Recycling Fe-rich slags in alkali activated cements and concretes for nuclear safety applications

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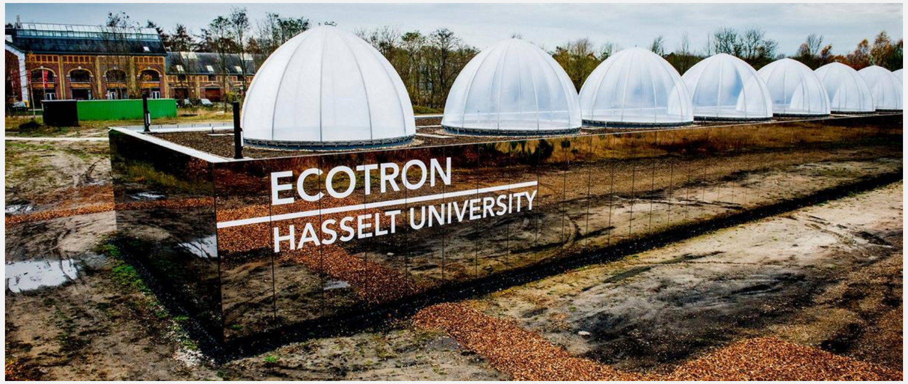
Nucleair Technologisch Centrum

Centre for Environmental Science (CMK):
KEY = MULTIDISCIPLINARITY

CMK conducts fundamental and applied research

1. To better understand **influences of the environment** on organisms
2. To develop and assess sustainable **clean technologies** to mitigate influences of the environment on organisms
3. To monitor, value and **optimize biodiversity and ecosystem services** under different stress conditions, including climate change



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Research @ NuTeC

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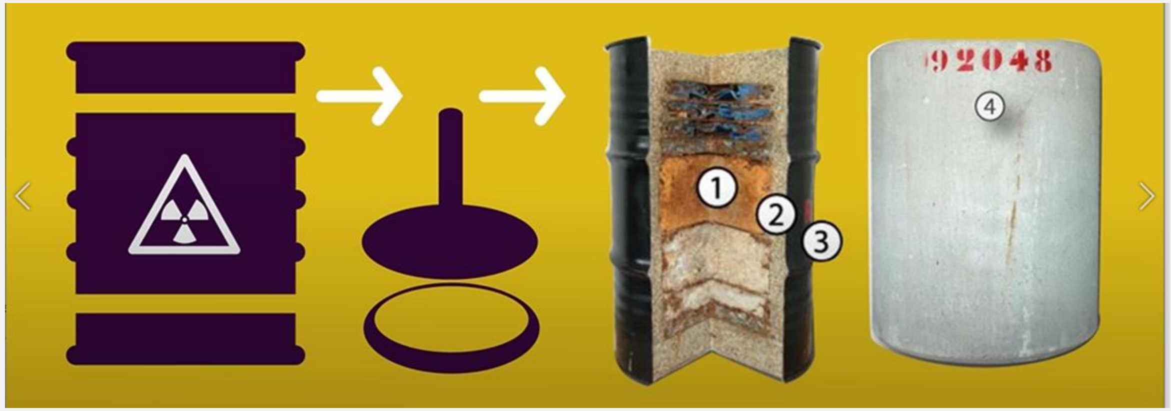

- **Environmental Technology**
  - **Nuclear decommisioning**
    - Mapping and characterisation
  - **Immobilisation of nuclear waste**
    - Developping new cementitious binders
  - **Recycling of NORM (naturally occurring radioactive materials) in construction**
    - Developping new cementitious binders

