

From Excavated Rock to Low-Carbon Structural Applications

Geopolymer Innovations for the Einstein Telescope

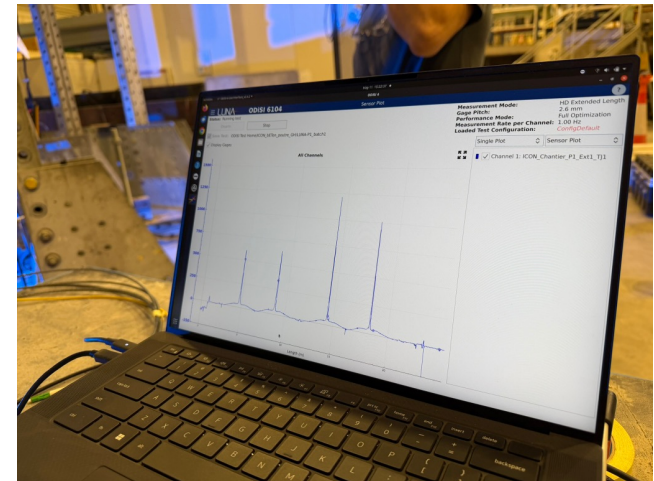
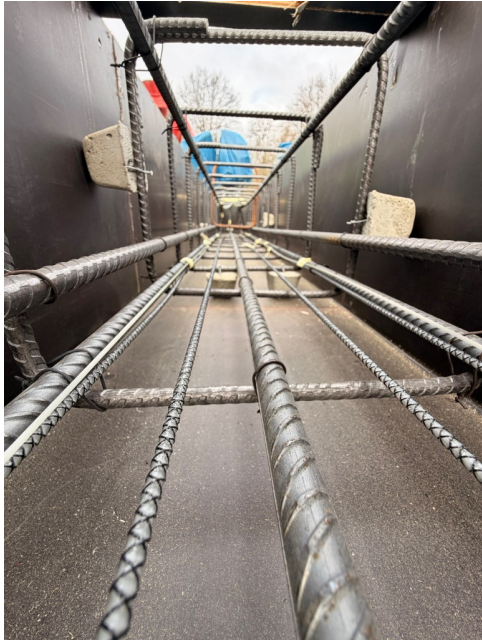
NIELS HULSBOSCH

R&D program lead *"Durable & Sustainable Structural Materials"*

BUILDWISE - BELGIUM

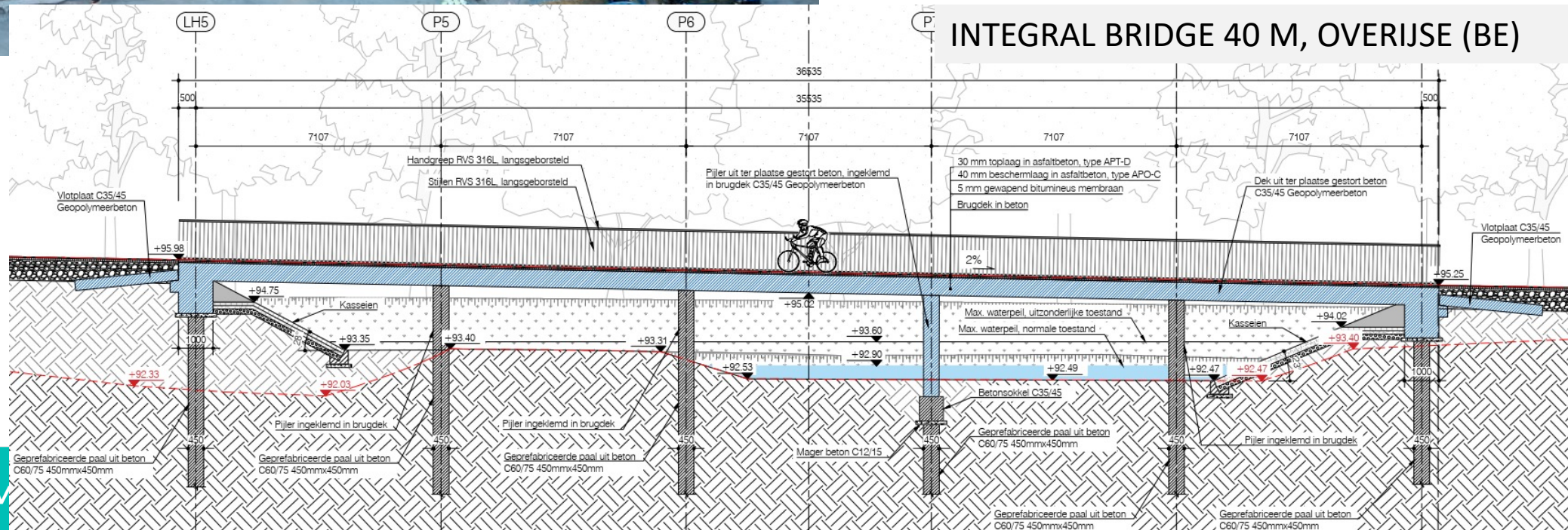
niels.hulsbosch@buildwise.be

Buildwise UNIT STRUCTURAL WORKS – Durable & Sustainable Structural Materials





From binder systems →
concrete (semi-finished product) →
element & structure



Goal

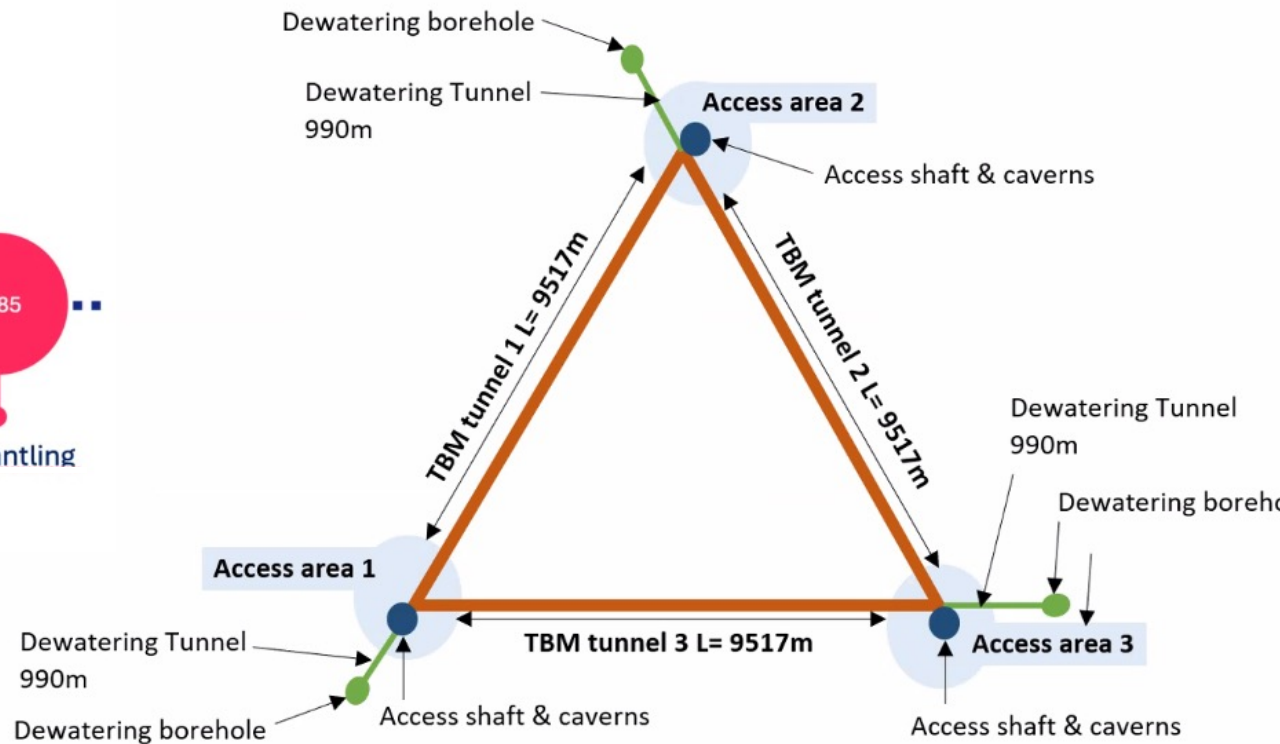
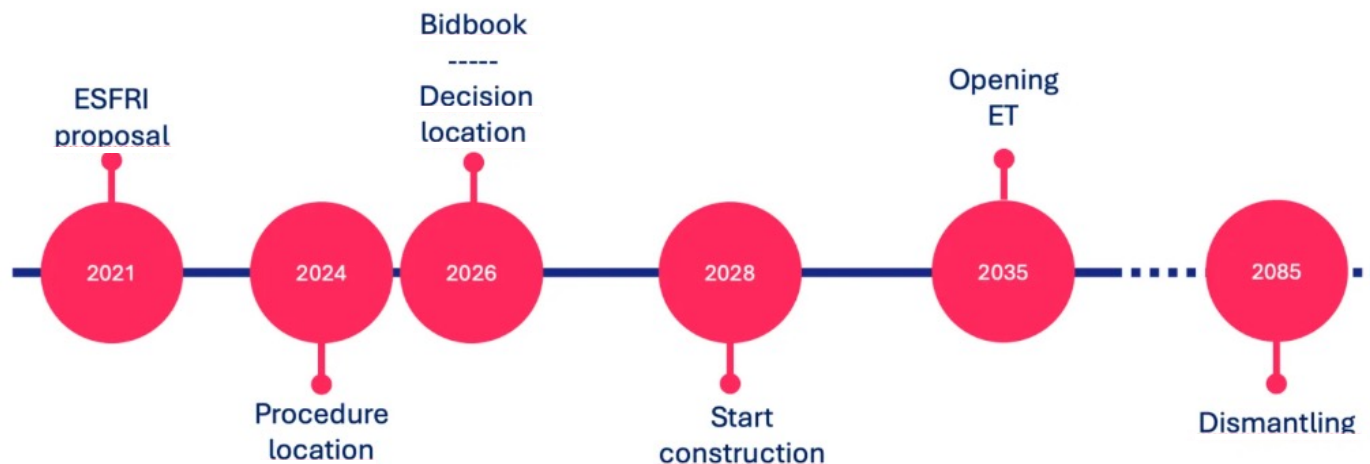
1. **General ET background & opportunities related to material science & engineering**
2. **Innovative (off-spec) materials in constructive concrete: novel research approach**
3. **ET: opportunities for geopolymer community & next steps**



