

Experimental section on the A1 Motorway for Full-Depth Reclamation validation technologies. Study on the Determination of Shear Properties of BSM

National Company for Road Infrastructure Administration - Romania

(www.cnadnr.ro)



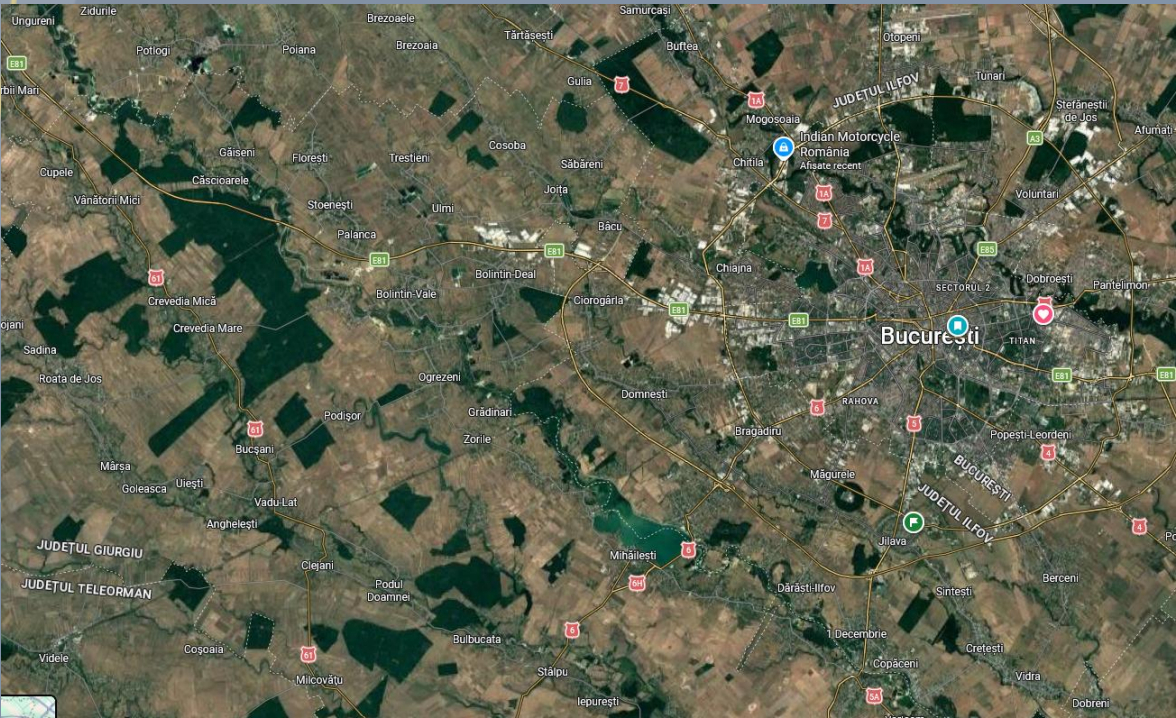
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A1 Motorway – test road section,

- km 19+348 –km 29+836
(8.6 km, way 2, lane 1)
- Traffic: 10.87MSA (115 KN)



Sector	Chainage	Road Structure for rehabilitation and FDR technologies applied
I	Km 19+348 – Km 19+740 Km 20+332 – Km 22+057	- 20 cm AC + 4 cm SMA 16 - granular base layer (0-063 mm) - FDR with Foam bitumen (FB) after removing wering coarse
II	Km 19+700 – Km 19+740 Km 19+800 – Km 20+332	- 20 cm AC + 4 cm SMA 16 - granular base layer (0-063 mm) - FDR with Bitumen emulsion (EB), after removing wering coarse
III	Km 23+760 – Km 24+826 Km 26+106 – Km 27+580 Km 27+700 – Km 29+836	- 17 cm AC + 4 cm SMA 16 - slab sub base layer - FDR with Bitumen emulsion (EB), after removing wering coarse
IV	Km 24+826 – Km 26+106	- 17 cm AC + 4 cm SMA 16 - slab sub base layer - FDR with Foam bitumen (FB), after removing wering coarse

Mix design by TG 2 Method*

ID of Mix design	Mix design	Dosage (by mass)	ITS Dry (KPa) - after 72h in oven and 24 h in climatic chamber	TSR (%) - after 72h in oven and 24 h in water	Volumic mass (t/m ³)	Stiffnes (KPa) - after 72h in oven and 24 h in climatic chamber
E 2.1	Emulsion CBCL 60 (add at 100% agregates)	2.5%	269	76	2.058	2177
	Active filler DOROPORT	2%				
	RAP	95.5%				
	Sand 0-4 mm	0%				
F 1.1	Foam bitumen	1.8%	275	61	2.066	2150
	Active filler DOROPORT	1%				
	RAP	97.2%				