- **Medical-Nuclear Technology**
  - Medical dosimetry for radiotherapy

NuTeC Nucleair Technologisch Centrum

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Outlook

1. **Introduction - Fe-rich slags in alkali activated cements / concretes**

2. Fe-rich slag based alkali-activated materials in shielding applications

3. Conclusions

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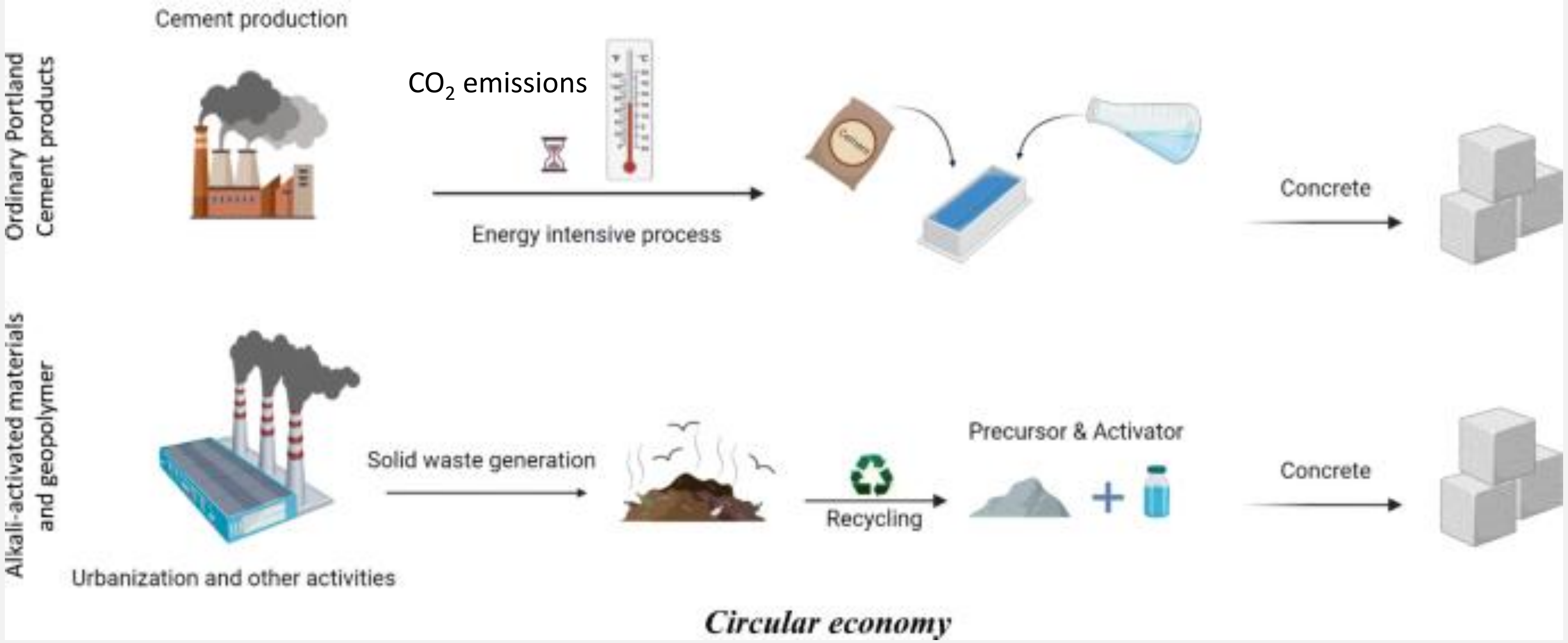
Towards a new industrial landscape?

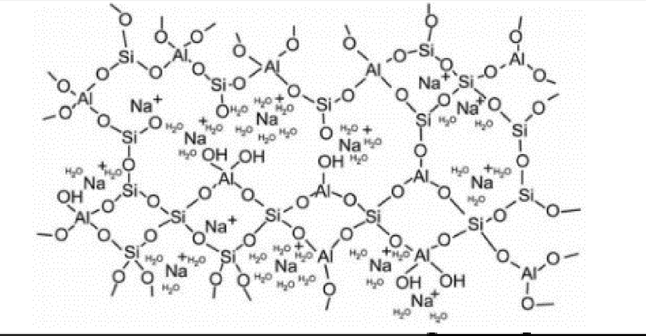


Alkali Activated Materials:

Source material = **SiO_2 and Al_2O_3** + Activator = Alkaline solution → Aluminosilicate polymer

