



# New challenges for the construction industry: CO<sub>2</sub> use and Recycling

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# Building ... an old story but a societal need





# Societal context



# Building ... a contemporary question

- ▶ 75% of the population living in city from 2050



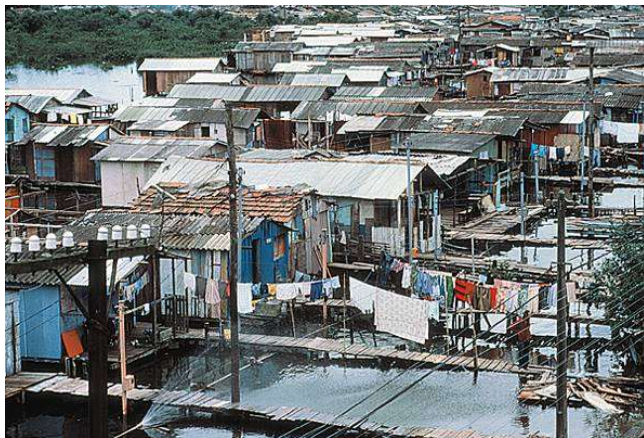
# Building ... how?



*Underground house  
([www.villavals.ch](http://www.villavals.ch))*



*4-façade house  
([www.immobelgique.com](http://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<sub>2</sub>)

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 XX<sup>e</sup> century



x 8



Beginning XXI<sup>e</sup> century



75% primary resources < biomass

30% primary resources < biomass

Biosourced economy

Mineral economy



→ Huge production of CO<sub>2</sub> et modification of the equilibrium of carbon sink (capture)