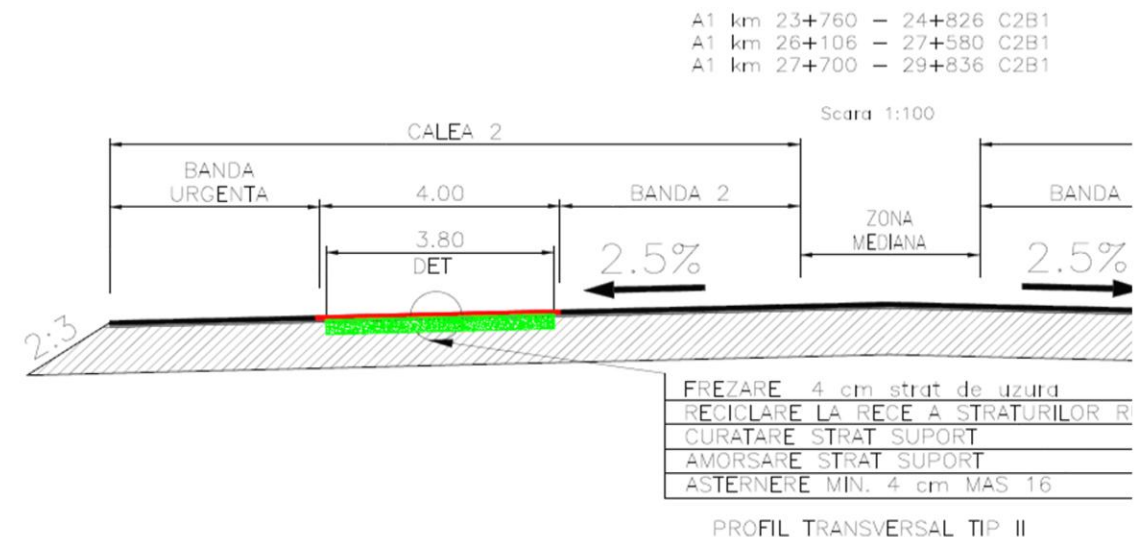
** With technical support with Loundon International (Memorandum CNAIR – WIRTGEN – Loundon International, signed in Aachen 2025)*

Technical solution for works



Equipments:

- **WIRTGEN W 240 CR**
- **VÖGELE SUPER 1800-5i**
- **HAMM HD 120** (~12t, steel cilinder, vibrare vertical) for 1-st compaction
- **HAMM HC 200** (~20 t, mix cilinders) for 2-nd comp
- **HAMM HP 160** (~18t, pneus cilinders) for final comp



FWD Testing for evolution Bearing Capacity

Sector 1: Chainage 19400 – 22057

This sector shows a noticeable increase in surface deflection in the 2026 "After" measurements compared to 2025.

Statistic (Approx.)	Sept 2025 (Before)	April 2026 (After)	Change
Avg. Load	~57.5 kN	~55.2 kN	-4%
Avg. Surface Temp	39.1°C	13.2°C	-25.9°C
Max Deflection (D_1)	~210 μm	~245 μm	+16.7%
Subgrade (D_{10})	~32 μm	~35 μm	+9.3%

Sector 2: Chainage 24826 – 29800

This sector shows a different trend, with more stability in the structural response.

Statistic (Approx.)	Sept 2025 (Before)	April 2026 (After)*	Trend
Avg. Load	~57.2 kN	~55.8 kN	Stable
Avg. Surface Temp	37.2°C	12.5°C	-24.7°C
Max Deflection (D_1)	~145 μm	~220 μm	Increase
Subgrade (D_{10})	~29 μm	~34 μm	Increase

Estimated Stiffness Modulus (E_{BSM})

For a 17 cm BSM layer on a rigid base, the $D_1 - D_3$ (Surface Curvature Index) is the best indicator of the BSM layer's health.

- **September 2025 Analysis:** The very low $D_1 - D_3$ gradient (27 μm) at high temperatures suggests that the BSM was exceptionally stiff, likely benefiting from the "anvil effect" of the underlying concrete slab. The estimated modulus here is 1,400 – 1,800 MPa.
- **April 2026 Analysis:** The gradient increased to 81 μm . While some of this is seasonal variation, a gradient of this size on a concrete base suggests the BSM is behaving more like a flexible material. The estimated modulus drops to 900 – 1,100 MPa.

Parameter	Sector 1 (Granular Base)	Sector 2 (Concrete Base)
Thickness	20 cm	17 cm
Est. Modulus (E_{BSM})	600 - 900 MPa	900 - 1,800 MPa
Structural Integrity	Moderate	High

Laboratory Study on the Determination of Shear Properties of BSM

- Preparation of cylindrical specimens
Ø50mm, h100mm
handling weight (mixture+mold)
≈0.430kg / cylinder
- Triaxial testing with hydraulic press
handling weight (mixture+mold)
≈11kg / cylinder
- Triaxial testing of 12 cylinders
>6 confining pressures (max. 2000kPa)
5kg (5%) handling weight of BSM mixture
100kg (25%) handling weight (mixture+mold)



