Alternative binders to portland cement to produce sustainable “special” concretes: feasibility and open issues

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WORLD POPULATION AND CEMENT PRODUCTION

S. Monkman, M. MacDonald / Journal of Cleaner Production 167 (2017) 365–375

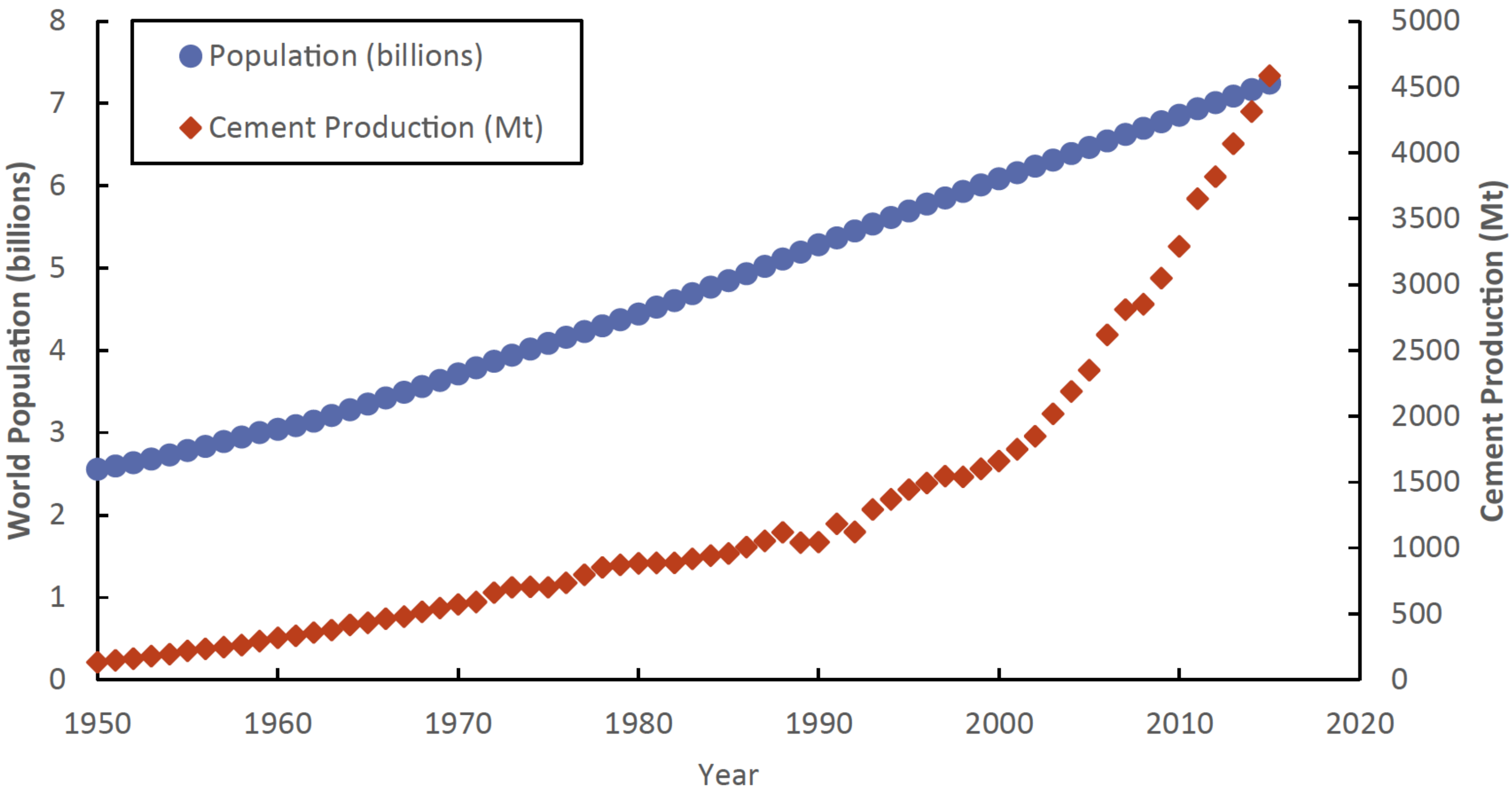
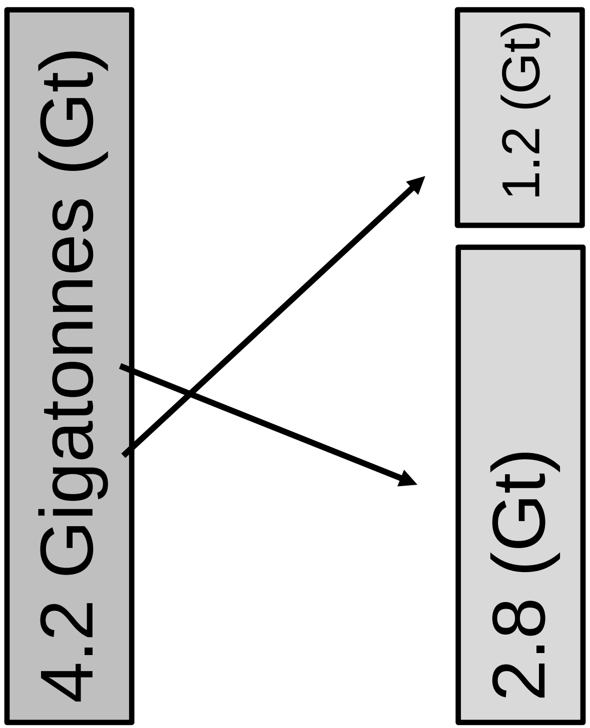


Fig. 1. Global population growth and cement production from 1950 to 2015 (population data from (U.S. Census Bureau, 2016), cement data to 2013 from (U.S. Geological Survey, 2016), cement data after 2013 from (CEMBUREAU, 2016)

CEMENT PRODUCTION

Fillers + Supplementary cementitious materials



Emitting about 38% of the about 10 Gt of carbon dioxide released globally by construction activities, approximately 450 kg per capita