Ground granulated blast furnace slag (*GGBFS*)
Fly ash
Metakaolin

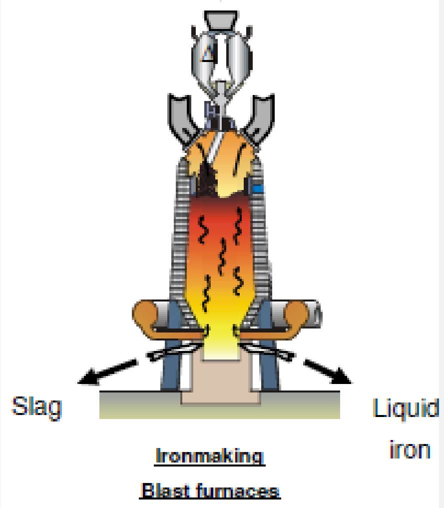
mainly alkali-hydroxide/silicate



REVIEW: Hertel & Pontikes, Journal of Cleaner Production 258 (2020) 120610
Nodehi & Taghvaee, Circular Economy and Sustainability, 2 (2022) 165–196

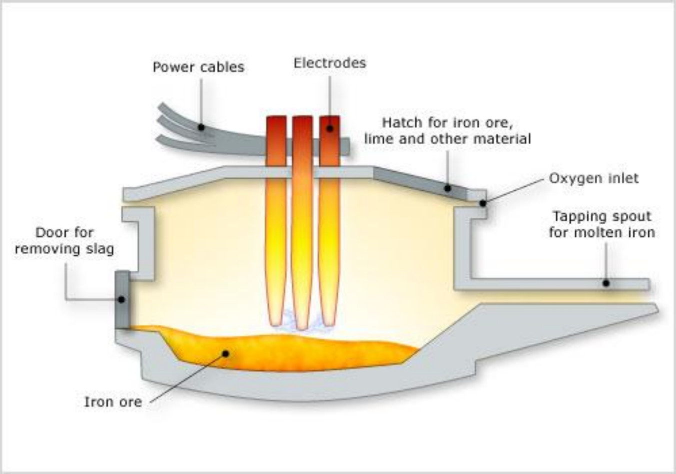
Towards a new industrial landscape?

- Iron & steel production



Blast Furnace

Blast Furnace Slag



Electric Arc Furnace

EAF slag

- Coal combustion

Fly ash

Alternative: Use of Non-ferrous metallurgy slag in AAMs?

- Secondairy melter
- Production of metals (Cu, Pb,…)

