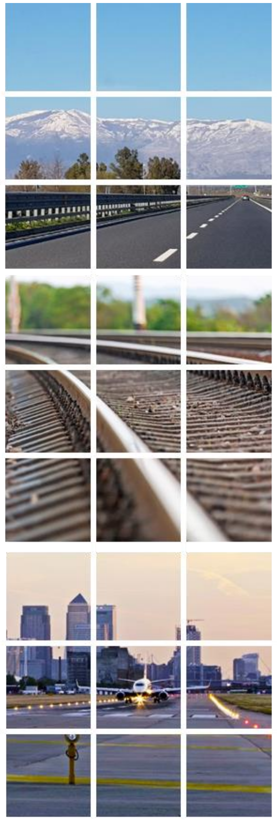
Società Italiana Infrastrutture Viarie
XIX International SIIV Summer School , Perugia 4th - 8th September 2023

Transportation Infrastructures towards Green Transition



Sustainability assessment of pavements containing unconventional construction materials

5th
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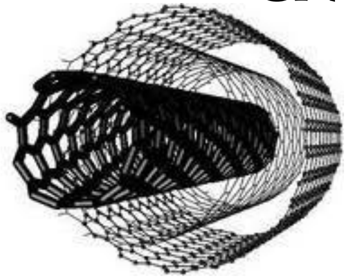
Sustainability assessment of pavements containing unconventional construction materials

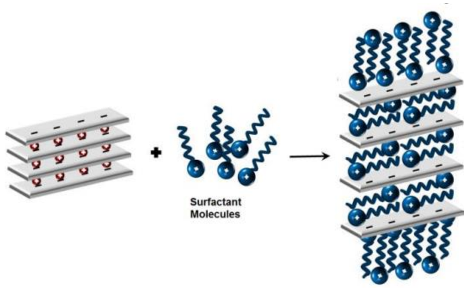
Lecture Outline

- *An overview of sustainability rating systems for transportation infrastructures*
- *Environmental analysis techniques: Life Cycle Assessment (LCA)*
- *Assessment of the potential environmental benefits related to the use of unconventional construction materials*
- *Presentation of case studies:*
    - *LCA of pavements for rural roads containing large quantities of reclaimed asphalt (RA) and mineral sludge (MS)*
    - *LCA of pavements for highways containing nano-reinforced materials, such as bituminous binders modified by means of carbon nanotubes (CNT) and nanoclays (NC)*

CNT



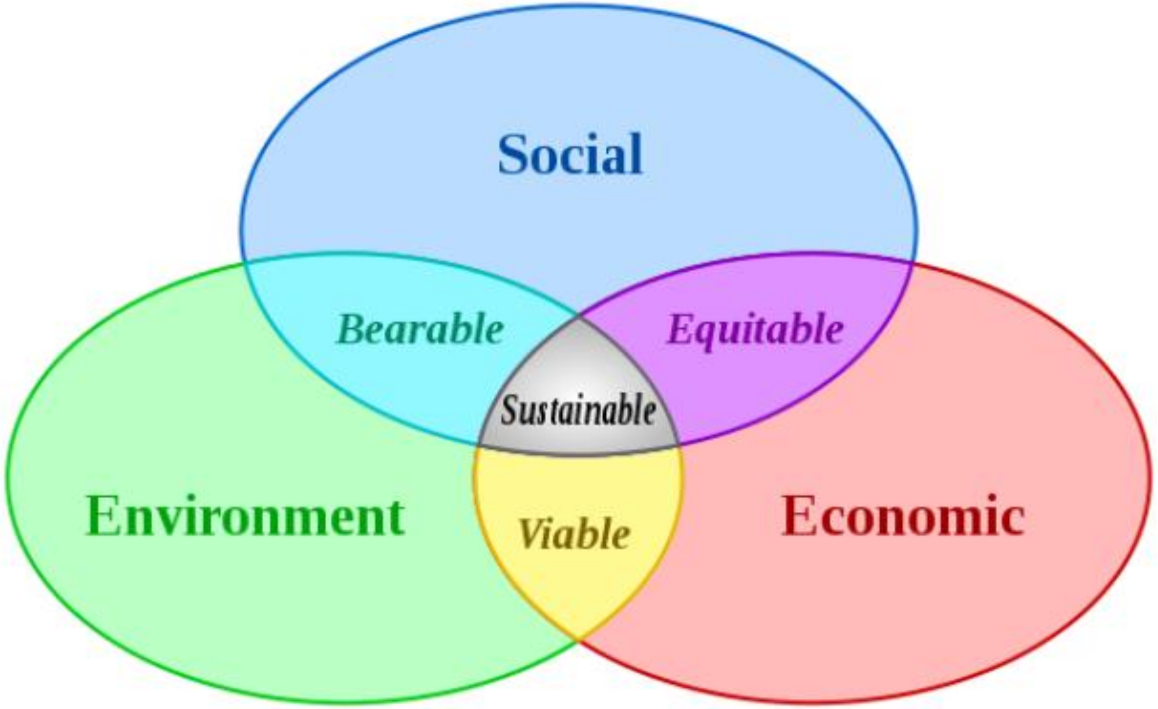
NC



Sustainability assessment of pavements containing unconventional construction materials

Sustainability rating systems for transportation infrastructures

- *Are we doing the project right?*
- *Are we doing the right project?*



Sustainability is often described as:

"...a quality that reflects the balance of three primary components - economic, environmental and social impacts – which are collectively referred to as the triple bottom line" (PIARC2019).

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Sustainability rating systems for transportation infrastructures

Highway construction and sustainability framework mapping (from Sustainable Highway Construction Guidebook, NCHRP 2019)

Sustainability is divided in its three common dimensions: human, environmental and economic well-being

- *Qualitative framework*

- *Quantitative framework*

Highway Construction Framework		Sustainability Framework									
		Human Well-being			Environmental Well-being				Economic Well-being		
Level	Category	Workers	Neighbors and Stakeholders	Users	Pollution	Local Ecosystem and Habitat	Consumption	Climate	Project Budget	Maintenance and Operations	Economic Development/ Employment
Project Delivery	Project Delivery Method								■	■	
	Financing								■	■	
	Procurement	■	■	■	■	■	■	■	■	■	■
	Contracting	■	■	■	■	■	■	■	■	■	■
Project	Scheduling	■	■	■					■		
	Estimating								■		
	Project Controls/Administration	■							■		
	Earthwork						■	■	■		
	Drainage/Sewer/Water		■		■	■			■	■	
	Aesthetics		■	■					■		
	Walls		■	■		■	■	■	■	■	
	Bridges					■	■	■	■		[illegible]
	Pavement			■			■	■	■	■	[illegible]
	Work Zone Traffic Control	■	■	■			■	■	■		[illegible]
	Materials				■	■	■	■	■	■	[illegible]
	Safety	■		■					■		[illegible]
	Employment	■							■		[illegible]
	Training	■			■	■			■		[illegible]
	Community Outreach		■	■	■				■		[illegible]
	Noise	■	■	■	■	■			■		[illegible]
	Lighting	■	■	■	■	■			■		[illegible]
	Constructability/Deconstruction	■	■				■		■		[illegible]
	Quality	■		■			■	■	■	■	[illegible]
	Equipment				■		■	■	■		[illegible]
	Utilities		■						■	■	[illegible]
	Landscaping		■	■		■			■	■	[illegible]

■ If a Highway Construction Category addresses a Sustainability Category, the corresponding cell is colored green.

Sustainability assessment of pavements containing unconventional construction materials

Sustainability rating systems for transportation infrastructures

Quantitative methods ➡ *SUSTAINABILITY RATING SYSTEM*

Developed to label the environmental performance of a civil engineering project

Final goal of rating:
- *Self-evaluation*
- *Third-party evaluation*
- *Labelling*
- *Awarding*

Type of tool:
- *Voluntary*
- *Mandatory*

Targeted at:
- *System planning and programming*
- *Project planning*
- *Project design*
- *Project construction*
- *Operations and maintenance*

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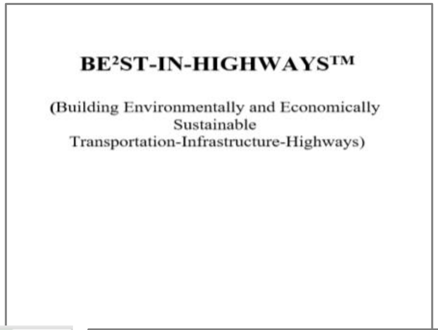
Sustainability rating systems for transportation infrastructures

Quantitative framework ➔ *SUSTAINABILITY RATING SYSTEM*

Developed to label the sustainability performance of a civil engineering project



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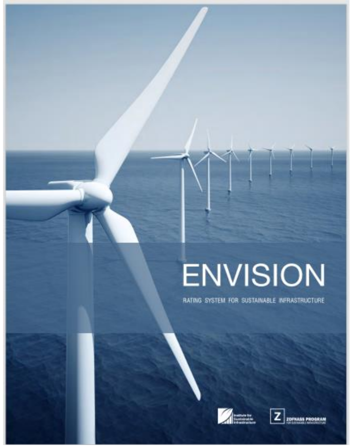
Sustainability rating systems for transportation infrastructures

ENVISION – Certification for the construction industry – developed in joint collaboration between the Harvard University Graduate School of Design and the Institute for Sustainable Infrastructure (ISI).



Quality Of Life
14 Credits

WELLBEING
- **QL1.1** Improve Community Quality of Life
- **QL1.2** Enhance Public Health & Safety
- **QL1.3** Improve Construction Safety
- **QL1.4** Minimize Noise & Vibration
- **QL1.5** Minimize Light Pollution
- **QL1.6** Minimize Construction Impacts

MOBILITY
- **QL2.1** Improve Community Mobility & Access
- **QL2.2** Encourage Sustainable Transportation
- **QL2.3** Improve Access & Wayfinding

COMMUNITY
- **QL3.1** Advance Equity & Social Justice
- **QL3.2** Preserve Historic & Cultural Resources
- **QL3.3** Enhance Views & Local Character
- **QL3.4** Enhance Public Space & Amenities

- **QL0.0** Innovate or Exceed Credit Requirement

Leadership
12 Credits

COLLABORATION
- **LD1.1** Provide Effective Leadership & Commitment
- **LD1.2** Foster Collaboration & Teamwork
- **LD1.3** Provide for Stakeholder Involvement
- **LD1.4** Pursue Byproduct Synergies

PLANNING
- **LD2.1** Establish a Sustainability Management Plan
- **LD2.2** Plan for Sustainable Communities
- **LD2.3** Plan for Long-Term Monitoring & Maintenance
- **LD2.4** Plan for End-of-Life

ECONOMY
- **LD3.1** Stimulate Economic Prosperity & Development
- **LD3.2** Develop Local Skills & Capabilities
- **LD3.3** Conduct a Life-Cycle Economic Evaluation

- **LD0.0** Innovate or Exceed Credit Requirements

Resource Allocation
14 Credits

MATERIALS
- **RA1.1** Support Sustainable Procurement Practices
- **RA1.2** Use Recycled Materials
- **RA1.3** Reduce Operational Waste
- **RA1.4** Reduce Construction Waste
- **RA1.5** Balance Earthwork On Site

ENERGY
- **RA2.1** Reduce Operational Energy Consumption
- **RA2.2** Reduce Construction Energy Consumption
- **RA2.3** Use Renewable Energy
- **RA2.4** Commission & Monitor Energy Systems

WATER
- **RA3.1** Preserve Water Resources
- **RA3.2** Reduce Operational Water Consumption
- **RA3.3** Reduce Construction Water Consumption
- **RA3.4** Monitor Water Systems

- **RA0.0** Innovate or Exceed Credit Requirements

Natural World
14 Credits

SITING
- **NW1.1** Preserve Sites of High Ecological Value
- **NW1.2** Provide Wetland & Surface Water Buffers
- **NW1.3** Preserve Prime Farmland
- **NW1.4** Preserve Undeveloped Land

CONSERVATION
- **NW2.1** Reclaim Brownfields
- **NW2.2** Manage Stormwater
- **NW2.3** Reduce Pesticide & Fertilizer Impacts
- **NW2.4** Protect Surface & Groundwater Quality