Cement

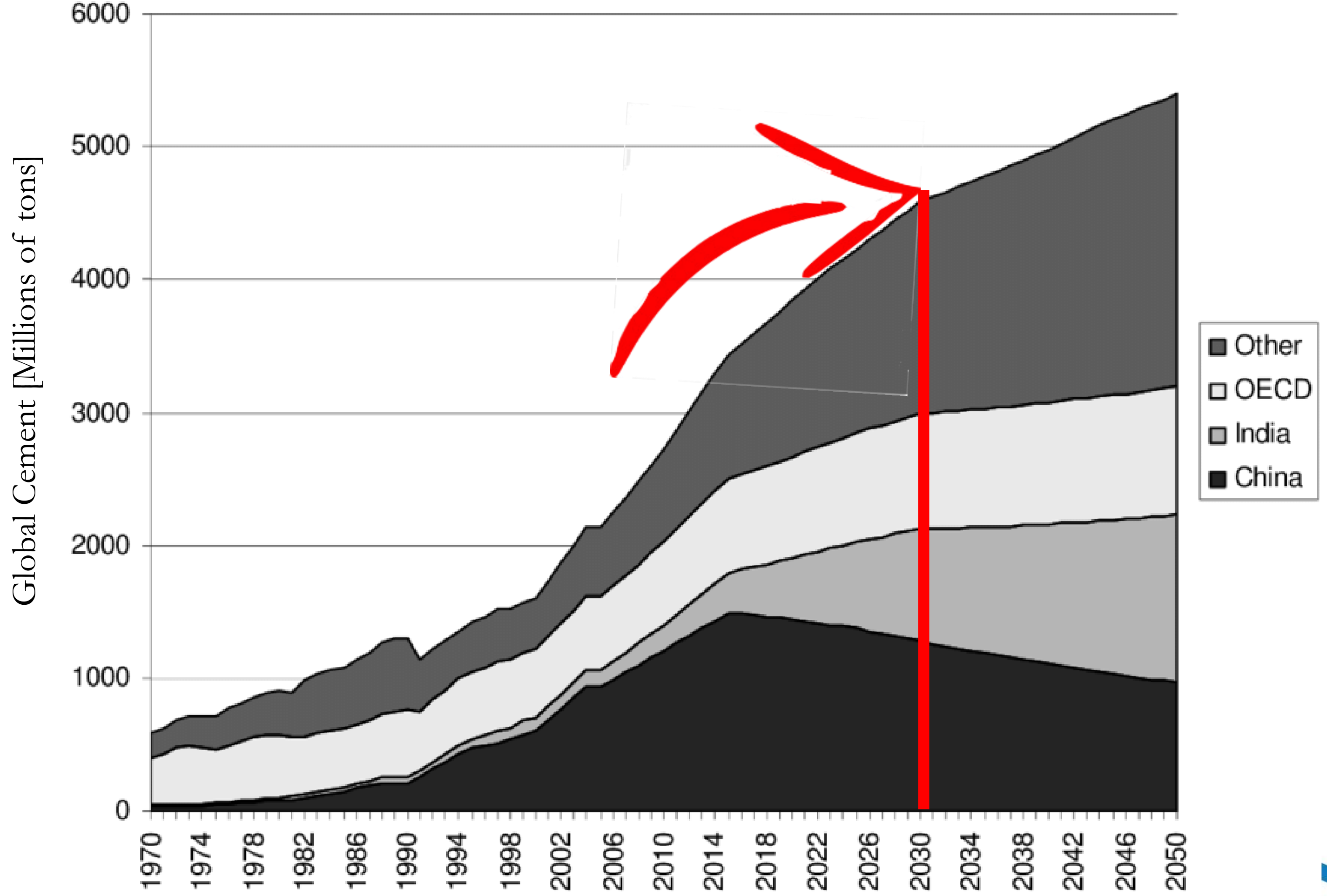
Ordinary Portland cement

REPLACEMENT OF PORTLAND–BASED CONCRETE??

- However, **despite the strong environmental impact** ascribable to the Portland cement and concrete industry, **no materials seem to be able to replace reinforced concrete at a low economic cost.** Taking into account not only the huge volumes involved, but also the simplicity of use and the outstanding properties, the **replacement of Portland-based concrete appears unlikely in the next fifty years**.

2030 ESTIMATED CEMENT PRODUCTION

About 4.8 Gt



Coffetti D, Crotti E, Gazzaniga G, Carrara M, Pastore T, Coppola L, "Pathways towards sustainable concrete", Cement and Concrete Research 154, 2022, 106718

2030 PORTLAND CEMENT DEMAND: 2 Gt

- Demand for cement (2030): 4.8 Gt
- Fly ash available: 1.5 Gt
- Blast furnace slag available: 0.3 Gt
- Demand for cement (2030): 3.0 Gt
- Replacement rate with natural limestone/pozzolans: (0.75 Gt)
- Other binders (i.e. calcium sulphoaluminate cement): 0.25 Gt

- **Clinker to be produced: 2 Gt**

NO. It is not possible to replace Portland cement

GREEN FUEL?? GREEN HYDROGEN??

Even if cement is produced using an ultra-efficient modern dry-process rotary kiln equipped with pre-calciner, the calcination of limestone represent about 65% (on average 520 kg CO_2/ton of clinker) of the total carbon dioxide emissions (about 870 kg CO_2/ton of clinker)

Cement production is a hard-to-abate sector because the decarbonization of the energy supply does not reduce the calcination-derived emissions

IL CARBON CAPTURE, UTILIZATION AND STORAGE (CCUS)

CLEANker (ITALY)

Calcium Looping: Capture of CO_2, fixing through a sorbent (usually based on Ca or Mg carbonate), use of exhausted sorbents as a partial substitute for natural raw materials

CLEAN clinKER by calcium looping for low-CO_2 cement

CLEANKER

ESTIMATED FUTURE DEMAND OF ALTERNATIVE BINDERS

For this, several authors **<u>estimated that alternative cements will not be able to exceed 5% of the projected future demand of cementitious materials</u>**.

Nevertheless, it is necessary to take into account that **only about 70% of all the huge amount of cement produced every year is used to manufacture traditional reinforced concrete structures and prefabricated elements**. **<u>A great deal of cement is used for mortars, plasters and "special" concretes such as pervious , expansive concrete and smart concretes</u>**

Alternative «green» binders may play a fundamental role in the formulation of special mixtures due to their peculiar properties

Jointless slabs on ground

Cement-free renders for structural applications

Pervious concrete

CALCIUM SULPHOALUMINATE BASED BLENDS

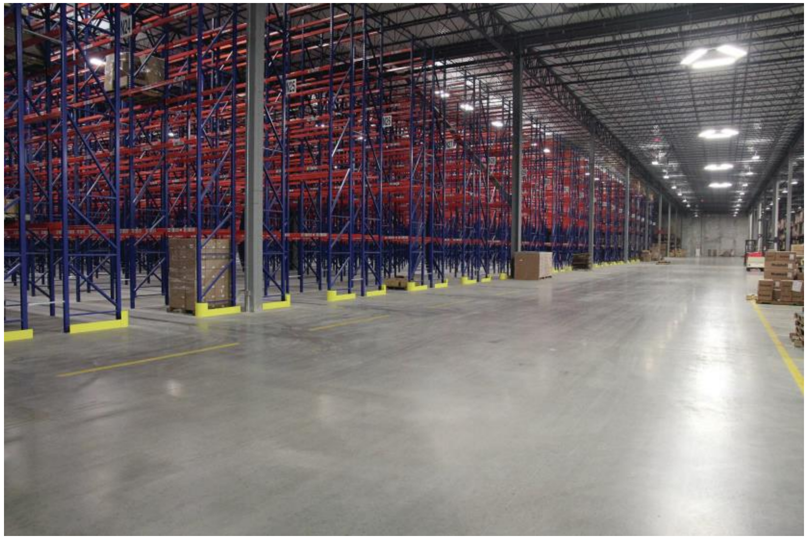
CSA is one of the most interesting non-Portland clinker due to the rapid setting times, high mechanical strength and low shrinkage or expansive behavior.