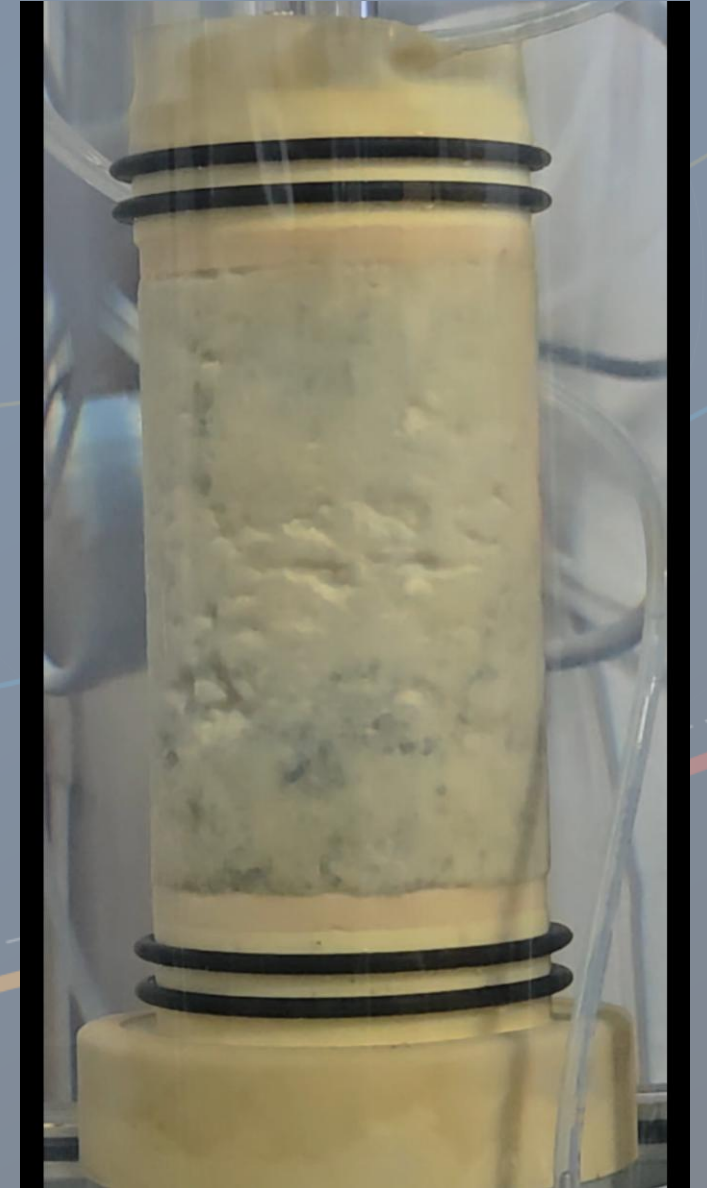
SR EN ISO 17892, with 0-16 mm RAP

Triaxial testing of the laboratory specimens

- Triaxial testing equipment typically employed for geotechnical investigations and testing
- The samples were subjected to compressive load, unconfined, and with confining pressure of 50kPa, 100kPa, 200kPa, 400kPa și 800kPa
- Retained Cohesion (RetC) has been evaluated, to 100kPa confining pressure (σ_3), on saturated samples by soaking in water for 24h prior of testing



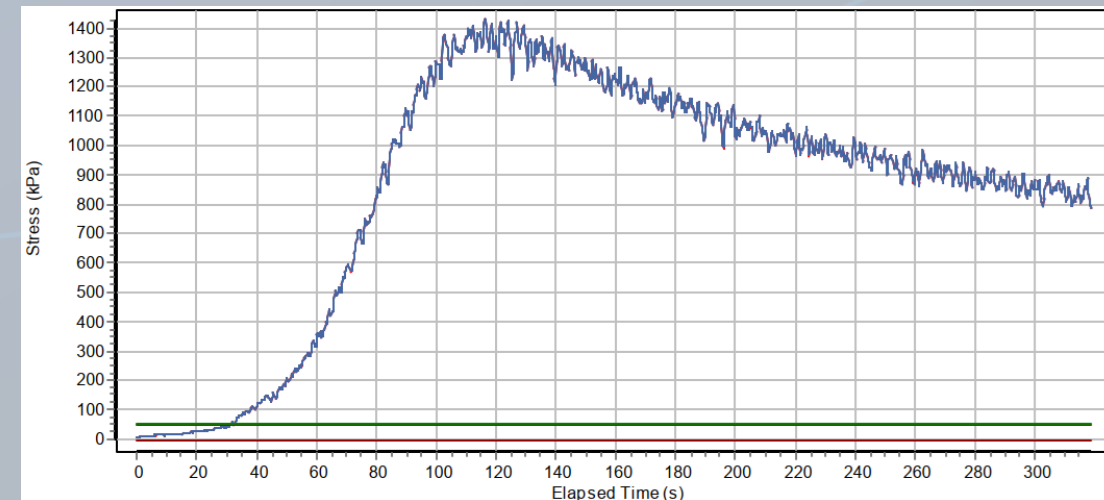
Determination of Shear Properties of BSM



