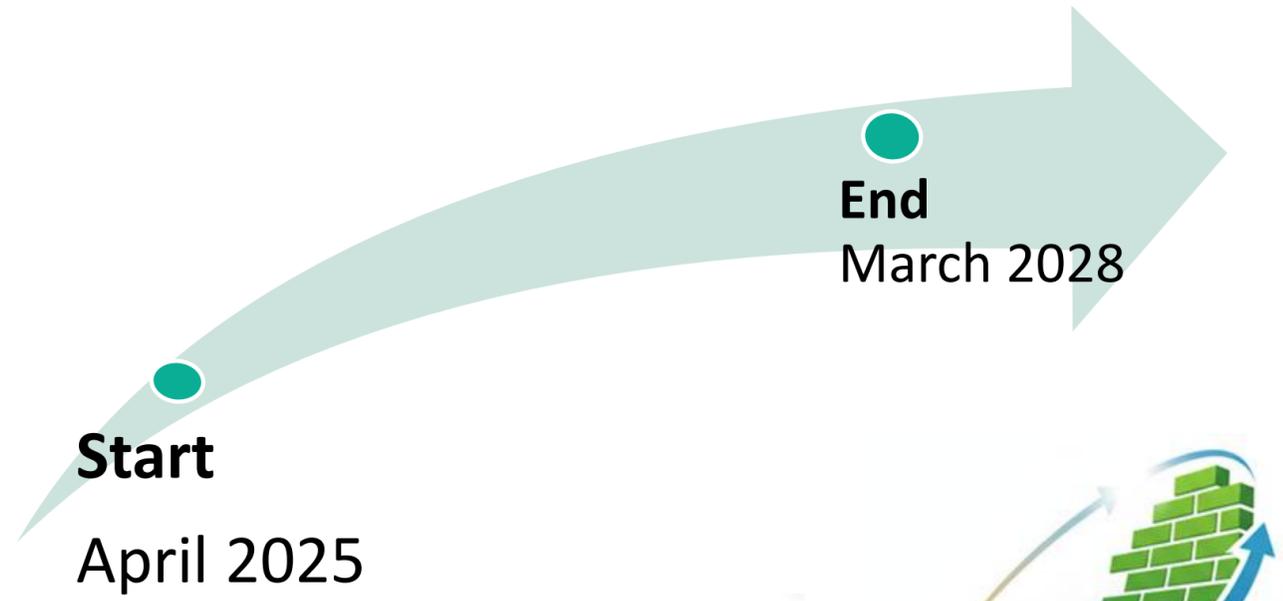
The research leading to these results has received funding from the European Union's Research Fund for Coal and Steel research programme under grant agreement number: 101193261



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General Info

Name	Forced air granulation of Ladle Furnace SLAG to enhance its hydraulic properties and allow its re-use as a replacement of Portland Cement in the BUILDing sector
Acronym	SLAG2BUILD
Project Number	101193261
Call	RFCS-2024-CSP
Topic	RFCS-2024-CSP
Type of action	RFCS Project Grants
Total Cost	9 100 419 €
EU Funded	4 550 209 €



8 partners



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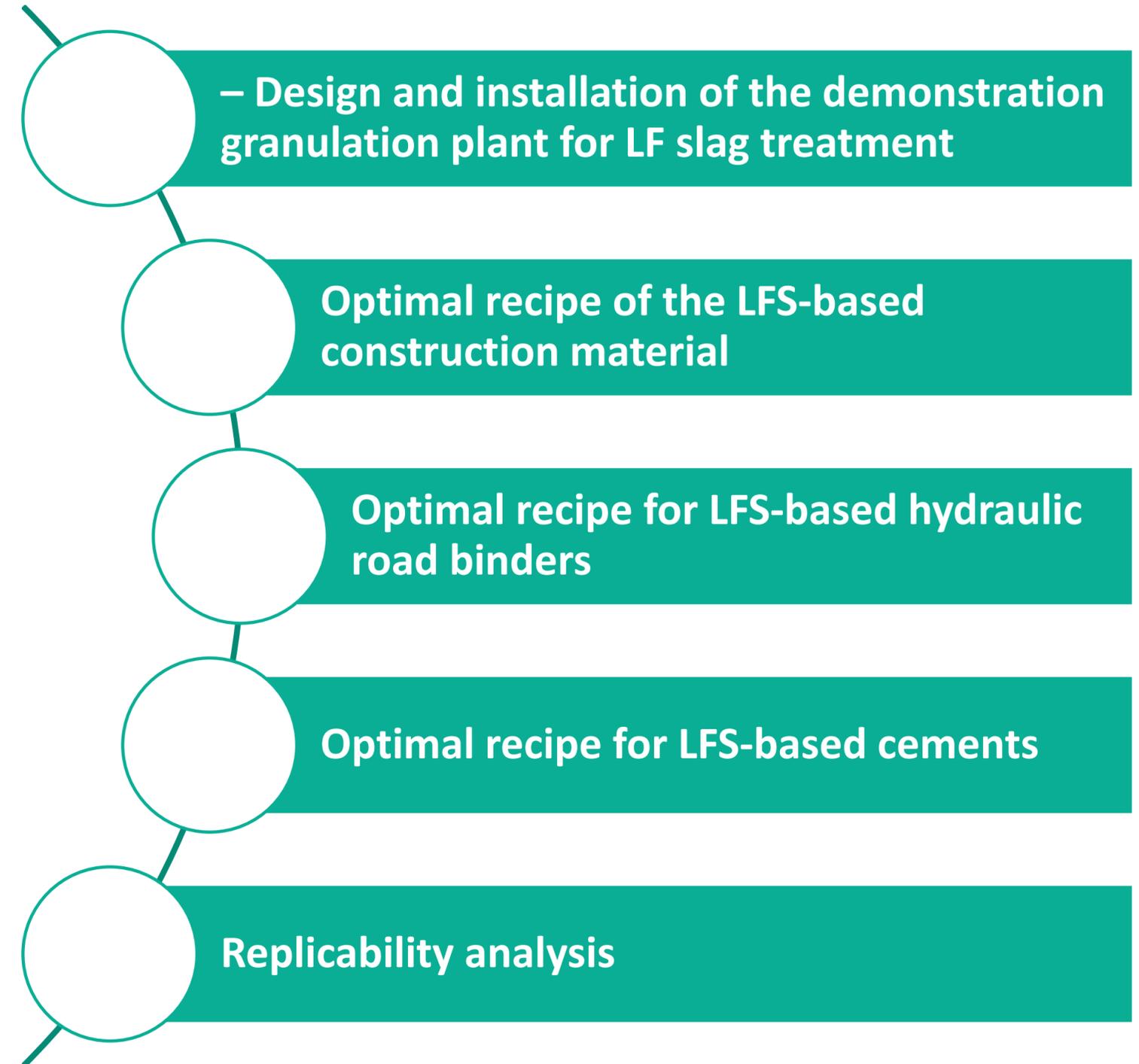
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Project Description and Objectives