Green binders

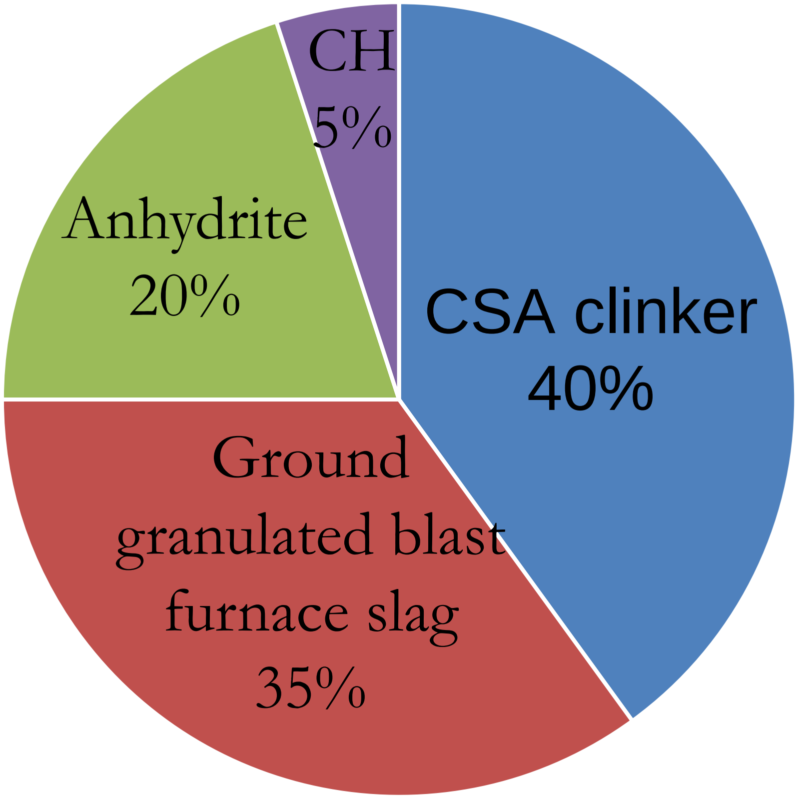
- The production requires limited kiln temperature (in the range of 1200-1250°C)
- Emits less carbon dioxide with respect to traditional OPC clinker (-50%) thanks to a limited content of calcium in the major phases

CALCIUM SULPHOALUMINATES BASED MIXTURES FOR JOINTLESS SLABS ON GROUND

Experimental research to develop an expansive Portland-free «special» concrete for jointless slabs on ground



