

Speaker:
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Lecture title:
**Enhancing Thermoelectric Response in
Cement Composites
by Introducing Industrial By-Products**

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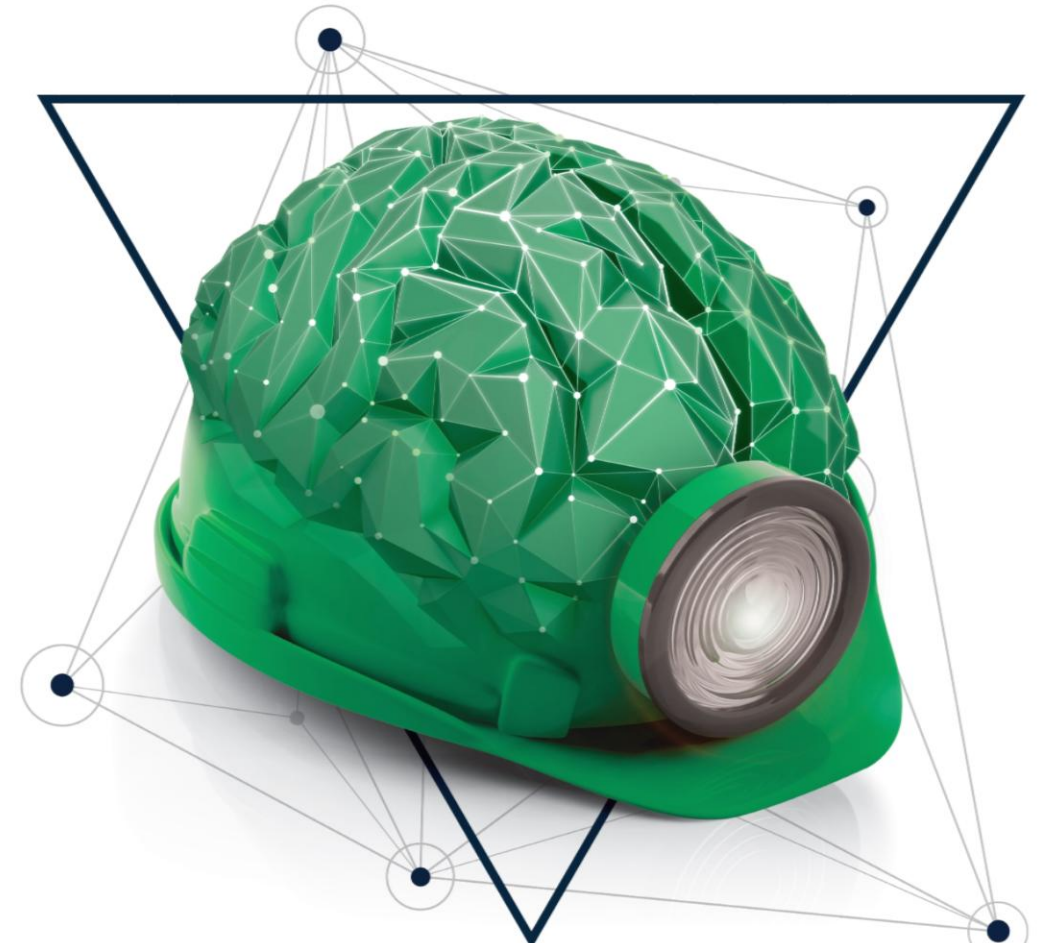
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BACKGROUND AND MOTIVATION



Sustainable and energy-efficient infrastructure is a global priority.



Growing need for **smart and multifunctional** materials.



Applications: self-powered sensors, energy harvesting, real-time monitoring.

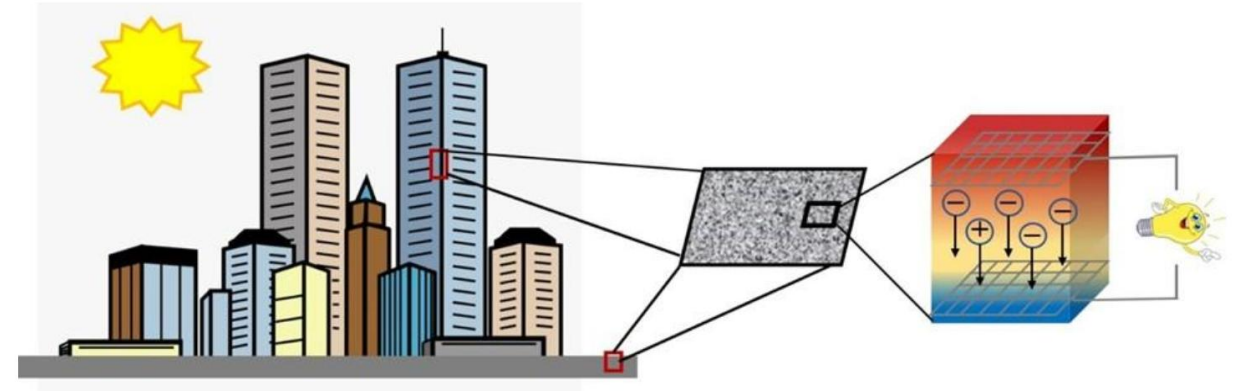


Cement-based composites with thermoelectric (TE) properties offer new potential.

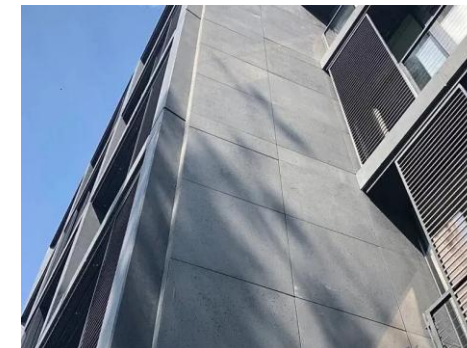
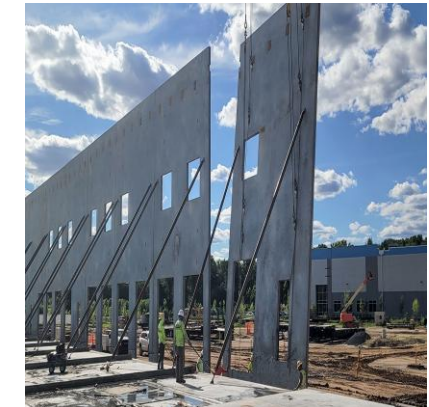
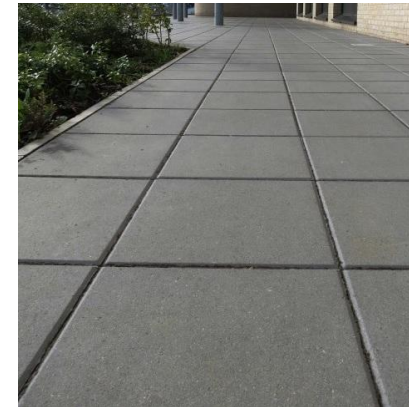
Cheap, strong and versatile, **concrete** is the second most consumed material globally after water, with 30 billion tonnes used annually ([*Nature* **597**, 593–594; 2021](#))



WHY THERMOELECTRIC CEMENT COMPOSITE?