General ET background & opportunities related
to material science & engineering

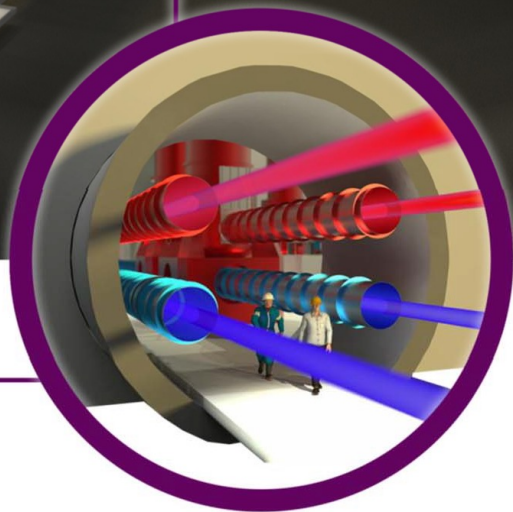
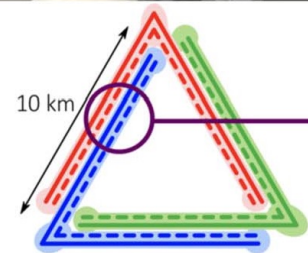
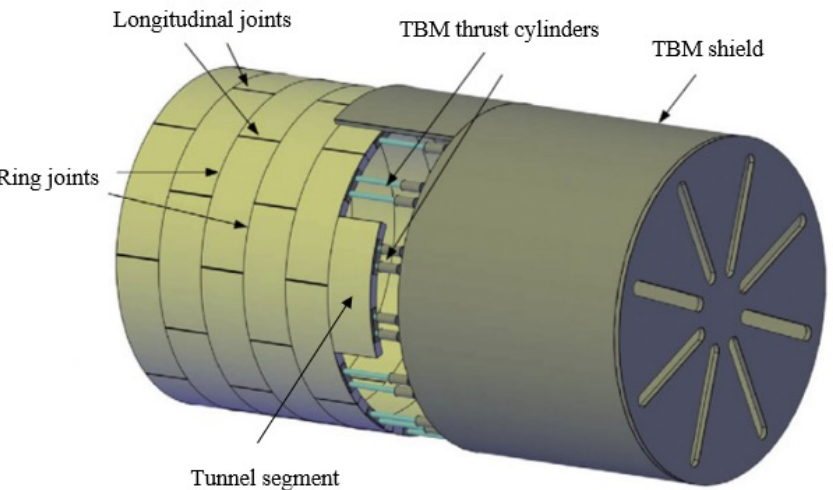
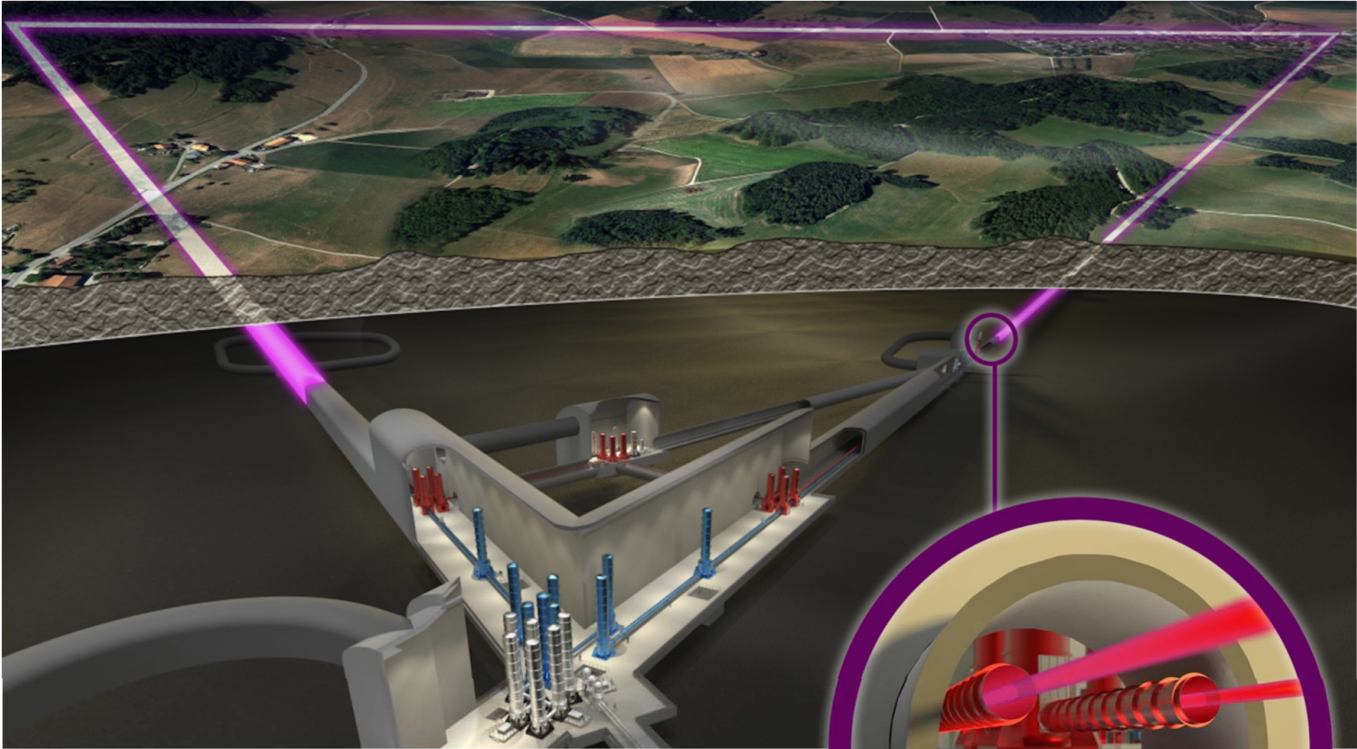
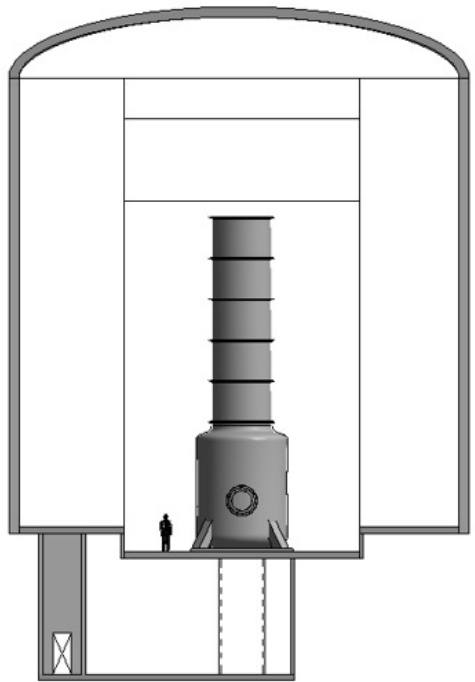
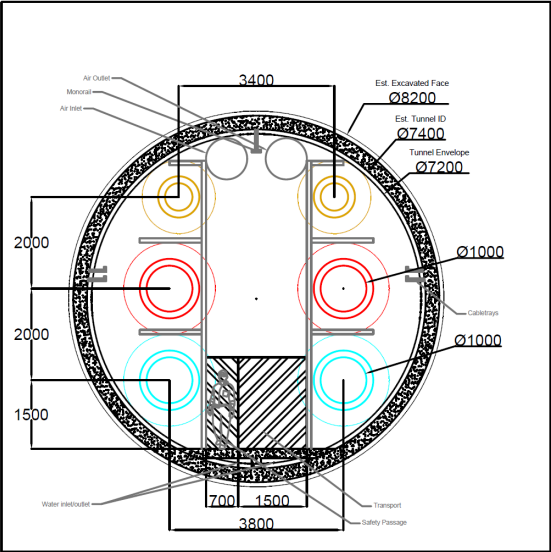
ET excavation waste

- €2.3 billion (2025!) with ~55% construction-related
- **Triangle design: Apr. 8 Mt of TBM-excavated materials will be generated by the ET project** (55% TBM tunnels; 35% Caverns; 10% non-TBM tunnels)
- **Several 100 kt of concrete will be required for its construction** (tunnel liners, access infrastructure, roads etc.)



[Amberg Engineering, 2023]

Design



Opportunities

- Recovery of excavated material and valorization for construction purposes
- Best practice for (very) large civil works
- E.g. Brenner base tunnel:
 - *On site processing facility for aggregates (crushing, washing, sieving)*
 - *Since 2014 all aggregates required for concreting etc. were recovered from aggregates*
 - Required extensive pre-studies as initially materials were deemed unsuitable
- Saves transport & primary resources



[Brenner Base tunnel]

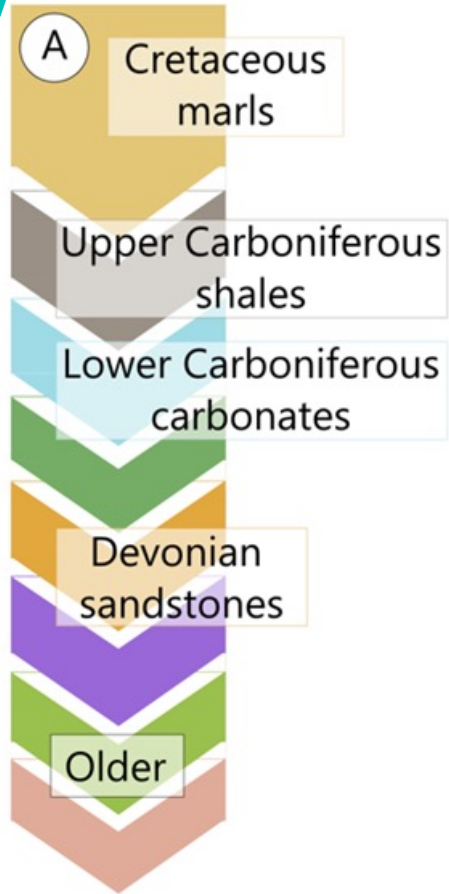
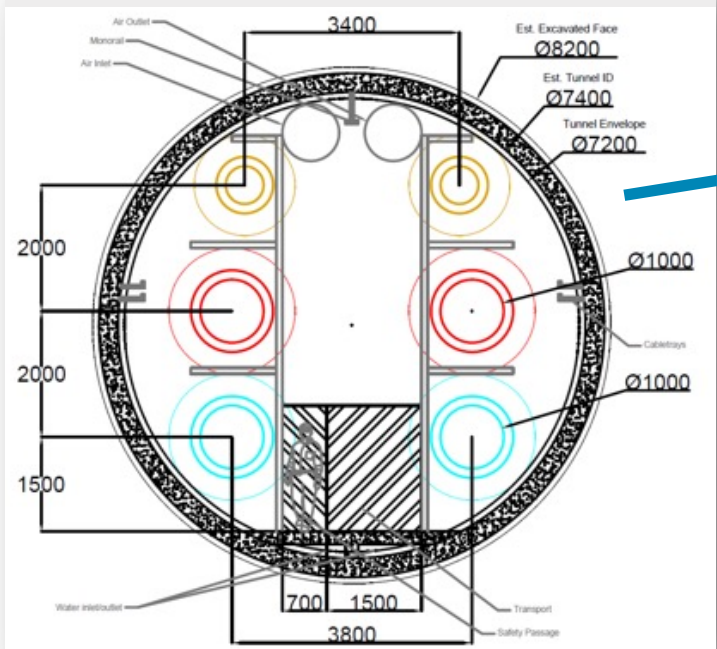


[Processing facility and deponie Brenner Base tunnel, 2022]

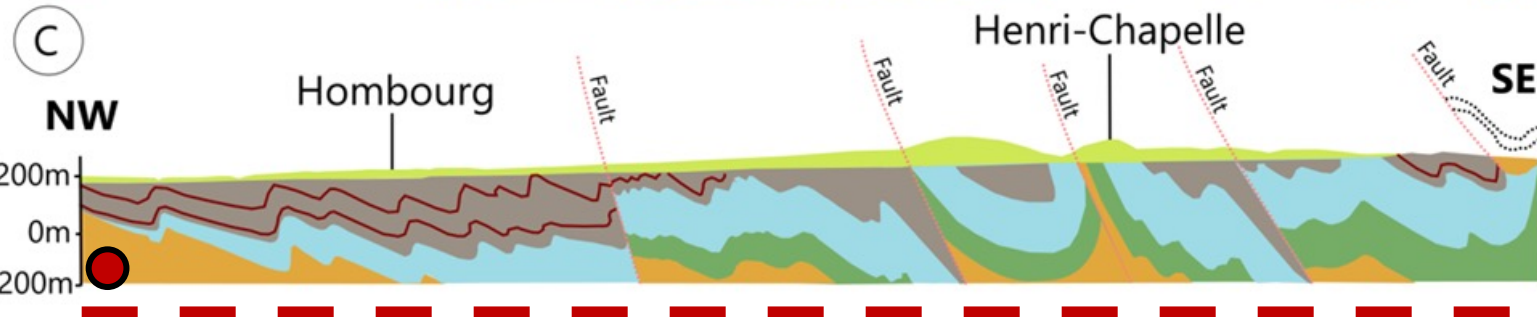
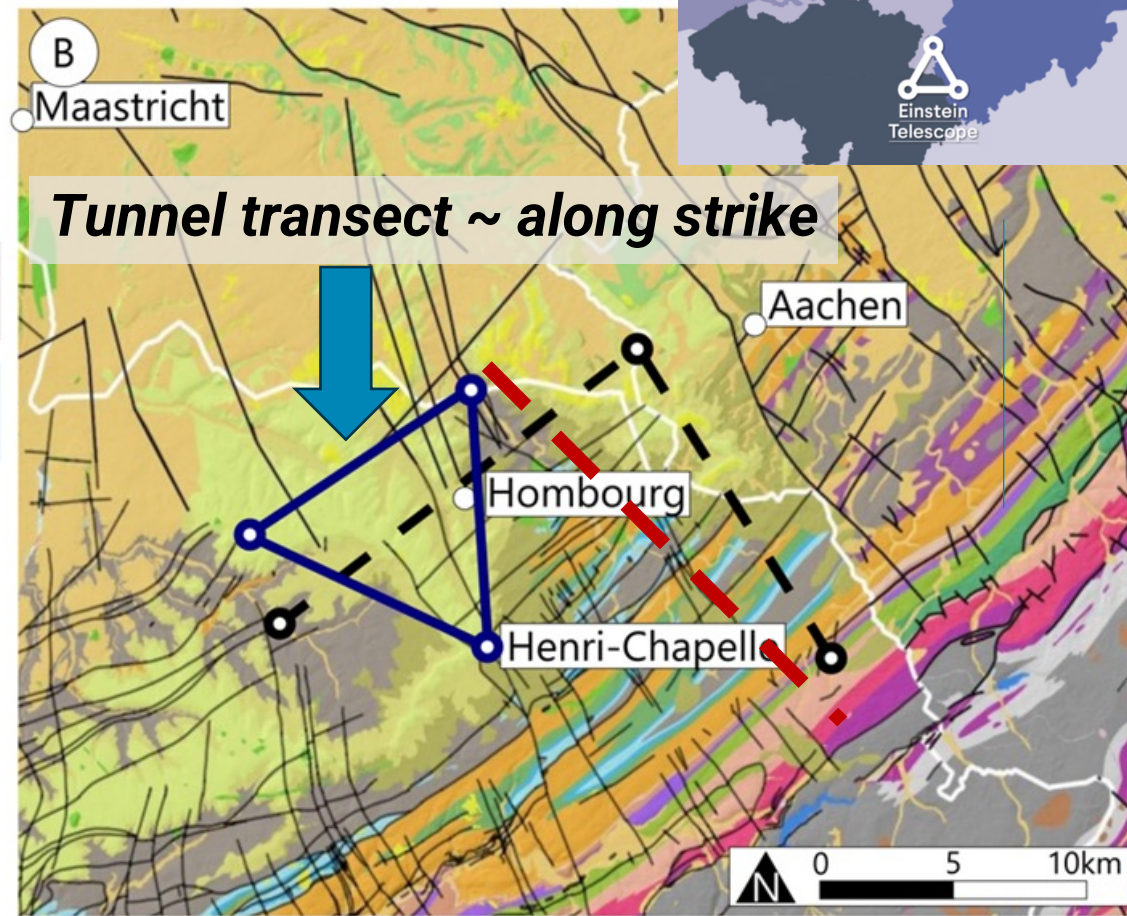
ICON bETon casestudy

