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# **Recycled Materials in Pavement Engineering: Fundamental Research and Collaboration with the Industry**

**prof. Ezio Santagata  
Politecnico di Torino**

Naples, September 8<sup>th</sup>, 2022

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- Self introduction
- Politecnico di Torino
- Research approach for recycled materials in pavements
- Significance of recycling in pavements
- Overview of research projects on recycling in pavements (and 4 examples)
- Final thoughts



*Lake Asphalt in Trinidad*

## Disclaimer:

All views expressed in this presentation are exclusively of prof. Santagata and do not represent the opinions of any organization, institution or entity with which he has been or is affiliated to.

## Full professor of “Roads, Railways and Airports” in the Politecnico di Torino

- Engineering Degree in 1991 (University of Ancona, Italy) - Visiting Scholar at Penn State University (USA) in 1993-1995
- Director of the “Laboratory for Innovative and Recycled Materials in Civil Engineering Infrastructures”
- Member of the Board of Directors of MESAT (Middle East Society of Asphalt Technologists)
- Involved in the “QA/QC Project” of Ashghal (Qatar) from December 2017 to January 2021
- Research focused on pavement materials and structures
- Member of the Editorial Board of 4 International Journals
- Consultant in Italy, Europe and in the MENA Region – Consultant for the World Bank for international projects



Presentation at CIC 2020 (Doha, Qatar)



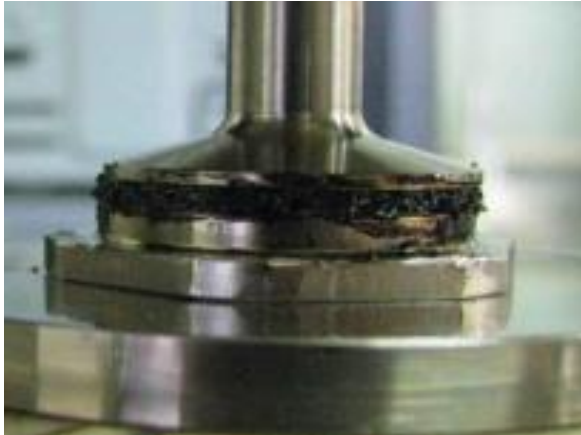
Interview during a site trial of European Project TYREC4LIFE in 2014



With Colleagues at SIIV Winter School 2017

## Pavement Engineering Research Group

- 2 Full, 4 Associates, several Post-docs and PhD candidates
- Wide offer of courses at the undergraduate and graduate level
- Main focus on bituminous materials and pavements
- Road Materials Laboratory: Experimental Laboratory of Innovative & Recycled Materials for Civil Engineering Infrastructures
- Field and laboratory testing, pavement performance modelling, forensic engineering
- Advanced consultancy services
- Specialized instruction



*Rheological testing*



*Asphalt mixing*

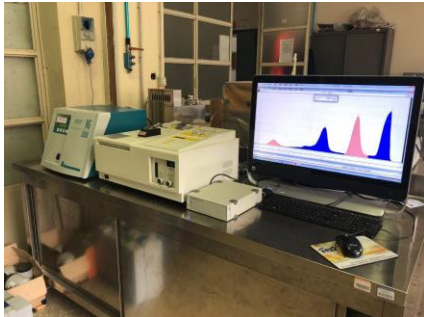


*Research group*

## Essential factors to be considered:

- Avoid “substitute & add” approach
- Use fundamental concepts, multidisciplinary know-how and diagonal thinking
- Focus on end-performance
- Create an added value
- Target a pre-industrial implementation level
- Quantify economic and sustainability factors
- Give equal dignity to top-to-bottom and bottom-to-top project
- Disseminate!

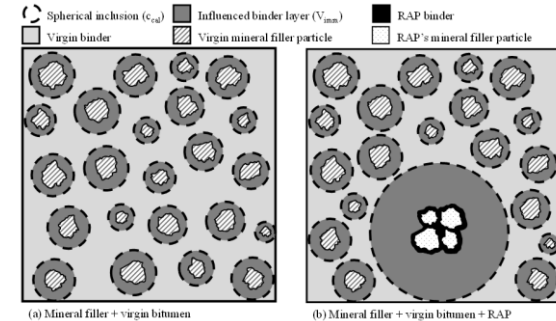
## Several success stories...



SARA analysis of bitumen



Laserscanning of pavement race tracks



Micromechanical modelling of bituminous mastics

## Projects developed by the PoliTO team

- Construction and demolition waste (CDW) (unbound granular materials and cement-stabilized mixes)
- Sawmilling and aggregate washing sludge (asphalt mixes and cement-stabilized materials)
- Ashes from municipal solid waste and biomass (asphalt mixes)
- Reclaimed asphalt (RA) (asphalt mixes, cement-stabilized materials)
- Crumb rubber (asphalt mixes and Portland cement concrete)
- Plastics (asphalt mixes and unbound granular materials)
- Waste polymers (asphalt mixes)
- Paint sludge (asphalt mixes)



*Roughness testing on pavement surfaces*



*Wheel tracking test on asphalt mixes*



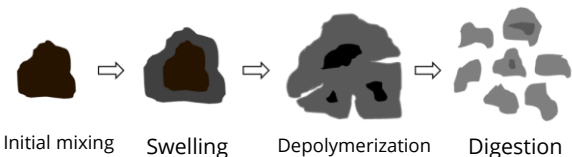
*Triaxial test on unbound materials*

- Understanding Crumb Rubber Modified Binders:

Funding: European Commission (EC), Ministry of Research, ECOPNEUS (Sector Organization)

**GOALS:**

- Improving the effectiveness of crumb rubber modification
- Creation of technology transfer know-how (pre-industrial implementation)



*Stockpile of end-of-life tires*

**BACKGROUND:**

- Desired/reference interaction conditions: swelling, to exploit gel formation phenomena
- General consensus on viscosity as reliable interaction indicator
- Effects of physical and morphological properties not fully understood
- Literature: → Descriptive CR morphology  
→ Physical properties (ASTM D6114 and Technical specifications)  
→ Surface area measurements (overestimate)  
→ Viscosity = f (%CR, SA, GR, composition)

- **Understanding Crumb Rubber Modified Binders:**

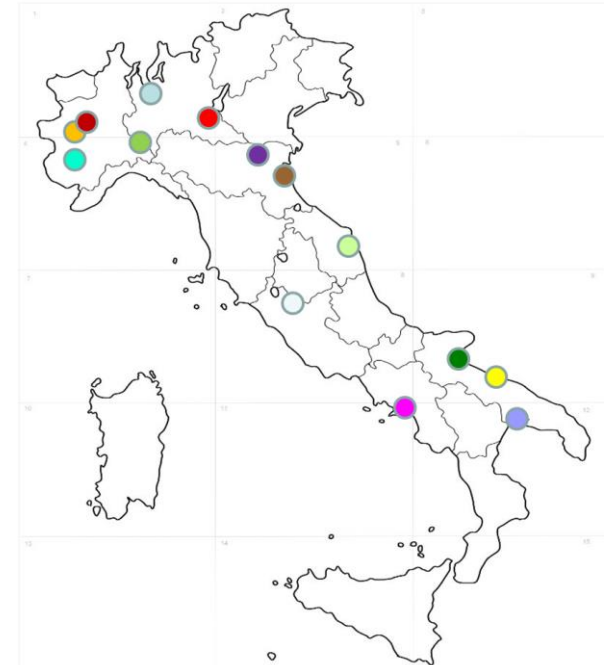
**Funding: European Commission (EC), Ministry of Research, ECOPNEUS (Sector Organization)**

**RESEARCH ACTIVITIES:**

- WP1 Characterization of crumb rubber
- WP2 Characterization of crumb rubber modified binders (CRMBs)
- WP3 Characterization of CRM bituminous mixtures
- WP4 Field trials
- WP4 Performance assessment
- WP5 Technical-economic feasibility and environmental sustainability
- WP6 Technical specifications

**STAKEHOLDERS:**

- 14 Italian tire processing plants + 2 international (38 products)
- 2 Italian refineries (2 base bitumens)



