Integrated LCA Toolkits for Sustainable Transportation Infrastructure

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Session IV: LCA focusing on transport infrastructure in India
Workshop under the DTEE and NDC-TIA projects
Life cycle assessment methods to support India's efforts to decarbonise transport
International Transport Forum & NITI Aayog

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भारतीय प्रौद्योगिकी संस्थान तिरुपति

TIRUPATI

Strategic Visions: India & Global

Global Sustainable Innovation & Programs

- *Academia*
- *Research Centers*
- *Industry*
- *Education*
- *Training*

Materials: Advanced Testing & Characterization

- *Development of IRC / ASTM / CEN standards*
- *Laboratory Testing*
- *Round-robin*

Sustainability

- *Novel materials*
- *Recyclable products*
- *Rubber*
- *Plastic*
- *Waste resource*
- *Textile*
- *Etc.*

Energy & Environment: Global Impact / Climate Change

- ***<u>LCA</u>***
- *LCCA*
- *Porous*
- *UHI*

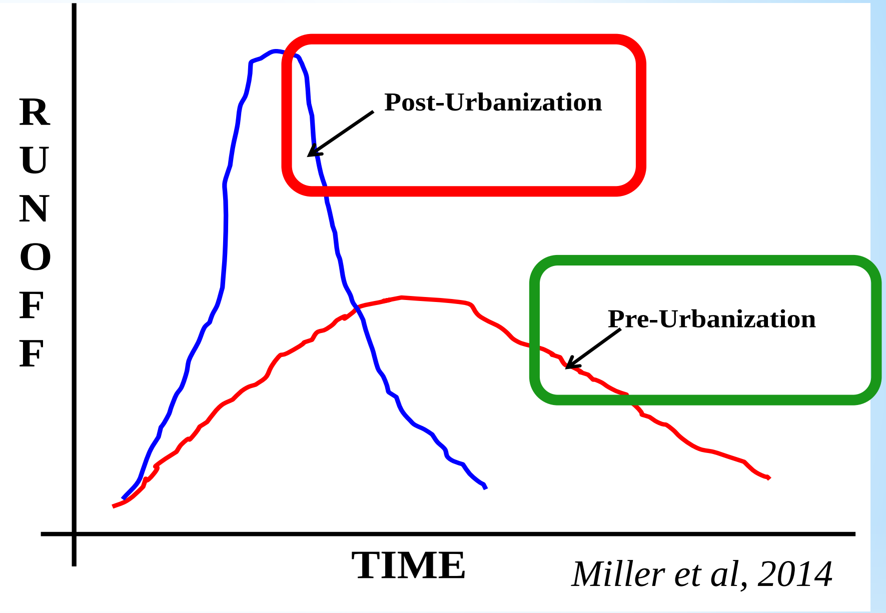
Holistic Approach: Constitutive Modeling / Fundamental Science

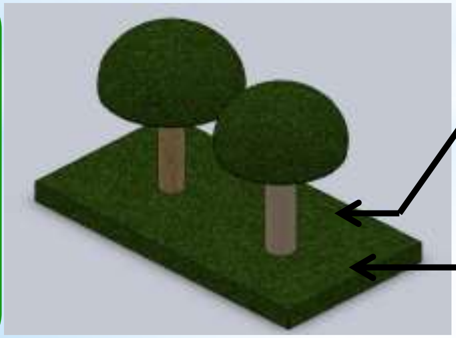
- *Mechanistic*
- *Lab-Field Correlations*
- *Numerical*
- *Analytical*

National / International Collaboration

- *Centers of Excellence*
- *Research Institutes*
- *Ministry*
- *NHAI*
- *EU*
- *IUSSTF*
- *Virtual Centers*
- *ITF*

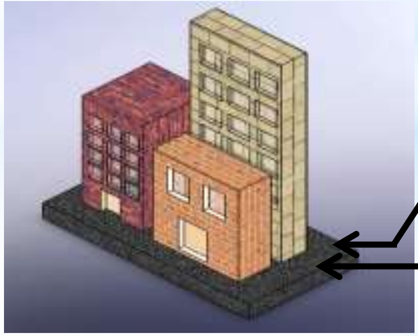
Smart Solutions: Climatic Impact & Decisions