Simplified geology

Tunnel transect ~ along strike



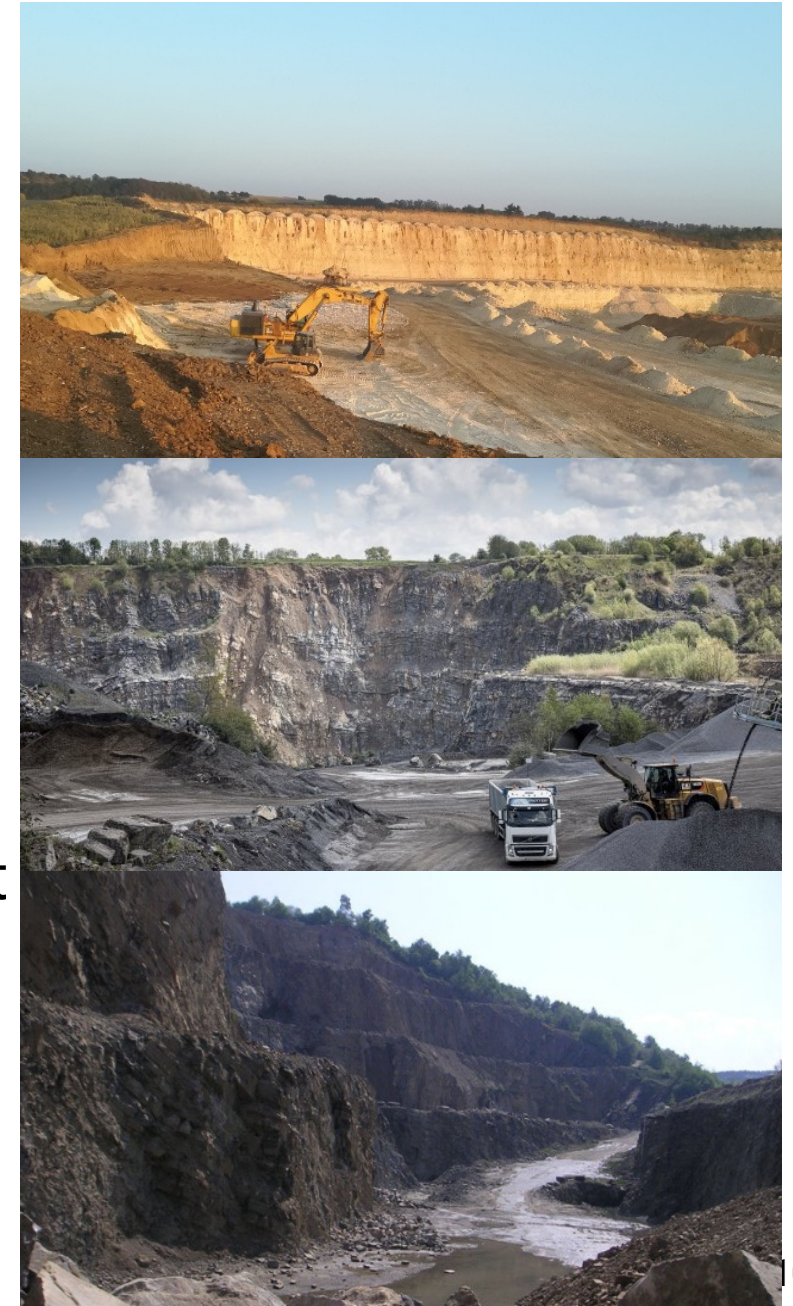
Tunnel transect ~ along strike



ET region opportunities

(Part of) the main excavated lithologies are quarried today:

- 1. Cretaceous marl**
e.g. Lixhe - cement production, filler
- 2. Lower carboniferous limestone**
e.g. Bay Bonnet – concrete aggregate, filler
- 3. Famennian sandstone & shale**
e.g. Trooz – concrete aggregate, filler or cement constituent (Q)



WP1 – Sensor-based, inline characterisation technology to steer extraction and processing of excavated and recycled materials



WP2 – Low-carbon composite cements with high amounts of SCMs recovered from activated excavation and processing fines

KU LEUVEN



WP3 – Multiscale experimentation, analysis and monitoring framework for mixture research and structural analysis of concrete with excavated aggregates

KU LEUVEN



WP4 – Dissemination, Communication and Exploitation

WP5 – Project management

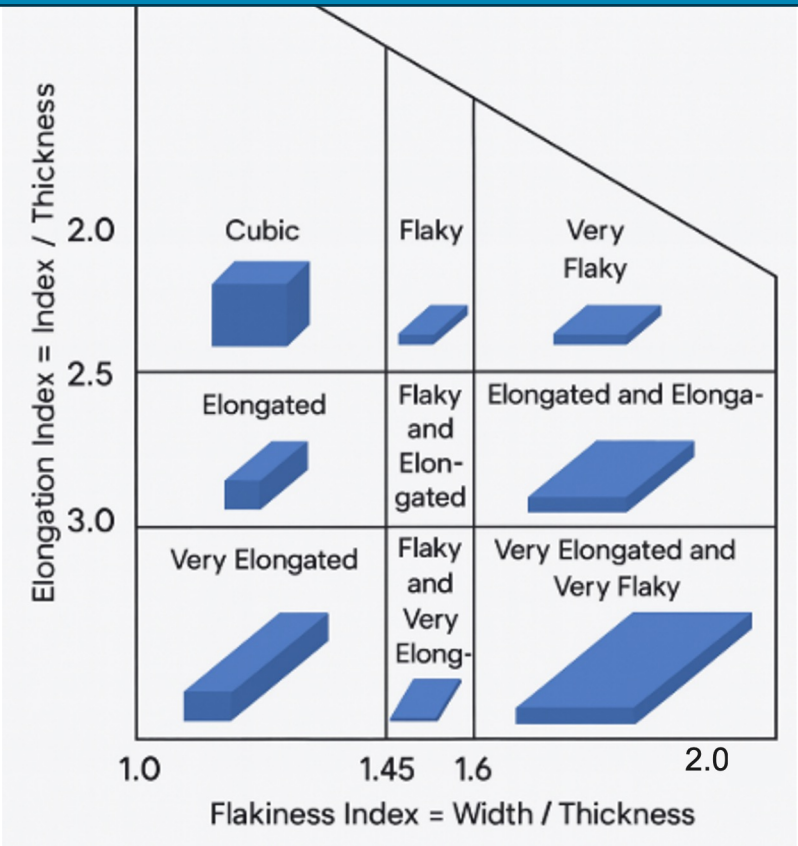
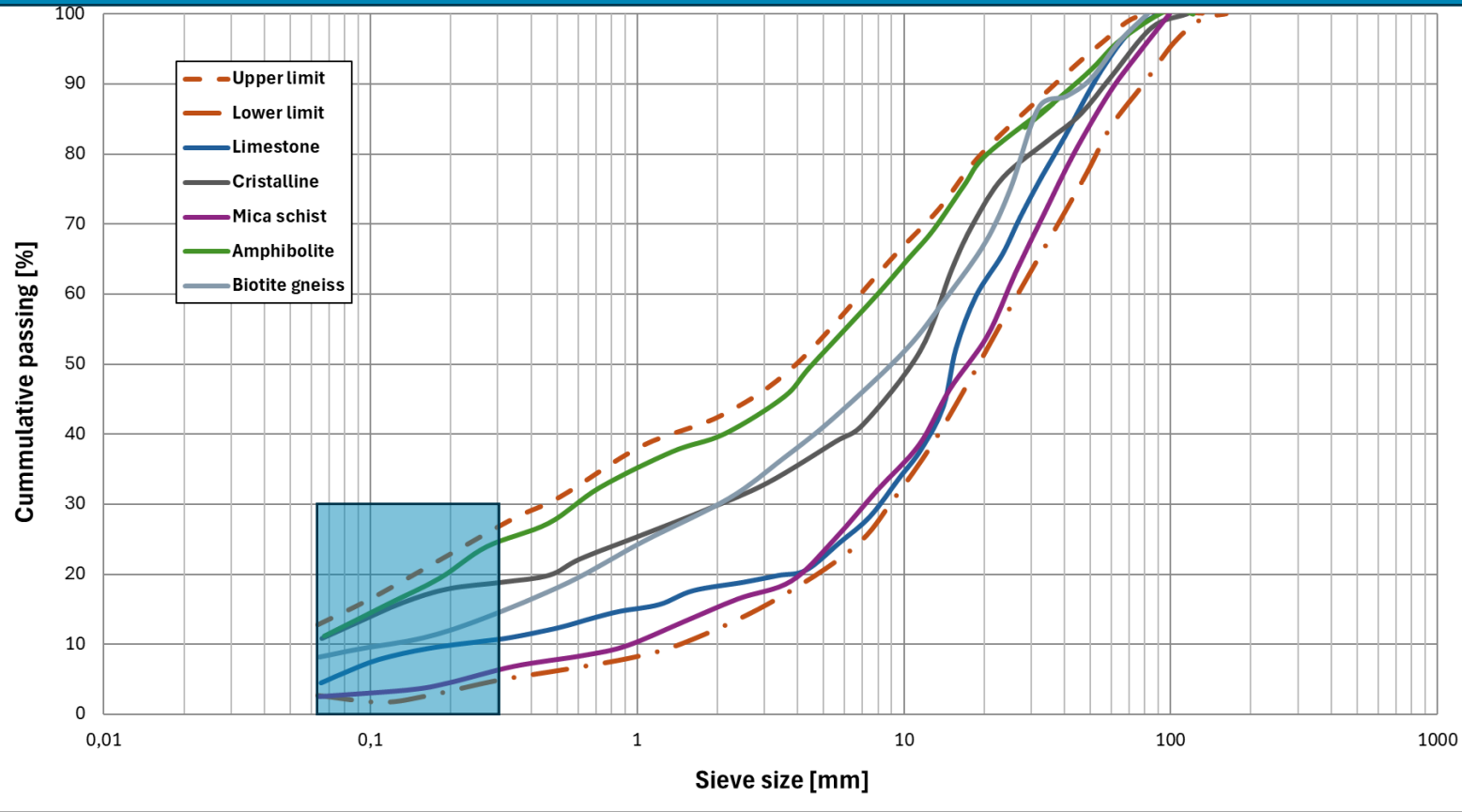