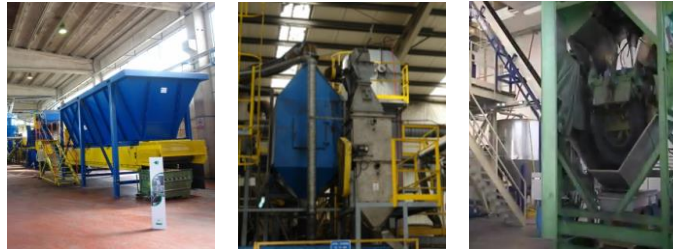
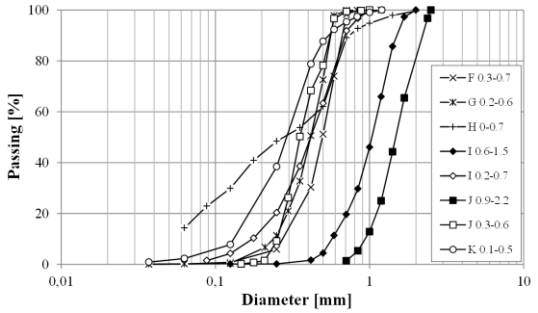
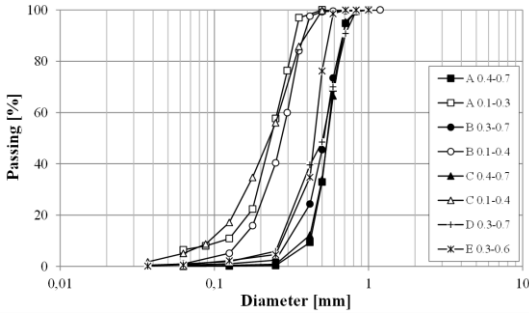
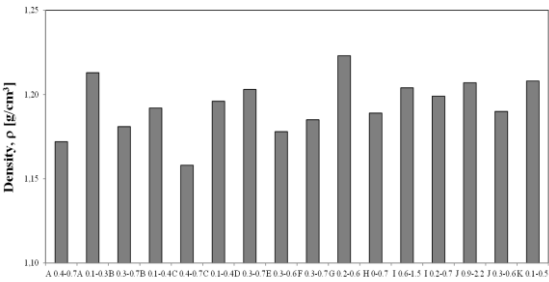
*Plants involved in the research project*



- Understanding Crumb Rubber Modified Binders:**  
**Funding: European Commission (EC), Ministry of Research, ECOPNEUS (Sector Organization)**

**MAIN RESULTS:**

Characterization of crumb rubber (standard):



Different types of tire processing plants

Phases	ELT processing plants										
	A	B	C	D	E	F	G	H	I	J	K
Primary shredding	x	x	x	x	x	x	x*	x**	n.a.	n.a.	x
Iron magnetic separation					x				n.a.	n.a.	
Secondary shredding		x				x	x*		n.a.	n.a.	x
Cold granulation		x	x						n.a.	n.a.	
Iron magnetic separation	x	x	x	x	x	x	x		n.a.	n.a.	x
Primary milling	x	x	x	x	x	x	x*		n.a.	n.a.	
Secondary milling	x								n.a.	n.a.	
Sieving	x	x	x	x	x	x	x	x	n.a.	n.a.	x

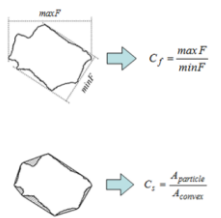
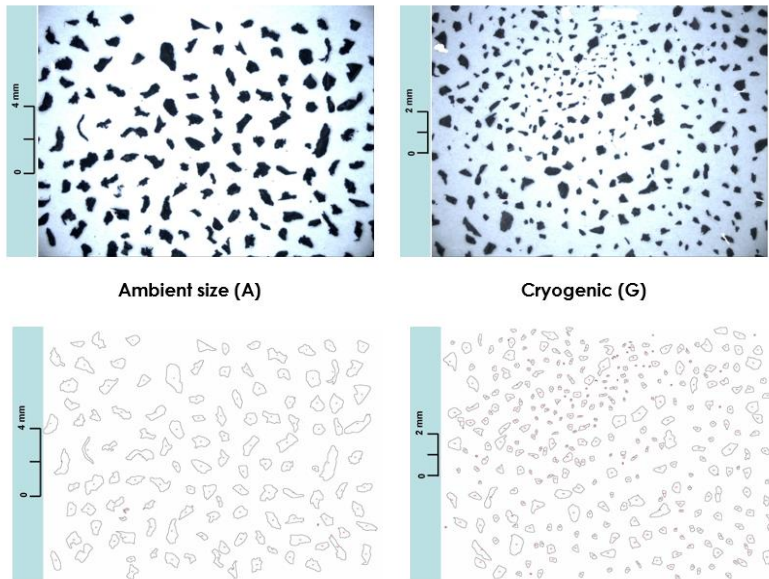
(\*) Carried out in cryogenic conditions  
 (\*\*) Carried out with waterjet treatment.  
 n.a. Information not available.

- Understanding Crumb Rubber Modified Binders:**

Funding: European Commission (EC), Ministry of Research, ECOPNEUS (Sector Organization)

**MAIN RESULTS:**

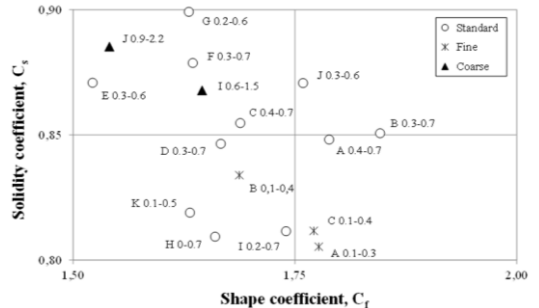
Characterization of crumb rubber (advanced):



Shape coefficient  $C_1$



Solidity coefficient  $C_2$



Shape and texture mapping from modelling

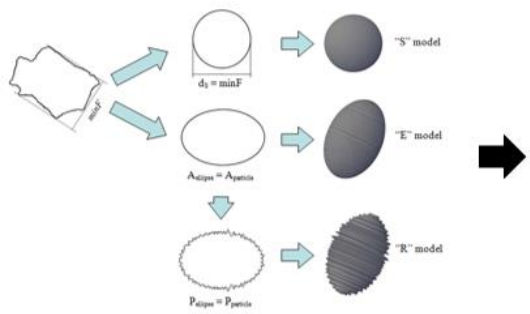
- Understanding Crumb Rubber Modified Binders:**

**Funding: European Commission (EC), Ministry of Research, ECOPNEUS (Sector Organization)**

**MAIN RESULTS:**

Characterization of crumb rubber (advanced):