MATERIALS

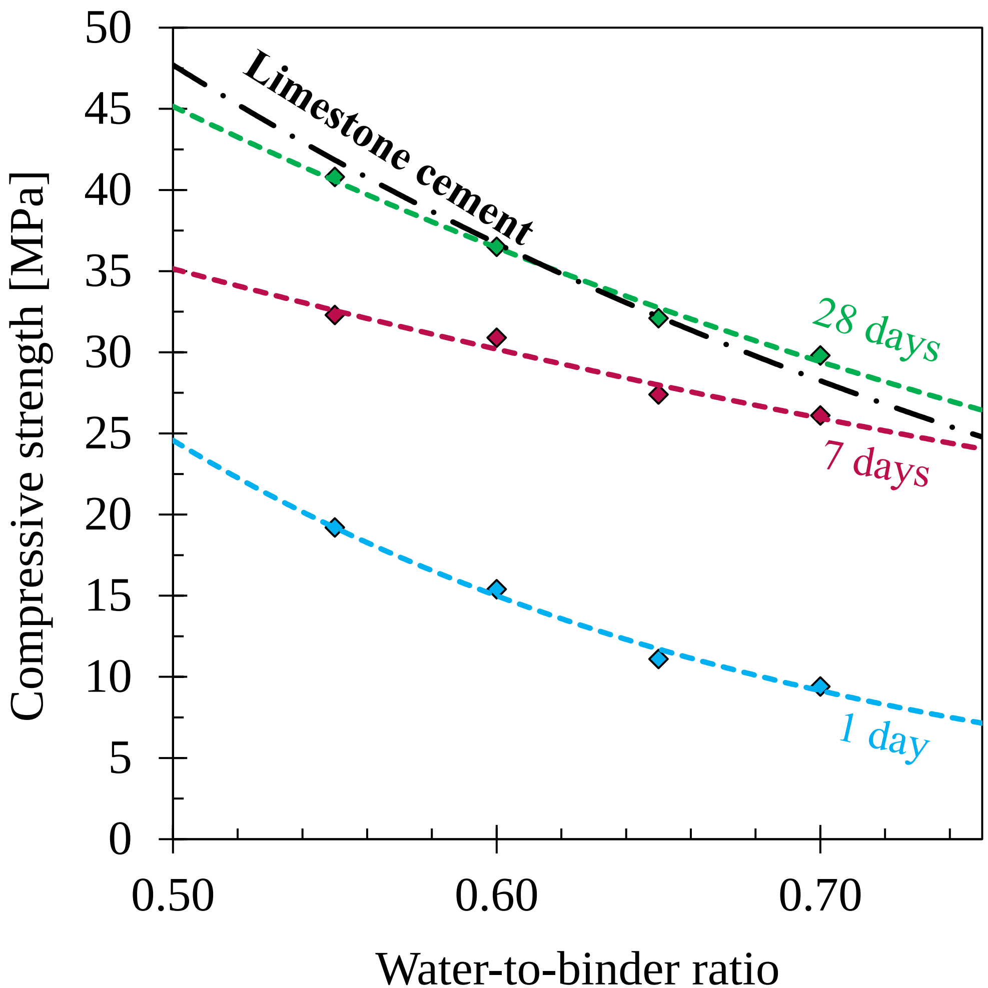


Natural calcareous aggregates: 32 mm

w/c ratio
0.55 –0.60 – 0.65 – 0.70

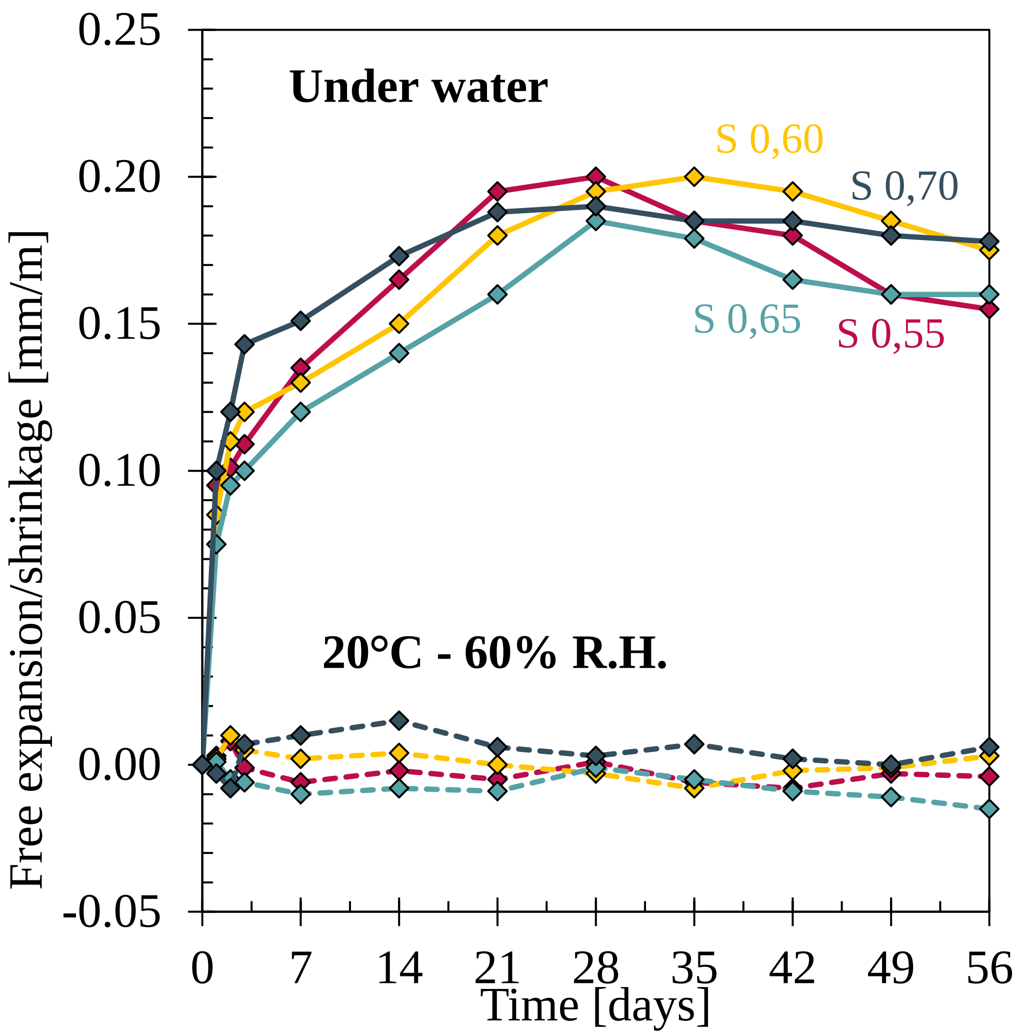
Tartaric acid-based set-retarding admixture was used at 0.4% by binder mass

COMPRESSIVE STRENGTH



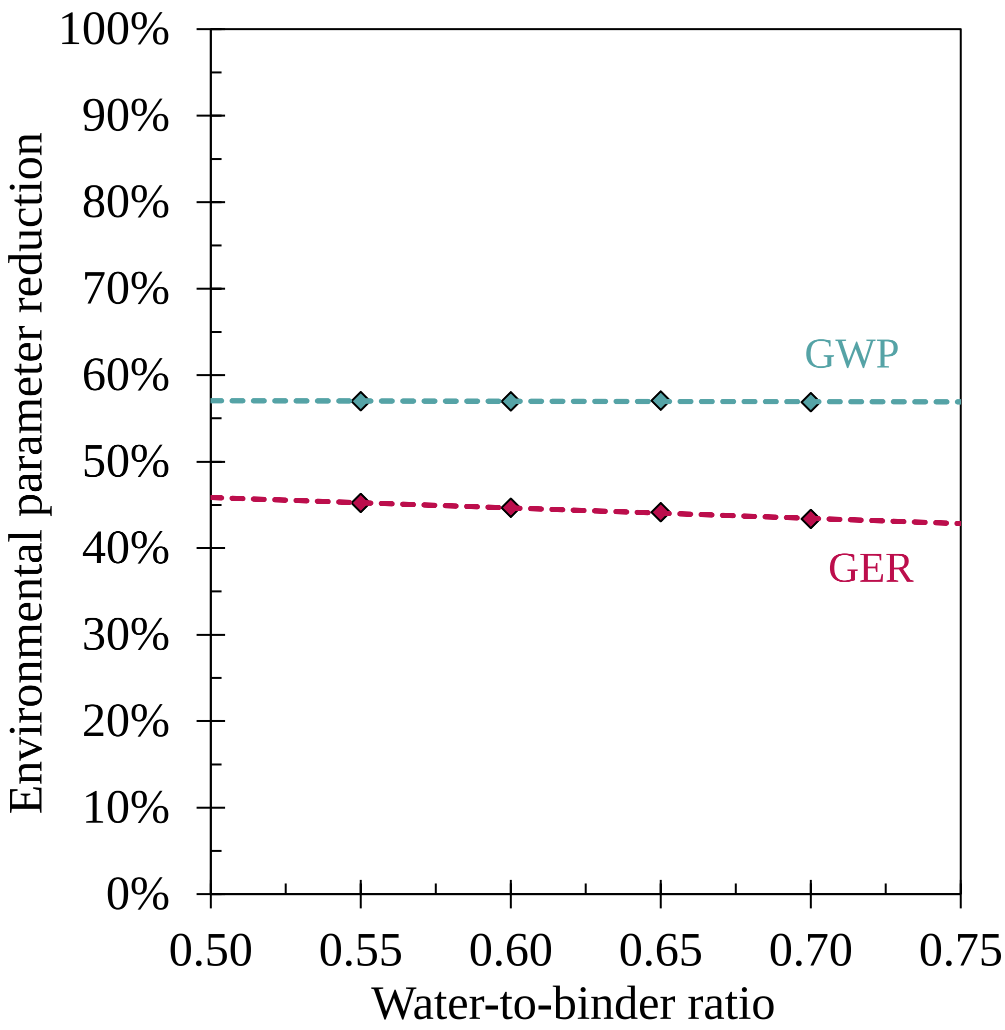
Concretes containing calcium sulphoaluminate clinker and slag with water-to-binder ratio from 0.55 to 0.70 exhibit 28-day compressive strength perfectly compatible with slabs on ground (25-40 MPa) and very similar to those of traditional concretes manufactured with limestone Portland cement

FREE EXPANSION-SHRINKAGE



The total replacement of OPC with a blend containing CSA and S allows to obtain a shrinkage compensating concrete characterized by a stable behavior over time when samples are stored in a dry environment. Concretes cured under water show an initial expansion followed by negligible shrinkage