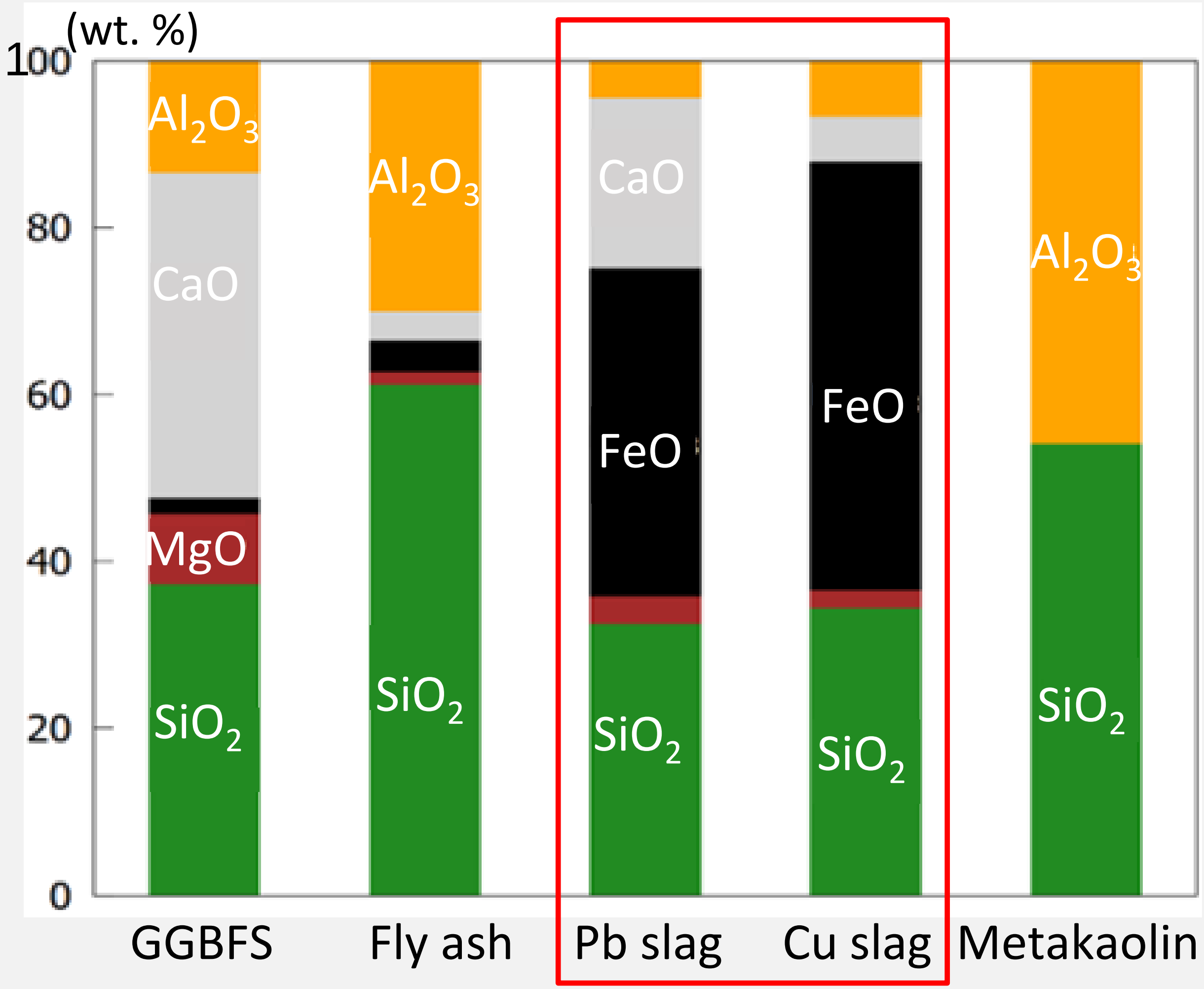


Figure based on PhD dissertation Hallet, V. High-Volume Replacement of Cement by Non-Ferrous-Metallurgy Slag and Impact of Limestone, Fineness and Grinding Aids, PhD dissertation (2022)

UHASSELT KNOWLEDGE IN ACTION

Alternative: Use of Non-ferrous metallurgy slag in AAMs?

- Fe-rich slag
  - **Quenched/granulated** ➔ increase **amorphous/reactive** content
  - Higher **CaO** content ➔ **higher reactivity**
    - Cu slag could use addition of CaO
    - Cu slag may require high-temperature treatment for removal hazardous elements
  - Fe can be present in reduced, **Fe(II)** state in this type of process, can be oxidized to Fe(III)

PhD dissertation Hallet, V. High-Volume Replacement of Cement by Non-Ferrous-Metallurgy Slag and Impact of Limestone, Fineness and Grinding Aids, PhD dissertation (2022)