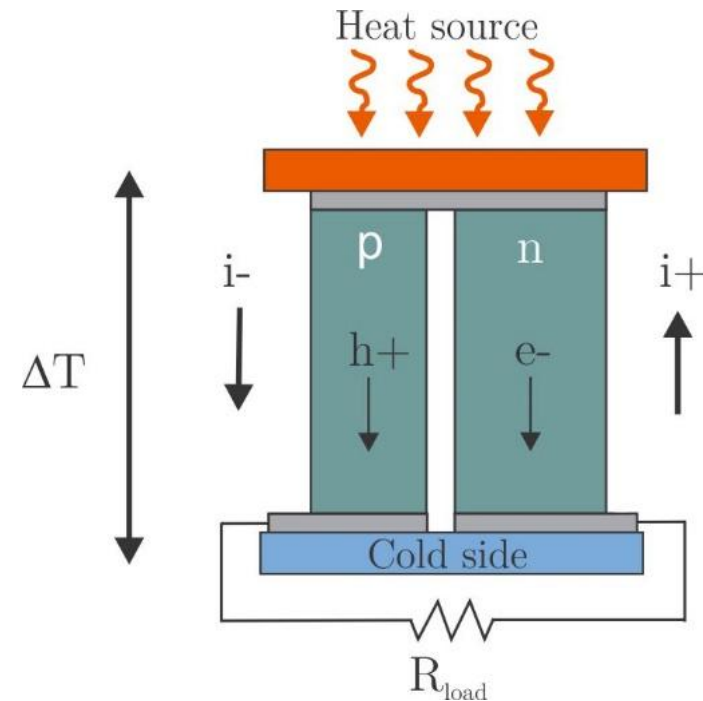


- Converts waste **heat** into electricity via the **Seebeck effect**.
- Supports circular economy through industrial waste revalorisation.
- Enables energy-autonomous, low-maintenance infrastructure.
- Aligns with EU goals for resource efficiency and climate neutrality.



THERMOELECTRIC FUNDAMENTALS

- Crucial parameters are **electrical conductivity (σ)**, **Seebeck coefficient (S)** and **thermal conductivity (κ)**.
- Efficiency defined by the **figure of merit (zT)**: $zT = (\sigma S^2 T) / \kappa$.
- **Conventional materials**: Alloys Bi_2Te_3 , PbTe – efficient but **costly for large area applications** and require special protection due to their corrosive nature.
- Cement materials are stable; however, they are **intrinsically poor in thermoelectric performance**.
- Require **enhancement** via fillers and additions of highly **electrically conductive materials**.



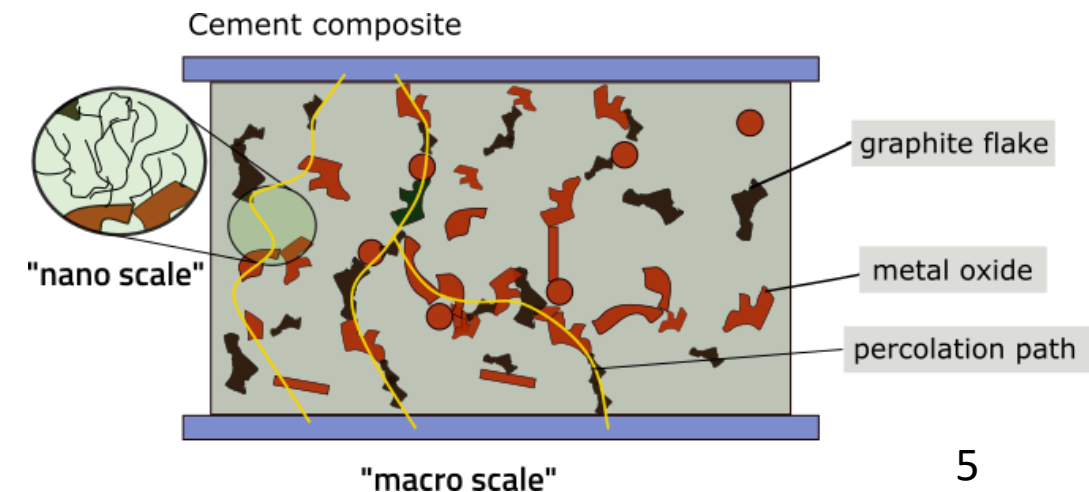
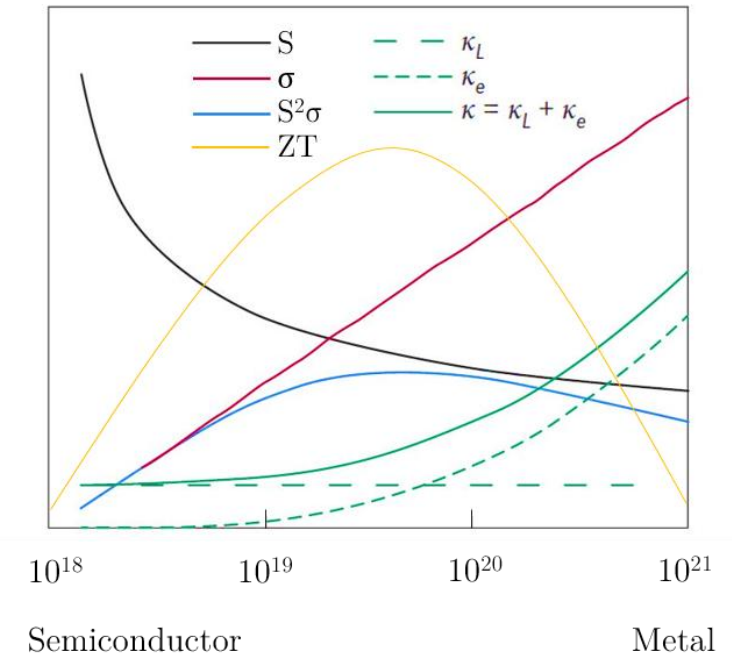
Temperature gradient causes charge carriers in the material to **diffuse from the hot side to the cold side**

Thermoelectric materials have the ability to **convert a temperature gradient into a voltage**

FROM INSULATOR TO FUNCTIONAL MATERIAL

- An **efficient** thermoelectric material should have **high electrical conductivity (σ)** to minimise the Joule heating, high **Seebeck coefficient (S)** for the maximum conversion of temperature gradient (heat) to electric power (voltage) and **low thermal conductivity (κ)**.
- These requirements are best met in **semiconducting materials**, traditionally alloys (Bi_2Te_3) and ceramics.
- Chung (1998): Carbon fibre–reinforced cement with Seebeck $\approx 17 \mu\text{V/K}$.
- Conductive and semiconductive fillers improve σ and S .
- Composite formation creates functional cement materials.