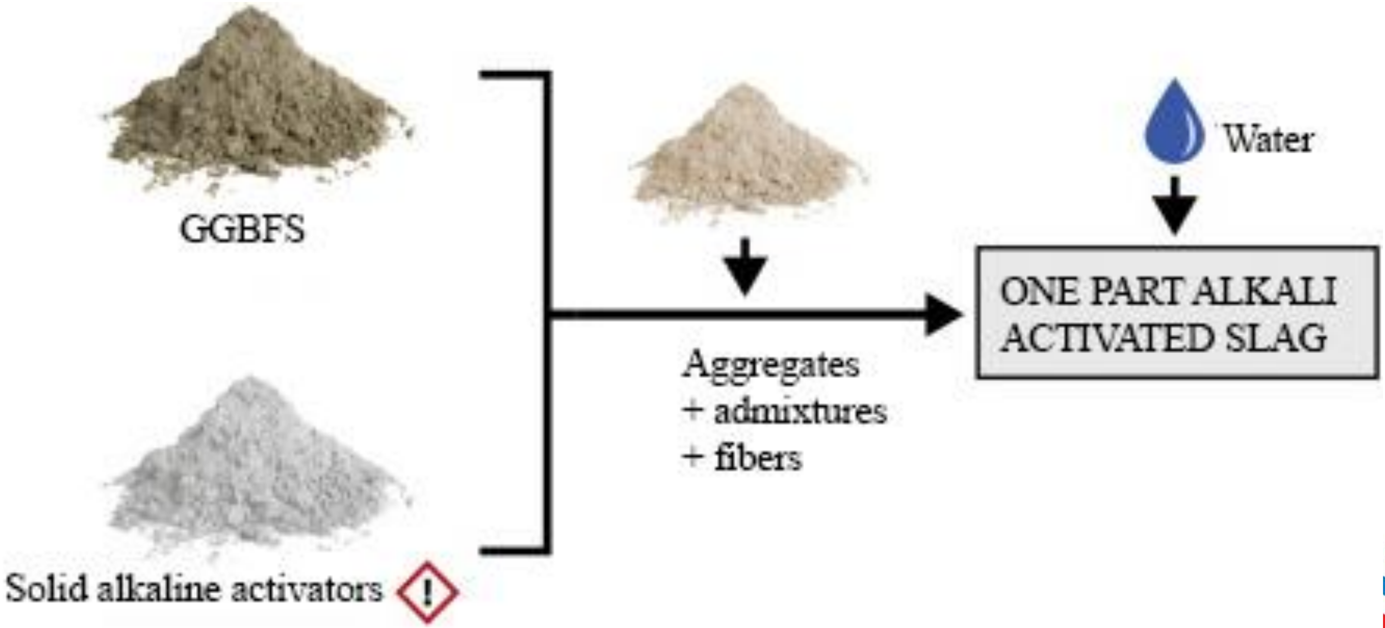
GER AND GWP PARAMETERS



The use of slag and calcium sulphoaluminate clinker instead of Portland cement to produce concrete reduces, at equal strength class, both the GWP and the GER of about 55% and 45%, respectively

ALKALI ACTIVATED SLAG BASED MIXTURE

The reaction of an alkali source with a silica-and alumina-containing solid precursor to form a solid material comparable to hardened Portland cement was first patented by Kùhl in 1908



ALKALI ACTIVATED SLAG BASED PLASTER

The purpose of this experimental research is to develop a premixed M10 (28-day compressive strength al least equal to 10 MPa) alkali-activated slag-based plaster for the structural retrofitting of existing masonry buildings.

First stage: effect of sand-to-binder ratio

	S8 4:1	S8 5:1	S8 6:1
GGBFS	365 kg/m^3	305 kg/m^3	260 kg/m^3
Calcareous filler	145 kg/m^3	150 kg/m^3	155 kg/m^3
Sand	1320 kg/m^3	1375 kg/m^3	1410 kg/m^3
Alkaline activators	29 kg/m^3	24 kg/m^3	21 kg/m^3
Water	**256 kg/m^3**	**253 kg/m^3**	**252 kg/m^3**
Initial workability	**170 mm**	**170 mm**	**170 mm**
Workability at 60 min	**150 mm**	**160 mm**	**160 mm**
Workability life	**110 min**	**110 min**	**120 min**
Air content	4.5%	5.0%	5.0%
Density of fresh mortar	2115 kg/m^3	2105 kg/m^3	2100 kg/m^3

The workability retention is very pronounced and it is not influenced by the sand-to-binder ratio, as well as the density at fresh state and the entrapped air are only marginally affected by the variation of sand dosage

Second stage: effect of viscosity modifiers

The aim of the second stage was to improve the applicability by trowel of AAS plasters due to the addition of commercial MS, MC and AEA.

Modified starch (MS)	0.01 wt% vs dry powder mass
Methylcellulose (MC)	0.03 wt% vs dry powder mass
Air entraining agent	0.04 wt% vs dry powder mass

Second stage: effect of viscosity modifiers

	S8 4:1_VM	S8 5:1_VM	S8 6:1_VM
1-day compressive strength	-	-	-
7-day compressive strength	13.1 MPa	9.2 MPa	5.1 MPa
28-day compressive strength	15.4 MPa	11.3 MPa	5.5 MPa

Reduction of about 35-40% (at 28 days, from 24 and 18.9 MPa to 15.4 and 11.3 MPa) can be observed compared to mortars manufactured without VM

Decrease in strength close to 70% (from 17.3 to 5.5 MPa)

Third stage: effect of shrinkage reducing admixture

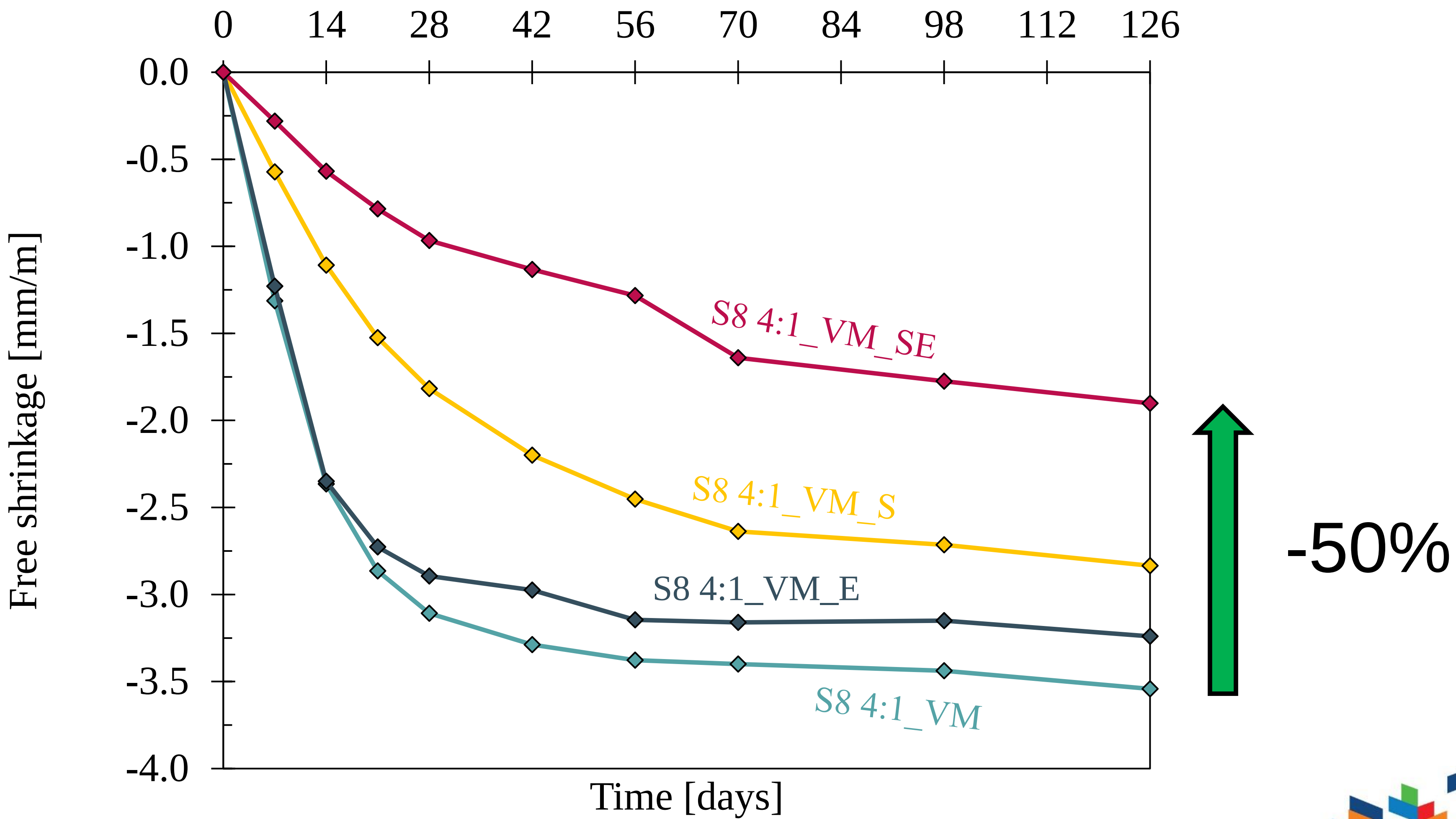
In the third phase an expansive agent (EA) and a shrinkage reducing admixture were used, alone or in combination, with polymeric fibers able to control the plastic cracking of mortars