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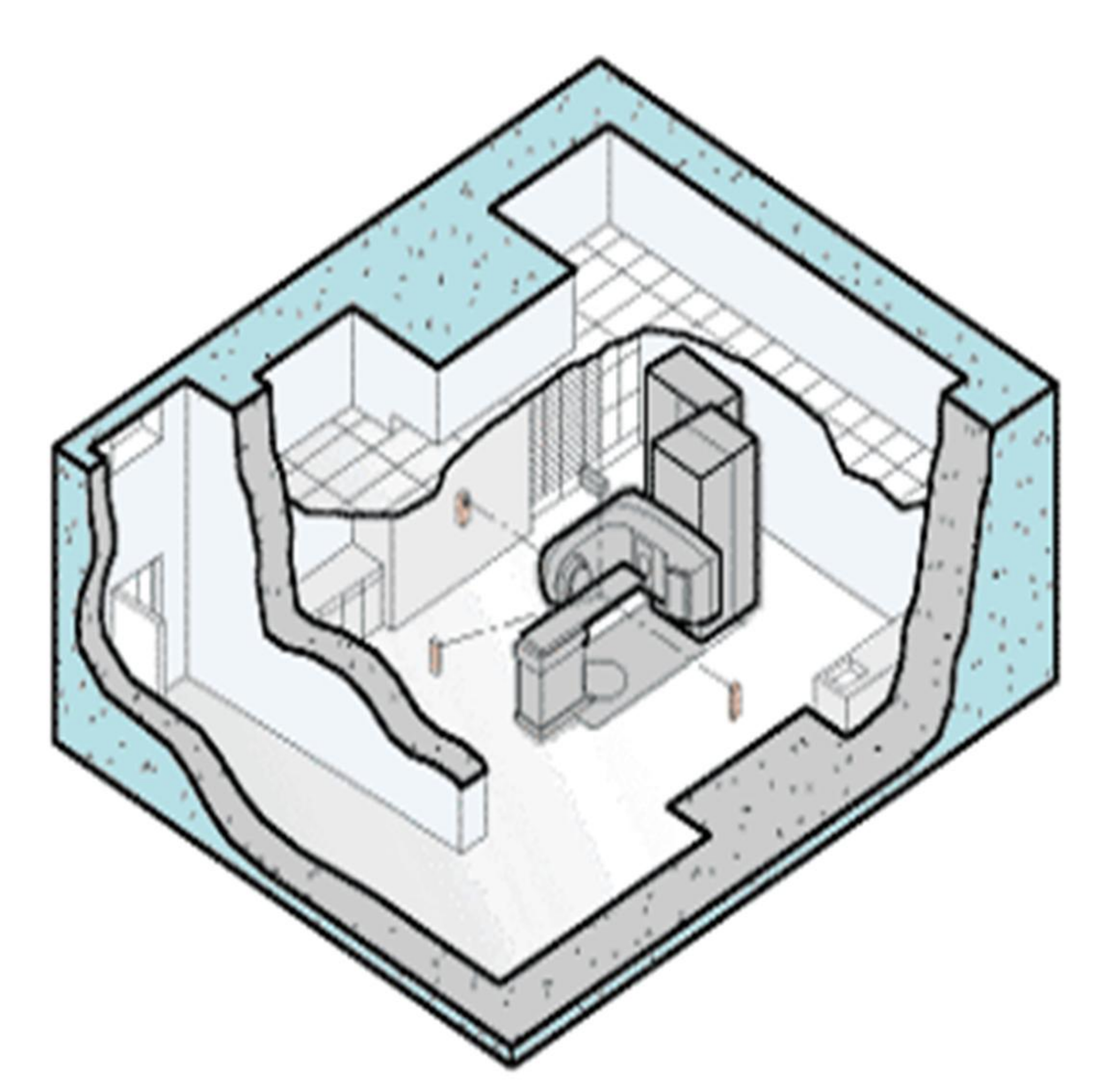
Nuclear safety applications



- **Healthcare** (radiology, radiation oncology and nuclear medicine)
- **Nuclear energy**
- **Industrial manufacturing** (e.g. industrial radiography for non-destructive testing)
- **Nuclear waste storage**

Costs comparison

Mineral	Cost of mineral 2023, US (dollars per ton)
Cement	150
Barites	150
Iron and steel scrap	338,63
Ilmenite	365
Sand and gravel	12,2
Iron-ore	170
Iron and steel slag (GGBFS) (no specific data on non-ferrous slag)	58 (140)

Data from USGS (2023)