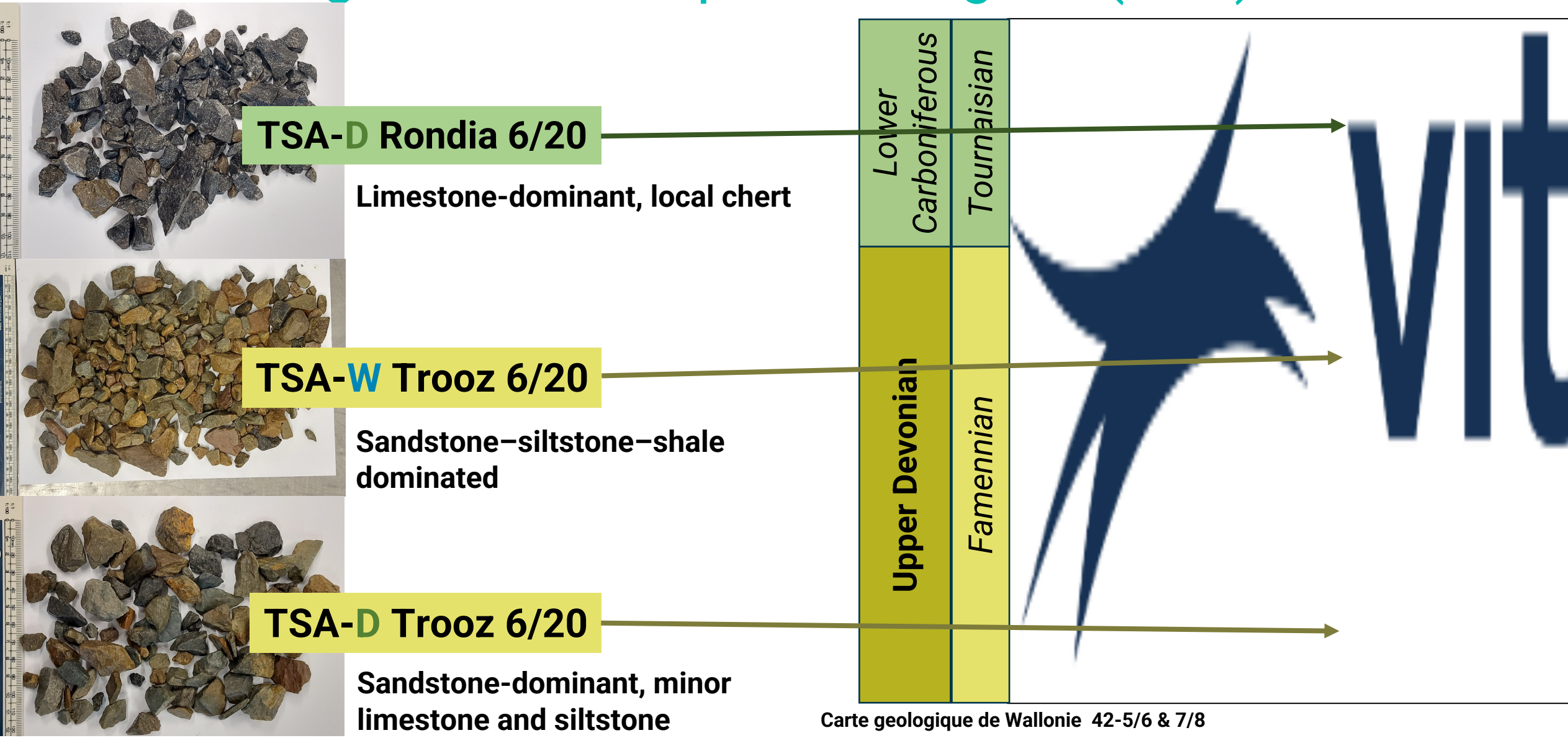
Innovative (off-spec) materials in constructive
concrete: novel approach

Quarry material as TBM material analogues

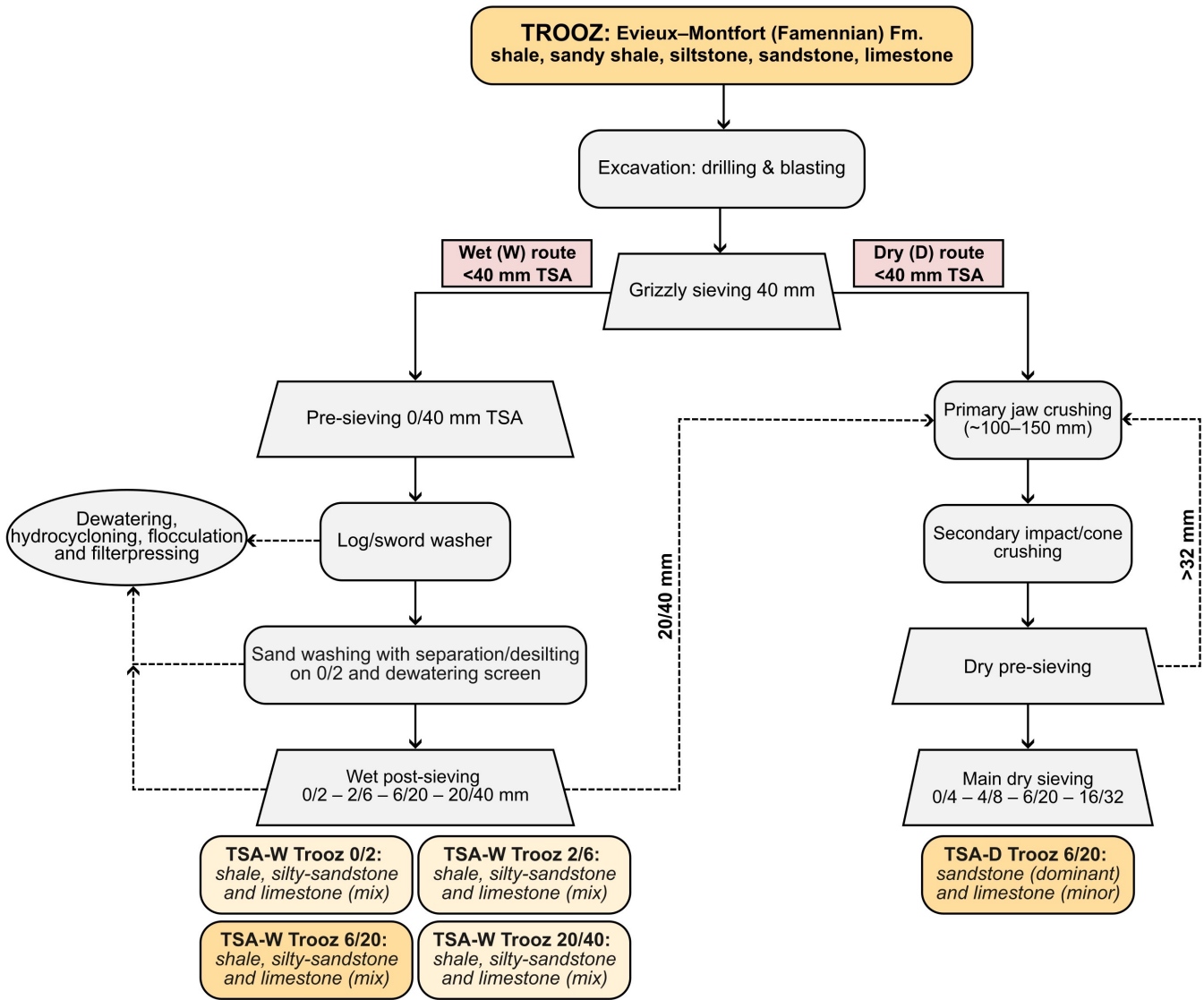
Need for experimental TBM material analogues at tonne-scale →
“Tunnel Spoil Analogues” (TSA)



ET analogues Tunnel Spoil Analogues (TSA)



Quarry material as TBM material analogues



Quarry material as TBM material analogues

Untreated TSATrooz 0/40 (wet route)



TSA-W Trooz 20/40



TSA-W Trooz 6/20



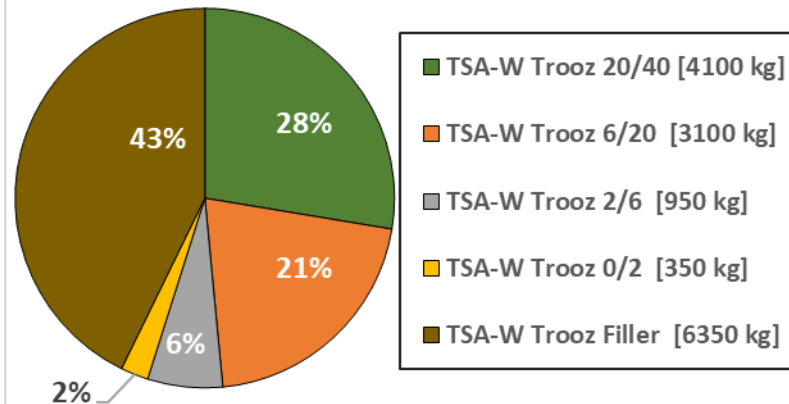
TSA-W Trooz 2/6



TSA-W Trooz 0/2



TSA Trooz 0/40 via wet route
[wt.%] - Start mass of 14 850 kg



- Tunnel Spoil Analogues =**
- very filler rich (< 250 μm)
 - Argillitic fines (Al-Si)

Experimental testing & stastical framework

Multi-level experiments & response surface models for multi-criteria models

- **Aggregate-level:**

- *PSD, fineness modulus and fine content*
- *Density and water absorption*
- *Flakiness and elongation indices*
- *Micro-Deval and Los Angeles*



- **Binder-level:**

- *XRF & Q-XRD*
- *Setting*
- *PSD & finesse (Blaine)*
- *Strength*

- **Concrete-level:**

- *Slump, air content and fresh density*
- *Compressive strength 28 days*
- *Tensile splitting strenght 28 days*
- *Dynamic E-modulus 28 days*
- *Shrinkage*

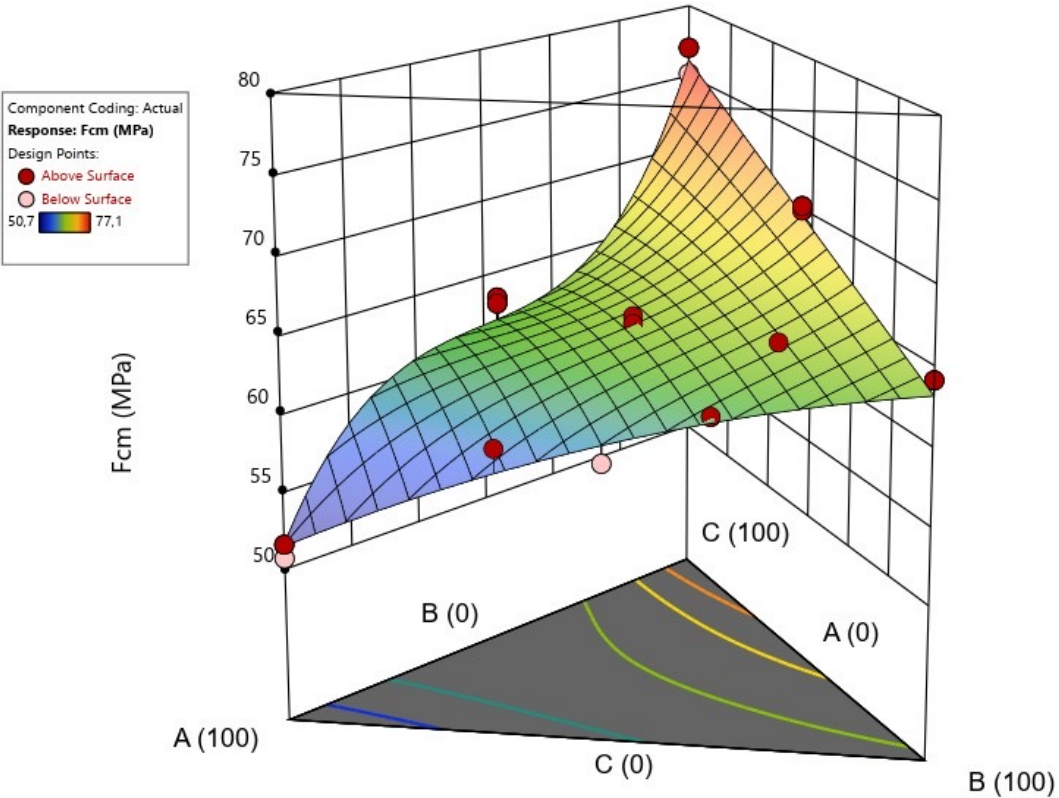
- **Structural-level**

- *Eurocode 2 compliant (EN 1992-1-1)*
- *Soil-structure modelling*



Experiments & statistical models

Concrete compressive strength 28d



Cubic model; Adj R² = 0,991; Pred R² = 0,973; LOF p = 0,50; Adeq Precision = 65,7

Concrete tensile splitting strength 28d



Linear model; Adj R² = 0,478; Pred R² = 0,248; LOF p = 0,85; Adeq Precision = 9,8

TSA-W Trooz 6/20	TSA-D Trooz 6/20	TSA-D Rondia 6/20
A	B	C
Sandstone–siltstone–shale dominated (Fam.)	Sandstone-dominant, minor limestone and siltstone (Fam.)	Limestone-dominant, local chert (Tourn.)