ECOLOGY
- **NW3.1** Enhance Functional Habitats
- **NW3.2** Enhance Wetland & Surface Water Functions
- **NW3.3** Maintain Floodplain Functions
- **NW3.4** Control Invasive Species
- **NW3.5** Protect Soil Health

- **NW0.0** Innovate or Exceed Credit Requirements

Climate and Resilience
10 Credits

EMISSIONS
- **CR1.1** Reduce Net Embodied Carbon
- **CR1.2** Reduce Greenhouse Gas Emissions
- **CR1.3** Reduce Air Pollutant Emissions

RESILIENCE
- **CR2.1** Avoid Unsuitable Development
- **CR2.2** Assess Climate Change Vulnerability
- **CR2.3** Evaluate Risk & Resilience
- **CR2.4** Establish Resilience Goals and Strategies
- **CR2.5** Maximize Resilience
- **CR2.6** Improve Infrastructure Integration

- **CR0.0** Innovate or Exceed Credit Requirements

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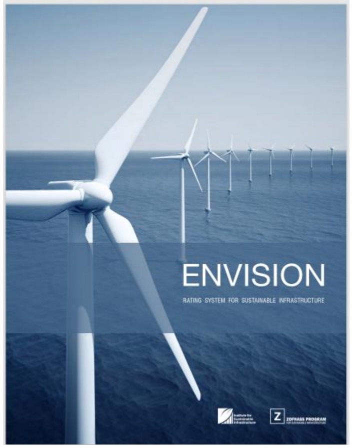


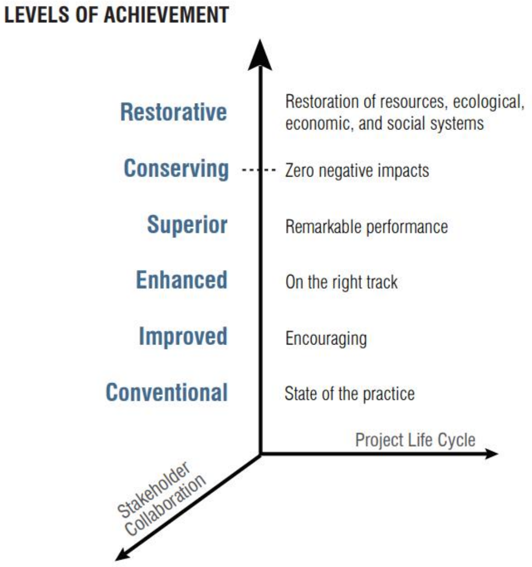
CR1.1 REDUCE GREENHOUSE GAS EMISSIONS

INTENT:

Conduct a comprehensive life-cycle carbon analysis and use this assessment to reduce the anticipated amount of net greenhouse gas emissions during the life cycle of the project, reducing project contribution to climate change.

LEVELS OF ACHIEVEMENT

IMPROVED	ENHANCED	SUPERIOR	CONSERVING	RESTORATIVE
(4) Life-cycle carbon assessment. A comprehensive life-cycle carbon assessment is undertaken to estimate carbon emissions caused by materials extraction and processing, transportation of materials to be used during construction and operation, and project maintenance and operation, including vehicle traffic. The assessment related to materials includes carbon emissions generated for the key materials to be used in the project from their extraction, refinement, and manufacture, distance transported, and carbon emissions released in use after their incorporation to the completed project. (A)	**(7) At least 10% greenhouse gas reduction.** Using a completed life-cycle carbon assessment, the project team works to design the project so that it reduces carbon emissions by at least 10%. (A, B)	**(13) At least 40% greenhouse gas reduction.** Using a completed life-cycle carbon assessment, the project team works to design the project so that it reduces carbon emissions by at least 40%. (A, B)	**(18) Carbon neutral.** The completed project is carbon neutral (does not produce any net carbon emissions, i.e., a 100% reduction). Using a completed life-cycle carbon assessment, the project team works to design the project so that it is carbon neutral. Extensive use of renewable energy and carbon sinks. (A, B)	**(25) Net carbon negative.** The completed project is carbon negative (i.e., sequesters more carbon than it produces). Using a completed life-cycle carbon assessment, the project team works to design the project so that it is carbon negative. Extensive use of renewable energy and carbon sinks. (A, B)



Sustainability assessment of pavements containing unconventional construction materials

Sustainability rating systems for transportation infrastructures

INVEST – Infrastructure voluntary evaluation sustainability tool – developed by FHWA (Federal Highway Administration – Washington)

INVEST is a voluntary, self-directed and free web tool created to help state departments of transportation (DOTs), metropolitan planning organizations (MPOs), local transportation agencies, and others assess and improve the sustainability of transportation projects and programs. It is organized in:

- *SPS/SPR - System Planning for States/Regions (17 criteria)*
- *OM – Operations and Maintenance (14 criteria)*

- SPS-01/SPR-01: Integrated Planning: Economic Development and Land Use
- SPS-02/SPR-02: Integrated Planning: Natural Environment
- SPS-03/SPR-03: Integrated Planning: Social
- SPS-04/SPR-04: Integrated Planning: Bonus
- SPS-05/SPR-05: Access & Affordability
- SPS-06/SPR-06: Safety Planning
- SPS-07/SPR-07: Multimodal Transportation and Public Health
- SPS-08/SPR-08: Freight and Goods Movement
- SPS-09/SPR-09: Travel Demand Management
- SPS-10/SPR-10: Air Quality
- SPS-11/SPR-11: Energy and Fuels
- SPS-12/SPR-12: Financial Sustainability
- SPS-13/SPR-13: Analysis Methods
- SPS-14/SPR-14: Transportation Systems Management & Operations
- SPS-15/SPR-15: Linking Asset Management and Planning
- SPS-16/SPR-16: Infrastructure Resiliency
- SPS-17/SPR-17: Linking Planning and NEPA

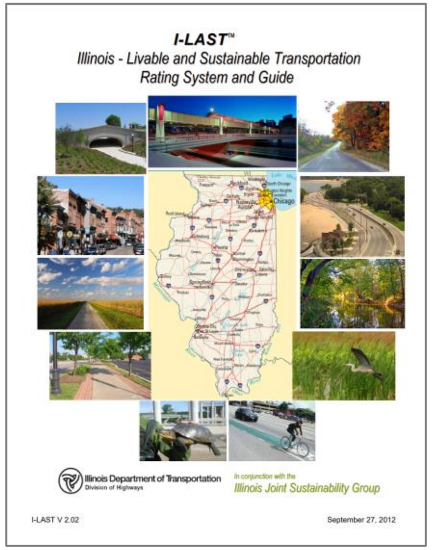
- OM-1: Internal Sustainability Plan
- OM-2: Electrical Energy Efficiency and Use
- OM-3: Vehicle Fuel Efficiency and Use
- OM-4: Reduce, Reuse, and Recycle
- OM-5: Safety Management
- OM-6: Environmental Commitments Tracking System
- OM-7: Pavement Management System
- OM-8: Bridge Management System
- OM-9: Maintenance Management System
- OM-10: Highway Infrastructure Preservation and Maintenance
- OM-11: Traffic Control Infrastructure Maintenance
- OM-12: Road Weather Management Program
- OM-13: Transportation Management and Operations
- OM-14: Work Zone Traffic Controls

Sustainability assessment of pavements containing unconventional construction materials

Sustainability rating systems for transportation infrastructures

I-LAST – Developed by the American Consulting Engineers Council, the Illinois Road and Transportation Builders Association and the Illinois Department of Transportation (153 Items)

- *Planning*
- *Design*
- *Environmental*
- *Water quality*
- *Transportation*
- *Lighting*
- *Materials*
- *Innovation*
- *Construction*



Scorecard:

CATEGORY		ID	DESCRIPTION	Available Points	Project Points
Planning	P-1 Context Sensitive Solutions	P-1a	Identify Stakeholders and develop Stakeholders Involvement Plan	2	
		P-1b	Engage Stakeholders to conduct Context Audit and develop project purpose	2	
		P-1c	Involve Stakeholders to develop and evaluate alternatives	2	
		P-1d	Employ Stakeholder involvement techniques to achieve consensus for Preferred Project Alternative	2	
	P-2 Land Use/ Community Planning	P-2a	Promote reduction in vehicle trips by accommodating increased use of public transit	2	
		P-2b	Accommodate multi-modal transportation uses (e.g. transit riders, pedestrians, and bicyclists)	2	
		P-2c	Increase transportation efficiencies for moving freight through features such as dedicated rail or intermodal facilities	2	
		P-2d	Partnerships that provide environmental or technological advancements while promoting environmental stewardship	2	
		P-2e	Project is consistent with regional plans and local managed growth-based Master or Comprehensive Plans	2	
		P-2f	Project is compatible with local efforts for Transit Oriented Design	1	
Design	D-1 Alignment Selection	D-1a	Avoid impacts to high quality undeveloped lands		
			D-1a-1 Avoid all impacts	2	
			D-1a-2 Avoid significant impacts	1	
		D-1b	Provide buffer between highway and high quality wetlands/water resources		
			D-1b-1 Provide 100 foot buffer to resources	2	
			D-1b-2 Avoid resource with less than 100 foot buffer	1	
		D-1c	Avoid impacts to environmental resources, such as INAI sites and sites with threatened or endangered species		
			D-1c-1 Avoid all impacts	2	
			D-1c-2 Avoid significant impacts	1	
		D-1d	Avoid impacts to socioeconomic resources		
			D-1d-1 Avoid all impacts	2	
			D-1d-2 Avoid significant impacts	1	
		D-1e	Cross section minimizes overall construction "footprint" to eliminate R.O.W. takes	2	
		D-1f	Minimize total earthwork by matching proposed vertical alignments as closely as possible to existing grades	1	
		D-1g	Utilize brownfield locations	2	

Sustainability assessment of pavements containing unconventional construction materials

Sustainability rating systems for transportation infrastructures

GreenLITES -Leadership In Transportation and Environmental Sustainability Planning - Certification Program for NYSDOT Designs Meeting Criteria for Sustainable Transportation Infrastructure using Environmentally Friendly Practices

GreenLITES certification categories are:

1) *Sustainable Sites*
2) *Water Quality*
3) *Materials and Resources*
4) *Energy and Atmosphere*
5) *Innovation/Unlisted*

Sustainable Sites (S)

- Alignment Selection
- Context Sensitive Solutions
- Land Use/Community Planning
- Protect, Enhance, or Restore Wildlife Habitat
- Protect, Plant, or Mitigate for Removal of Trees and Plant Communities

Water Quality (W)

- Stormwater management (volume and quality).
- Reduce runoff and associated pollutants by treating stormwater runoff through BMPs .

Materials and Resources (M)

- Reuse of Materials
- Recycled Content
- Locally Provided Material
- Bioengineering Techniques
- Hazardous Material Minimization

Energy and Atmosphere (E)

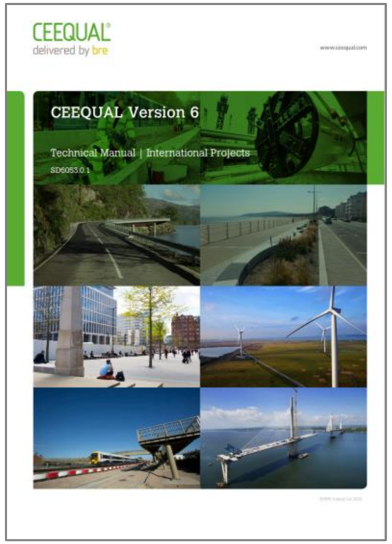
- Improve Traffic Flow
- Reduce Electrical Consumption
- Reduce Petroleum Consumption
- Improve Bicycle and Pedestrian Facilities
- Noise Abatement
- Stray Light Reduction

Innovation/Unlisted (I)

Sustainability assessment of pavements containing unconventional construction materials

Sustainability rating systems for transportation infrastructures

CEEQUAL – The Civil Engineering Quality Assessment and Awards Scheme – developed by UK ICE (Institution of Civil Engineers). It is usually completed at the end of the design and construction when solid evidence to support the scoring is available.