$$SA_m = \phi \cdot \frac{\sigma}{\rho} \cdot \sum_i \frac{f_i}{d_{m,i}}$$

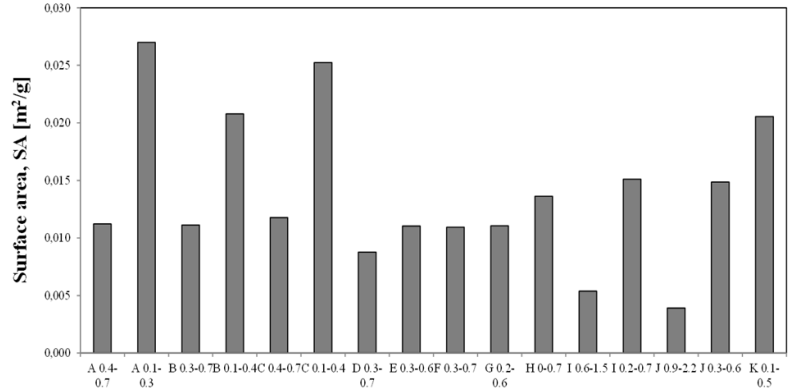


$$\phi = \phi_f \cdot \phi_r$$

$$\phi_f = \frac{(SA_v)_E}{(SA_v)_S}$$

$$\phi = \frac{(SA_v)_R}{(SA_v)_S}$$

$$\phi_r = \frac{\phi_i}{\phi_{f,i}}$$



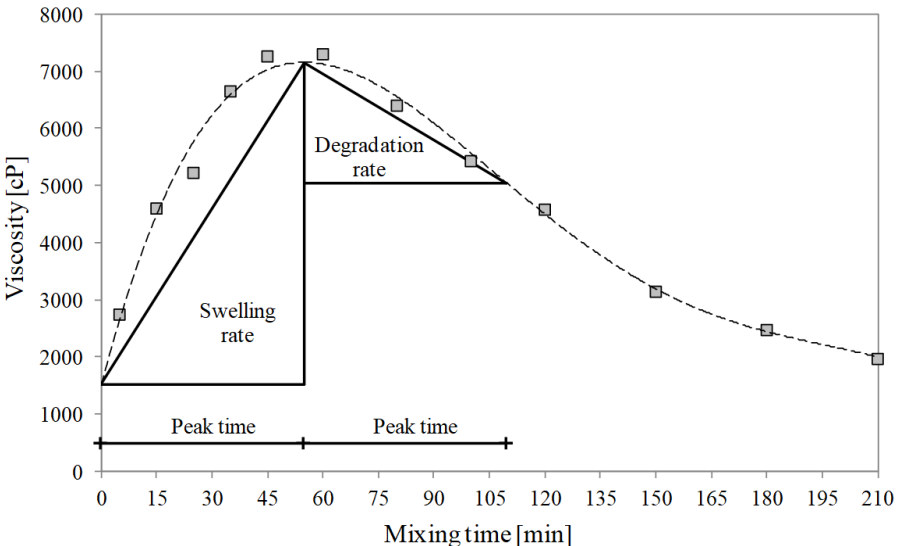
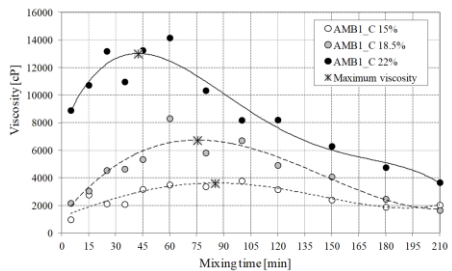
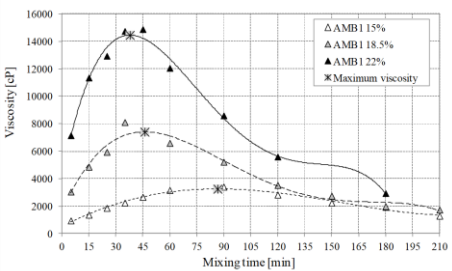
Surface area from image analysis and modelling

- Understanding Crumb Rubber Modified Binders:**

Funding: European Commission (EC), Ministry of Research, ECOPNEUS (Sector Organization)

**MAIN RESULTS:**

Characterization of crumb rubber modified binders:



- Understanding Crumb Rubber Modified Binders:**

**Funding: European Commission (EC), Ministry of Research, ECOPNEUS (Sector Organization)**

**MAIN RESULTS:**

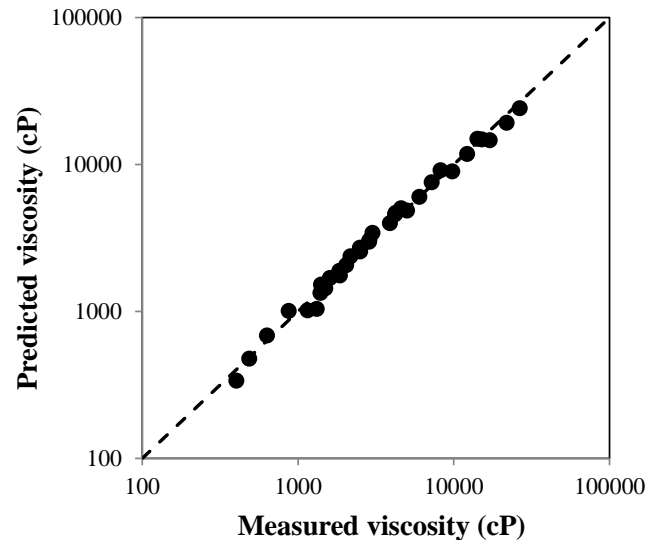
Characterization of crumb rubber modified binders:



$$\eta = 10^{a_1} \cdot T^{-a_2} \cdot \rho^{-a_3} \cdot \phi^{a_4} \cdot \left( 6 \cdot \sum_i \frac{f_i}{d_{m,i}} \right)^{a_5}$$

	i = 1	i = 2	i = 3	i = 4	i = 5
Model parameter $a_i$	15.65	6.36	12.62	0.443	8.93
Standard error $se_i$	0.45	0.12	2.18	0.05	0.94

Viscosity prediction model

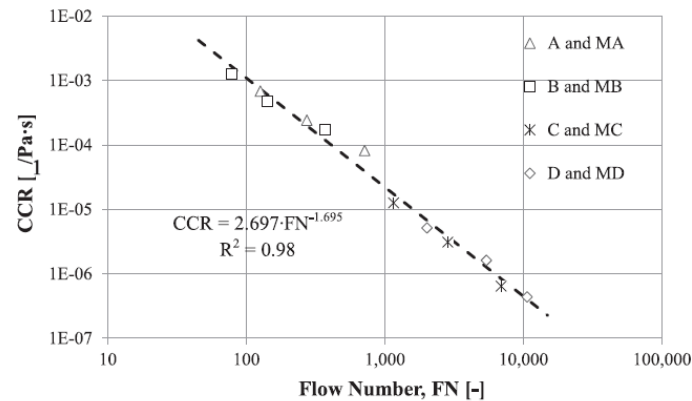
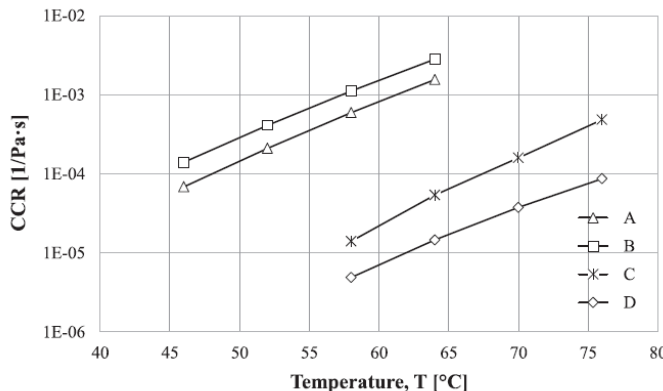


- Understanding Crumb Rubber Modified Binders:**

**Funding: European Commission (EC), Ministry of Research, ECOPNEUS (Sector Organization)**

**MAIN RESULTS:**

Characterization of crumb rubber modified binders:



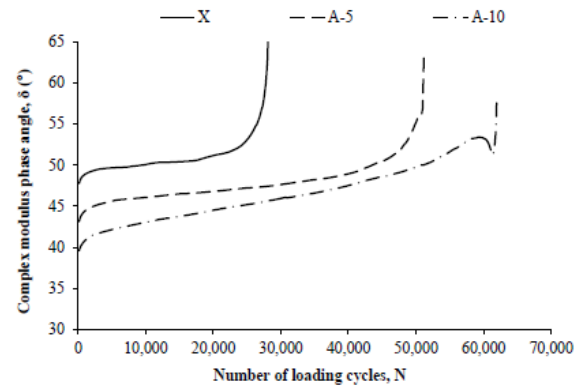
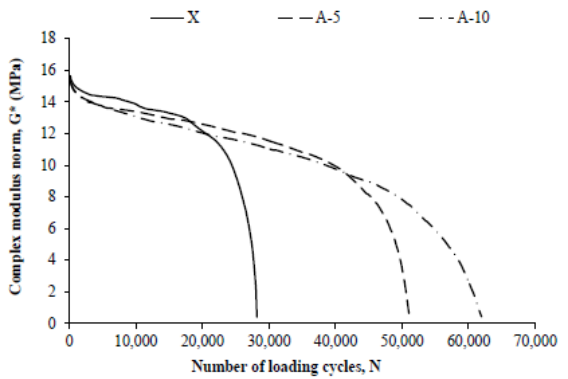
Creep compliance tests on binders and flow number tests on mixes  
CRMB (code D) outperforms PMB (code C)  
Excellent correlation between binder and mix data

- Understanding Crumb Rubber Modified Binders:**

**Funding: European Commission (EC), Ministry of Research, ECOPNEUS (Sector Organization)**

**MAIN RESULTS:**

Characterization of crumb rubber modified binders:



Time sweep tests in equistiffness conditions (300 kPa) 10 Hz  
Damage rate decreases with increasing CR dosage

- **Effect of rejuvenating agents on reclaimed asphalt:**

**Partner: -**

**GOALS:**

- Quantify the effectiveness of rejuvenating agents
- Identify the (RA-specific) optimal dosage of rejuvenating agents



*RA stockpile subjected to processing*

**BACKGROUND:**

- Controversial acceptance of rejuvenating agents (“black rock theory” and “diffusion phenomena”)
- Softening effects often perceived as negative
- Lack of an effective tool in evaluating the true effects of rejuvenating agents
- Literature: → Biasing effects of solvent extraction  
→ Potentially misleading information from mixture testing

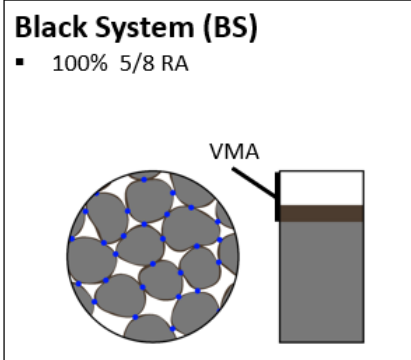
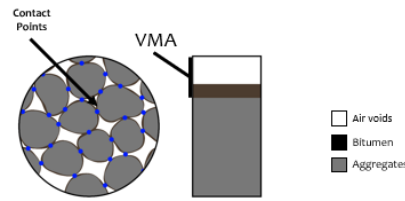


- Effect of rejuvenating agents on reclaimed asphalt:**

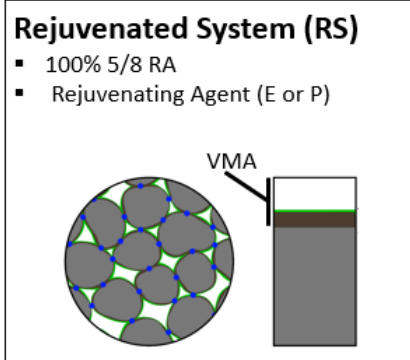
Partner: -

**Innovative concept of MODEL SYSTEMS:**

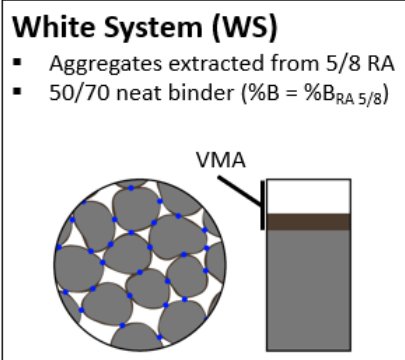
- Selection of a single-sized 5/8 RA
- Target VMA (Voids in Mineral Aggregates) equal to 30%
- Main advantage: maximization of binder phase response



- Air Voids
- Aged Bitumen
- Aggregates



- Air Voids
- Rejuvenating Agent
- Aged Binder
- Aggregates



- Air Voids
- Virgin Binder
- Aggregates

- 3 RA sources (B, C and S)
- 1 aggregate source
- 2 rejuvenating agents (E and P)
- Variable dosages

- Effect of rejuvenating agents on reclaimed asphalt:

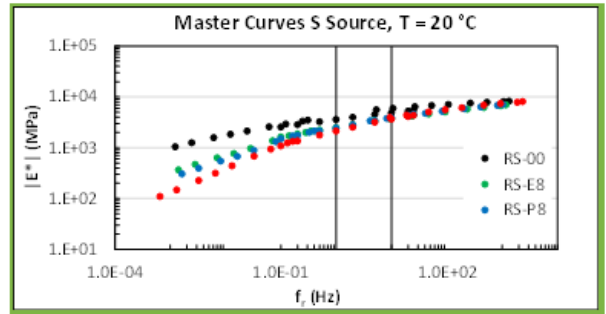
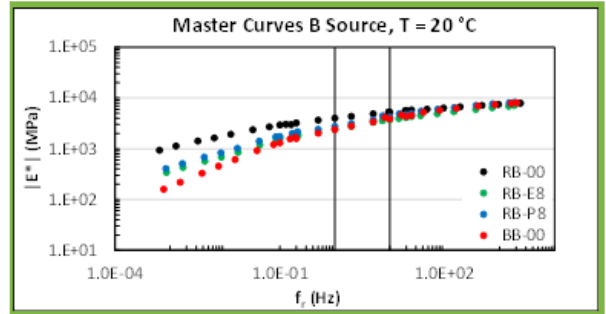
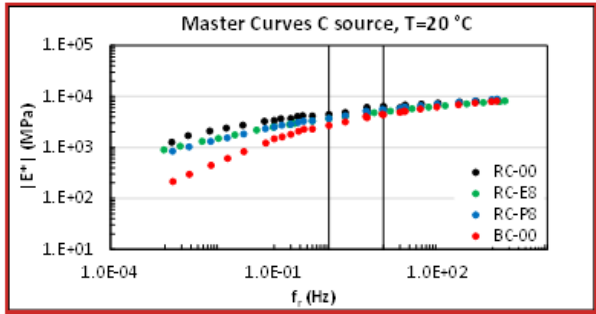
Partner: -

**MAIN RESULTS:**

Dynamic modulus testing at 4, 20 and 40°C (8% dosage for all rejuvenators):



$$\log(|E^*|) = \delta + \frac{\alpha}{1 + e^{\beta - \gamma \log(fr)}}$$
$$f_r = f \cdot a(T)$$



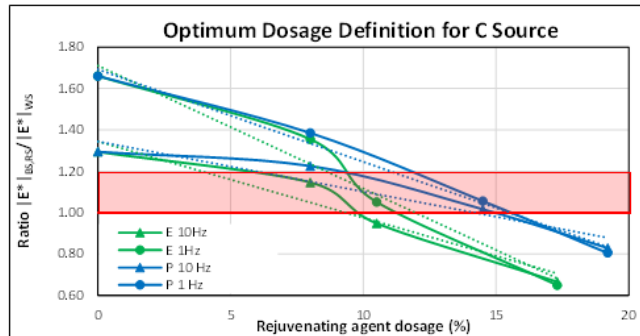
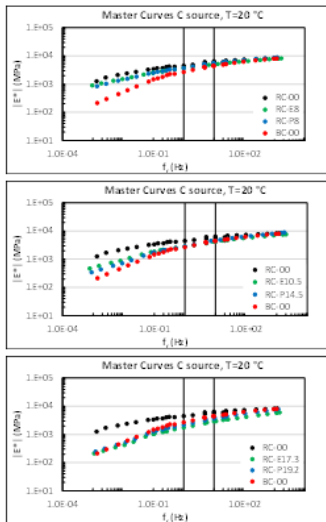
Dynamic modulus test set-up

- Effect of rejuvenating agents on reclaimed asphalt:

Partner: -

### MAIN RESULTS:

Dynamic modulus testing at 4, 20 and 40°C (identification of optimal dosage):



Optimum dosages:

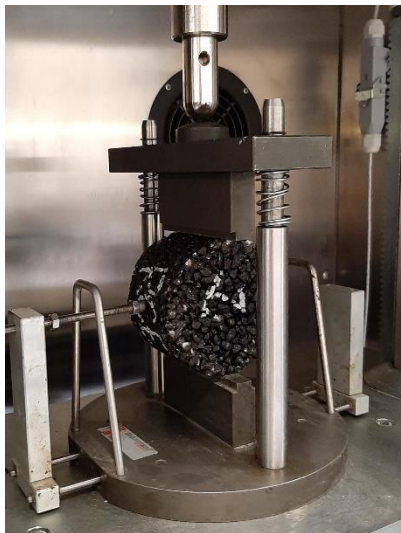
- 10.5% for rejuvenator E
- 14,5% for rejuvenator P

- Effect of rejuvenating agents on reclaimed asphalt:

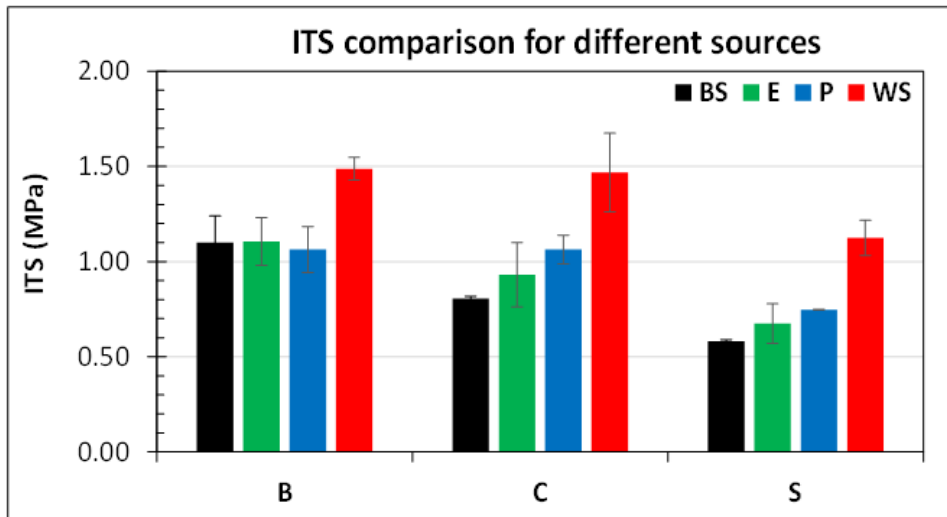
Partner: -

### MAIN RESULTS:

Indirect tensile strength (ITS) testing at 4°C (identification of optimal dosage):



Optimum Dosage		
B	E	8
	P	8
C	E	10.5
	P	14.5
S	E	8
	P	8



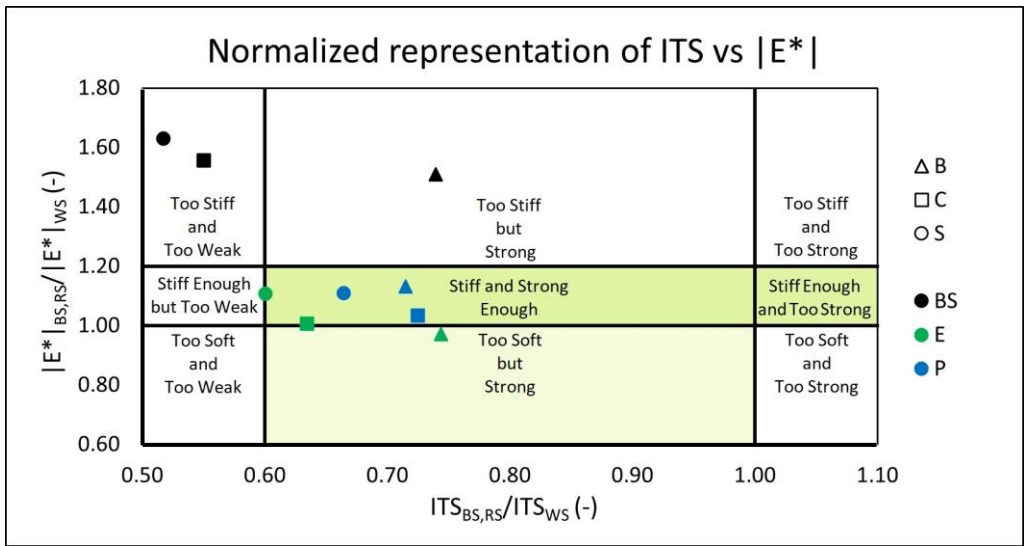


- Effect of rejuvenating agents on reclaimed asphalt:

Partner: -

**MAIN RESULTS:**

Rejuvenator mapping:

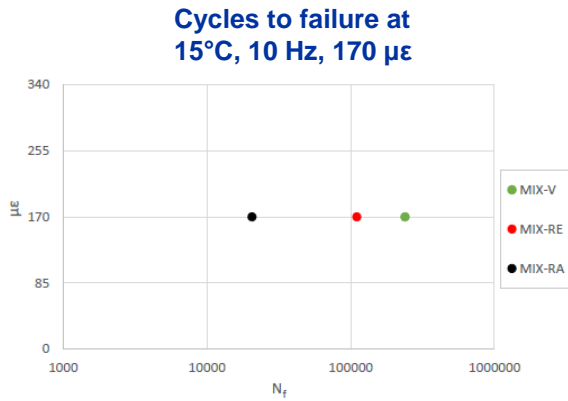
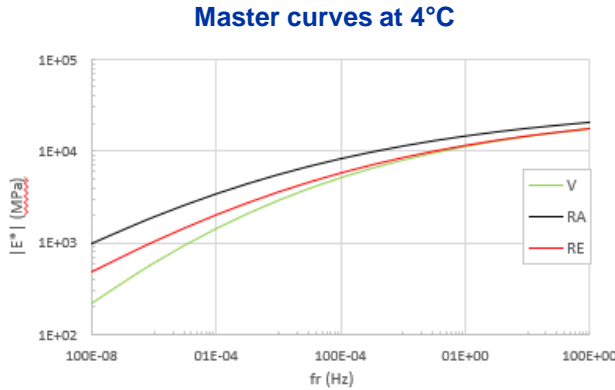


- Effect of rejuvenating agents on reclaimed asphalt:**

Partner: -

**MAIN RESULTS:**

Dynamic modulus and fatigue (validation on asphalt mixes with 50% RA):



**Effects of rejuvenator:**

- Master curve closer to mix with 100% virgin aggregates
- Increase of fatigue life



- **Reuse of Paint Sludge in Road Pavements (RP2):**

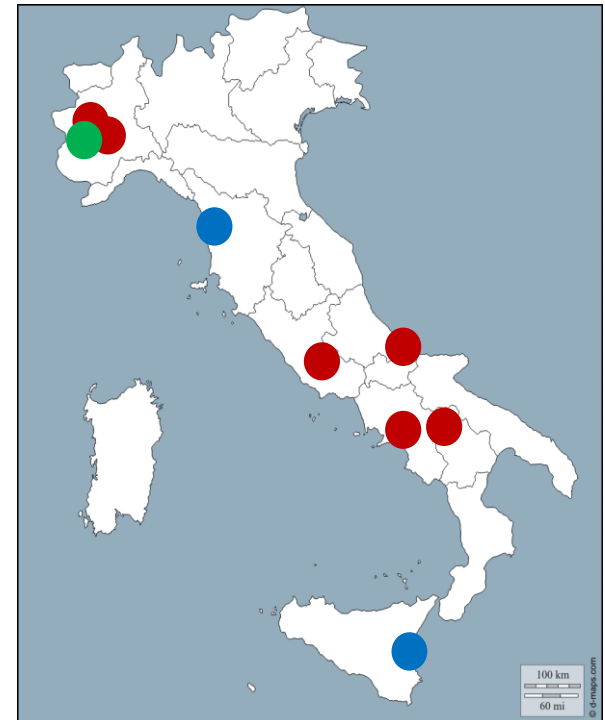
**Industrial Partner: FIAT Chrysler Automobiles (FCA) S.p.A.**

**RESEARCH ACTIVITIES:**

- WP1 Characterization of paint sludge
- WP2 Characterization of paint sludge modified binders (PSMBs)
- WP3 Characterization of PSMB bituminous mixtures
- WP4A Process development
- WP4B Construction of pavement trial sections
- WP5 Evaluation of pavement trial sections
- WP6 Technical-economic feasibility and environmental sustainability

**STAKEHOLDERS:**

- 6 FCA S.p.A. Italian plants (14 paint sludges)
- 2 Italian refineries (2 base bitumens)
- 1 Italian quarry (local aggregates)
- 1 Italian road Contractor
- 2 Specialized plant producers