Laboratory results from triaxial testing

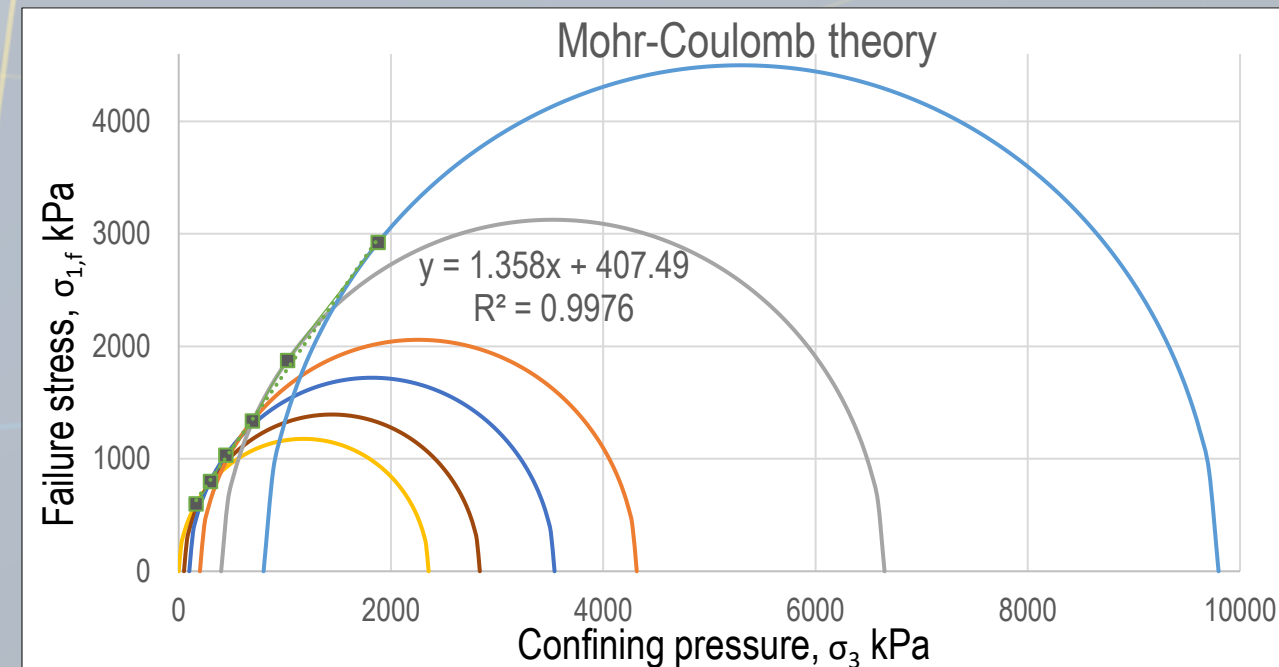
Sample identification	P1 & P2	P3 & P4	P5 & P6	P7 & P8	P9 & P10	P11 & P12
Confining pressure (σ_3), kPa	0	50	100	200	400	800
Failure stress ($\sigma_{1,f}$), kPa	1177	1394	1721	2058	3125	4499

Sample identification	P5 & P6	P13 & P14
Specimen conditioning	unconfined (u)	soaking (s)
Confining pressure (σ_3), kPa	100	100
Failure stress ($\sigma_{1,f}$), kPa	1721	1329
Retained Cohesion (RetC), %	76	



Interpretation of the laboratory results

- Graphical representation of the linear regression, using the Mohr-Coulomb method, for the relationship between the failure compressive strengths and confining pressures
- Characteristics of linear regression
slope $A = 1.358$
intercept with Y ax, $B = 407.49$
- Characteristics of BSM
Angle of internal friction $\varphi' = 53.63^\circ$
Cohesion $C' = 407.49\text{kPa}$