Carrier concentration correlation with TE properties



RESEARCH GOAL AND OBJECTIVES

- **The goal** is to develop thermoelectric cement-based composites using standard cements and industrial secondary raw materials (SRMs), primarily composed of metal oxides or graphite, which are otherwise non-reusable and would require environmentally responsible disposal.
- **Objective 1:** Achieve electrical conductivity on the order of tens of S/cm, a Seebeck coefficient of several hundred $\mu\text{V/K}$, a power factor in the range of a few hundred $\mu\text{W/mK}^2$, and thermal conductivity below 5 W/mK.
- **Objective 2:** Develop environmentally sustainable thermoelectric cement-based composites.
- **Objective 3:** Optimize the composition of thermoelectric cement-based composites to achieve an effective balance between improved thermoelectric performance and adequate mechanical strength.

SECONDARY RAW MATERIALS (SRM_s) INVESTIGATED

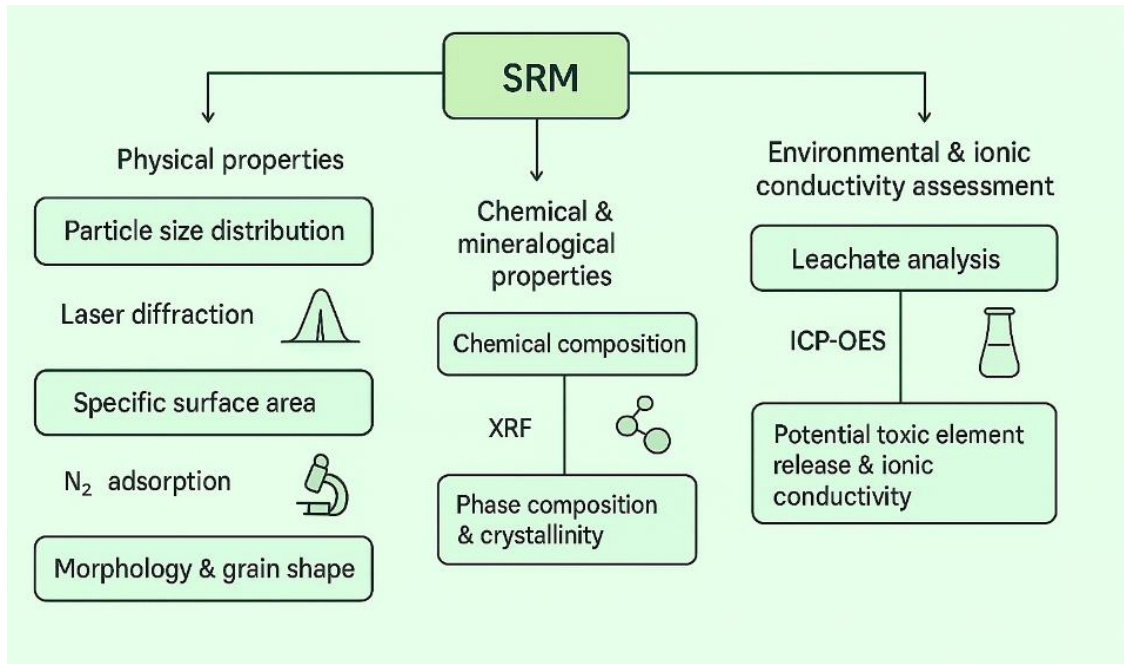
- Selection of SRMs that contain conductive and semiconductive metal oxides or graphite.



Material	Abbreviation	Provenance/Source
Sandblasting powder HP	SP HP	Waste from SIJ Acroni d.o.o., steel producer (Slovenia)
Copper slag from dry-air granulation process	CS D	KIC EIT RM Whisper (project no. 18034)
Copper slag from wet-granulation process	CS W	KIC EIT RM Whisper (project no. 18034)
Red mud	RM	KIC EIT RIS-Restore (project no. 19269)
Mine sludge	MS	Sludge from Sitarjevec mine (Litija, Slovenia)
Graphite powder	G COM	Commercial product
Graphite SPL	G SPL	Secondary product from spent pot lining (SPL) recycling pilot plant (ZAG, Slovenia) / EIT RM SPL-CYCLE (project. no. 17141)

EXPERIMENTAL METHODOLOGY

CHARACTERIZATION OF SRMs



CHARACTERIZATION OF CEMENT COMPOSITES INCLUDING SELECTED SRMs

- Cement replacement rate: 1–25 wt.%.
- Criteria for evaluation (by the order of priority):
 1. Thermoelectric properties testing: Seebeck coefficient (S), electrical conductivity (σ), thermal conductivity (κ).
 2. Environmental acceptability: leaching behaviour.
 3. Mechanical testing: compressive and flexural strength (28 days).

MATERIAL CHARACTERIZATION

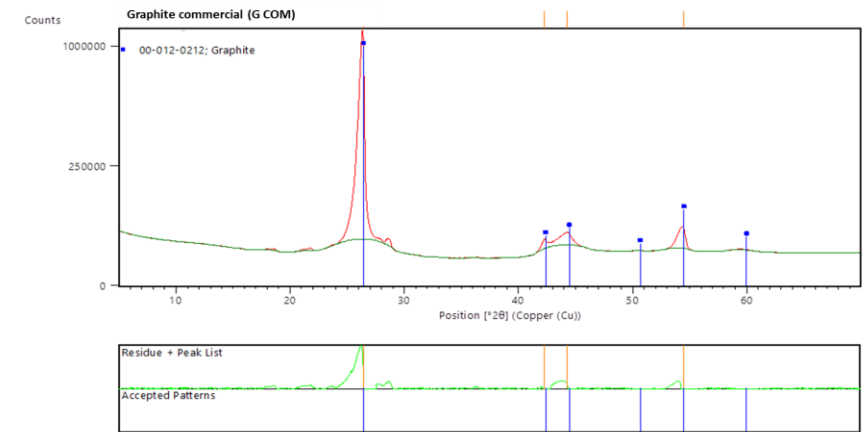
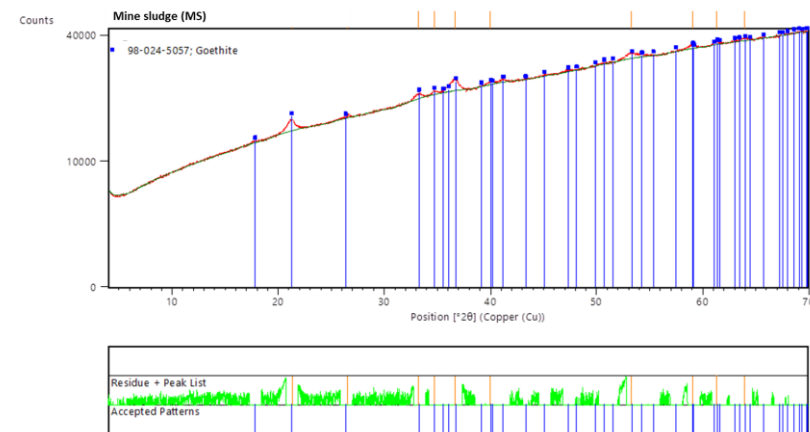
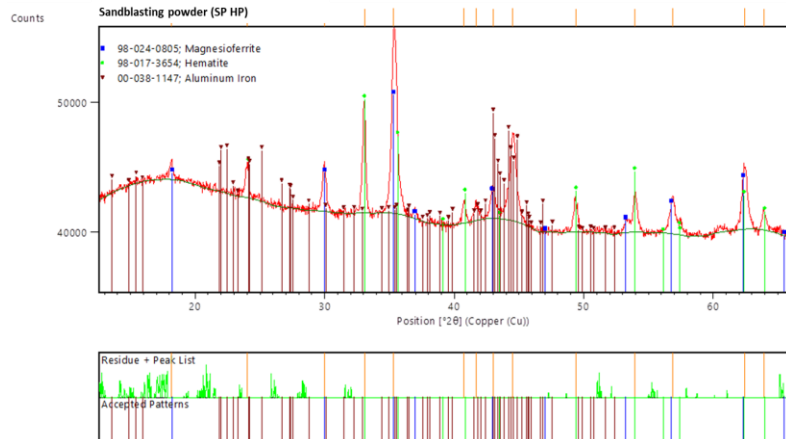
X-RAY FLUORESCENCE SPECTROSCOPY (XRF)