# Environment and materials

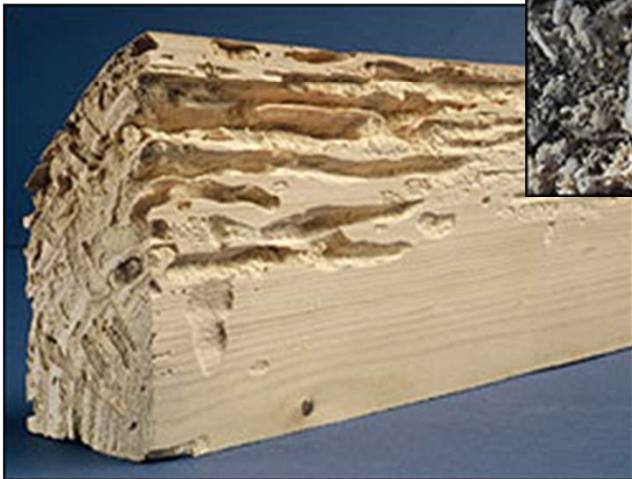


# Environment and materials



## ▶ Wood

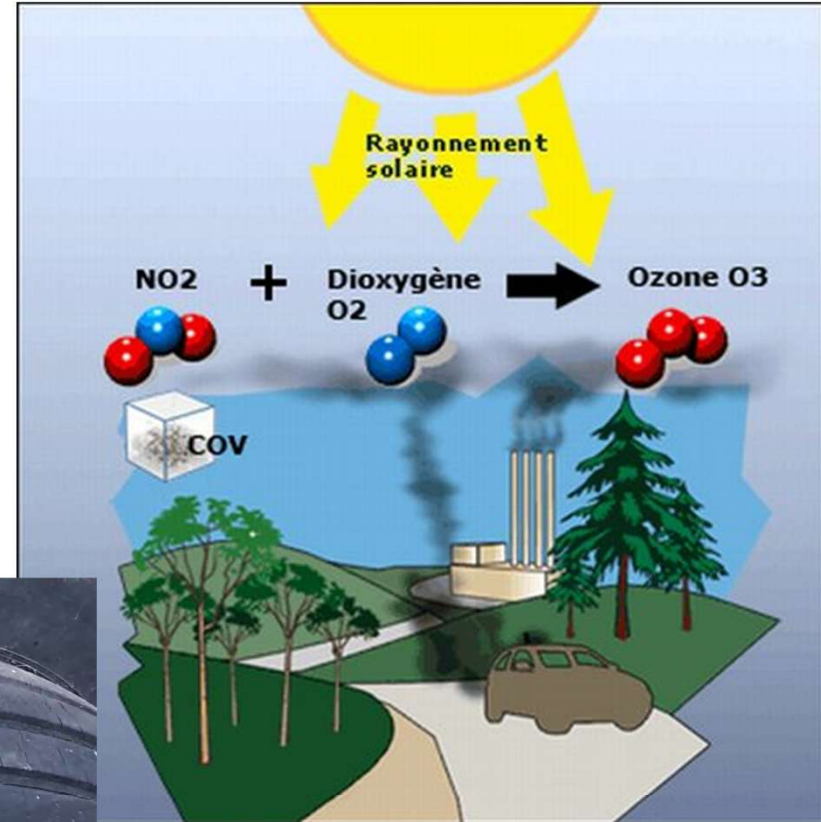
- fungi
- insects



# 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

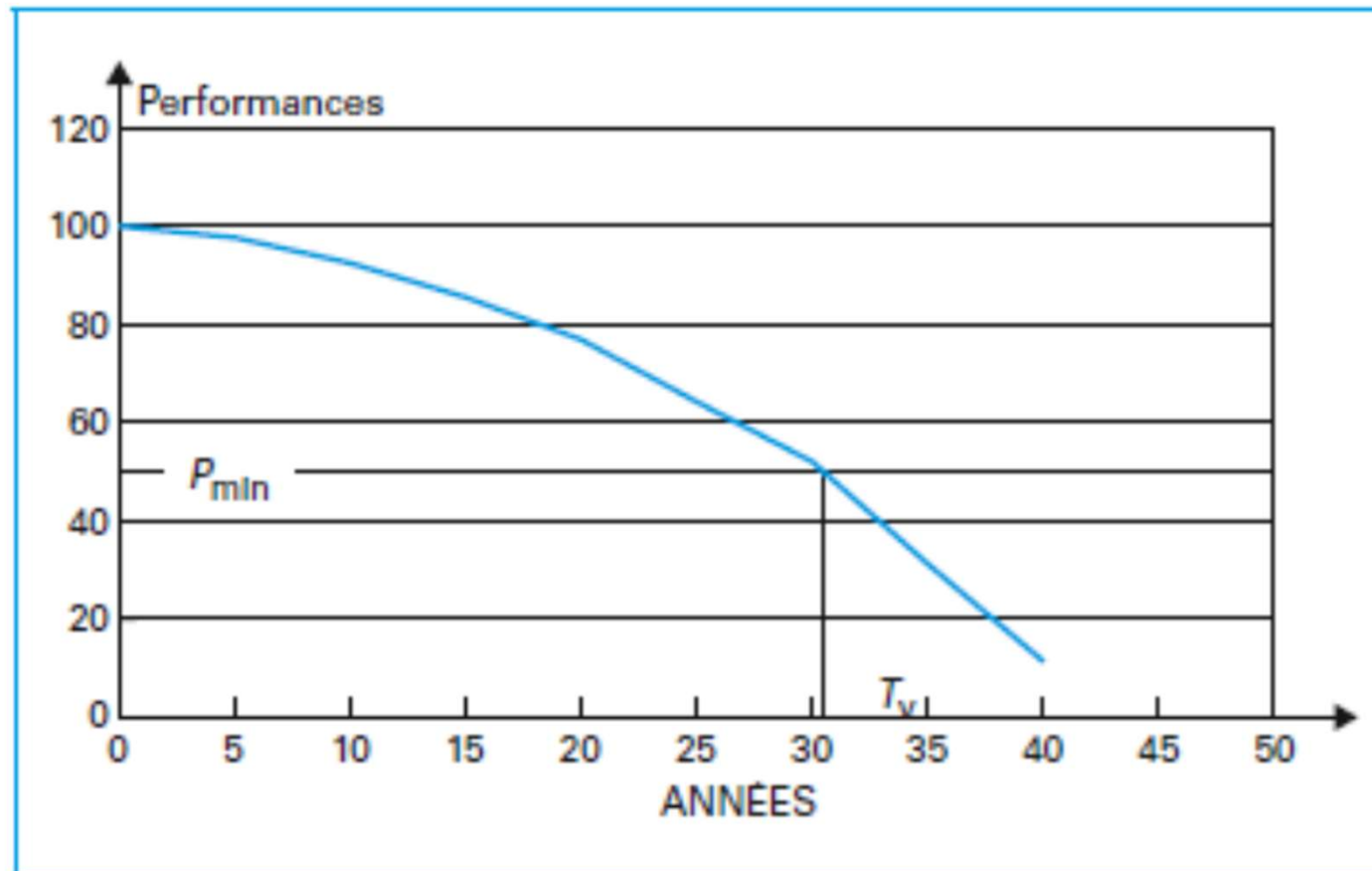


## ► Metals



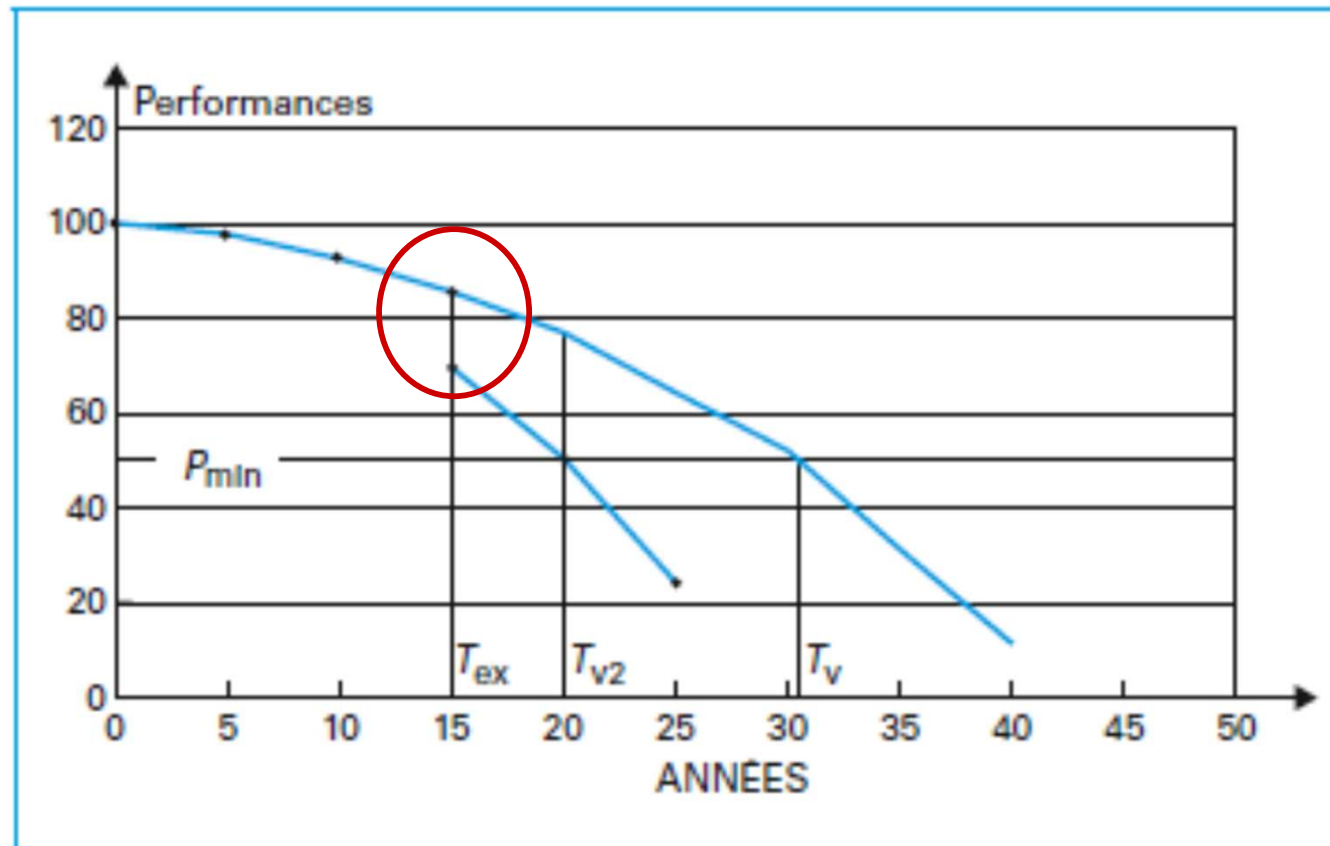
# Environment and materials

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



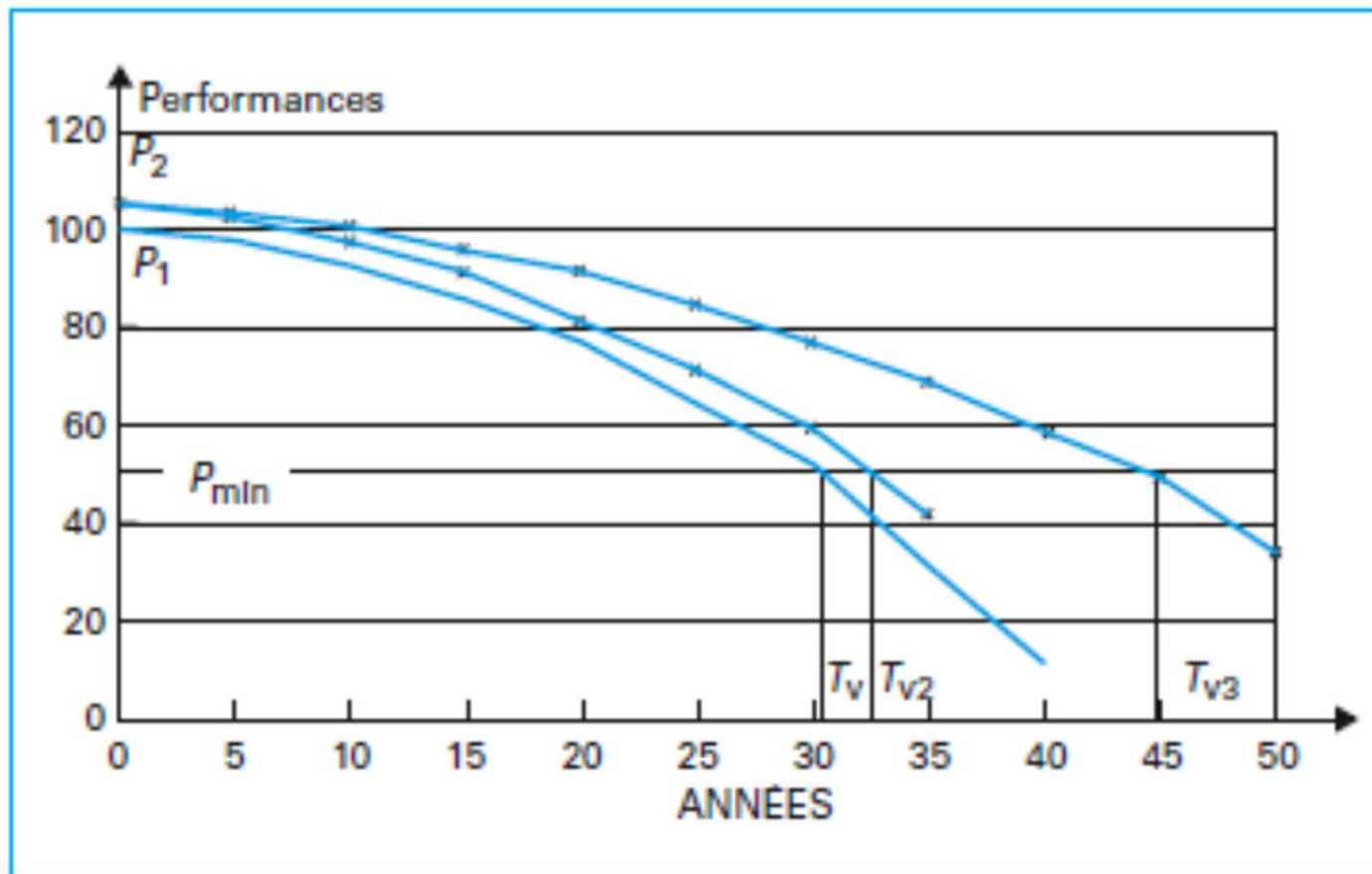
# Environment and materials

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



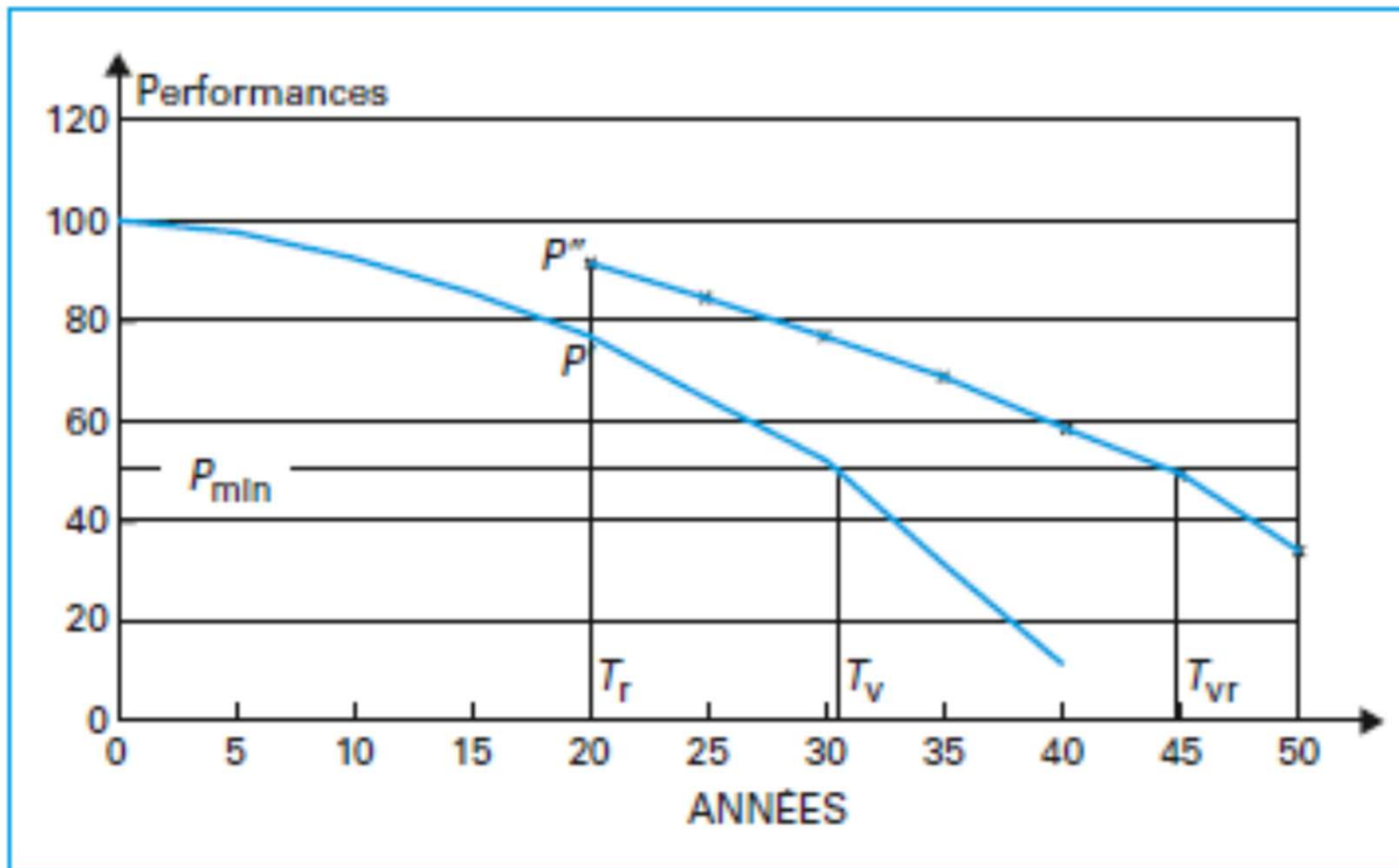
# Environment and materials

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



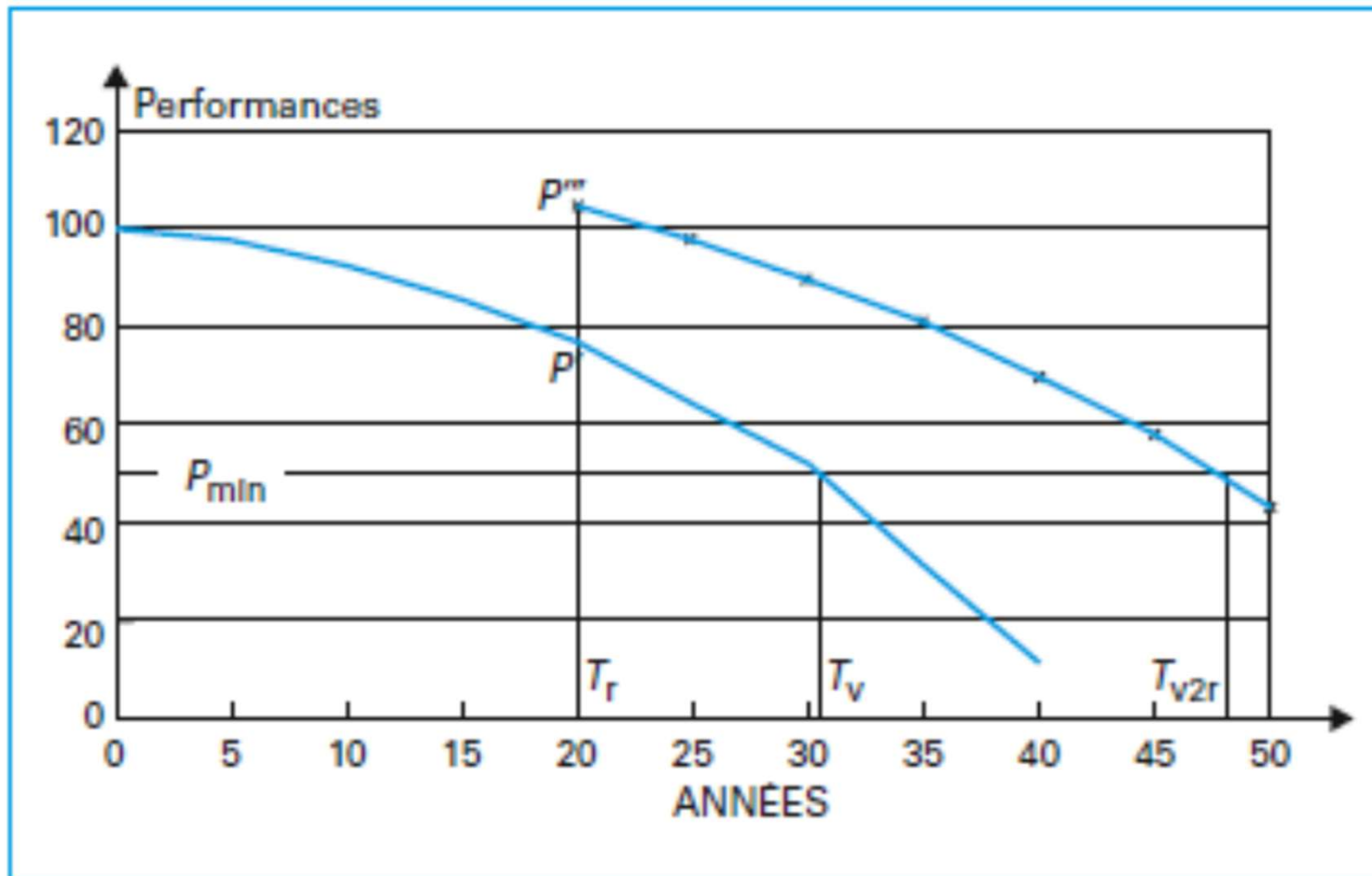
# Environment and materials

- 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



# Materials and environment

# Materials and environment

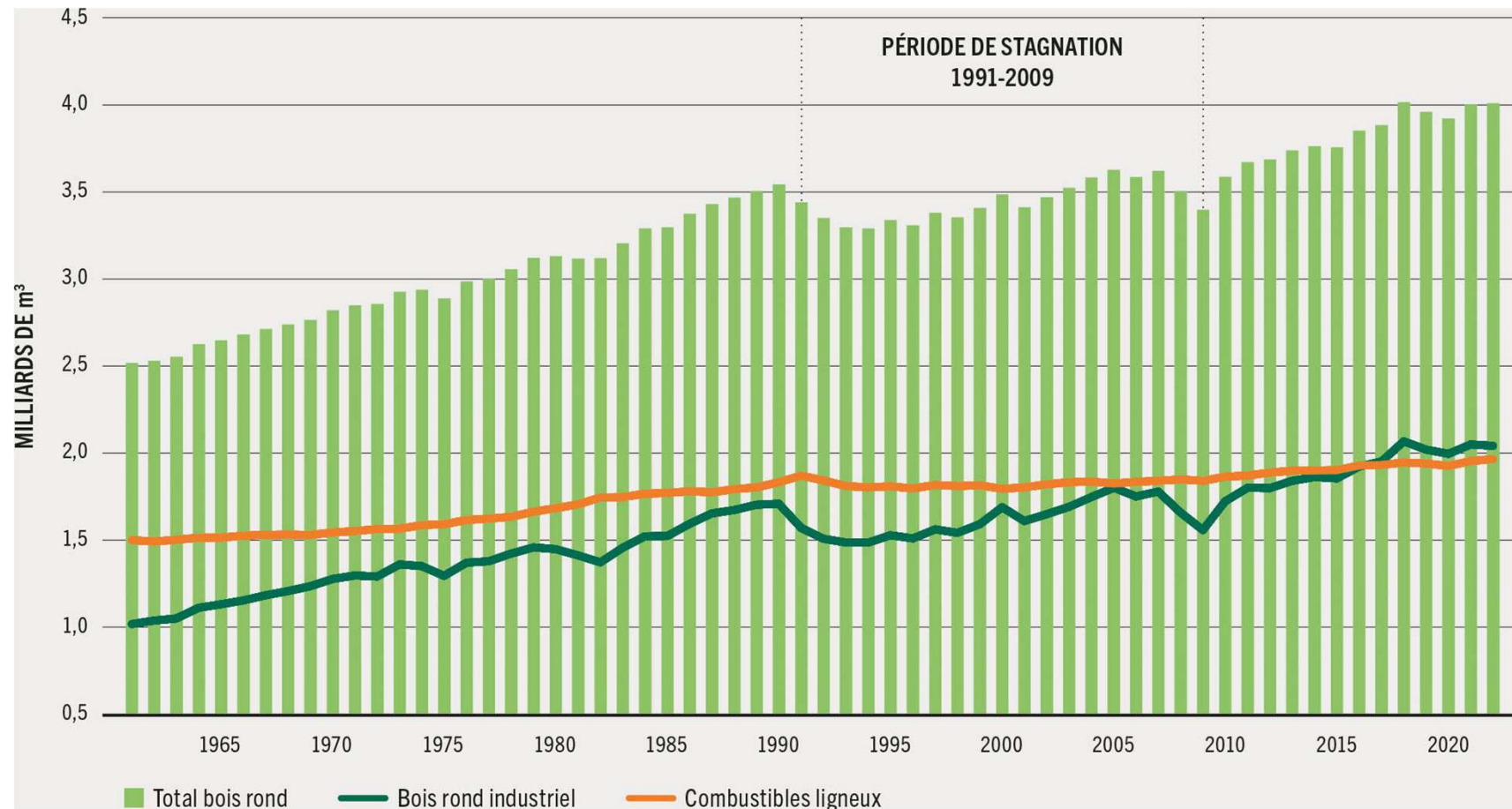
- Limited world
  - Space
  - Natural resources
  - Energy
- Waste management
  - Reduce the production
  - Support reuse/recycling
  - Support safe storage
- 3R theory



# Materials and environment

*We consume natural resources (per year)*

4 billions m<sup>3</sup> wood/year including 2 for construction industry



# Materials and environment

*We consume natural resources (per year)*

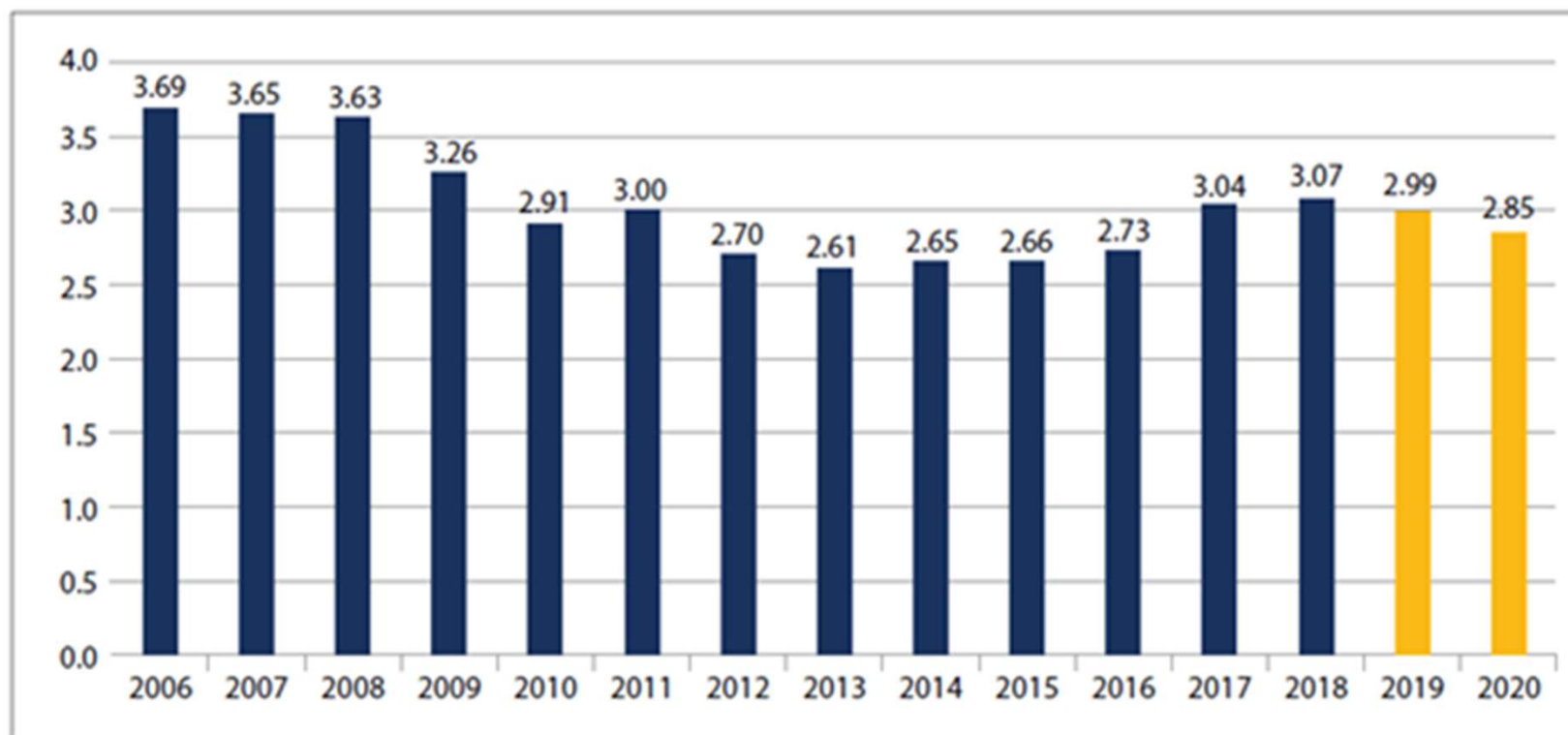
- ❑ Aggregates: 4.7 billions tons
  - (670 pyramids of Cheops)
- ❑ Sand: 2.2 billions tons
  - (22 millions wagons = train 264000 km long)
- ❑ Cement: 1.3 billions tons
  - (17000 ocean liner type *Norway* = 2.34 billions tons of limestone and clay)
- ❑ Water: 800 billions litres
  - (23 times the daily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