The Slag2Build project aims to demonstrate, at industrial scale (TRL 8), the technical and environmental feasibility of a large demonstrator **dry granulation technology** for the treatment of **Ladle Furnace Slag (LFS)**

The technology relies on a **controlled air-jet collision system to instantly quench liquid slag without using water**, thus preventing the generation of dust and alkali fumes typically associated with the Best Available Technique (BAT) currently adopted in the EU iron and steel industry

Slag2Build's innovation lies in transforming an unstable **by-product** into a **valuable secondary raw material** for hydraulic binders, road stabilisers, and cementitious products, addressing both industrial decarbonisation and resource efficiency goals set by EU policy



Project Targets and Environmental Benefits



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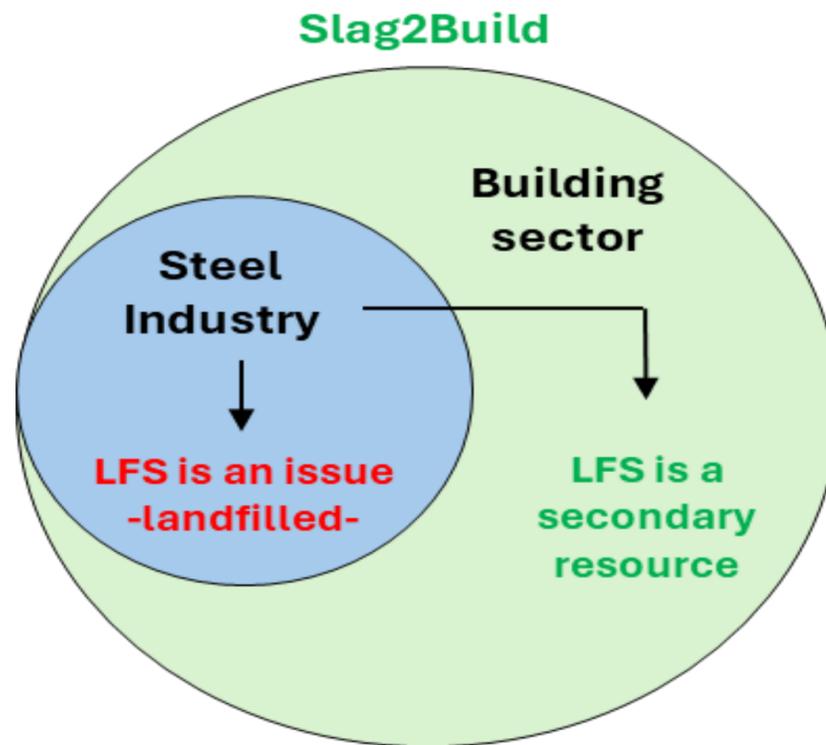


Figure 1 – Slag2Build circular economy approach

Current Challenge: STOMANA treats 25,000 t/y of LFS using BAT, generating:

- 25,000 t/y of SiO₂-rich dust
- 25,000 m³/y of water consumption
- 25 t/y of sulphur-rich compounds
- 8,250 m³/y of landfilling

Slag2Build Solution: Demonstration of TENOVA's patented dry granulation (TRL5 → TRL8), enabling:

- Air-jet quenching of LFS into granules
- On-site treatment of 2,000–2,500 t of LFS

Circular Economy Impact:

- Carmeuse to recycle 2,500 t of LFS into 7,000 t of construction materials
- Avoids 2,500 t of Portland cement, saving:
 - 5,500 t of raw materials
 - 3.3 GWh of energy
 - 2,500 t of CO₂ emissions

EU-Wide Potential (3.4 MtLFS/y):

- Save 3.4 Mm³ water & 1.1 Mm³ landfill space
- Avoid 3,400 t/y sulphur-rich waste
- Prevent 3.4 Mt CO₂ emissions & 448 GWh energy use



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Current LFS Production in the EU

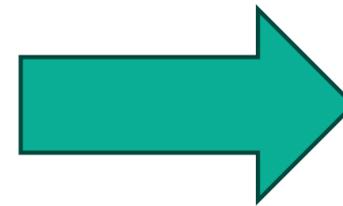
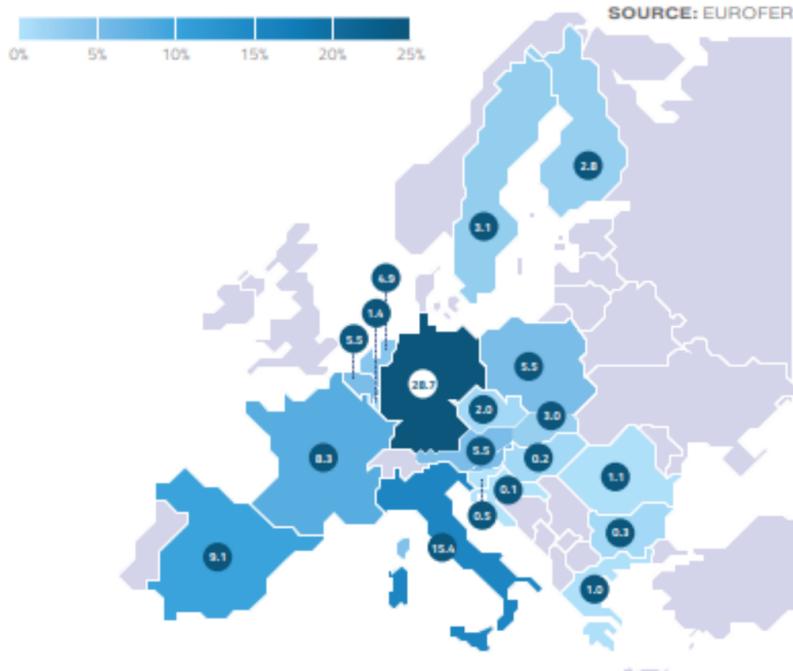
The EU steel industry produces approximately 40 Mt of slags per year, of which Ladle Furnace Slag (LFS) represents around 8–10 %, or 3.4 Mt / year. Despite advances in internal recycling, 14 % of total slags—including most LFS—are still landfilled [Eurofer - EUROPEAN STEEL IN FIGURES 2025].