SP HP		CS D		CS W		RM		MS		G COM		G SPL	
pressed pellet		fused bead		fused bead		fused bead		fused bead		pressed pellet		pressed pellet	
El/Ox	m/m%	El/Ox	m/m%	El/Ox	m/m%	El/Ox	m/m%	El/Ox	m/m%	El/Ox	m/m%	El/Ox	m/m%
Fe2O3	95.45	Fe2O3	57.84	Fe2O3	57.84	Fe2O3	39.45	Fe2O3	93.27	C	>99	C	>95
SiO2	1.60	SiO2	27.49	SiO2	27.49	Al2O3	22.38	SiO2	2.93	Fe2O3		F	
MnO	0.74	Al2O3	4.44	Al2O3	4.44	SiO2	14.36	Al2O3	1.55	CaO		CaO	
Cr2O3	0.47	CaO	2.1	CaO	2.1	Na2O	8.31	Na2O	0.76	Na2O			
Na2O	0.31	ZnO	1.45	ZnO	1.45	CaO	8.00	ZnO	0.38	SiO2			
NiO	0.27	CuO	1.15	CuO	1.15	TiO2	5.21	MgO	0.35	MgO			
Al2O3	0.22	MgO	1.3	MgO	1.3	MgO	0.56	K2O	0.18				
MgO	0.08	K2O	0.83	K2O	0.83	SO3	0.26	MnO	0.12				
Co3O4	0.06	Na2O	0.76	Na2O	0.76	As2O3	0.23	CaO	0.12				
		SO3	0.72	SO3	0.72	MnO	0.17						
		MoO3	0.61	MoO3	0.61	ZrO2	0.17						
		PbO	0.19	PbO	0.19	P2O5	0.15						
		TiO2	0.28	TiO2	0.28	Cr2O3	0.14						
		As2O3	0.22	As2O3	0.22	V2O5	0.13						
		P2O5	0.18	P2O5	0.18	K2O	0.08						
		BaO	0.18	BaO	0.18	NiO	0.07						
						BaO	0.05						
LOI	N.A.	LOI	-6.38	LOI	-5.51	LOI	7.37	LOI	22.47	LOI	N.A.	LOI	N.A.

MATERIAL CHARACTERIZATION

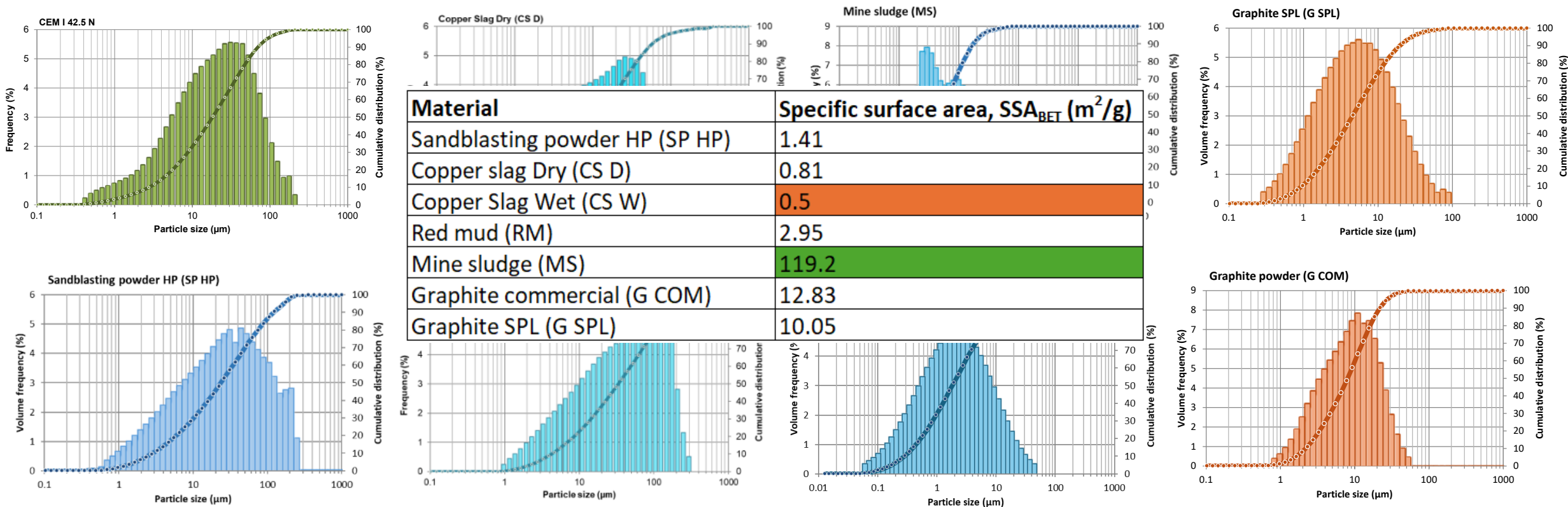
X-RAY POWDER DIFFRACTION (XRD)

SP HP	CS D	CS W	RM	MS	G COM	G SPL
Phase	Phase	Phase	Phase	Phase	Phase	Phase
Magnesioferrite (MgFe_2O_4)	Fayalite (Fe_2SiO_4)	Fayalite (Fe_2SiO_4)	Hematite (Fe_2O_3)	Goethite ($\alpha\text{-FeO(OH)}$)	Graphite	Graphite
Magnetite (Fe_3O_4)	Magnesioferrite (MgFe_2O_4)	Magnetite (Fe_3O_4)	Cancrinite ($\text{Na}_6\text{Ca}_2[\text{AlSiO}_4]_6(\text{CO}_3)_2 \cdot 2\text{H}_2\text{O}$)	Quartz (SiO_2)		
Ferro Aluminum (FeAl) alloy			Hydrogarnet			
			Perovskite (CaTiO_3)			
			Calcite (CaCO_3)			
			Boehmite ($\gamma\text{-AlO(OH)}$)			
			Diaspore ($\alpha\text{-AlO(OH)}$)			



MATERIAL CHARACTERIZATION

PARTICLE SIZE ANALYSIS (PSA) AND SPECIFIC SURFACE AREA (SSA_{BET})



