1st CIRKLA SUMMER SCHOOL

“Sustainable Construction: Materials, Circularity, and Innovation”

Use and practice for recycling concrete aggregate

Luc Courard, A. Grellier, J. Hubert, I. E. Kanjo, R. Libert, F. Michel, Y. Muy, J. Troquay, Z. Zhao

UEE Building Materials – www.uee.uliege.be

Luxembourg

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LIÈGE université Sciences Appliquées

UEE Urban & Environmental Engineering

What’s the problem?

We are producing wastes (Construction and Demolition Waste –C&DW)

What is the challenge?

Transforming wastes ….


What is the challenge?

… into secondary resources

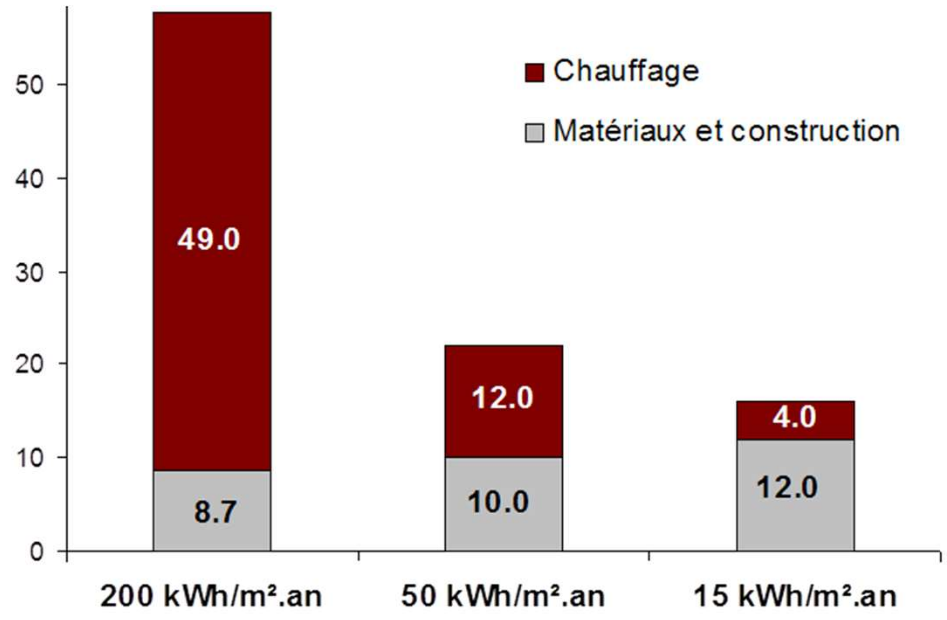

Global context

Development of materials and alternative techniques for buildings

Increasing insulation (energy) performances of housing

Increase of relative weight of building materials *vs.* environmental impact

Needs for developing new materials



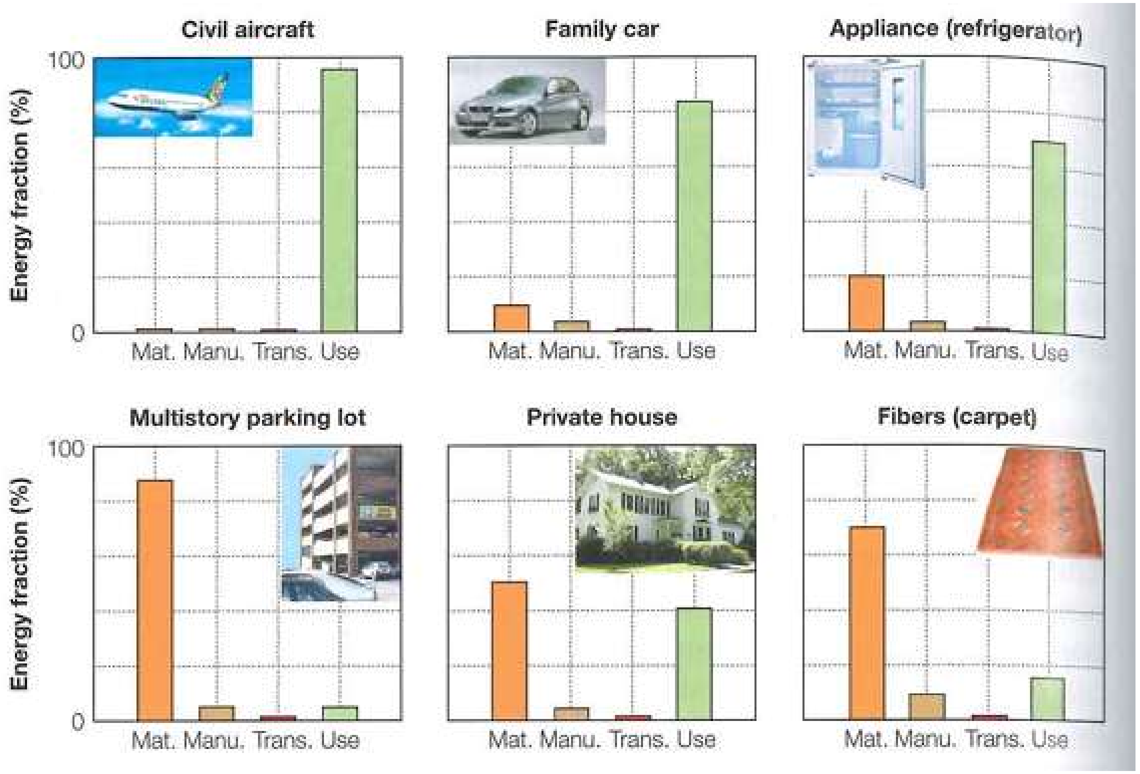
G. Escadeillas, Métamorphoses, Liège, 2011

Global context

Approximate value of energy consumed at each phase

➡ Importance of **material selection** for infrastructures and housing

3R theory: **R**educe, **R**euse and **R**ecycle

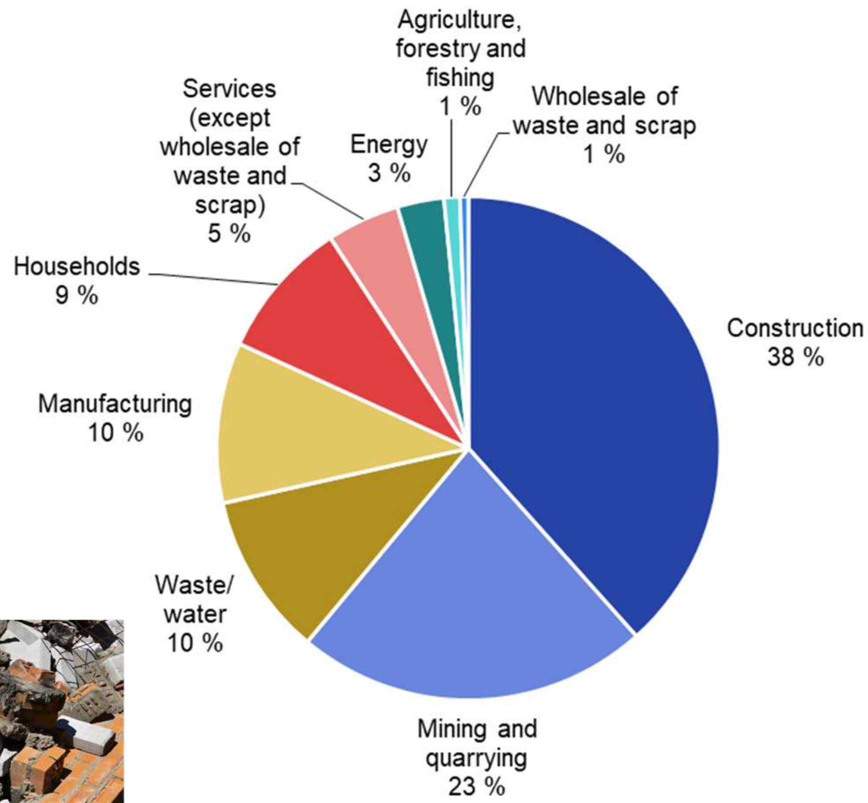


Ashby, 2022

Global context

Construction sector (/year)

- 850 millions tons of waste
- 1/3 world waste production
- 30% CO_2 total emissions
- 9 billion tons of concrete
  - 50% vol. aggregates
  - 25% vol. sand

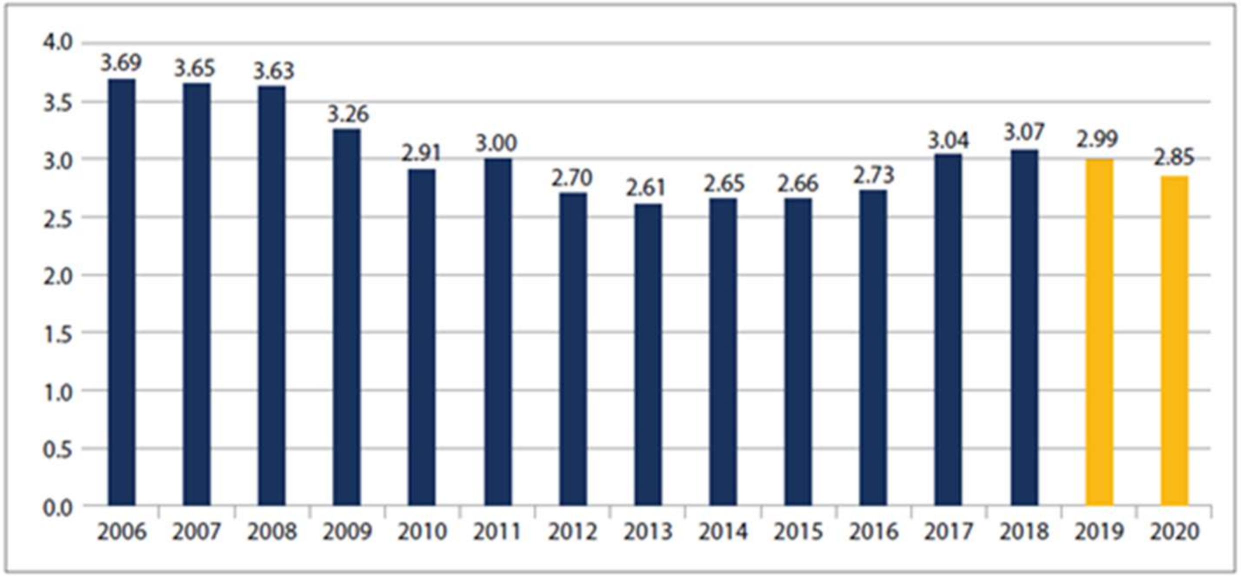


(Eurostat, 2022)

Global context

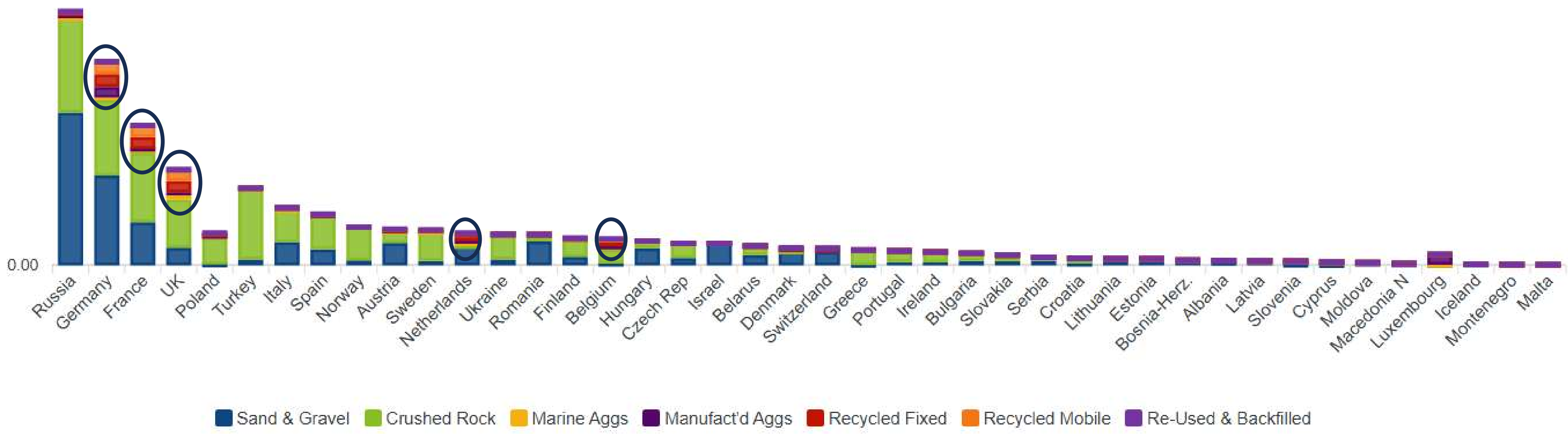
Market for aggregates/sand

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



Global context

2019 aggregates production in Europe in millions of tonnes by country and type



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

Global context

3 billion tons produced in EU27+UK+EFTA in 2019 (UEPG 2021)

Virgin Aggregates

46.9% crushed rock

39.7% sand & gravel

Recycled Aggregates

Construction & demolition wastes (CDW)

