CO_2 capture and Recycling in the built environment: challenges and solutions

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Universitatea Politehnica Timişoara,
Seminar for master students
November 19, 2025

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Urban & Environmental Engineering

Building … an old story but a societal need

esperance » spiritualité
coline3unblogfunblogfrr.unblog.fr

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Societal context

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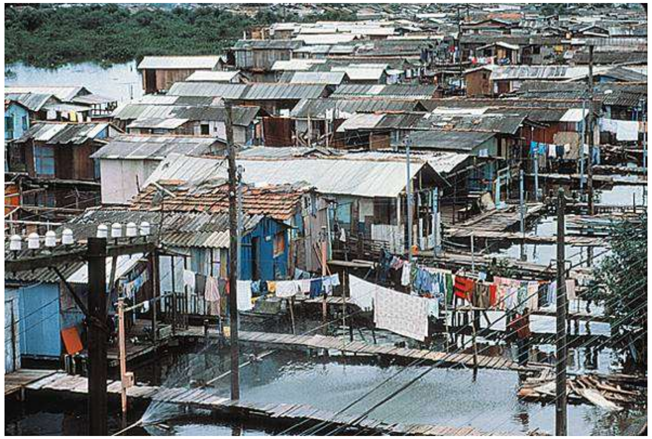
Building … a contemporary question

- 75% of the population living in city from 2050

Building … how?

Underground house
(www.villavals.ch)

4-façade house
(www.immobelgique.com)



Floating houses

Big bend, New York (1219m)

Building … with materials

- 4 main impacts

- **energy consumption** (40%)
- **natural resources consumption** (40-50%)
- **GW gas production** (around 40% CO_2)
- **waste production** (40%)

Building … with materials

- 3R: Reduce, Reuse and Recycle
- Meeting Sustainable Development Goals: recovery targets to 70% of construction and demolition wastes (CD&W) by 2020 in European Union (**Directive 2008/98/EC**)
- Reducing use of natural aggregates (preservation of natural resources)

Building … with biobased materials

- Biobased *vs* mineral *economy*

Beginning XXᵉ century

x 8

Beginning XXIᵉ century

75% primary resources < biomass

30% primary resources < biomass

Biosourced economy

Mineral economy

→ Huge production of CO_2 et modification of the equilibrium of carbon sink (capture)

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Environment and materials

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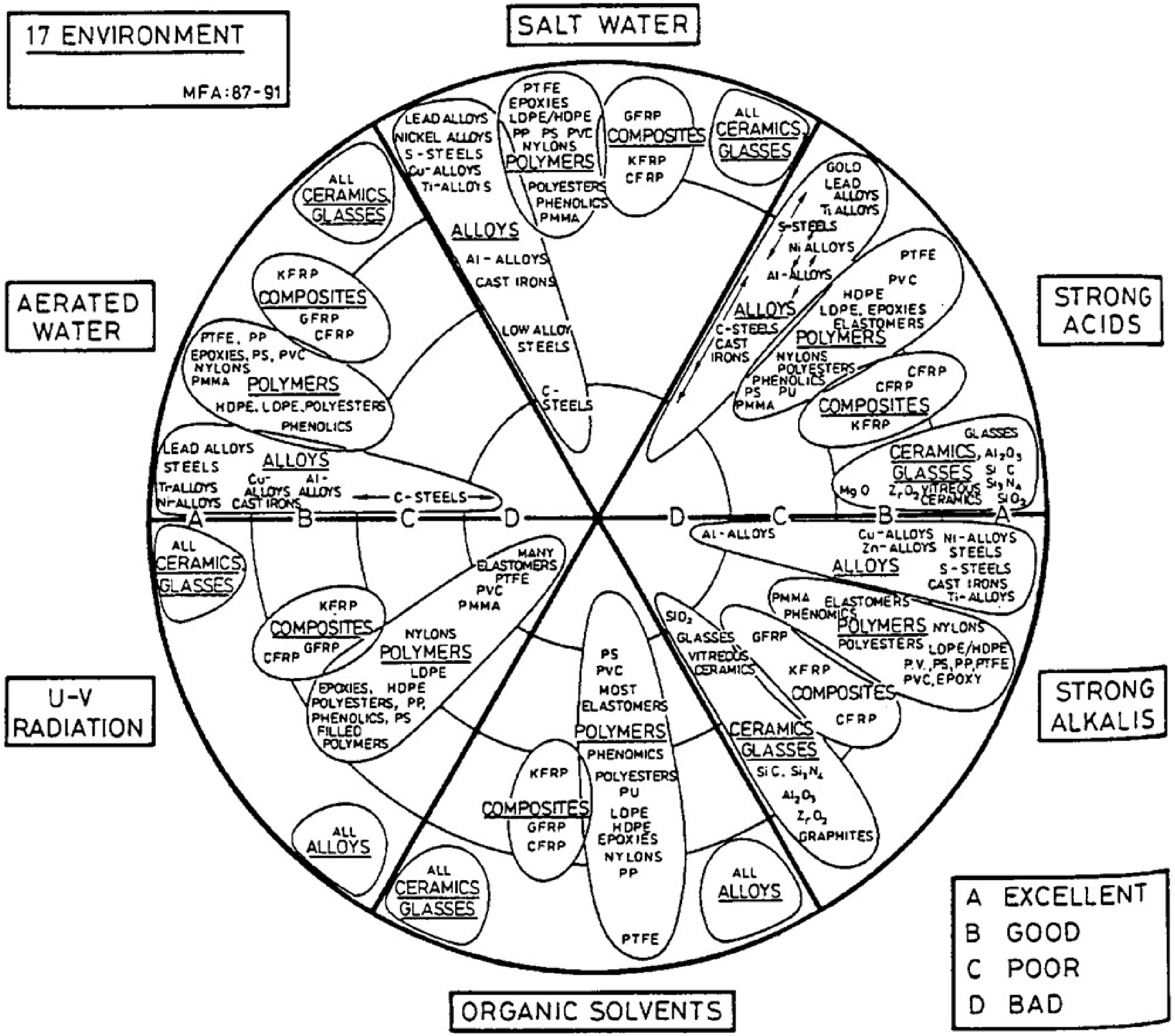
Environment and materials

- Actions

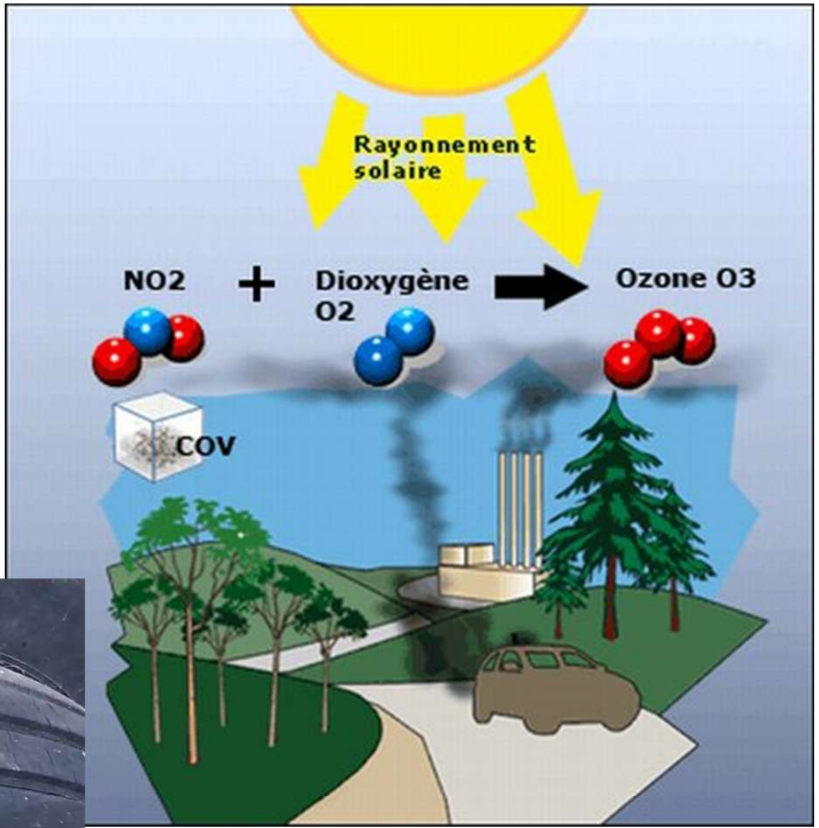


Environment and materials

- Wood
  - fungi
  - insects

Environment and materials

- Polymers and rubber



Environment and materials

- Bitumen

Environment and materials

- Concrete

Environment and materials

- Ceramics
  - Efflorescences
  - Freeze thaw cycles

Environment and materials

- Natural stones

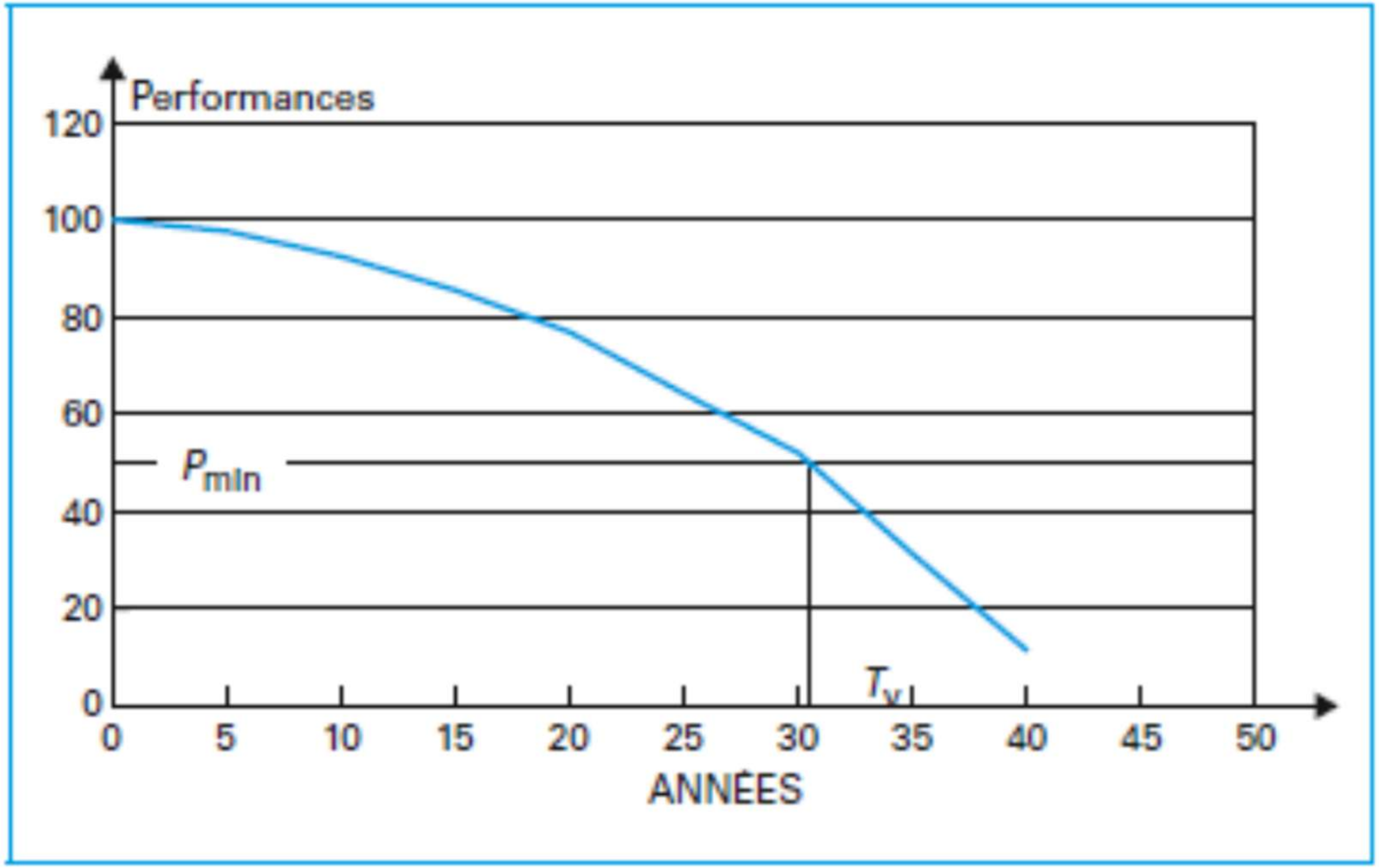
Environment and materials

- Metals



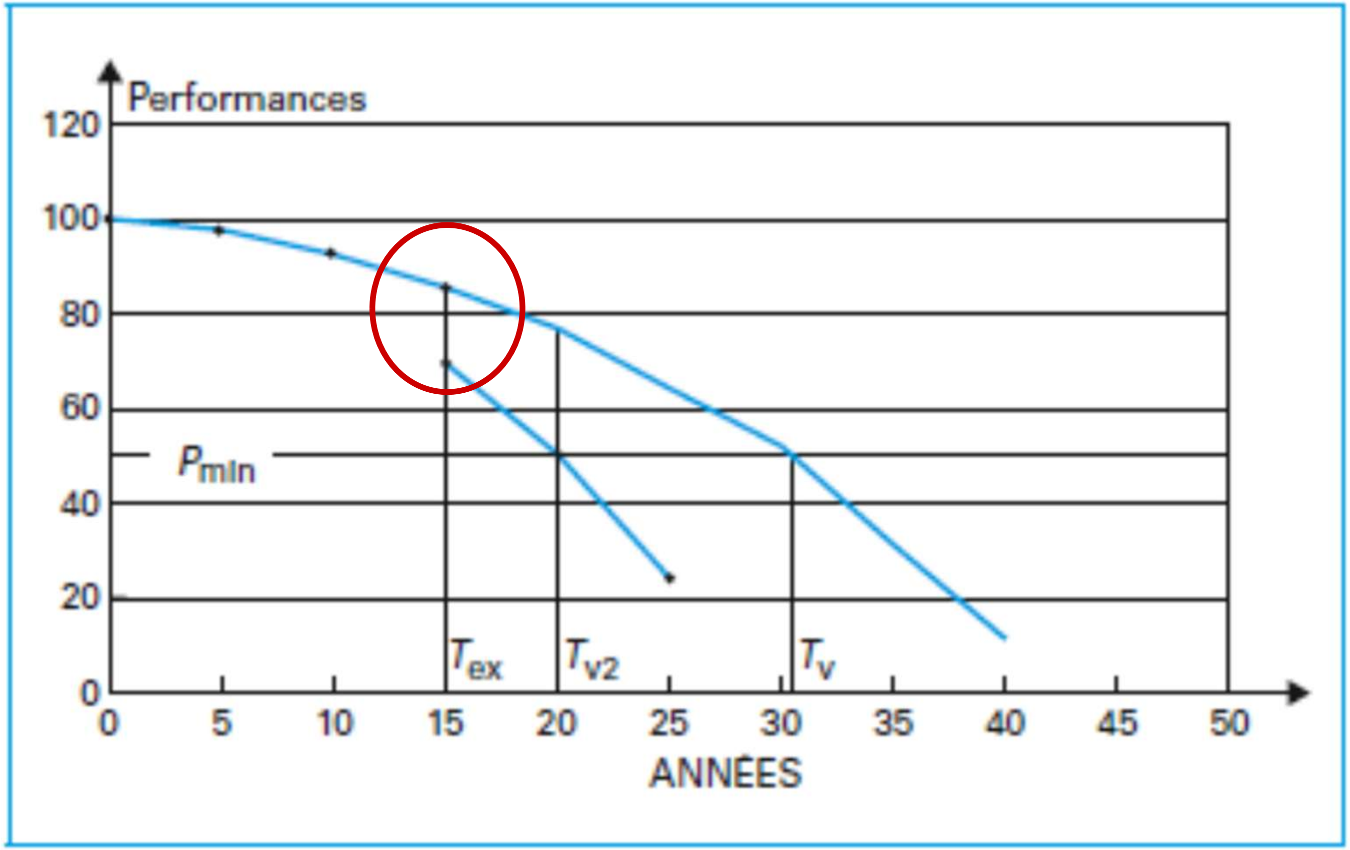

Environment and materials

- Service life of structures (T_V)
  - Maximum permissible reduction of one or more (selected) performance(s)