$$\varphi' = \tan^{-1}(A), ^\circ$$

$$C' = B, \text{kPa}$$

Interpretation of the laboratory results

- Graphical representation of the deviatoric stresses at failure

$(\sigma'_v - \sigma'_h)/2$ versus $(\sigma'_v + \sigma'_h)/2$

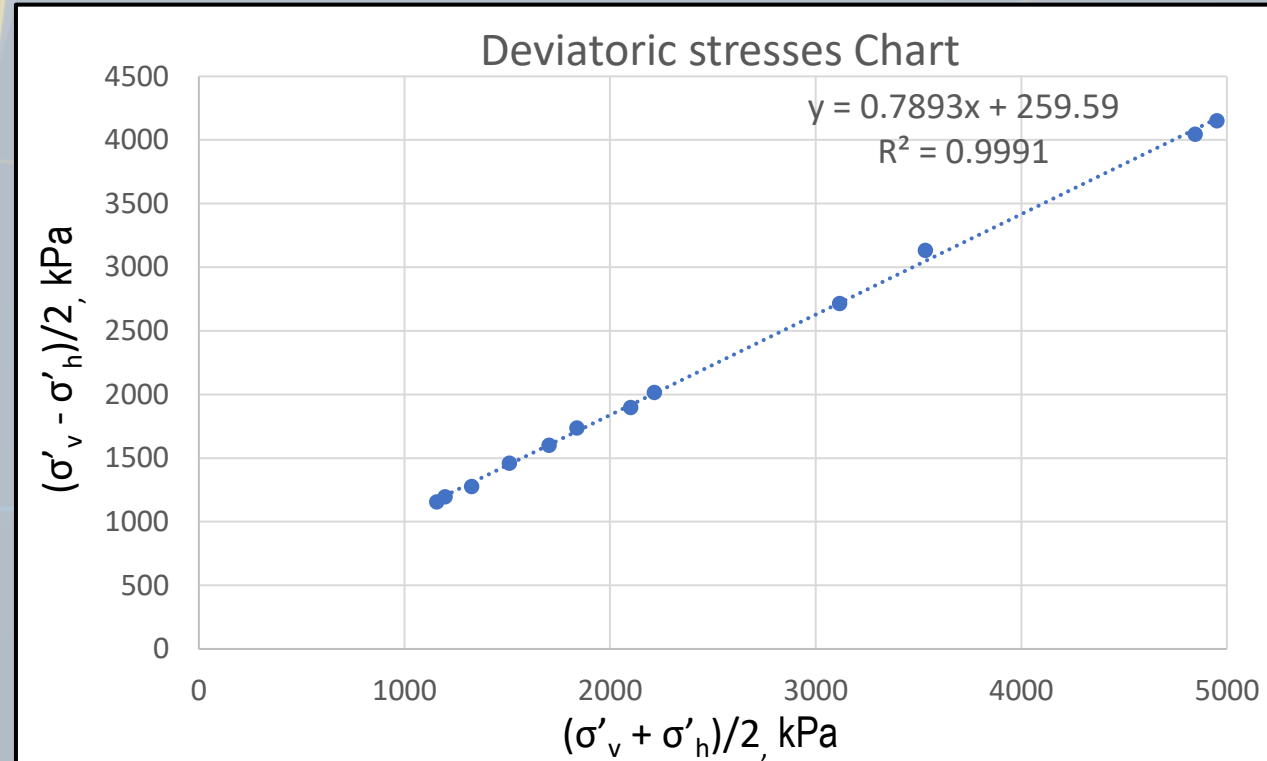
- Characteristics of linear regression
slope $A = 0.7893$

intercept with Y ax, $B = 259.59$

- Characteristics of BSM

Angle of internal friction $\alpha' = 38.28^\circ$

Cohesion $k = 259.52\text{kPa}$



$$\alpha' = \tan^{-1}(A), ^\circ$$

$$k = B, \text{kPa}$$

Interpretation of the laboratory results

- Graphical representation of the shear strength envelope in the p-q space

$$p = \frac{\sigma_{1,f} + 2\sigma_3}{3}, kPa$$

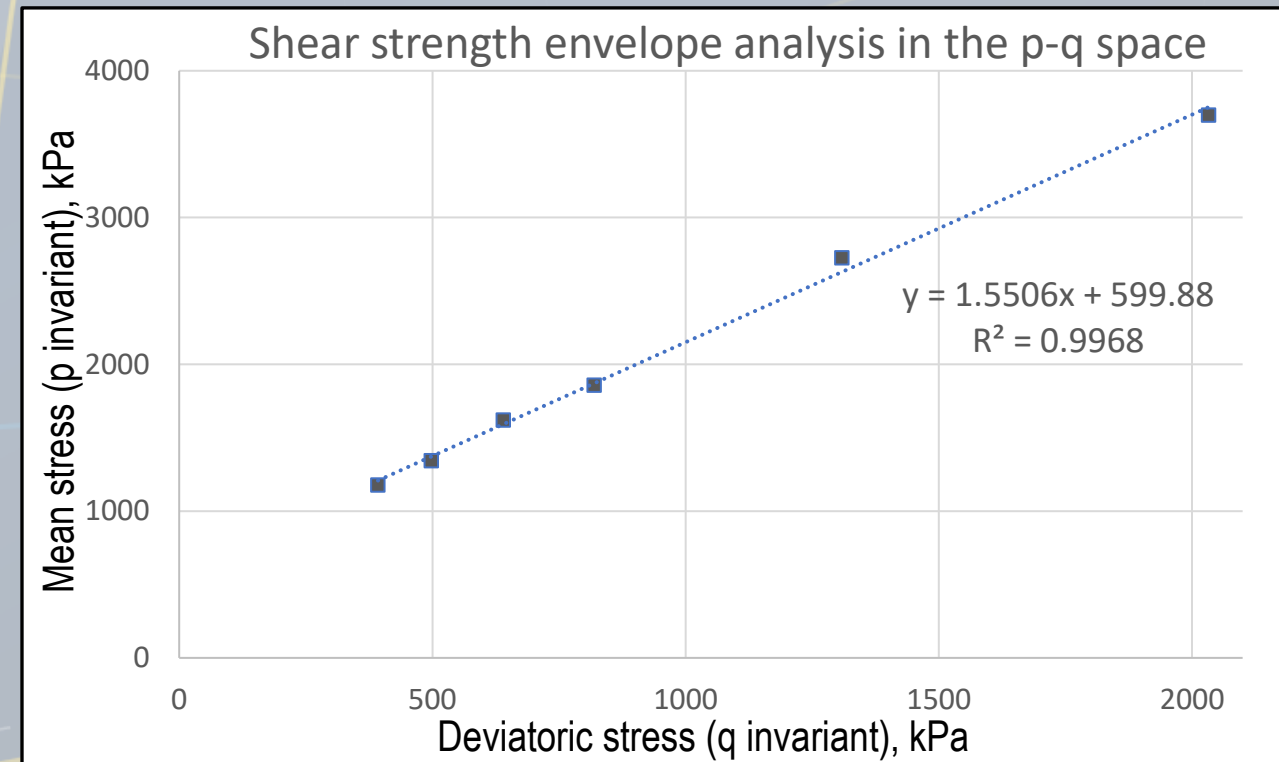
$$q = \sigma_{1,f} - \sigma_3, kPa$$

- Characteristics of linear regression
slope $M = 1.5506$
intercept with q ax, $k = 599.88$