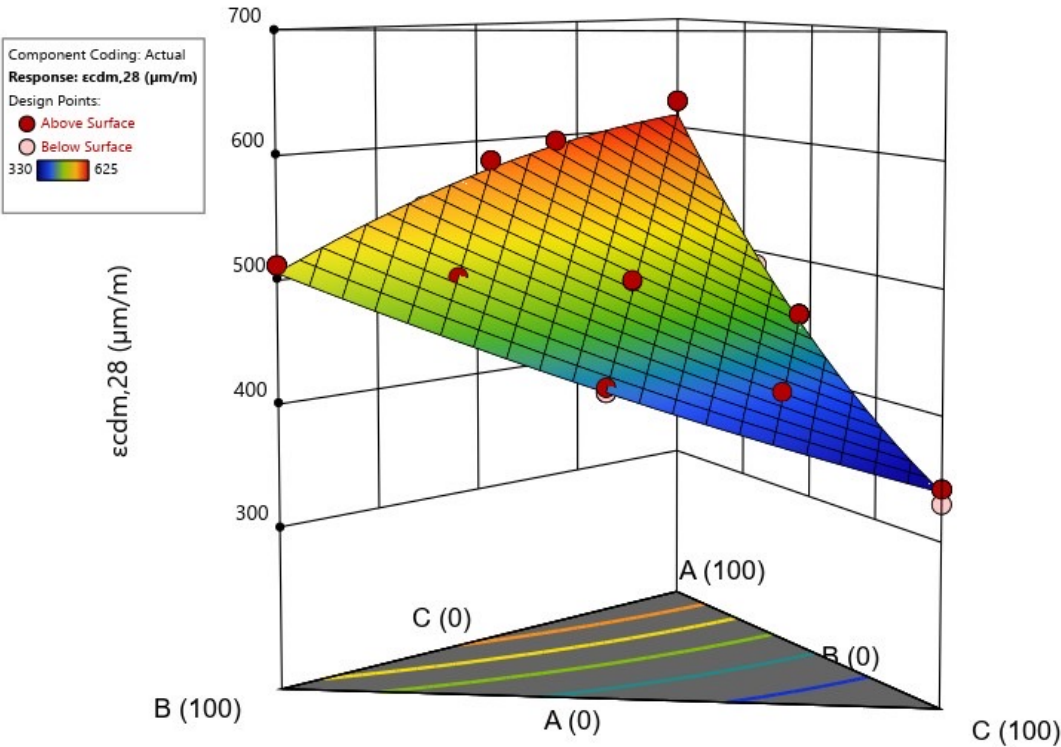
Experiments & statistical models

Concrete E-modulus 28d



Linear model; Adj R² = 0,946; Pred R² = 0,918; LOF p = 0,64; Adeq Precision = 31,7

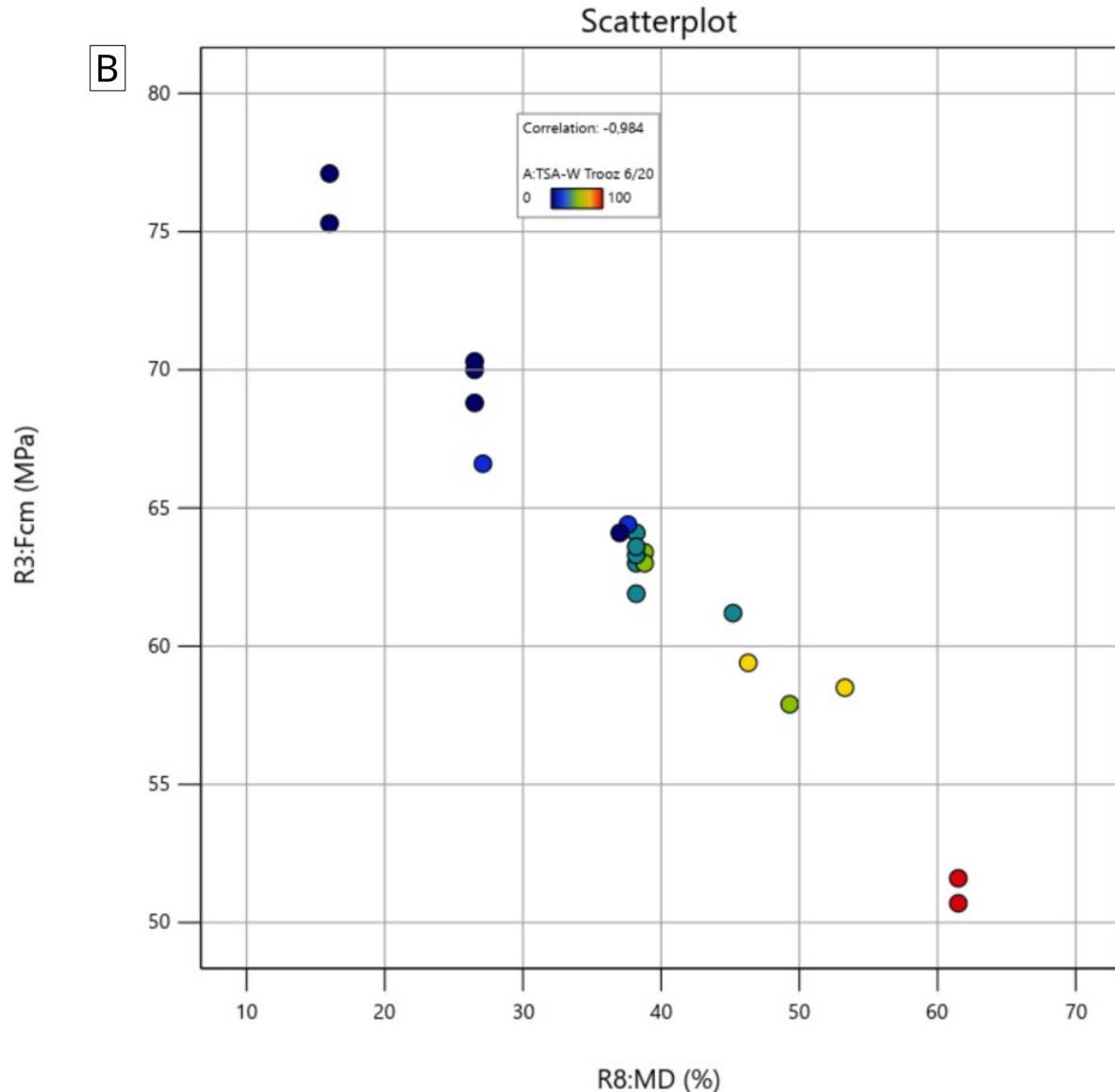
Concrete shrinkage



Quadratic model; Adj R² = 0,983; Pred R² = 0,963; LOF p = 0,85; Adeq Precision = 42,0

TSA-W Trooz 6/20	TSA-D Trooz 6/20	TSA-D Rondia 6/20
A	B	C
Sandstone–siltstone–shale dominated (Fam.)	Sandstone-dominant, minor limestone and siltstone (Fam.)	Limestone-dominant, local chert (Tourn.)

Experiments & statistical models



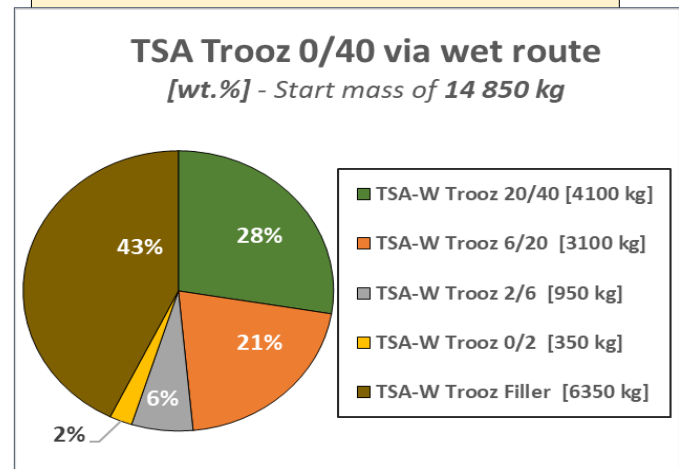
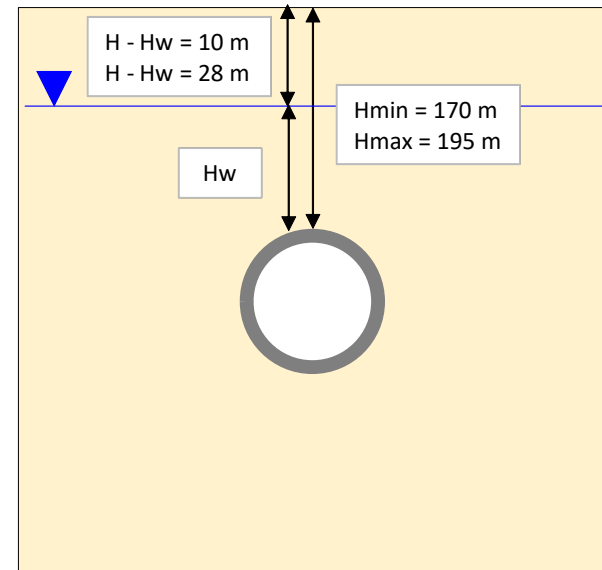
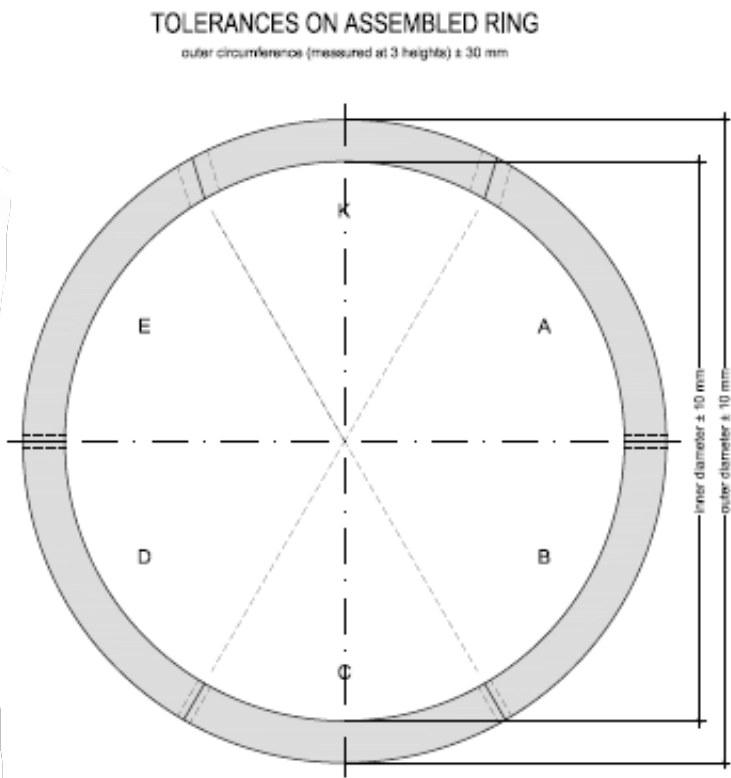
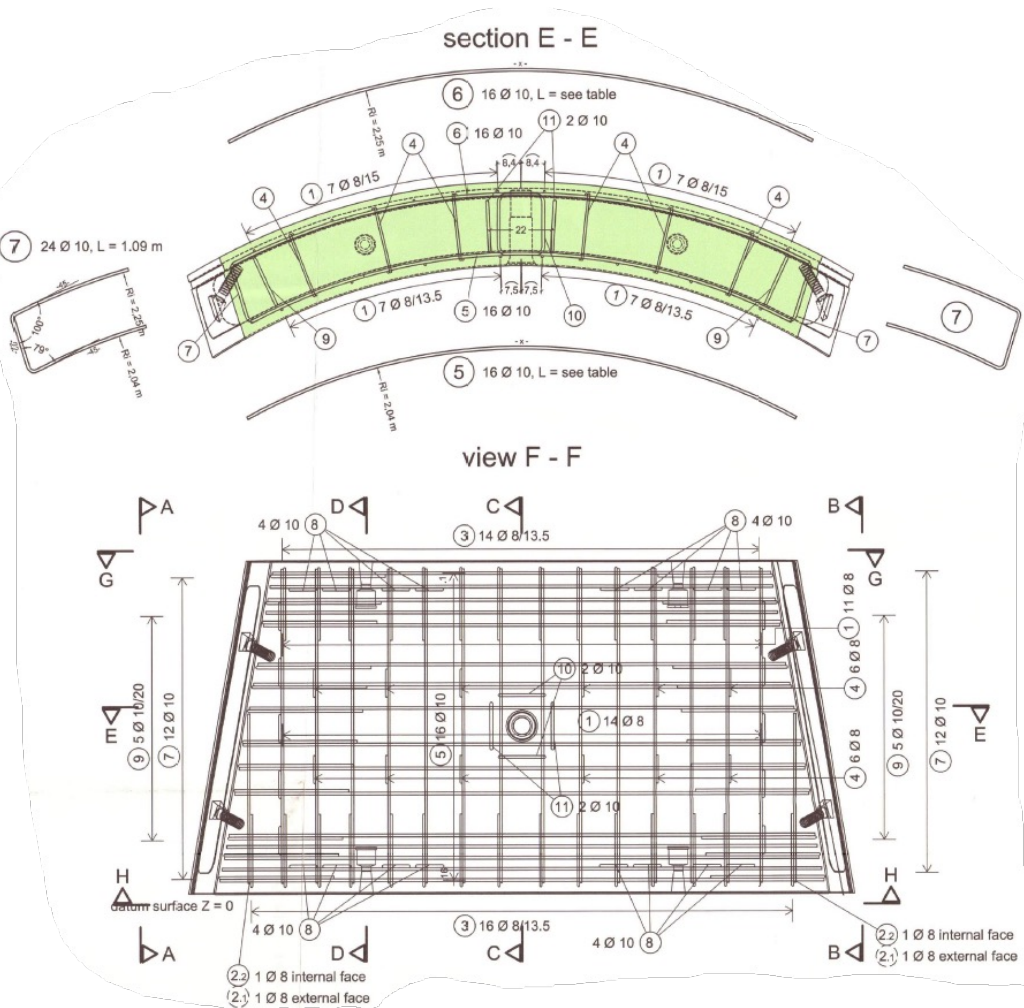
Linking aggregate with concrete