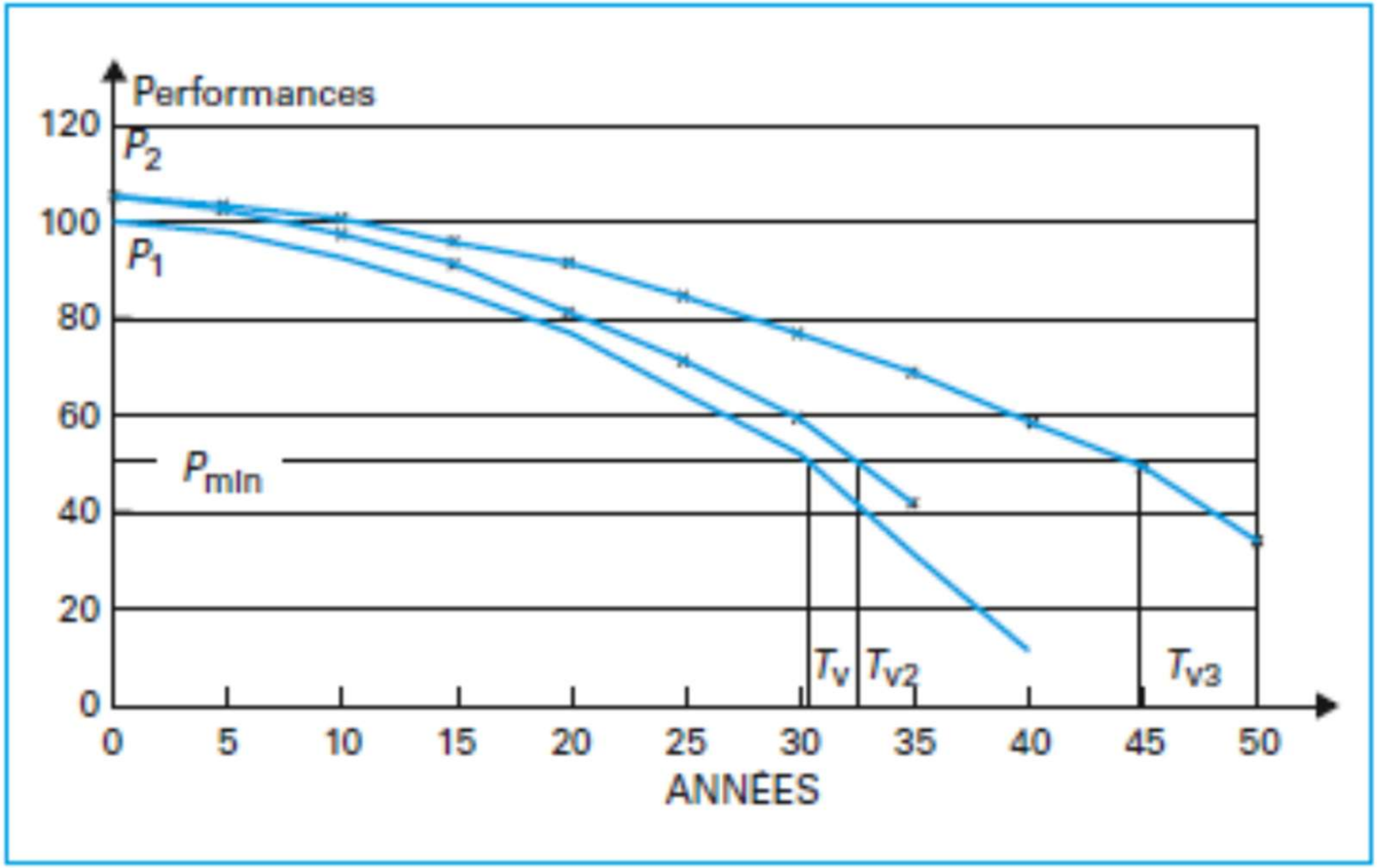
Environment and materials

- Effect of exceptional stresses
  - Earthquake, tornado, overloading, …



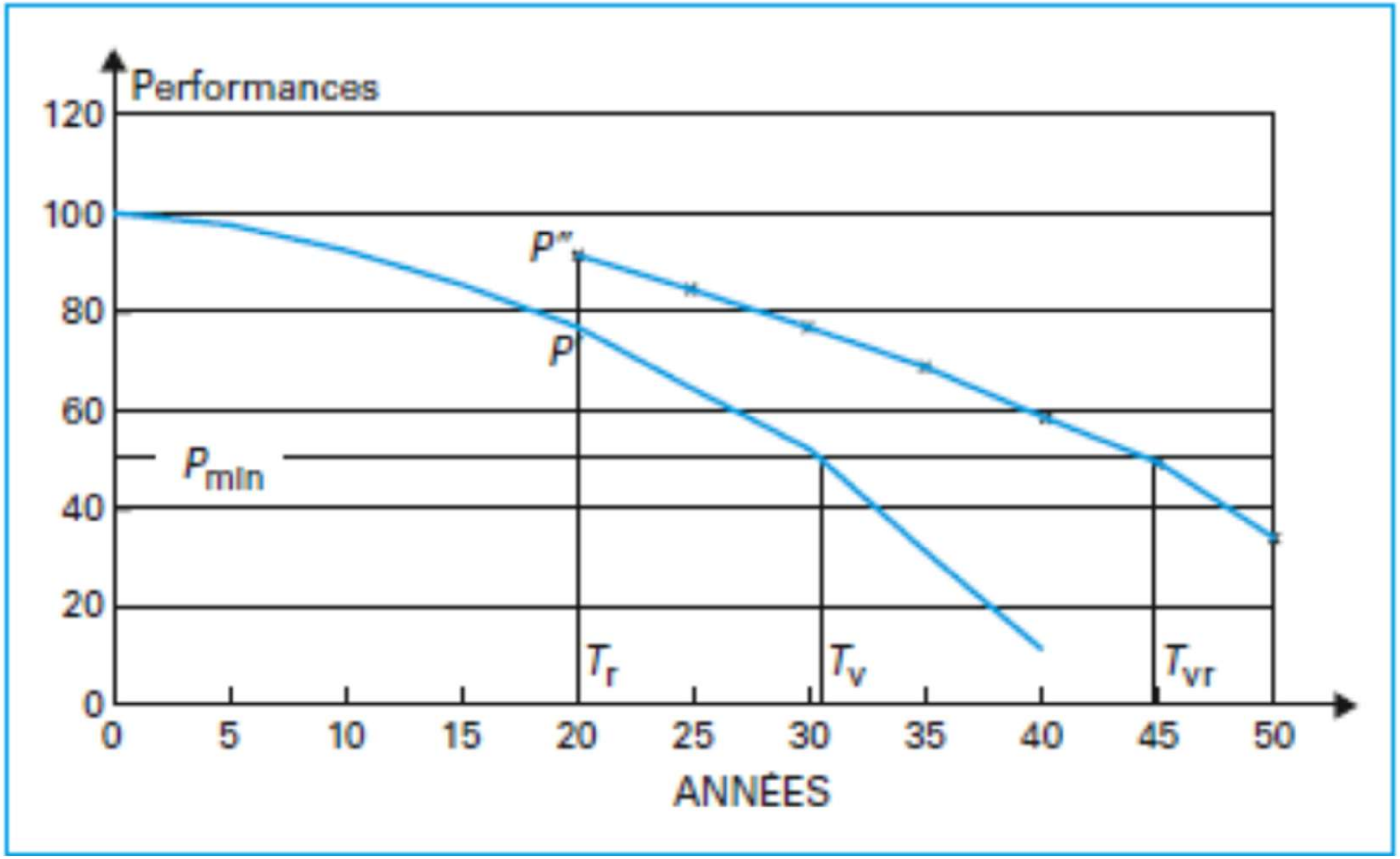
Environment and materials

- Service life of structure: effect of increasing initial performances (P_1 to P_2 ⇒ T_V to T_{V2}) + effect of supplementary protection T_{V3}



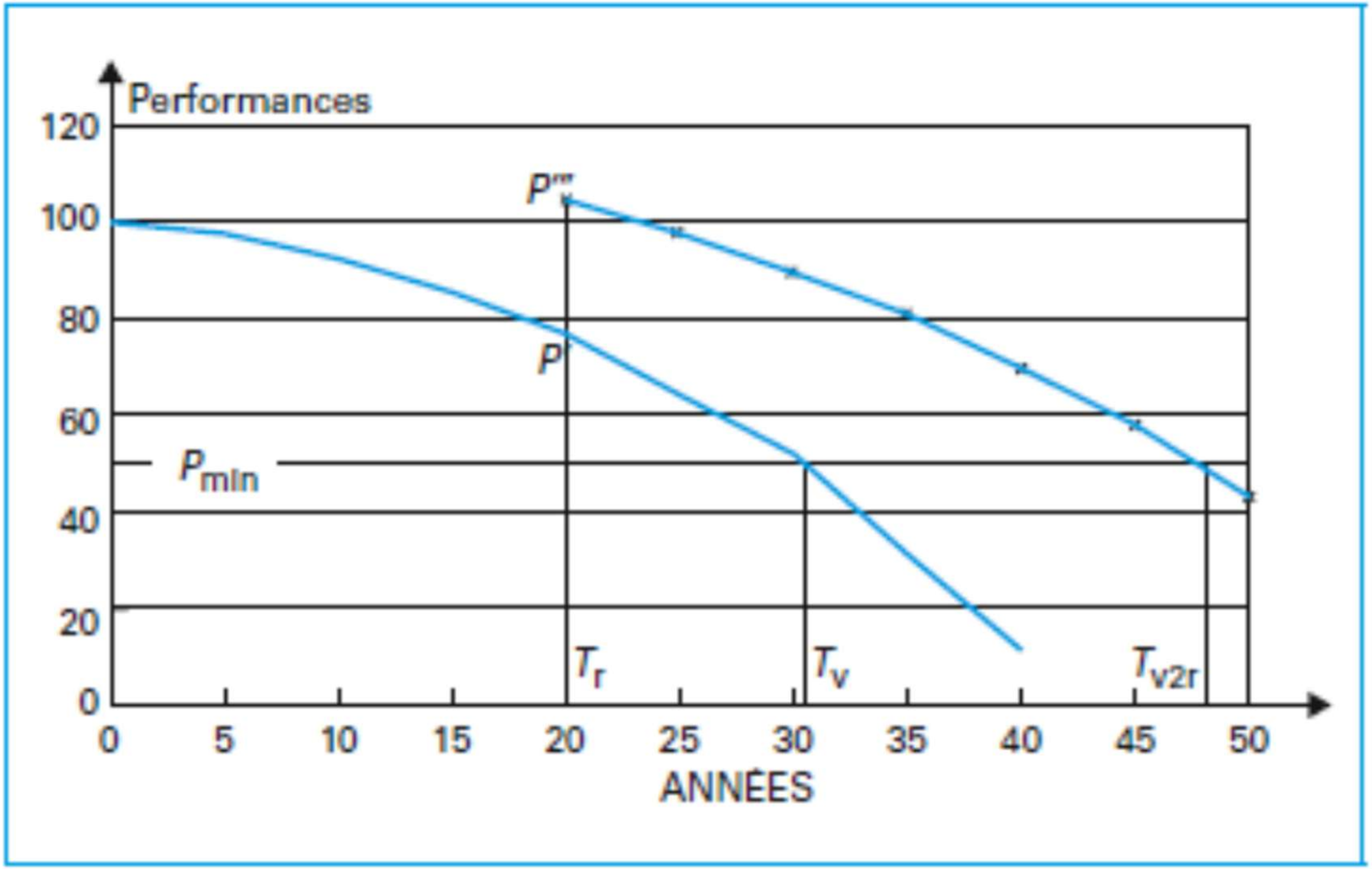
Environment and materials

- Service life: repair (P′ to P″) - restoration



Environment and materials

- Service life: repair (P′ to P‴) - reinforcement



Main options *(Maage, 2004)*

- **do nothing** for a certain time,
- re-analysis of **structural capacity**, possibly leading to downgrading of the function of the concrete structure,
- **prevention** or reduction of future deterioration, without improvement of the concrete structure,
- **improving, strengthening** or refurbishment of all the concrete structure,
- **reconstruction** of part of all of the concrete structure
- **demolition** of part of all the concrete structure.

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Materials and environment

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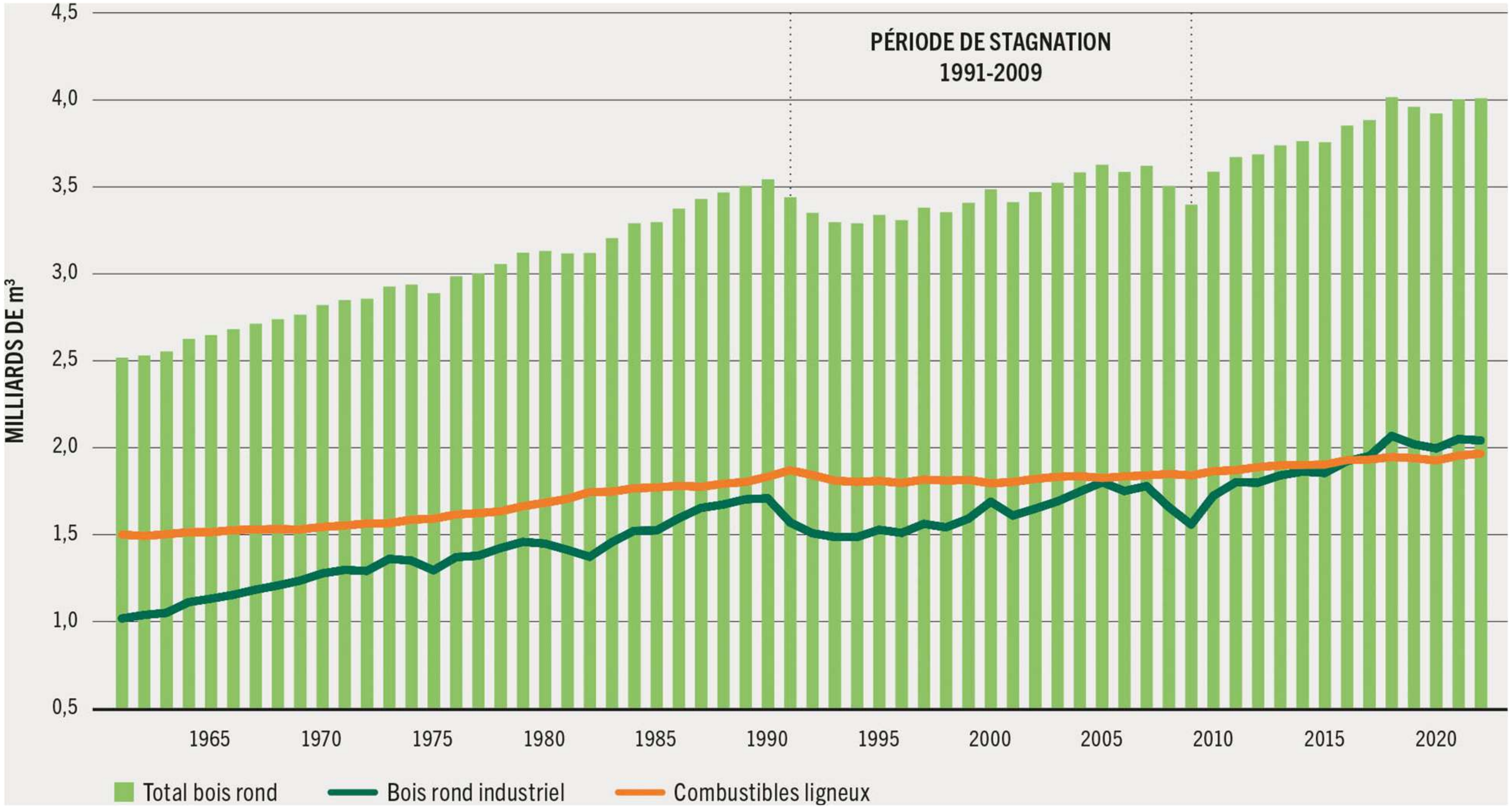
Materials and environment

- Limited world
  - Space
  - Natural resources
  - Energy
- Waste managment
  - Reduce the production
  - Support reuse/recycling
  - Support safe storage
- 3R theory

Materials and environment

We consume natural resources (per year)