- **Origin non-ferrous slags**: secondary Melter

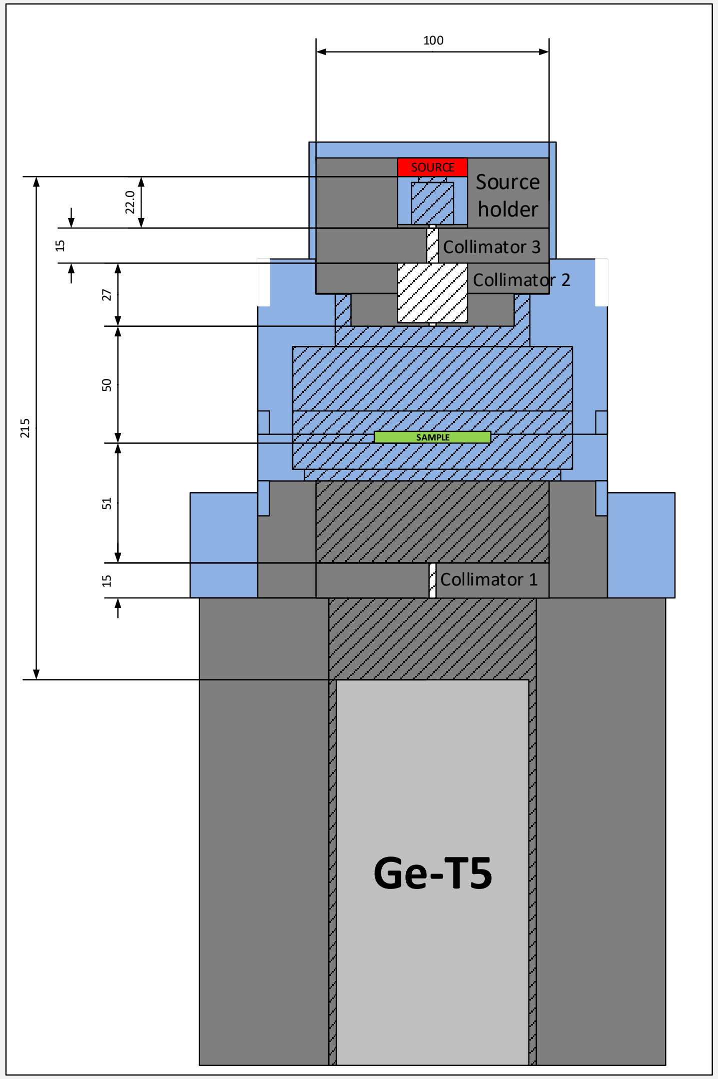
Chemical composition (mass%)											
	FeO	**SiO_2**	**Na_2O**	**Al_2O_3**	**CaO**	**ZnO**	**CrO**	**PbO**	**MnO**	**CuO**	**SnO**
Slag	51.4	33.1	4.9	4.1	2.6	2.3	0.5	0.2	0.4	0.4	0.1

- **AAM synthesis:** Binder/Aggregate/Activating Solution 1/4.2/0.4
  - Binder matrix: (amorphous) **water-quenched Fe-rich slags** secondary smelting plant
  - Aggregates: **slowly cooled Fe-rich slags** smelting plant
  - Activator: 6M NaOH-waterglass (50-50 mass%)

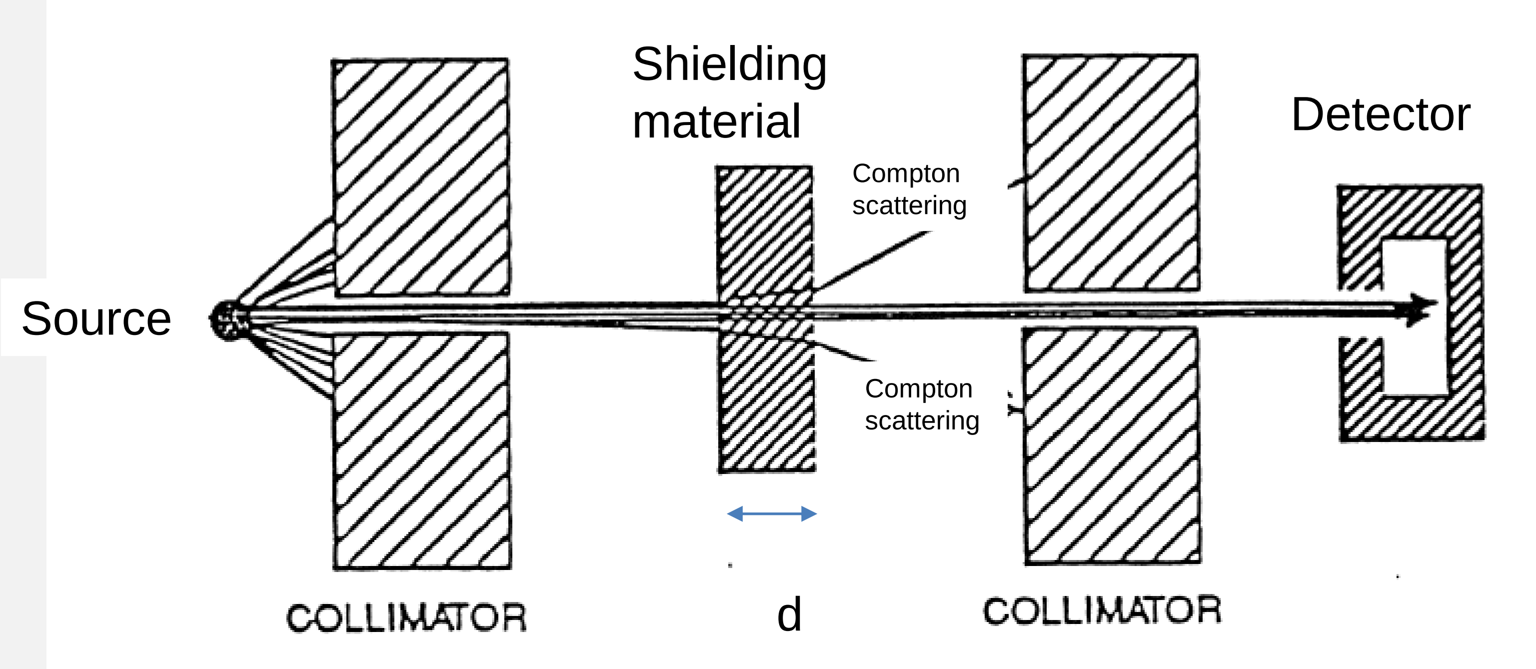
- Pressed 100 bar → (3 cuboid and 8 cylindrical shaped) **AAM mortars**
- Dried and cured (28 days, 20 °C, 60 % humidity)