S8 4:1_VM_S ⇒ Fiber (0.06 wt% dry powder mass)
SRA (0.50 wt% binder mass)

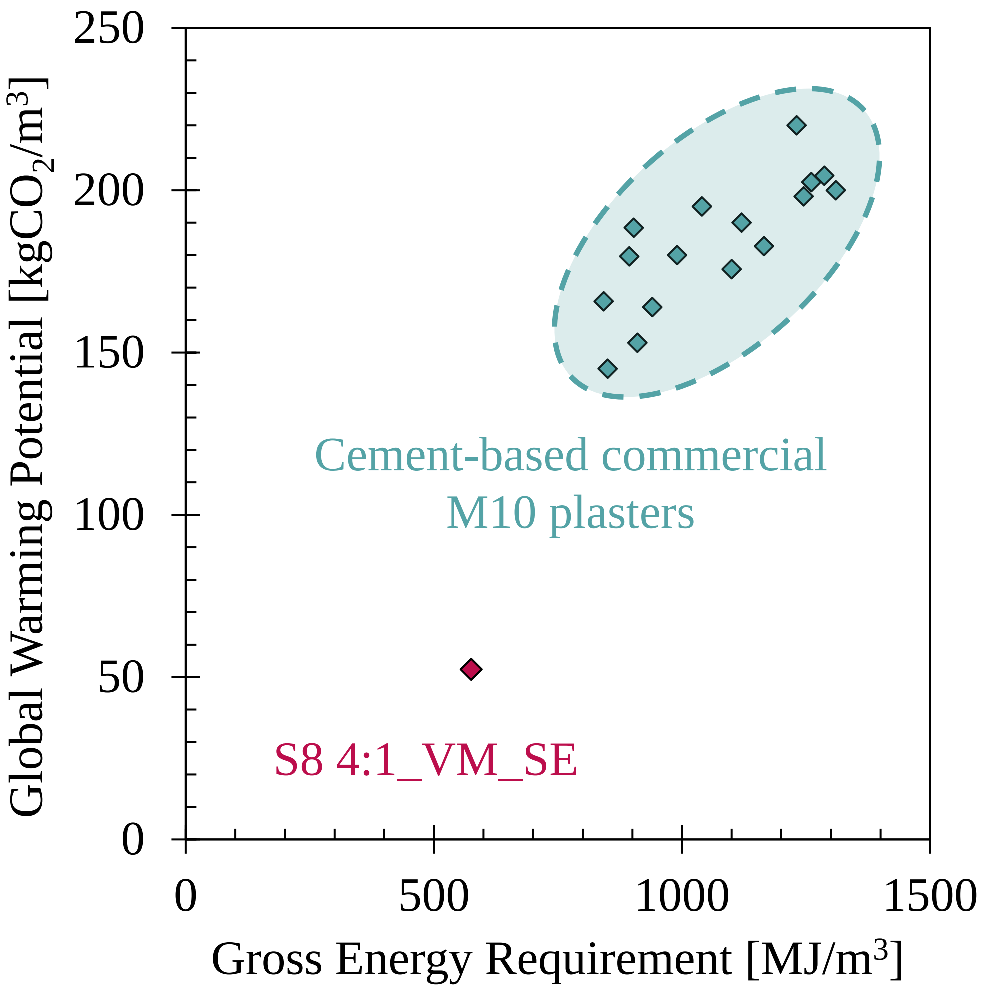
S8 4:1_VM_E ⇒ Fiber (0.06 wt% dry powder mass)
EA (0.08 wt% dry powder mass)

S8 4:1_VM_SE ⇒ Fiber (0.06 wt% dry powder mass)
EA (0.08 wt% dry powder mass)
SRA (0.50 wt% binder mass)

Third stage: effect of shrinkage reducing admixture



Third stage: effect of shrinkage reducing admixture



The CO_2 emissions (GWP) slump from about 140-230 to 50 kgCO$_2$/m^3 while the energy consumptions (GER) drop from 750-1400 to 600 MJ/m^3

The purpose of this experimental research is to investigate an alkali-activated slag-based pervious concrete manufactured with tunnel muck (TM) as recycled aggregate instead of natural sand and gravel and to evaluate the relationship between aggregate size and physico-mechanical properties of no-fines concrete

Composition of pervious concretes

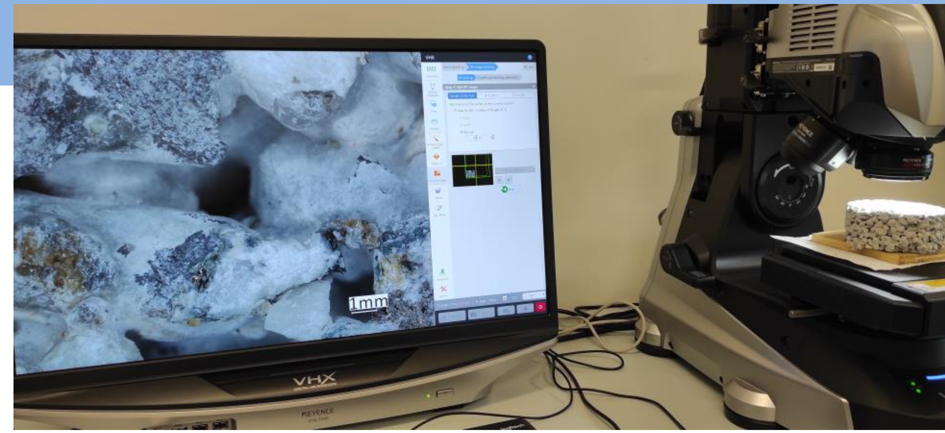
	PC 1-2	PC 2-4	PC 4-8	PC 8-12	PC 12-16	PC 16-22
GGBFS [kg/m³]	350	350	350	350	350	350
Alkaline activators [kg/m³]	70	70	70	70	70	70
TM X-Y [kg/m³]	1450					
Natural sand [kg/m³]	80	80	80	80	80	80
Water [kg/m³]	110	110	110	110	110	110
Air entraining agent [g/m³]	20	20	20	20	20	20
Superplasticizer [kg/m³]	5,0	4,2	3,5	1,75		

Small amount of an air entraining agent and 80 kg/m^3 of natural sand with maximum size of 0.25 mm were added to the concrete to enhance the porosity and the rheology of the mixtures, respectively.