4 billions m³ wood/year incuding 2 for construction industry



Materials and environment

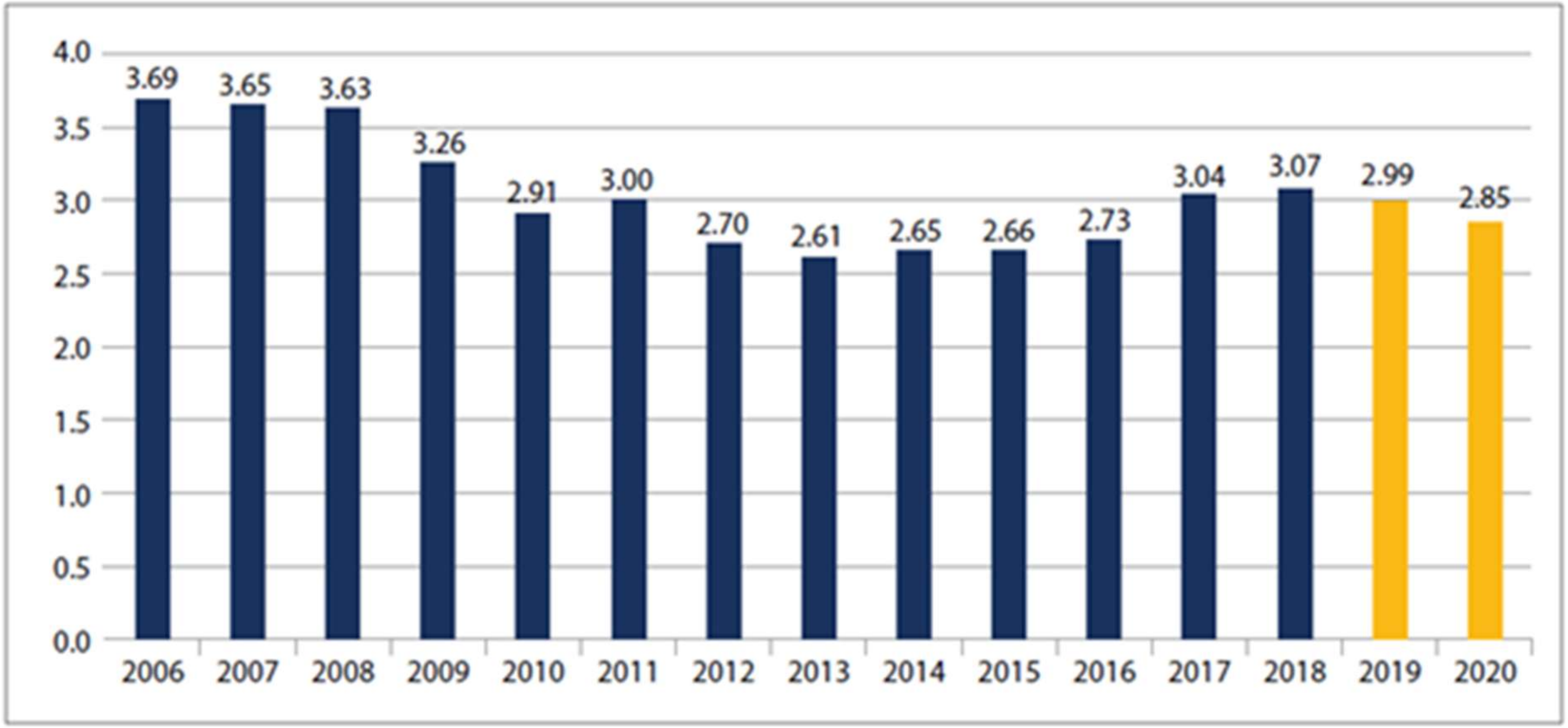
We consume natural resources (per year)

- Aggregates: 4.7 billions tons
  - (670 pyramids of Cheops)
- Sand: 2.2 billions tons
  - (22 millions wagons = train 264000 km long)
- Cement: 1.3 billions tons
  - (17000 ocean liner type *Norway* = 2.34 billions tons of limestone and clay)
- Water: 800 billions litres
  - (23 times the dayly flow of river Seine, Paris)
- *Concrete: 9 billions tons*
  - *(30000 archs of Defense, Paris)*

Materials and environment

We consume natural resources (per year)

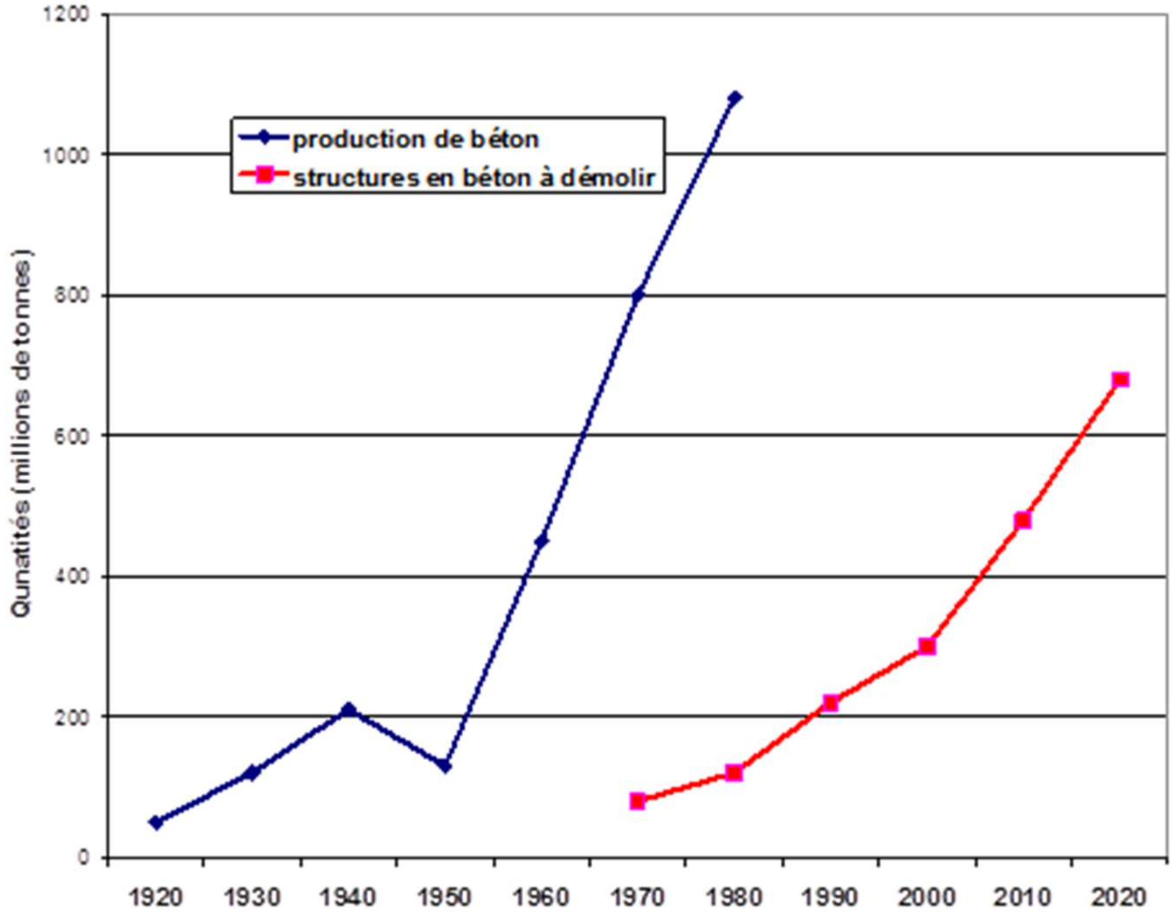
- Trend in total EU27 + UK + EFTA Tonnages (in billions of tonnes) for the production of aggregates (UEPG 2021) - 26,000 quarries and pits, operated by 15,000 companies



Materials and environment

We consume natural resources (per year)

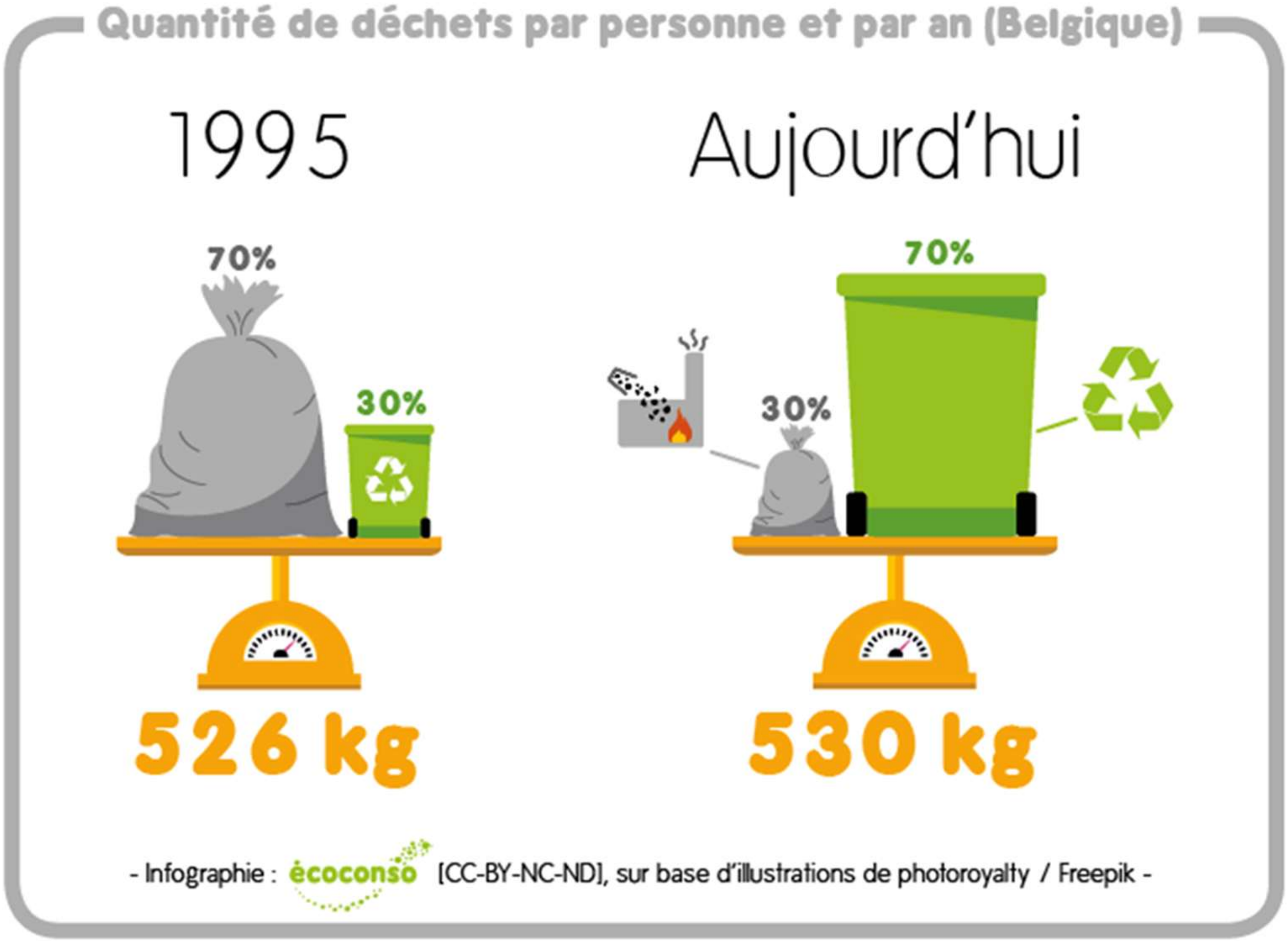
- Quantity of concrete produced in Belgium (*blue*) *vs* construction to be demolished (*red*)



Materials and environment

We produce a lot of wastes

- Comparison of the production of municipal wastes in Wallonia (per year and capita) between 1995 and 2017 (www.ecoconso.be)



Materials and environment

We produce a lot of wastes

- Comparison of the production of municipal wastes in Wallonia (per year and capita) between 1995 and 2017 (www.ecoconso.be)

513 kg/year.inh.

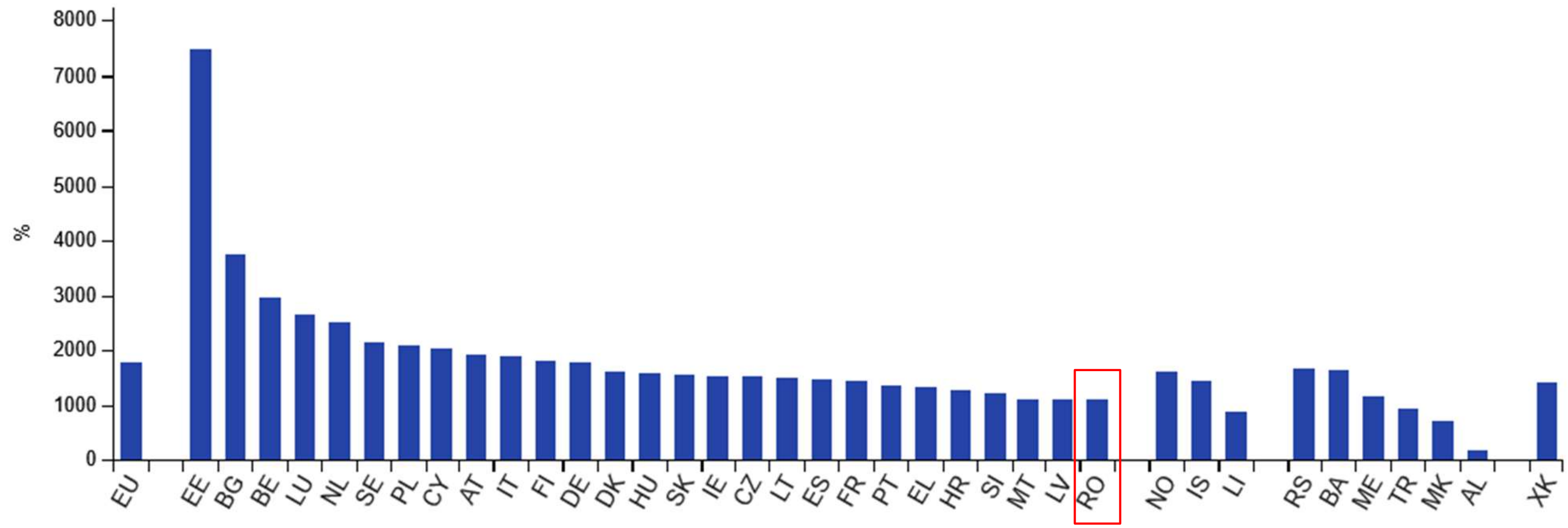
301 kg/year.inh. (36 recycled)

https://www.eea.europa.eu/en/topics/in-depth/waste-and-recycling/municipal-and-packaging-waste-management-country-profiles-2025/ro-municipal-waste-factsheet.pdf/@@download/file

Materials and environment

We produce a lot of wastes

- Waste generation (kg/capita), excluding major mineral waste, 2022



Provisional data: Greece.
2020 data:Iceland.
2021 data :Albania.
This designation is without prejudice to positions on status, and is in line with UNSCR 1244/1999 and the ICJ Opinion on the Kosovo Declaration of Independence.
Source: Eurostat (online data code: env_wasgen)

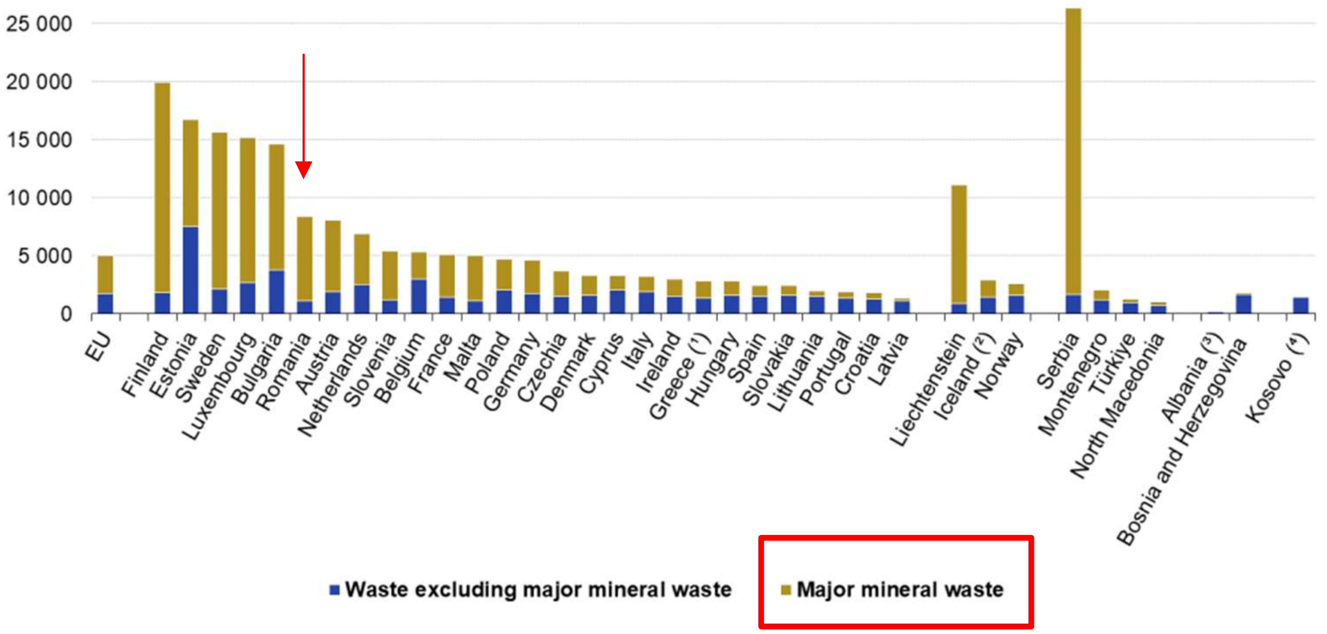
eurostat

Materials and environment

We produce a lot of wastes

- In 2022, 5 tons of waste were generated per EU inhabitant.
- In 2022, 40.8% of waste were **recycled** and 30.2% landfilled in the EU.

