

Towards circular self-compacting repair mortars

DoE-based optimisation of a reference formulation using natural materials

S. Lanckohr¹, L. Courard¹

¹Urban and Environmental Engineering, University of Liège, Belgium



Context: the environmental footprint of concrete



50 Gt/yr

Natural resources

High demand for natural aggregates and sand in concrete production

UNEP (2022)



38 %

Waste

Large volumes of concrete waste from construction and demolition

Eurostat (2022)



25 %

CO₂ emissions

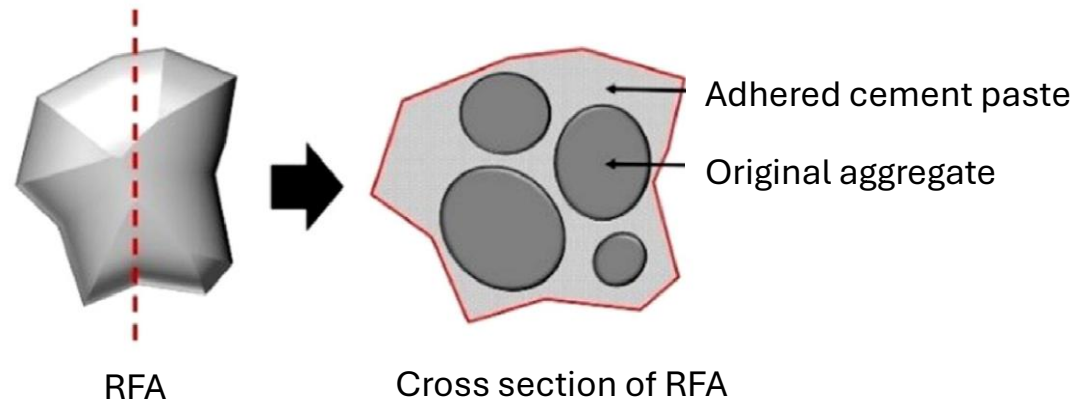
Concrete production is a major contributor to the sector's footprint

Kajaste & Hurme (2016)



Circular pathway: turn concrete waste into recycled aggregates and use them in repair materials for ageing infrastructure

The challenge of recycled fine fractions



Modified from Ng & Engelsen (2018)

Adhered cement paste

Higher porosity & absorption

Higher water demand

Sánchez de Juan & Alaejos Gutiérrez (2009)

Conflict: water needed for workability vs. low water/binder ratio needed for strength and durability
→ delicate mix design for high-performance self-compacting repair mortars

Objective and two-phase approach

Develop high-performance self-compacting repair mortars incorporating recycled sands and fines, using a Design of Experiments (DoE) methodology



PHASE 1 - ONGOING

- Characterisation of materials: natural sand, cements, limestone filler, recycled sand and fines
- DoE 1 on natural materials only, 3 cement types

→ 3 optimised reference mixes

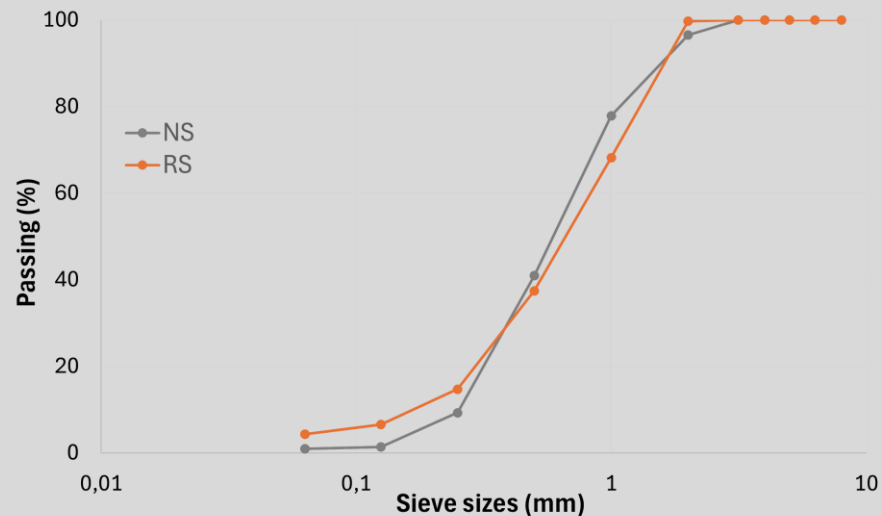


PHASE 2 - UPCOMING

- DoE 2 based on the reference mixes
- Full or partial substitution of natural materials by recycled fractions

Materials characterisation

Sand 0/2 mm: natural (NS) vs. recycled (RS)



	Natural	Recycled
Fines content (%)	0.82	4.96
Oven-dry density (kg/m ³)	2612	2105
Water absorption (%)	0.6	9.7
Cement paste content (%)	-	12.3

Powders: cements, filler, recycled fines

	Composition	Absolute density (kg/m ³)	Blaine (cm ² /g)
CEM I	97 % clinker	3079	4776
CEM II/B-M (Q-LL)	68 % clinker, 21 % quartz, 11 % limestone	2912	6426
CEM III/A	59 % clinker, 38 % slag	3054	6482
Limestone filler	97 % CaCO ₃	2684	5164
Recycled fines	ground recycled sand	2582	7089