Steel production (EU-27): ~129 Mt steel/year.
Slag generation (EU): ~40 Mt total/year [Huang et al, 2022]

EU COUNTRIES IN DESCENDING ORDER OF CRUDE STEEL PRODUCTION
TABLE • 2023-2024
SOURCE: EUROFER

	2023	2024
1 GERMANY	35,395	37,234
2 ITALY	21,055	20,007
3 SPAIN	11,352	11,832
4 FRANCE	10,011	10,753
5 BELGIUM	5,864	7,135
6 AUSTRIA	7,133	7,130
7 POLAND	6,428	7,113
8 NETHERLANDS	4,677	6,395
9 SWEDEN	4,235	4,002
10 SLOVAKIA	4,377	3,866
11 FINLAND	3,811	3,664
12 CZECH REPUBLIC	3,369	2,548
13 OTHERS	2,040	1,948
14 LUXEMBOURG	1,900	1,825
15 ROMANIA	1,622	1,364
16 GREECE	1,181	1,336
17 SLOVENIA	559	598
18 BULGARIA	489	450
19 HUNGARY	477	232
20 CROATIA	212	153
EU27	126,186	129,586

EU COUNTRIES SHOWN BY RELATIVE SHARE OF CRUDE STEEL PRODUCTION
MAP • 2024
SOURCE: EUROFER



30–80 kg LFS per tonne of steel refined through secondary metallurgy [Jeongmin Ra et Al, 2025]



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LFS, origin, properties and current management

LFS arises from secondary metallurgy and is typically characterized by high basicity ($\text{CaO}/\text{SiO}_2 > 2$)

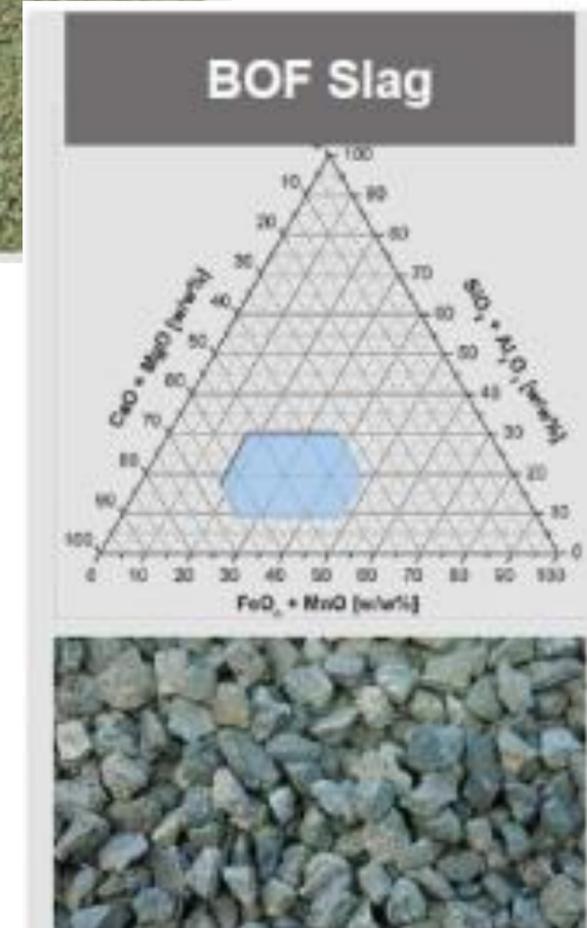
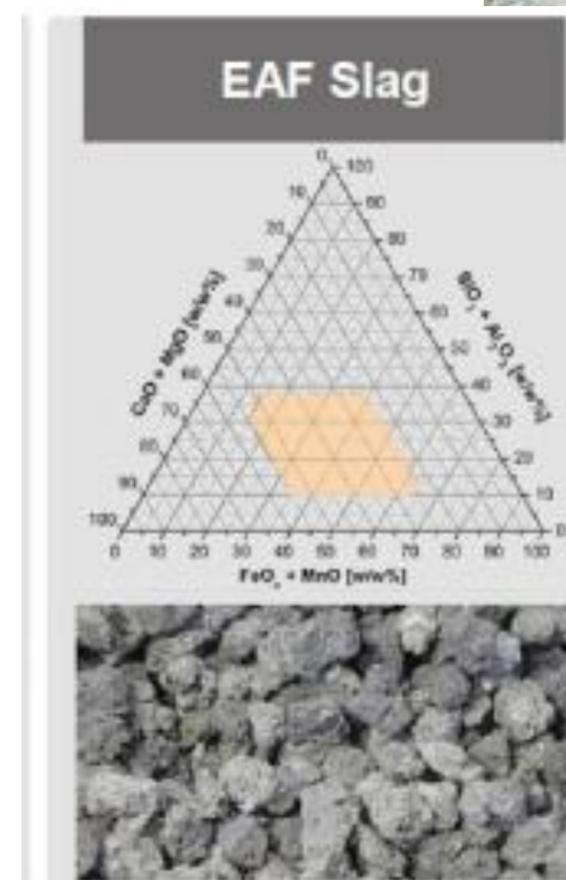
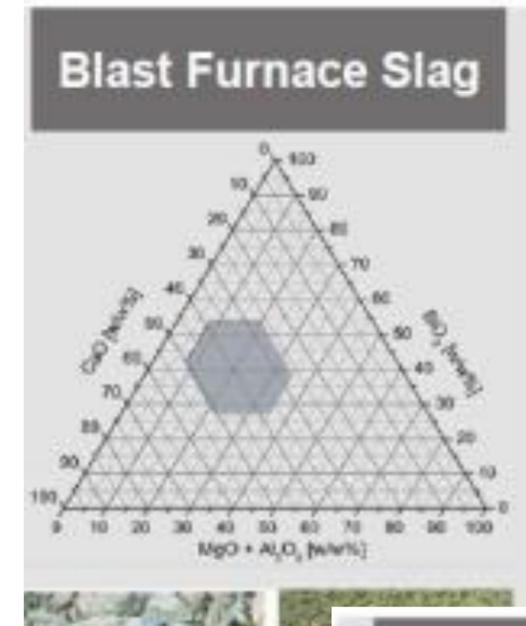
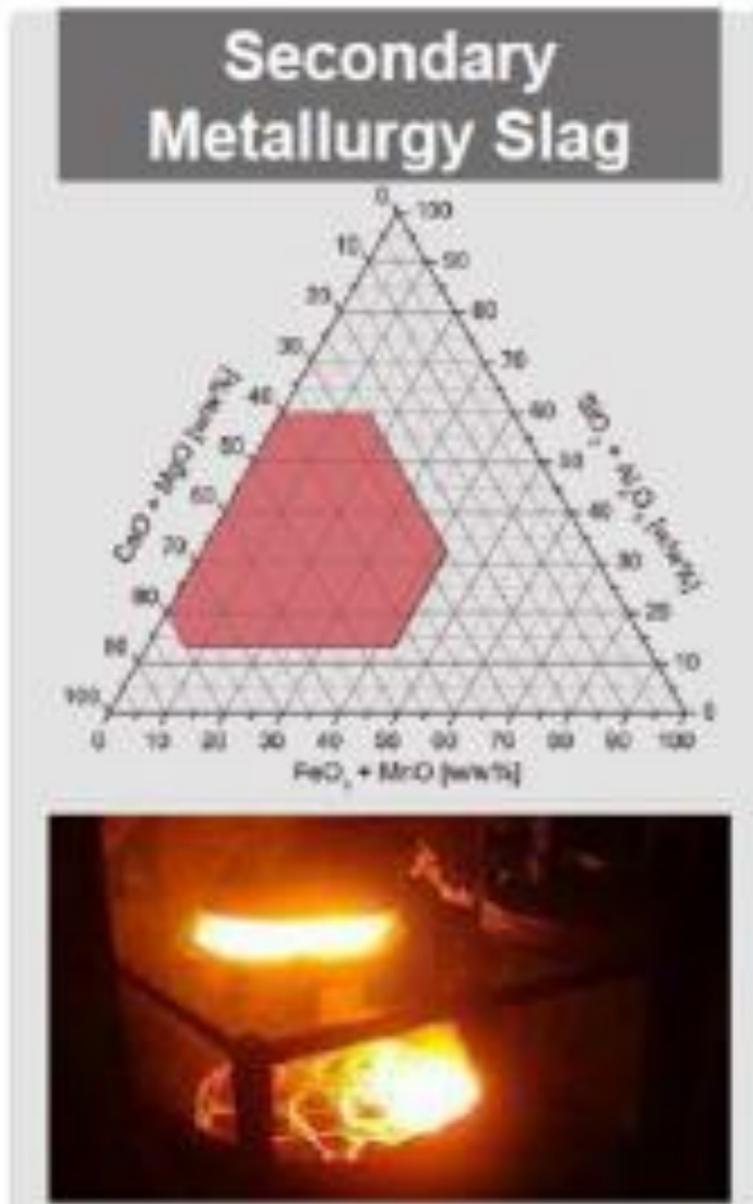
- Density: 2.6–2.8 g/cm³.
- Particle size: up to 70% <200 μm.