Waste generation, 2022
(kg per capita)



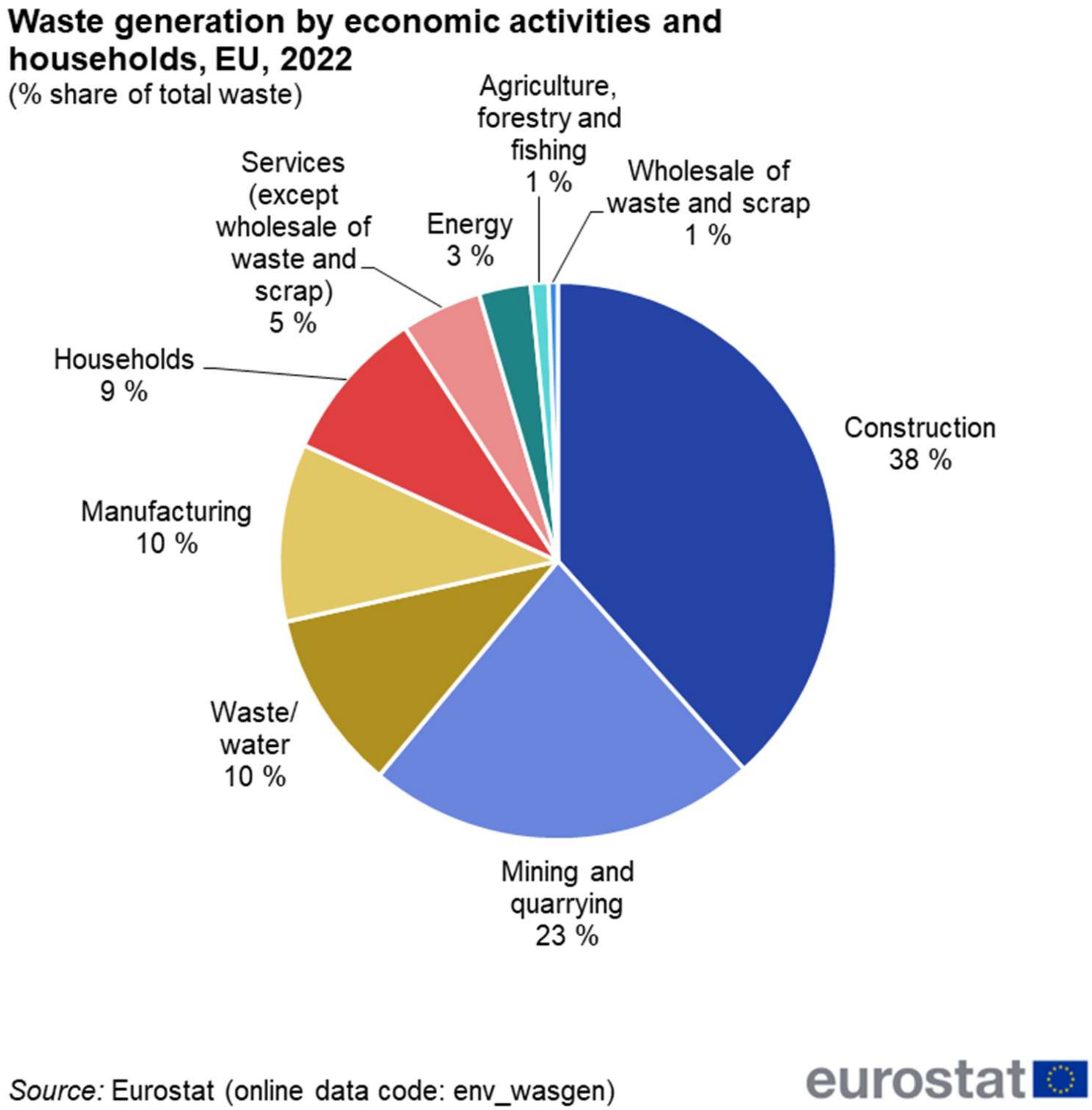
Note: sorted on total waste generated.
(¹) provisional data.
(²) data 2020.
(³) data 2021.
(⁴) This designation is without prejudice to positions on status, and is in line with UNSCR 1244/1999 and the ICJ Opinion on the Kosovo Declaration of Independence.
Source: Eurostat (online data code: env_wasgen)

eurostat

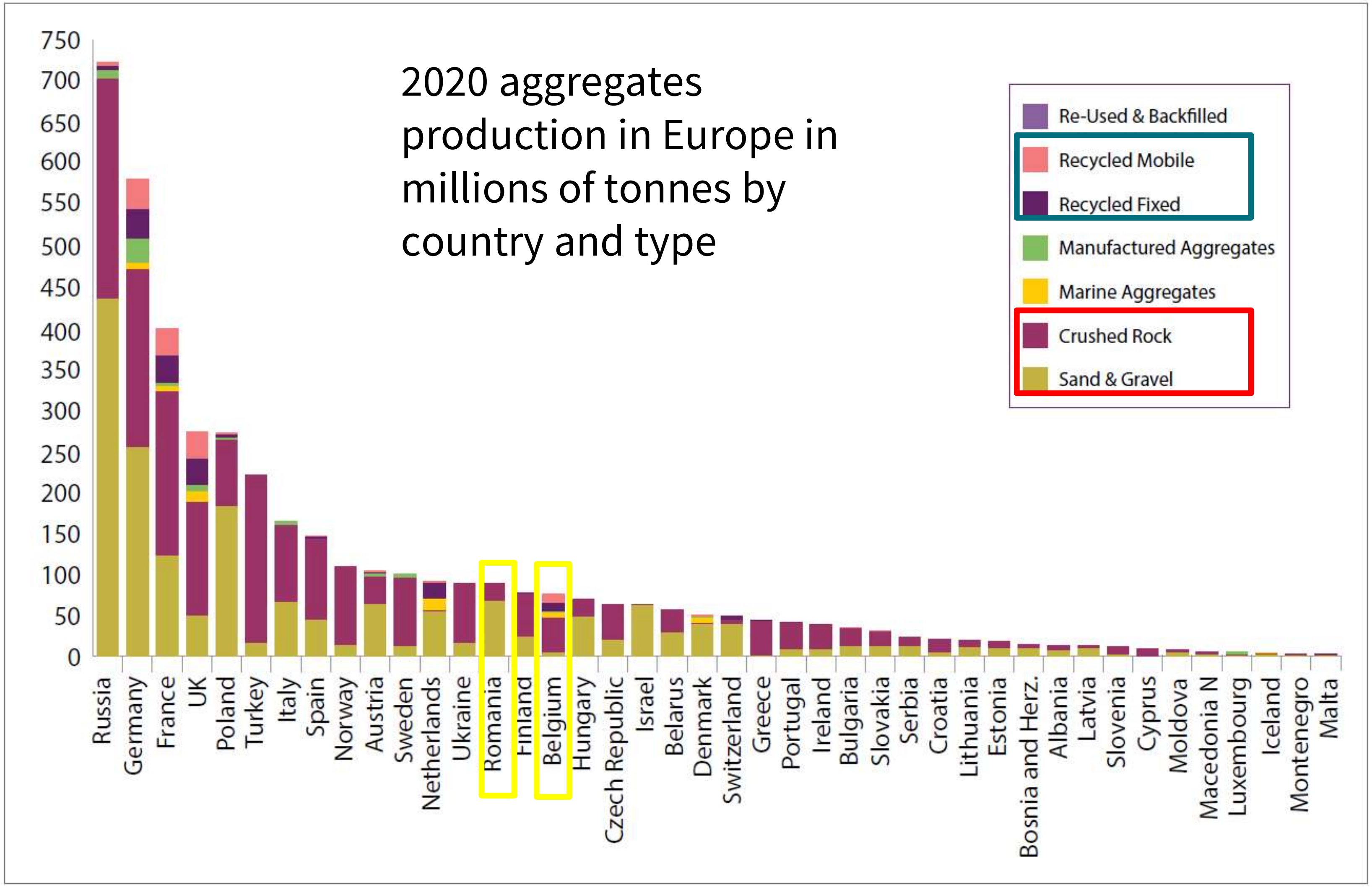
Materials and environment

We produce a lot of wastes

- 1725 kg C&DW per capita in the EU28



Materials and environment



UEPG, 2021. European Aggregates Association – Annual Review 2020-2021, Brussels, 30 p.

Materials and environment

- 3 billion tons produced in EU27+UK+EFTA in 2022 (UEPG 2023)

Virgin Aggregates	
46.9% crushed rock	**39.7%** sand & gravel

Recycled Aggregates	
Construction & demolition wastes (CDW)	**9.3%** recycled (278 million tonnes)

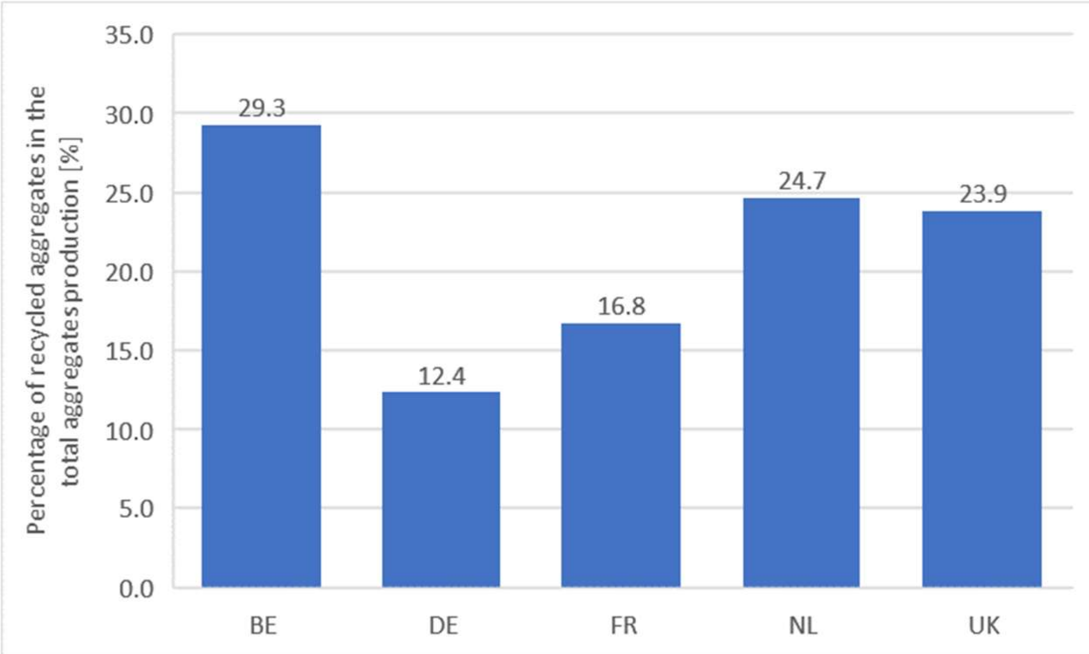
Concrete

Mixed

Materials and environment

- NWE countries (BE, DE, FR, NL, UK) are responsible for:
  - 47% of the virgin aggregates production (1417 Mtons)
  - 89% of the recycled aggregates production (248.4 Mtons)

Recycled aggregates/natural aggregates



Materials and environment

- Transforming wastes …

Materials and environment

- … into secondary ressources

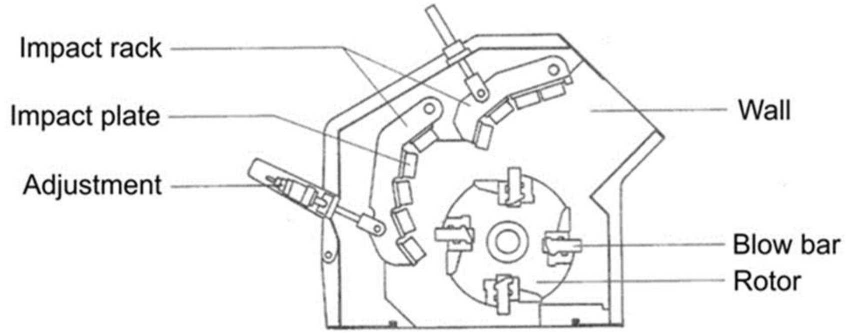
Research and innovation

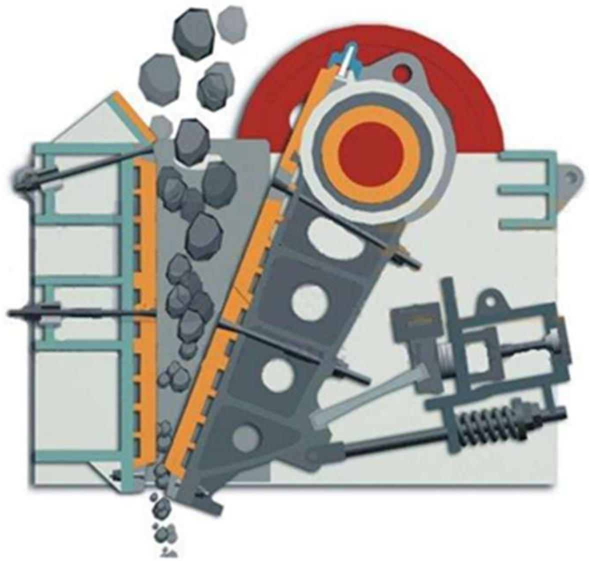
Research and innovation

- Research and innovation in improved methods for reuse and recycling
  - Preparation of recycled concrete aggregates: materials processing
  - Recycling production waste for concrete blocks
  - RA for prefab elements
  - Valorization of fine bricks
  - Use of recycled sand for 3D printing
  - CO_2 capture for increasing RCA properties

Material processing

- Impact crusher
  - allows producing very fine fractions
  - induces the biggest wear
  - limited by the primary size of waste to be treated
- Jaw crusher
  - to treat bulky waste like concrete slabs
  - does not allow to produce very fine particles
  - generally requires a secondary crushing





Effects of crushing method on the properties of produced recycled concrete aggregates. J. Hubert, Z. Zhao, F. Michel, L. Courard. Buildings 2023, 13, 2217 (https://doi.org//10.3390/buildings13092217)

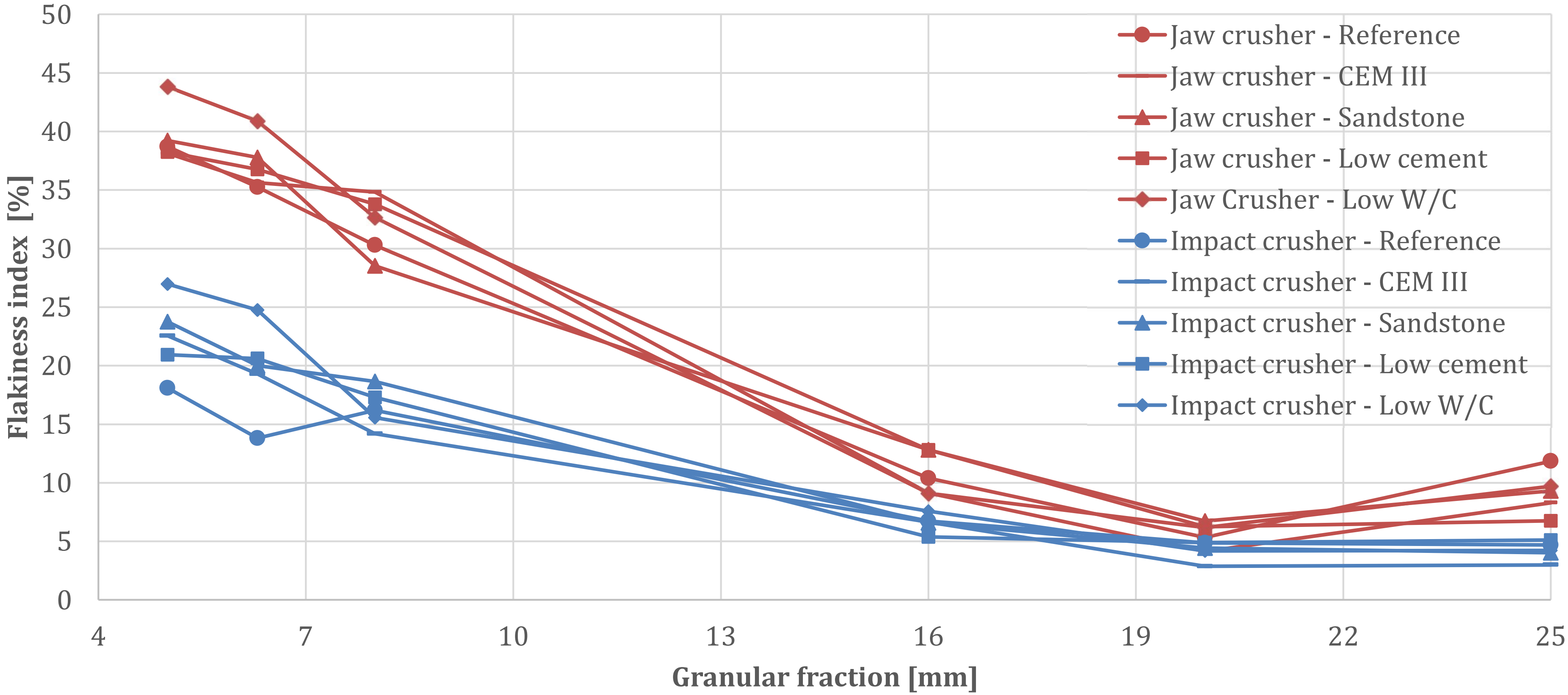
Material processing

▶ Experimental mixes

Name	Reference	CEM III	Sandstone	Low cement	Low W/C
Aggregates nature	Limestone	Limestone	**Sandstone**	Limestone	Limestone
Aggregates 2/7 mm (kg/m³)	368.8	368.8	368.8	405.1	367.1
Aggregates 7/14 mm (kg/m³)	345	345	345	379	343.4
Aggregates 14/20 mm (kg/m³)	433.5	433.5	433.5	476.2	431.5
Sand 0/4 mm (kg/m³)	604.9	604.9	604.9	664.4	602.1
Cement type	CEM I 52.5	**CEM III 52.5**	CEM I 52.5	CEM I 52.5	CEM I 52.5
Cement quantity (kg/m³)	400	400	400	**320**	452
Cement paste volume (dm³/m³)	351	358	351	282	351
Efficient water (kg)	224.2	224.2	224.2	180.6	207.1
W/C ratio	0.56	0.56	0.56	0.56	**0.46**
Superplasticizer (g/kg cement)	0	0	0	6.8	3.3