- Characteristics of BSM

Angle of internal friction $\varphi = 38.06^\circ$

Cohesion $C = 302.51kPa$



$$M = \frac{6 \cdot \sin \varphi}{3 - \sin \varphi}$$

$$k = \frac{6 \cdot C \cdot \cos \varphi}{3 - \cos \varphi}$$

Interpretation of the laboratory results

- Evaluation of the BSM mechanical properties based on the calculation method used

Interpretation method	Angle of internal friction	Cohesion
Linear regresion ($\sigma_{1.f}$) şı (σ_3)	37.91°	304.85kPa
Linear regresion ($\sigma_{1.f}$) şı (σ_3) with Mohr-Coulomb theory	53.63°	407.49kPa
Deviatoric stresses ($\sigma'_v - \sigma'_h$)/2 şı ($\sigma'_v + \sigma'_h$)/2	38.28°	259.52kPa
p-q	38.06°	302.51kPa

- It can be deduced that the evaluation of shear characteristics using the Mohr-Coulomb method is not suited for application to BSM-type materials
- The other three methods offer quite similar results

Interpretation of the laboratory results

- Evaluation of the secant modulus of elasticity (E_{50})

$$E_{50} = \frac{\sigma_{50}}{\varepsilon_{50}}, MPa$$

σ_{50} – 50% of the Failure stress ($\sigma_{1,f}$) resulted on triaxial tests of samples subjected to a Confining pressure (σ_3) of 50kPa

ε_{50} – axial strain recorded at σ_{50}

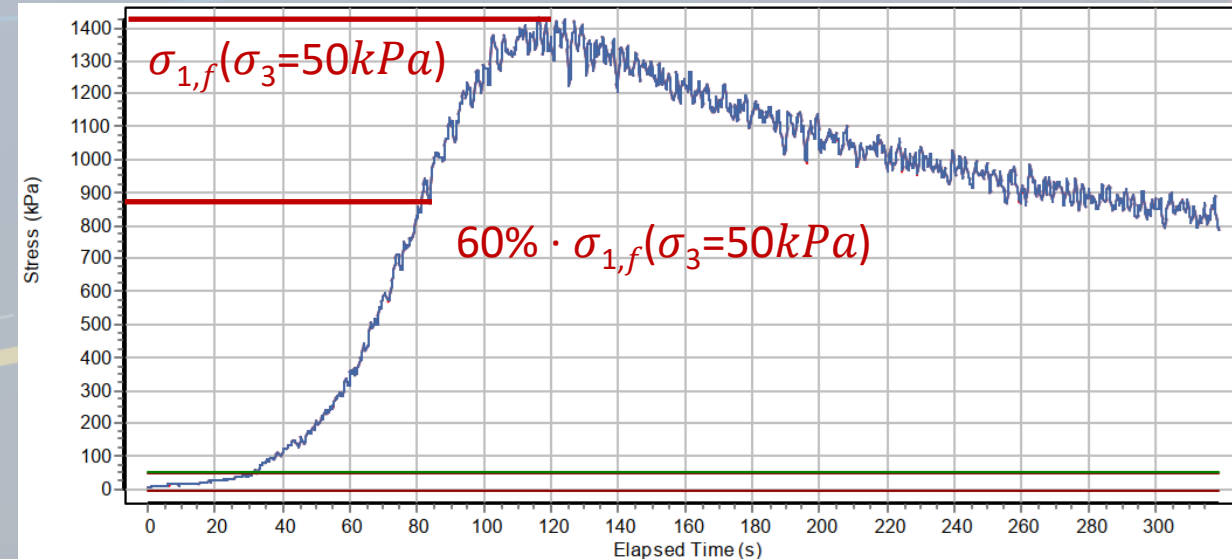
- **$E_{50} = 107.59MPa$**
- secant modulus of elasticity (E_{50}) generally varies between 50MPa and 300MPa , in the case of BSM-type materials

Interpretation of the laboratory results

- Evaluation of the elastic behavior range of the BSM (the stress range within which the material responds reversibly, without permanent damage)
- in the literature, it is considered to be 60% of the Failure stress ($\sigma_{1,f}$) resulted to a Confining pressure (σ_3) of 50kPa

$$\sigma_{\text{elastic}} = 0.6 \cdot \sigma_{1,f}(\sigma_3 = 50\text{kPa}), \text{MPa}$$