Typical LFS composition includes:

- CaO (40–60 %)
- Al₂O₃ (5–40 %)
- SiO₂ (3–30 %)
- MgO (2–15 %)

- **High variability due to steel composition and refining practice.**

- Dicalcium silicate (C₂S)—mainly α, β, or γ polymorphs **depending on cooling.**
- Free CaO and MgO, responsible for hydration expansion.
- Calcium aluminates (C₁₂A₇, C₃A) and gehlenite (C₂AS) in high-alumina slags.



LFS, origin, properties and current management



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Secondary Metallurgy Slag



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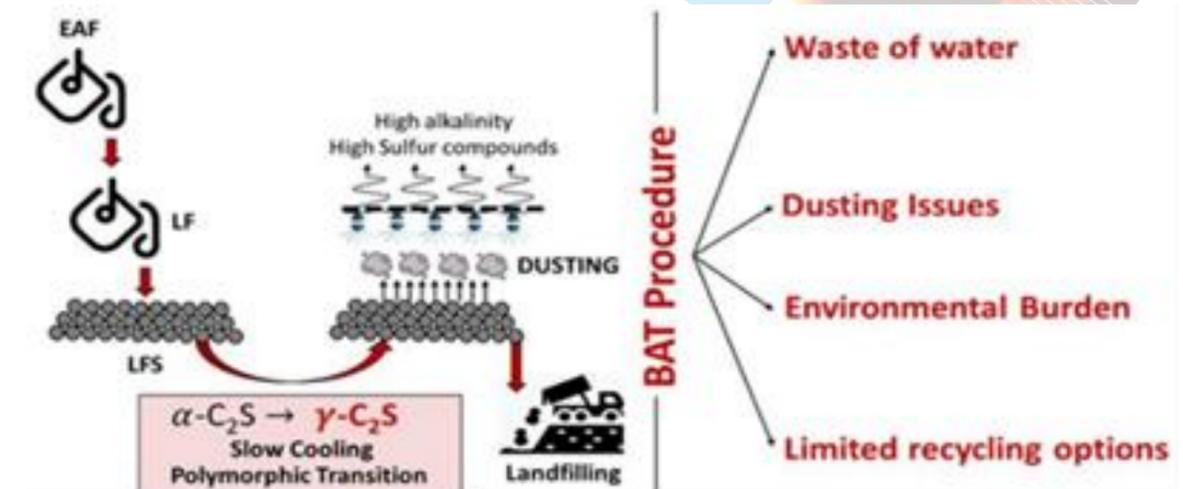
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The standard BAT for LFS management in European steelworks involves **iron recovery followed by slow air cooling and landfilling**, with only limited internal recycling into the EAF practiced at a few sites

Slow cooling solidification promotes belite polymorphic transformation ($\alpha \rightarrow \gamma$), leading to disintegration, dusting, and instability.

This mandates **water-spray cooling** (~ 1 m³ / t LFS) to control fine dusts. Such practices result in the release of alkali **sulphur-bearing fumes** (~ 1 kg / t LFS), thus increasing both water and air pollution





Possible applications and Main Barriers

LFS possible applications:

- Supplementary Cementitious Material (SCM).
- Hydraulic road binders.
- Soil stabilization and filler.

The main obstacles are:

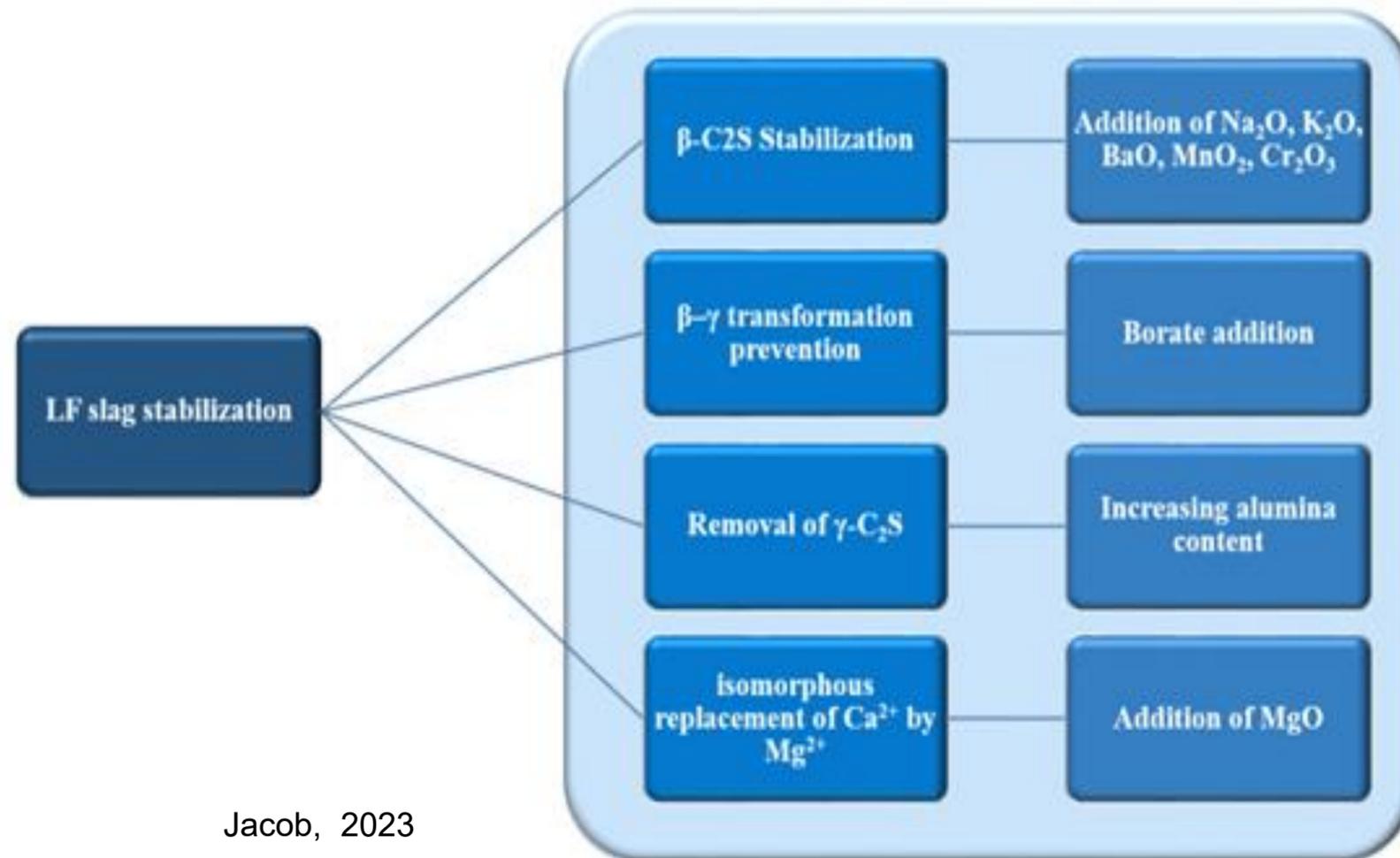
1. Volume instability ($\beta \rightarrow \gamma$ - C_2S and CaO/MgO hydration).
2. Dusting and disintegration during cooling .
3. Leaching risks of minor oxides
4. Conversely, **calcium-aluminate slags**, enriched in phases such as mayenite ($C_{12}A_7$) and tricalcium aluminate (C_3A), exhibit high hydraulic reactivity but can suffer strength degradation due to the metastability of intermediate hydrates (C_2AH_8 , C_4AH_{13} , CAH_{10}) that eventually convert to the stable C_3AH_6 phase
5. Lack of standardized recycling routes