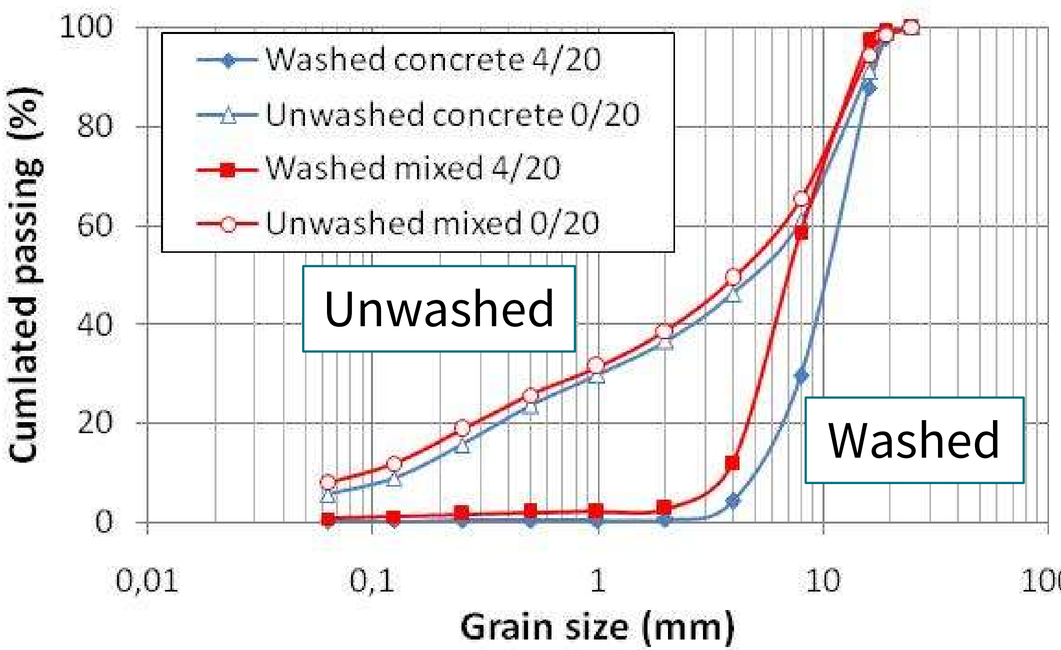
Material processing

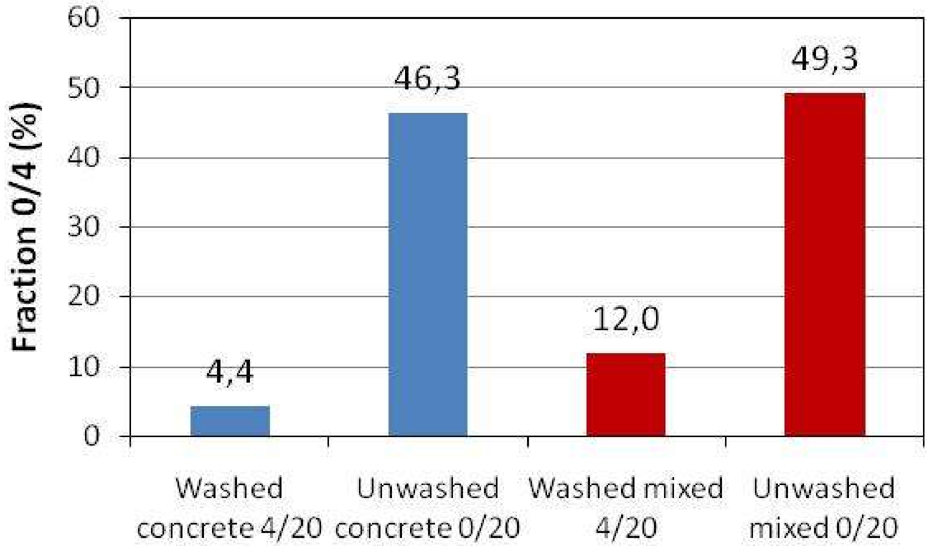
- The flakiness index decreases with increasing granular fraction
- The jaw crusher produces flakier aggregates
- No influence of the concrete composition



Materials processing: washing

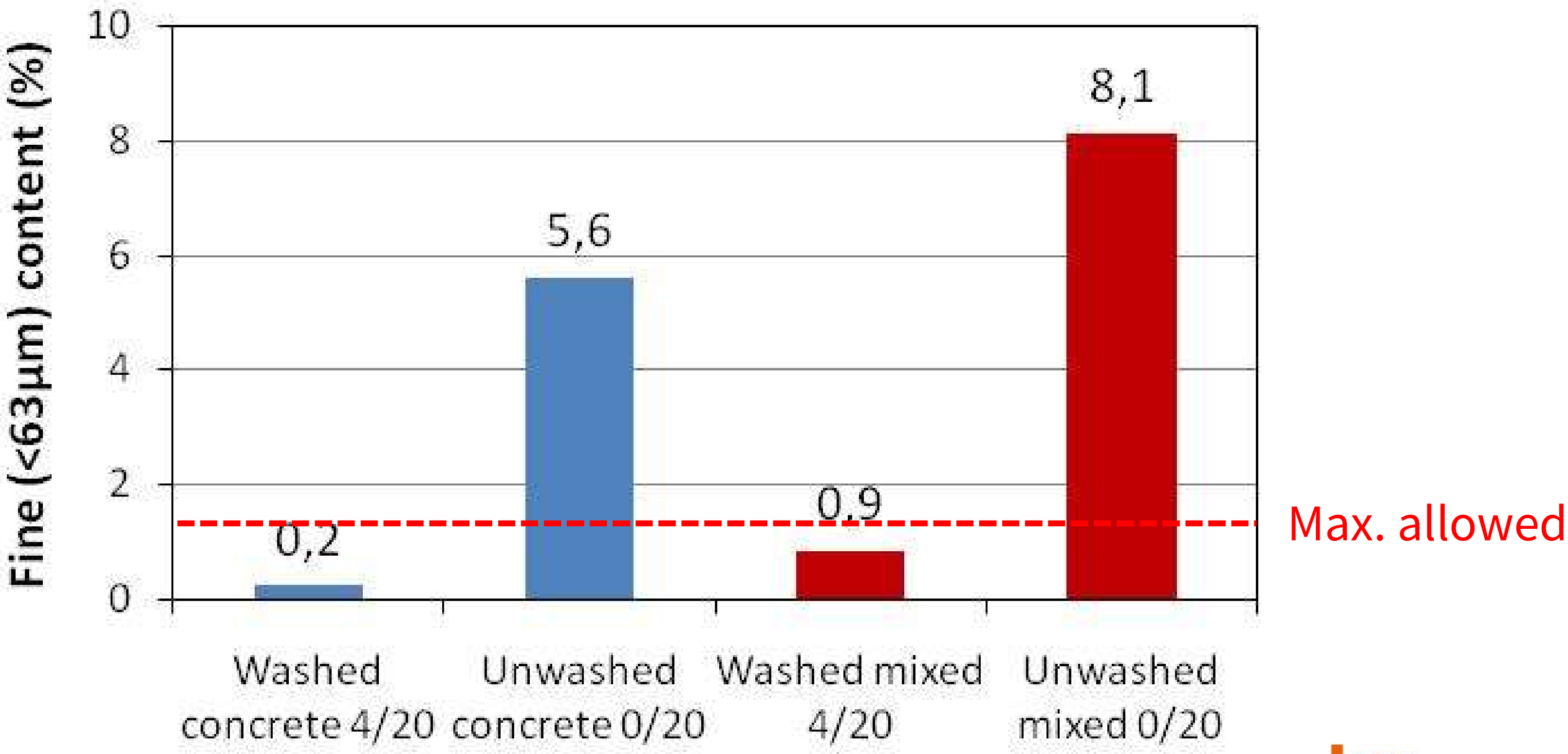
- 0/4 fraction comprises nearly 50% of the unwashed aggregates composition
- 0/4 fraction a bit higher in mixed aggregates
- Washing significantly reduces the sand fraction of the aggregates





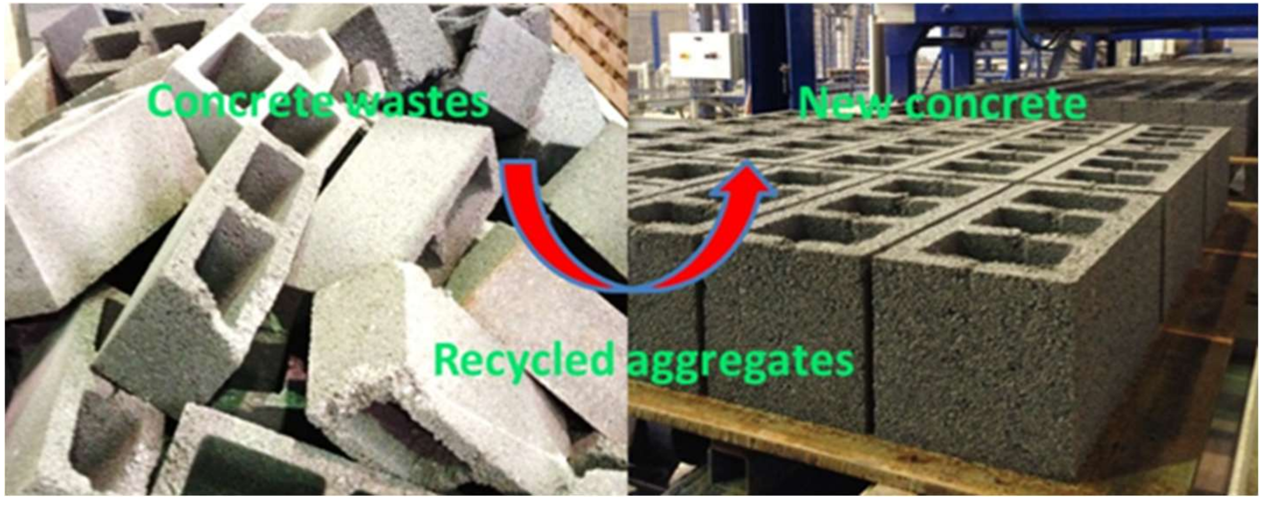
Materials processing: washing

- Fine content (< 63µm) higher in mixed aggregates and significantly reduced by washing
- Fine fraction higher in mixed aggregates
- Washed aggregates respect regulations in all considered countries



Using wastes

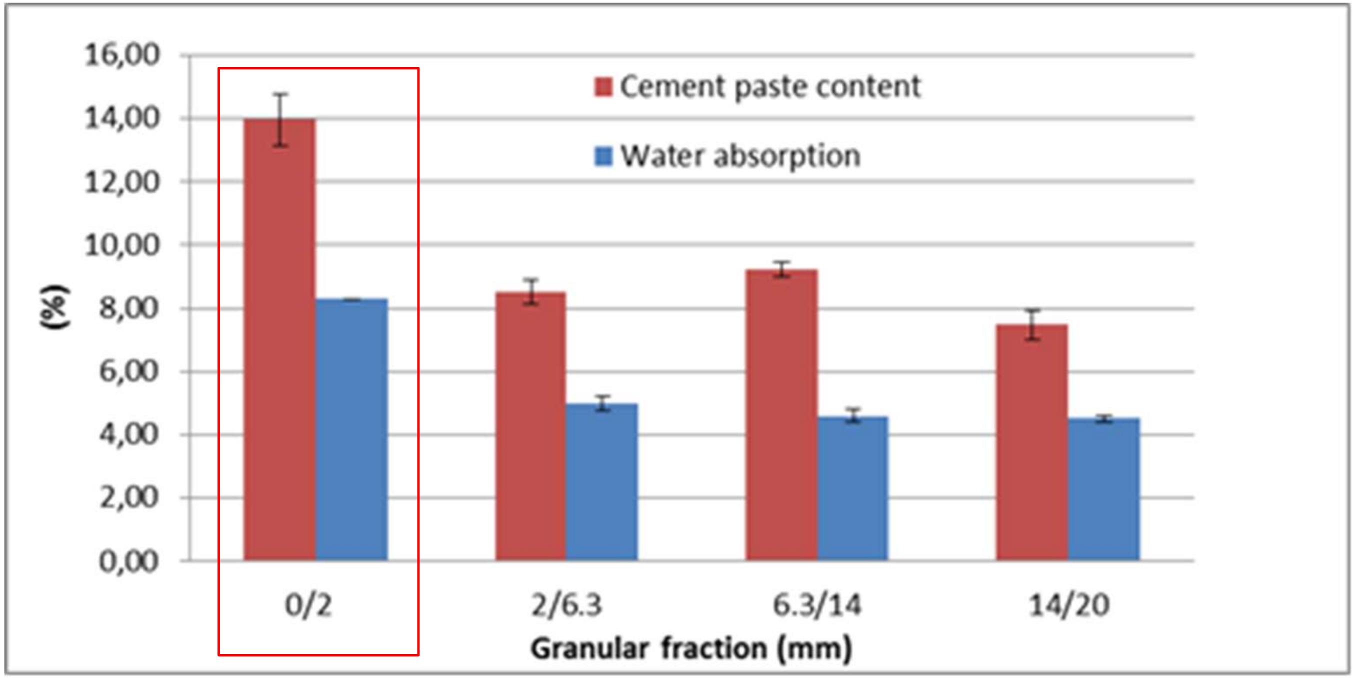
- ▶ RCA manufactured in laboratory
  - Old concrete from block wastes (C8/10 concrete)
  - Crushing (jaw crusher in laboratory, opening ≈10mm)
  - Separation of RCA by sieving (0/20mm)
    - ➢ Four granular classes: 0/2 - 2/6.3 - 6.3/14 - 14/20



Use of RCA from precast blocks for the production of new concrete building blocks: an industrial scale study. Z. Zhao, L. Courard, S. Groslambert, Th. Jehin, A. Léonard, J. Xiao. Resources, Conservation & Recycling 157 (2020) 1-13 (https://authors.elsevier.com/a/1ahbs3HVLKiAuJ)(http://hdl.handle.net/2268/246444)

Using wastes

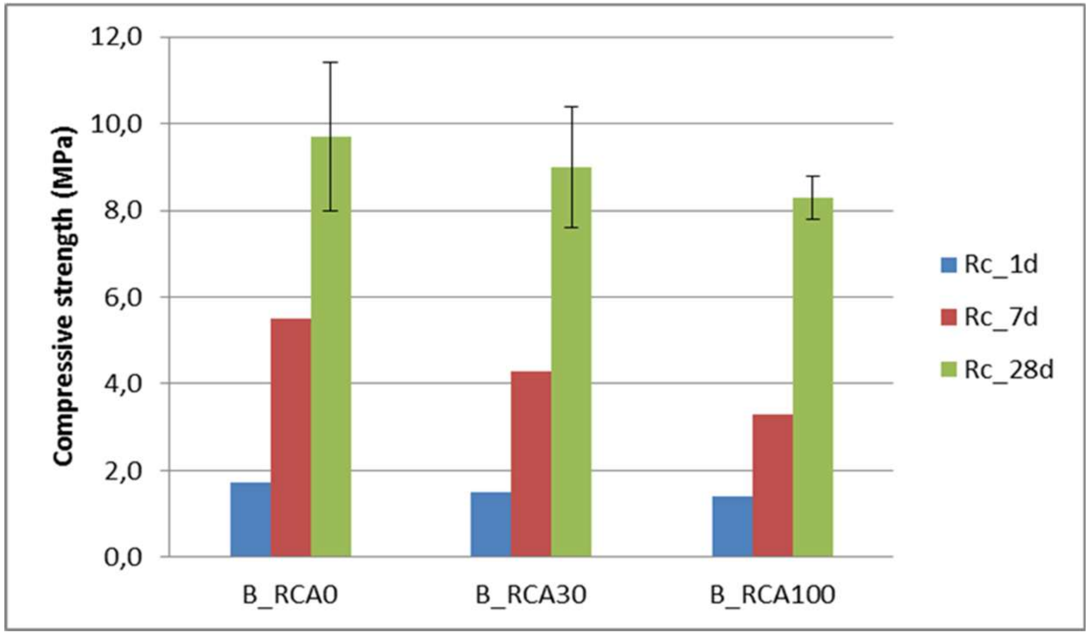
- Water absorption W_A (EN 1097-6)