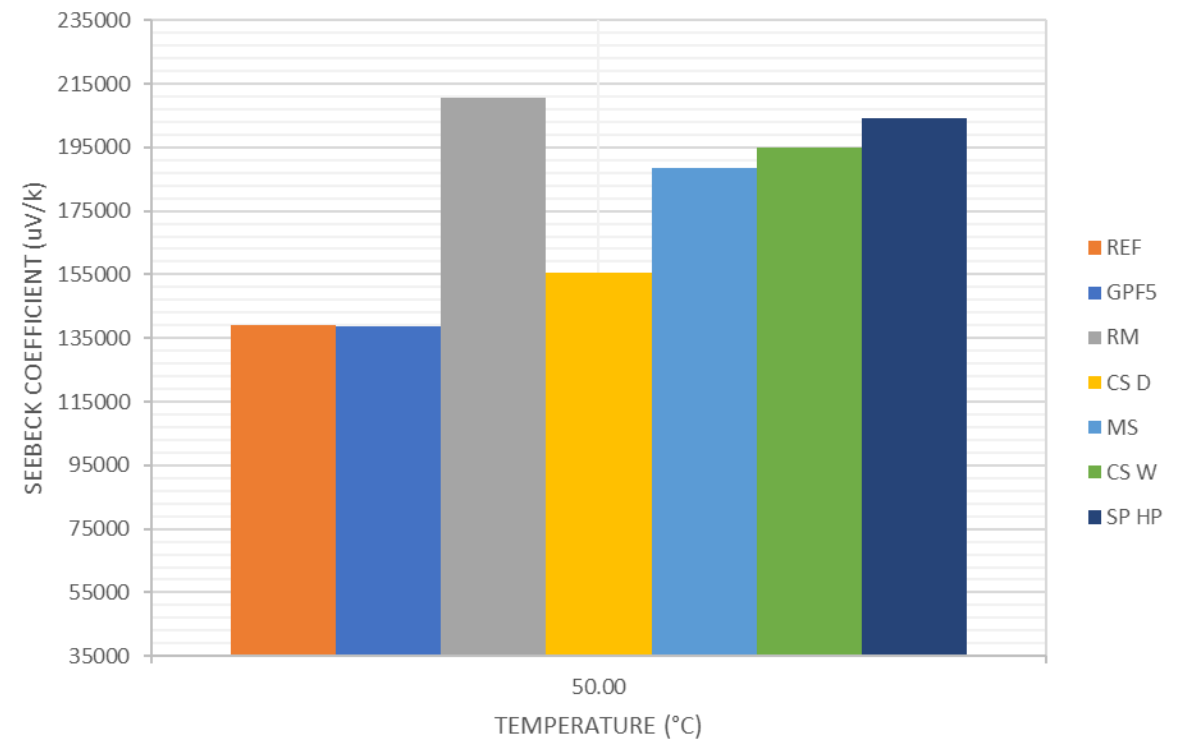
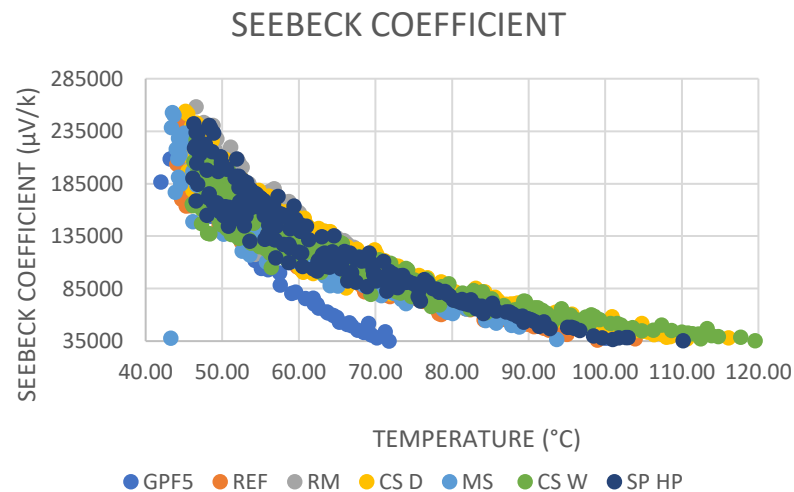
RESULTS: THERMOELECTRIC PARAMETERS

- TE parameters were measured on a Z-meter, a device that measures all quantities simultaneously
- Vacuum $1.4 \cdot 10^{-5}$ mBar
- Large ΔT – up to 100 °C
- In-house built – automated system



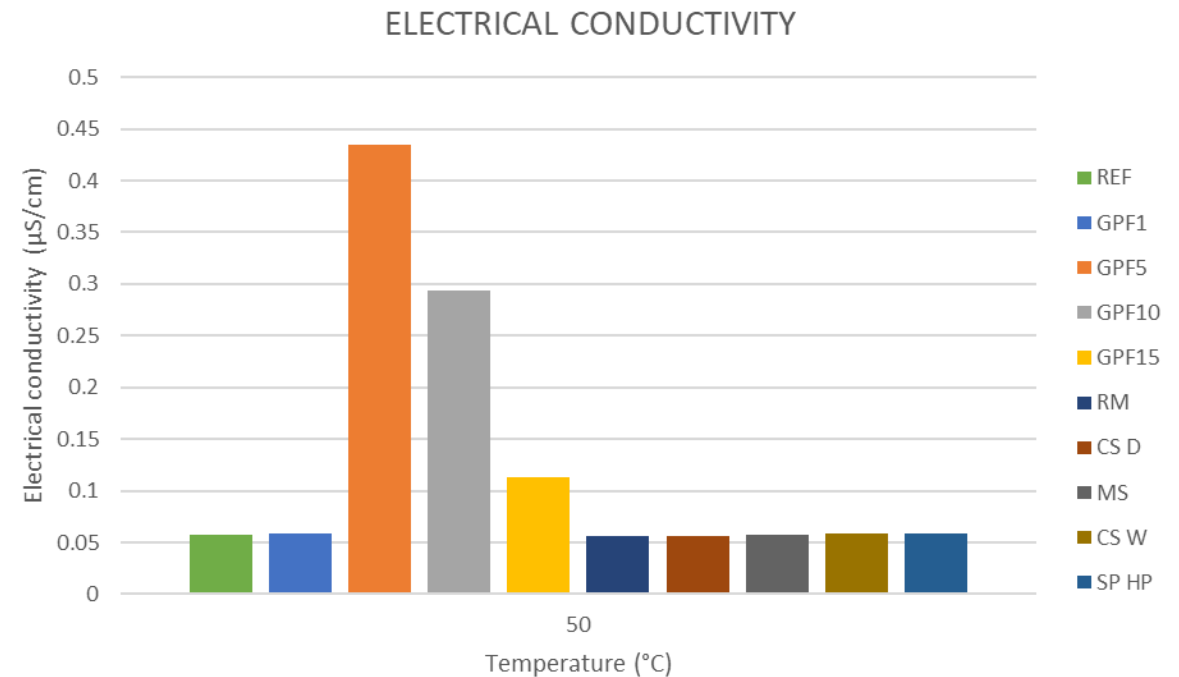
RESULTS: SEEBECK COEFFICIENT

- Red mud: $2 \times 10^5 \mu\text{V/K}$ at 50°C (8× higher than reference)
- Graphite and metal oxides → effective in enhancing Seebeck