Micro Deval – Compressive strength

TSA-W Trooz 6/20	TSA-D Trooz 6/20	TSA-D Rondia 6/20
A	B	C
Sandstone-siltstone-shale dominated (Fam.)	Sandstone-dominant, minor limestone and siltstone (Fam.)	Limestone-dominant, local chert (Tourn.)

MD: “Resistance to wear and degradation under wet abrasion, simulating mechanically stressed and humid tunnel excavation, processing, and service conditions.”

Finite Element (FE) soil–structure interaction analysis



TSA-W Trooz 6/20	TSA-D Trooz 6/20	TSA-D Rondia 6/20
A	B	C
Sandstone-siltstone-shale dominated (Fam.)	Sandstone-dominant, minor limestone and siltstone (Fam.)	Limestone-dominant, local chert (Tourn.)

Design limits & optimization

Multi-criteria assessment
(EN 1992-1-1 & FE-soil model)



TSA-W Trooz 6/20	TSA-D Trooz 6/20	TSA-D Rondia 6/20
A	B	C
Sandstone-siltstone-shale dominated (Fam.)	Sandstone-dominant, minor limestone and siltstone (Fam.)	Limestone-dominant, local chert (Tourn.)

Design limits & optimization

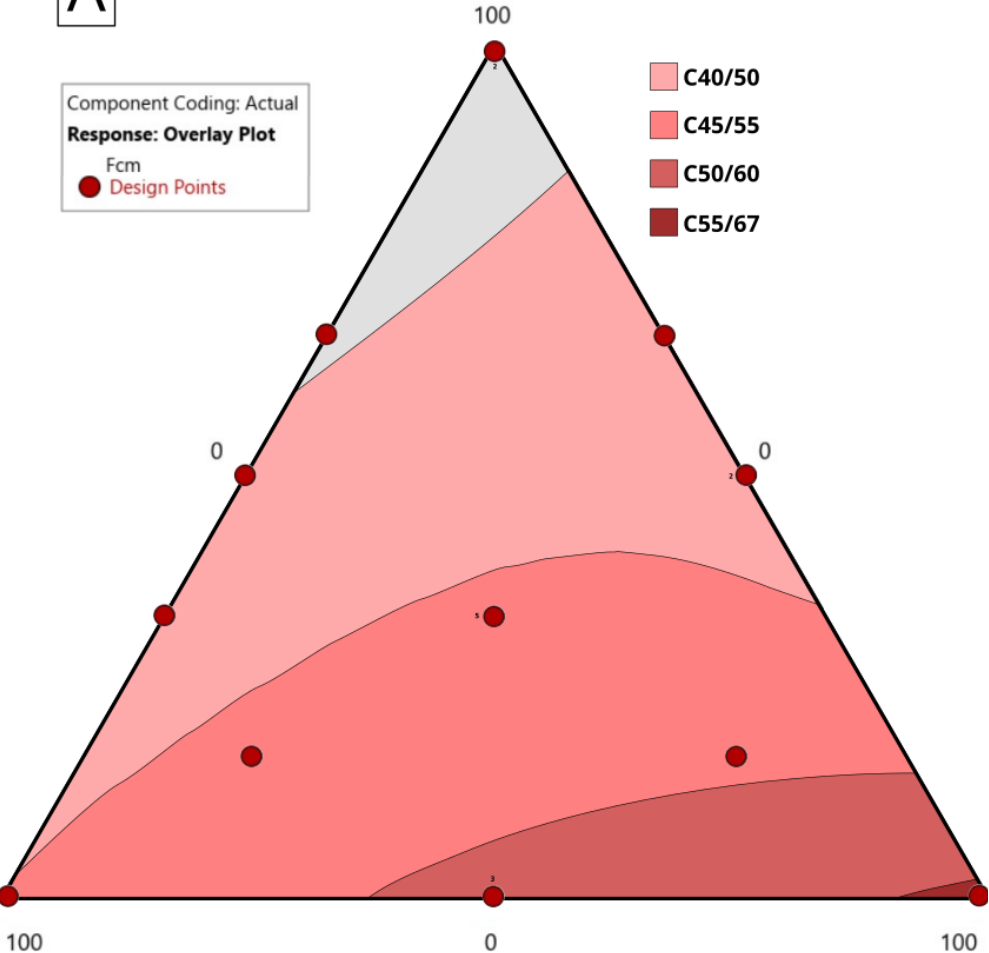
Multi-criteria assessment (EN 1992-1-1 & FE-soil model)

A

A: TSA-W Trooz 6/20 (vol.%)

Component Coding: Actual
Response: Overlay Plot
F_{cm}
● Design Points

- C40/50
- C45/55
- C50/60
- C55/67



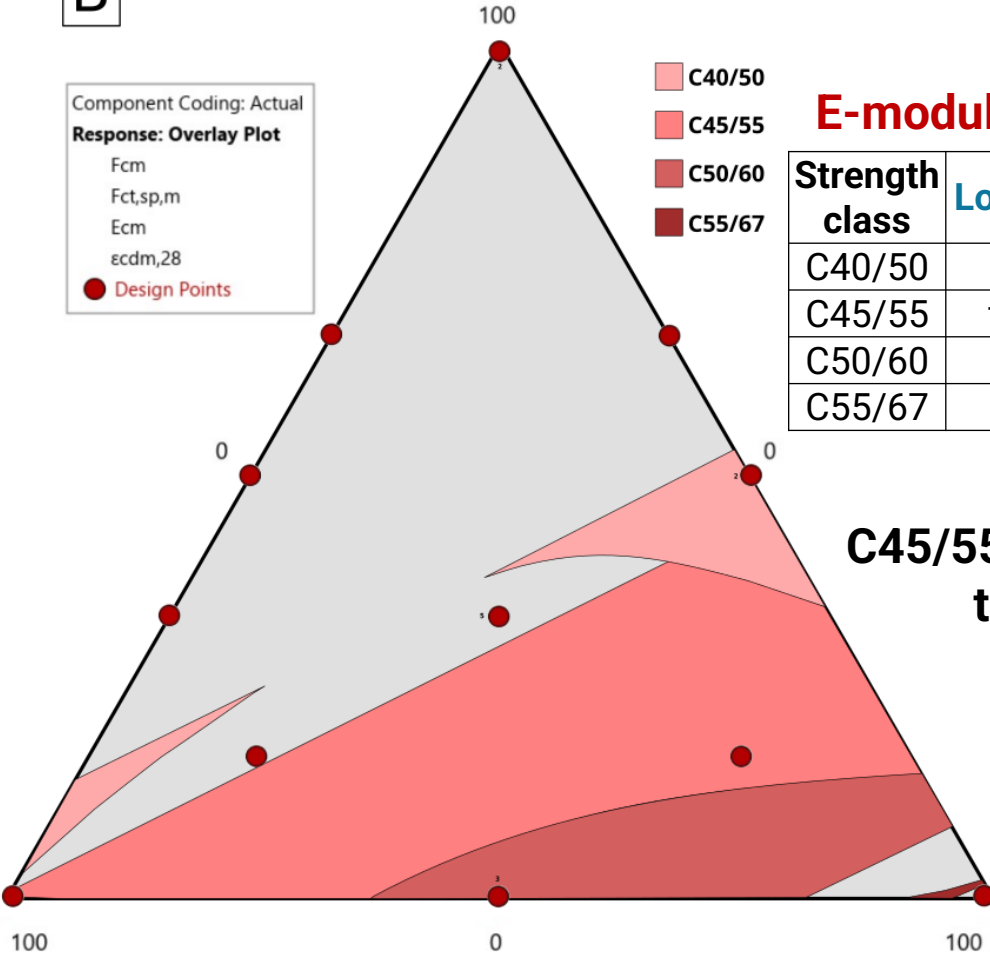
B: TSA-D Trooz 6/20 (vol.%)

B

A: TSA-W Trooz 6/20 (vol.%)

Component Coding: Actual
Response: Overlay Plot
F_{cm}
F_{ct,sp,m}
E_{cm}
e_{cdm,28}
● Design Points

- C40/50
- C45/55
- C50/60
- C55/67



B: TSA-D Trooz 6/20 (vol.%)

E-modulus is defining criterium

Strength class	Lower boundary	Upper boundary
C40/50	E_{cm}	$f_{cm,cube}$
C45/55	$f_{cm,cube} + E_{cm}$	$f_{cm,cube} + E_{cm}$
C50/60	$f_{cm,cube}$	E_{cm}
C55/67	$f_{cm,cube}$	E_{cm}