Composition: manufacturer data (Heidelberg Materials, Carmeuse)

Design of Experiments strategy

Factors

Mixture (mass fractions, sum=1)

Sand	0.60 – 0.75
Cement	0.20 – 0.30
Limestone filler	0.05 – 0.15

Process (continuous)

Superplasticiser (% by binder mass)	0.2 – 2.5
Water (2 linear constraints)	W/B 0.30 – 0.45

Categorical

Cement type	CEM I / II / III
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Binder = cement + filler

Mixing temperature recorded (21.1 – 25.1 °C)



Mixture-process design

JMP custom design
I-optimal criterion

40
mixes

Model selection: forward
selection (AICc)

Responses

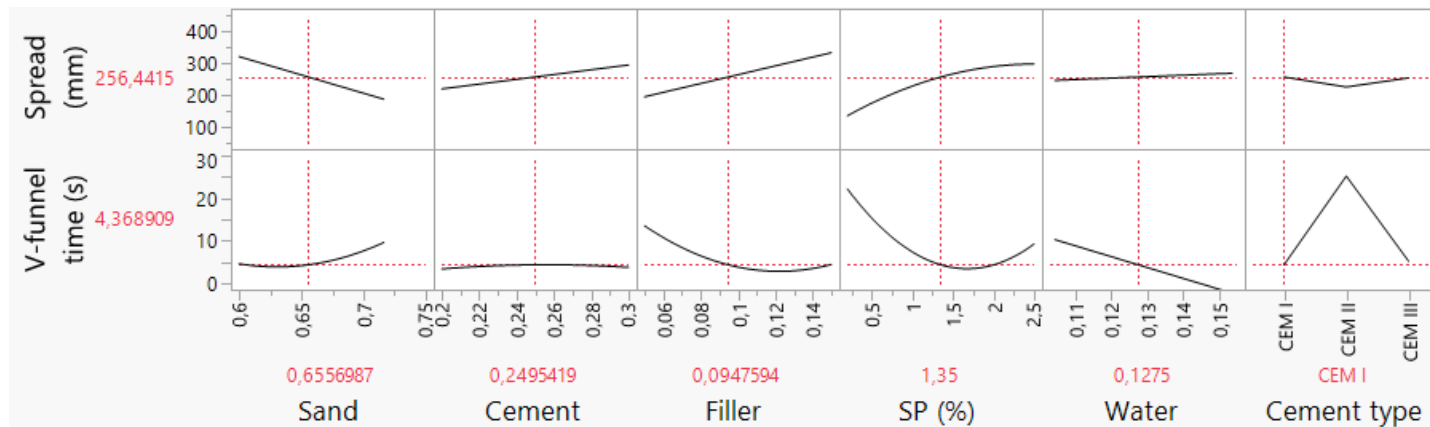
Quantitative

Spread (mini cone)
Flow time (mini V-funnel)
Flexural strength (28 d)
Compressive strength (28 d)

Qualitative (visual)