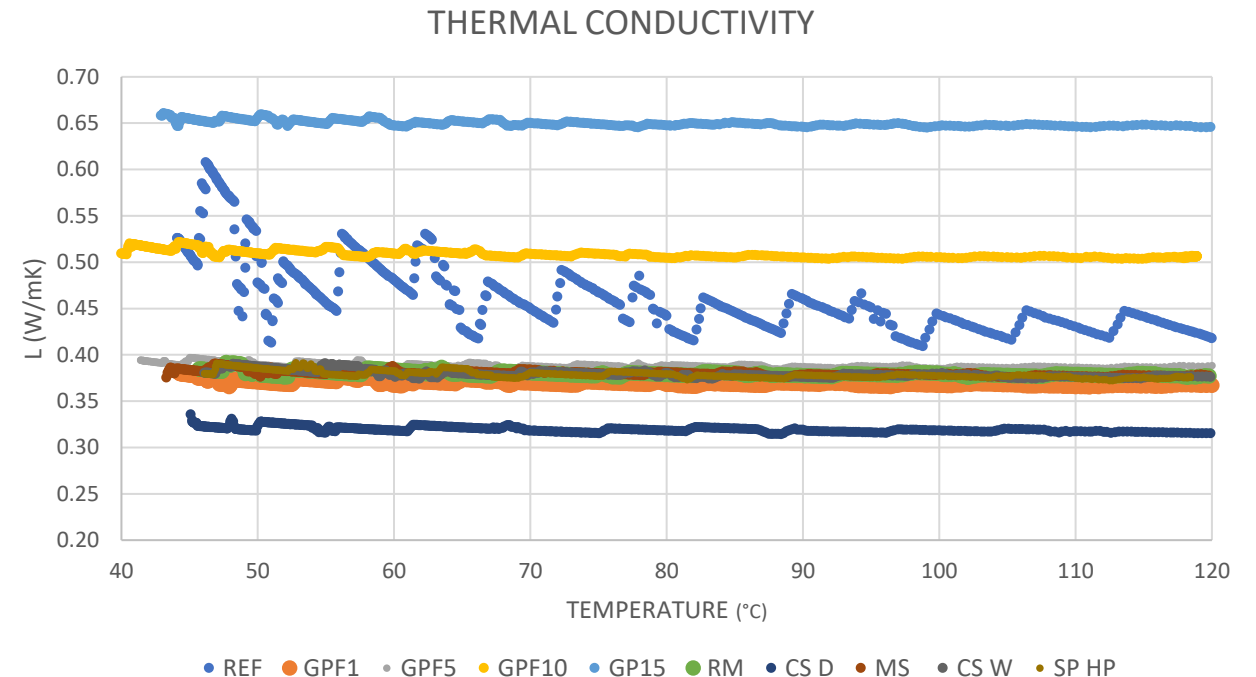
RESULTS: ELECTRICAL CONDUCTIVITY

- Adding 5 wt% graphite results in the highest increase in electrical conductivity.
- Beyond 10 wt% graphite, the positive effect on conductivity starts to decline.
- Other additives do not significantly improve electrical conductivity.



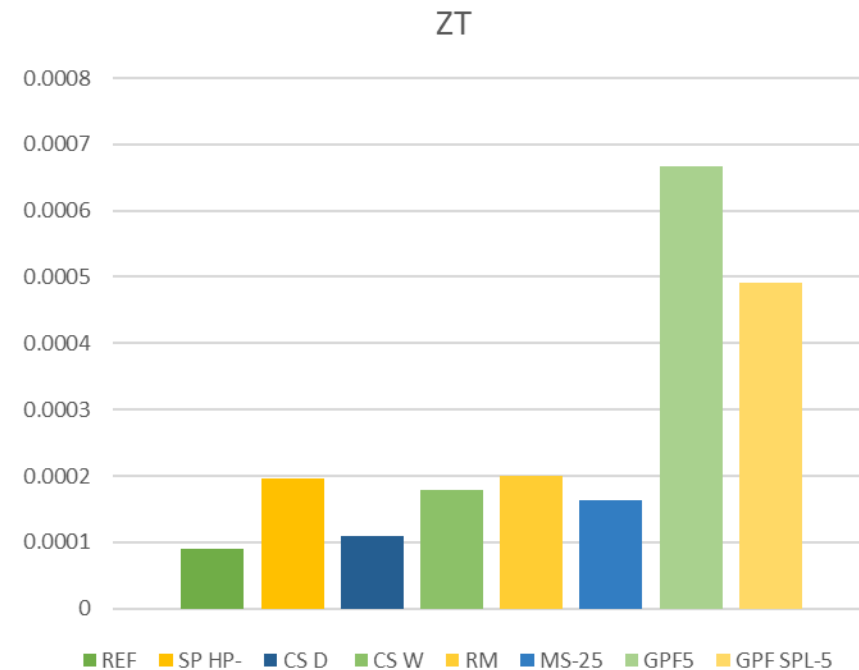
RESULTS: THERMAL CONDUCTIVITY

- Reference cement composites have 0.45-0.4 W/mK electrical conductivity
- Carbon-based additives above 5 wt% significantly increase thermal conductivity
- Low thermal conductivity is crucial parameter in high ZT values



RESULTS: FIGURE OF MERIT (ZT)

- Graphite and metal oxides effectively enhance the Seebeck coefficient while maintaining low thermal conductivity.
- Graphite-based mixtures show the best overall performance.
- Further optimization is required to achieve a balance among all influencing parameters.