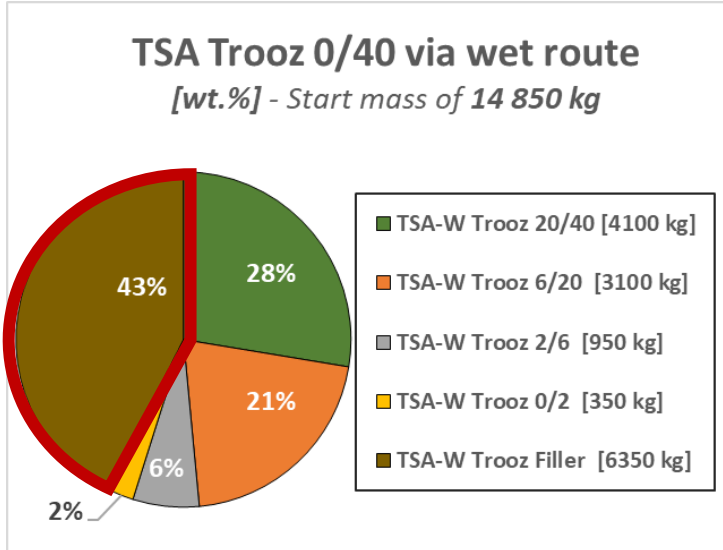
C45/55 & C50/60 are practical target mix designs (~45% of design)

C: TSA-D Rondia 6/20 (vol.%)

ET: opportunities for geopolymer community & next steps

TBM spoil filler fraction: untreated fingerprint

Oxide / property	Clay-rich Famennian shale	quartz-rich, shale–siltstone	Main mineralogical control
SiO ₂	~50–56 wt.%	~68–70 wt.%	Quartz + silicates
Al ₂ O ₃	~20–22 wt.%	~14–17 wt.%	Illite/muscovite + kaolinite + chlorite
Fe ₂ O ₃ total	~9–13 wt.%	~6–7 wt.%	Chlorite, Fe-bearing mica , Fe-carbonate/oxides.
K ₂ O	~7–12 wt.%	~2–3 wt.%	Illite/muscovite
MgO	~5–6 wt.%	~2 wt.%	Mainly chlorite ± dolomitic/Fe-Mg phases
CaO	~1 wt.%	<1 wt.%	Minor carbonate or Ca-bearing silicates
Na ₂ O	~0.5–0.7 wt.%	~0.4–0.5 wt.%	Minor feldspar/albite
TiO ₂	~1 wt.%	Not clearly reported / low	Accessory Ti phases
SO ₃	~0.5 wt.%	~0.4–0.5 wt.%	Sulfur-bearing minor phases
P ₂ O ₅	<0.3 wt.%	Not clearly reported / low	Accessory apatite or minor phases
LOI	~7–8 wt.%	~6–7 wt.%	Physically bound water + clay dehydroxylation



Key message for filler fraction: Fammenian shale is clay-mineral rich and K-Fe-Mg bearing. The opportunity is controlled activation, not direct use as an inert filler.

Potential routes for the geopolymers community

Thermal activation (600-850 °C):
dihydroxylation, reactive Al-Si phase...

Mechanochemical activation:
amorphization, surface activation...

Co-calcination / hybrid Q-LL logic (CEM II/C-M; CEM V/B):
tune Ca, heat use, limestone synergy...

CLAY-RICH SHALE FILLER FRACTION
ILLITE-rich

Hybrid AAM / geopolymer:
Shale + slag + activator, tune Ca/Si/Al, curing...

Beneficiation + QA window:
Enrich clay fraction, manage quartz, carbonate, pyrite and variability

Scientific opening

Move beyond metakaolin-only thinking: illite/chlorite-rich shale can become a designed precursor when mineralogy, activation and hybrid binder chemistry are coupled.

Take action: Interreg cross-border projects

A Belgium-France-Netherlands testbed connecting geology, geopolymers expertise, cement/concrete validation, LCA/EPD and demonstrators.

- **Shared geology and residues:** *Famennian/Namurian shales, quarry interburden, excavation fines and processing sludges.*
- **Shared market pull:** *Low-clinker binders, geopolymers, precast products, circular procurement and local CO2 reduction.*
- **Shared infrastructure need:** *XRD/Rietveld, XRF/ICP, TGA, milling, calcination, durability labs and pilot-scale validation.*

➔ **"Shale-to-binder": convert local clay-rich residues and quarry fines into geopolymer binders.**

Additional info

Type	TSA-W Trooz 6/20		TSA-D Trooz 6/20		TSA-D Rondia 6/20	
BW nr.	2025/47/008		2025/43/003		2025/42/008	
Flakiness index FI [%]	22	2	29	2	23	2
Shape Index SI [%]	17	1	13	2	32	2
WA24 [%]	3.3	0.6	1.8	0.3	0.5	0.1
pa [kg/m³]	2630	45	2340	33	2730	25
prd [kg/m³]	2420	41	2240	32	2690	25
pssd [kg/m ₃]	2500	43	2280	32	2710	25
LA [%]	30	2	22	0	23	0
MD [%]	62	5	37	3	16	0
n = 3						

Aggregate	Main conclusions
A – TSA-W Trooz	Highest WA24 and MD; weakest mechanical quality; intermediate density; lower FI/SI
B – TSA-D Trooz	Intermediate WA24 and MD; lowest density; highest FI
C – TSA-D Rondia	Lowest WA24 and MD; highest density; highest SI

Property	Correlation with concrete performance
WA24	● ● ●
Particle density	● ● ●
Micro-Deval (MD)	● ● ●
Grading	● ● ●
Los Angeles (LA)	● ●
Flakiness Index (FI)	● ●
Shape Index (SI)	●

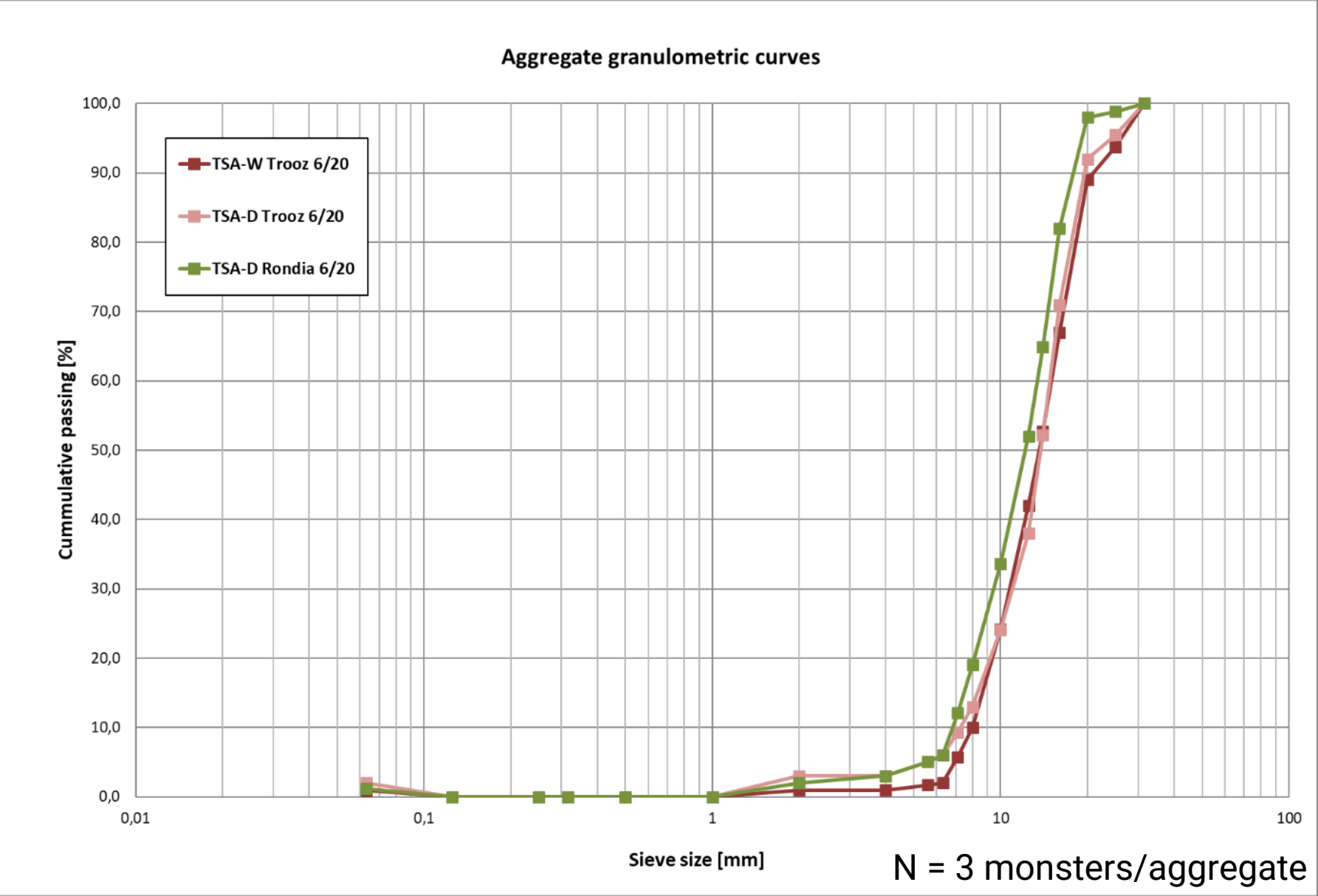
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Experimental and statistical concrete mix design

Final model design:

- Response surface methodology
- (q-1)-dimensional simplex design
- Mixture components = coarse aggregates 6/20 (vol.%)
 - A: Quartz sand 0/4 = constant
 - B: Limestone 2/6 = constant
 - C: TSA-W Trooz 6/20
 - D: TSA-D Trooz 6/20
 - E: TSA-D Rondia 6/20
- Constrained design (C+D+E=100 vol.%)
- Blocked on fabrication week
- I-optimal design & Special cubic design
 - Model points = 9
 - Additional model points = 2
 - Lack-of-fit points = 5
 - Replicate points = 5
 - Blocking points = 3
 - References = 3 (1 per block)

Block	Exp. Run	Build type	Space type	TSA-W Trooz 6/20	TSA-D Trooz 6/20	TSA-D Rondia 6/20	Milieu 6/20
1	1	Replicate	Center	33,3	33,3	33,3	/
	2	Lack of Fit	ThirdEdge	66,7	33,3	0,0	/
	3	Lack of Fit	AxialCB	16,7	66,7	16,7	/
	4	Model	Vertex	0,0	0,0	100,0	/
	5	Model	Center	33,3	33,3	33,3	/
	6	Lack of Fit	ThirdEdge	66,7	0,0	33,3	/
	7	Model	Vertex	0,0	100,0	0,0	/
	8	Ref. B1	/				100,0
2	9	Replicate	Vertex	0,0	0,0	100,0	/
	10	Replicate	CentEdge	50,0	0,0	50,0	/
	11	Model	CentEdge	50,0	0,0	50,0	/
	12	Model	CentEdge	0,0	50,0	50,0	/
	13	Model	Center	33,3	33,3	33,3	/
	14	Model	CentEdge	50,0	50,0	0,0	/
	15	Replicate	CentEdge	0,0	50,0	50,0	/
	16	Ref. B1	/	/	/	/	100,0
3	17	Model	CentEdge	50,0	50,0	0,0	/
	18	Replicate	Center	33,3	33,3	33,3	/
	19	Model	Vertex	100,0	0,0	0,0	/
	20	Model	CentEdge	0,0	50,0	50,0	/
	21	Lack of Fit	AxialCB	16,7	16,7	66,7	/
	22	Lack of Fit	ThirdEdge	33,3	66,7	0,0	/
	23	Model	Center	33,3	33,3	33,3	/
	24	Ref. B1	/	/	/	/	100,0



TSA-W Trooz 6/20	TSA-D Trooz 6/20	TSA-D Rondia 6/20
A	B	C
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Design limits & optimization

First assessment: coherent model behaviour (EN 1992-1-1)