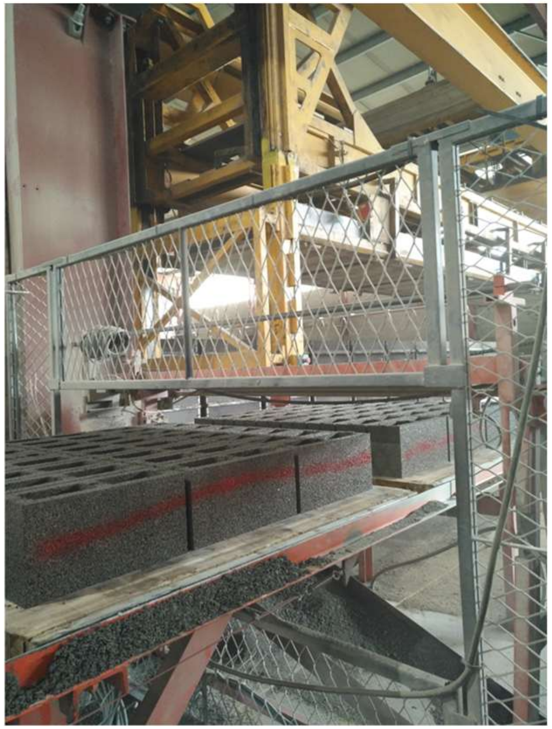


  - Cement Paste Content and W_A of 0/2mm fraction larger than three coarse fractions

Using wastes

- Compressive strength



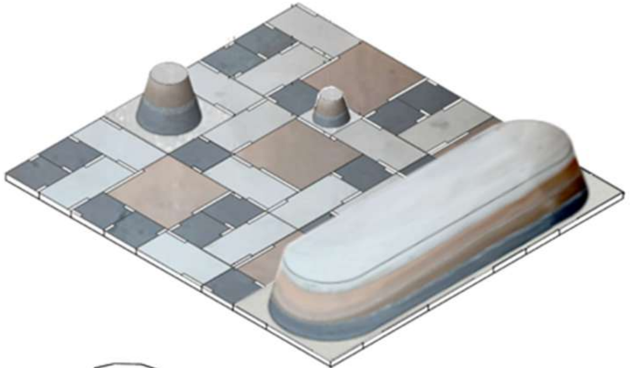
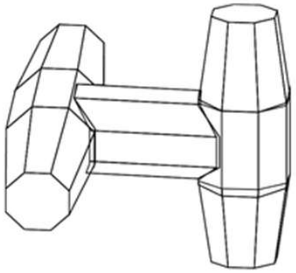


  - Compressive strengths of concretes with RCA are slightly lower than those of concrete with natural aggregate
  - Compressive strength of concrete made with 100% RCA at 28 days is 8 MPa (14.4% decrease)

Prefab products

1. **Hollow Core Floor Slab**
2. **Urban SeRaMCo Elements**
3. **Sound Absorbing L-Wall**
4. **Façade Cladding**
5. **Salty Concrete**
6. Rammed Concrete
7. Energy Sound Barrier
8. Foam Concrete Insulated Wall
9. Cooling Wall
10. Energy Bench

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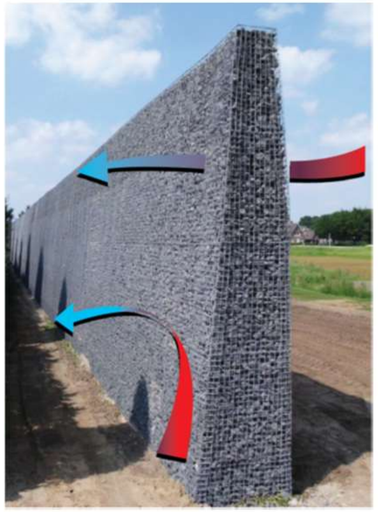
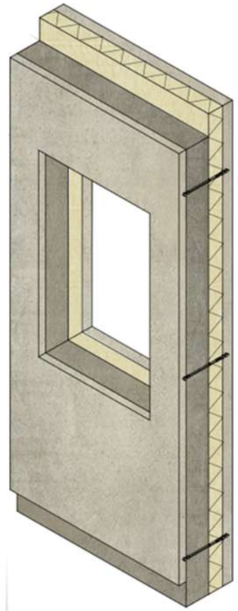
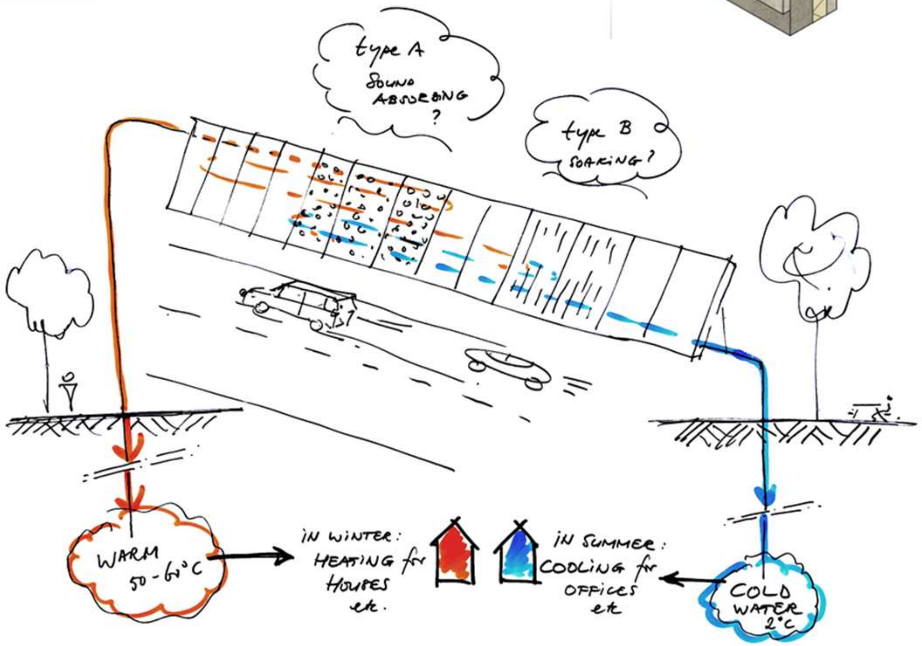
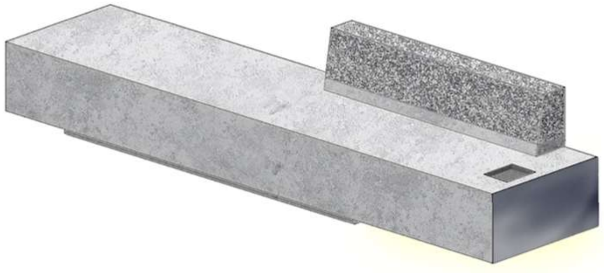




Prefab products: Parkour Park

Cement produced with recycled fines

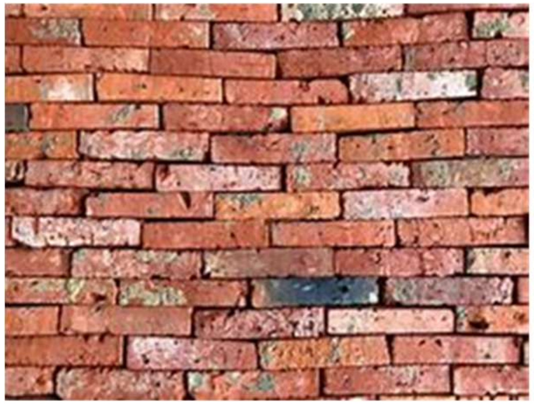
Recycled concrete aggregates

Natural sand

Rc : 50-55 MPa
W/C <= 0.45
Cement >= 340 kg/m^3
WAI <= 6.5%

Fine bricks

- Flow of brick waste: 1-2% of C&DW in BE/North of France
- Valorization
  - Reuse of bricks
  - Aggregates: landfilling/recycling for backfilling
  - Brick fine particles



Recycled brick fines for new alkali activated binder. A. Grellier, D. Bulteel, L. Courard. 17th International Congress on Polymers in Concrete ICPIC 2023, Sept. 17-20th, Warsaw.

Fine bricks

- Brick fine particles
  - 3 types of granulometry
    - B1: d_{50} = 3.3 µm (with supplementary cyclogrinding)
    - B2: d_{50} = 20 µm
    - B3: d_{50} = 190 µm
- Mineralogy

Oxides (%)	CaO	SiO_2	Al_2O_3	Fe_2O_3	K_2O	Na_2O	MgO	TiO_2	Total
Brick fine	1.7	62.8	10.4	16.3	2.1	0.6	2.2	2.4	99.3
GGBFS	42.9	38	10.8	0.5	0.3	-	6.5	0.7	99.5

Fine bricks

- Alcali Activated Material production

Brick fine particles
B2

GGBFS

Alcali-Activating Solution

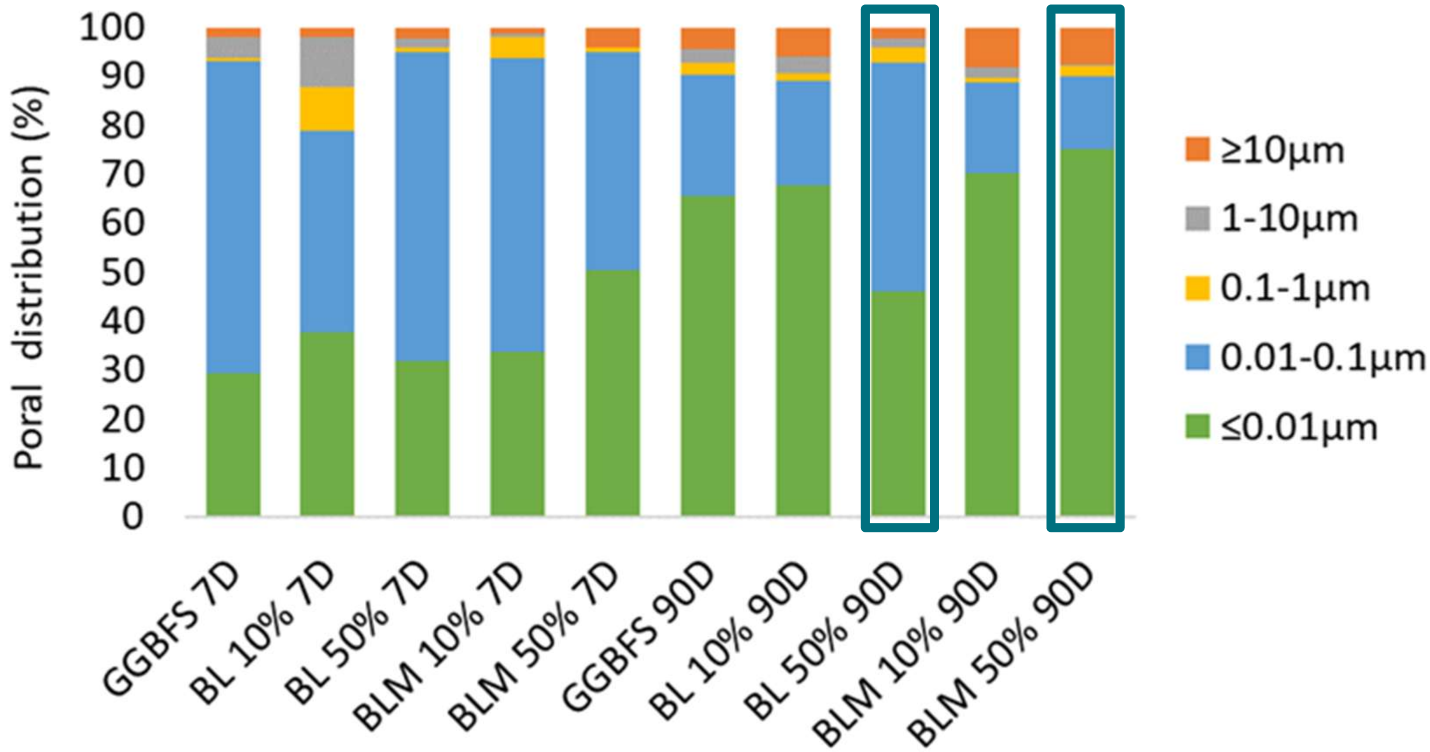
Soda (NaOH)
Sodium Silicates (Na_2SiO_3)
(SiO_2/Na_2O: 1.45)

Substitution
10, 20, 30 and 50 %

Characterization at
7 and 90 days

Fine bricks

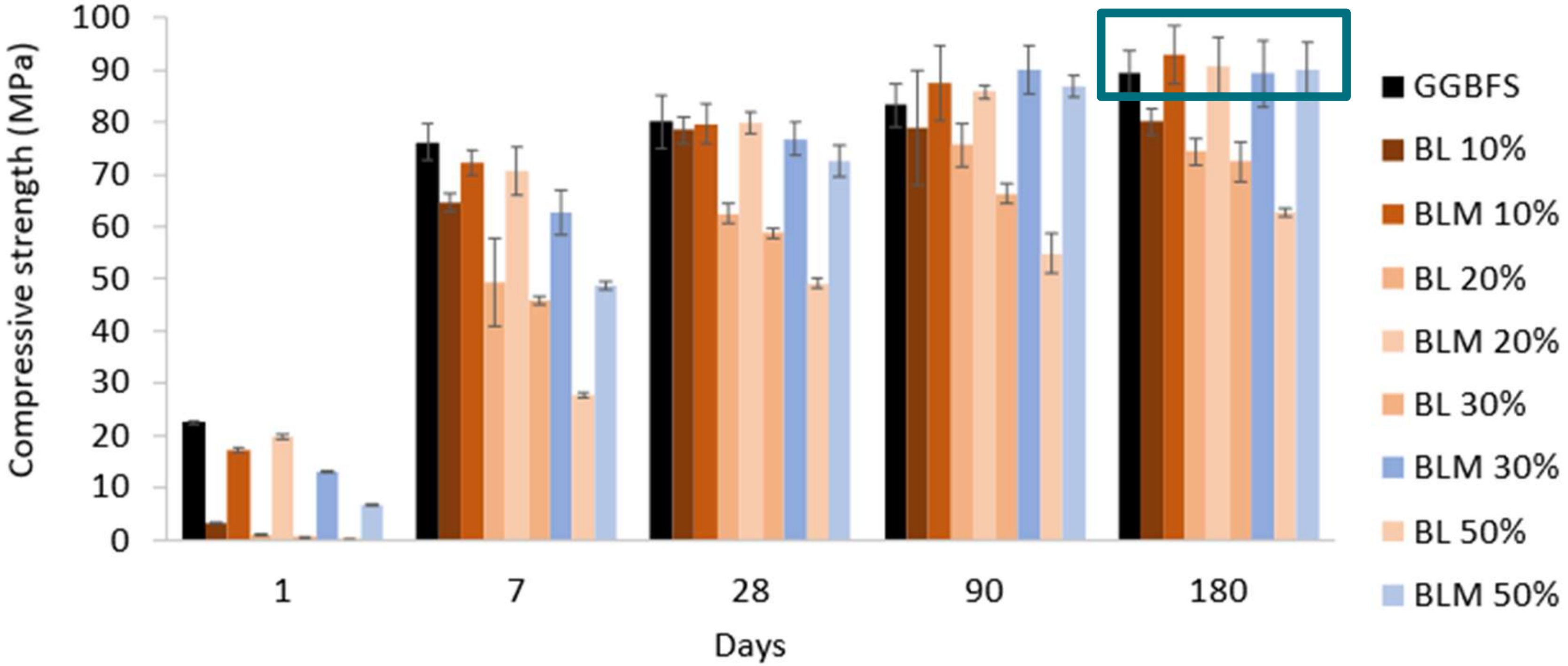
- Poral distribution



- Finer porosity with time for all the mixes
- Finer porosity with BLM 50% than BL 50%

Fine bricks

- Mechanical strength



  - BL: slower kinetics – Rc ↓ when [brick fines] ↑
  - BLM: quicklier kinetics - Rc ≥ GGBFS from 90 days
  - Brick fines can act as a *precursor*

Recycled sand for 3D printing

3D printing:

(+) Design opportunities

(−) Environmental impact

→ Binder

Granular skeleton (100% recycled sand)

Siam Research and Innovation Company – Triple S (2017)