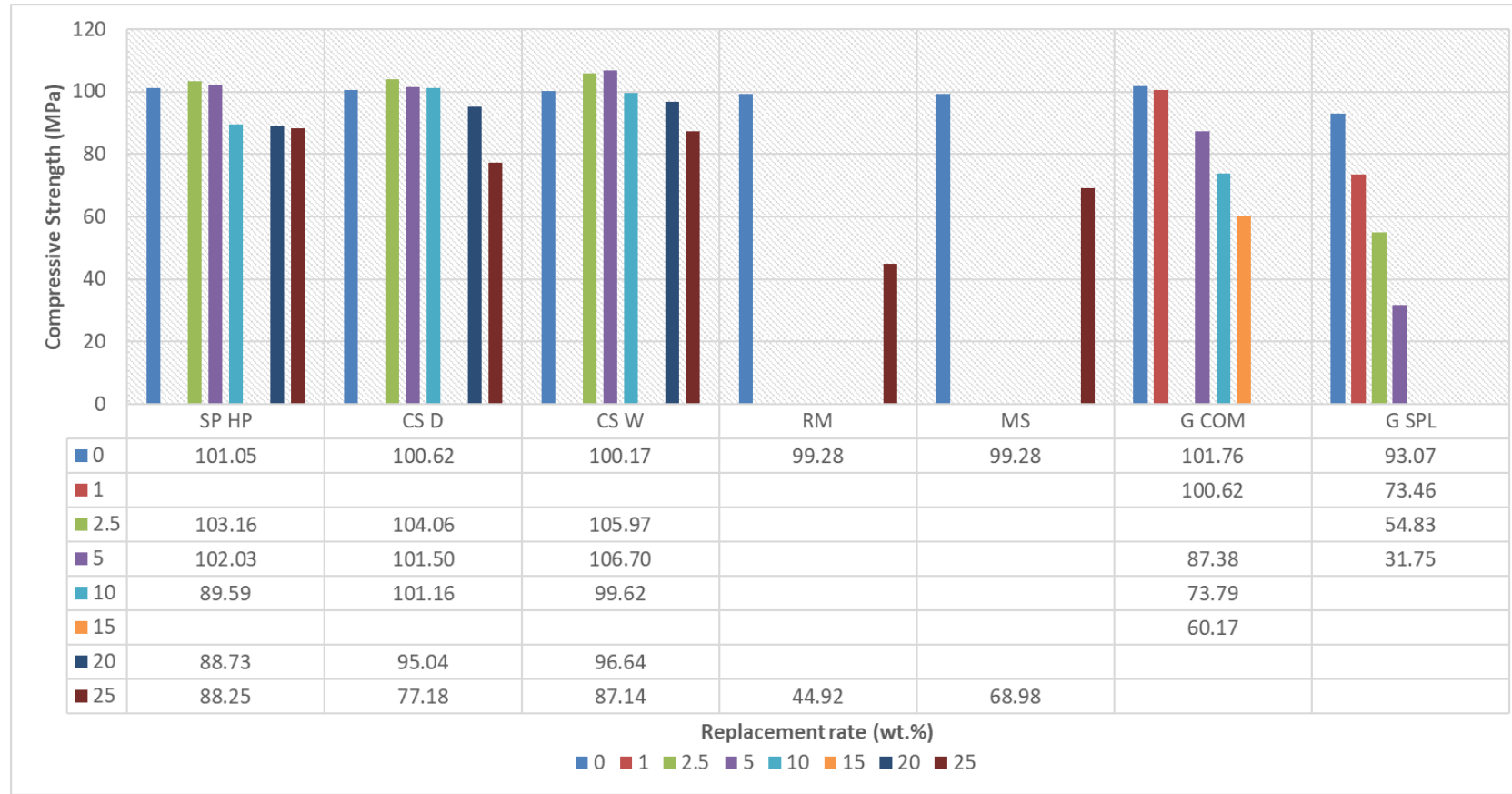


RESULTS: LEACHING BEHAVIOUR (SIST EN 1744- 3:2002)

	Concentration of elements in leachates								
Parameter/ Sample label	Concentration (mg/ kg d.m.)							Permissible concentrations of pollutants in product leachates for areas without protection regimes according to water regulations (Official Gazette of the Republic of Slovenia, No. 77/22	Stanadard
	CP-SP HP-25	CP-CS D-25	CP-CS W-25	CP-RM-25	CP-MS-25	CP-G COM-5	CP-G SPL-5		
Cadmium (Cd)	<0.0025	<0.0025	<0.0025	<0.0025	<0.0025	<0.0025	<0.0025	0.025	SIST EN ISO 17294-2:2024
Copper (Cu)	<0.05	0.08	<0.05	<0.05	<0.05	<0.05	<0.05	0.5	SIST EN ISO 17294-2:2024
Nickel (Ni)	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	0.4	SIST EN ISO 17294-2:2024
Lead (Pb)	<0.035	<0.035	<0.035	<0.035	<0.035	<0.035	<0.035	0.5	SIST EN ISO 17294-2:2024
Zinc (Zn)	<0.35	<0.35	<0.35	<0.35	<0.35	<0.35	<0.35	2	SIST EN ISO 17294-2:2024
Mercury (Hg) #	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.005	SIST EN ISO 17294-2:2024
Cobalt (Co)	<0.003	<0.003	<0.003	<0.003	0.006	<0.003	0.005	0.03	SIST EN ISO 17294-2:2024
Molybdenum (Mo)	0.5	1.9	0.7	<0.1	0.2	<0.1	<0.1	0.5	SIST EN ISO 17294-2:2024
Antimony (Sb)	<0.03	0.04	<0.03	<0.03	<0.03	<0.03	<0.03	0.3	SIST EN ISO 17294-2:2024
Selenium (Se)	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	0.6	SIST EN ISO 17294-2:2024
Barium (Ba)	<0.5	<0.5	<0.5	<0.5	3.0	<0.5	<0.5	20	SIST EN ISO 17294-2:2024
Arsenic (As)	<0.01	0.03	0.03	0.04	<0.01	<0.01	<0.01	0.1	SIST EN ISO 17294-2:2024
Fluorides (F ⁻)	<5	<5	<5	<5	<5	5	25	10	SIST EN ISO 10304- 1:2009
Chlorides (Cl ⁻)	<50	<50	<50	<50	<50	<50	<50	800	SIST EN ISO 10304- 1:2009
Sulfates (SO ₄ ²⁻)	330	340	82	340	87	200	600	2500	SIST EN ISO 10304- 1:2009
pH (25°C)	12.0	12.2	12.0	12.4	12.4	12.1	11.9	/	SIST EN ISO 10523:2012
Conductivity (mS/m)	173.0	293.0	175.0	416.0	423.0	245.0	158.0	/	SIST EN 27888:1998