$f_{ck}/f_{ck,cube}$	MPa	C40/50		C45/55		C50/60		C55/67	
f_{ck}	MPa	40	45	45	50	50	55	55	60
$f_{ck,cube}$	MPa	50	55	55	60	60	67	67	75
f_{cm}	MPa	48	53	53	58	58	63	63	68
$f_{cm,cube}$	MPa	58	63	63	68	68	75	75	83
f_{ctm}	MPa	3.5	3.8	3.8	4.1	4.1	4.2	4.2	4.4
$f_{ctk,sp,0.05}$	MPa	2.7	3.0	3.0	3.2	3.2	3.3	3.3	3.4
$f_{ctk,sp,0.95}$	MPa	5.1	5.5	5.5	5.9	5.9	6.1	6.1	6.3
E_{cm}	MPa	35220	36283	36283	37278	37278	38214	38214	39100
E_{cm1}	MPa	33620	34634	34634	35583	35583	36477	36477	37323
E_{cm2}	MPa	36821	37932	37932	38972	38972	39951	39951	40877
ϵ_{cd0}	$\mu m/m$	380	360	360	340	340	320	320	300
ϵ_{cd1}	$\mu m/m$	194	184	184	173	173	163	163	153
ϵ_{cd2}	$\mu m/m$	566	536	536	507	507	477	477	447

Geophysical parameterization

Tunnel
Fammenian

Category	Parameter	Symbol	Unit	Description	Evieux/Montfort Fm sandstone/siltstones/shales (Upper Devonian - Famennian)
Hoek–Brown rock mass parameters	Rock mass Young’s modulus	Erm	MPa	Elastic modulus of rock mass	17000
	Poisson’s ratio	ν	–	Poisson’s ratio of rock mass	0,07
	UCS of intact rock	σ_{ci}	MPa	Uniaxial compressive strength of intact rock	50
	Intact rock constant	m_i	–	Hoek–Brown intact rock parameter	6
	Geological Strength Index	GSI	–	Rock mass quality index	55
	Dilatancy angle	ψ_{max}	°	Dilatancy angle at $\sigma'_3 = 0$	55
	Confining pressure at $\psi = 0$	σ_ψ	MPa	Pressure where dilatancy becomes zero	6
	Depth above ground level	D	m	Depth above ground level	140-260
In-situ stress and groundwater conditions	Horizontal in-situ stress ratio	K_0	–	Ratio of horizontal to vertical stress	1-2
	Unit weight of ground	γ	MN/m ₃	Rock mass unit weight	0,026-0,028
	Groundwater level	GW	m	Water table relative to ground level	40
	Water head above tunnel crown	Hw	m	Hydrostatic head above tunnel crown	150
Permeability	Horizontal permeability	k_x	m/s	Horizontal hydraulic conductivity	3,6E-08 - 1,3E-05
	Vertical permeability	k_y	m/s	Vertical hydraulic conductivity	

FE soil–structure interaction analysis with Tractebel

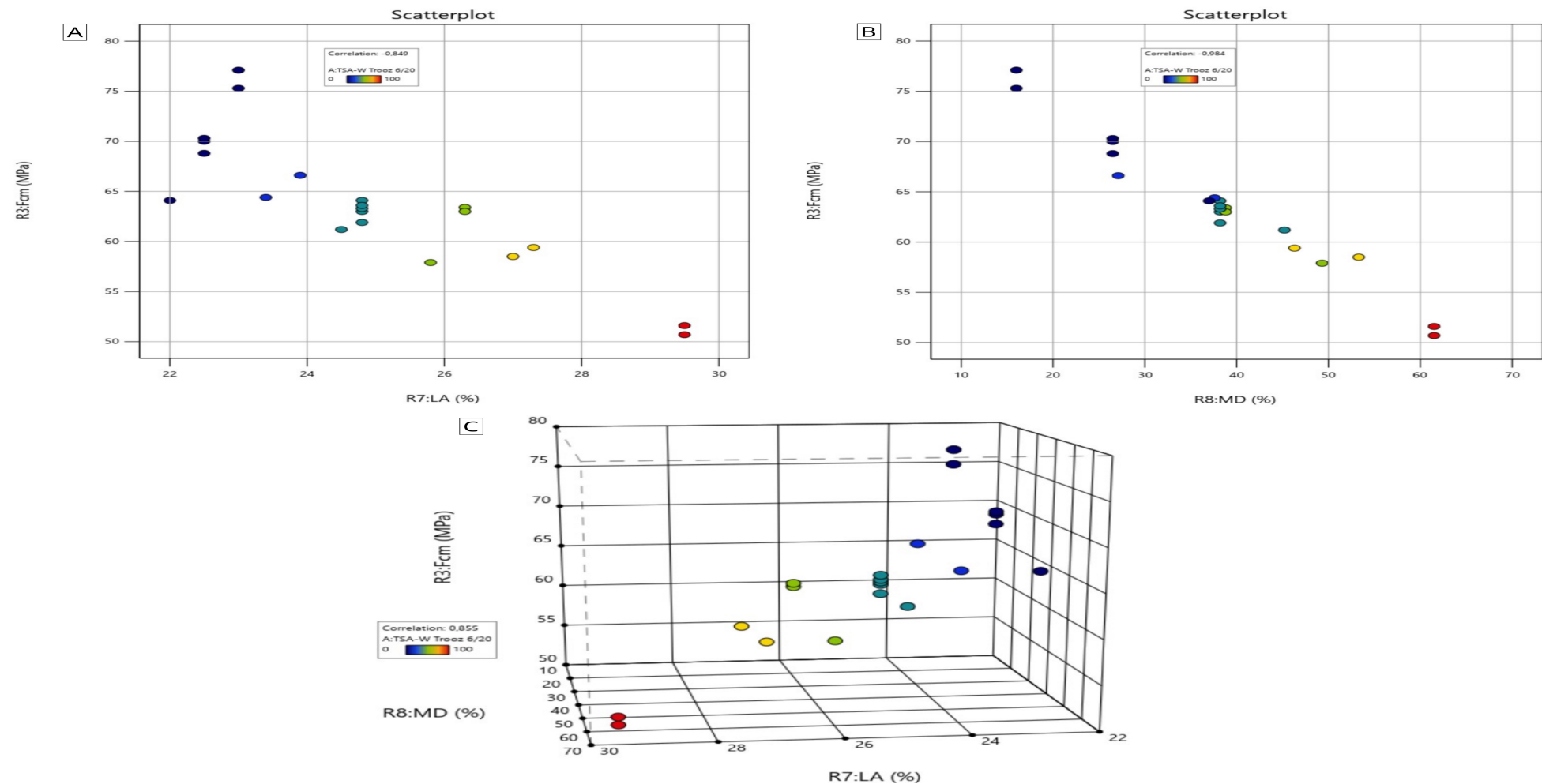
Finite Element (FE) soil–structure interaction analysis

- PLAXIS 2D plane-strain tunnel model
- Ground stresses varied by K_0
- Concrete stiffness varied parametrically
- Segment joints represented by reduced stiffness
- Outputs: μ_2 , N, M, Q
- Capacity checked using M–N diagrams
- Higher stiffness increases strength demand

At-rest earth pressure coefficient

$$K_0 = \frac{\sigma_h}{\sigma_v}$$

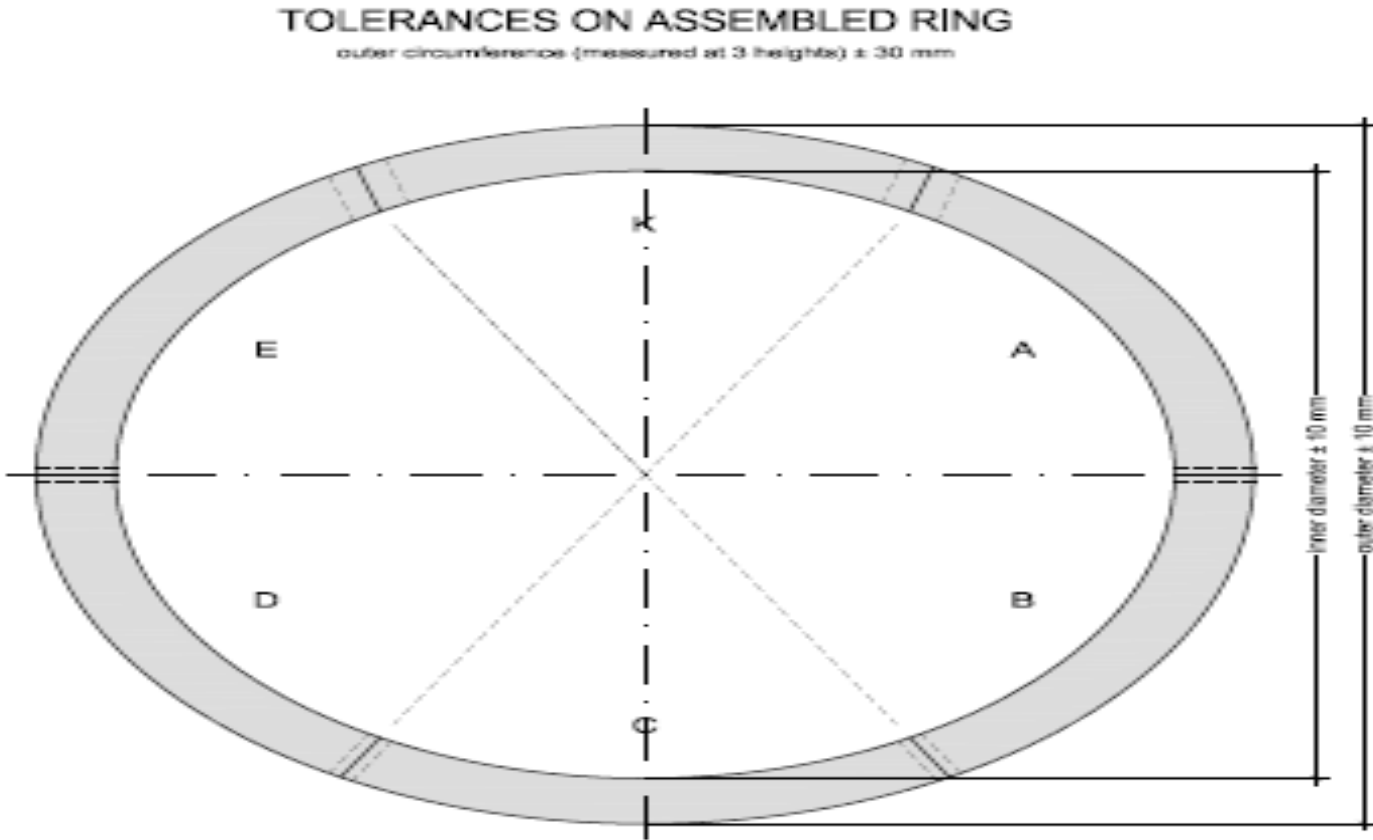
FE soil–structure interaction analysis with Tractebel



Modelling ongoing with Tractebel

	Storage phase/Early stage	Gasket	Earth pressure			TBM Jacking thrust	
			$K_0 = 1,0$	$K_0 = 1,5$	$K_0 = 2,0$	Nominal and accidental thrust	
						No eccentricity	With eccentricity
E_c	$f_{ck,min}$	$f_{ck,min}$	$f_{ck,min}$	$f_{ck,min}$	$f_{ck,min}$	$f_{ck,min}$	$f_{ck,min}$
	[MPa]	[MPa]	[MPa]	[MPa]	[MPa]	[MPa]	[MPa]
11 GPa	12	§11.2	12	20	25	40	40
32 GPa			22	33	45		
35 GPa			23	35	47		
37 GPa			24	36	49		

- C40/50 minimum baseline (TBM jacking) with $E_{cm} = 32\text{--}37$ GPa
- $K_0 < 1,7 \rightarrow$ minimum baseline
- $K_0 \geq 1,8$ requires **C50/60**



Maximum compressive stress $\sigma_{c,max}$ in the tunnel liner as a function of the geostatic stress ratio K_0 , shown for two concrete stiffness values ($E_{cm} = 37$ GPa and $E_{cm} = 32$ GPa)

Major take-home messages D3.1

1. **DOE-FEM** links aggregates to liner performance.
2. **Aggregate** quality is a **critical** decision parameter, not passive.
3. **C-rich/B-C blends** are **priority** design zones.
4. **E-modulus** is **structurally critical**, not secondary.
5. C40/50 for $K_0 < 1,7$ but **C50/60** for $K_0 \geq 1,8$.
6. **DOE** procedure enables **circular TBM-spoil reuse** for ET.
7. **DOE** procedure directly applicable for « next-level » **general concrete design**.

TSA-W Trooz 6/20	TSA-D Trooz 6/20	TSA-D Rondia 6/20
A	B	C
Sandstone–siltstone–shale dominated (Fam.)	Sandstone-dominant, minor limestone and siltstone (Fam.)	Limestone-dominant, local chert (Tourn.)