These constraints have prevented the large-scale reuse of LFS, making landfilling the default solution across Europe.



Example of Slag stabilization

Chemical stabilization aims to inhibit the $\beta \rightarrow \gamma$ transition of C_2S or to replace unstable phases with more stable compounds.



Jacob, 2023

The addition of oxides such as Na_2O , K_2O , BaO , MnO_2 , or Cr_2O_3 can promote the formation of secondary stabilized C_2S phases or prevent their formation altogether [**Suguna et al, 2025**]:

- A maximum of 0.5 wt% B_2O_3 addition at the industrial scale could stabilize LF slag with a basicity of 1.54.
- Using B_2O_3 in Cr_2O_3 bearing stainless steel slags as B_2O_3 (>2%) addition increases chromium distribution in the Ca_2SiO_4 phase.
- increase in B_2O_3/Al_2O_3 ratio, the Ca_2SiO_4 phase decreased, and $Ca_{11}B_2Si_4O_{22}$ phase increased, sufficient to prevent the disintegration of LF slag
- addition of 10 wt% B_2O_3 to LF slag \rightarrow borosilicate glass for semiconductor applications

Borax and barium carbonate were also used to stabilize the β phase. Present investigation reveals that disintegration of ladle furnace slag can be prevented either by addition of 0.2% borax or 2% barium carbonate. [**Ghorai 2017**]

Other approaches involve increasing alumina content to promote stable phases such as mayenite ($C_{12}A_7$), gehlenite (C_2AS), and β - C_2S , effectively reducing γ - C_2S formation [**Jacob, 2023**]

Effect of Cooling on LFS: Cooling Rate as Key Driver of Mineral Stability

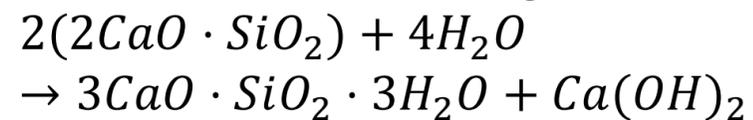


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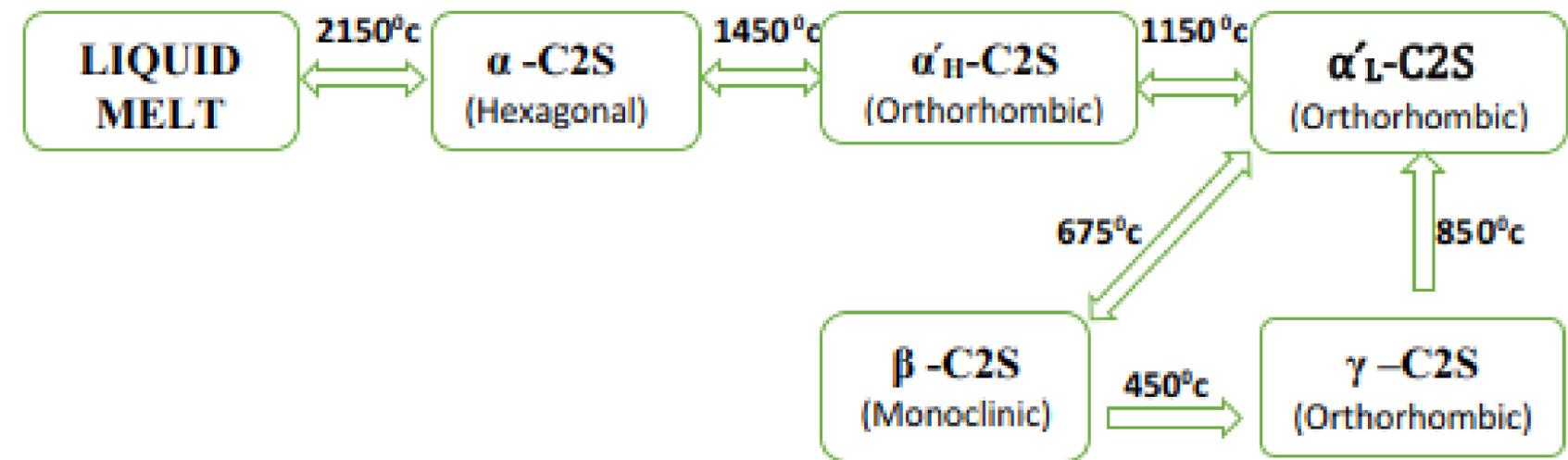
SILICA SLAG → SiO₂ > 10%

During the slow cooling process, these slags tend to self-pulverize due to the conversion of β -C₂S into γ -C₂S, a phase that **is not hydraulically active**

The β -C₂S phase is hydraulically active, reacting with water to form **calcium silicate hydrate (C-S-H)**, which contributes to cement strength:



This difference is linked to crystallography: β -C₂S has a disordered monoclinic structure conducive to hydration, whereas γ -C₂S has an orthorhombic and inert configuration