9.3% recycled (278 million tonnes)

Concrete

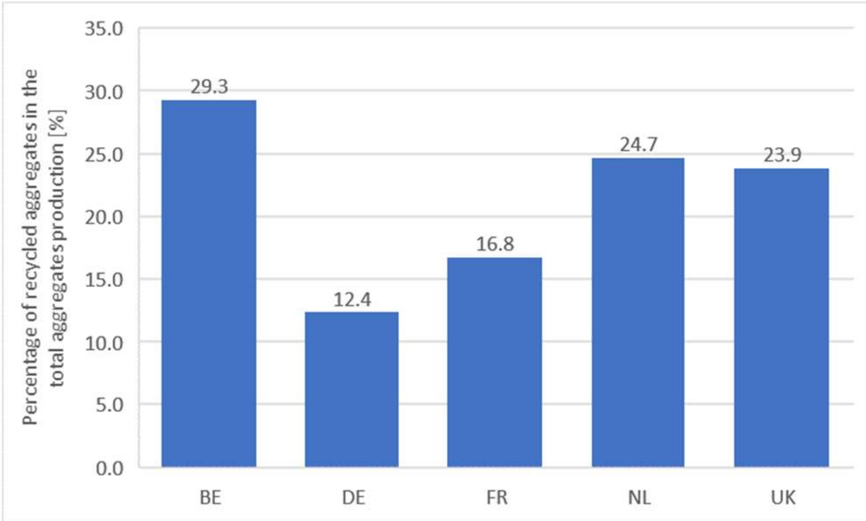
Mixed

Global context

NWE countries (BE, DE, FR, NL, UK) are responsible for:

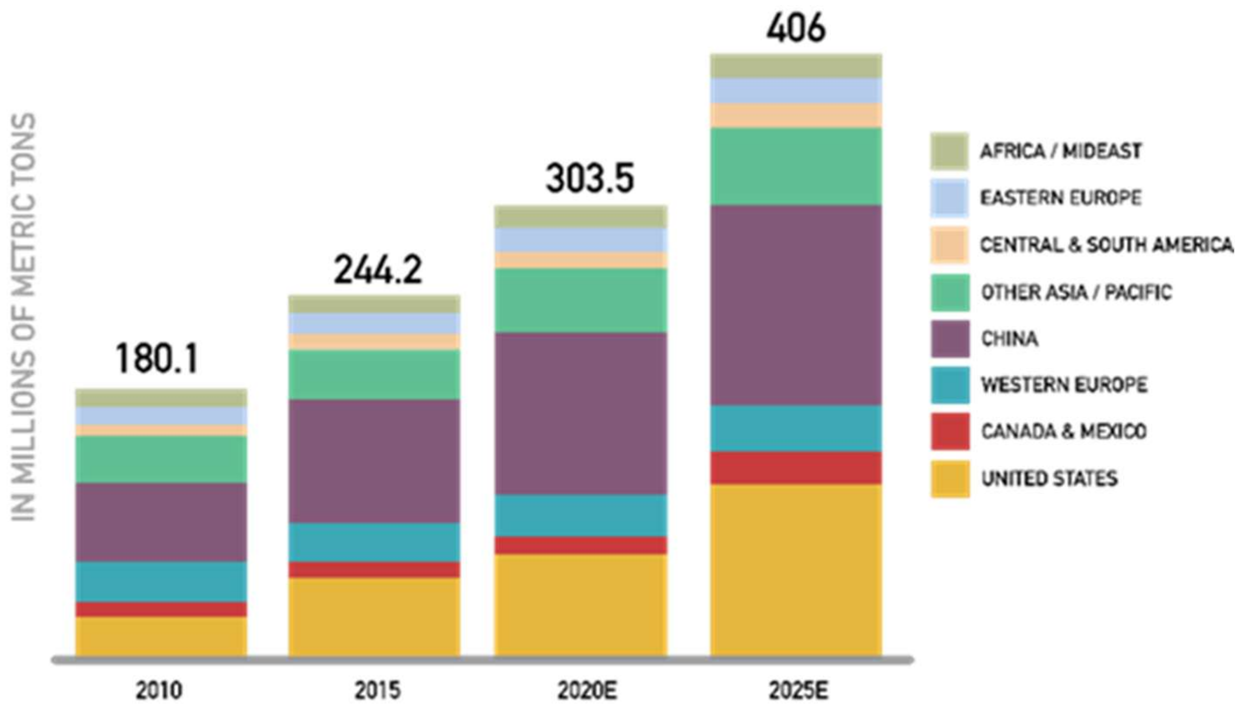
- 47% of the virgin aggregates production (1417 Mtons)
- 89% of the recycled aggregates production (248 Mtons)

Recycled aggregates/natural aggregates



Global context

In 2023, the leading exporters of sand were United States (563 M$), Australia (273 M$) and Netherlands (208 M$)



World sand demands in millions of metric tons (https://iveybusinessreview.ca/6580/lafargeholcim-the-plastic-solution-to-the-global-sand-wars/graphic-2-world-sand-demand/)

https://oec.world/en/profile/hs/sand

Global context

Extraction of sand (BGS, 2023)

Erosion (rivers, coasts, ...)

(Nedeljkovic et al., 2021)

Conditions for recycling: requirements, barriers, applications

Conditions for recycling

Possible applications

- **(Back)Filling** materials: low requirements, consumed in large quantities, for embankments but transportable over short distances due to costs;
- **Aggregates**: high quality requirements to lead to finished products of quality identical to that of traditional materials;
- **Binders**: very precise specifications, properties must remain constant over time;
- **Activators**: small quantities, which can cause problems of collection, storage, distribution and regularity.

Possible restrictions/barriers

Transport

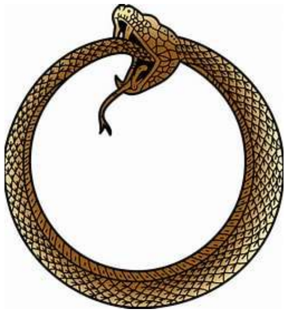
- Transport price = f(quantity, distance)
- Independent of the quality

Recycling interesting if

- Landfill far away (if landfilling is accepted)
- High dumping charge
- Expensive raw materials and difficult supply

Standards

- a material has not specification because it is new and not used
- a material is little used because it is uncovered by specifications



Possible restrictions/barriers

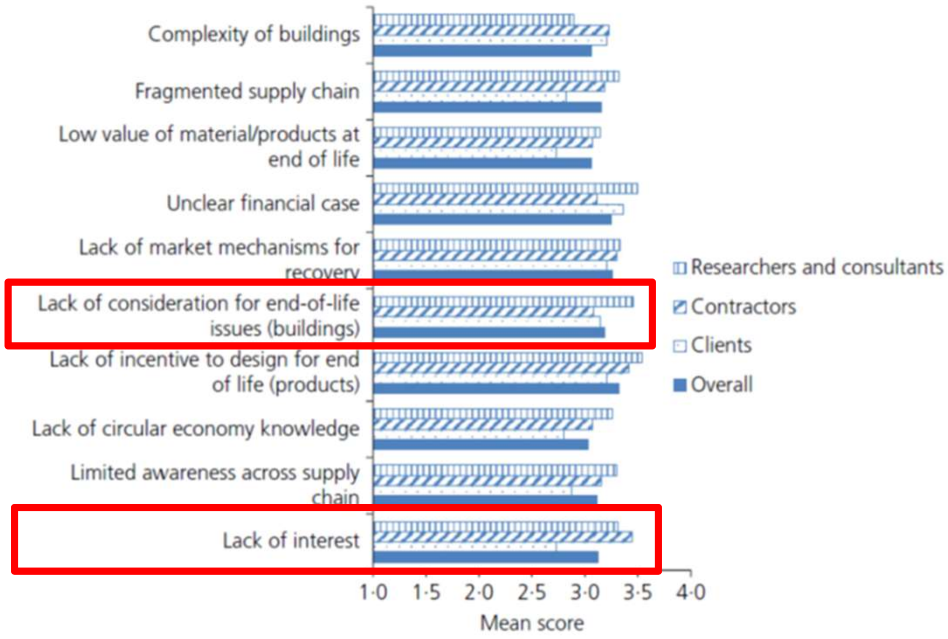
Possible applications

- Technique
  - Constant properties - Material quality
- Logistic et economic
  - Constant production
- Environmental impact
  - LCA

Use of recycled aggregates in concrete – opportunities for upscaling in Europe. J. N. Pacheco, J. de Brito, M. L. Tornaghi, 2023 (JRC Science for policy report (ISSN 1831-9424))

Possible restrictions/barriers

Most significant challenges for implementing circular economy in industrywide (survey-2017)



Tebbat Adams, K., Thorpe T., Osmani M., Thornback J., "Circular economy in construction: current awareness, challenges and enablers". Waste and resources management 170 (1) (2017) 15-24

Natural Aggregates *vs.* Recycled Aggregates

Recycled aggregate production

Reception of C&DW

First crushing

Magnetic separator

Second crushing

Manual separation

Washing + air separation

Sieving

Recycled aggregates sorted by granulometry

Recycled aggregate production

Construction and
Demolition Waste

FRCA (d < 4 mm)

CRCA (d > 4 mm)

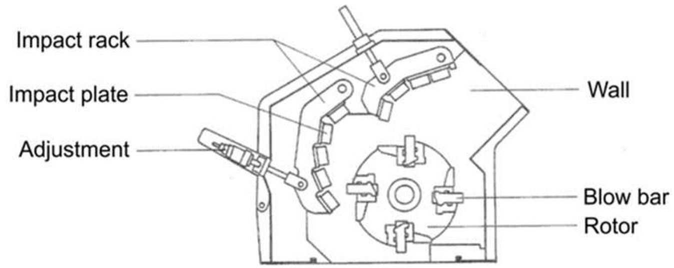
Sands
(0.125 mm < d < 4 mm)

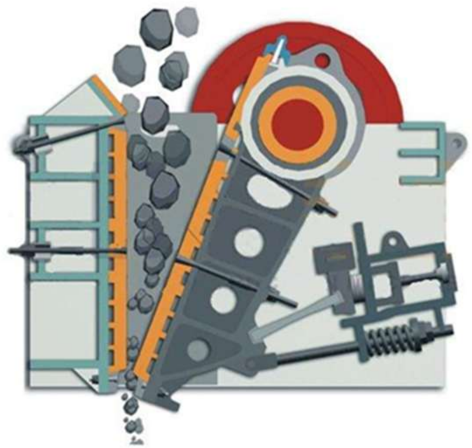
Fines
(0 mm < d < 0.125 mm)

Recycled aggregate production

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)