Interreg North-West Europe CIRMAP

European Regional Development Fund

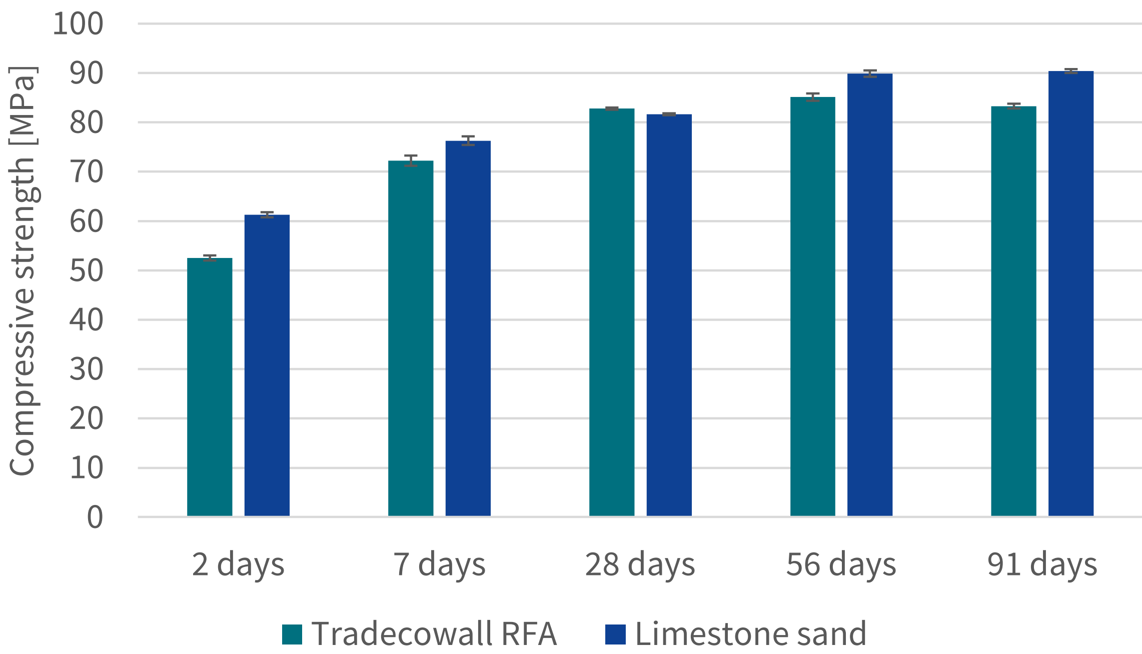
Mortar characterization

Casted samples (4x4x16 cm prismatic samples are casted)

Printed samples (4x4x16 cm prismatic samples are extracted from S shaped printed éléments)

Compressive strength :

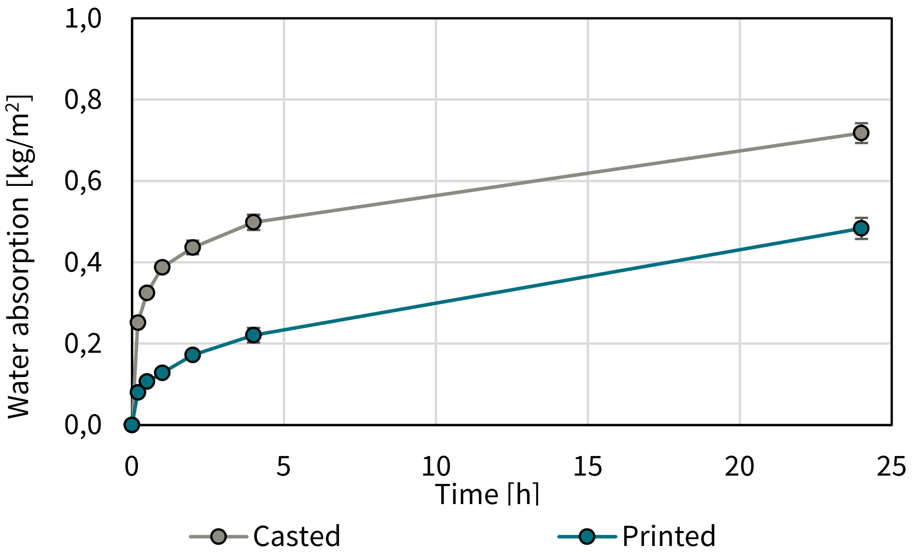
- Influence of the ***type of sand*** (natural crushed limestone sand vs concrete RFA)
- Compressive strength
- Water curing (20°C and 95±5% relative humidity)



Mortar characterization

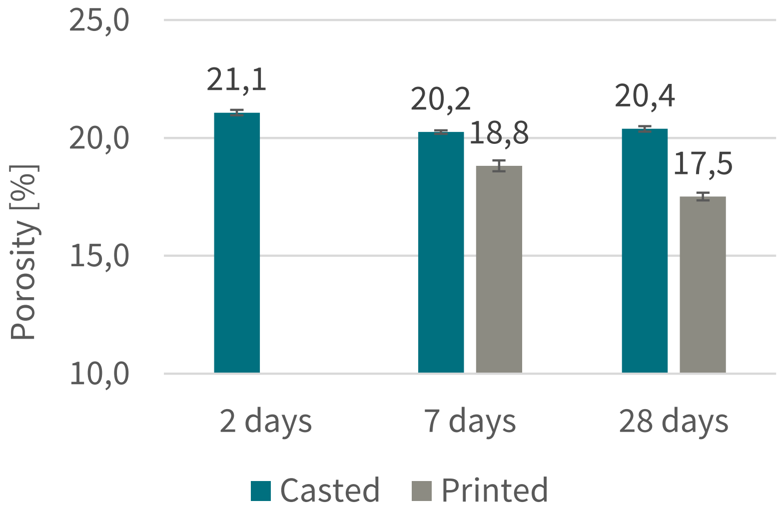
Capillary absorption tests NBN EN13057

- Influence of the ***printing process*** (casted samples vs printed samples)
- Water absorption [kg/m²] and absorption coefficient [mm/h^0,5]



Porosity

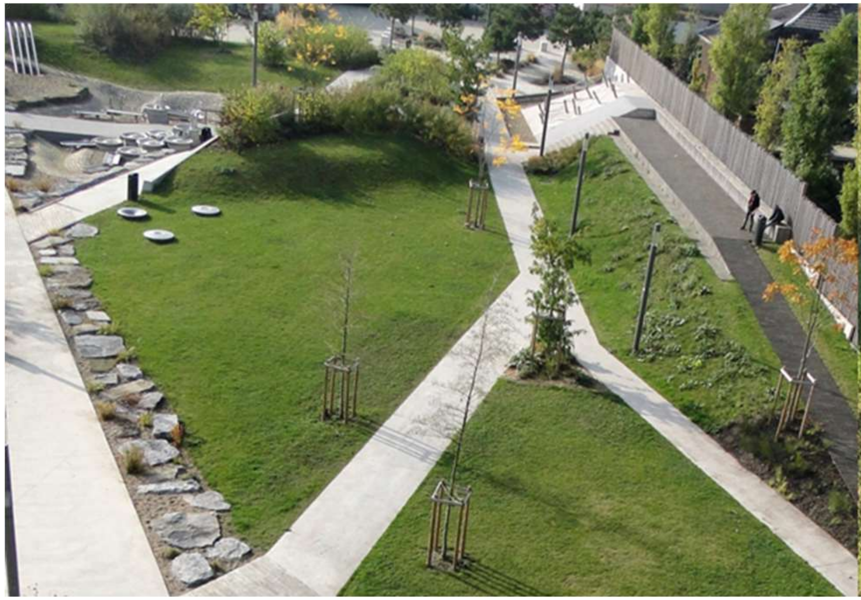
- Influence of the ***printing process*** (casted samples vs printed samples)]



Conclusions

Urban furniture

Bernard Serin park in Seraing



LIÈGE université
Sciences Appliquées

Accelerated carbonation of incinerated municipal solid waste

UEE
Urban & Environmental Engineering

STATISTICS OVERVIEW

- Consumption
  - Sand and naturel aggregates : 2.2 billions tonnes *[Eurostat 2021]*
- Production
  - Municipal solid waste: 230 millions tonnes *[Eurostat 2022]*

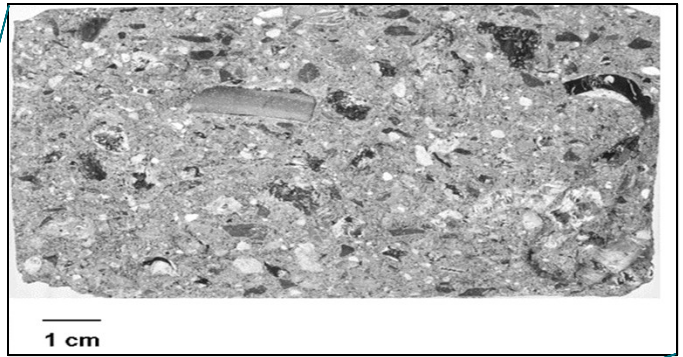
→ 18 millions tonnes MSWI BA

Piles of sand/aggregates

Piles of MSW

MSWI BA POTENTIAL USE

- Partial or total substitution of sand and aggregates for :
  - Road foundations
  - Concrete pavements*
  - Concrete blocks



Road foundations

*Concrete pavements**

Concrete blocks

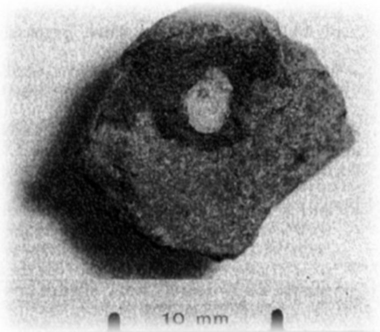
* *Courard, L., Degeimbre, R., Darimont, A., Laval, A.-L., Dupont, L., Bertrand, L. (2002). "Utilisation des mâchefers d'incinérateur d'ordures ménagères dans la fabrication des pavés en béton", Mater. Struct, 35: 365-372.*

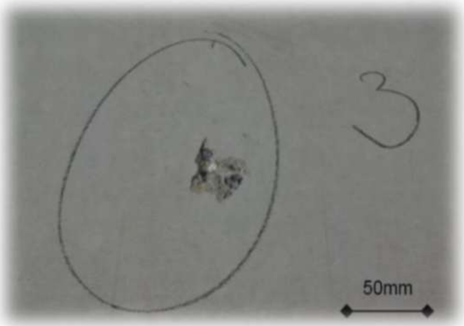
MSWI BA RISKS

- Lixiviation
- Lime nodule swelling

$$CaO + H_2O \rightarrow Ca(OH)_2 + 15.5cal$$

Molecule	CaO	H_2O	$Ca(OH)_2$
Molecular weight	56	18	74
Real density (g/cm^3)	3.3	1	2.24
Molecular volume (cm^3/mole)	16.8		33.1





MSWI BA TREATEMENT: AGING

- Treatment (maturation) period: 18 weeks up to 6 months
- Chemical reaction occurring during the aging treatment*:
  1. $CaO + H_2O \rightarrow Ca(OH)_2$
  2. $Ca^{2+} + 2\,OH^- + CO_2 \rightarrow CaCO_3 + H_2O$
  3. $Ettringite + 12\,H^+ \rightarrow 2\,Al^{3+} + 3\,SO_4^{2-} + 6\,Ca^{2+} + 38\,H_2O$
  4. $Al + 4\,OH^- + 4\,H_2O \rightarrow 4\,AlO_2^- + 6\,H_2$
  5. $AlO_2^- + 2\,H_2O \rightarrow Al(OH)_3 + OH^-$
- Limitations of this treatment:
  - Long treatment period
  - Inefficient in some cases
  - Dependent on weather conditions

* Descamps, P., Janssens, B., Dupont, L., Lefevre, L. (2011). "Memorandum technique pour l'utilisation des mâchefers de l'unité de valorisation par incinération de Thumaide".

MSWI BA TREATEMENT: ACCELERATED CARBONATION

- Accelerated treatment: static carbonation
- Chemical reaction occurring during the accelerated carbonation:
    1. $CO_2 + H_2O \leftrightarrow H_2CO_3$
    2. $H_2CO_3 + OH^- \leftrightarrow H_2CO_3^{2-} + H_2O$
    3. $H_2CO_3^{2-} + OH^- \leftrightarrow CO_3^{2-} + H_2O$
    4. $Ca(OH)_2 \leftrightarrow Ca^{2+} + 2\,OH^-$
    5. $Ca^{2+} + CO_3^{2-} \leftrightarrow CaCO_3$
- Advantages of this method:
    - Short treatment period
    - CO_2 sequestration

Static carbonation chambers

Special Equipment

Static carbonation climatic chambers

Dynamic carbonation process tool

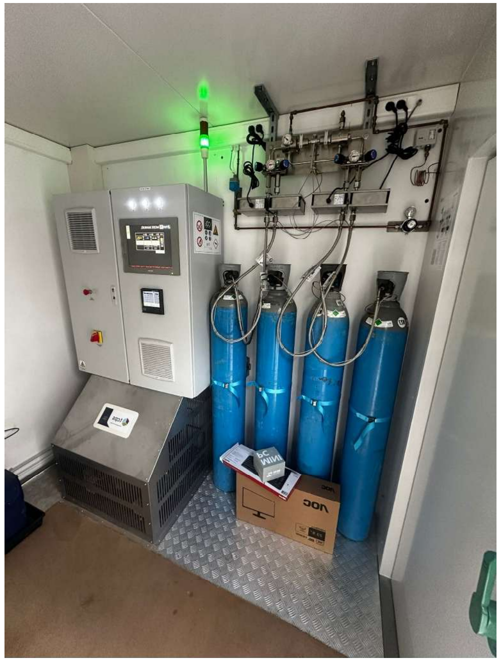
CarbonEx: experimental room for accelerated carbonation

Special Equipment

Static carbonation climatic chambers

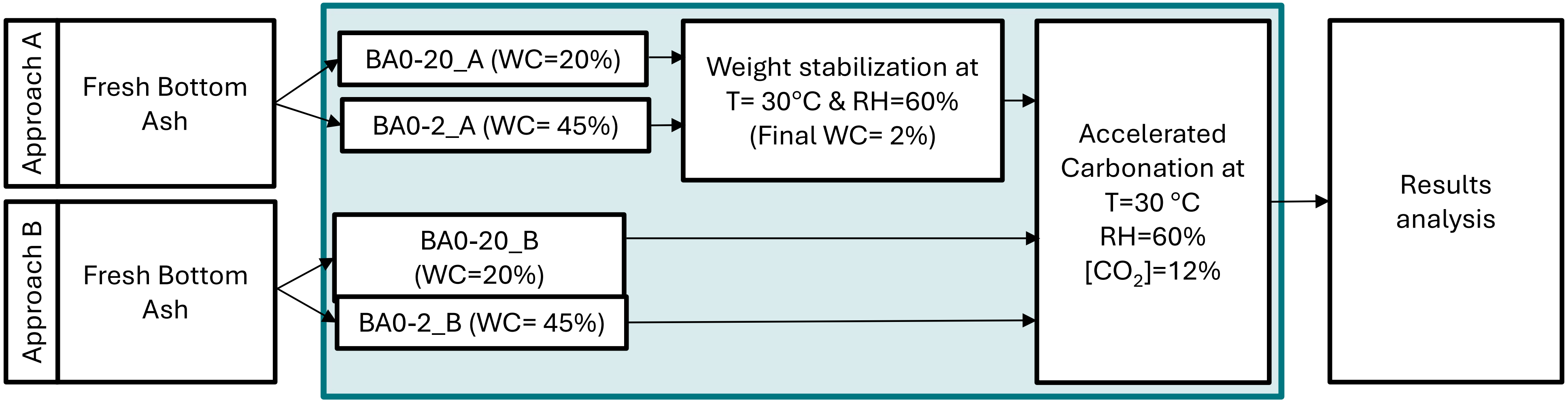
Dynamic carbonation process tool

CarbonEx: experimental room for accelerated carbonation



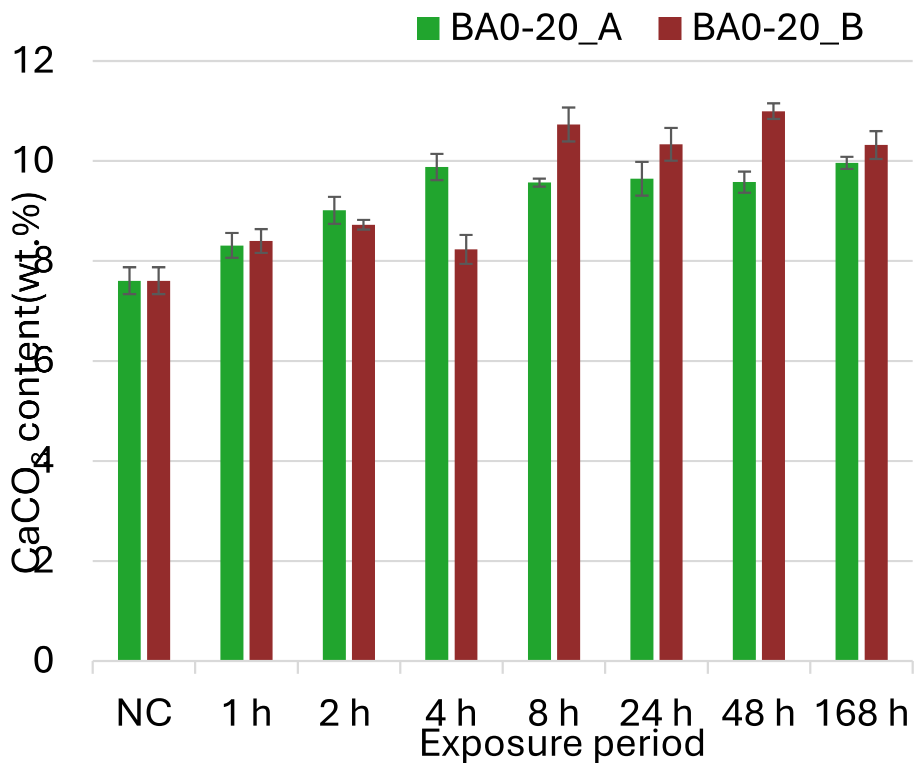
ACCELERATED CARBONATION TREATEMENT

- Parameters studied:
  - Particle size: 0/2 & 0/20 mm
  - Exposure period: 1, 2, 4, 8, 24, 48 & 168 h
  - Moisture content (WC): 2, 20 & 45%
- Carbonation conditions:
  - Temperature: 30±1 °C
  - Relative humidity: 60±3%
  - CO_2 concentration: 12 %vol