Croymans, T., Valorization of Fe-rich industrial by-products in construction materials: a radiological assessment, PhD dissertation (2018)

Materials and Methods - Narrow beam setup for gamma shielding evaluation



(distances in cm)



$$\phi_1 = \phi_0 . e^{-\mu d}$$

Linear Attenuation Coefficient (μ)
Incoming (ϕ_0) and outgoing (ϕ_1) radiation flux

Croymans, T., Valorization of Fe-rich industrial by-products in construction materials: a radiological assessment, PhD dissertation (2018)

Results – Simulated and experimental **Linear Attenuation Coefficient (μ)**

Energy (keV)	Fe-rich slag based AAM	
	μ EGSnrc (cm^{-1})	μ EXP (cm^{-1})
609	0.243 ± 0.002	0.244 ± 0.001
661	0.234 ± 0.001	0.232 ± 0.001
1120	0.181 ± 0.002	0.183 ± 0.001
1173	0.177 ± 0.001	0.177 ± 0.001
1332	0.166 ± 0.001	0.167 ± 0.001
1765	0.143 ± 0.001	0.146 ± 0.001
2204	0.130 ± 0.002	0.133 ± 0.001
2447	0.122 ± 0.001	0.130 ± 0.004

Croymans, T., Valorization of Fe-rich industrial by-products in construction materials: a radiological assessment, PhD dissertation (2018)

Results – Comparison with other types of shielding materials

	Density (g/cm³)	Compressive strength (MPa)
Barite concrete	3.5-3.7	24.8-42.2
Ilmenite concrete	3.49-3.92	20.6-75.3
Limonite concrete	2.96	40.4
Hematite concrete	3.73-4.2	16.2-89.3
Ferrophosphous concrete	4.65	30.4
Magnetite concrete	3.41-4.38	19.2-41.8
Steel concrete	6.3	76
Fe-rich slag based AAM [this study]	3.10 ±0.01	25 ± 2

Kaplan, M.F., Concrete radiation shielding, 1st ed., Longman Scientific & Technical, 1989
Croymans, T., Valorization of Fe-rich industrial by-products in construction materials: a radiological assessment, PhD dissertation (2018)

Results – Comparison, simulated Linear Attenuation Coefficient (µ)