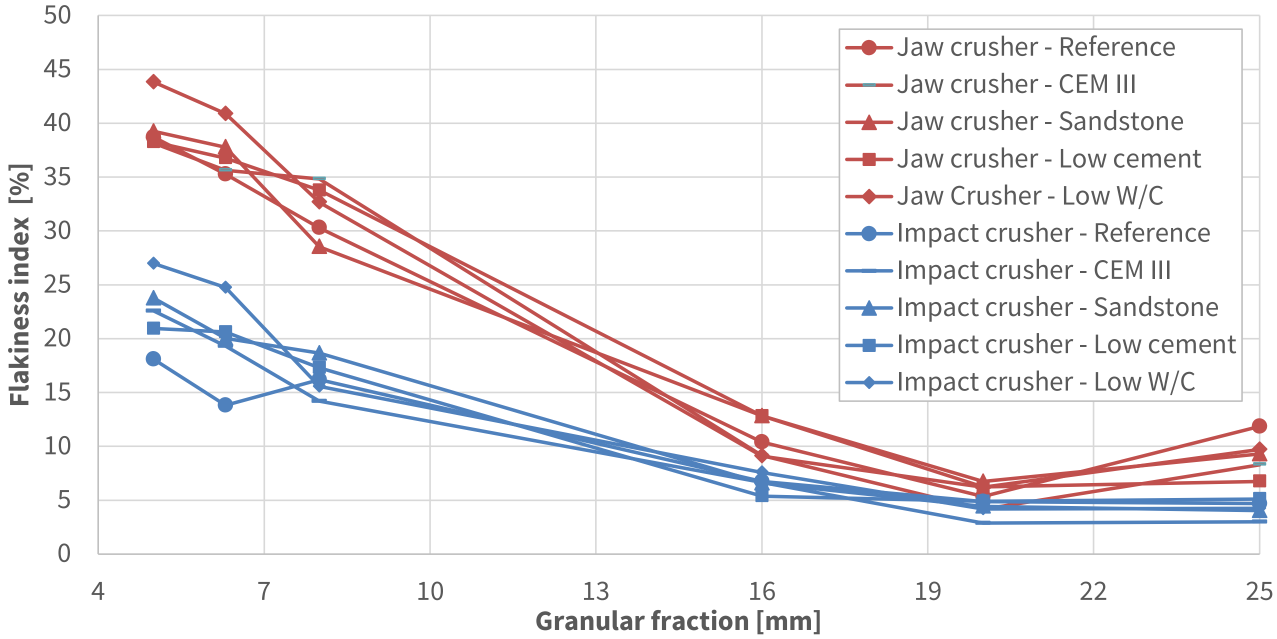
Recycled aggregate production

Experimental program

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

Materials processing: washing

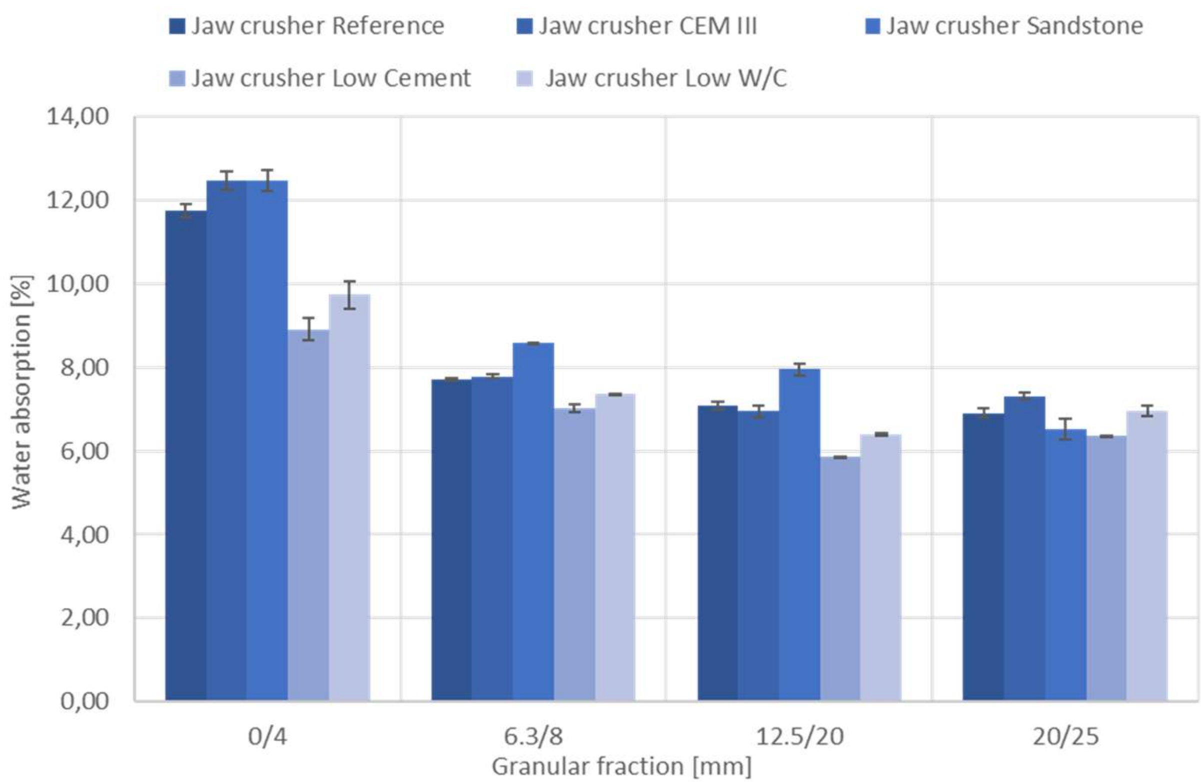
- The flakiness index decreases with increasing granular fraction
- The jaw crusher produces **flakier aggregates sand!**
- No influence of the concrete composition



Effects of crushing method on the properties of produced recycled concrete aggregates. J. Hubert, Z. Zhao, F. Michel, L. Courard. Buildings 2023, 13(9), 2217 (https://doi.org//10.3390/buildings13092217)

Materials processing: crushing

- **Porosity** is due to the presence of hardened cement paste and mortar
- **Water absorption** coefficient of aggregates increases as coarse particle size decreases



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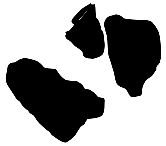
Material processing

Evaluation of cement paste content



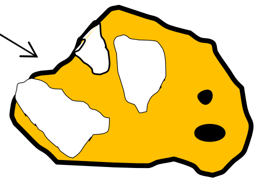
Originel aggregate

Quartz, Dolomite, Calcite
Not solubles in salicylic acid

Natural aggregate

Adherent cement paste

C_2S, C_3S, $Ca(OH)_2$, C-S-H, Ettringite
Soluble in salicylic acid



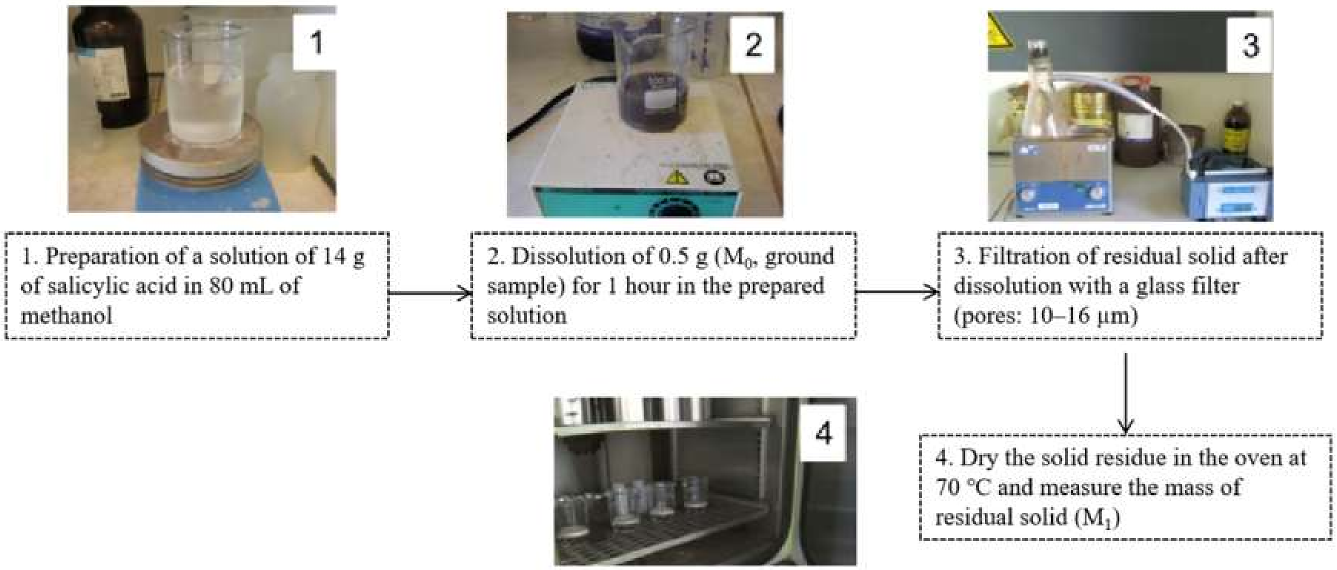
Cement paste

Not soluble in salicylic acid
C_4AF, AFm → CEM I
Calcite, GGBFS… → CEM II, III

Quantification of hardened cement paste content in fine recycled concrete aggregates by means of salicylic acid dissolution. Z. Zhao, J. Xiao, D. Damidot, S. Remond, D. Bulteel, L. Courard. Materials 2022, 15, 3384. (https://doi.org/10.3390/ma15093384)

Material processing

Evaluation of cement paste content



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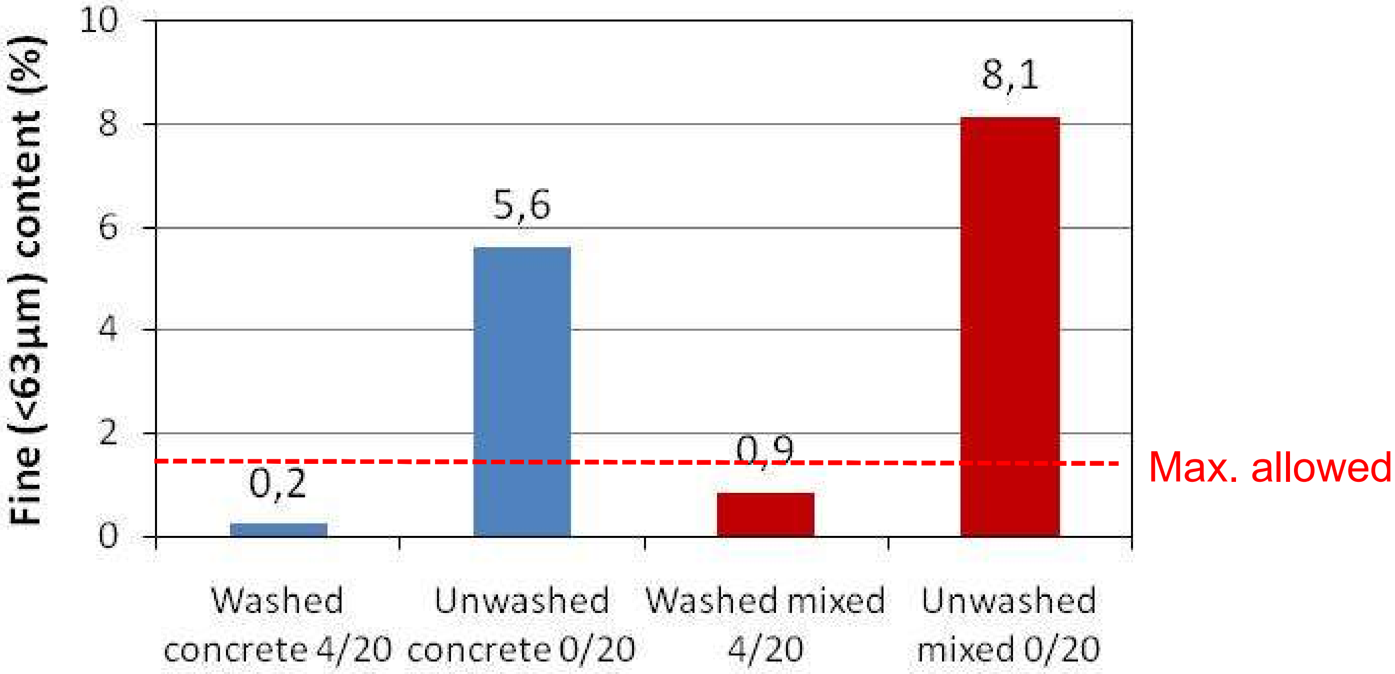
recycled mixed/concrete aggregates/sand

Materials processing: crushing

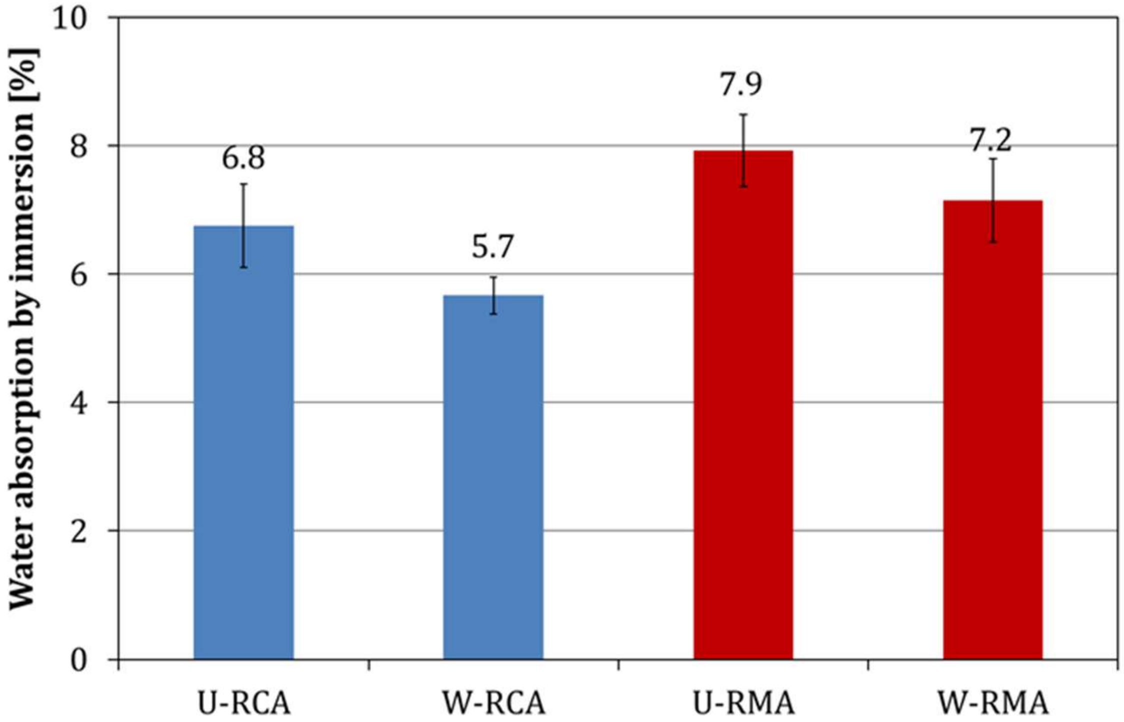
- Fine content (< 63µm) higher in mixed aggregates and **significantly reduced by washing**
- Fine fraction **higher in mixed aggregates**
- **Washed aggregates** respect **regulations** in all considered countries



Effects of crushing method on the properties of produced recycled concrete aggregates. J. Hubert, Z. Zhao, F. Michel, L. Courard. Buildings 2023, 13(9), 2217 (https://doi.org//10.3390/buildings13092217)

Materials processing: crushing

- Water absorption of the washed RCA significantly **decreases after washing**: from 6.5 to 5% between U-RCA and W-RCA, and from 7.9 to 7.2% between U-RMA and W-RMA.