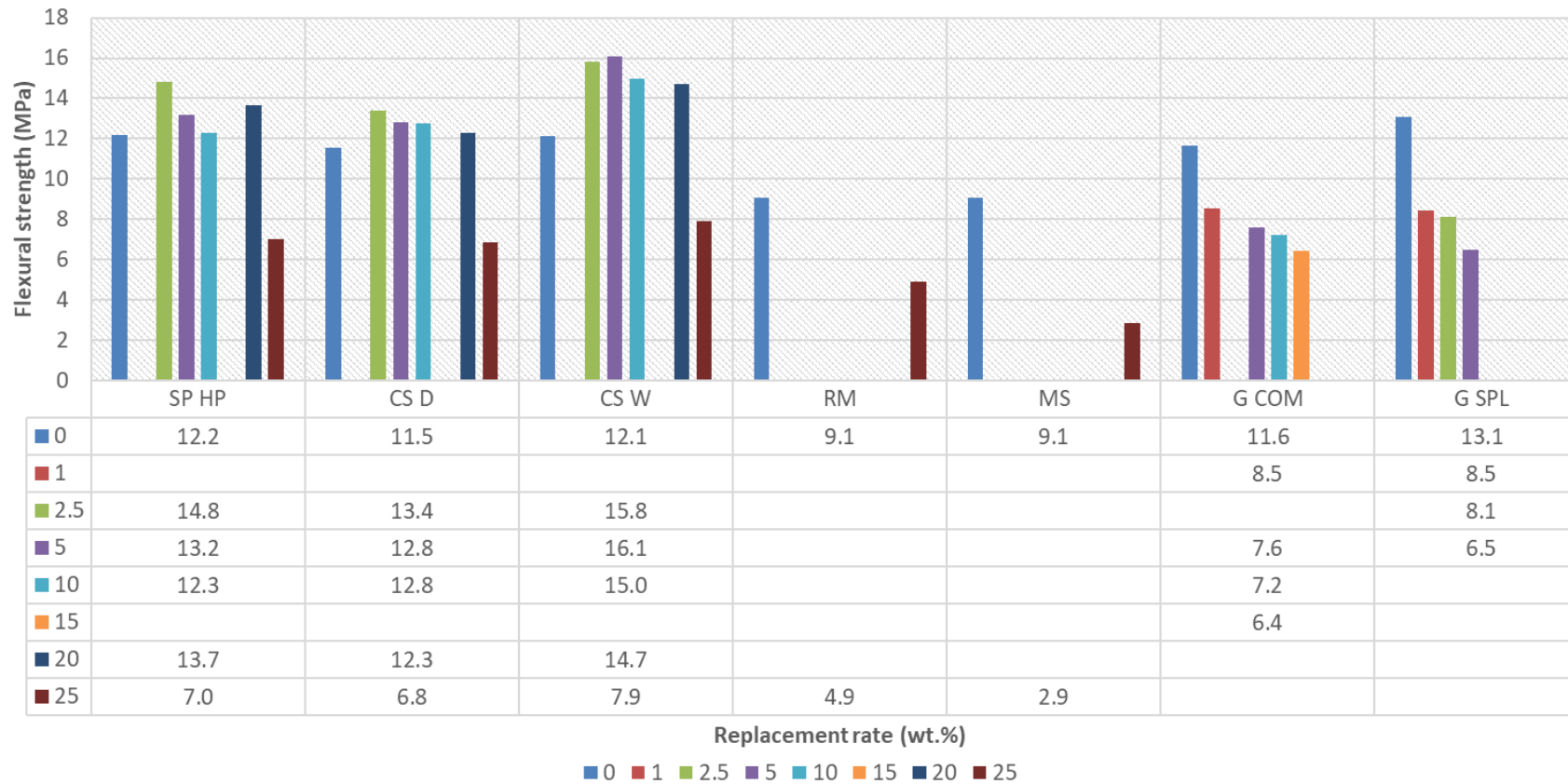
RESULTS: MECHANICAL PROPERTIES

COMPRESSIVE STRENGTH (SIST EN 196-1:2016)

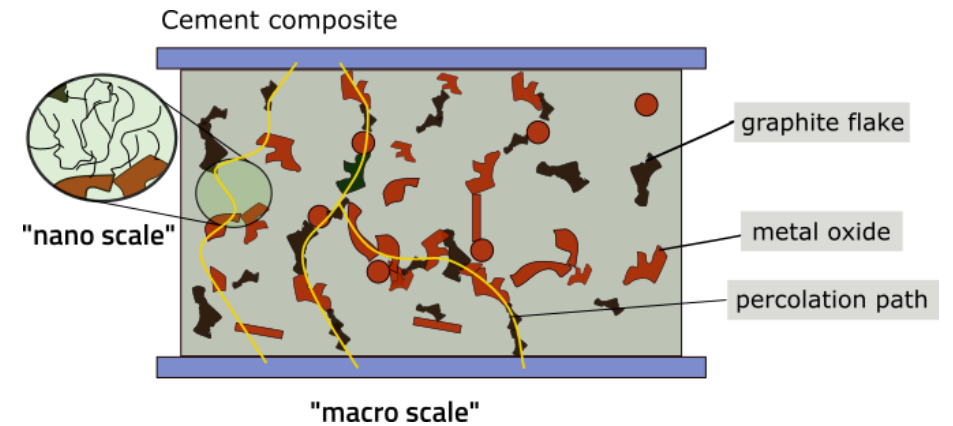


RESULTS: MECHANICAL PROPERTIES

FLEXURAL STRENGTH (SIST EN 196-1:2016)



RESULTS OVERVIEW



	CP-REF		CP-SP HP-25		CP CS D 25		CP-CS W-25		CP-RM-25		CP-MS-25		CP-G COM-5		CP-G SPL-5		Criteria for evaluation
Main phases	CSH gel		Magnesioferrite (MgFe ₂ O ₄)		Fayalite (Fe2SiO4)		Fayalite (Fe ₂ SiO ₄)		Hematite (Fe ₂ O ₃)		Goethite (α-FeO(OH))		Graphite		Graphite		Metal oxide/Graphite
	C3S, C3A, C2S, C4AF		Magnetite (Fe ₃ O ₄)		Magnesioferrite (MgFe2O4)		Magnetite (Fe ₃ O ₄)										Metal oxide/Graphite
Specific surface area of SRM			1.41		0.81		0.5		2.95		119.2		12.83		10.05		High SSA
Electrical conductivity (σ)	0.057 μS/cm	3	0.058 μS/cm	3	0.056 μS/cm	3	0.058 μS/cm	3	0.056 μS/cm	3	0.057 μS/cm	3	0.43 μS/cm	5	0.3 μS/cm	5	high electrical conductivity (σ)
Seebeck coefficient (S)	139,260 μV/K	0	204,217 μV/K	5	155,586 μV/K	3	194,931 μV/K	3	210,757 μV/K	5	188,318 μV/K	5	138,598 μV/K	3	142,456 μV/K	3	high Seebeck coefficient (S)
Thermal conductivity (κ)	0.4-0.45 W/mK	0	0.37-0.4 W/mK	3	0.33-0.35W/mK	5	0.37-0.4 W/mK	3	0.37-0.4 W/mK	3	0.37-0.4 W/mK	3	0.37-0.4 W/mK	3	0.37-0.4 W/mK	3	low thermal conductivity (κ)
zT	8.92627E-05	0	0.000195323	3	0.000109464	3	0.000177964	3	0.000200861	3	0.00016323	3	0.000666999	3	0.000491615	3	
Environmental acceptability		5	Cr tot	3	Mo	0	Mo	3	Cr tot	3		5		5	F-	0	Exceding concentration in accordance to permissible limit
Compressive strength	100%	5	-12.7%	5	-23.3%	5	-13.0%	5	-54.8%	0	-30.5%	3	-14.0%	5	-66.0%	0	-25%
Flexural strength	100%	5	-42.6%	0	-41.0%	0	-34.0%	3	-46.0%	0	-68.0%	0	-34.0%	3	-50.0%	0	-25%
Score		18		20.5		16.5		22		20		25.5		28		14	

CONCLUSIONS

- Criteria for evaluation of the obtained results (by the order of priority):
 1. Thermoelectric properties testing: Seebeck coefficient (S), electrical conductivity (σ), thermal conductivity (κ).
 2. Environmental acceptability: leaching behaviour.
 3. Mechanical testing: compressive and flexural strength (28 days).
- SRM-enhanced cement composites achieve measurable TE performance
- Support circular economy & sustainable construction
- Suitable for integration in smart, energy-harvesting infrastructure
- Future: optimize formulations, scale-up TEG development

Thank you for your attention!

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ESP32 MODULE