*Plants, refineries, quarries and Partners*

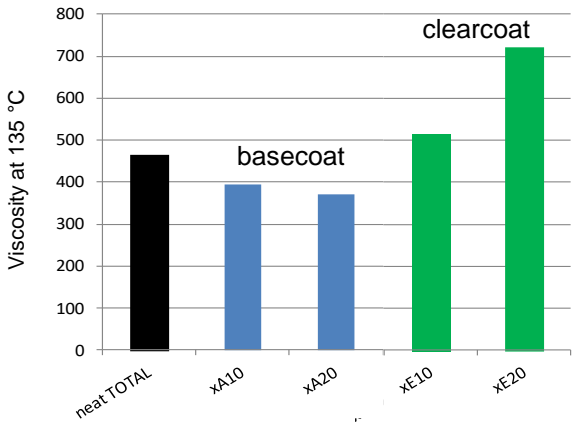




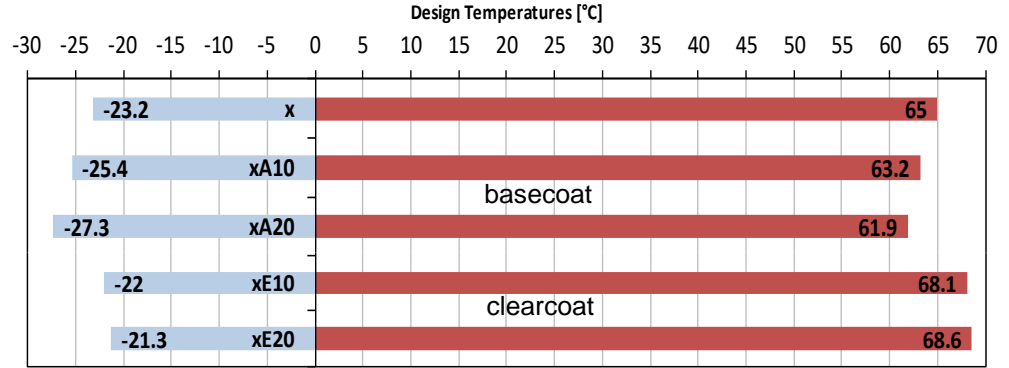
- Reuse of Paint Sludge in Road Pavements (RP2):**  
Industrial Partner: FIAT Chrysler Automobiles (FCA) S.p.A.

### MAIN RESULTS:

Characterization of PSMBs:



Viscosity (workability)

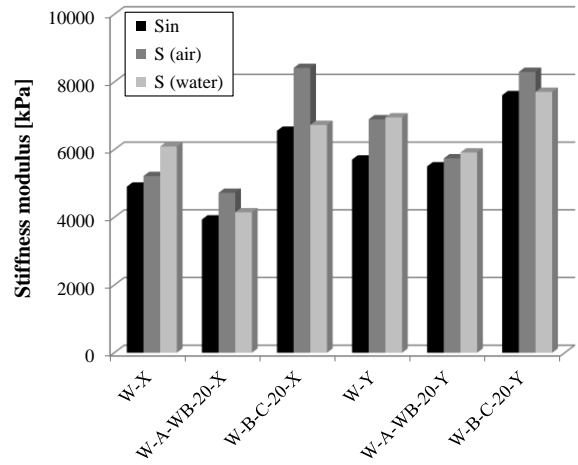


High and low temperature performance (PG grading)

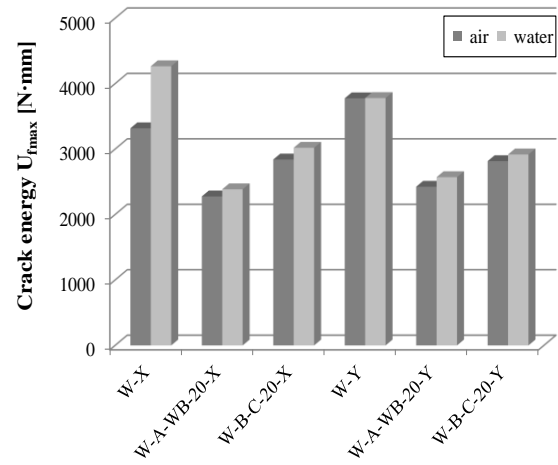
- **Reuse of Paint Sludge in Road Pavements (RP2):**  
**Industrial Partner: FIAT Chrysler Automobiles (FCA) S.p.A.**

## MAIN RESULTS:

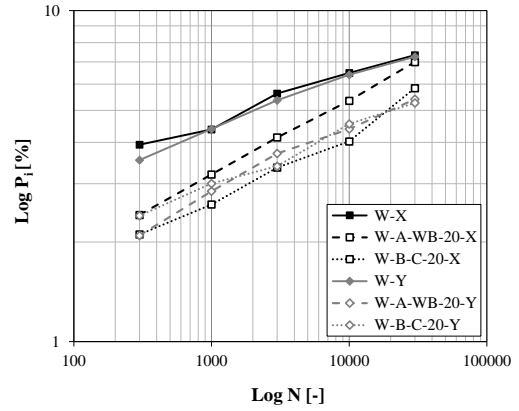
Characterization of PSMB mixtures:



Moisture sensitivity



Resistance to crack propagation



Resistance to permanent deformation

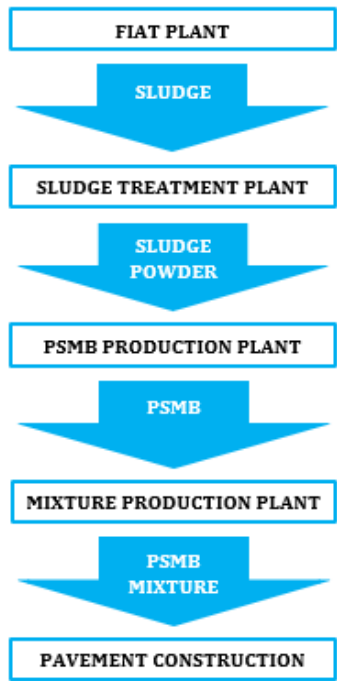
- **Reuse of Paint Sludge in Road Pavements (RP2):**  
**Industrial Partner: FIAT Chrysler Automobiles (FCA) S.p.A.**

### MAIN RESULTS:

Process development (with Industrial Partner):

Identification of optimal operative conditions for:

- Sludge drying
- Sludge milling
- Bitumen-sludge mixing



**FCA-PoliTo PATENT**

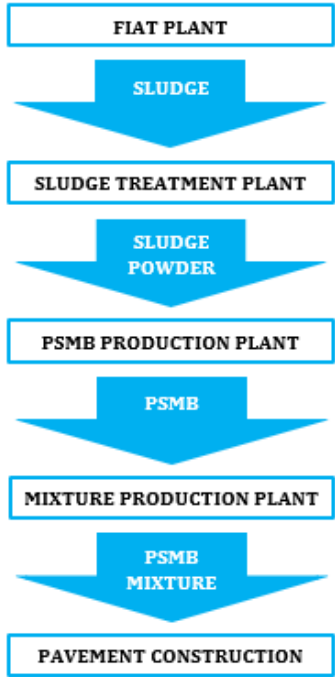
- **Reuse of Paint Sludge in Road Pavements (RP2):**  
**Industrial Partner: FIAT Chrysler Automobiles (FCA) S.p.A.**

### MAIN RESULTS:

Construction of full-scale trial sections (with Industrial Partner):

Monitoring of pavement construction activities and sampling:

- Bituminous mixtures
- Paint sludge modified binders
- Gaseous emissions



**FCA-PoliTo PATENT**

- **Reuse of Paint Sludge in Road Pavements (RP2):**  
**Industrial Partner: FIAT Chrysler Automobiles (FCA) S.p.A.**

## MAIN RESULTS:

Evaluation of pavement trial sections:

Field work:

- Texture and friction of pavement surface
- Sampling of cores and loose mixtures
- Sampling of gaseous emissions

Laboratory and office work:

- Performance-based evaluation
- Comparison with data from WP2 and WP3
- Development of Technical Specifications