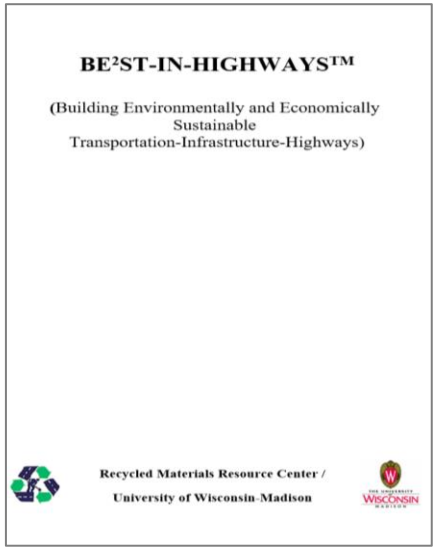
Category	Category weighting, %
Management	11
Resilience	12
Communities and stakeholders	11
Land use and ecology	12
Landscape and historic environment	9
Pollution	8
Resources	
Materials, including waste	16
Energy and carbon (operational)	4
Energy and carbon (construction)	5
Water use	4
Transport	8

CEEQUAL rating	Overall score, %
Outstanding	≥ 90
Excellent	≥ 75
Very Good	≥ 60
Good	≥ 45
Pass	≥ 30
Unclassified	< 30

Sustainability assessment of pavements containing unconventional construction materials

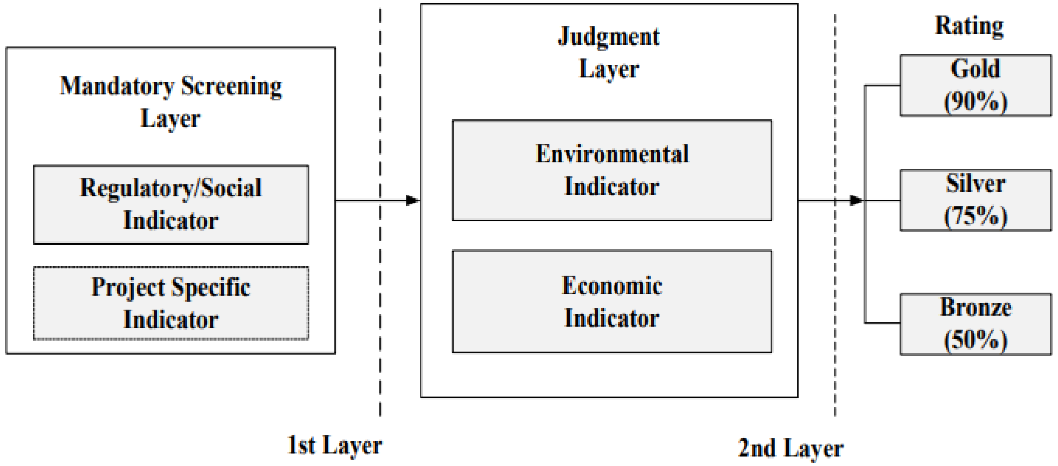
Sustainability rating systems for transportation infrastructures

BE²ST in Highways –Building Environmentally and Economically Sustainable Transportation-Infrastructure-Highways Developed by Recycled Materials Resource Center and University of Wisconsin-Madison


BE²ST-IN-HIGHWAYS™

(Building Environmentally and Economically Sustainable Transportation-Infrastructure-Highways)

Recycled Materials Resource Center / University of Wisconsin-Madison



Major Criteria	Subcriteria	Target (1 point each)
Mandatory Screening	Social Requirements Including Regulation & Local Ordinances	Satisfied or unsatisfied
Judgment	Greenhouse Gas Emission	10% reduction
		20% reduction
	Energy Use	10% reduction
		20% reduction
	Waste Reduction (Including *Ex situ* Materials)	10% reduction
		20% reduction
	Waste Reduction (Recycling *In situ* Materials)	Utilize *in situ* waste for 10% volume of the structure
		20%
	Water Consumption	5% reduction of water consumption
		10% reduction
	Social Carbon Cost Saving	Greater than \$12,344/km
		Greater than \$24,688/km
	Life Cycle Cost	5% reduction by recycling
		10% reduction by recycling
	Traffic Noise	1 point for HMA
		Additional 1 point for adapting ideas to reduce noise
	Hazardous Waste	10% less hazardous waste
		20% less hazardous waste

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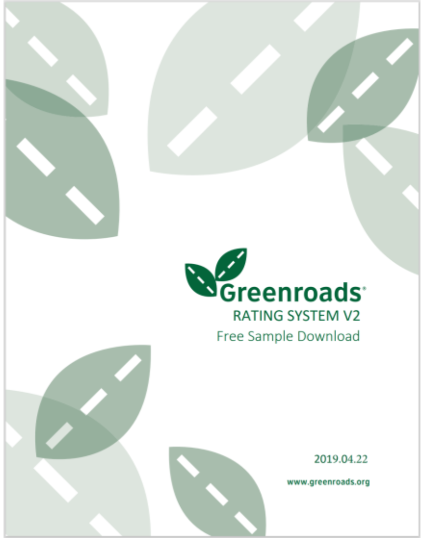
Sustainability assessment of pavements containing unconventional construction materials

Sustainability rating systems for transportation infrastructures

GREENROADS – The sustainability rating system for road design and construction projects – Developed by University of Washington, CH2M HILL and a number of other industry groups and consultants.

PROJECT REQUIREMENTS (mandatory)
Environment and water – 21 points
Access and equity – 30 points
Construction activities – 14 points
Materials and resources – 23 points
Pavement technologies – 20 points
CUSTOM CREDIT – 10 points

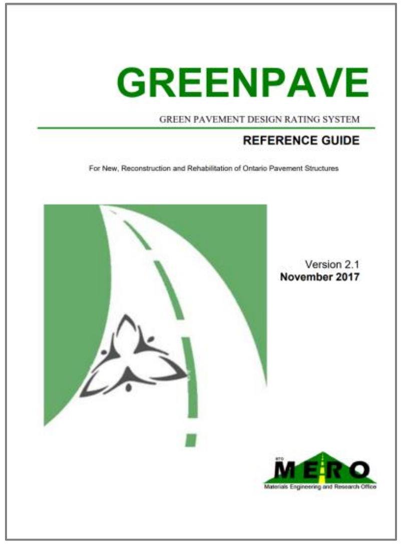


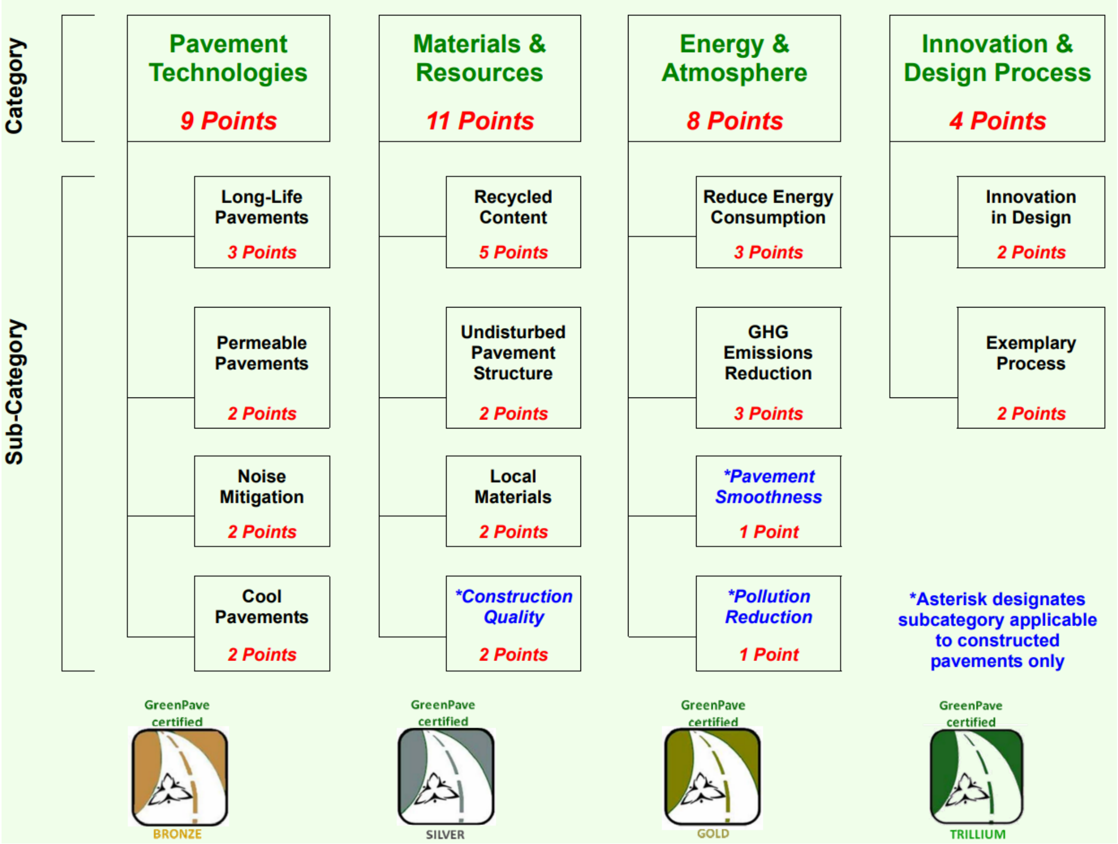
Project Requirements (PR) – Mandatory for all projects			
PR-1	Environmental Review Process	Req	Complete a comprehensive environmental review
PR-2	Lifecycle Cost Analysis (LCCA)	Req	Perform LCCA for pavement section
PR-3	Lifecycle Inventory (LCI)	Req	Perform LCI of pavement section
PR-4	Quality Control Plan	Req	Have a formal contractor quality control plan
PR-5	Noise Mitigation Plan	Req	Have a construction noise mitigation plan
PR-6	Waste Management Plan	Req	Have a plan to divert C&D waste from landfill
PR-7	Pollution Prevention Plan	Req	Have a TESC/SWPPP
PR-8	Low Impact Development (LID)	Req	Complete a LID feasibility study
PR-9	Pavement Management System	Req	Have a pavement management system
PR-10	Site Maintenance Plan	Req	Have a roadside maintenance plan
PR-11	Educational Outreach	Req	Publicize sustainability information for project
Environment & Water (EW) – Up to 21 Points			
EW-1	Environmental Management System	2	ISO 14001 certification for general contractor
EW-2	Runff Flow Control	1-3	Reduce runoff quantity
EW-3	Runoff Quality	1-3	Treat stormwater to a higher level of quality
EW-4	Stormwater Cost Analysis	1	Conduct an LCCA for stormwater elements
EW-5	Site Vegetation	1-3	Use native low/no water vegetation
EW-6	Habitat Restoration	3	Restore habitat beyond what is required
EW-7	Ecological Connectivity	1-3	Connect habitat across roadways
EW-8	Light Pollution	3	Discourage light pollution
Access & Equity (AE) – Up to 30 Points			
AE-1	Safety Audit	1-2	Perform roadway safety audit
AE-2	Intelligent Transportation Systems (ITS)	2-5	Implement ITS solutions
AE-3	Context Sensitive Solutions	5	Plan for context sensitive solutions
AE-4	Traffic Emissions Reduction	5	Reduce emissions with quantifiable methods
AE-5	Pedestrian Access	1-2	Provide/improve pedestrian accessibility
AE-6	Bicycle Access	1-2	Provide/improve bicycle accessibility
AE-7	Transit Access	1-5	Provide/improve transit accessibility
AE-8	Scenic Views	1-2	Provide views of scenery or vistas
AE-9	Cultural Outreach	1-2	Promote art/culture/community values
Construction Activities (CA) – Up to 14 Points			
CA-1	Quality Management System	2	ISO 9001 certification for general contractor
CA-2	Environmental Training	1	Provide environmental training
CA-3	Site Recycling Plan	1	Have a plan to divert waste from landfill
CA-4	Fossil Fuel Reduction	1-2	Use alternative fuels in construction equipment
CA-5	Equipment Emissions Reduction	1-2	Meet EPA Tier 4 standards for non-road equip.
CA-6	Paving Emissions Reduction	1	Use pavers that meet NIOSH requirements
CA-7	Water Tracking	2	Develop data on water use in construction
CA-8	Contractor Warranty	3	Warranty on the constructed pavement
Materials & Resources (MR) – Up to 23 Points			
MR-1	Life Cycle Assessment (LCA)	2	Conduct a detailed LCA of the entire project
MR-2	Pavement Reuse	1-5	Reuse existing pavement sections
MR-3	Earthwork Balance	1	Use native soil rather than import fill
MR-4	Recycled Materials	1-5	Use recycled materials for new pavement
MR-5	Regional Materials	1-5	Use regional materials to reduce transportation
MR-6	Energy Efficiency	1-5	Improve energy efficiency of operational systems
Pavement Technologies (PT) – Up to 20 Points			
PT-1	Long-Life Pavement	5	Design pavements for long-life
PT-2	Permeable Pavement	3	Use permeable pavement as a LID technique
PT-3	Warm Mix Asphalt (WMA)	3	Use WMA in place of HMA
PT-4	Cool Pavement	5	Contribute less to urban heat island effect (UHI)
PT-5	Quiet Pavement	2-3	Use a quiet pavement to reduce noise
PT-6	Pavement Performance Tracking	1	Relate construction to performance data
Custom Credits (CC) – Available for all projects based on context and innovation, subject to approval			
CC-1	Custom Credit 1	1-5	Design a new voluntary credit
CC-2	Custom Credit 2	1-5	Design a new voluntary credit
	Greenroads Total Points:	**118**	

Sustainability assessment of pavements containing unconventional construction materials

Sustainability rating systems for transportation infrastructures

GREENPAVE – Semplified Rating System based on LEED and GreenRoads, customized for Ontario, with a focus on pavement design and construction.