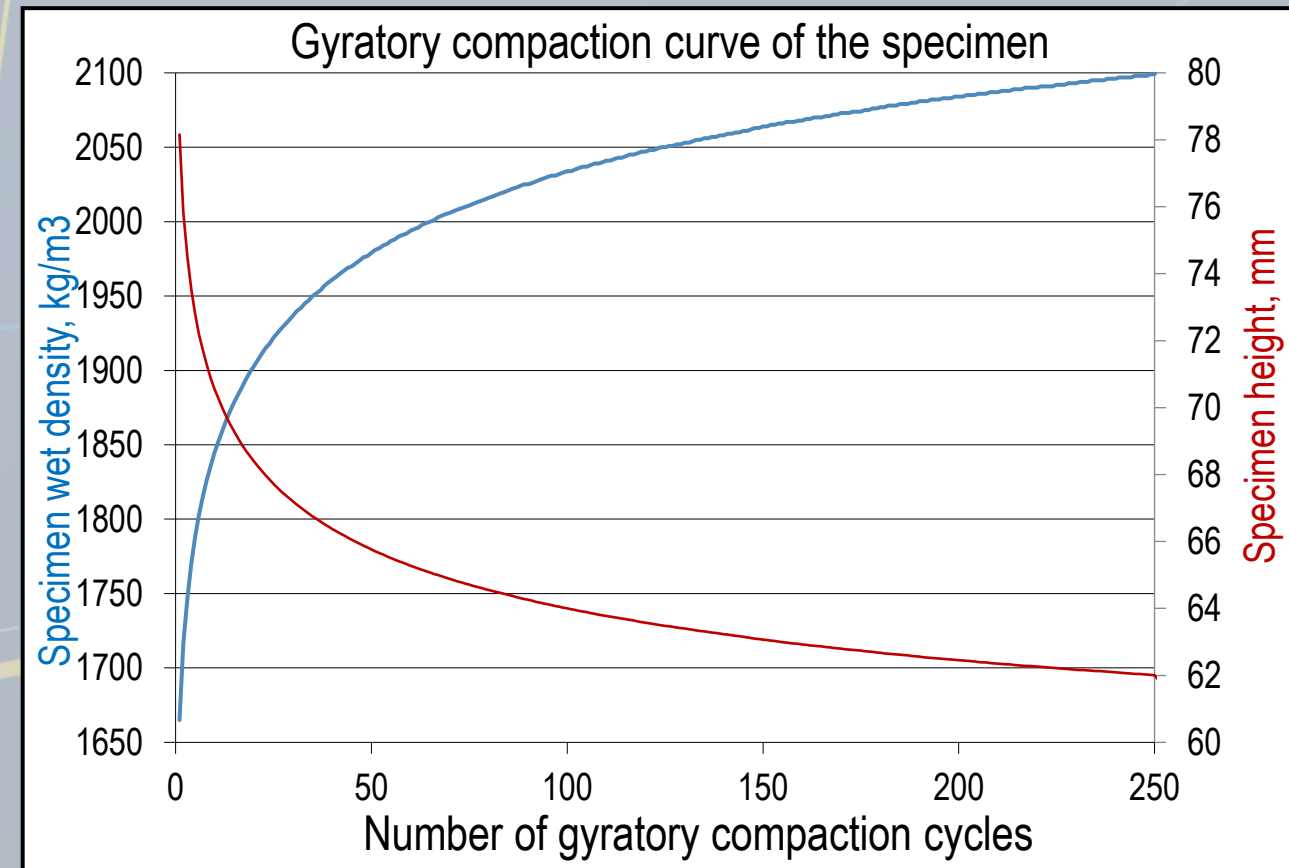
- Thus, the elastic domain is obtained σ_{elastic} up to **836.23kPa**



Extension of the study on specimens compacted with gyratory compactor

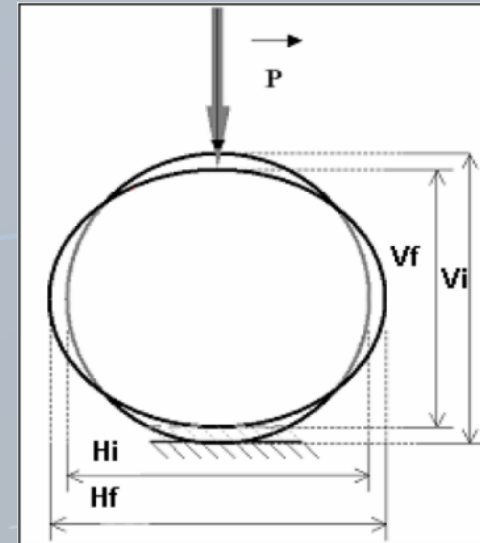
Further mechanical characterization of BSM with respect to:

- Stiffness modulus
IT-CY (E)
- Poisson's ratio
(μ)
- corresponding number of gyrations
for (Gc)=100%



Extension of the study on specimens compacted with gyratory compactor

Sample identification	Degree of compaction (G_c), %	Corresponding gyration for (G_c)=100%	Rigidity IT-CY (E), MPa	Poisson coefficient (ν)
<i>Mean</i>	100.8	180	1165	0.30