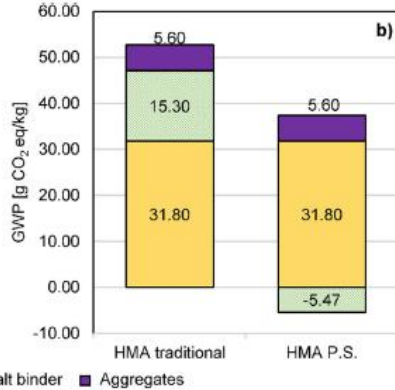
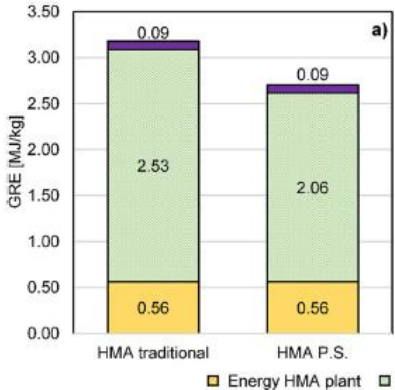
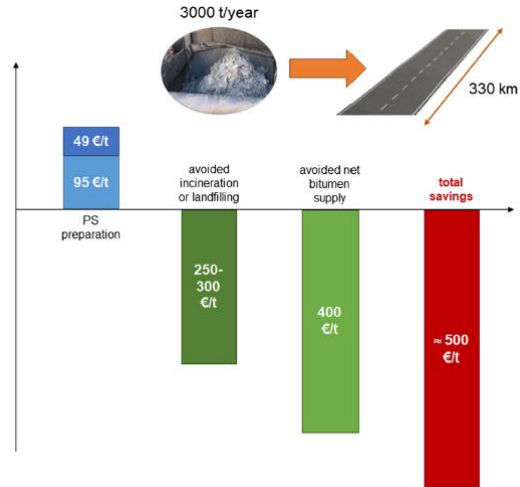


- **Reuse of Paint Sludge in Road Pavements (RP2):**  
**Industrial Partner: FIAT Chrysler Automobiles (FCA) S.p.A.**

**MAIN RESULTS:**

Economical feasibility and environmental assessment:

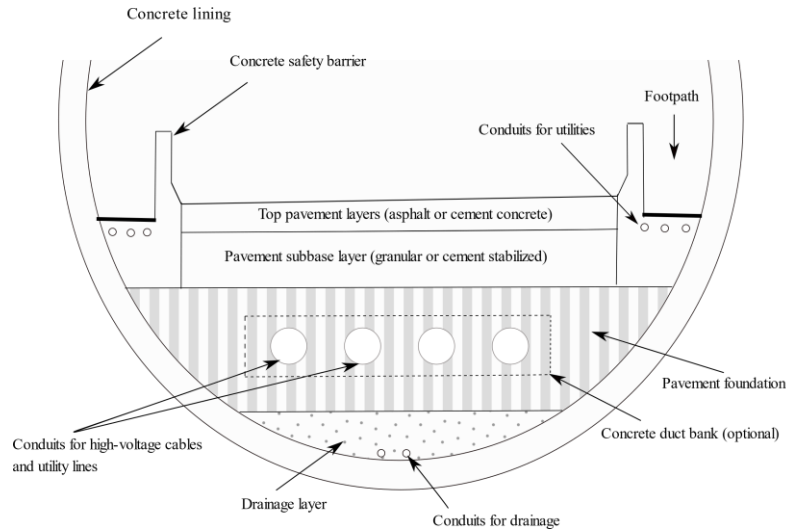
- Life-cycle costs (including maintenance)
- Life-cycle assessment: Gross Energy Requirement (GER) and Global Warming Potential (GWP)



- **Self-compacting cement-bound mixtures for pavement foundations of road tunnels:**  
**Industrial Partners: SITAF (Motorway Company), SITALFA (Contractor)**

## GOALS:

- Identification of an innovative solution: reduction of economic burden and environmental impact
- Full-scale extensive implementation



## BACKGROUND:

- Construction of second Italy-France Frejus Tunnel
- Complex cross-section with multiple utilities (including high voltage cables)
- Design requirement: cement-stabilized soil for foundation
- Significant interest in recycled materials

- **Self-compacting cement-bound mixtures for pavement foundations of road tunnels:**  
**Industrial Partners: SITAF (Motorway Company), SITALFA (Contractor)**

## RESEARCH ACTIVITIES:

- WP1 Mix design
- WP2 Thermal properties
- WP3 Field trials and optimization
- WP4 Pavement design
- WP5 Development of Technical Specifications

## STAKEHOLDERS:

- SITAF (Motorway Company)
- SITALFA (Contractor)
- 1 Italian quarry (local aggregates)
- Producers of admixtures



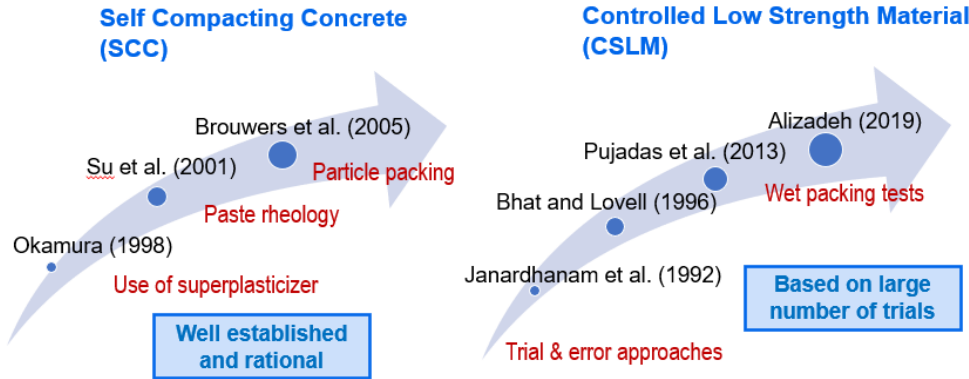
*Frejus Tunnel during construction*



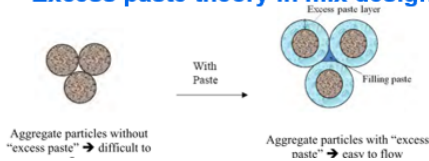
- Self-compacting cement-bound mixtures for pavement foundations of road tunnels:**  
Industrial Partners: SITAF (Motorway Company), SITALFA (Contractor)

## MAIN RESULTS:

Mix design approach:



### Excess paste theory in mix design of cement concrete



*"Pack the aggregate fraction to its maximum dense state provide enough paste"*

Use of secondary aggregates:



RAP stockpiles



Mineral sludge

## Self-compacting cement-bound mixtures for pavement foundations of road tunnels:

Industrial Partners: SITAF (Motorway Company), SITALFA (Contractor)

### MAIN RESULTS:

Mix design:

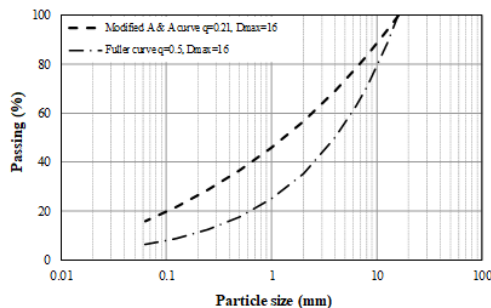
#### Identification of target particle size distribution

Fuller curve

$$P(D) = 100 \cdot \left( \frac{D}{D_{\max}} \right)^{0.5}$$

Modified Andersen&Andreasen curve  
(Funk and Dinger, 1994)

$$P(D) = 100 \cdot \frac{(D^q - D_{\min}^q)}{(D_{\max}^q - D_{\min}^q)}$$



Percentage by weight (%)

Fraction	q = 0.21	q = 0.23	q = 0.25
Sand 0-6	34	33	33
Gravel 8-16	10	11	11
RAP	28	30	32
Sludge	28	26	24

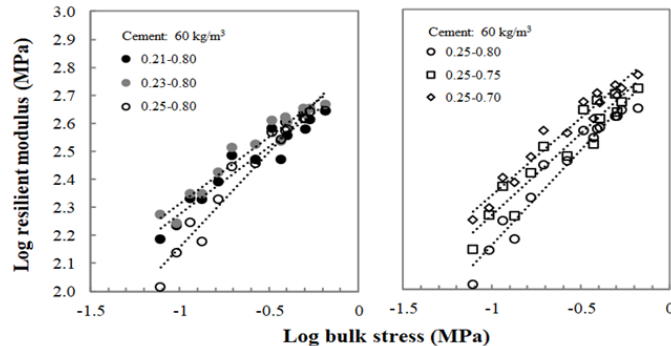
Testing (e.g. flowability and resilient modulus):



q = 0.21  
w/p = 0.80

q = 0.23  
w/p = 0.80

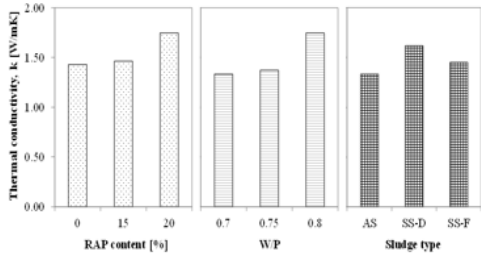
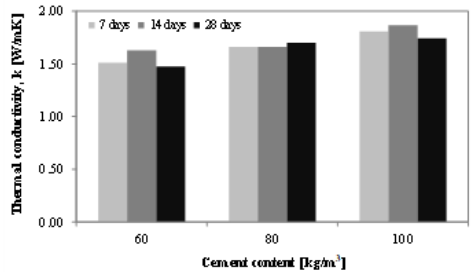
q = 0.25  
w/p = 0.80