# Materials and environment

*We consume natural resources (per year)*

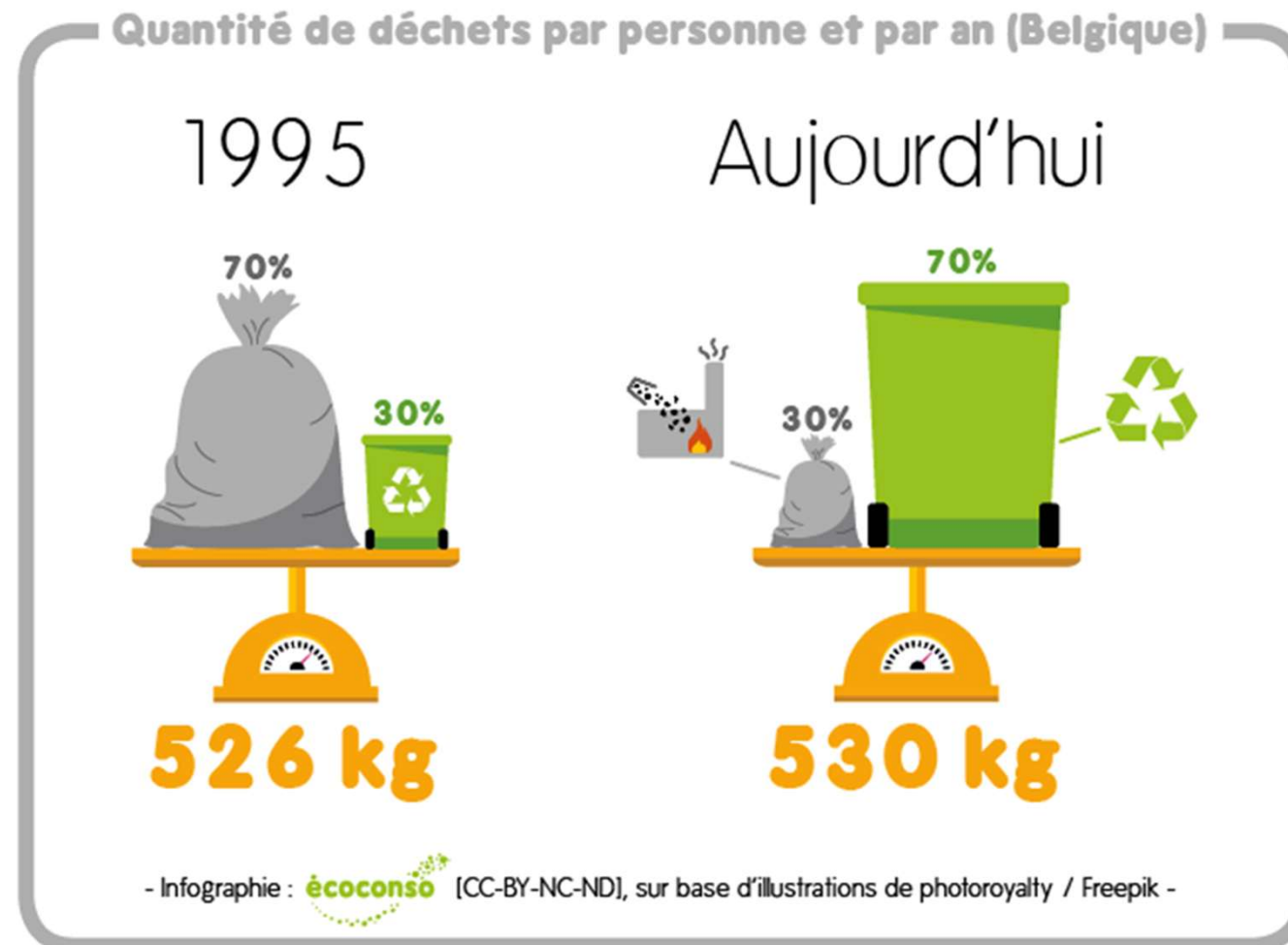
- Trend in total EU27 + UK + EFTA Tonnages (in billions of tonnes) for the production of aggregates (UEPG 2021) - 26,000 quarries and pits, operated by 15,000 companies



# Materials and environment

## *We 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](http://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](http://www.ecoconso.be))



690 kg/year.inh. (380 kg recycled)



513 kg/year.inh.

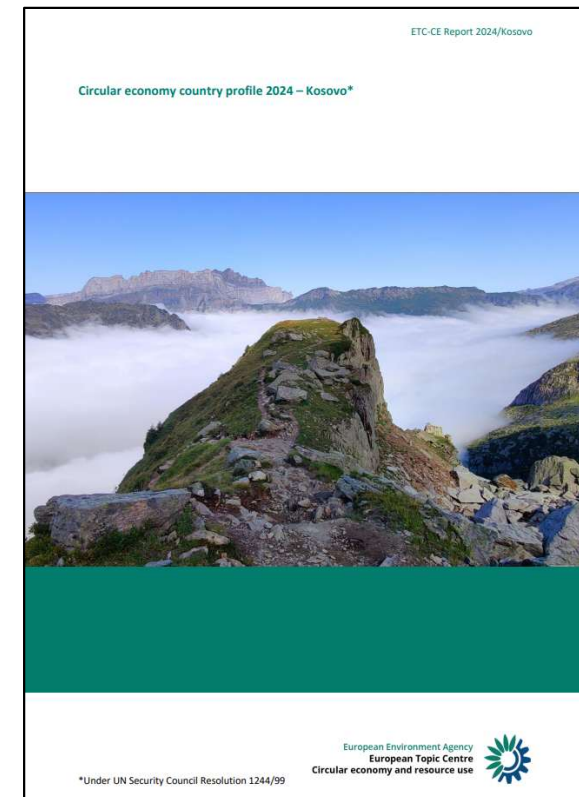


293 kg/year.inh. (36 kg recycled)

Municipal waste generation in Kosovo increased from 100 kg/capita in 2010 to 292.5 kg/capita in 2022

The trend in municipal waste generation is not aligned with the EU's 2030 policy targets

[https://www.eea.europa.eu/en/topics/in-depth/circular-economy/country-profiles-on-circular-economy/circular-economy-country-profiles-2024/kosovo\\_2024-ce-country-profile\\_final.pdf/@@download/file](https://www.eea.europa.eu/en/topics/in-depth/circular-economy/country-profiles-on-circular-economy/circular-economy-country-profiles-2024/kosovo_2024-ce-country-profile_final.pdf/@@download/file)

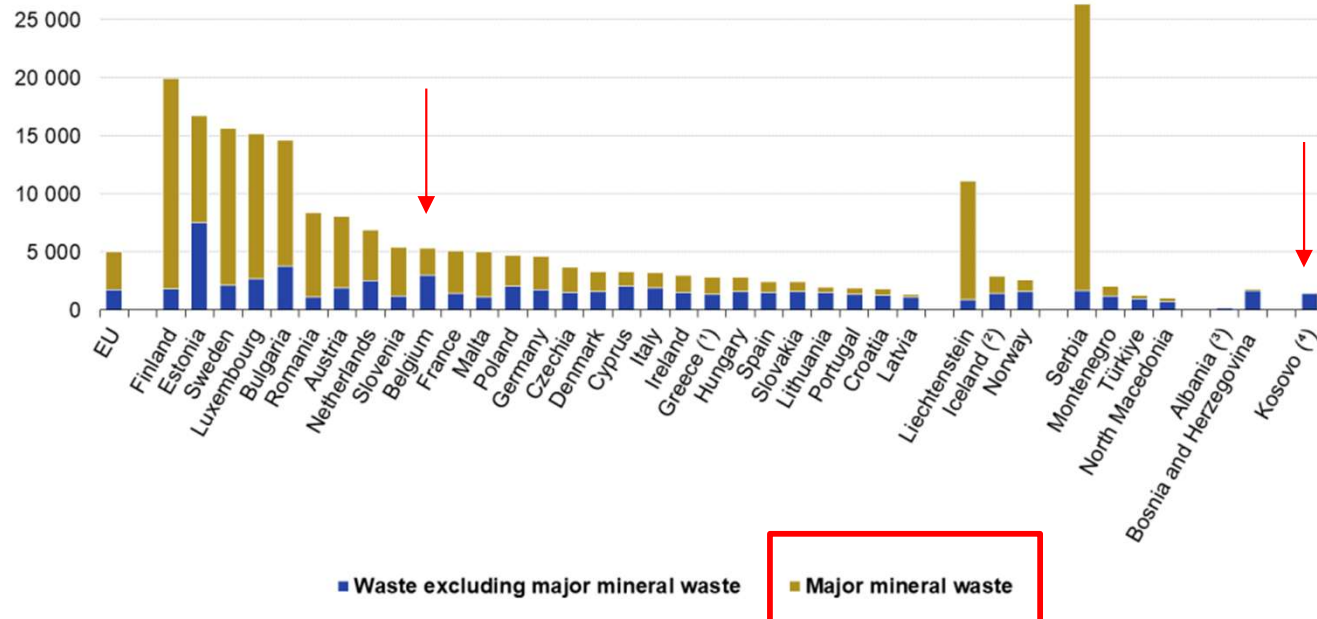


# Materials and environment

## *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.

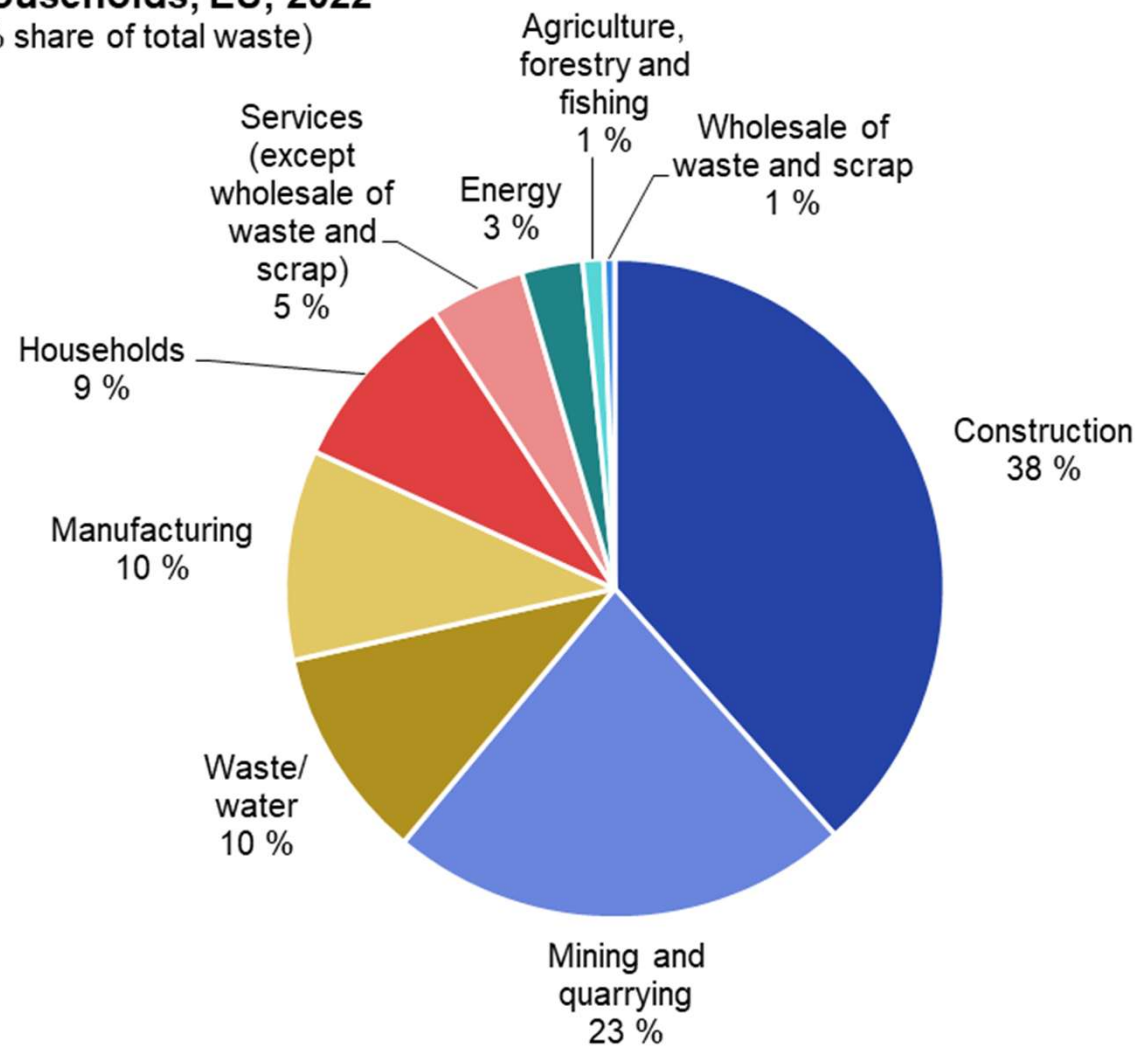
Source: Eurostat (online data code: env\_wasgen)