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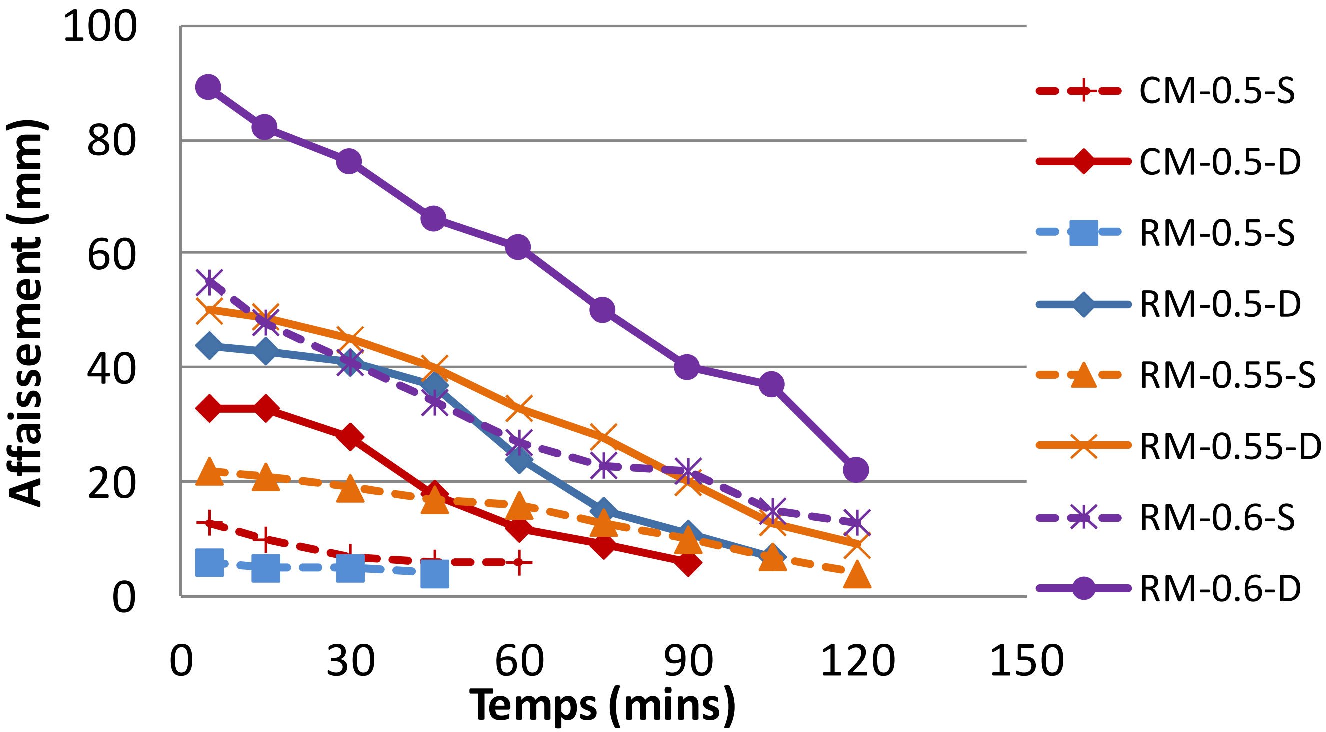
Recycled aggregate concrete production

Influence of the recycled sand saturation level
(S =Saturated and D = Dry)

Slump (Abrams cone) higher for RM-D *vs* RM-S

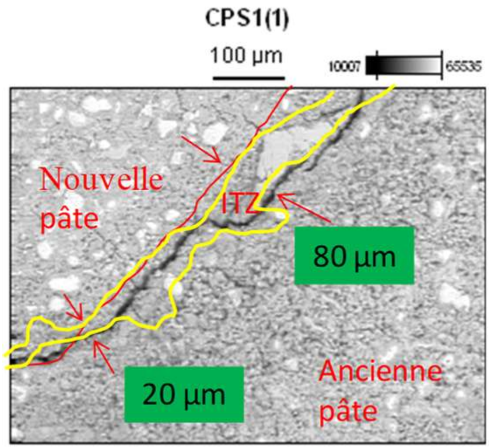
Slope higher for RM-D *vs* RM-S

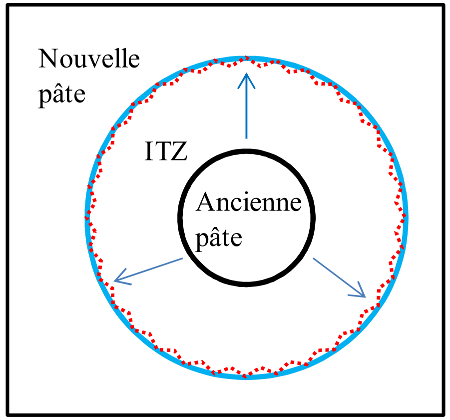


Recycled aggregate concrete production

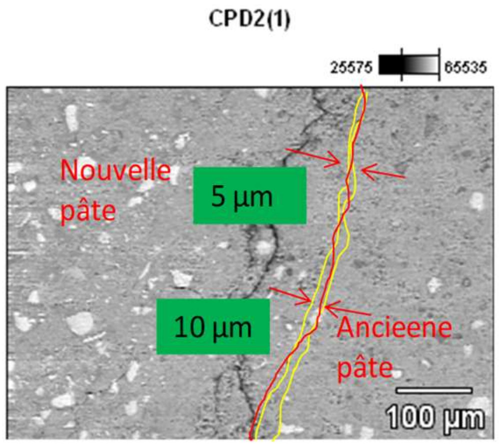
ITZ microstructure

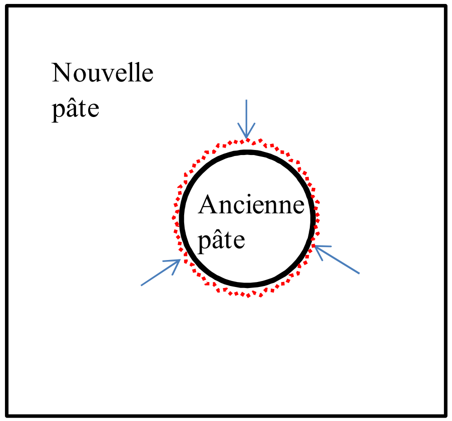
Saturated





Dry





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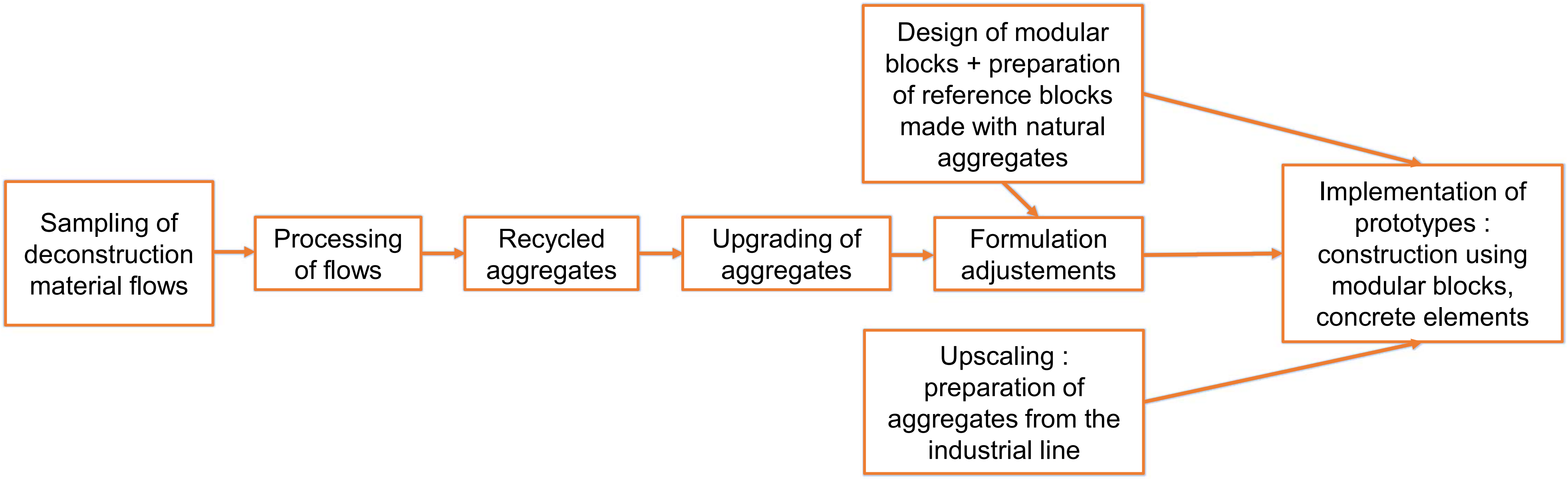
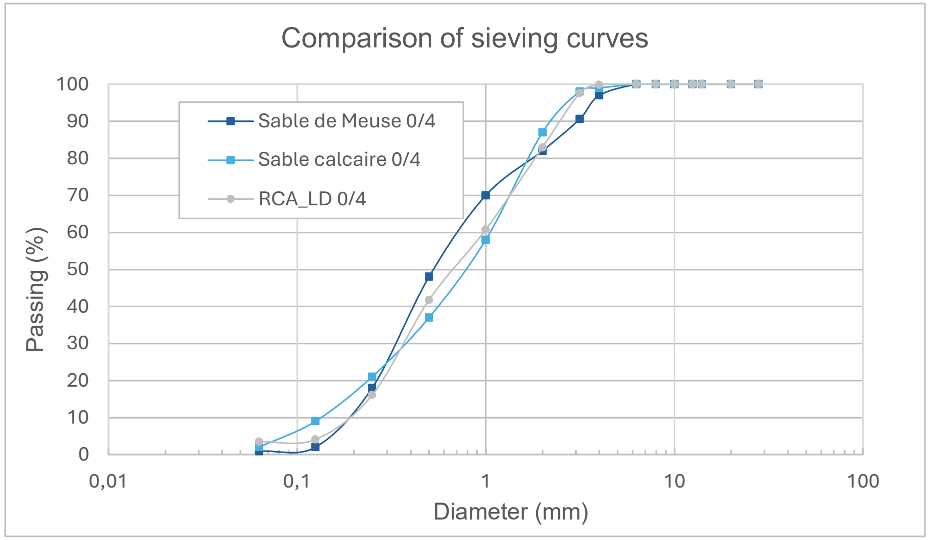
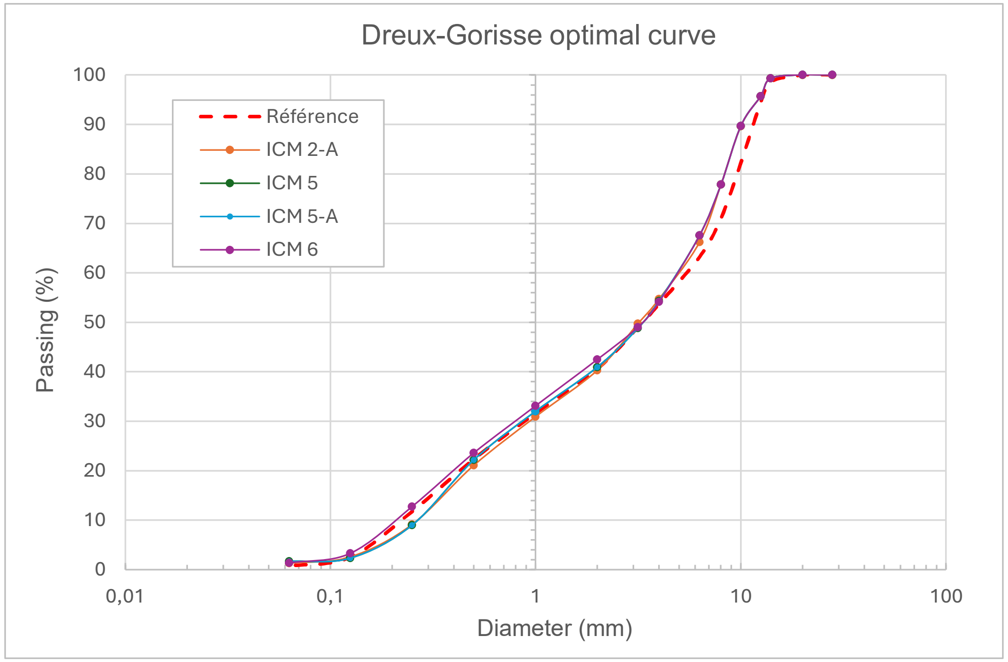
Circularity of Prefabricated Concrete