GREENPAVE
GREEN PAVEMENT DESIGN RATING SYSTEM
REFERENCE GUIDE
For New, Reconstruction and Rehabilitation of Ontario Pavement Structures
Version 2.1
November 2017
MERO
Materials Engineering and Research Office



Sustainability assessment of pavements containing unconventional construction materials

Sustainability rating systems for transportation infrastructures

PhD Program: Development of a sustainable rating system tool for road pavements

PhD candidate: Rajab Ali Mehraban

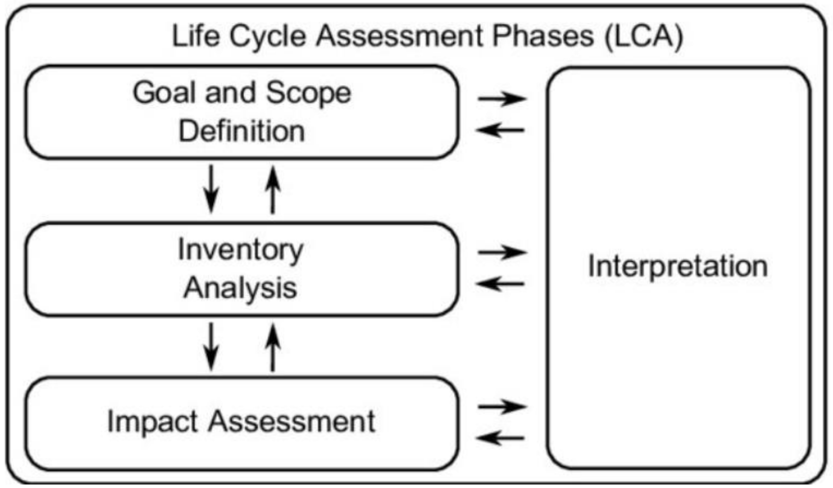
Supervisors: prof. Lucia Tsantilis, prof. Pier Paolo Riviera and prof. Ezio Santagata

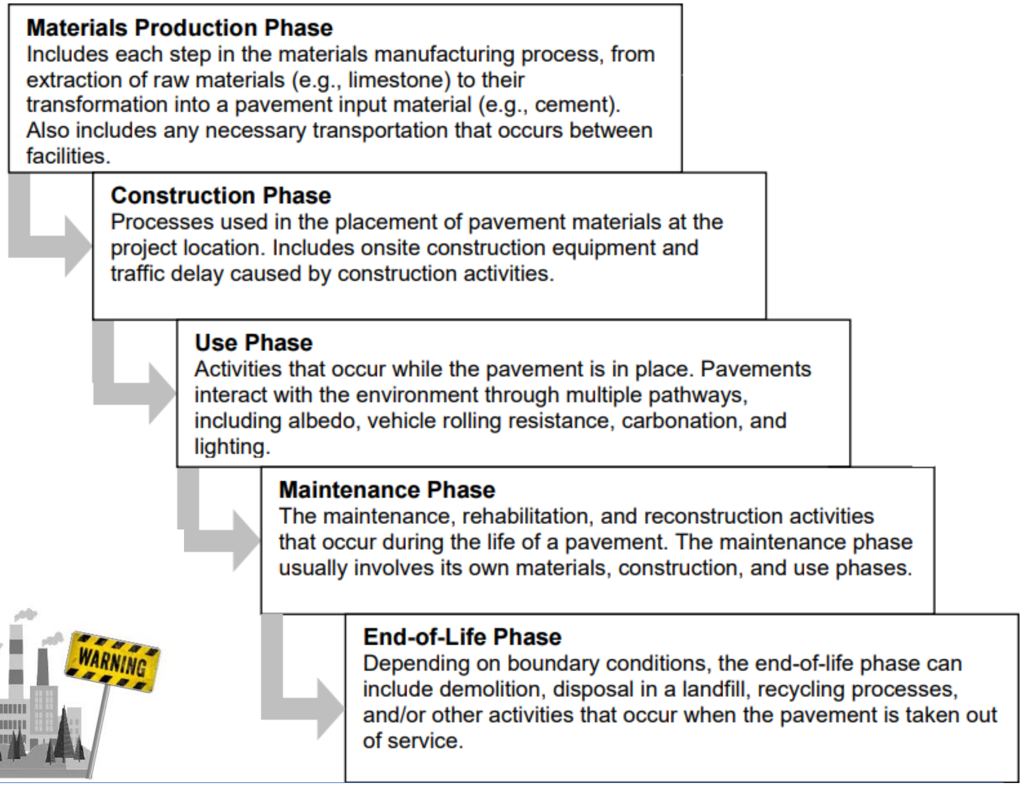
- Sustainable rating system tool
- *Assignment of relative weights to categories and indicators*
- *Development of parametric equations to be embedded in the sustainability rating system*
- *Definition of the categories of the rating system (related to environment, costs and social aspects), with the identification of the specific parameters to be used as quantitative indicators for each category*
- *Critical analysis of the existing rating systems*

Sustainability assessment of pavements containing unconventional construction materials

Sustainability rating systems for transportation infrastructures

LIFE CYCLE ASSESSMET (LCA) is an internationally standardized method (ISO 14040, ISO 14044) for the evaluation of the environmental burdens and resources consumed along the life of products



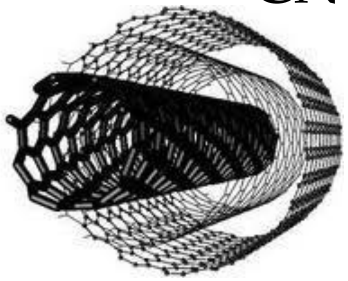


Sustainability assessment of pavements containing unconventional construction materials

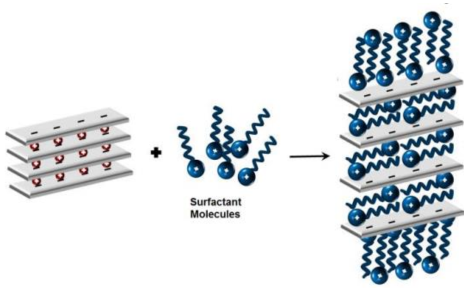
Lecture Outline

- *An overview of sustainability rating systems for transportation infrastructures*
- *Environmental analysis techniques: Life Cycle Assessment (LCA)*
- ***Assessment of the potential environmental benefits related to the use of unconventional construction materials***
- *Presentation of case studies:*
    - ***LCA of pavements for rural roads containing large quantities of reclaimed asphalt (RA) and mineral sludge (MS)***
    - *LCA of pavements for highways containing nano-reinforced materials, such as bituminous binders modified by means of carbon nanotubes (CNT) and nanoclays (NC)*

CNT



NC



Sustainability assessment of pavements containing unconventional construction materials

LCA of pavements for rural roads containing large quantities of reclaimed asphalt (RA) and mineral sludge (MS)

Impacts of the pavement construction industry

- *Large volumes of aggregates in pavement construction*
- *Massive exploitation of natural resources*
- *Significant environmental concerns*

Recycling of by-products in paving mixtures for rural roads

- *Replacement of large volumes of virgin aggregates*
- *Reduction in the depletion of raw materials*
- *Valuable option due to the lower performance requirements*

Sustainability assessment of pavements containing unconventional construction materials

LCA of pavements for rural roads containing large quantities of reclaimed asphalt (RA) and mineral sludge (MS)

Major distress type in rural roads

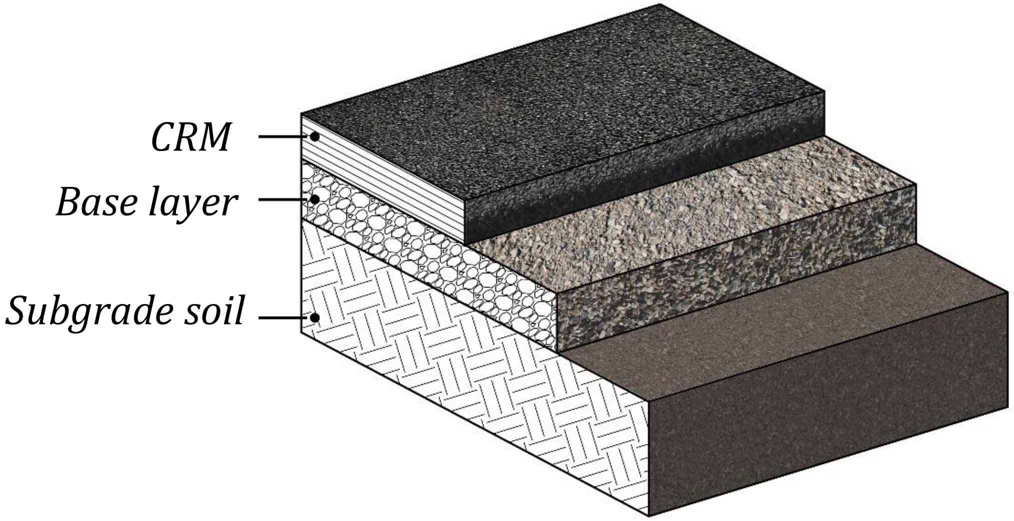
- Dustiness
- Erosion
- Ravelling
- Potholing
- Corrugation
- Rutting

→ Reduced by using bound-mixtures for the road surface finishing

Sustainability assessment of pavements containing unconventional construction materials

LCA of pavements for rural roads containing large quantities of reclaimed asphalt (RA) and mineral sludge (MS)

Emulsion-based cold recycled mixture (CRM) for the surface finishing of unpaved rural roads containing large quantities of reclaimed asphalt and mineral sludge.



Component	Value
Reclaimed Asphalt	68.3 %
Mineral sludge	16.4 %
Silica Sand	6.4 %
Bituminous Emulsion	3.5 %
Water (added)	5.4 %

Sustainability assessment of pavements containing unconventional construction materials

LCA of pavements for rural roads containing large quantities of reclaimed asphalt (RA) and mineral sludge (MS)

Assessment of the environmental benefits related to the use of innovative construction solutions for rural roads containing large quantities of waste materials.