# Materials and environment

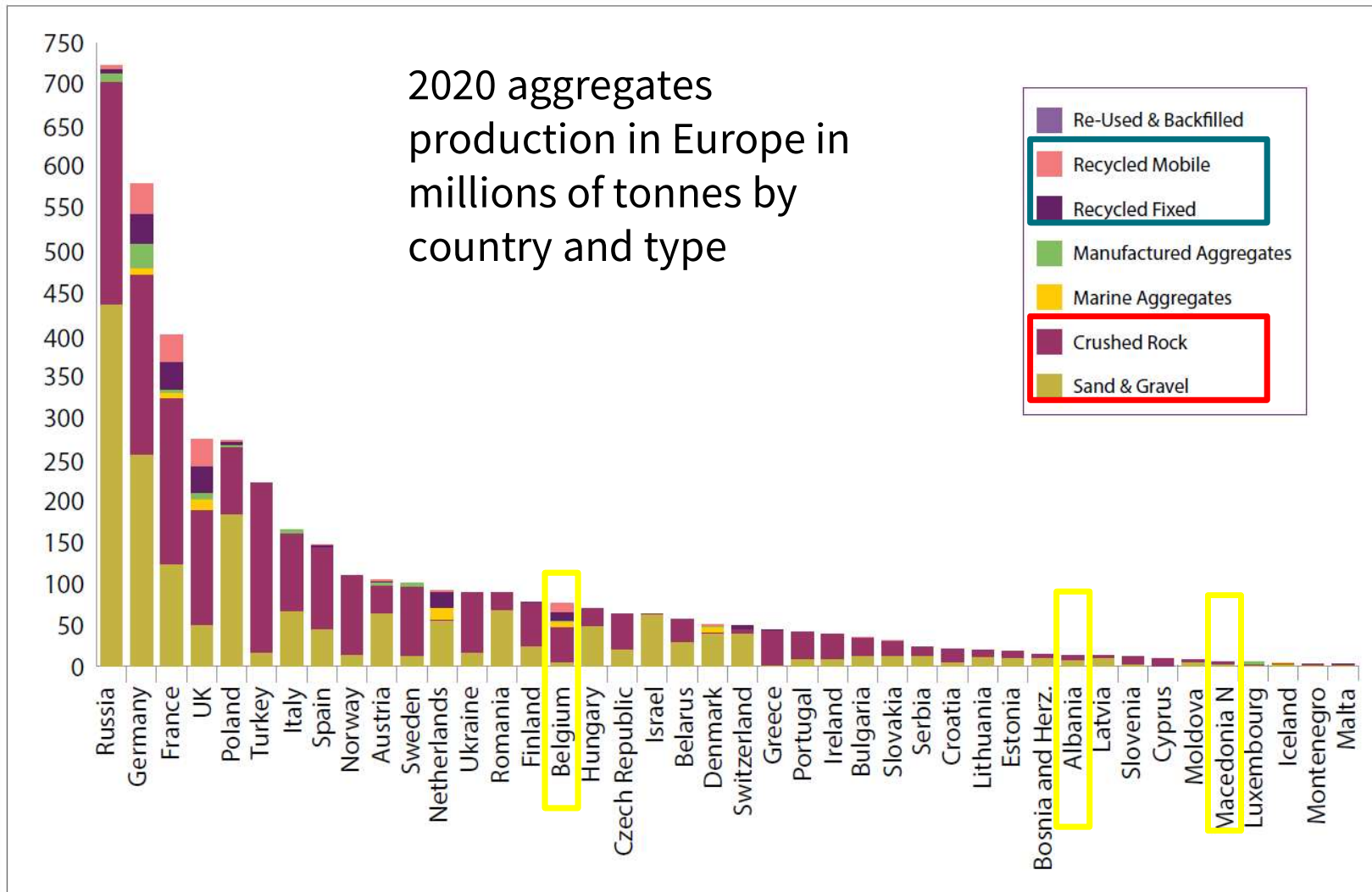
*We produce a lot of wastes*

□ 1725 kg  
C&DW per  
capita in  
the EU28

**Waste generation by economic activities and households, EU, 2022**  
(% share of total waste)



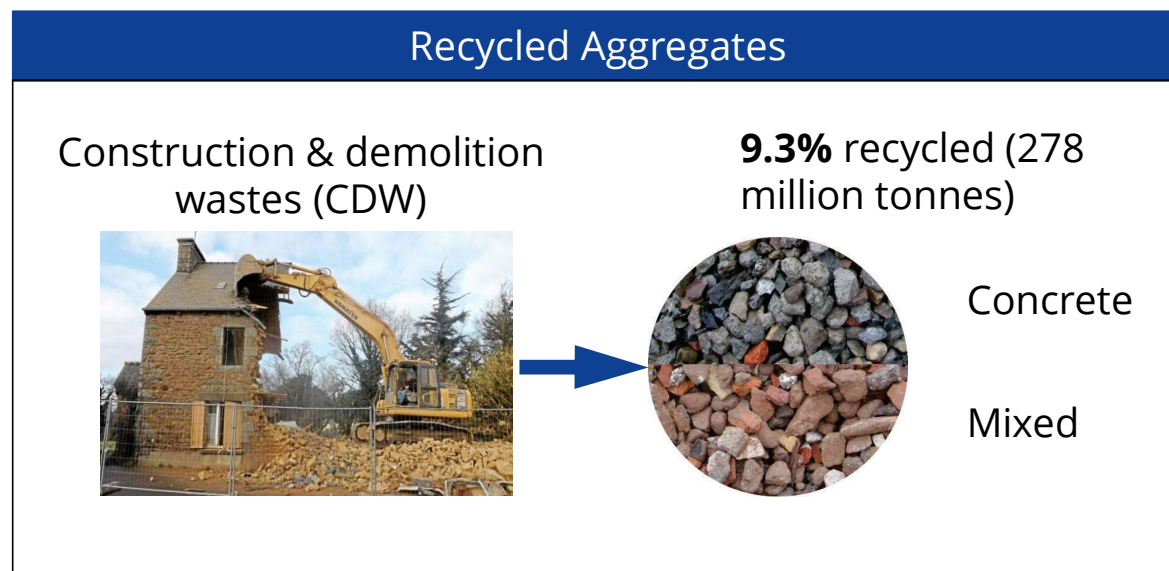
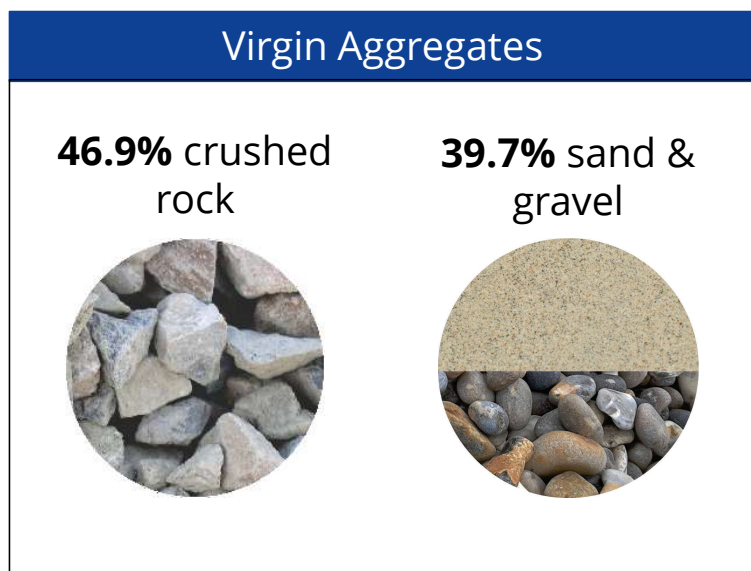
# Materials and environment





# Materials and environment

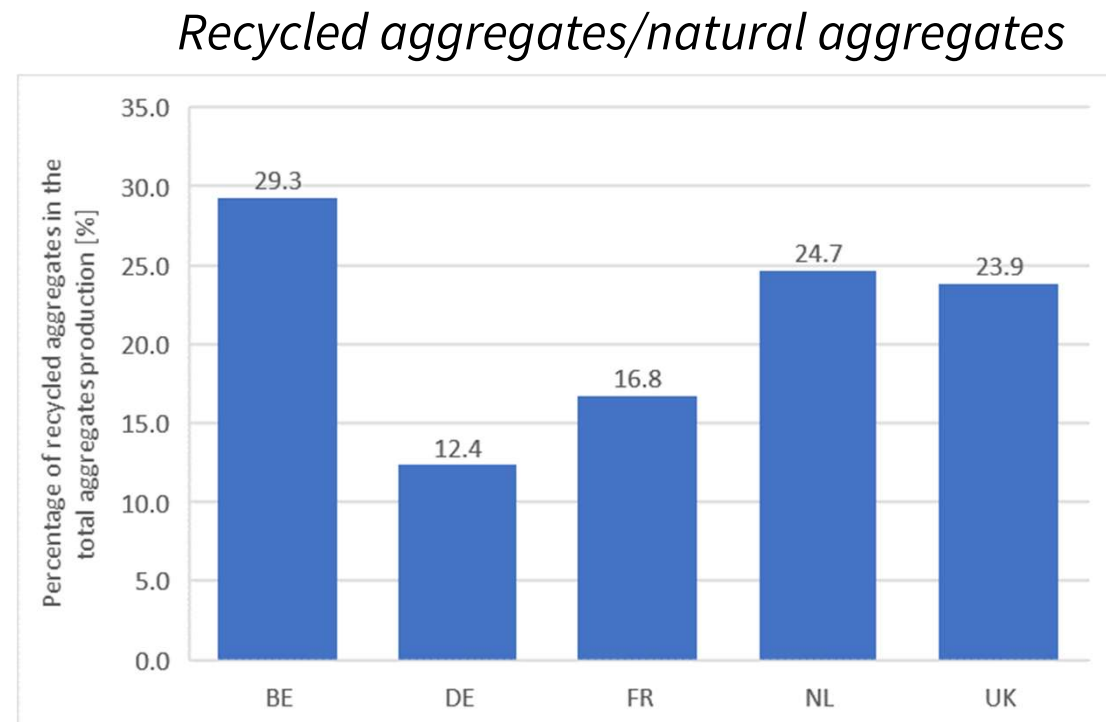
- ▶ 3 billion tons produced in EU27+UK+EFTA in 2022 (UEPG 2023)



# 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)





## ■ Transforming wastes ...





- ... into secondary resources





# Research and innovation



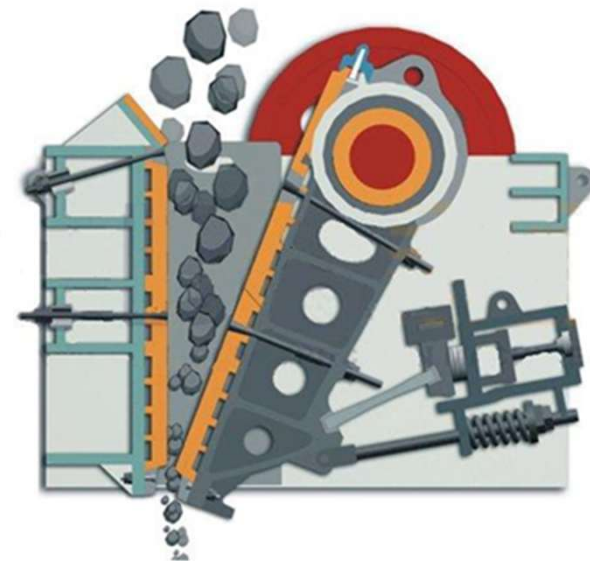
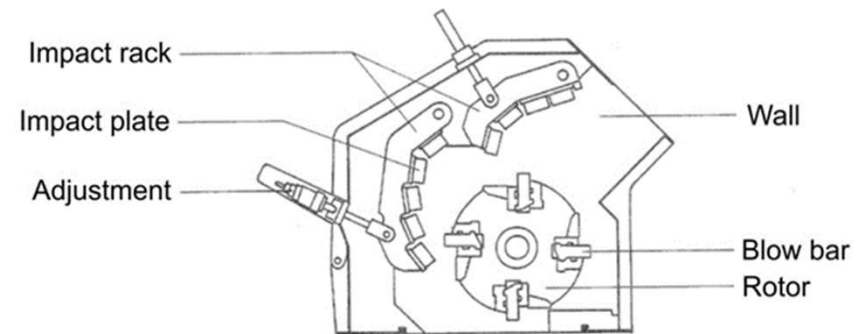
# Research and innovation

- ▶ 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<sub>2</sub> 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





# Material processing

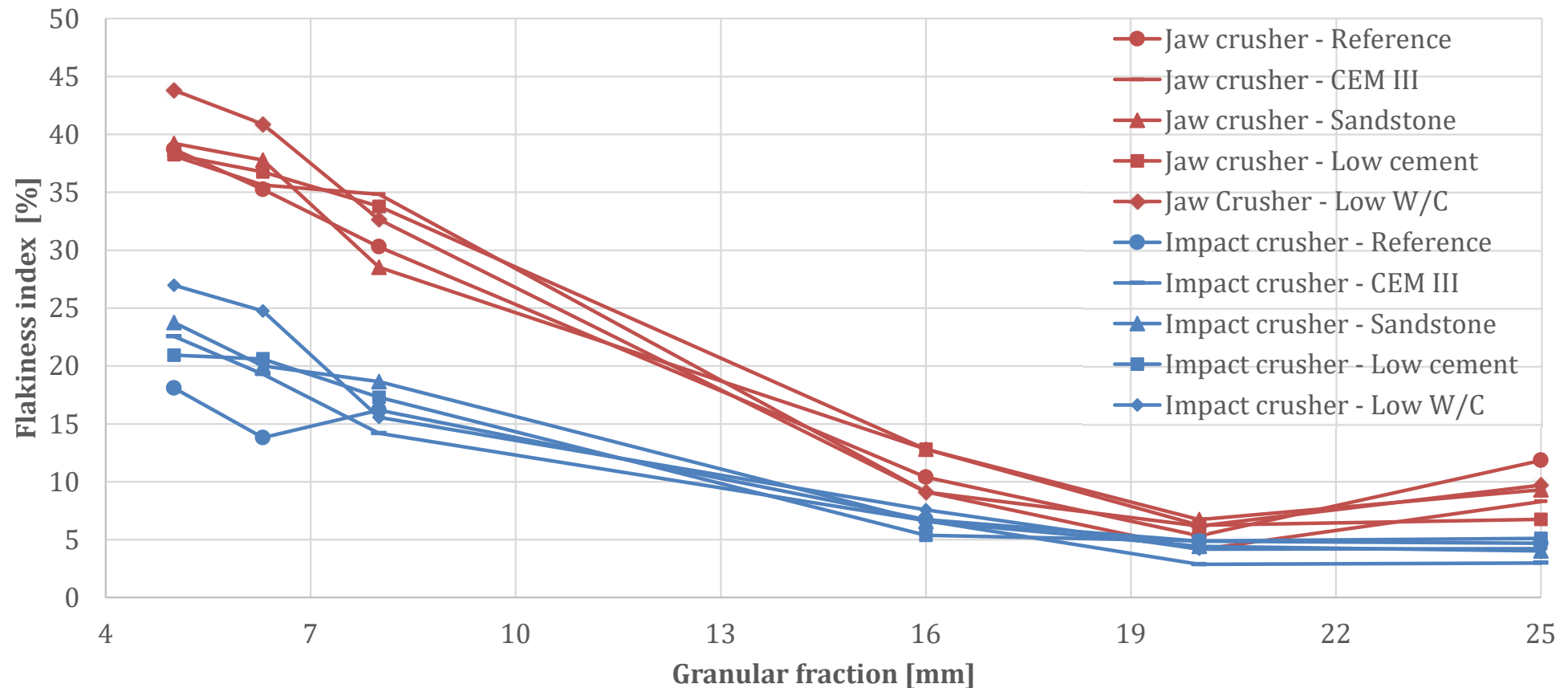
## ► Experimental mixes

| Name   | Reference  | CEM III             | Sandstone        | Low cement | Low W/C     |
|--|------------|---------------------|------------------|------------|-------------|
| Aggregates nature                                      | Limestone  | Limestone           | <b>Sandstone</b> | Limestone  | Limestone   |
| Aggregates 2/7 mm (kg/m <sup>3</sup> )                 | 368.8      | 368.8               | 368.8            | 405.1      | 367.1       |
| Aggregates 7/14 mm (kg/m <sup>3</sup> )                | 345        | 345                 | 345              | 379        | 343.4       |
| Aggregates 14/20 mm (kg/m <sup>3</sup> )               | 433.5      | 433.5               | 433.5            | 476.2      | 431.5       |
| Sand 0/4 mm (kg/m <sup>3</sup> )                       | 604.9      | 604.9               | 604.9            | 664.4      | 602.1       |
| Cement type  | CEM I 52.5 | <b>CEM III 52.5</b> | CEM I 52.5       | CEM I 52.5 | CEM I 52.5  |
| Cement quantity (kg/m <sup>3</sup> )                   | 400        | 400                 | 400              | <b>320</b> | 452         |
| Cement paste volume (dm <sup>3</sup> /m <sup>3</sup> ) | 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       | <b>0.46</b> |
| Superplasticizer (g/kg cement)                         | 0          | 0                   | 0                | 6.8        | 3.3         |