CIBER project: PREFAB concrete elements



Comparison between natural and recycled sands



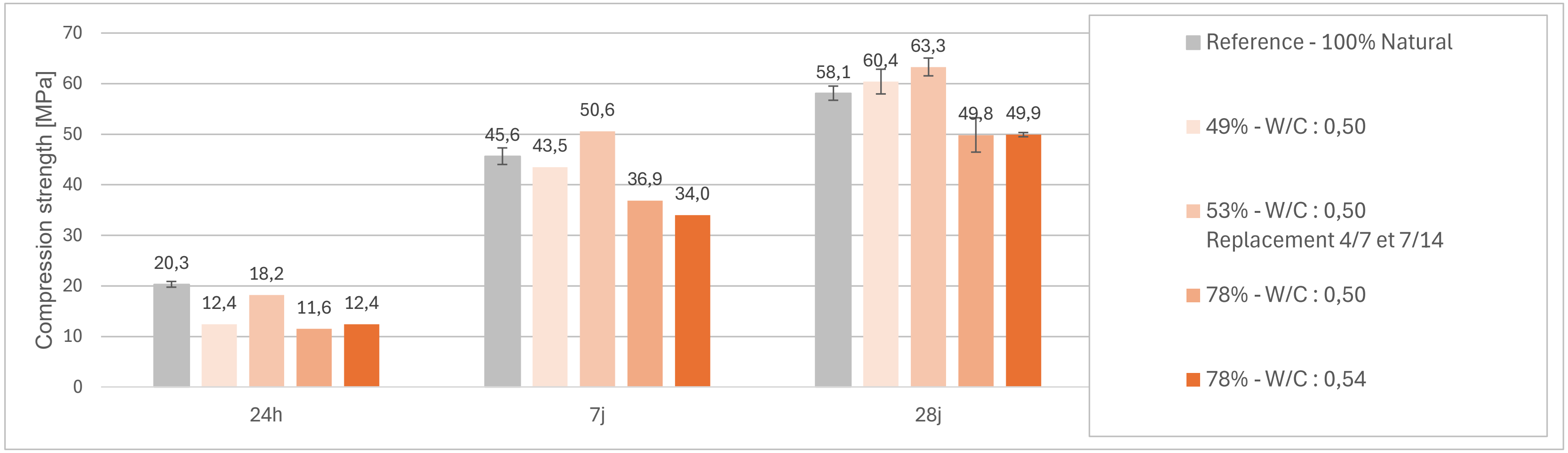


Aggregates	Fine content (%)	Water absorption (%)	Density (kg/m³)
Meuse sand 0/4	0.9	0.5	2750
Limestone sand 0/4	2	0.75	2700
RCA_LD 0/4	**3.44**	**5.88**	**2296**

Results for fresh and hardened concrete

Resistance : C30/37
Environment : EE3

Results			
Composition	**Density (kg/m³)**	**Slump (mm)**	**Air content (%)**
Reference	**2361**	**230**	**2,2**
ICM 2-A	2266	245	2,8
ICM 5	2190	220	3,6
ICM 5-A	2204	210	3,1
ICM 6	2313	230	1,6



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Recycling Concrete Aggregates from industrial production waste

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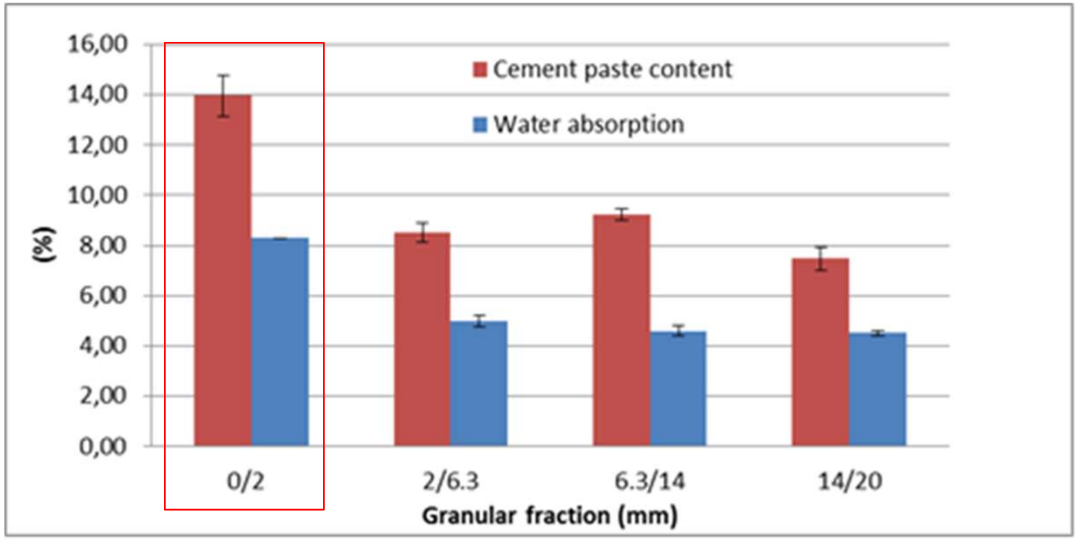
RCA manufactured in laboratory

- 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)

Water absorption Wa (EN 1097-6)

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



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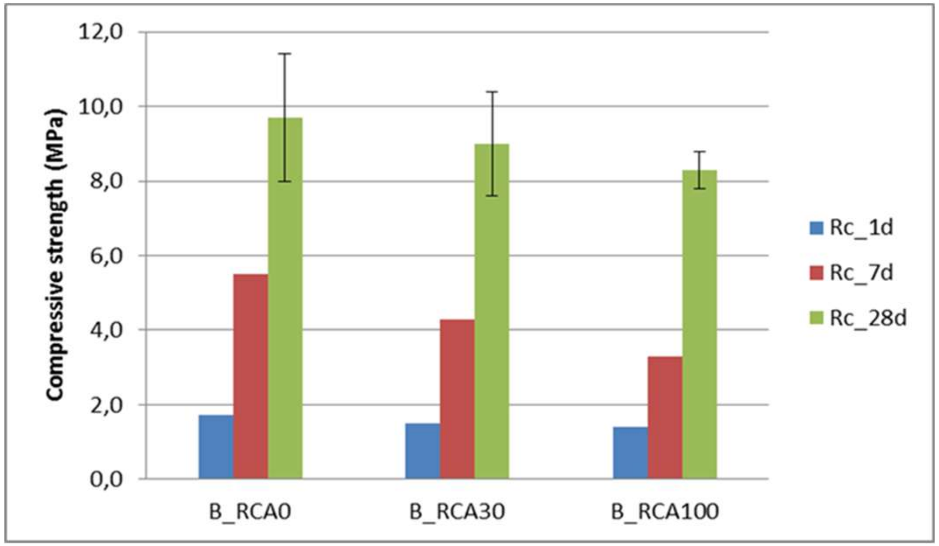
Compressive strength

- 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)



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3D Printing with Recycled Sand

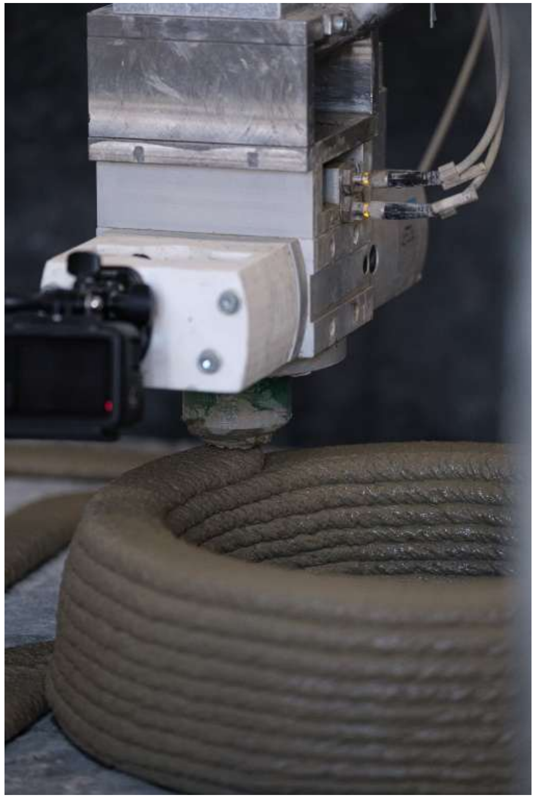
3D printing

(+) design opportunities

(−) environmental impact

→ alternative binder

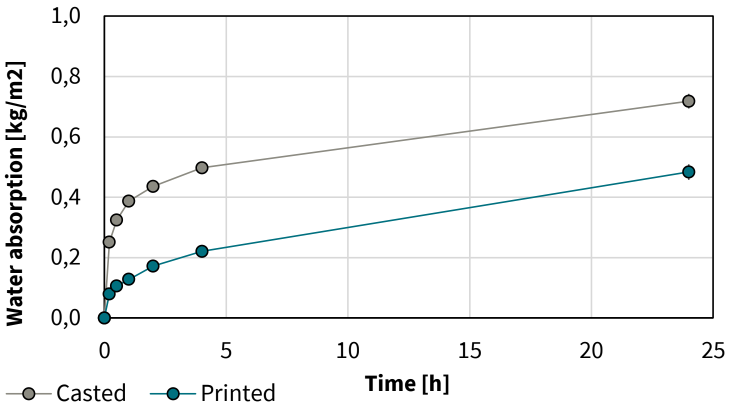
100% recycled sand



3D printing

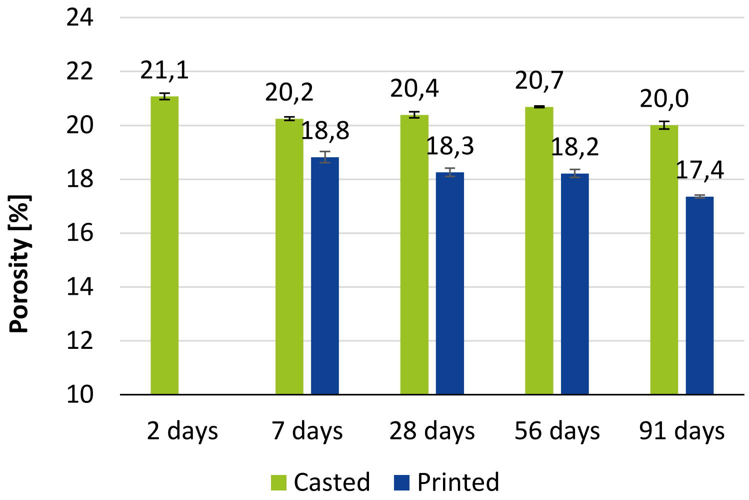
Capillary absorption tests NBN EN13057

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



Porosity

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



Use of recycled fine aggregates in high added value applications. J. Hubert, Y. Muy, L. Courard. International Conference on Advances in Engineering and Technology for Sustainable Development. Hanoi University of Civil Engineering, Hanoi, Vietnam, Nov 2-3, 2023 (https://hdl.handle.net/2268/308792)

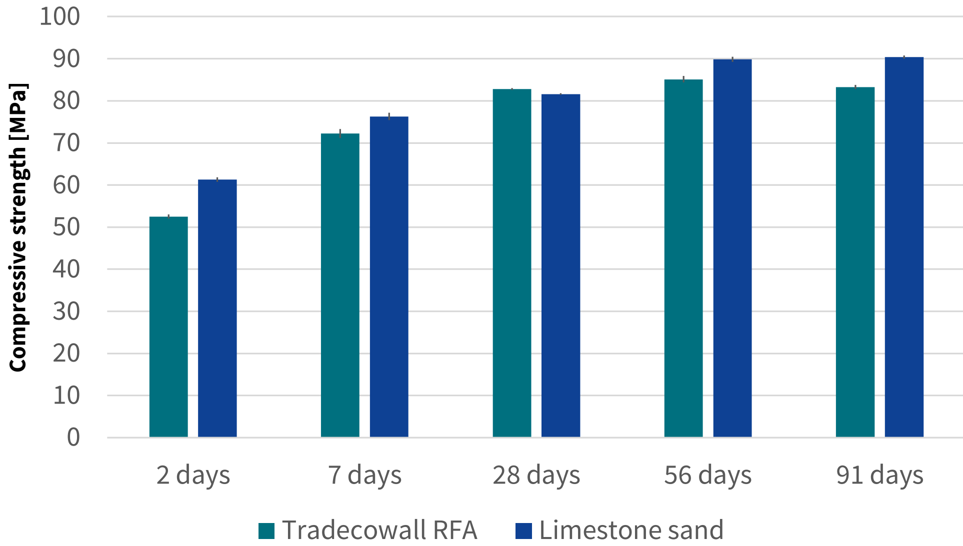
3D printing

Three points bending and compressive strength

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

Casted samples (4x4x16 cm prismatic samples)

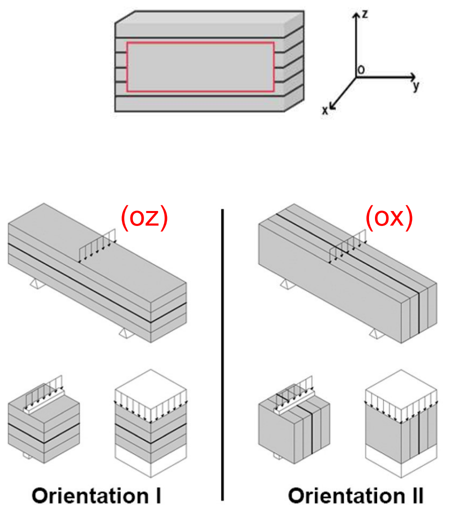
Printed samples (4x4x16 cm prismatic samples extracted from S shaped printed elements)