Effect of Cooling on LFS: Cooling Rate as Key Driver of Mineral Stability

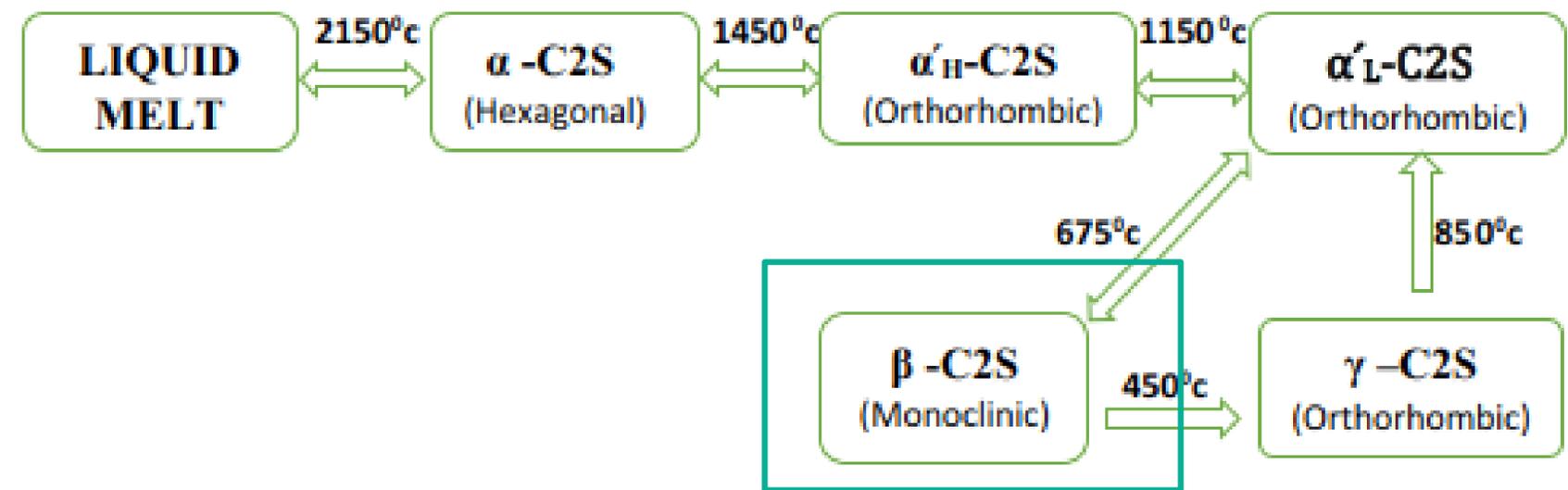
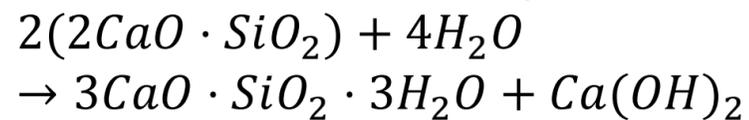


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□ Main findings:

1. Rapid cooling can stabilize the β-C₂S phase over a wide temperature range (25–700 °C) [Sheshukov, 2017]
2. The optimum cooling rate for successful C₂S stabilization using laboratory studies was 5°C/s. [Jacob, 2023]
3. Tests carried out at Sandvik Materials Technology demonstrated that air granulation at slag flow rates of 15–30 kg/min produced stable, dust-free granules containing predominantly β-C₂S with little or no γ-C₂S [Lindvall, 2019]
4. Optimizing cooling conditions through air quenching can thus minimize free MgO (f-MgO) and free CaO (f-CaO) phases, which are responsible for volume expansion during hydration. When water is present, free lime (f-CaO, hard-burned lime) and free magnesia (f-MgO, periclase) can undergo a reaction to respectively form portlandite (Ca(OH)₂) and brucite (Mg(OH)₂). As a result, f-CaO and f-MgO expand by 92% and 120%, respectively [Erlin, , 2003]. These reactions may also contribute to the disintegration phenomenon.

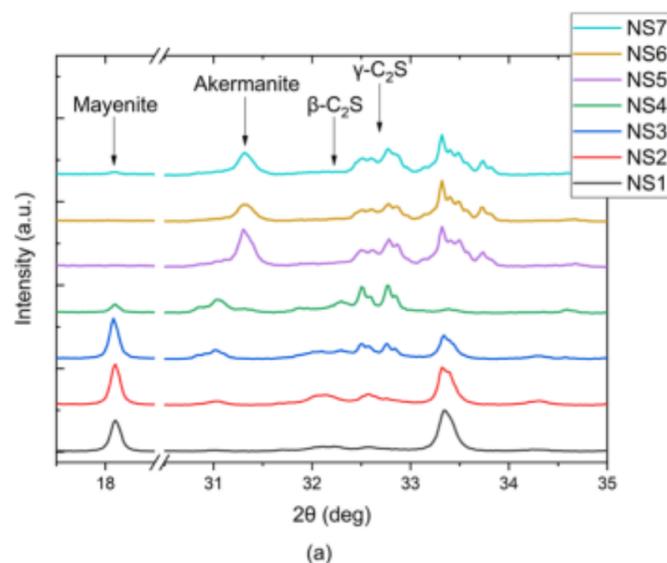
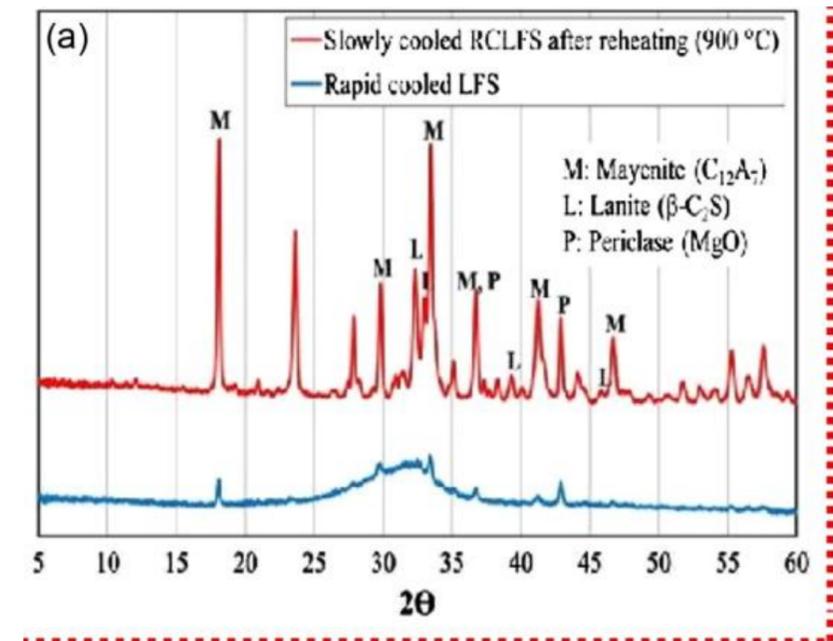
Effect of Cooling on LFS: Cooling Rate as Key Driver of Mineral Stability