# Material processing

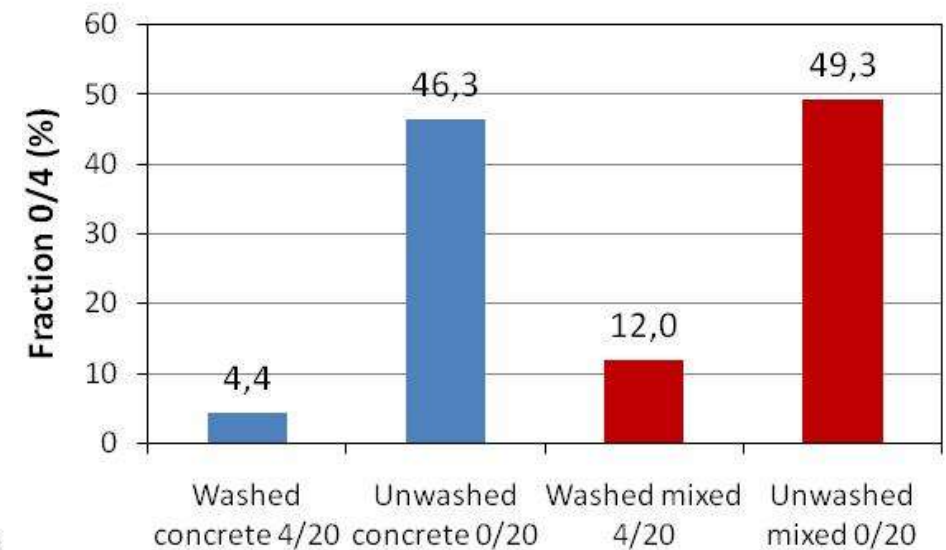
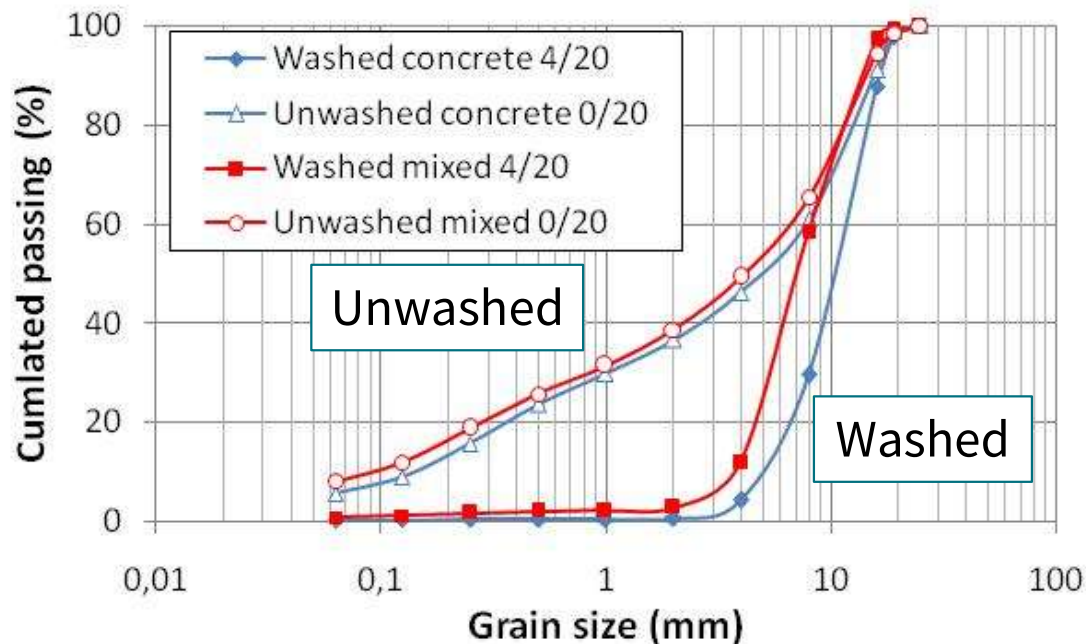
- The flakiness index decreases with increasing granular fraction
- The jaw crusher produces flakier aggregates
- No influence of the concrete composition





# Materials processing: washing

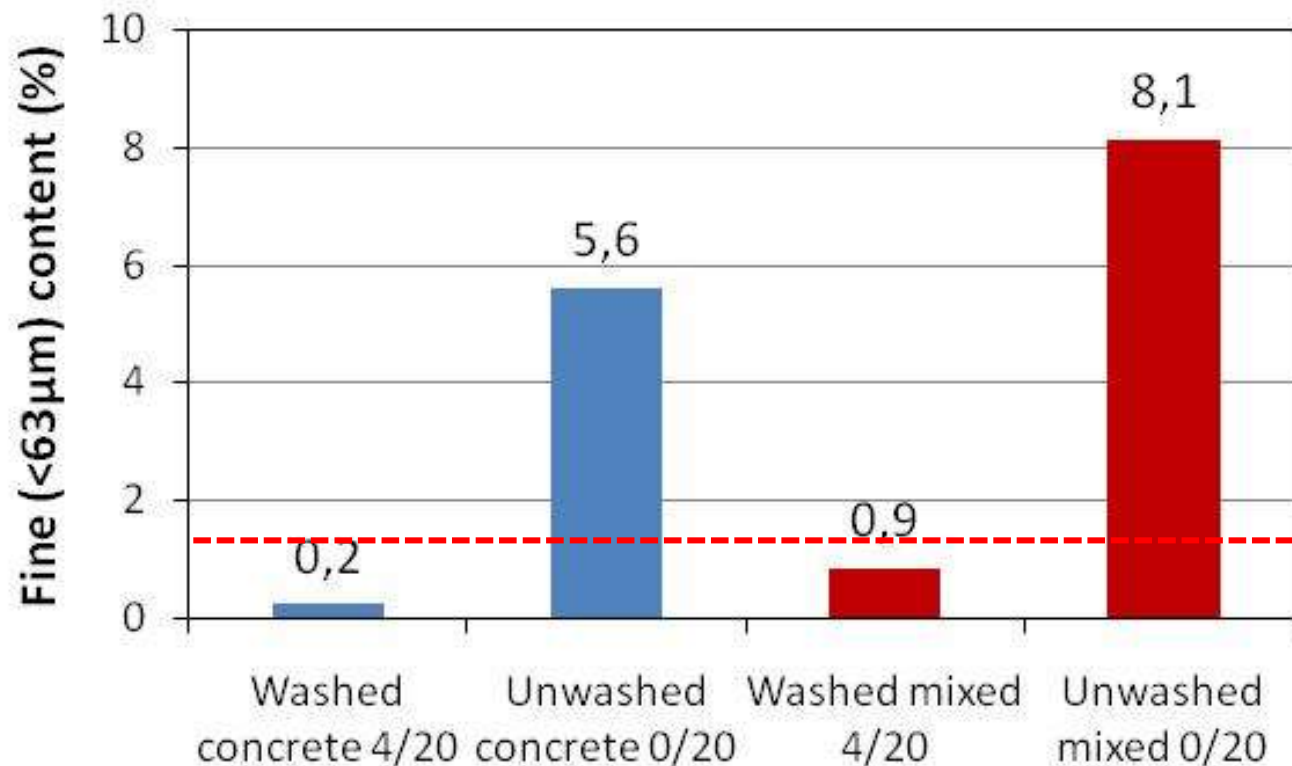
- 0/4 fraction comprises nearly 50% of the unwashed aggregates composition
- 0/4 fraction a bit higher in mixed aggregates
- Washing significantly reduces the sand fraction of the aggregates





# Materials processing: washing

- Fine content ( $< 63\mu\text{m}$ ) higher in mixed aggregates and significantly reduced by washing
- Fine fraction higher in mixed aggregates
- Washed aggregates respect regulations in all considered countries



Max. allowed

# Using wastes

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

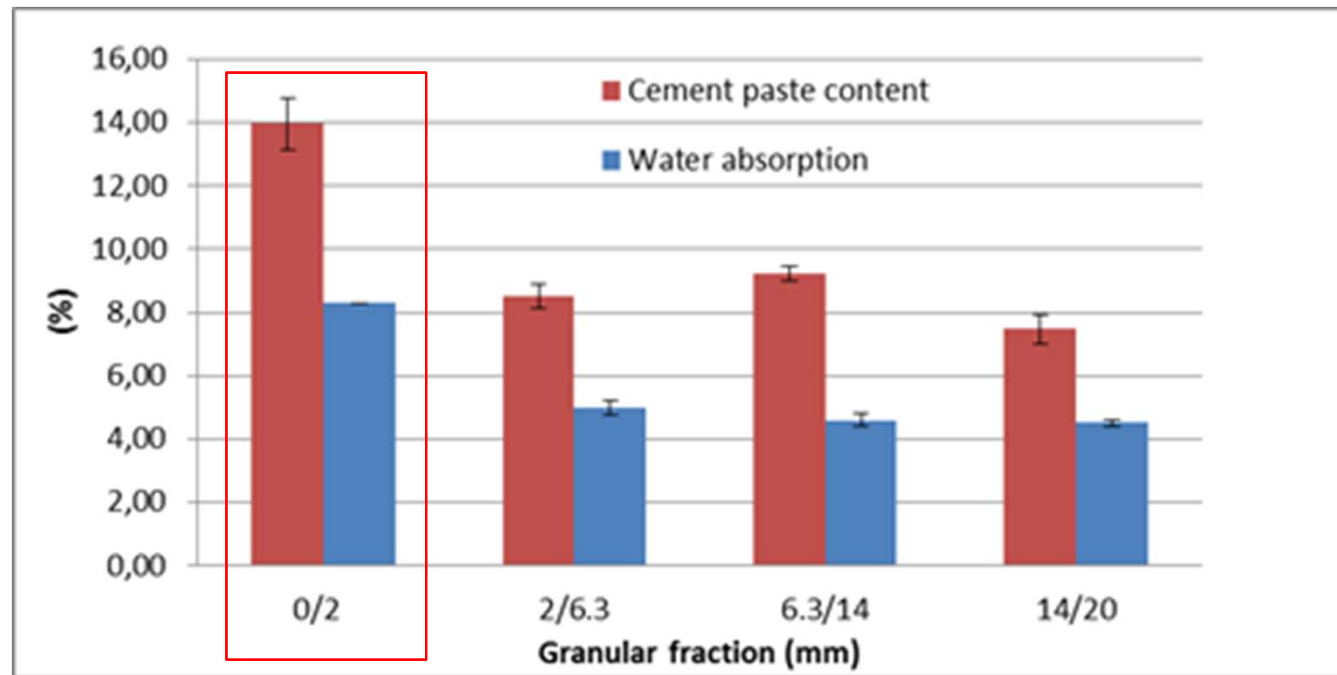


Use of RCA from precast blocks for the production of new concrete building blocks: an industrial scale study. Z. Zhao, L. Courard, S. Gros Lambert, Th. Jehin, A. Léonard, J. Xiao. *Resources, Conservation & Recycling* 157 (2020) 1-13 (<https://authors.elsevier.com/a/1ahbs3HVLKiAuJ>) (<http://hdl.handle.net/2268/246444>)



# Using wastes

## ► Water absorption $W_A$ (EN 1097-6)

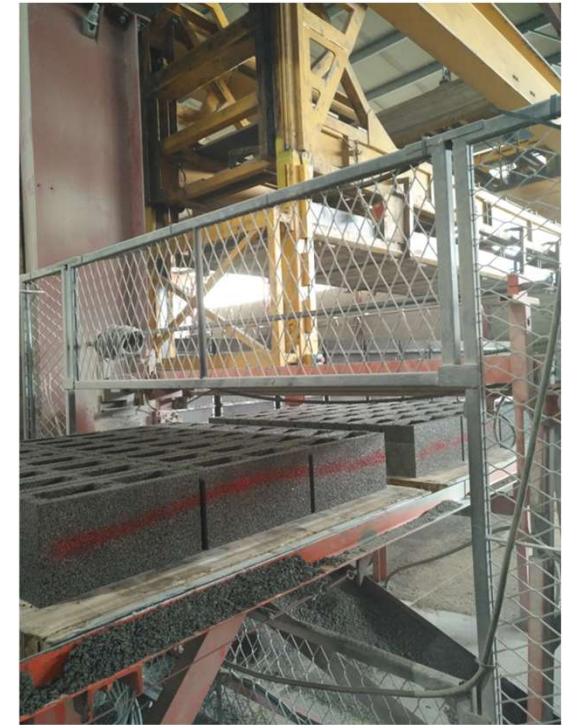
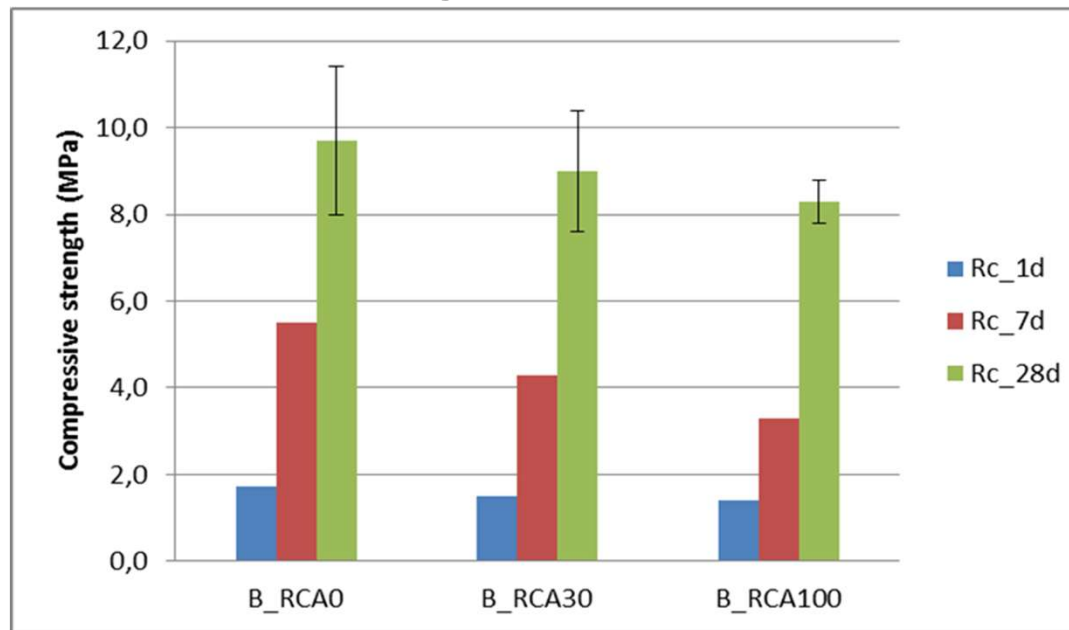


- Cement Paste Content and  $W_A$  of 0/2mm fraction larger than three coarse fractions



# Using wastes

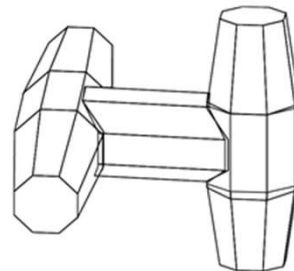
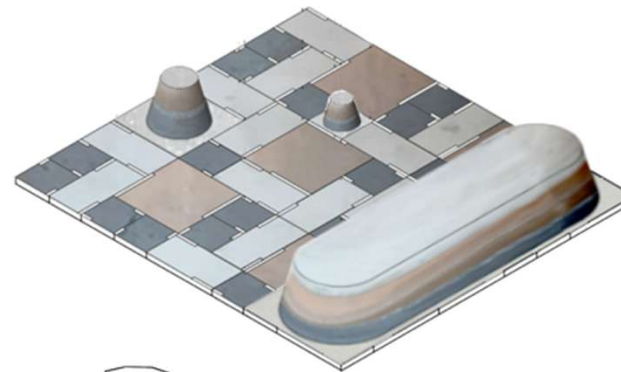
## ► Compressive strength



- 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)