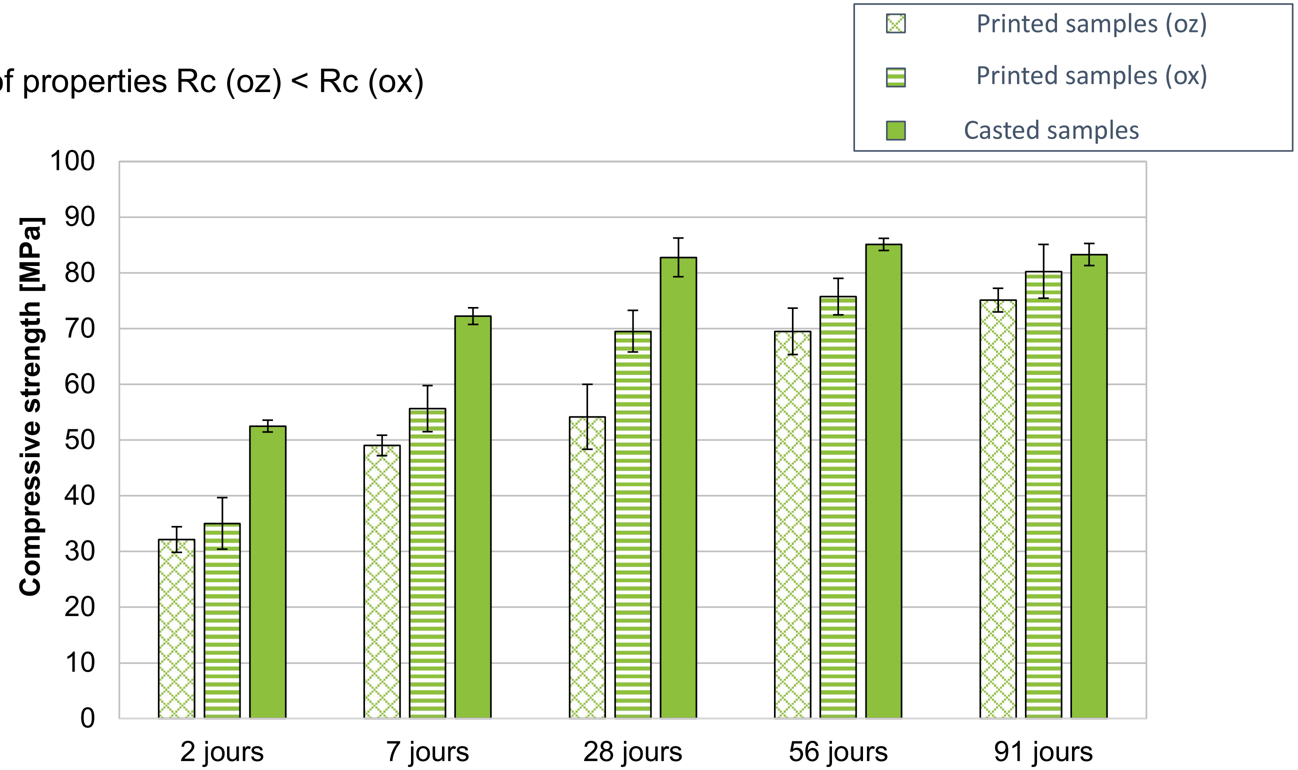


3D printing

Compressive strength

- Comparison printed *vs* casted : lower resistance
- Influence of the orientation of the layers: anisotropy of properties Rc (oz) < Rc (ox)





3D printing

Influence of curing conditions

- Casted samples with RFA - 4x4x16 cm
- Curing in « ambiant » conditions (60% H.R.) for simulation on site conditions
- Water curing (20°C and 95±5% relative humidity)

3D printing

Influence of curing conditions

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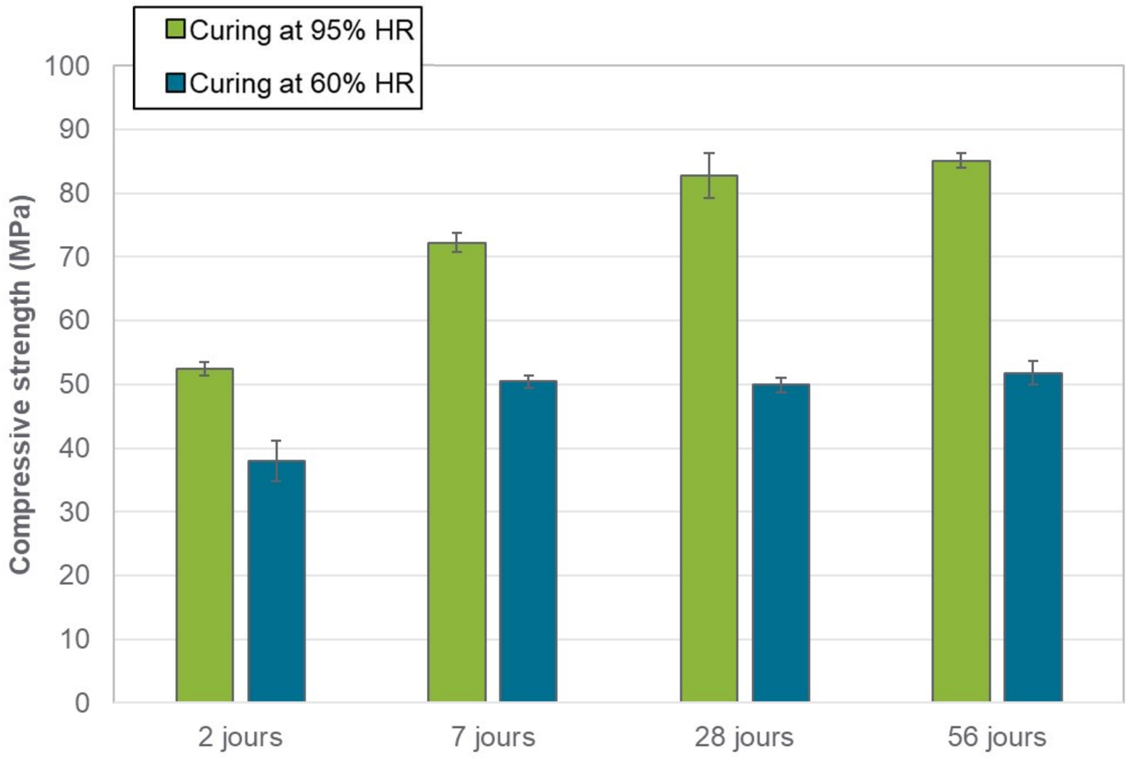
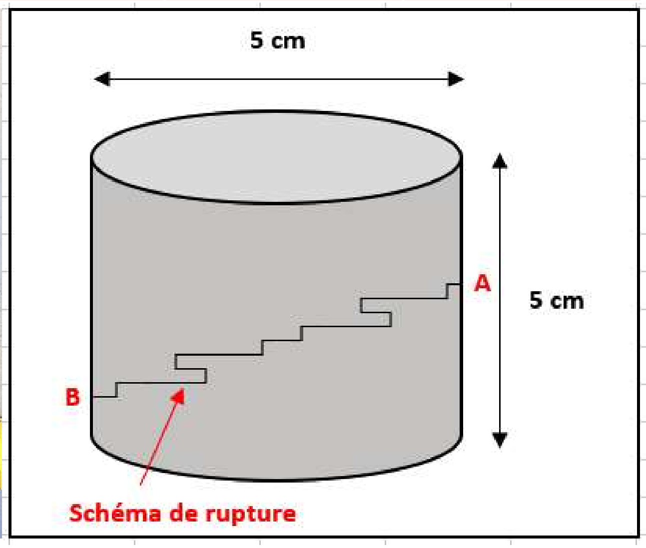


3D printing

Adhesion between layers via direct tensile strength (NBN B15-211)

	7 days	28 days	56 days	91 days
Moded samples	-	-	-	2,92 ± 0,06
Printed samples	2,03 ± 0,11	2,51 ± 0,20	2,69 ± 0,31	2,25 ± 0,13



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Interreg
North-West Europe
CIRMAP
European Regional Development Fund

3D printing: student contest

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Interreg
North-West Europe
CIRMAP

3D printing

Rammed Concrete with Recycled Fine Aggregates

Rammed earth (« pisé »)
with recycled fine aggregates

Peter Zumthor's Secular
Retreat (Walsh, 2018)

Rammed concrete for one-storey
private house (Astbury, 2019)

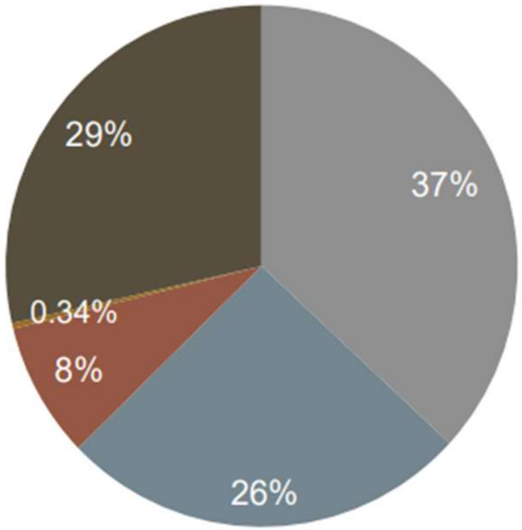
The chapel, by Thomas von Arx

Rammed earth (« pisé ») with recycled fine aggregates

- low maintenance, low-tech construction process and economical to build

Recycled fine aggregates

- Composition
- Granulometry 0/4



Percentage by component mass

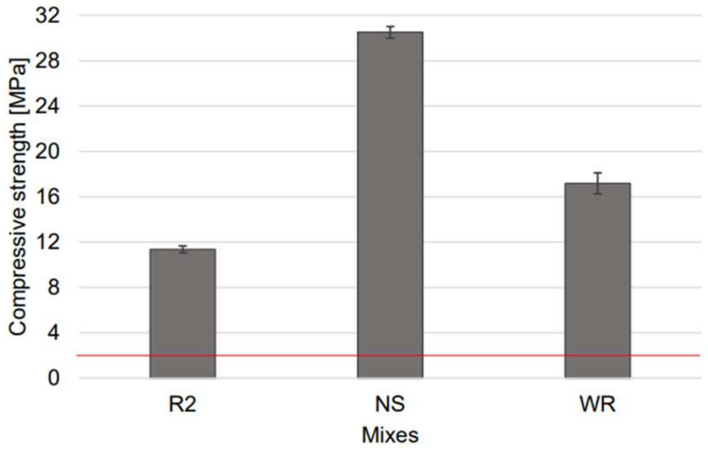
- Rc: concrete, mortar (37%)
- Ru: natural stone (26%)
- Rb: brick (8%)
- Rg: glass (0.34%)
- X: other; wood, rubber, plastic, … (29%)

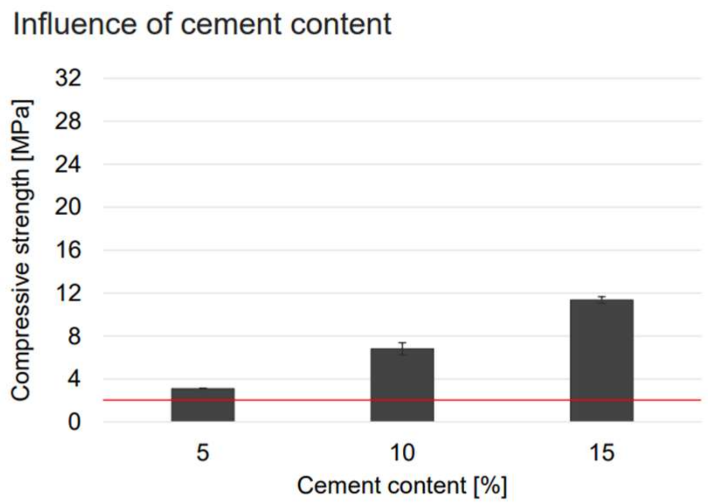
Rcu: 63%
XRg: 29.34%

Rammed Concrete with Recycled Concrete Aggregates : opportunities and performances. M. Long, S. Grigoletto, R. Libert, J. Troquay, L.Courard. Building Materials (under reviewing)

Recycled fine aggregates (Makara, 2023)

- Compressive strength *vs* mixes (15% cement + 10% water + 75% RFA 0/4) with different aggregates (NS = natural sand – R2 = Original RFAs – WR = Washed RFAs)





Rammed Concrete with Recycled Concrete Aggregates : opportunities and performances. M. Long, S. Grigoletto, R. Libert, J. Troquay, L.Courard. Building Materials (under reviewing)

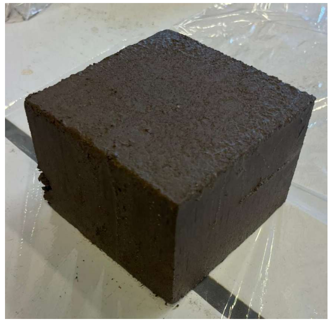
DUN^{3}ES FTJ project: composition & design