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Alumina SLAG → Al₂O₃ > 10%

- Ladle slags with high alumina content (Al₂O₃) are typically dominated by calcium aluminate phases such as mayenite (Ca₁₂Al₁₄O₃₃, C₁₂A₇) and tricalcium aluminate (3CaO·Al₂O₃, C₃A).
- The phases are highly sensitive to cooling conditions, which determine their degree of crystallinity and hydration reactivity [Ouffa, 2024]. In the hydrated state, these slags can form portlandite (Ca(OH)₂), brucite (Mg(OH)₂), katoite (Ca₃Al₂(OH)₁₂), hydrotalcite, and other layered double hydroxides, contributing to mechanical strength and chemical stability.
- Conventional air-cooled LFS usually contains C₁₂A₇ in crystalline form. Rapid air cooling has proven to be an effective and practical approach for achieving partial amorphization, increasing the content of active C₁₂A₇, and improving both early hydration activity and mechanical strength.
- to promote amorphization of C₁₂A₇, other techniques are mechanical activation, chemical activation, and high-pressure treatment, but rapid cooling remains the most cost-effective and industrially viable option for large-scale application.



The effect of slag basicity and sulfur content on dusting behavior was studied in controlled laboratory conditions using synthetic LFS compositions [Mombelli, 2023]: while dissolved sulfur can also stabilize the β phase, excess sulfur tends to form CaS, which reacts with mayenite and locally reduces basicity, promoting dusting. Mayenite acts as a crucial phase for the overall slag stability, especially for its structural role as a matrix. Its presence has been detected for an Al₂O₃ content above 17.5 wt%. However, to provide sufficient hydro-static pressure on C₂S particles and suppress the β to γ transition, a mayenite content of at least 31.3 wt% is required. This can be reached when Al₂O₃ is higher than 25 wt%.



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Summary of Cooling Effects

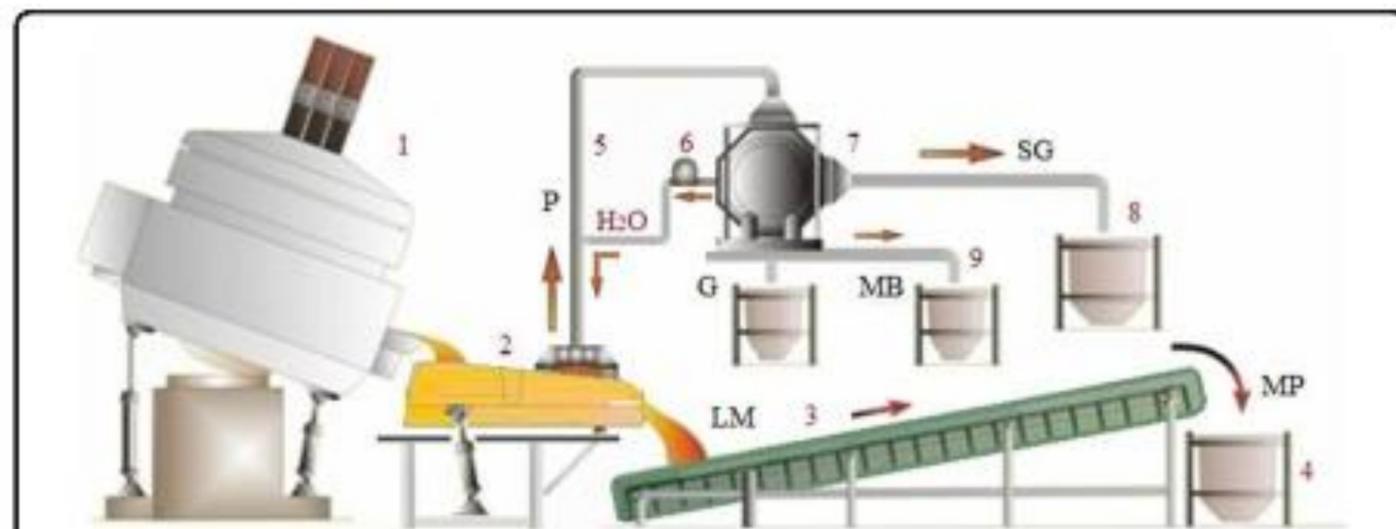
Cooling Type	Dominant Phase	Volume Stability	Reactivity	Environmental Impact
Slow (BAT)	γ -C ₂ S, f-CaO	Poor	Inert	High water use, dusting
Rapid (water quenching)	β -C ₂ S (amorphous)	Moderate	High	Explosion/leaching risks
Rapid (air quenching)	β -C ₂ S, vitreous	Excellent	High	Dry, safe, sustainable



LFS Granulation technologies

Several dry or semi-dry slag granulation systems have been proposed:

- Air blast granulation (Mitsubishi, FEhS) – uses pressurized air to form spherical granules but requires large facilities and contact maintenance [Ando, 1985]
- Rotating drum systems (Sumitomo, Slag-Rec) – promote controlled cooling but need extensive plant modification. [Nakada, 1983]
- Centrifugal atomization (CSIRO) – produces high glass content (> 95 %) but low throughput and complex design. [CSIRO Annual Report 2007/08]
- Hydro-vacuum granulation (HVG) – hybrid water/air vortex cooling, still water-dependent.