Bleeding
Segregation

Results: fresh-state properties



JMP profiler

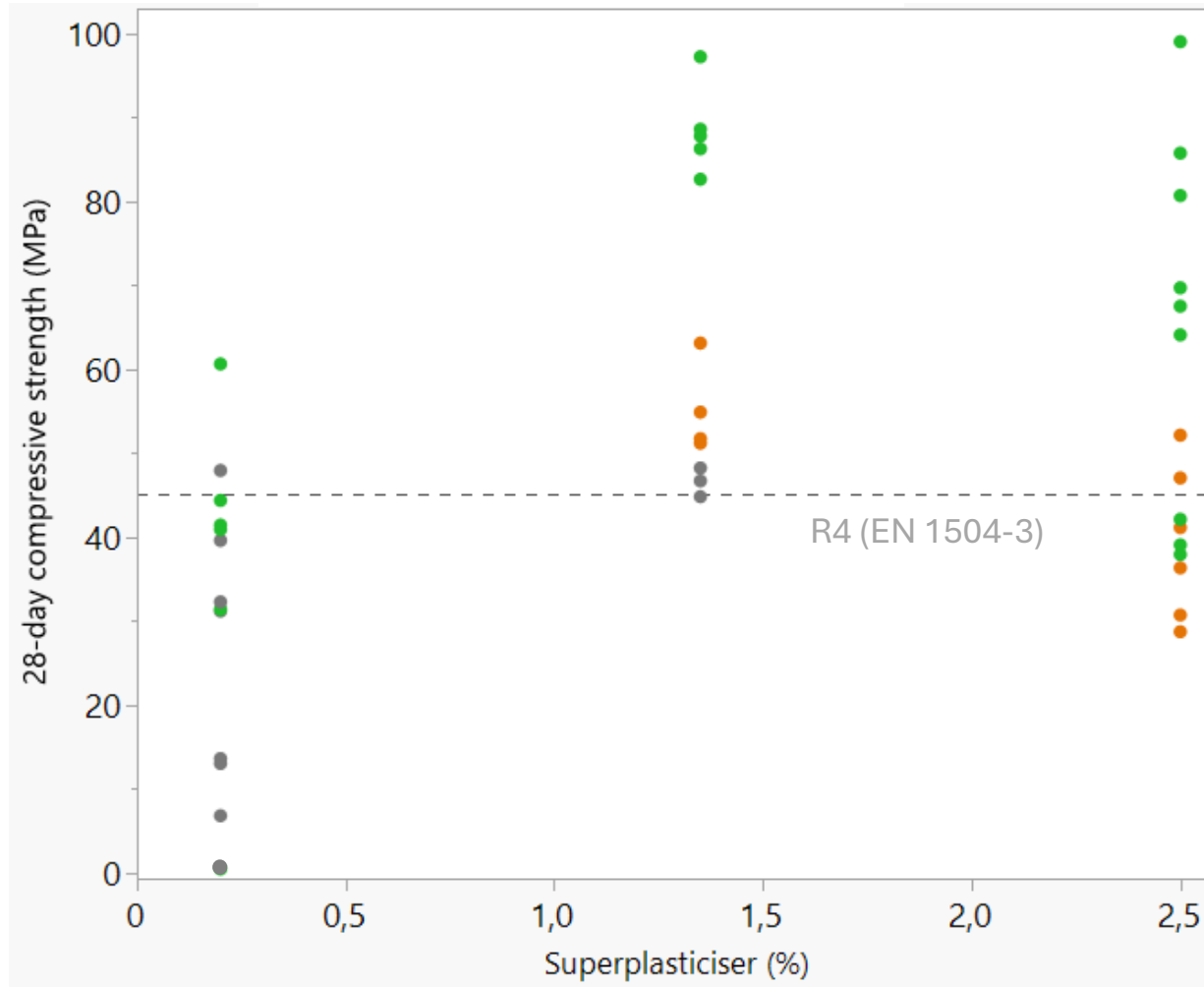
Key findings

- Superplasticiser → deformability
spread ↑; optimum at ~1.5-2 % by mass of binder
- Water → viscosity
V-funnel time ↓; little effect on spread
- More sand → less paste → lower flow
- Cement type: CEM III/A ≈ CEM I; CEM II/B-M (Q-LL) tends to be more viscous (7 of 13 mixtures > 30 s)

Stability trade-off: 10 mixtures bled, 9 of which also segregated; risk rises with water and SP; no cement type effect.

Consistent with SCC mix-design principles
(Okamura & Ouchi (2003))

Results: hardened-state properties (28 days)



Key findings

- Only **flowing, stable** mixtures exceed 65 MPa (up to 99 MPa)
- **No flow** (max 48 MPa) or **bleeding** (max 63 MPa) limits strength
- Same trends for **flexural strength**, confirmed by the statistical models
- **Cement type:** no effect at 28 days

21 of 40 mixtures ≥ 45 MPa (R4, EN 1504-3, indicative)
 $\rightarrow$ 7 for each cement type

Preliminary optimisation and first validation

Desirability targets: spread 250 mm, V-funnel 9 s, maximise flexural and compressive strength
(stability not included)

	CEM I	CEM III/A	CEM II/B-M (Q-LL)
Sand / cement / filler	0.66 / 0.28 / 0.07	0.65 / 0.29 / 0.06	0.60 / 0.25 / 0.15
SP (%)	1.94	2.20	0.96
W/B	0.30	0.30	0.44
Fresh state	Predicted → measured		
Spread (mm)	250 → 297	250 → 327	250 → 390
V-funnel (s)	9.0 → 9.8	9.0 → 10.5	9.0 → 1.1
Bleeding	slight	very slight	severe
Segregation	slight	none	yes
28-day strength	Predicted (measurements in progress)		
Flexural (MPa)	11.2	11.6	9.5
Compressive (MPa)	86	90	63

Key findings

- CEM I and CEM III/A: self-compacting and stable; V-funnel time well predicted
- Spread underestimated by the model
- CEM II/B-M (Q-LL) unstable: stability was not an optimisation target

Next steps: towards recycled repair mortars

Phase 1: natural materials

- 28-day strengths of the optimised mixes
- Refined optimisation: stability as a constraint

→ 3 reference mixes, one per cement type



Phase 2: DoE with recycled fractions

- Starting from the 3 reference mixes
- Recycled sand replacing natural sand
- Recycled fines replacing part of the cement and filler

Goal: stable self-compacting repair mortars with recycled fine fractions and less clinker

Conclusions

1

DoE captures the workability / strength trade-off

Superplasticiser optimum $\sim 1.5\text{--}2\%$; excess water and SP cause bleeding and strength loss

2

Lower-clinker cements perform as well as CEM I

Same 28-day strengths (7 mixes per cement $\geq 45\text{ MPa}$); CEM III/A also equivalent in the fresh state

3

Stability must be part of the optimisation

CEM I and CEM III/A mixes are self-compacting and stable: basis for DoE 2 with recycled fractions

Thank you! Questions?

Acknowledgements:

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