EN 12697-27 – IT-CY (Annex C)

$$S_m = \frac{F \cdot (\nu + 0.27)}{h \cdot \Delta z}$$

$$\nu = 3.59 \cdot \frac{\Delta H}{\Delta V} - 0.27$$

Extension of the study on specimens compacted with gyratory compactor

- Evaluation of the Shear modulus (G) and the Bulk modulus (K)

$$G = \frac{E}{2 \cdot (1 + \mu)} = 448 \text{MPa}$$

$$K = \frac{E}{3 \cdot (1 - 2\mu)} = 971 \text{MPa}$$

- The Shear modulus (G) for typical BSMs reanges between 300 and 800MPa
- The Bulk modulus (K) for typical BSMs reanges between 600 and 1500MPa

Overview of BSM performance characteristics relevant in pavement design

• Angle of internal friction (φ)	φ	= 37.91 ÷ 38.28°
• Cohesion (C)	C	= 259.52 ÷ 304.85kPa
• Secant modulus of elasticity (E_{50})	E_{50}	= 107.59MPa
• Elastic behavior range (σ_{elastic})	σ_{elastic}	= 836.23kPa
• Retained Cohesion (RetC)	RetC	= 76%
• Rigidity modulus IT-CY (E)	E	= 1165MPa
• Poisson coefficient (μ)	μ	= 0.3
• Shear modulus (G)	G	= 448MPa
• Bulk modulus (K)	K	= 971MPa

CONCLUSION

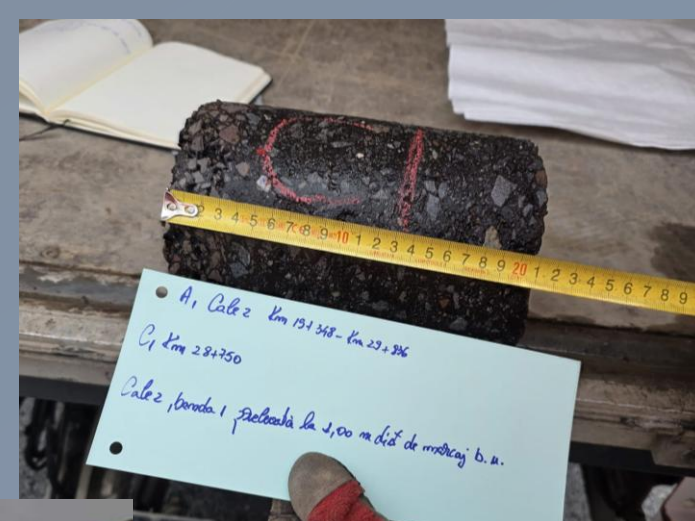
- After a year of intensive use—characterized by high hydrological activity from October 2025 through May 2026, including heavy snowfall and periods of severe frost following precipitation—the road remains in excellent technical condition, with no structural deterioration.
- Laboratory testing using triaxial analysis confirmed the rheological properties of the bitumen-stabilized recycled layer.
- Beyond material and technological performance, the construction of this experimental section helped refine operational procedures for organizing the in-situ recycling worksite.
- **CNAIR** management highly values the collaboration with partners **WIRTGEN** and **Loundon International**. A national regulation for FDR design is currently being drafted. We consider that the technology has been validated under the most severe operating conditions.

- Comparative costs and environmental impact assessment for the works carried out on A1 Mororway

Restoration road structure with hot asphalt mixtures (AC 31.5 + AC22.4+ SMA 16 PmB)	Restoration road structure with cold stabilization using bituminous binder (BSM + SMA 16 PmB)
- 9280 t of AB31.5 type mixture - o Estimated cost (450 lei/t $\approx$ 85.65 EUR/t) - $\approx$ 794,838 EUR - 4709 t of BAD 22.4 type mixture - o Estimated cost (580 lei/t $\approx$ 110.40 EUR/t) $\approx$ 519,850 EUR	- Recycled with FB – 912.967 t - Recycled with BE – 250.443 t Total recycled mixture: 11.634 t Estimated execution cost: $\approx$ 215,000 EUR materials, equipment and labor (in-house management) $\approx$ 246,800 EUR equipment rental Wirtgen
TOTAL cost of base and binder restoration with hot mixtures $\approx$ 1,315,000 EUR	TOTAL cold recycling restoration BSM: $\approx$ 462,000 EUR
Wearing course restoration with SMA 16 PmB	
Procurement and execution of a 4 cm thick wearing course mixture over an area of 34,420 m² (approx. 3,500 t) $\approx$ 328,500 EUR	
TOTAL execution RK with hot mixtures $\approx$ 1,643,000 EUR	TOTAL execution BSM "full depth recycle": $\approx$ 790,200EUR
Carbon footprint	
- 13989 t of AC 31.5 and AC 22.4 mixture = 839 t CO₂ - 3500 t of SMA 16 mixture = 210 t Total: 1.049 t CO₂	- 28,648 l Diesel fuel consumed = 76.2 t CO₂ - 351.96 t bitumen used = 186.5 t CO₂ - 3500 t of SMA 16 mixture = 210 t CO₂ Total: 473 t CO₂



After 9 months , sampling
core and intervention after
accidental diesel fuel spill.





THANKS YOU !