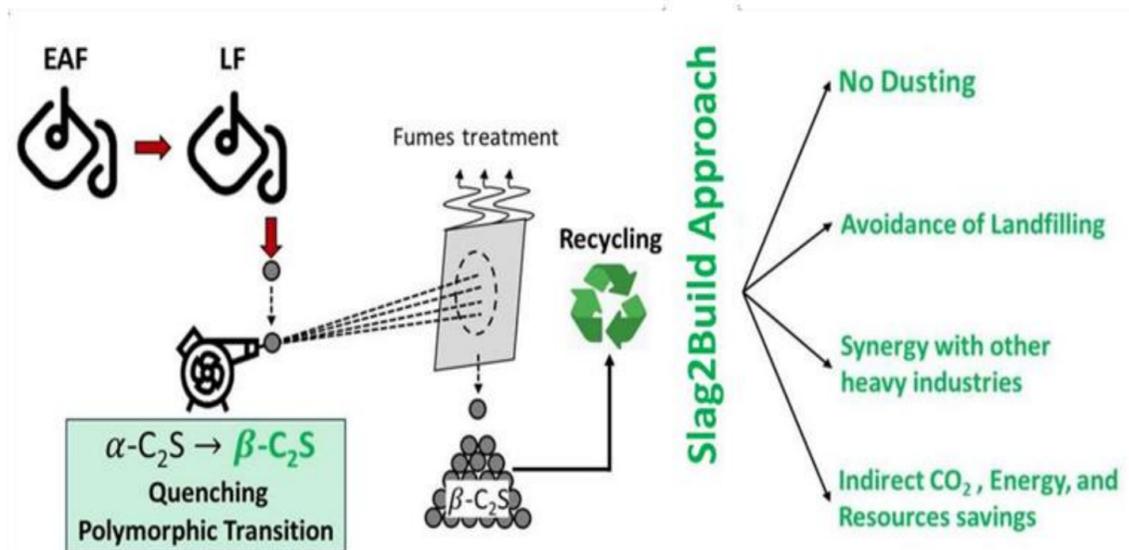
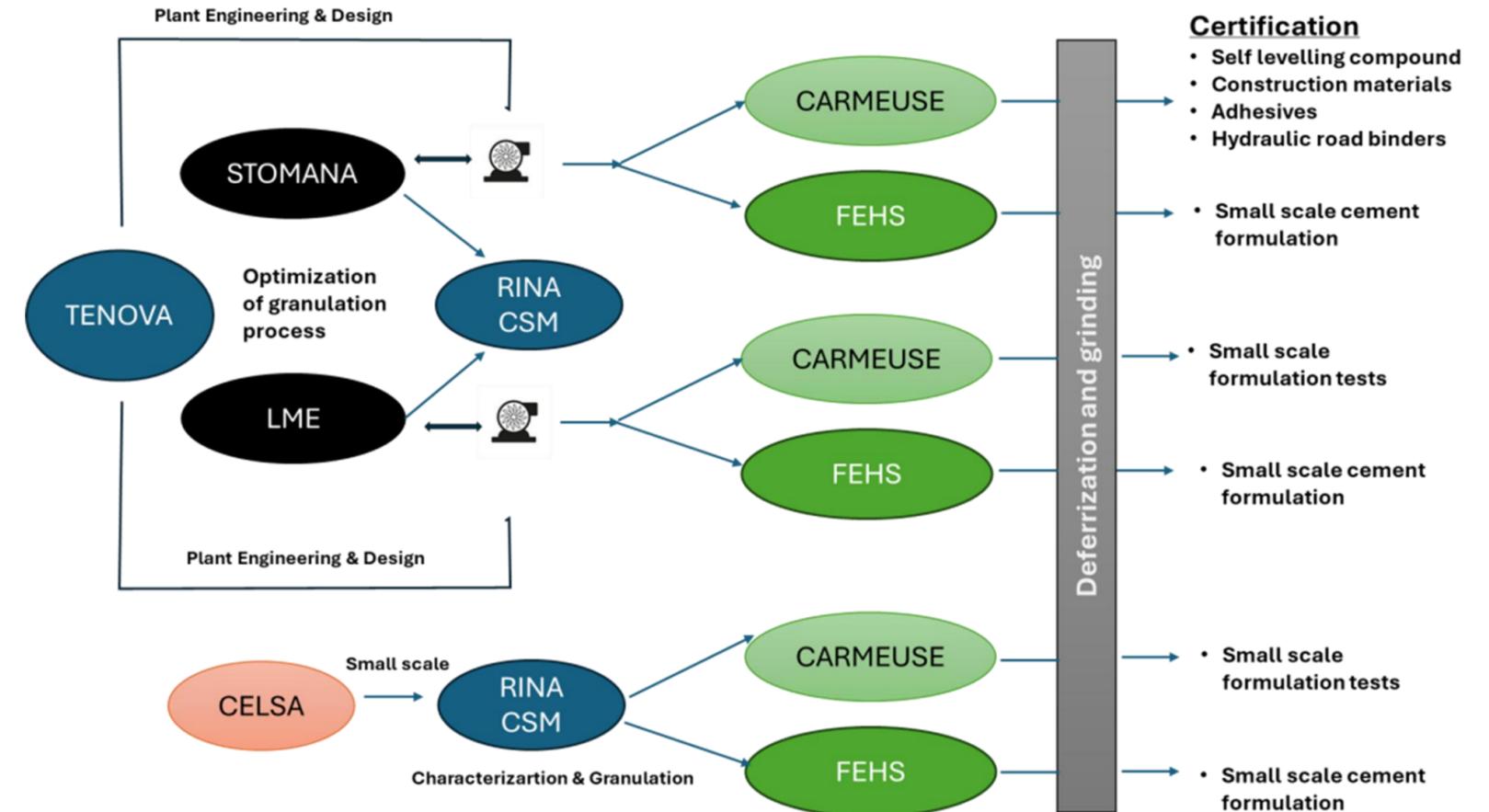
[Sakhvadze, 2021]

All these systems involve direct contact between molten slag and mechanical parts, leading to erosion, clogging, and limited operational reliability [Damidot, 2011]. None has yet reached TRL 8 demonstration for LFS, especially under EU conditions.



Slag2Build: Innovative Air-Jet Technology

The Slag2Build process introduces a non-contact air-jet granulation system in which a high-velocity air stream intercepts the molten LFS, promoting instantaneous fragmentation and solidification within a few meters of flight. The resulting granules (1–5 mm) are β -C₂S-rich, stable, and suitable for downstream milling and blending.



Advantages over existing approaches include:

- No water usage → eliminates dust suppression and alkali fume generation.
- No equipment–slag contact → drastically reduced maintenance.
- Compact installation → minimal retrofitting to the existing steel plant.
- High process yield (\approx 50 %) at pilot scale (TRL 5 – Ecoslag project).



Conclusions

Current Status

Conventional BAT treatment → high water use, dusting, landfilling. This mandates **water-spray cooling (~ 1 m³ / t LFS)** to control fine dusts. Such practices result in the release of alkali **sulphur-bearing fumes (~ 1 kg / t LFS)**, thus increasing both water and air pollution

Major obstacles to LFS use

1. Volume instability ($\beta \rightarrow \gamma$ -C₂S and CaO/MgO hydration).
1. Dusting and disintegration during cooling .
2. Calcium-aluminate slags, suffer strength degradation due to the metastability of intermediate hydrates (C₂AH₈, C₄AH₁₃, CAH₁₀) that eventually convert to the stable C₃AH₆ phase
3. Lack of standardized recycling routes

Findings from Literature:

- Rapid cooling can stabilize the β -C₂S phase for silica slags and can increase the content of active C₁₂A₇, and improving both early hydration activity and mechanical strength .
- Optimizing cooling conditions through air quenching can thus minimize free MgO (f-MgO) and free CaO (f-CaO) phases
- The content of Alumina is beneficial for glassy formation

How to realize:

- Systems involve direct contact between molten slag and mechanical parts, leading to erosion, clogging, and limited operational reliability
- The **Slag2Build project establishes** a technological breakthrough over current BAT and other granulation routes by combining non-contact dry quenching, industrial-scale implementation, and material valorisation pathways. Reuse pathway include:
 - Formulation of Construction Material
 - Formulation of Hydraulic Road Binders
 - Formulation of Cements



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Future activities

Next step:

- ✓ Benchmark analysis of current regulations
- ✓ Thermodynamic properties calculation
- ✓ Commissioning and operation of the demonstration unit at STOMANA
- ✓ Preliminary granulation test in RinaCSM

THANKS FOR YOUR ATTENTION!

For any questions:

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For any further information on the project:

SLAG2BUILD



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