<u>LCA study:</u>
- *Global warming potential*
- *Energy requirement*
- *Water consumption*

Tool: SimaPro

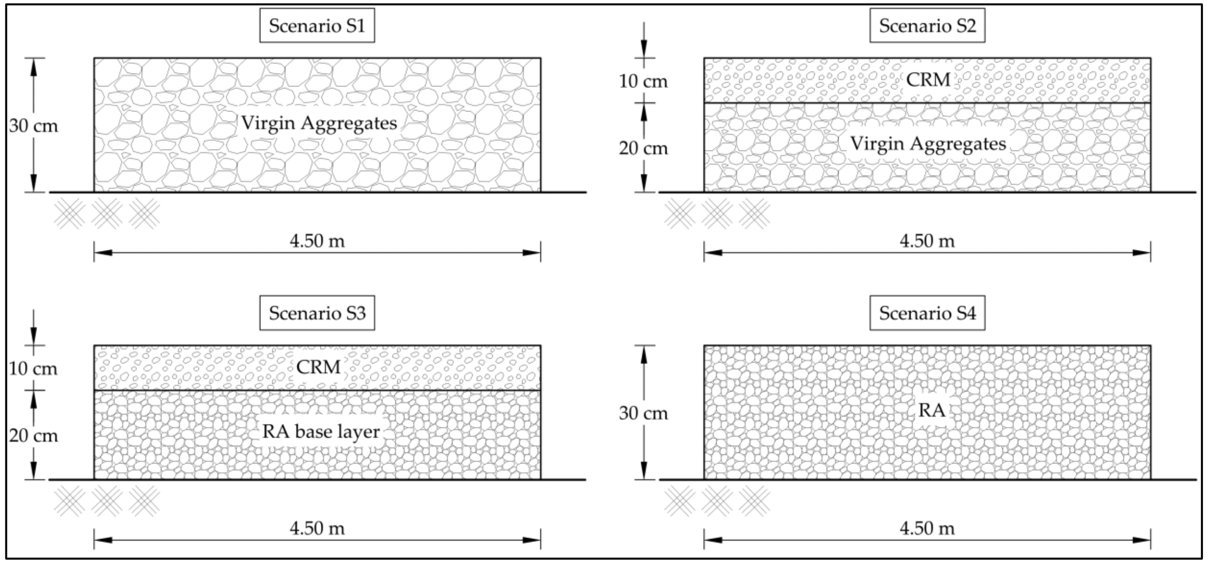
Functional unit: 1 km of road with a service life of 10 years

System boundaries: Materials production; Construction; Maintenance operations

Sustainability assessment of pavements containing unconventional construction materials

LCA of pavements for rural roads containing large quantities of reclaimed asphalt (RA) and mineral sludge (MS)

Scenarios



	S1	S2	S3	S4
Service Life	10 years			
Maintenance Activities	2	1	1	2
Materials employed	0/45 Ga 90	CRM	CRM	20 RA 0/14
Thickness of the new layer	9 cm	3 cm	3 cm	9 cm

Sustainability assessment of pavements containing unconventional construction materials

LCA of pavements for rural roads containing large quantities of reclaimed asphalt (RA) and mineral sludge (MS)

Transportation distances

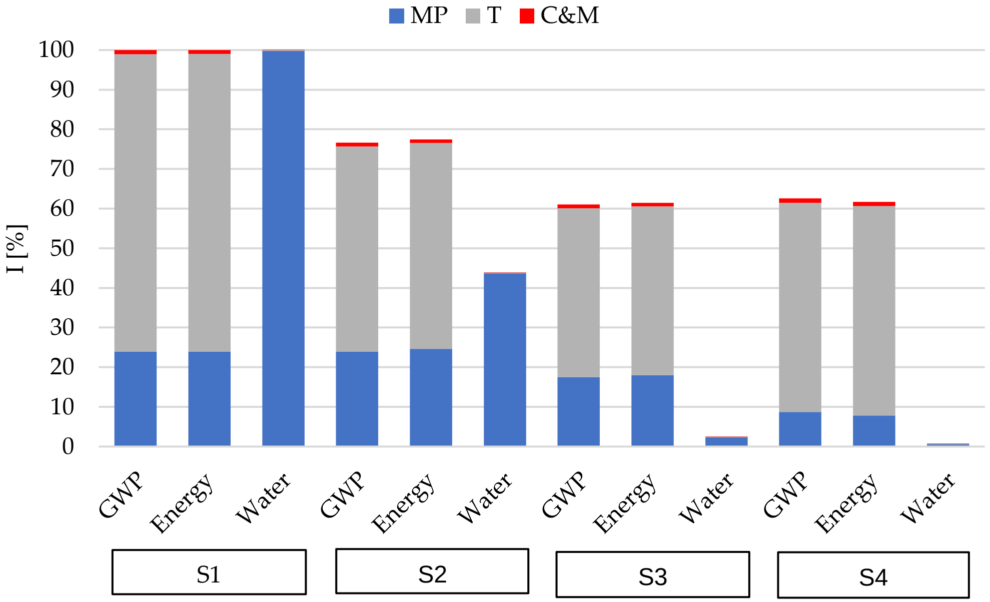
Material	Production or extraction site to plant facility (km)	Plant facility to construction site (km)
Virgin aggregates	14.5	43.8
Reclaimed asphalt (RA)	0	43.8
Emulsion	372	0
Cold-recycled mixture (CRM)	0	43.8

Sustainability assessment of pavements containing unconventional construction materials

LCA of pavements for rural roads containing large quantities of reclaimed asphalt (RA) and mineral sludge (MS)

LC Impact assessment and interpretation

Stage	S1	S2	S3	S4
GWP (t of CO_2eq)				
MP	14.2	14.2	10.4	5.2
T	44.6	30.8	25.3	31.3
C&M	0.7	0.6	0.6	0.7
Total	59.4	45.6	36.3	37.2
Energy (GJ)				
MP	220.9	228.2	166.4	72.6
T	695.0	479.9	394.0	488.8
C&M	9.3	8.2	8.2	9.3
Total	925.1	716.3	568.6	570.7
Water (m^3)				
MP	5 500.6	2 408.0	129.1	31.2
T	14.2	9.8	8.1	10.0
C&M	0.2	0.2	0.2	0.2
Total	5 515.0	2 418.0	137.3	41.4



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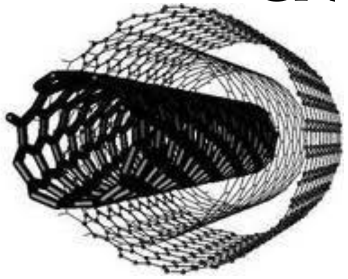
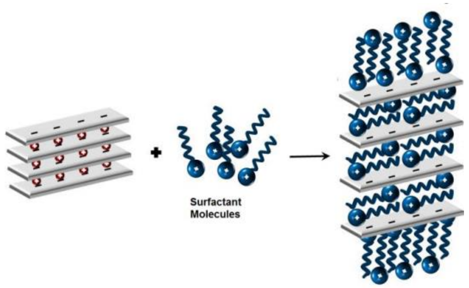
CNT

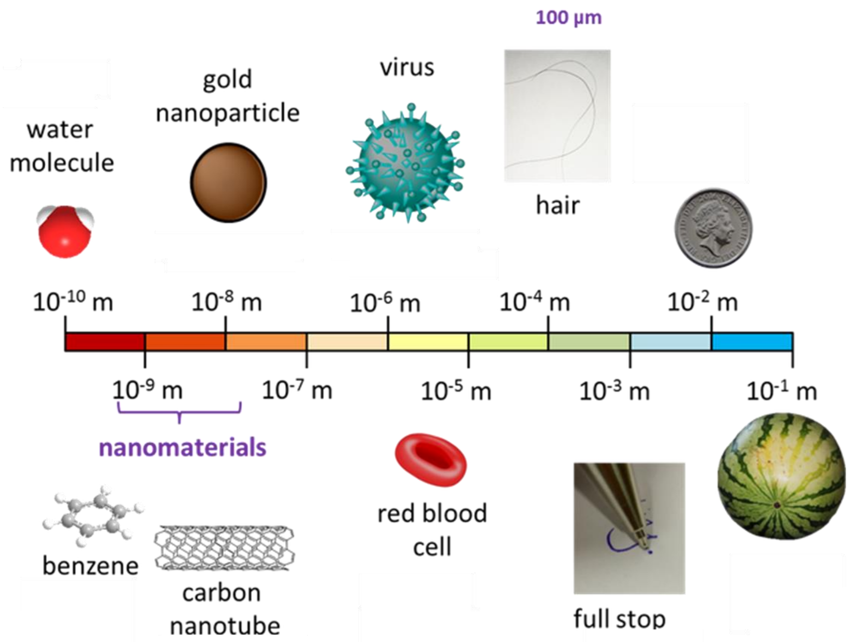


NC



Sustainability assessment of pavements containing unconventional construction materials

LCA of pavements for highways containing carbon nanotubes (CNT) and nanoclays (NC)



"DAMAGE AND HEALING OF INNOVATIVE NANO-STRUCTURED AND POLYMER MODIFIED BITUMINOUS MATERIALS"

Italian Ministry of Education, University and Research (MIUR)

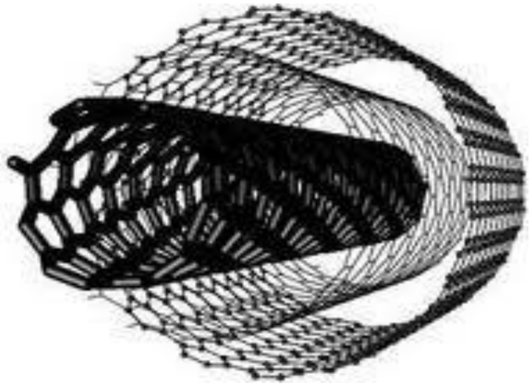
RESEARCH UNITS:

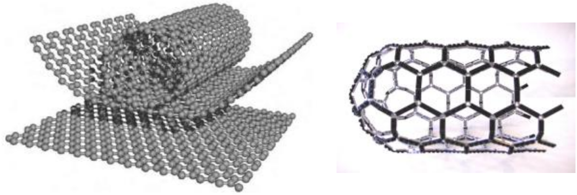
- POLITECNICO DI TORINO (Nano-structured)
- UNIVERSITA' POLITECNICA DELLE MARCHE (Polymer-modified materials)

Sustainability assessment of pavements containing unconventional construction materials

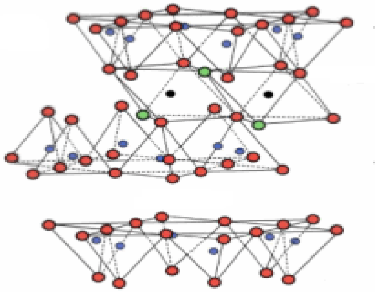
LCA of pavements for highways containing carbon nanotubes (CNT) and nanoclays (NC)

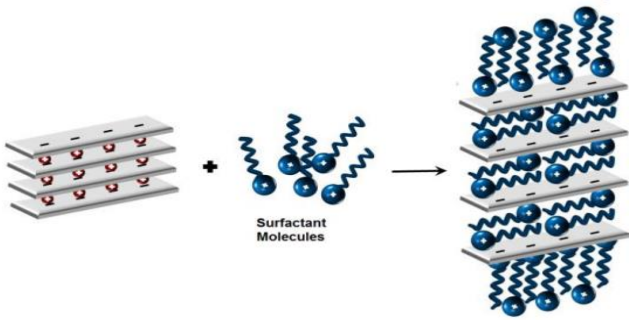
CARBON NANOTUBES (CNT)





NANOCLAYS (NC)





Sustainability assessment of pavements containing unconventional construction materials

LCA of pavements for highways containing carbon nanotubes (CNT) and nanoclays (NC)

Assessment of the potential environmental benefits related to the use of nano-structured bituminous mixtures in bound-layer of highway pavements.