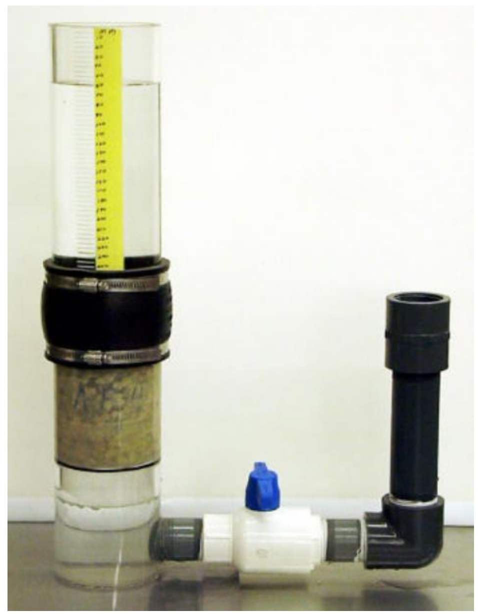
A commercial PCE superplasticizer was used to obtain a proper consistency at fresh state

Experimental tests

Compressive strength



Porosity



Water permeability

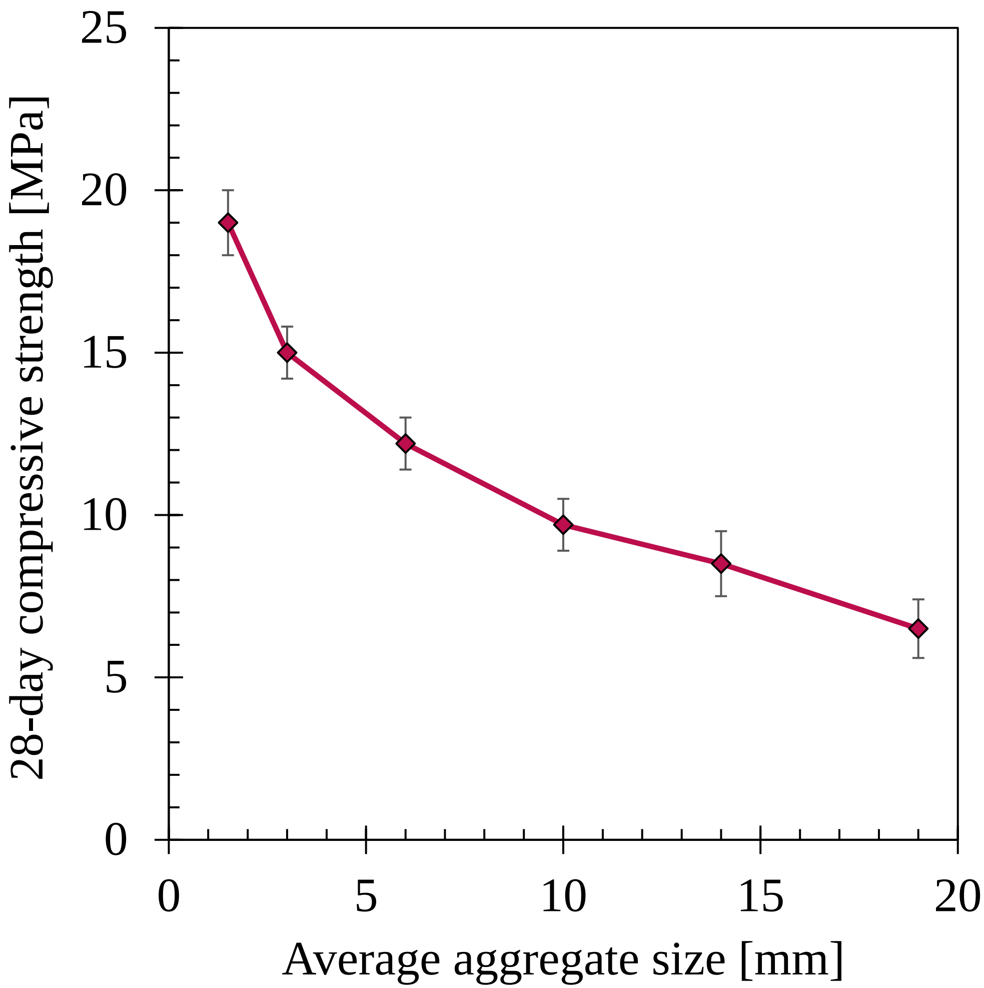
Permeability (Darcy law) – Constant head test