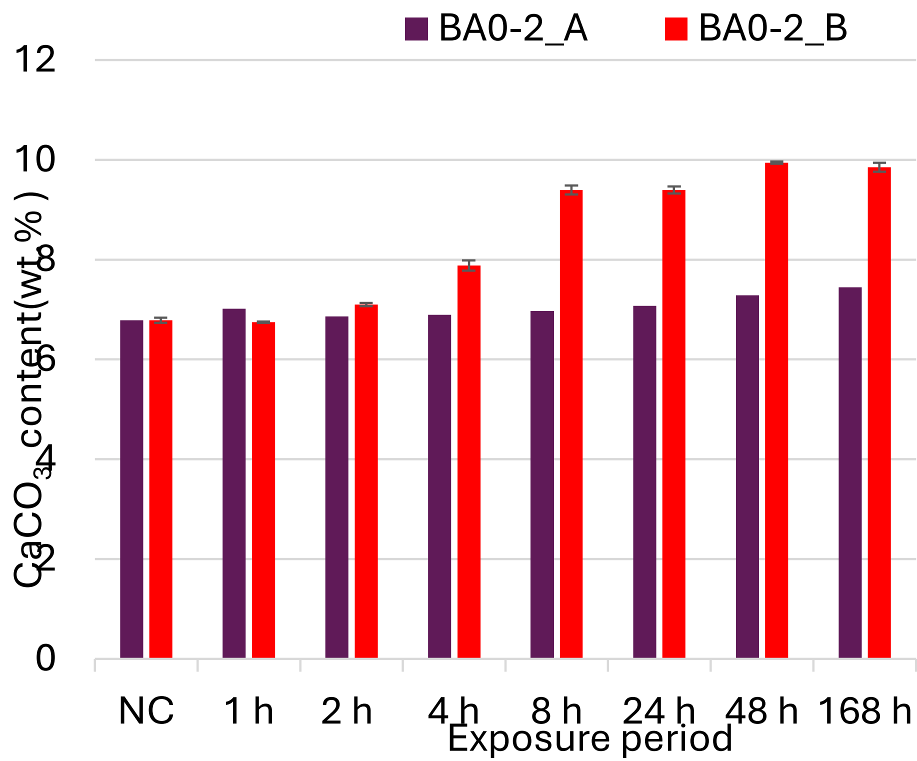


RESULTS – $CaCO_3$ content

- **BA particle size: 0/20 mm**

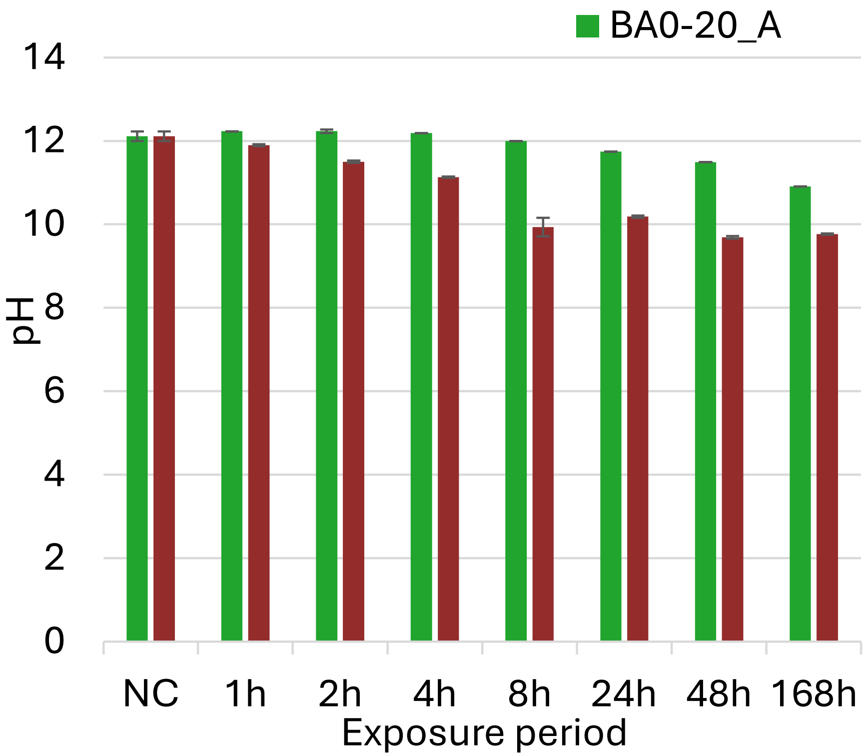


- **BA particle size: 0/2 mm**

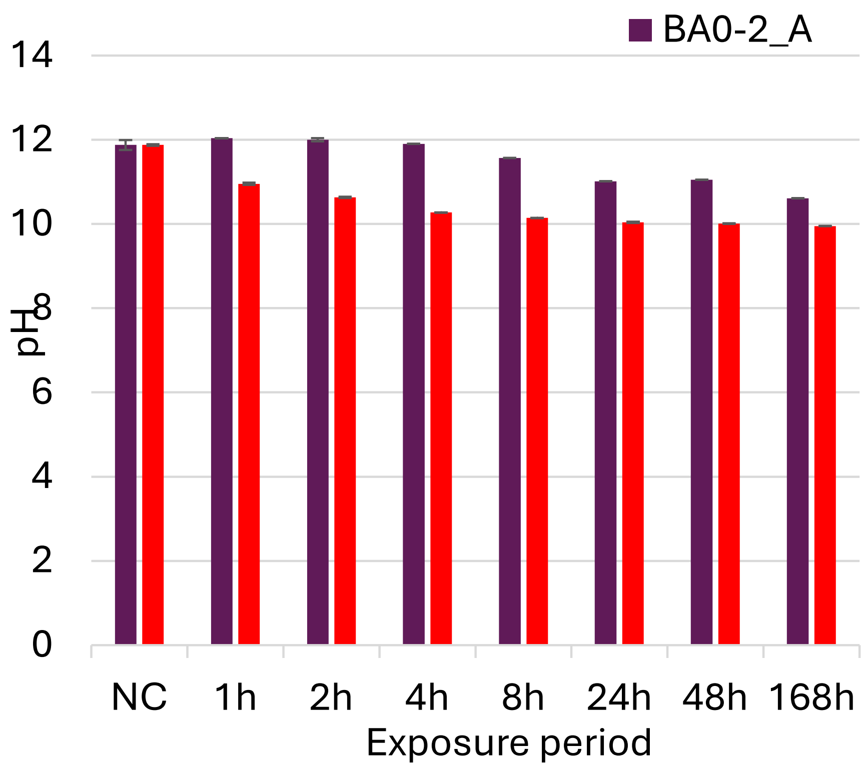


RESULTS – pH

- **BA particle size: 0/20 mm**



- **BA particle size: 0/2 mm**



RESULTS – Physical properties

- ## Real density & water absorption

		Fresh	Carbonated	Maturated	Literature*
Fines MSWI-BA aggregates	Density (kg/m^3)	1840	2145	2239	2150-2850
	Water absorption (%)	6.9	7.3	8.24	2.2-17.3
Coarse MSWI-BA aggregates	Density (kg/m^3)	2280	2360	2239	1860-2680
	Water absorption (%)	2	2.4	4	7.2-15

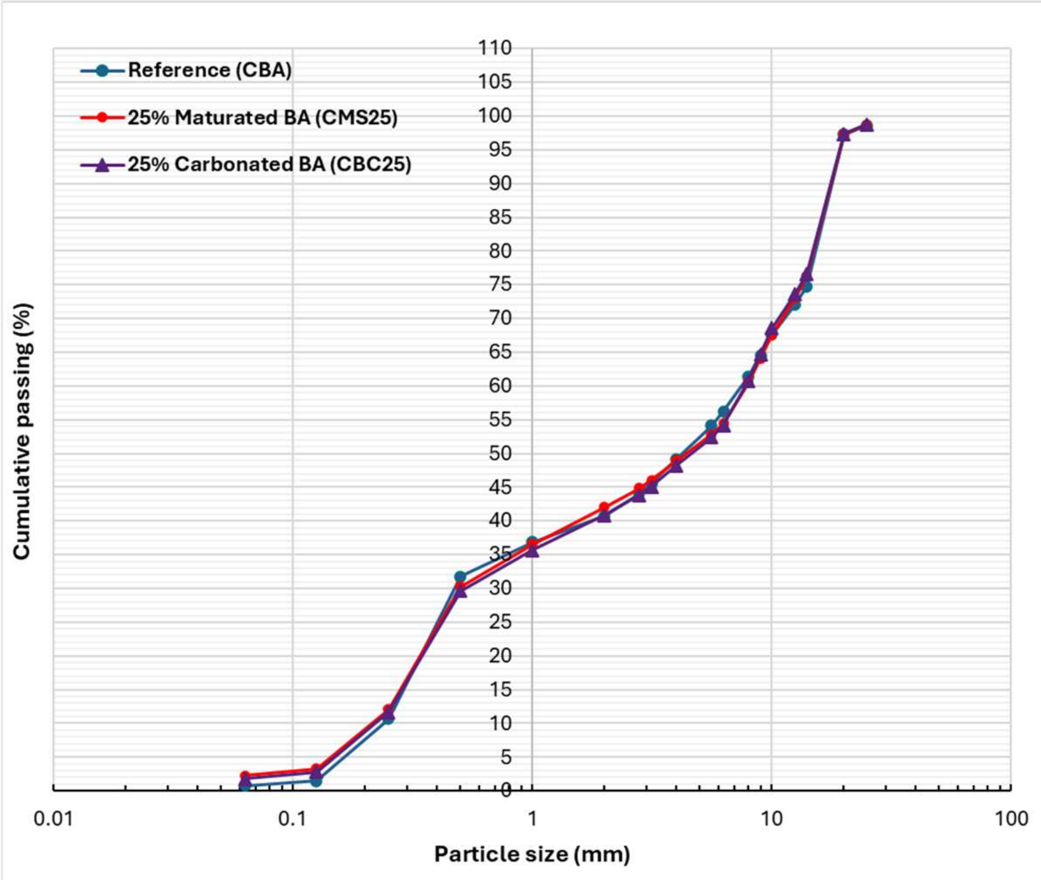
- ## Wear resistance (M_{DE}) & Freeze-thaw resistance (MS)

	Fresh	Carbonated	Maturated	Literature*
Wear resistance (wt.%)	21	24	21	18-31
Freeze-thaw resistance (wt.%)	21	20	19	15-25

* *Descamps, P., Janssens, B., Dupont, L., Lefevre, L. (2011). "Memorandum technique pour l'utilisation des mâchefers de l'unité de valorisation par incinération de Thumaide".*
* *Dhir, R.K., Brito, J. de, Lynn, C.J., Silva, R.V., (2018a). "Municipal Incinerated Bottom Ash Characteristics", Sustainable Construction Materials: 91–138.*
* *Becquart, F., Abriak, N.E., (2013). "Experimental investigation of the Rowe's dilatancy law on an atypical granular medium from a municipal solid waste incineration bottom ash", POWDERS AND GRAINS 2013: Proceedings of the 7th International Conference on Micromechanics of Granular Media,, Sydney, Australia, 471–474.*

BA based concrete

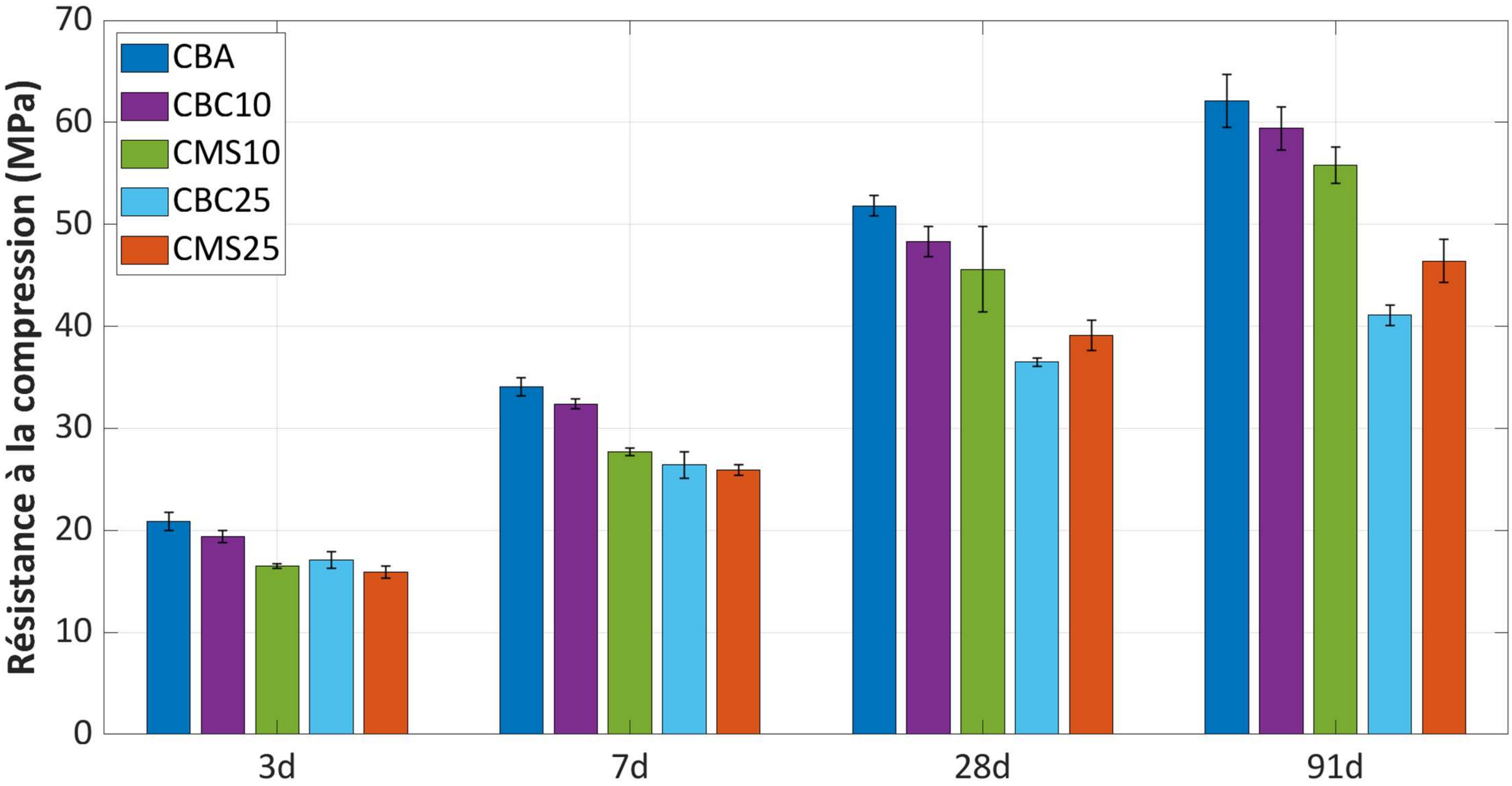
- Two concrete formulas were produced by replacing 25% (v/v) of the **total** volume of natural sand & aggregates with maturated and carbonated BA.
- Target class of strength : ***C30/37***
- Sand and aggregates substitution rates:
  - Sand 0/2: 60%
  - Sand 0/4: 0%
  - Aggregates 2/6: 100%
  - Aggregates 6/20: 15%



RESULTS – Fresh concrete properties

Results				
Composition	**Density[kg/m³]**	**Slump [mm]**	**Flow [mm]**	**Air content[%]**
Reference (CBA)	2367	175	535	3
10% MIOM carbonated (CBC10)	2322	150	465	2.2
10% MIOM matured (CMS10)	2310	200	585	1.8
25% MIOM carbonated (CBC25)	2272	207	470	4.7
25% MIOM matured (CMS25)	2200	170	490	5.8

RESULTS – Compressive strength



Acknowledgment

- Wallonia Brussels International
  - WalRoCarb – Carbonatation accélérée de bétons produits avec matériaux recyclés et cendres de biomasse (*Accelerated Carbonation of Concrete produced with Recycled Materials and Biomass Ash*)

Wallonie - Bruxelles
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