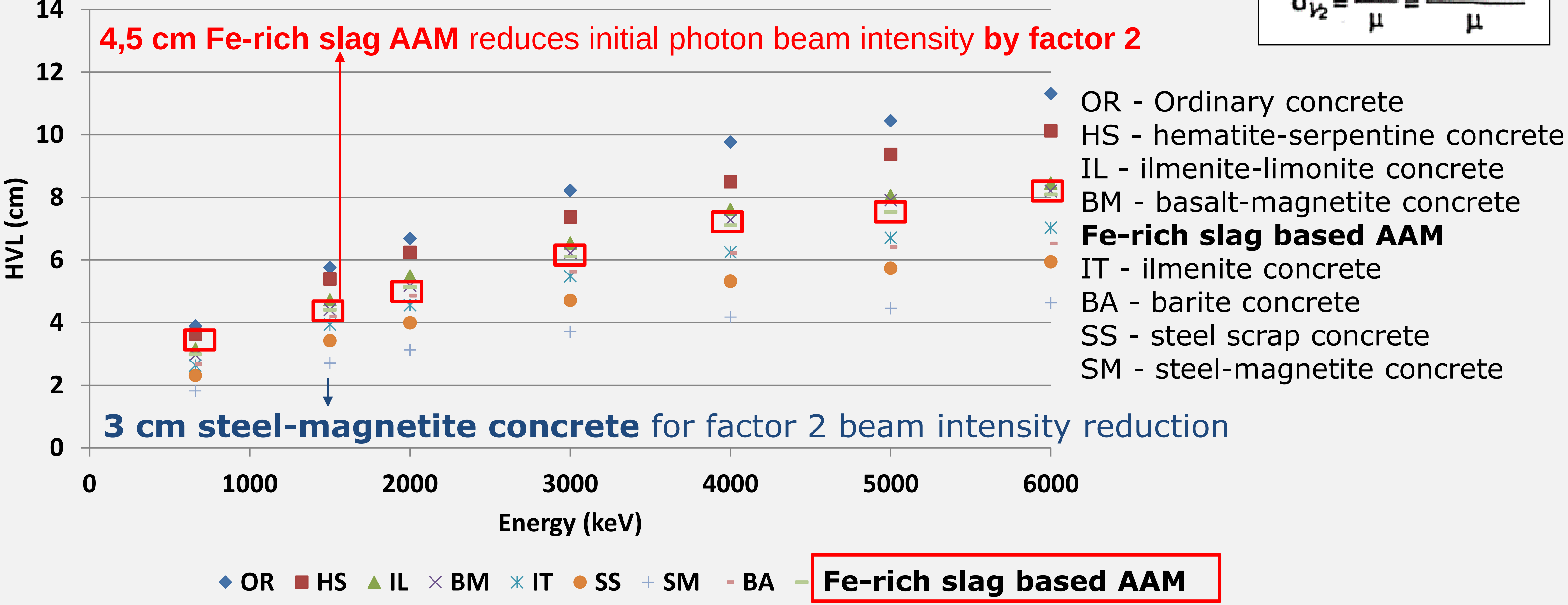
Energy (keV)	Steel-magnetite concrete (5.11 g cm^{-3}) µ EGSnrc (cm^{-1})	Barite concrete (3.35 g cm^{-3}) µ EGSnrc (cm-1)	Fe-rich slag based AAM (3.1 g cm^{-3}) µ EGSnrc (cm-1)
1500	0.256	0.165	0.157
2000	0.222	0.142	0.135
3000	0.187	0.123	0.113
4000	0.166	0.111	0.097
5000	0.156	0.108	0.092
6000	0.15	0.106	0.086

Croymans, T., Valorization of Fe-rich industrial by-products in construction materials: a radiological assessment, PhD dissertation (2018)

Results – Half value layer shielding materials

$$e^{-\mu \cdot d_{1/2}} = 1/2$$

$$d_{1/2} = \frac{\ln 2}{\mu} = \frac{0{,}69315}{\mu}$$



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Conclusions - outlook

- Recycling **Fe-rich slags** in **AAMs** for nuclear **safety applications**
  - **Gamma radiation shielding**:
    - **Comparable μ as conventional gamma-ray shielding materials**
    - **Smaller expected mineral cost**

- **Future plans:**
  - Shielding studies for other types or radiation (neutron, clinical beams)
  - Targeting the nuclear & healthcare sector
  - Ultra High Performance Concrete (UHPC)

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