Tool:
- *PaLATE - customized to account for the specific context*

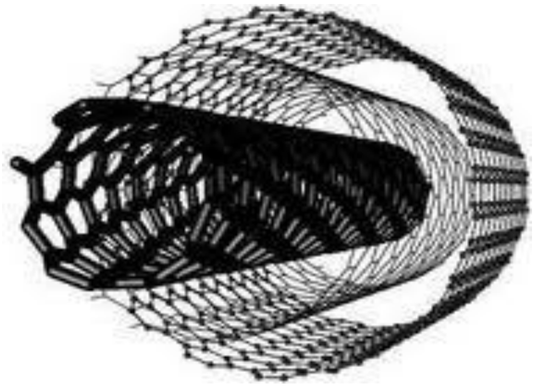
Functional unit:
- *1 km of a single lane of highway*

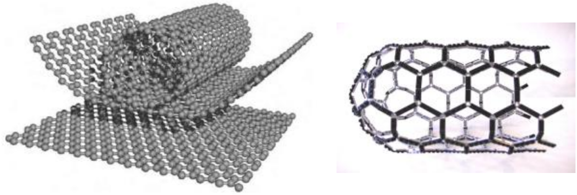
System boundaries:
- *Materials production*
- *Initial construction*

Sustainability assessment of pavements containing unconventional construction materials

LCA of pavements for highways containing carbon nanotubes (CNT) and nanoclays (NC)

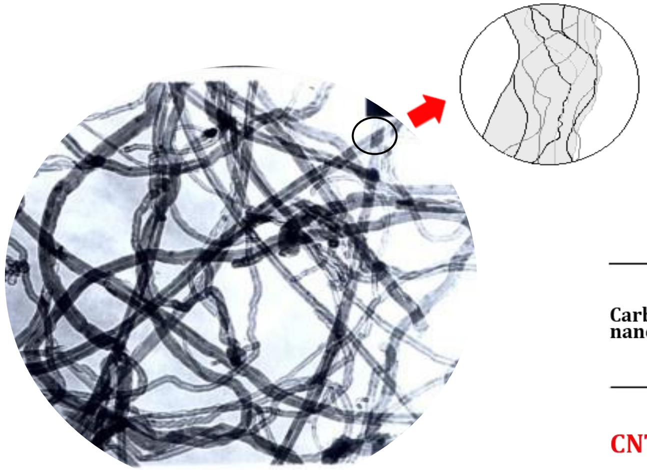
CARBON NANOTUBES (CNT)





CNT COMPOSITES

Several hierarchical morphologies of bundles



Carbon nanotubes	Average diameter [nm]	Average length [µm]	Surface area [m²/g]	Carbon purity (%)	Metal oxide (%)
CNT	9.5	1.5	250-300	90	10

Sustainability assessment of pavements containing unconventional construction materials

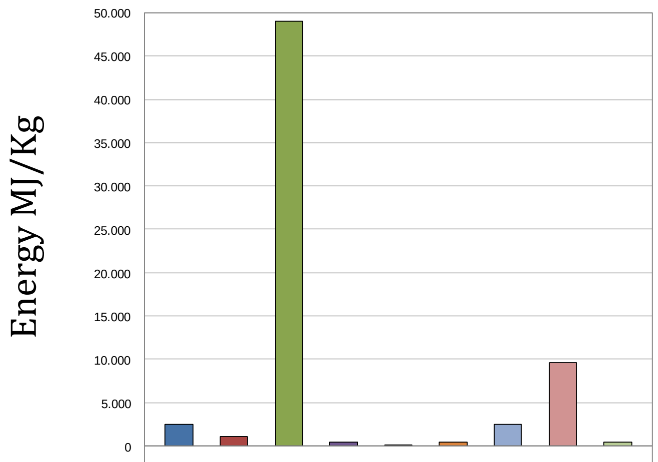
LCA of pavements for highways containing carbon nanotubes (CNT) and nanoclays (NC)

Production of MWCNT

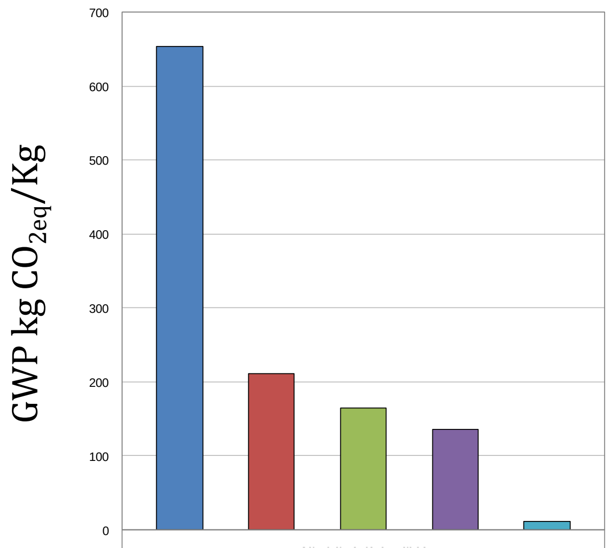
- *Production technique (CVD, EAD, LA, etc...)*
- *Carbon source, catalyst, carrier gas, purification process, etc...)*
- *Production scale*

LCA

- *Space and time-dependency*
- *System boundaries*



CVD - Trompeta, et al., 2016	2.480
Fixed Bed CVD - Trompeta, et al., 2016	1.100
Floating Catalyst CVD - Griffiths, et al., 2013	49.000
Floating Catalyst CVD - Wu, et al., 2020	482
Fluidized Bed CVD - Roes, et al., 2010	95
Floating Catalyst CVD - Kushnir, et al., 2008	482
Arco elettrico - Kushnir, et al., 2008	2.480
Ablazione laser - Kushnir, et al., 2008	9.640
Fornace solare - Kushnir, et al., 2008	442

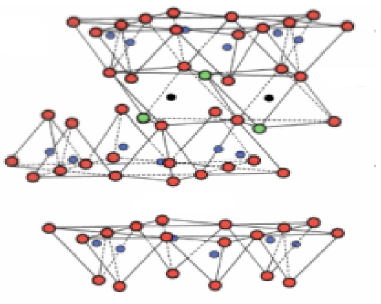


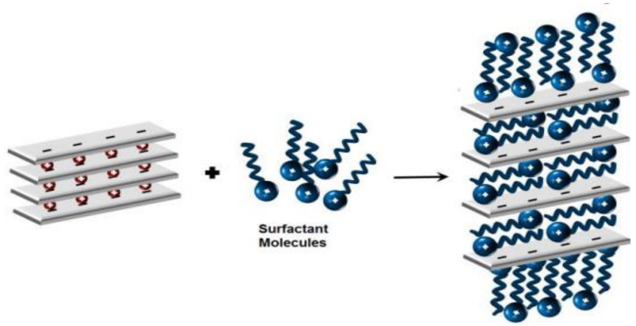
CVD - Trompeta, et al., 2016	653
Fixed Bed CVD - Trompeta, et al., 2016	211
Floating Catalyst CVD - Griffiths, et al., 2013	165
Floating Catalyst CVD - Wu, et al., 2020	136
Fluidized Bed CVD - Roes, et al., 2010	11

Sustainability assessment of pavements containing unconventional construction materials

LCA of pavements for highways containing carbon nanotubes (CNT) and nanoclays (NC)

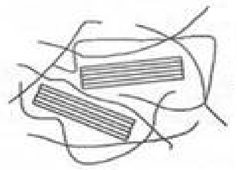
NANOCLAYS (NC)



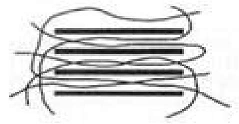


NC COMPOSITES

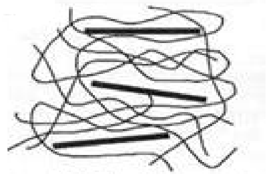
Conventional composites



Intercalated composites



Exfoliated composites



Nanoclay	Organic modifier	Anion	Basal spacing [nm]	Cation Exchange Capacity (CEC) [meq/100g]	Density [g/cm^3]
NCA	Dimethyl, dihydrogenatedtallow, quaternary ammonium	Chloride	3.15	125	1.66

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Sustainability assessment of pavements containing unconventional construction materials

LCA of pavements for highways containing carbon nanotubes (CNT) and nanoclays (NC)

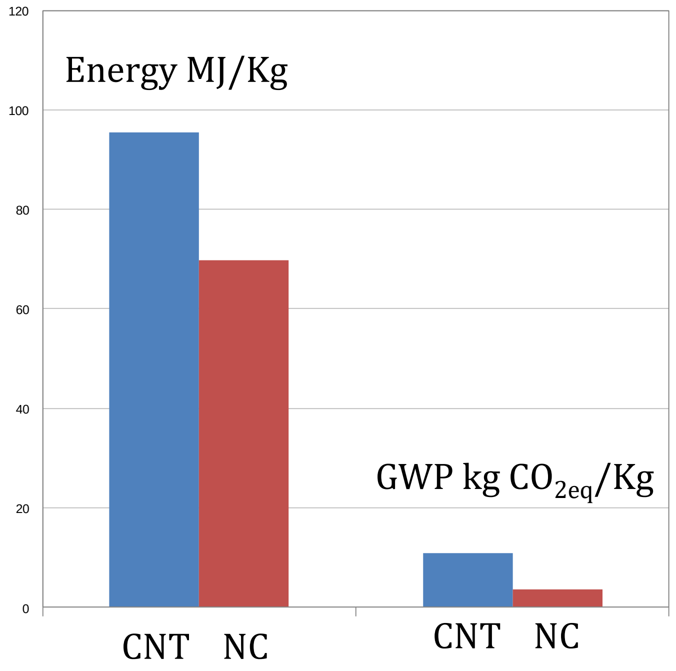
Production of NC (organo-montmorillonite)

- *Production process (clay mining, organic modifier, clay processing)*
- *Production scale*

LCA

- *Space and time-dependency*
- *System boundaries*

Source	Energy (MJ/kg)	GWP (kg CO_2 eq/kg)
Joshi, 2008	4,01E+01	1,52E+00
Roes, et al., 2010	6,97E+01	3,55E+00
Schrijvers, et al., 2014	7,28E+01	3,25E+00



Sustainability assessment of pavements containing unconventional construction materials

LCA of pavements for highways containing carbon nanotubes (CNT) and nanoclays (NC)

Preparation of nano-reinforced binders

Base bitumen: PG 58-22; pen. 70/100

Nano-additive dosages:

- *0.5% CNT (CVD)*
- *3% NC (organo-montmorillonite)*
- *Shear mixing and sonication*

Preparation of nano-reinforced mixtures

Standard protocol

SHEAR MIXING

- Mechanical stirrer
- Speed: 1550 rpm
- Time: 90 minutes
- Temperature: 150 °C

SONICATION

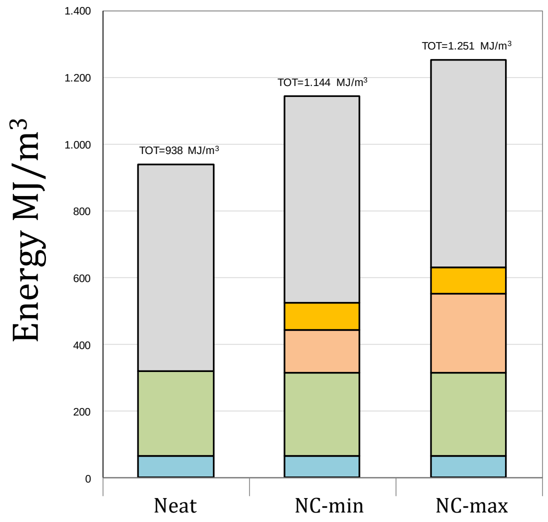
- Amplitude: 158 μm
- Frequency: 24 kHz
- Time: 60 minutes
- Temperature: 150 °C

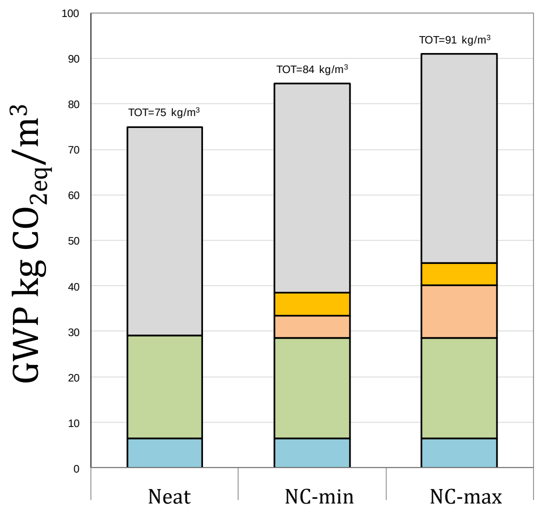
Sustainability assessment of pavements containing unconventional construction materials

LCA of pavements for highways containing carbon nanotubes (CNT) and nanoclays (NC)