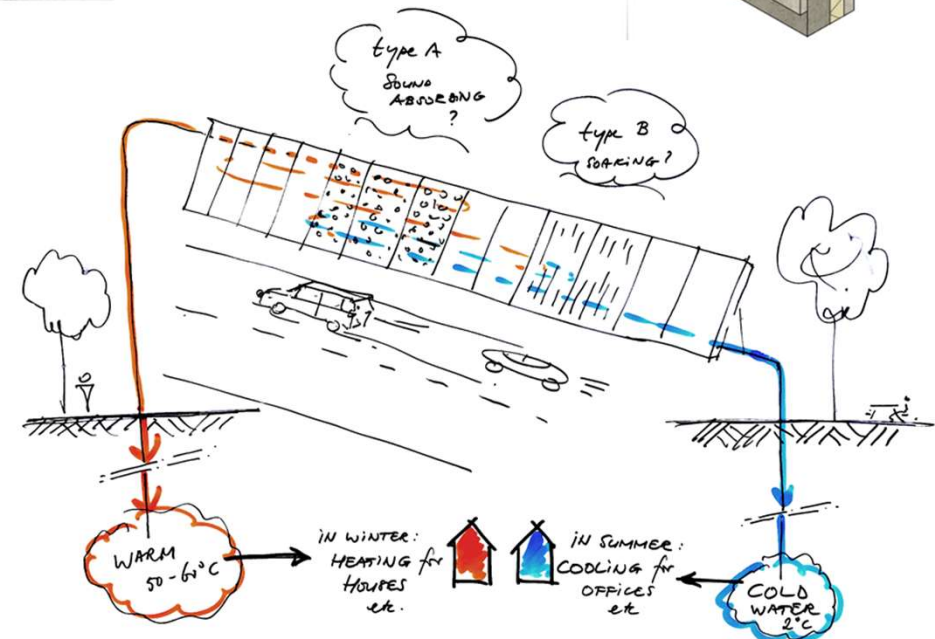
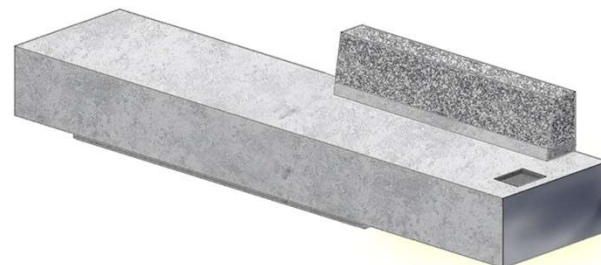
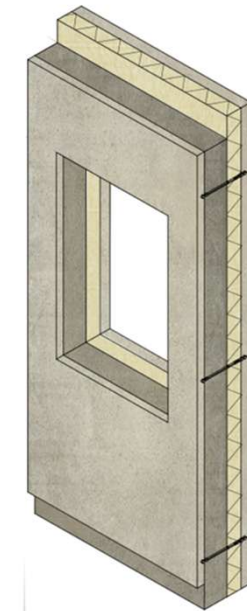
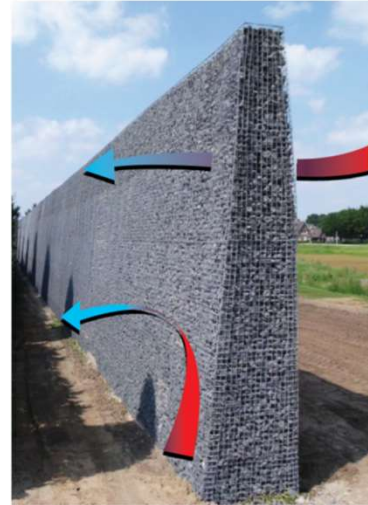
# Prefab products

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**



# Prefab products

1. Hollow Core Floor Slab
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# Prefab products: Parkour Park



Cement produced with recycled fines

Recycled concrete aggregates

Natural sand



$R_c$  : 50-55 MPa  
W/C  $\leq$  0.45  
Cement  $\geq$  340 kg/m<sup>3</sup>  
WAI  $\leq$  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





# Fine bricks

## ► Brick fine particles

### ■ 3 types of granulometry

➤ B1:  $d_{50} = 3.3 \mu\text{m}$  (with supplementary cyclogrinding)

➤ B2:  $d_{50} = 20 \mu\text{m}$

➤ B3:  $d_{50} = 190 \mu\text{m}$

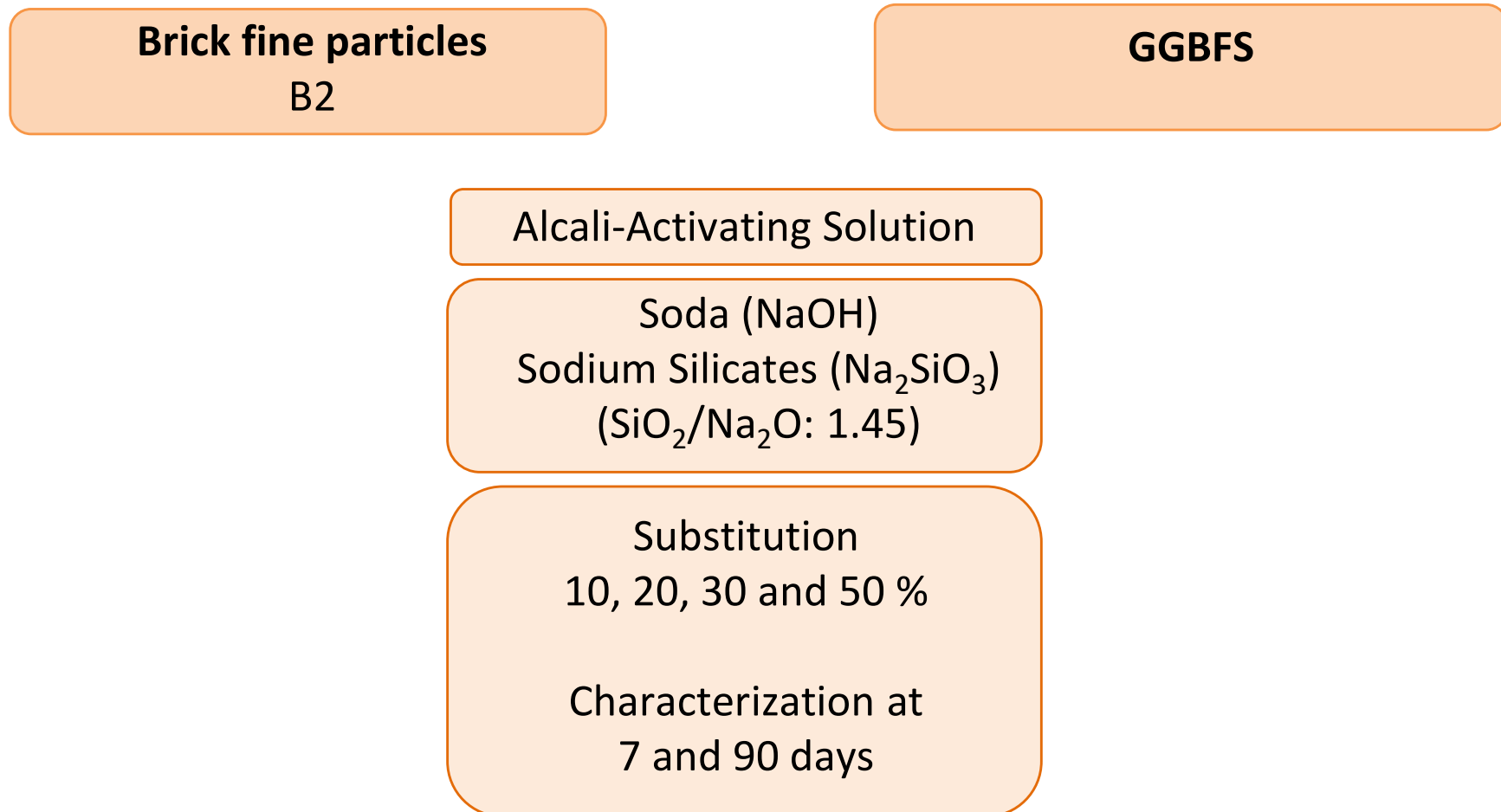
## ► Mineralogy

| Oxides (%) | CaO  | SiO <sub>2</sub> | Al <sub>2</sub> O <sub>3</sub> | Fe <sub>2</sub> O <sub>3</sub> | K <sub>2</sub> O | Na <sub>2</sub> O | MgO | TiO <sub>2</sub> | 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

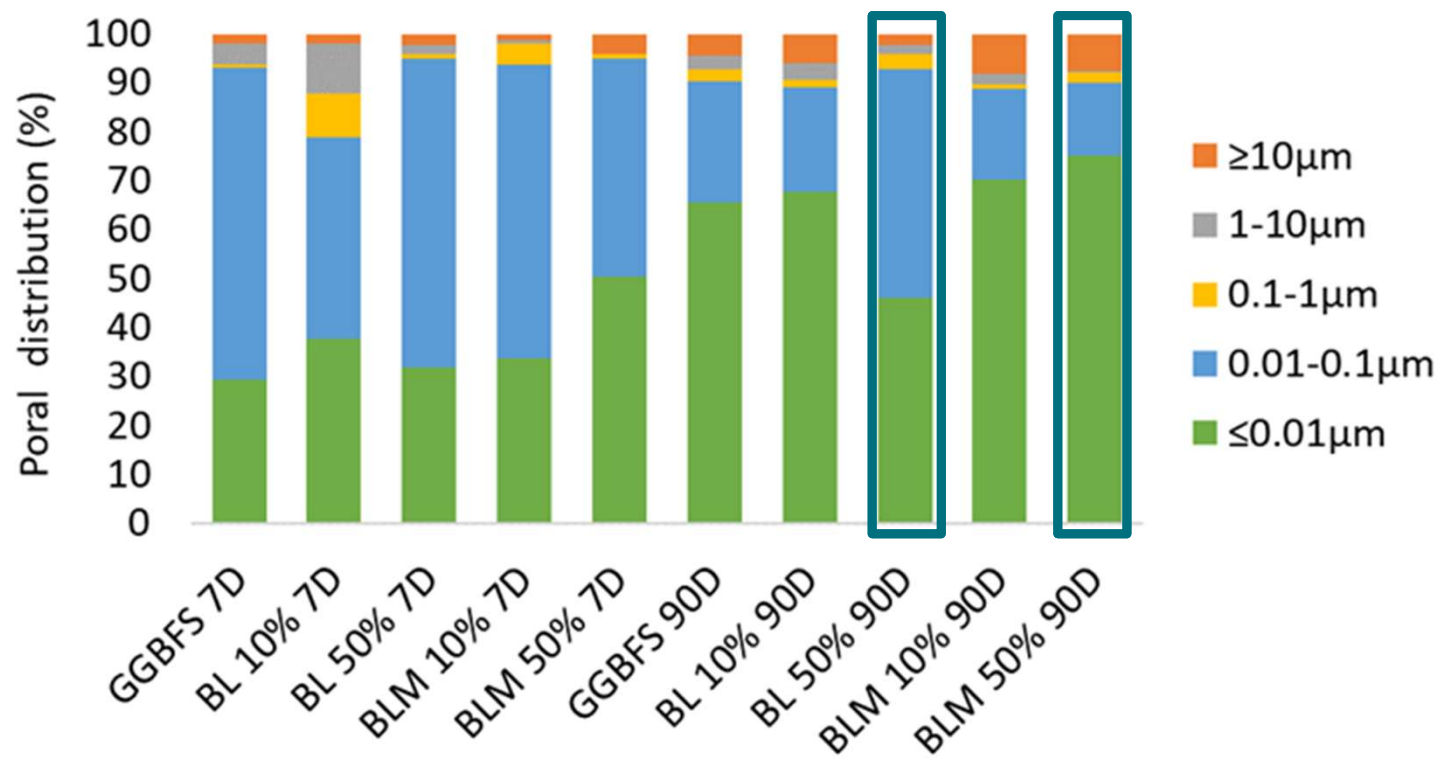
## ► Alkali Activated Material production





# Fine bricks

## ► Poral distribution

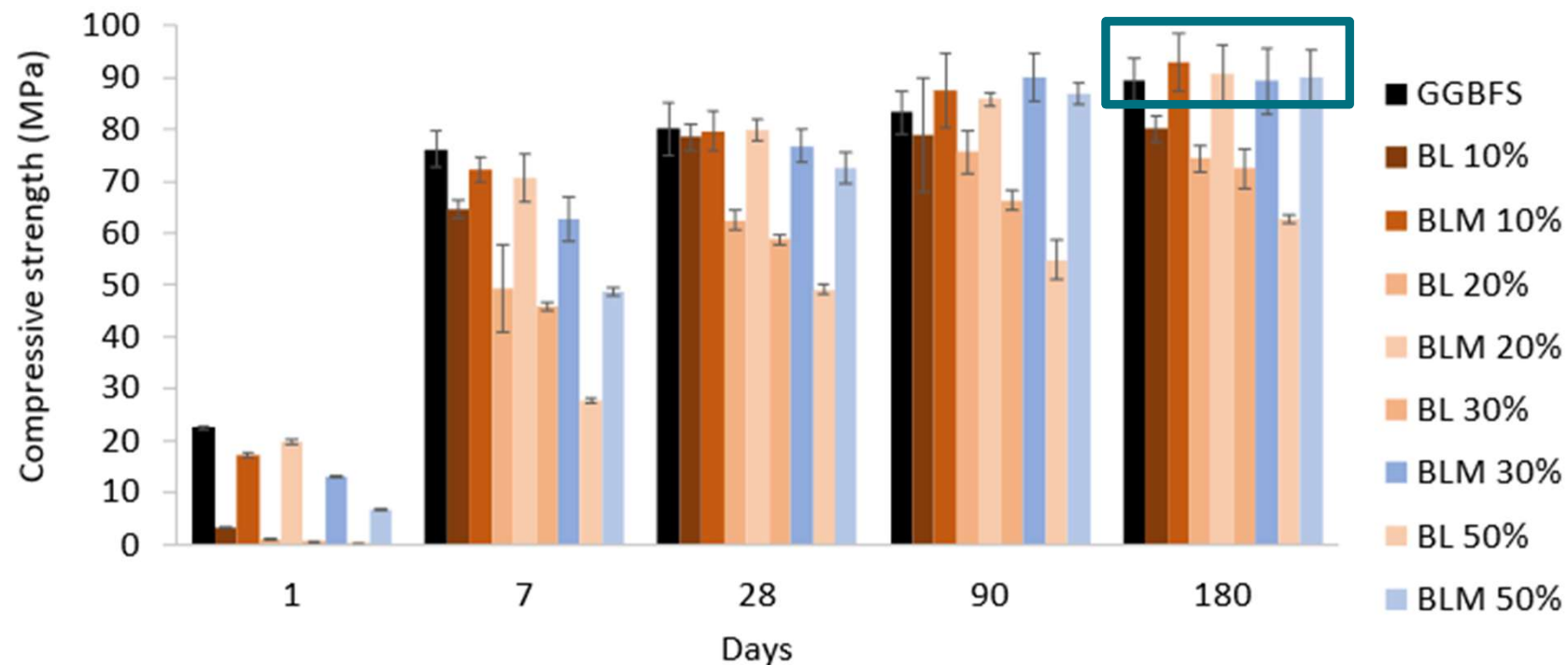


- Finer porosity with time for all the mixes
- Finer porosity with BLM 50% than BL 50%



# Fine bricks

## ► Mechanical strength



- BL: slower kinetics –  $R_c \downarrow$  when [brick fines]  $\uparrow$
- BLM: quicker kinetics -  $R_c \geq$  GGBFS from 90 days
- Brick fines can act as a *precursor*

# Recycled sand for 3D printing

3D printing:



Design opportunities



Environmental impact



Siam Research and Innovation Company - Triple S (2017)

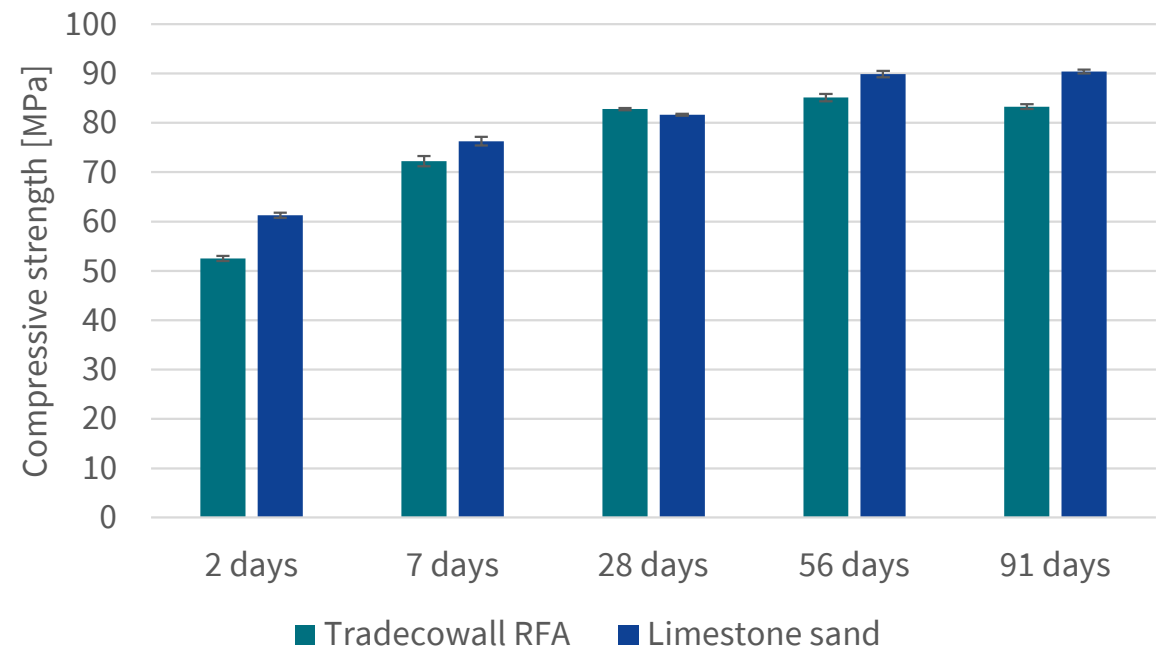


Casted samples (4x4x16 cm prismatic samples are casted)