Fines


Sand

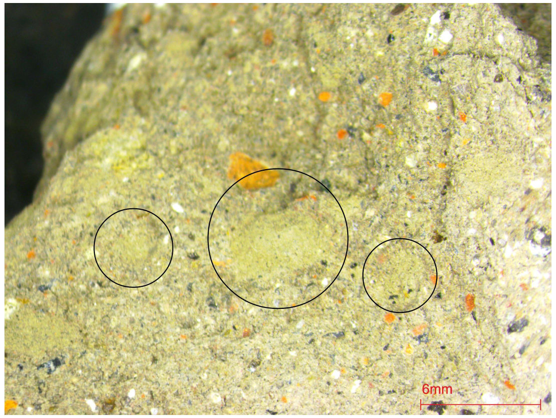

Cement


Water

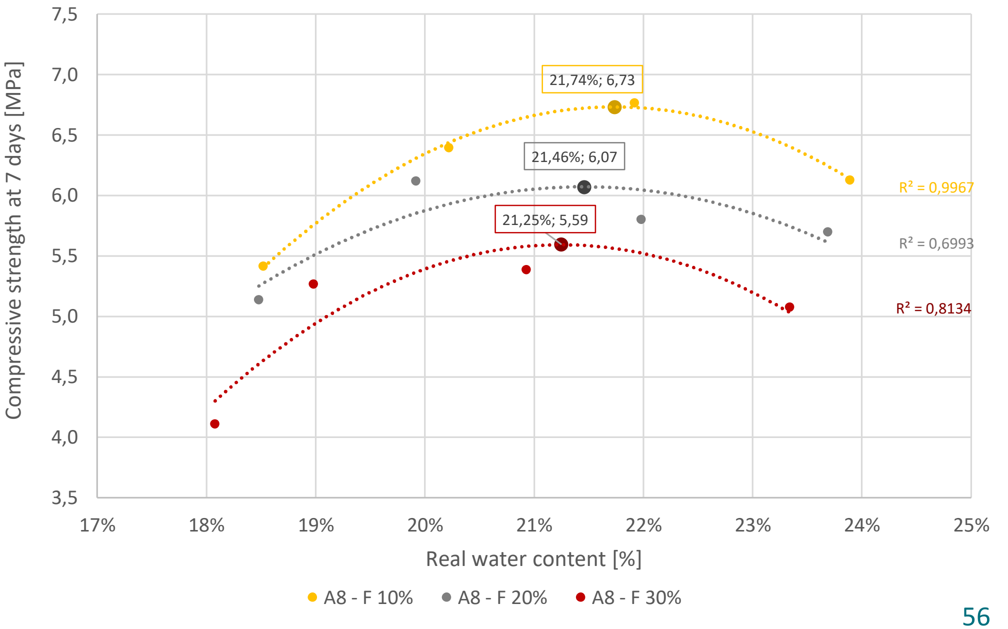


DUN³ES FTJ project: composition & design

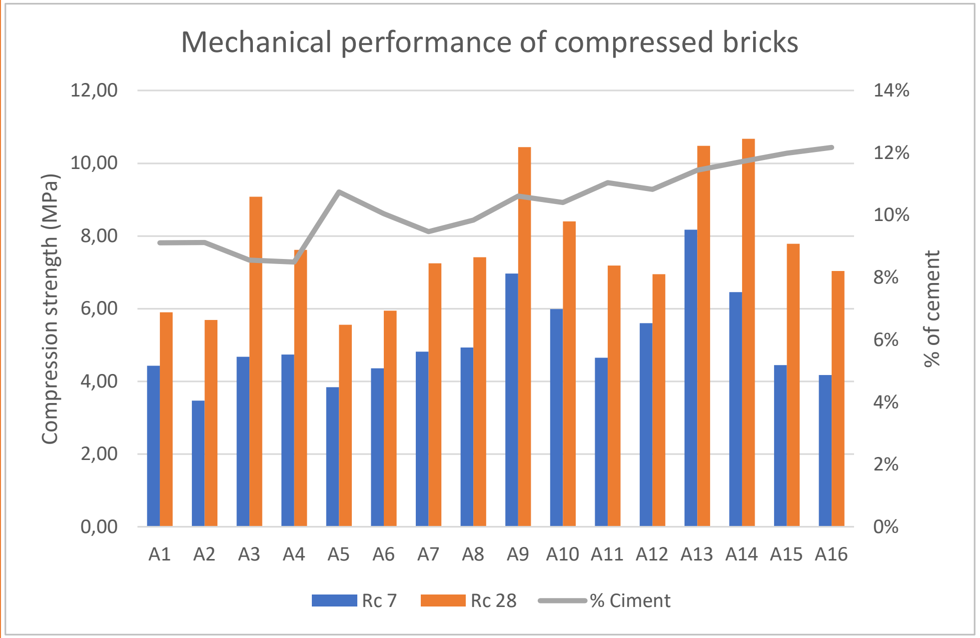
- Optimal water content at 7 days (cement content = 180 kg/m³) - 10%, 20% & 30% of RFA (F)
- Until 30% F, real compressive strength at 28 days increases with RFA content
- Optimum fines content not reached yet
- Variations between real and theoretical water contents
- After investigation, fines behave like aggregates



Fines content (%)	$\sigma_{7d,th}$ (MPa)	$\sigma_{7d,real}$ (MPa)	$\sigma_{28d,th}$ (MPa)	$\sigma_{28d,real}$ (MPa)
10%F	6.73	6.75	11.34	10.82
20%F	6.07	6.67	9.94	11.37
30%F	5.59	6.91	9.16	11.61

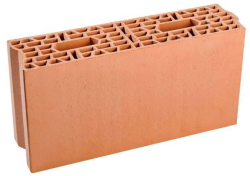


DUN³ES FTJ project: mechanical performances



Cement : CEM III/B 32.5 N

Concrete block : 15 MPa



Fire bricks : 10 MPa

Gypsum : 5-6 MPa

Compressed earth brick : 4 MPa

Stabilised Compressed Earth Brick : 6 MPa

Reuse of fines particles from concrete recycling (< 63 µm) for the manufacture of compressed bricks. R. Libert, J. Troquay, F. Michel, L. Courard. 2nd International Conference on Net-Zero Built Environment: Innovations in Materials, Structures, and Management, November 05 - 07, 2025 | Cape Town, South Africa.

Carbonated Sand from Incinerated Municipal Solid Waste

Carbonated IMSW

Grey colour material (200 kg/ton)

Variable granulometry

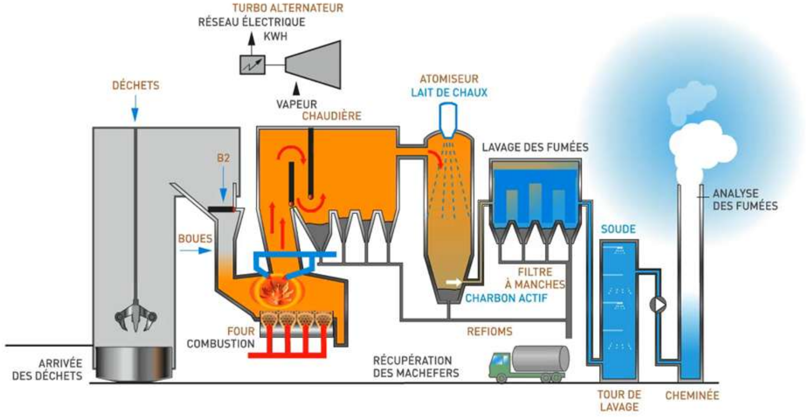
CaO content → 18 weeks maturation

Humidity content

- up to 20% by weight after extinction
- 10% by weight after draining

Density

- 1000 kg/m^3 when extracted
- 1100 to 1200 kg/m^3 after treatment



ReMEX GmE

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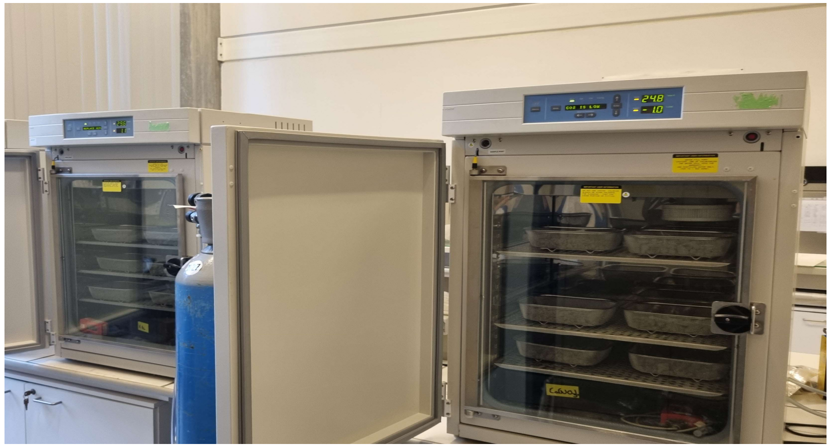
REMIND Wallonia

CARBOC

Carbonated IMSW

Parameters

- Particle sizes: 0/2 & 0/20 mm
- Exposure period: 1, 2, 4, 8, 24, 48 & 168 h
- Moisture content (WC): 2, 20 & 45%



Carbonation

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

$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$

Carbonation conditions:

- Temperature: 30 ±1 °C
- RH: 60 ±3%
- CO_2 concentration: 12 % (vol.)

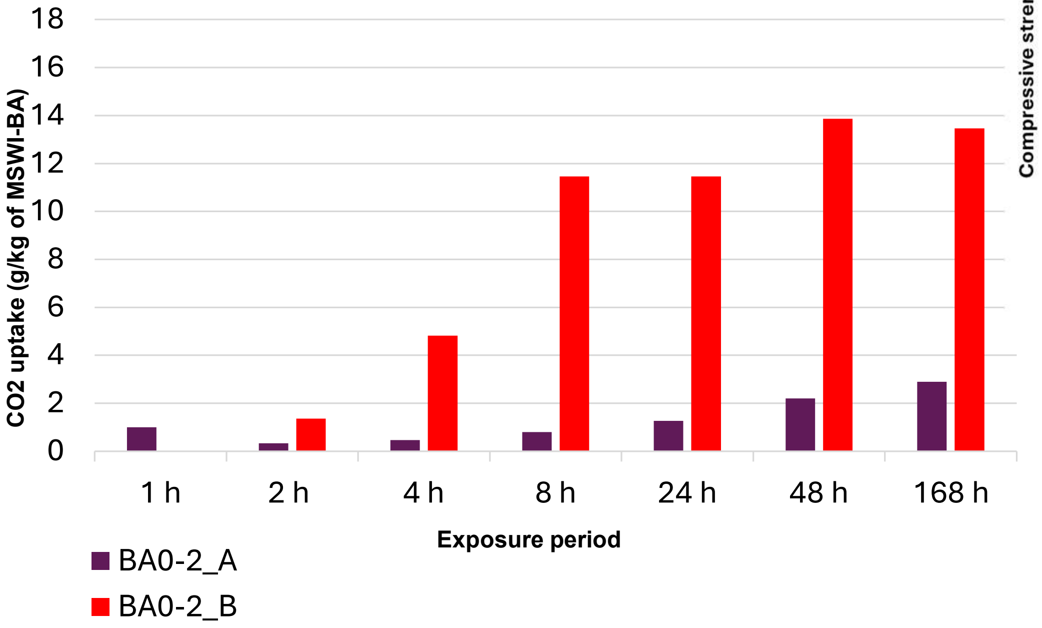
Accelerated carbonation of municipal solid waste incineration bottom ash for alternative aggregate production. I.E. Kanjo, J. Hubert, J.T. Tchuindjang, S. Marquis, Ph. Descamps, L. Dupont, L. Courard. 10th International Conference on CONcrete under SEvere Conditions – Environment and Loading 2024, Chennai, India

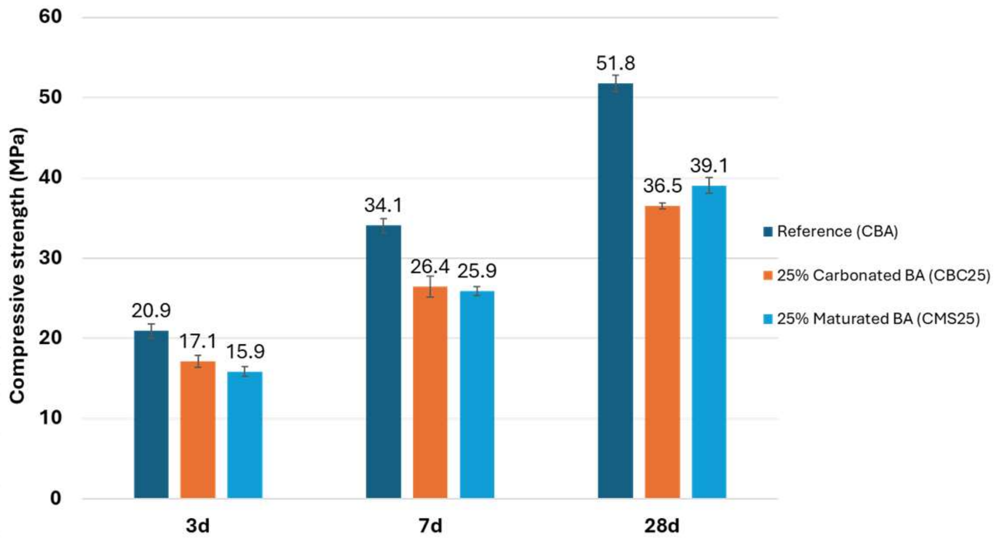
REMIND Wallonia

CARBOC

Carbonated IMSW

- CO_2 uptake - 0/2 particle size





Efficiency of processes for the carbonation of municipal solid wastes bottom ash. I. J. Kando, L. Courard, J. Hubert. 1st International Conference on Research and Application of Carbonation Technology for Wastes and Concrete (ReACT2024), Hong-Kong, 11-13 Dec 2024