Production of 1 m^3 of bituminous mixture

- HMA
- Nano-binder
- Nano-additive
- Bitumen
- Aggregates





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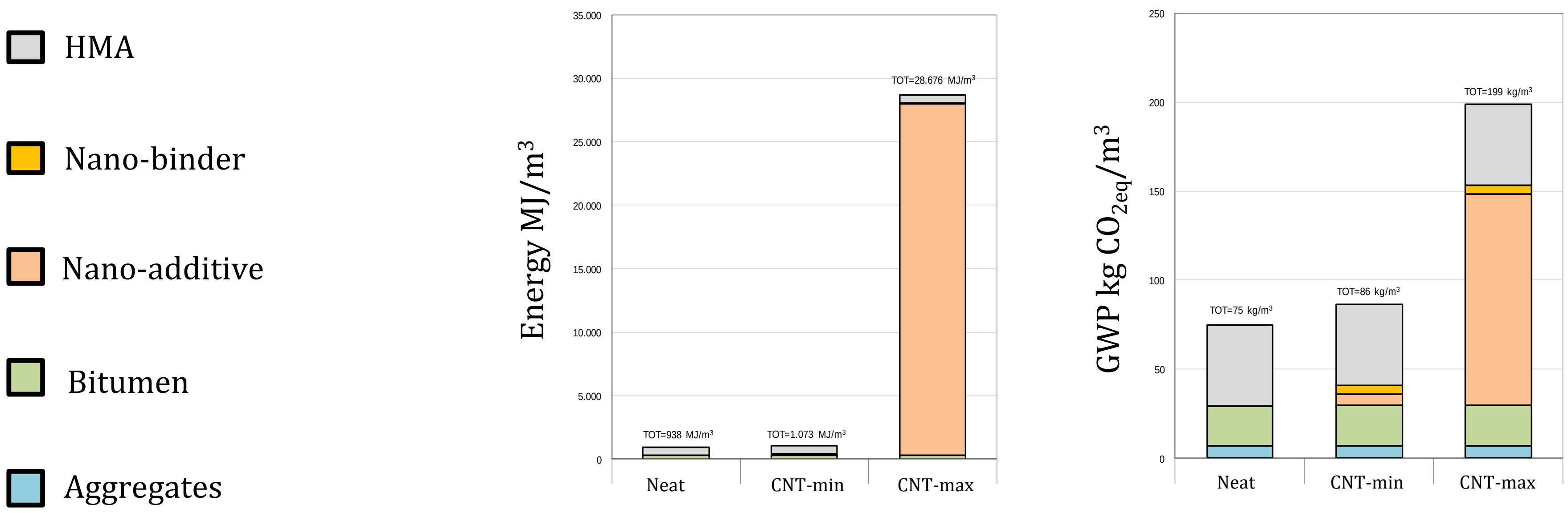
Production of 1 m^3 of bituminous mixture

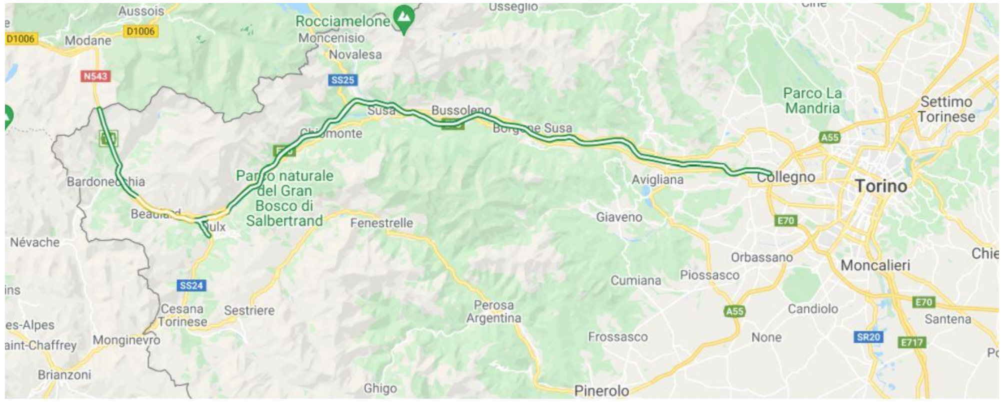


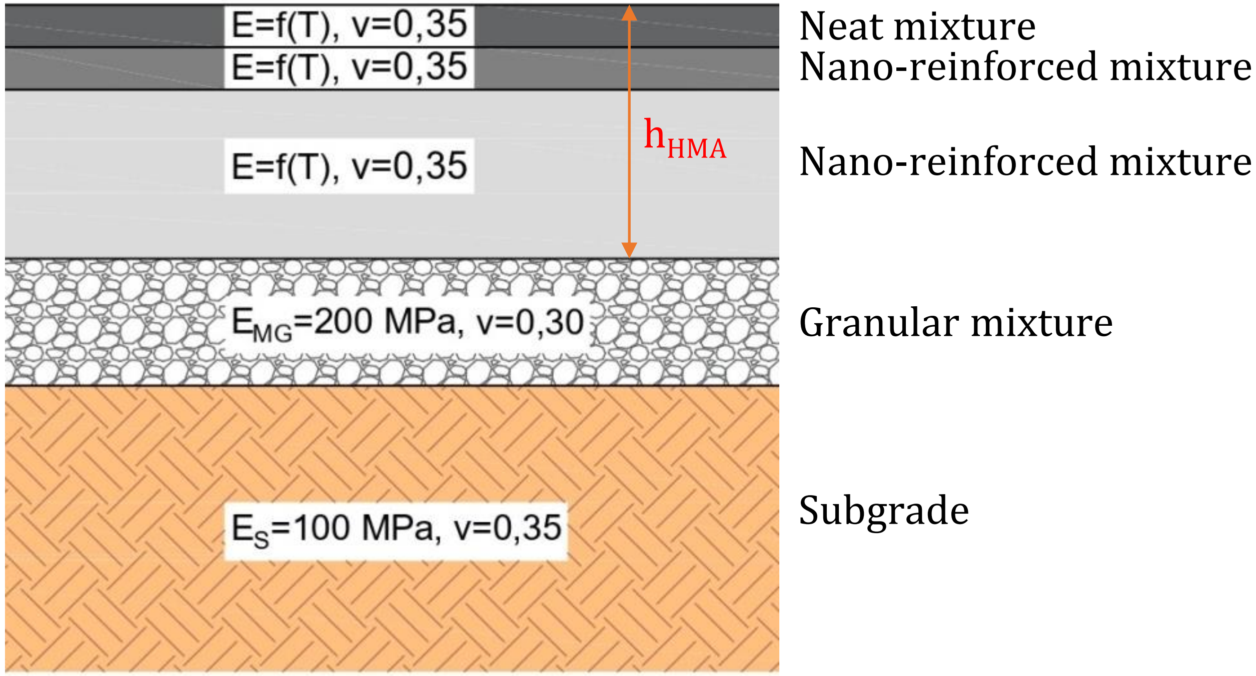
Sustainability assessment of pavements containing unconventional construction materials

LCA of pavements for highways containing carbon nanotubes (CNT) and nanoclays (NC)

<u>Structural design</u>

- Mechanistic empirical approach based on fatigue and subgrade rutting





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Sustainability assessment of pavements containing unconventional construction materials

LCA of pavements for highways containing carbon nanotubes (CNT) and nanoclays (NC)

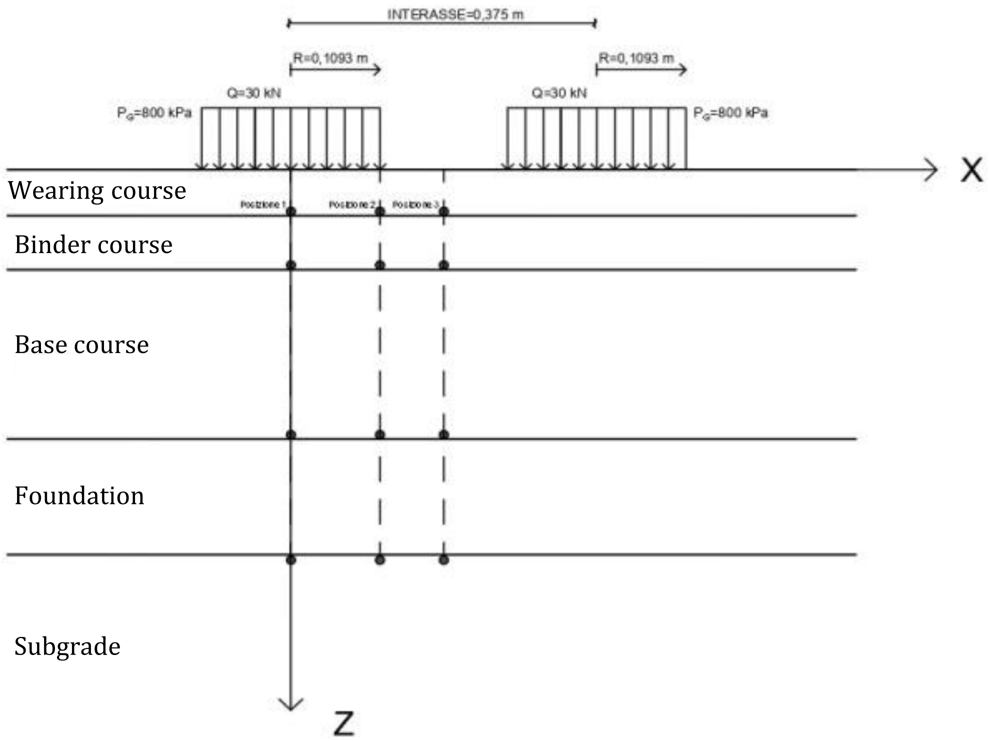
Structural analysis

- 12 periods of analysis
- Design traffic modelled based on data available from surveys (homogenized in equivalent axle)
- Fatigue transfer function

$$N_f = \frac{1}{F_{aff}} \cdot F_{lab} \cdot F_a \cdot f_1 \cdot \left(\frac{1}{\varepsilon_t}\right)^{f_2} \cdot \left(\frac{1}{E}\right)^{f_3}$$

- Rutting transfer function

$$N_d = f_4 \cdot \left(\frac{1}{\varepsilon_c}\right)^{f_5}$$

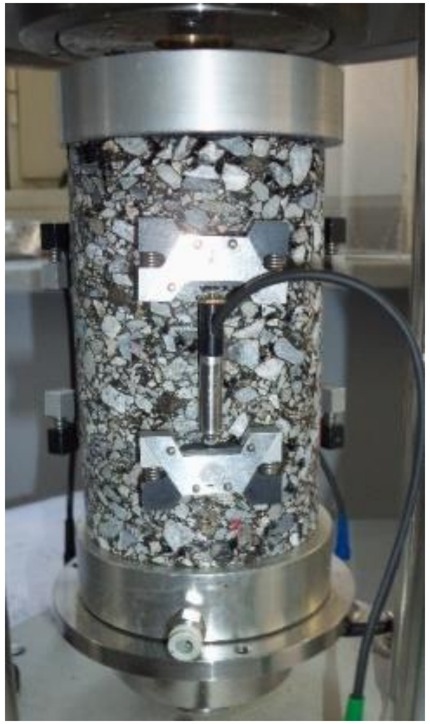


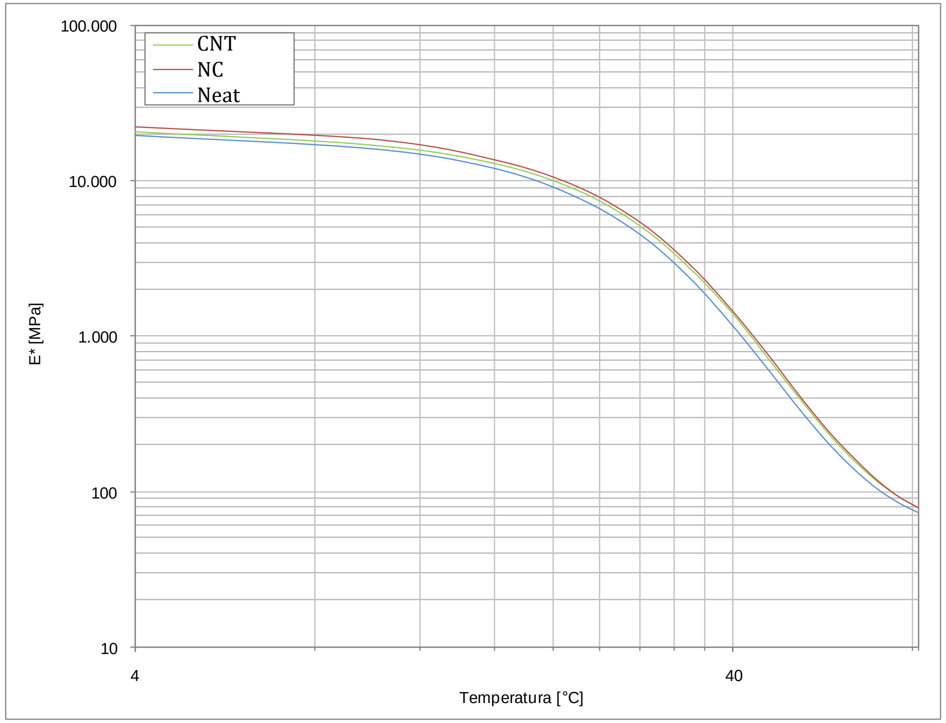
Sustainability assessment of pavements containing unconventional construction materials