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

## Compressive strength :

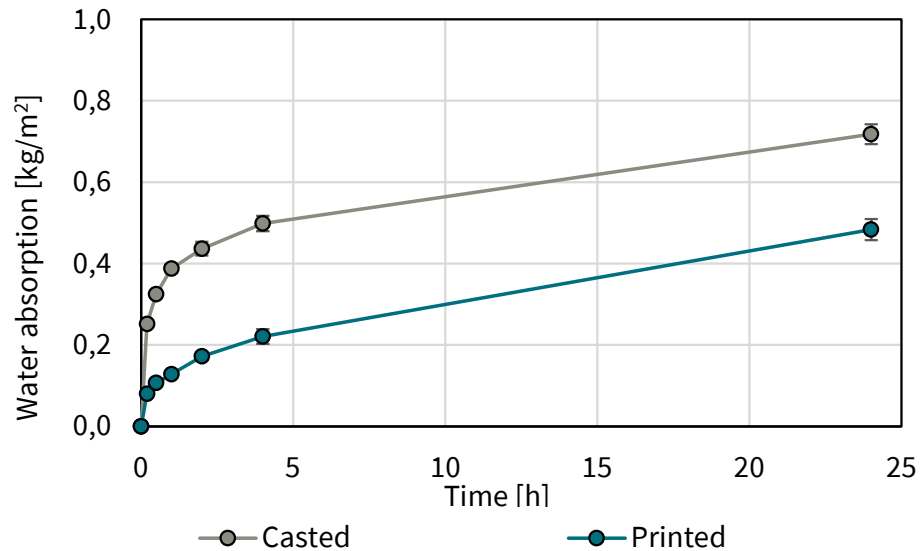
- Influence of the **type of sand** (natural crushed limestone sand vs concrete RFA)
- Compressive strength
- Water curing (20°C and 95±5% relative humidity)





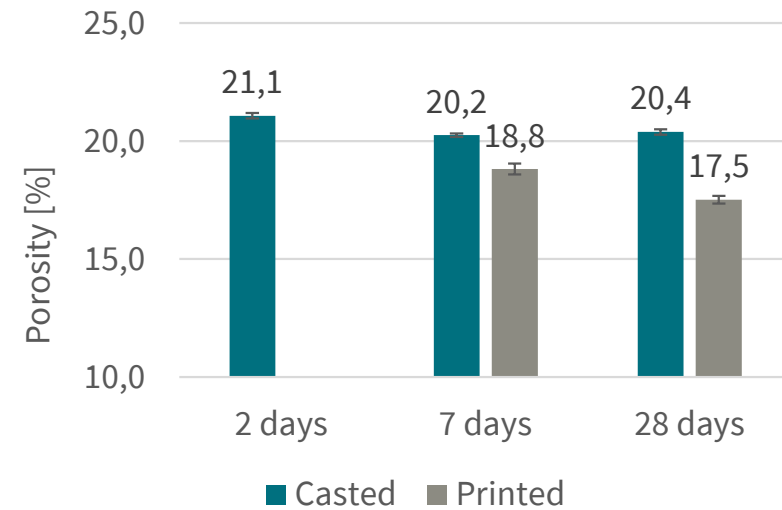
## Capillary absorption tests NBN EN13057

- Influence of the **printing process** (casted samples vs printed samples)
- Water absorption [kg/m<sup>2</sup>] and absorption coefficient [mm/h<sup>0,5</sup>]



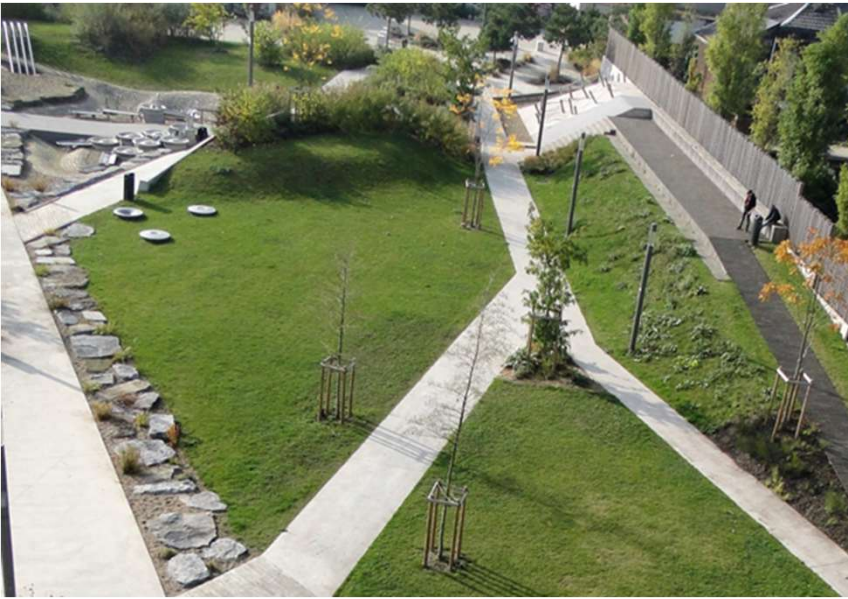
## Porosity

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





## Urban furniture Bernard Serin park in Seraing



# Accelerated carbonation of incinerated municipal solid waste



# 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

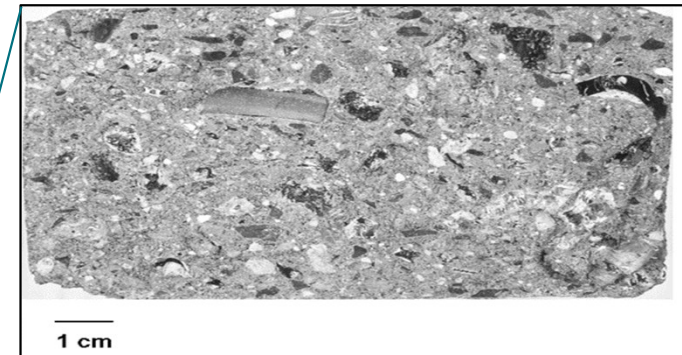
- Partial or total substitution of sand and aggregates for :
  - Road foundations
  - Concrete pavements\*
  - Concrete blocks



*Road foundations*



*Concrete pavements\**



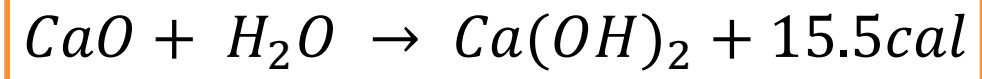
*Concrete blocks*

\* 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.

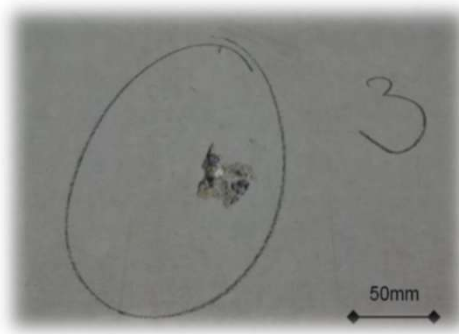
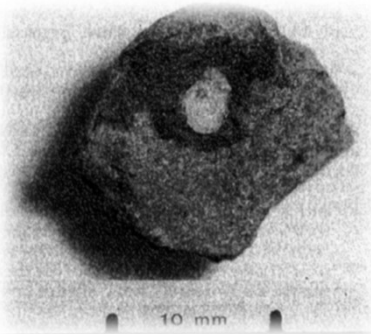


# MSWI BA RISKS

- Lixiviation
- Lime nodule swelling



| Molecule                                 | CaO  | H <sub>2</sub> O | Ca(OH) <sub>2</sub> |
|--|------|------------------|---------------------|
| Molecular weight                         | 56   | 18               | 74                  |
| Real density (g/cm <sup>3</sup> )        | 3.3  | 1                | 2.24                |
| Molecular volume (cm <sup>3</sup> /mole) | 16.8 |                  | 33.1                |





## MSWI BA TREATMENT: 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 TREATMENT: ACCELERATED CARBONATION

- Accelerated treatment: static carbonation
- Chemical reaction occurring during the accelerated carbonation:
  1.  $\text{CO}_2 + \text{H}_2\text{O} \leftrightarrow \text{H}_2\text{CO}_3$
  2.  $\text{H}_2\text{CO}_3 + \text{OH}^- \leftrightarrow \text{H}_2\text{CO}_3^{2-} + \text{H}_2\text{O}$
  3.  $\text{H}_2\text{CO}_3^{2-} + \text{OH}^- \leftrightarrow \text{CO}_3^{2-} + \text{H}_2\text{O}$
  4.  $\text{Ca}(\text{OH})_2 \leftrightarrow \text{Ca}^{2+} + 2 \text{OH}^-$
  5.  $\text{Ca}^{2+} + \text{CO}_3^{2-} \leftrightarrow \text{CaCO}_3$
- Advantages of this method:
  - Short treatment period
  - $\text{CO}_2$  sequestration



*Static carbonation chambers*

# Special Equipment

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**Static  
carbonation  
climatic chambers**

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**Dynamic  
carbonation  
process tool**

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**CarbonEx:**  
experimental room  
for accelerated  
carbonation

# Special Equipment

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Static carbonation  
climatic chambers

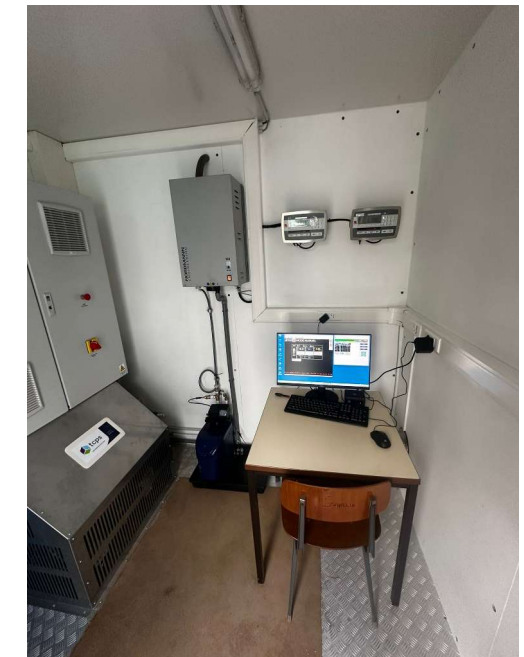
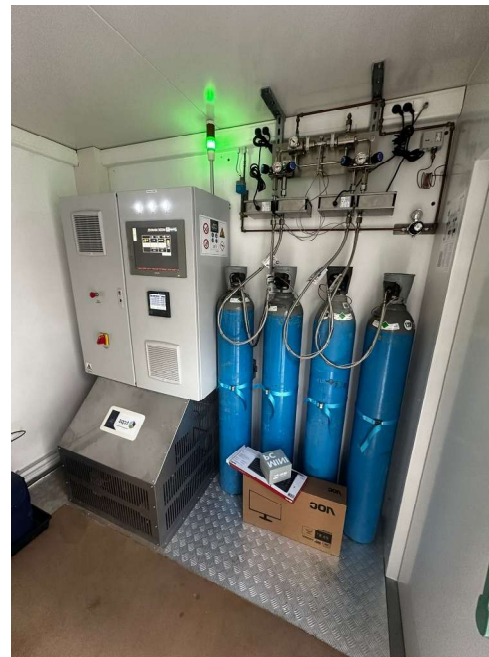
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Dynamic  
carbonation  
process tool

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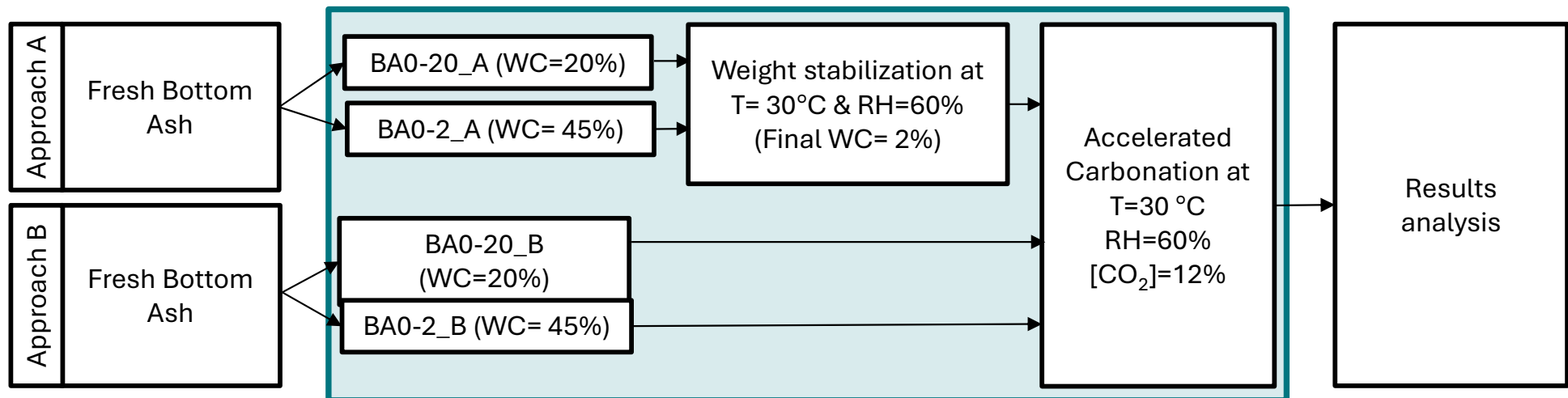
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**CarbonEx:**  
experimental room  
for accelerated  
carbonation



# ACCELERATED CARBONATION TREATMENT

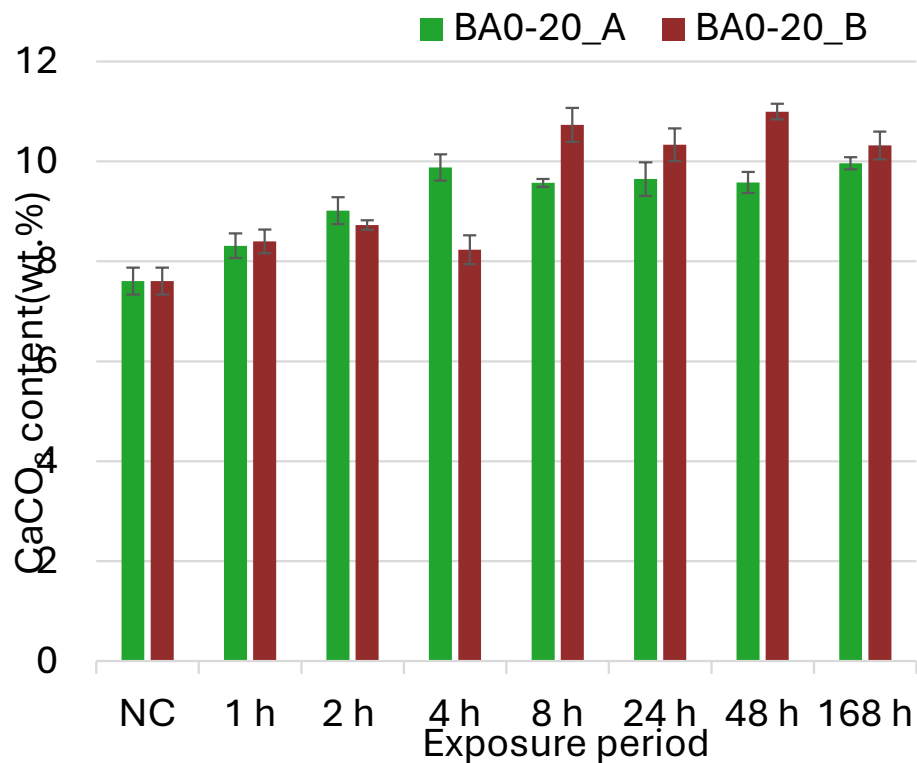
- Parameters studied:
  - Particle size: 0/2 & 0/20 mm
  - Exposure period: 1, 2, 4, 8, 24, 48 & 168 h
  - Moisture content (WC): 2, 20 & 45%
- Carbonation conditions:
  - Temperature:  $30 \pm 1$  °C
  - Relative humidity:  $60 \pm 3\%$
  - CO<sub>2</sub> concentration: 12 %vol