CARBOC

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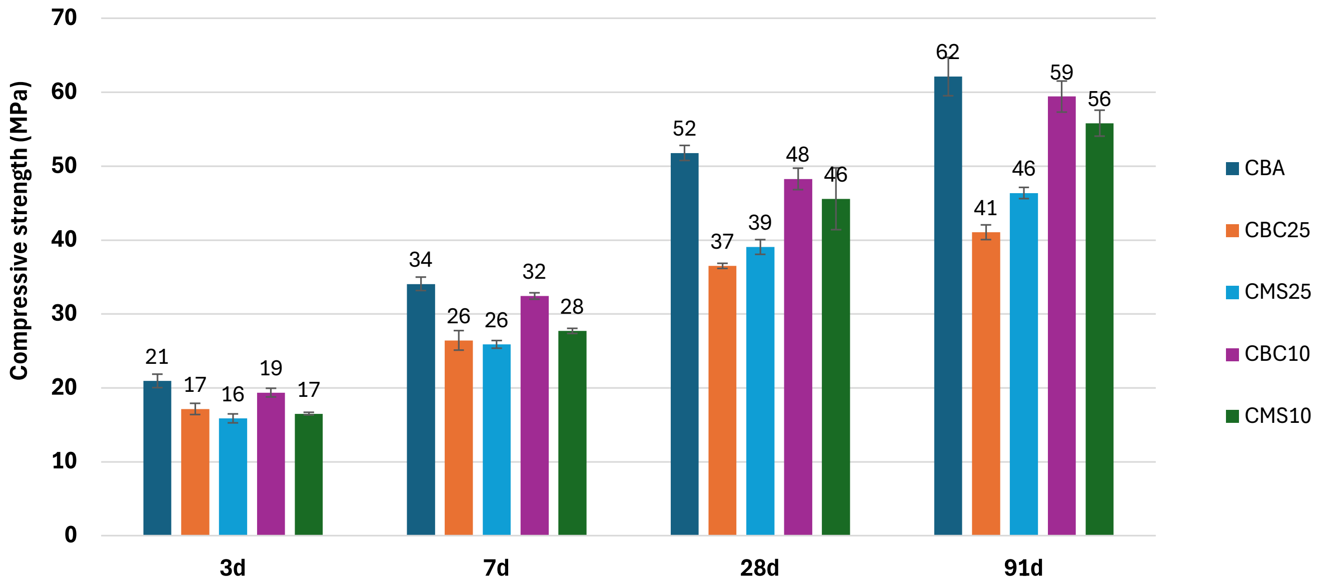
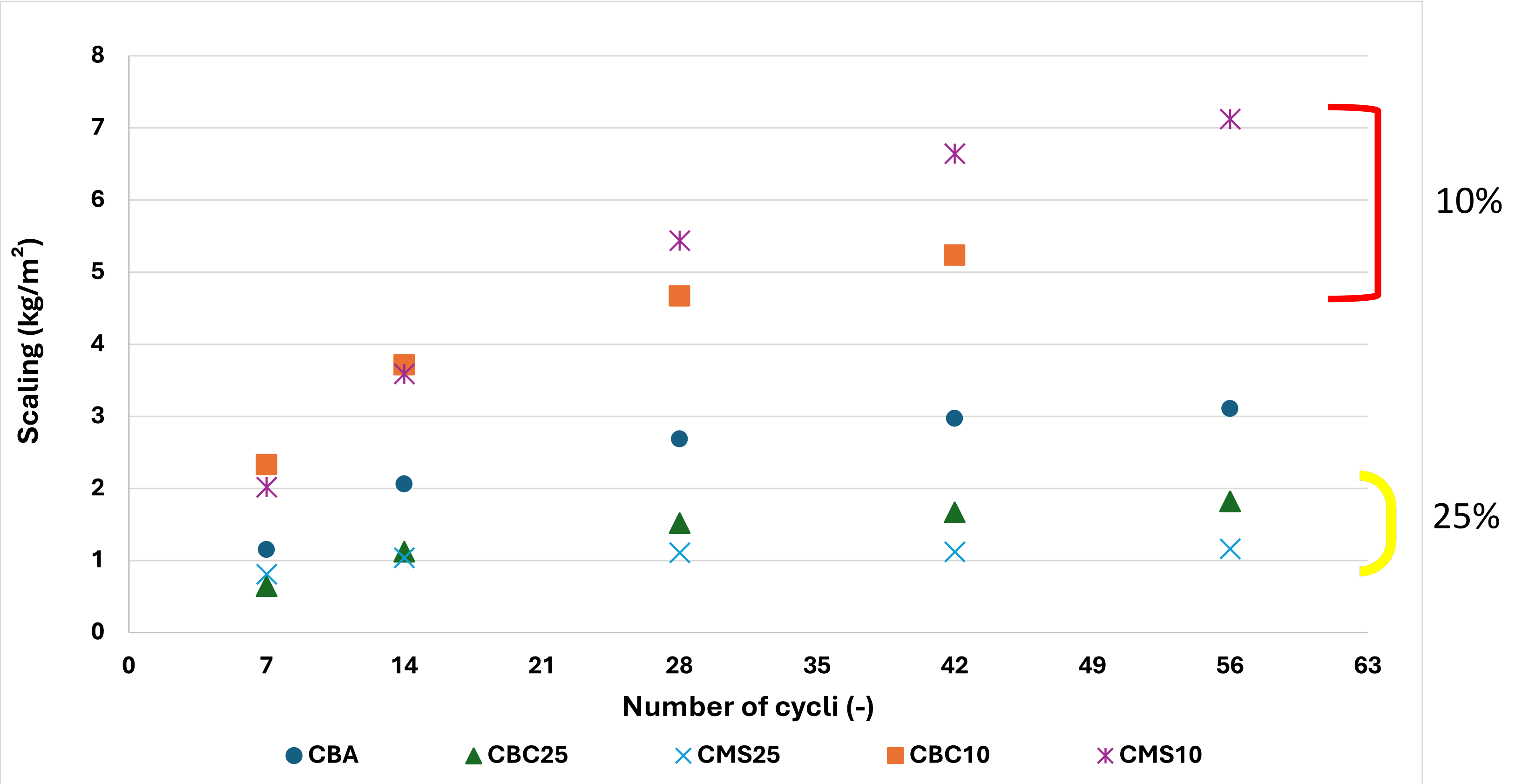
Carbonated IMSW

- Compressive strength – 10 vs 25% IMSW – carbonated vs natural maturation



Carbonated IMSW

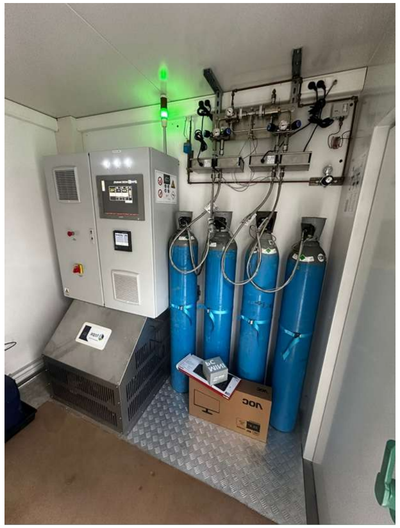
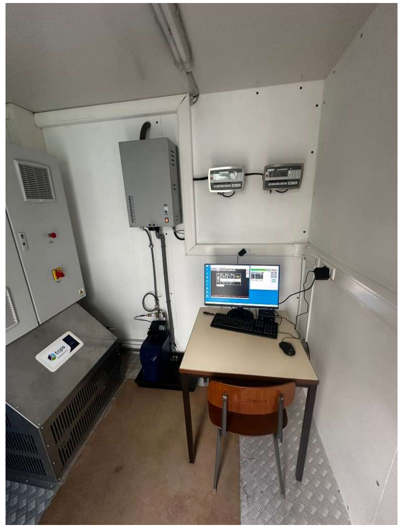
- Freeze-thaw cycles – 10 vs 25% IMSW – carbonated vs natural maturation



CarboNEX

- Experimental room for accelerated carbonation (temperature, humidity and CO_2 concentration)



PNRR Wallonia

Wallonie

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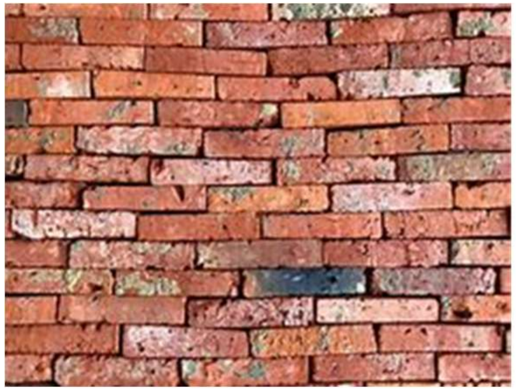
Recycled Fine Aggregates from Bricks

Brick fines

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.

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Interreg France-Wallonie-Vlaanderen
UNION EUROPÉENNE EUROPESE UNIE
VALDEM

Brick fines

- 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

- 3 types of grading
  - B1 : d_{50} = 3.3 µm (with supplementary cyclogrinding)
  - B2 : d_{50} = 20 µm
  - B3 : d_{50} = 190 µm

Substitution of limestone filler by waste brick powder in self-compacting mortar: properties and durability. Z. Zhao, A. Grellier, M.E.K. Bouarroudj, F. Michel, D. Bulteel, L. Courard. Journal of Building Engineering 43, 102898 (2021) (https://doi.org/10.1016/j.jobe.2021.102898) (http://hdl.handle.net/2268/261528)

Brick fines: alkali-activated materials

Brick fine particles
B2

GGBFS

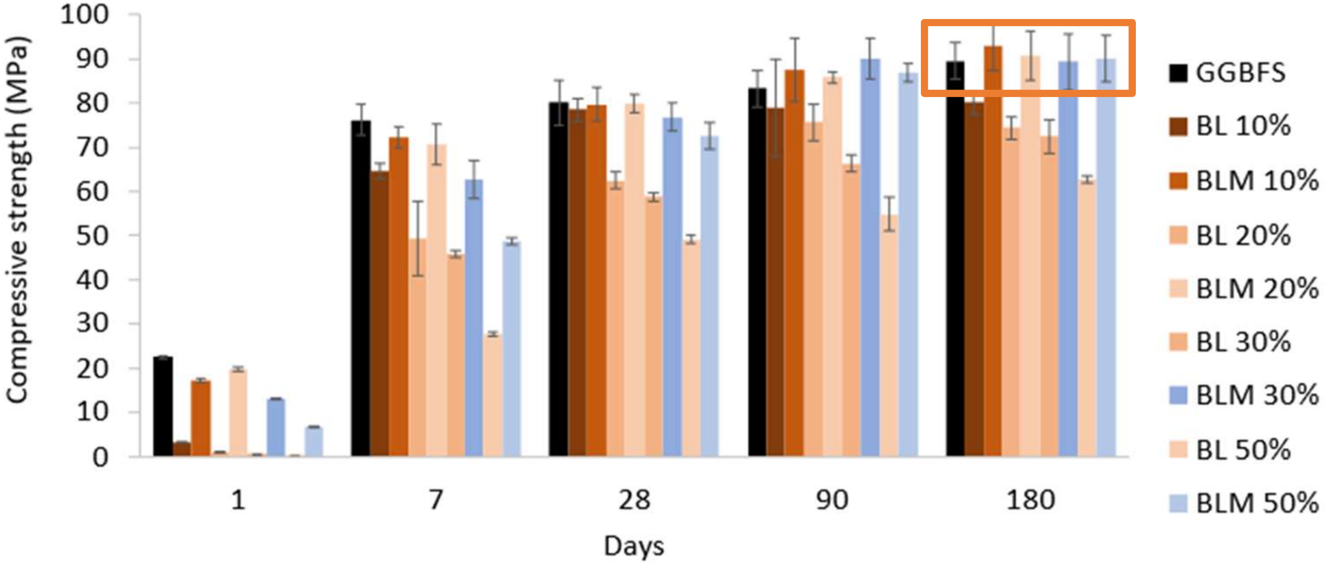
Alcali-Activating Solution

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

Bricks fines: mechanical strength



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

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Conclusions

Natural resources *vs.* recycled resources for sand

Good opportunities (quantities)

Preparation is important

Grading and washing

Specific treatment (fineness, shape, grading)

AGGREGATES and SAND FROM C&DW

are suitable for several applications