LCA of pavements for highways containing carbon nanotubes (CNT) and nanoclays (NC)

Mixtures

- *Linear viscoelastic characterization*
- *Dynamic modulus tests*





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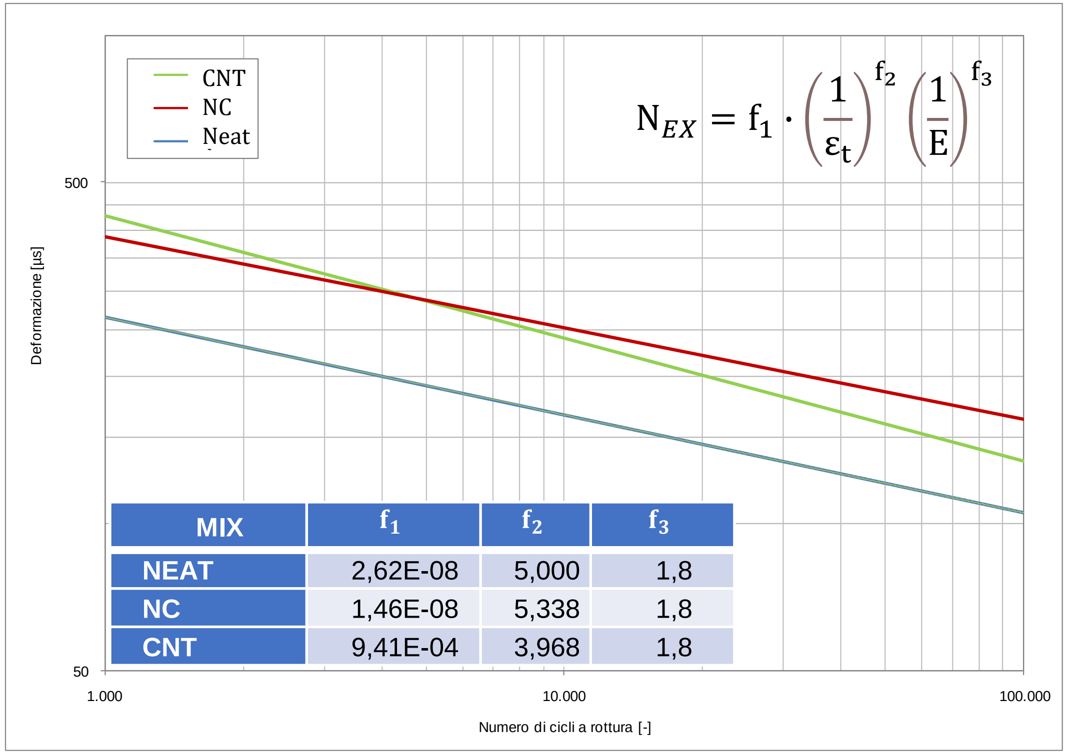
Sustainability assessment of pavements containing unconventional construction materials

LCA of pavements for highways containing carbon nanotubes (CNT) and nanoclays (NC)

Mixtures

- *Fatigue resistance*
- *Direct tension cyclic fatigue tests*



$$N_{EX} = f_1 \cdot \left(\frac{1}{\varepsilon_t}\right)^{f_2} \left(\frac{1}{E}\right)^{f_3}$$

MIX	f_1	f_2	f_3
NEAT	2,62E-08	5,000	1,8
NC	1,46E-08	5,338	1,8
CNT	9,41E-04	3,968	1,8

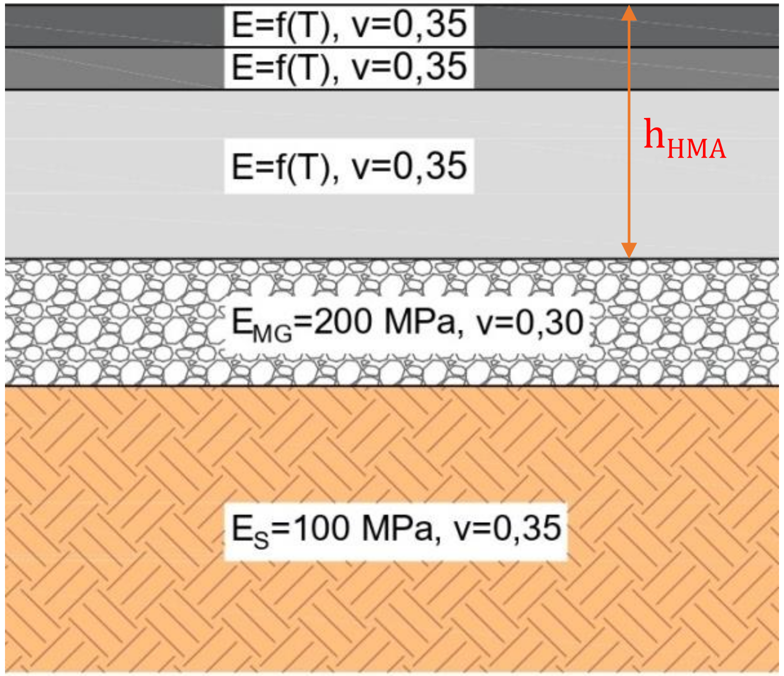
Sustainability assessment of pavements containing unconventional construction materials

LCA of pavements for highways containing carbon nanotubes (CNT) and nanoclays (NC)

Structural design

- Mechanistic empirical approach based on fatigue and subgrade rutting

Mixture type	h_{HMA}
Neat	48 cm
NC	38 cm
CNT	44 cm



Neat mixture
Nano-reinforced mixture
Nano-reinforced mixture
Granular mixture
Subgrade

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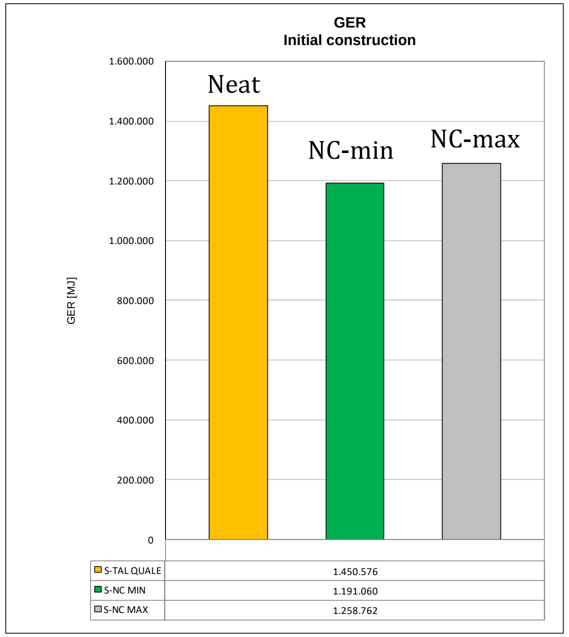
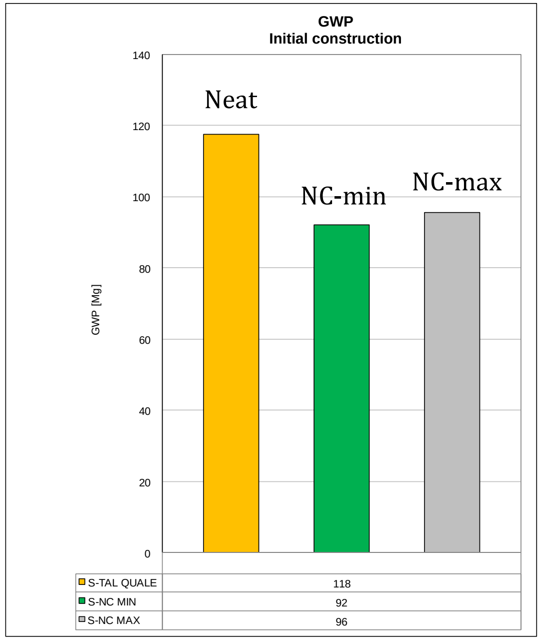
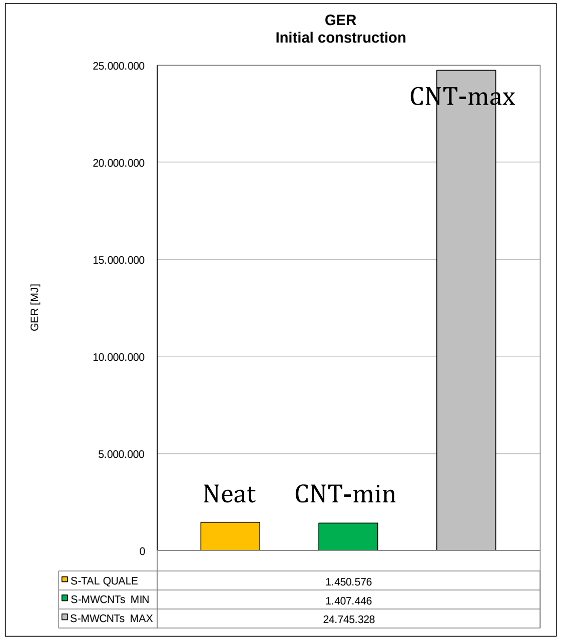
Sustainability assessment of pavements containing unconventional construction materials

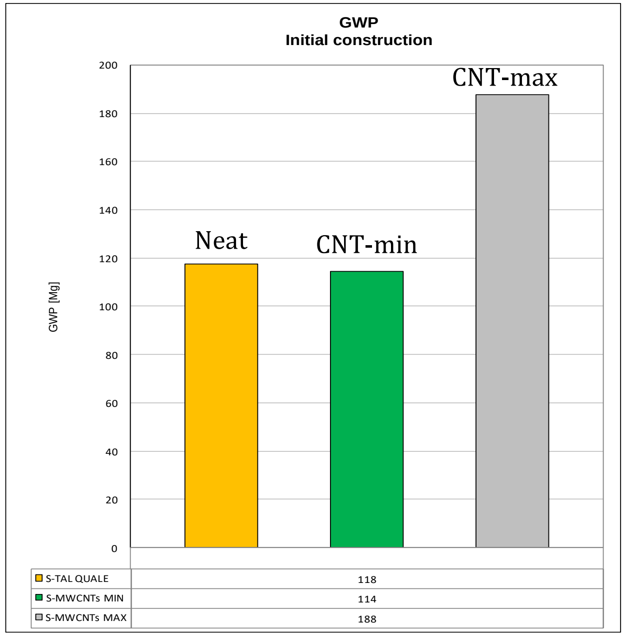
LCA of pavements for highways containing carbon nanotubes (CNT) and nanoclays (NC)

Construction of 1 km of a highway lane







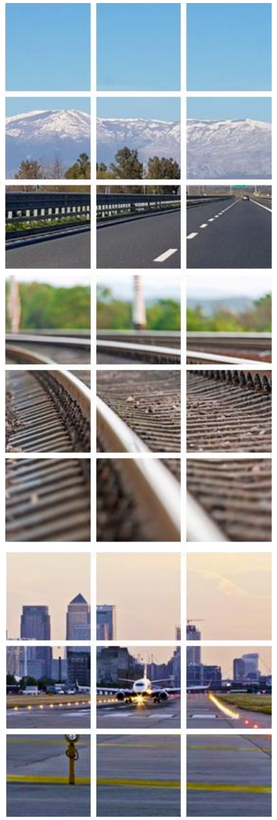


Sustainability assessment of pavements containing unconventional construction materials

Food for thoughts…

There is the need to consider all the dimensions of sustainability.

- *Sustainability rating systems allow the economic, environmental and social performances to be quantitatively assessed, thus providing a practical and concrete tool to support the green transition process in transportation infrastructure projects.*
- *When considering the use of unconventional construction materials, it is worth noting that their sustainability performance can be context specific. Moreover, their effectiveness in terms of structural and economic performances must not be jeopardized by detrimental environmental and social impacts.*
- *The use of recycled materials in transportation infrastructures is an imperative of our time. This must necessarily be accompanied by a widespread increase in specialized technical competences at all the professional levels.*



Thanks for your attention!

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