$$K_{CH} = \frac{Q}{\Delta t} \cdot \frac{H}{S \cdot h_f}$$

Permeability (ACI 522R-10) – Falling head method

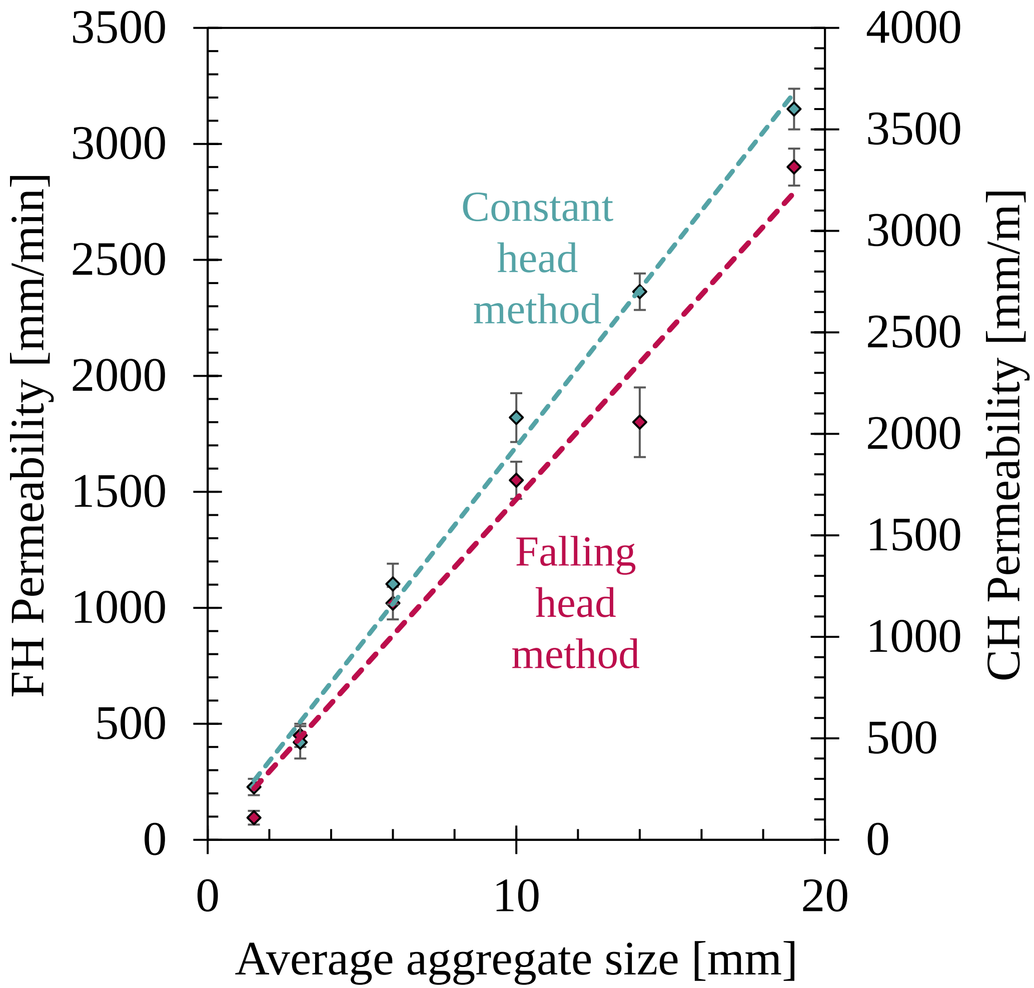
$$K_{FH} = \frac{S_1 l}{S_2 t} \cdot log \frac{h_2}{h_1}$$

Experimental results: compressive strength



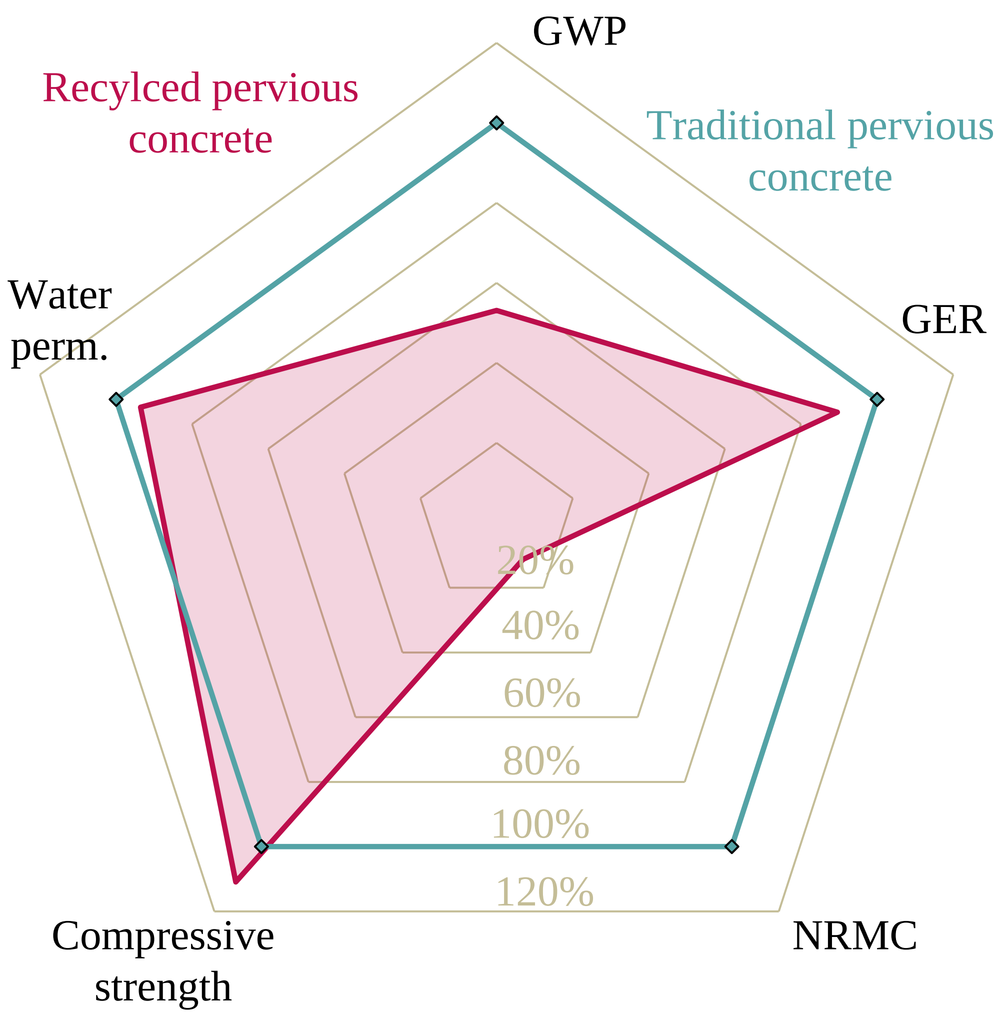
After 28 days, pervious concretes containing small sized aggregates achieve compressive strength ranging from 12 to 19 MPa, while concretes manufactured with coarse aggregates with size higher than 8 mm evidence compressive strength lower than 10 MPa

Experimental results: FH and CH permeability



Both FH and CH methods gave the same permeability trend in the tested pervious concrete.
Mixtures containing large aggregates show a more pronounced permeability, in general one order of magnitude higher with respect to the PC1-2 and PC2-4 manufactured with small-sized recycled gravel

Experimental results: GER and GWP



SAME COMPRESSIVE STRENGTH AND WATER PERMEABILITY

The CO_2 emissions (GWP) decrease of about 50% and the natural raw materials consumption (NRMC) is reduced of more than 80% while limited advantages can be highlighted in energy consumption to produce one cubic meter of pervious concrete

Conclusions

Binders containing CSA clinker, GGBFS, anhydrite and hydrate lime can be used to produce very low environmental impact shrinkage-compensating concretes with properties at fresh and hardened state perfectly suitable for jointless slabs on ground

The replacement of traditional binders with an alkali activated slag-based binder to produce a premixed M10 plaster requires a proper evaluation not only to the rheological, physical and mechanical properties of the mortars but also the application feasibility. However, despite the massive use of admixtures, the AAS plaster has, at equal strength class, much less environmental impact than traditional plasters on the market.

Conclusions

The production of a pervious concrete with both binder and aggregates deriving from industrial wastes is technically feasible. By using an AAS binder and single-sized recycled aggregates from tunnel muck, it is possible to obtain pervious concrete with excellent properties and significantly reduced environmental impact compared to tradition no-fines concretes

THANKS FOR THE ATTENTION

THE WORLD'S GATHERING PLACE FOR ADVANCING CONCRETE

aci CONCRETE CONVENTION