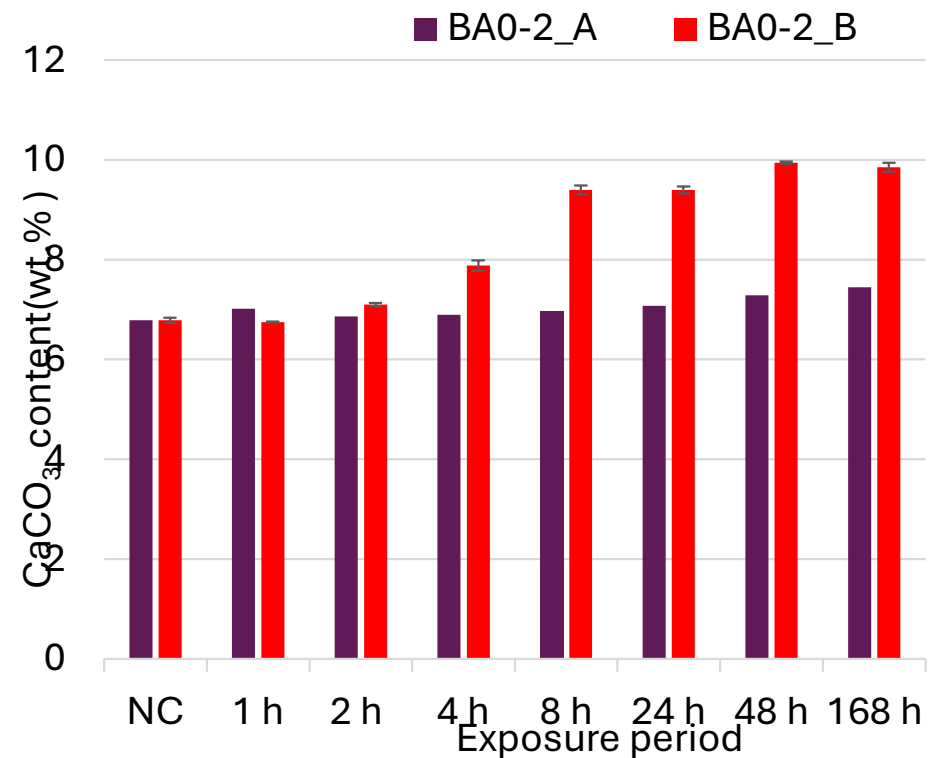


# RESULTS – CaCO<sub>3</sub> content

- BA particle size: 0/20 mm



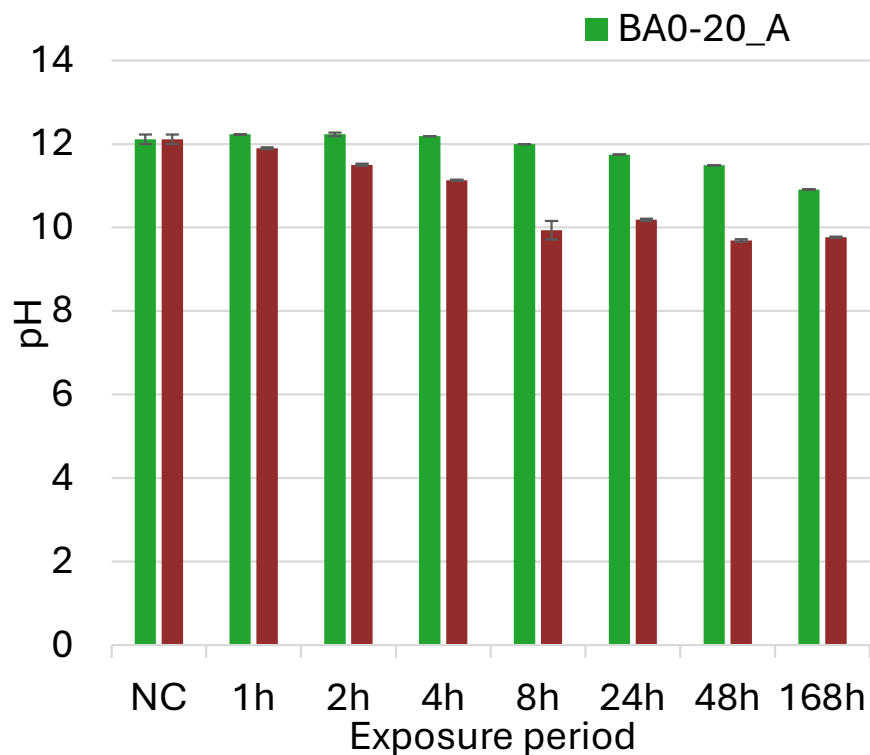
- BA particle size: 0/2 mm



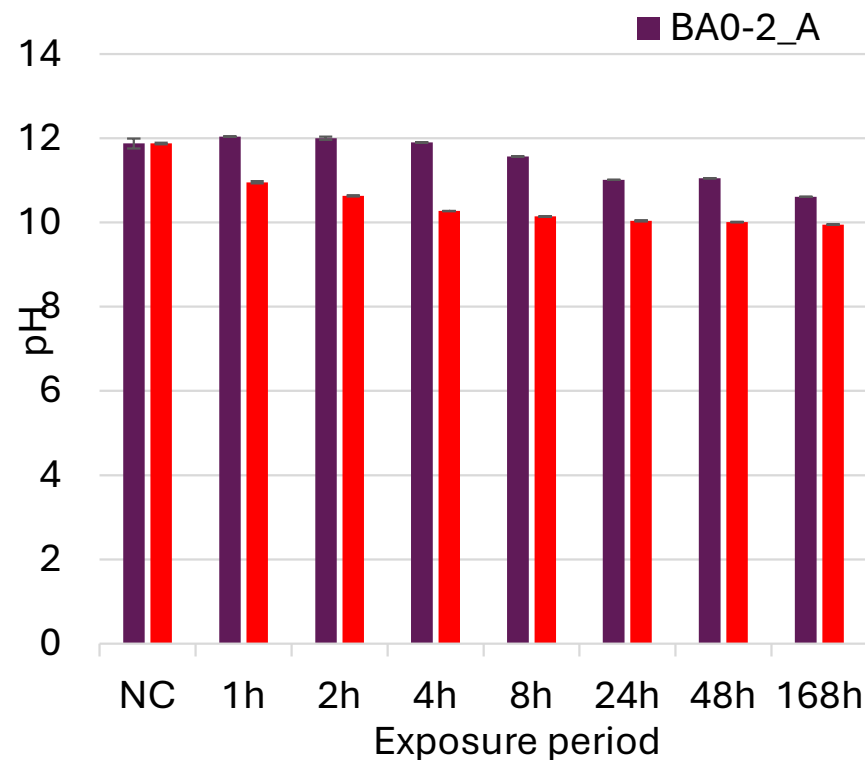


# RESULTS – pH

- 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-<br>BA aggregates  | Density (kg/m <sup>3</sup> ) | 1840  | 2145       | 2239      | 2150-2850   |
|                               | Water absorption (%)         | 6.9   | 7.3        | 8.24      | 2.2-17.3    |
| Coarse MSWI-<br>BA aggregates | Density (kg/m <sup>3</sup> ) | 2280  | 2360       | 2239      | 1860-2680   |
|                               | Water absorption (%)         | 2     | 2.4        | 4         | 7.2-15      |

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

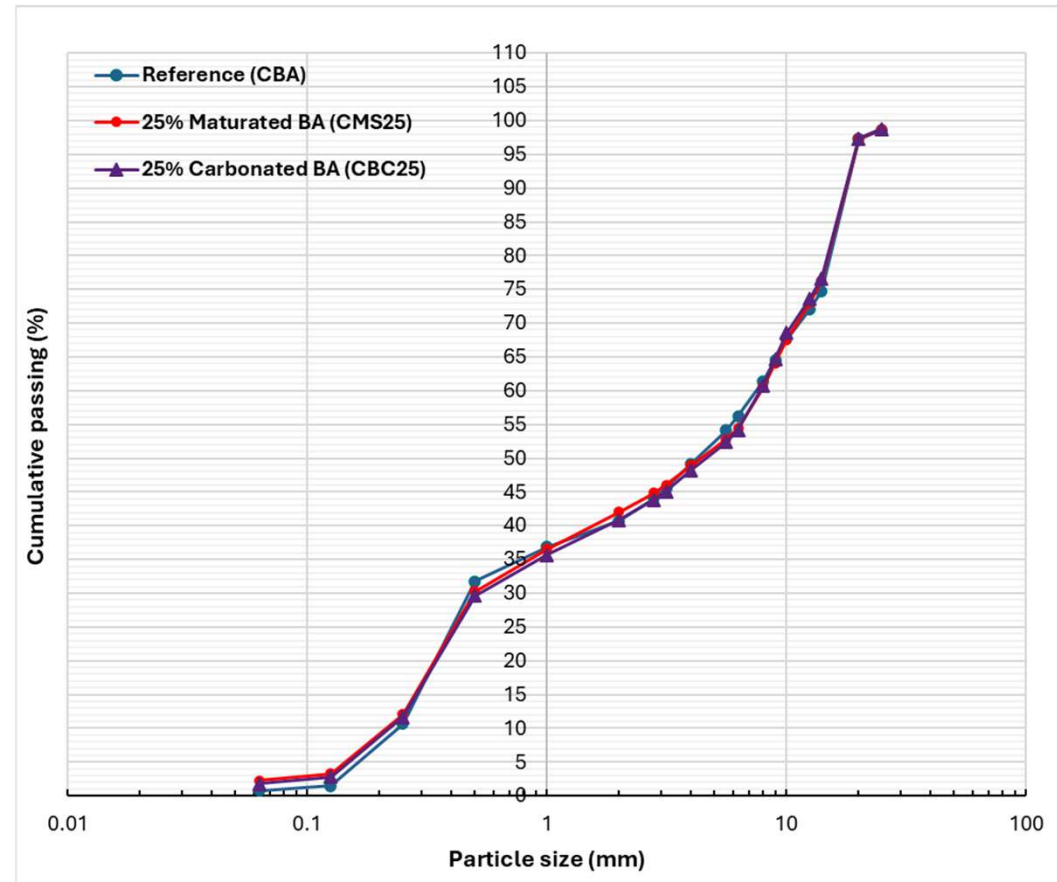
|                               | Fresh | Carbonated | Maturated | Literature* |
|-------------------------------|-------|------------|-----------|-------------|
| Wear resistance (wt.%)        | 21    | 24         | 21        | 18-31       |
| Freeze-thaw resistance (wt.%) | 21    | 20         | 19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





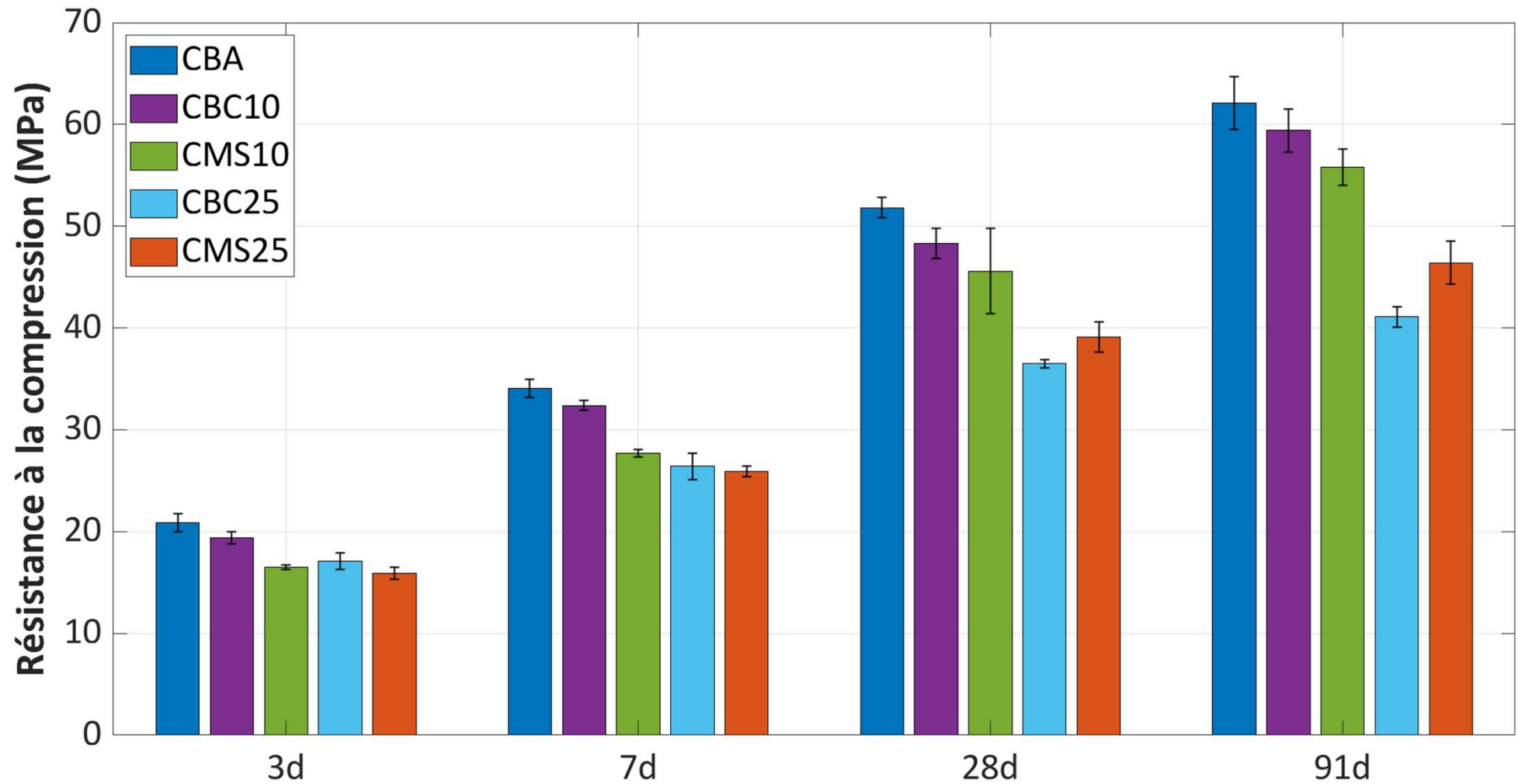
# RESULTS – Fresh concrete properties

| Results                     |                             |            |           |                |
|-----------------------------|-----------------------------|------------|-----------|----------------|
| Composition                 | Density[kg/m <sup>3</sup> ] | 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

*Merci pour votre attention*  
*Thank you for your attention*  
*Faleminderit për vëmendjen tuaj*

Erasmus Mobility Program