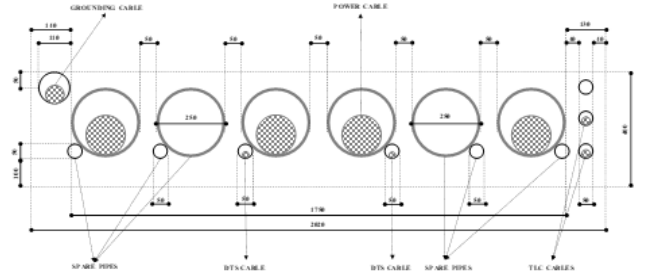
- Self-compacting cement-bound mixtures for pavement foundations of road tunnels:  
**Industrial Partners: SITAF (Motorway Company), SITALFA (Contractor)**

## MAIN RESULTS:

Thermal properties:



Ampacity calculations:



Short-term		Long-term	
$\rho_{sc-CBM}$ (K.m/W)	Ampacity (MW)	$\rho_{sc-CBM}$ (K.m/W)	Ampacity (MW)
0.524-0.661	764.9-718.1	0.936-1.220	644.8-588.0

- Self-compacting cement-bound mixtures for pavement foundations of road tunnels:  
Industrial Partners: SITAF (Motorway Company), SITALFA (Contractor)

**MAIN RESULTS:**

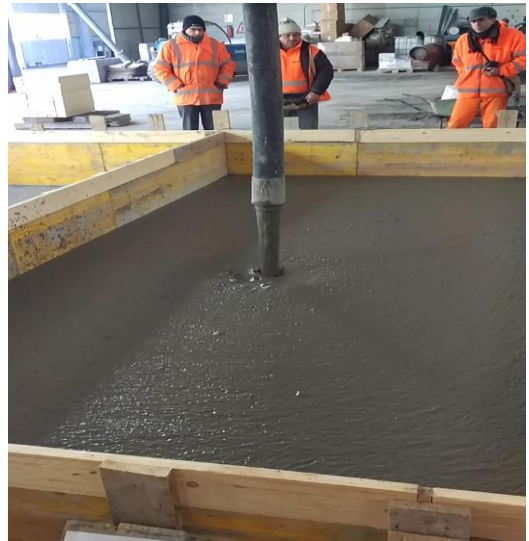
Field trials (production):



- Self-compacting cement-bound mixtures for pavement foundations of road tunnels:  
Industrial Partners: SITAF (Motorway Company), SITALFA (Contractor)

## MAIN RESULTS:

Field trials (construction of full-size slabs):

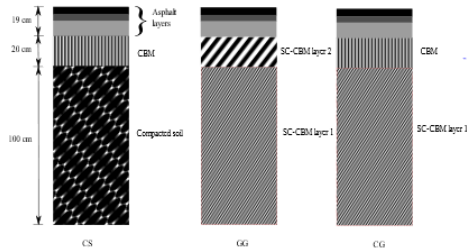


- Self-compacting cement-bound mixtures for pavement foundations of road tunnels:**  
**Industrial Partners: SITAF (Motorway Company), SITALFA (Contractor)**

## MAIN RESULTS:

Pavement design:

### Optimization of design



### Input data: Design temperature

Period	Months	T <sub>air,p</sub> (°C)	T <sub>pav,p</sub> (°C)			
			Final phase of construction	Service life		
				CS-GG-CG	CS	GG
1	January-March	20.8	20.8	22.7	22.2	22.2
2	April-May	24.6	24.6	26.3	25.9	25.9
3	June-November	28.4	28.4	30.0	29.6	29.5
4	December	20.8	20.8	22.7	22.2	22.2

### Input data: Design traffic

Design period	20 years
Truck factor during construction	2.14
Truck factor during service life	2
Growth factor	3%
Design traffic	<b>16.2 millions of 80kN ESALs</b>

### Assessment of mechanical properties



- Measured temperature: 16 °C
- Air void content of HMA: 9.7%

### Correction for temperature

$$E = 10^a (T^2_{ref} - T^2). E_{ref}$$

### Correction for air void content

Using stiffness and volumetrics relationship of the asphalt mixtures (Bonnaure et al.1977)

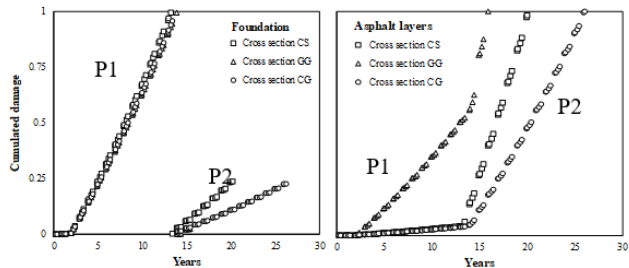
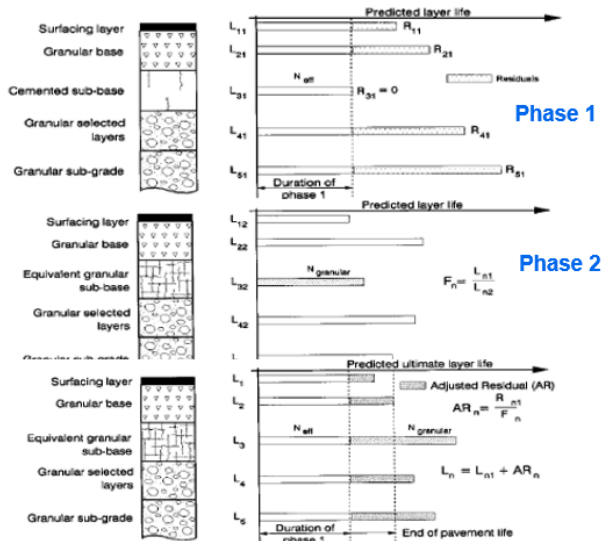
Layer	Thickness (cm)	Stiffness (MPa)
Asphalt layers	15	3500
Foundation	100	350
Subgrade	20	1000

- Self-compacting cement-bound mixtures for pavement foundations of road tunnels:**  
**Industrial Partners: SITAF (Motorway Company), SITALFA (Contractor)**

## MAIN RESULTS:

### Pavement design:

#### South-African Pavement Engineering Manual (SAPEM)



Laying of the SC-CBM foundation for a length of 1 km consumes 1,700 tons of RAP and 2,000 tons of aggregate sludge

	ESALs			Years		
	CS	GG	CG	CS	GG	CG
Construction + Phase 1 (P1)	9.19E+06	9.83E+06	9.71E+06	13.3	14.0	13.8
Phase 2 (P2)	7.25E+06	1.78E+06	1.42E+07	6.9	1.8	12.2
Total	1.64E+07	1.16E+07	2.39E+07	20.2	15.8	26.0

## Recycling can indeed be the option for better pavements:

- **Academic research** can:
  - support the Industry in satisfying specific needs (top-to-bottom)
  - identify unknown areas of improvement that can be of use to the Industry (bottom-to-top)
- **New experimental techniques** and **innovative approaches** are essential for the success of recycling
- A **strong technological support** can maximize the effectiveness of proposed solutions
- Continuous **update of specifications and standards** should be pursued
- **Environmental impacts** are part of the assessment of modern pavement engineers
- **Dissemination** is essential for the advanced education of all players involved in pavement recycling

*To be continued...*



Misano World Circuit



Torino-Caselle airport



A32 highway Torino-Bardonecchia



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**Recycled Materials in Pavement Engineering:  
Fundamental Research and Collaboration with the Industry**

**prof. Ezio Santagata  
Politecnico di Torino**

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**Thank you for listening**