Better recharge, reduced runoff

Pervious natural ground

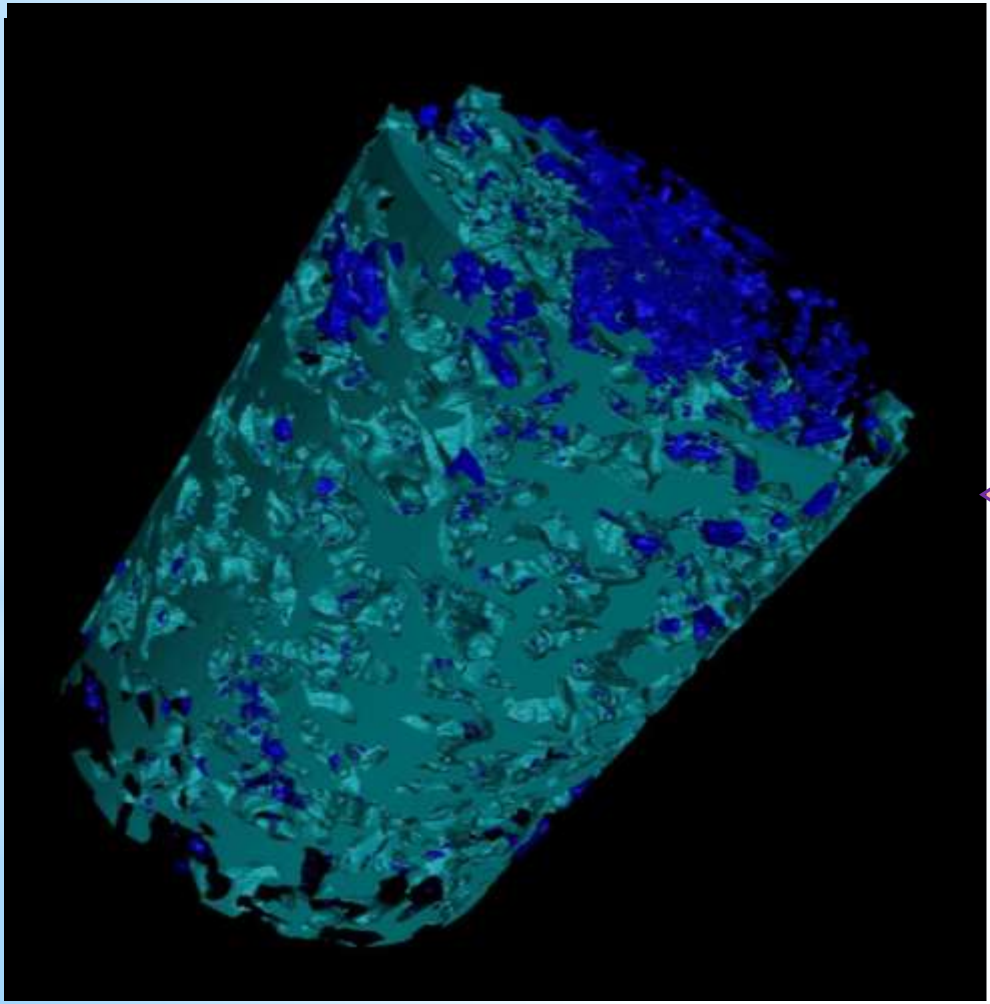


reduced recharge, increased runoff

impervious ground

PERVIOUS CONCRETE

Special type of concrete having characteristic inter-connected pore structure



- **Interconnected pores**
- **Coarse aggregates**
- **No / limited fines**
- **Reduces runoff quantity**
- **High latent heat capacity**

Pervious Concrete: Field Demonstration

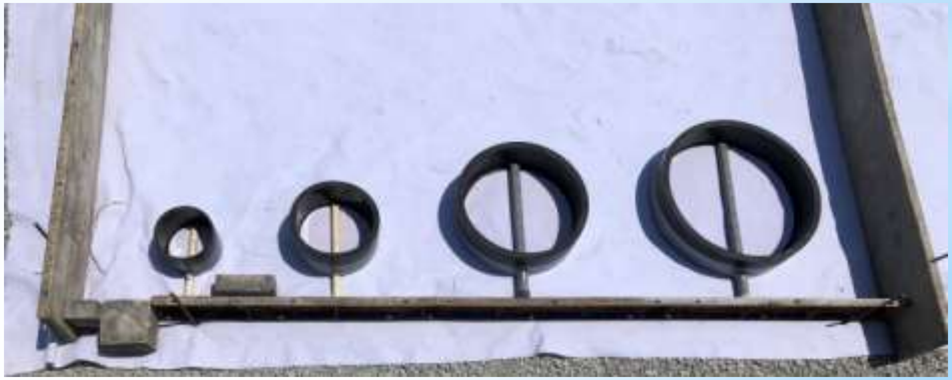
IIT Kharagpur, India, June 2017

July 2017

Tirupati Smart City, India, 2018

Pervious Concrete: New Generation Designs

IIT Tirupati, India, March 2019



Pervious Concrete: New Generation Designs

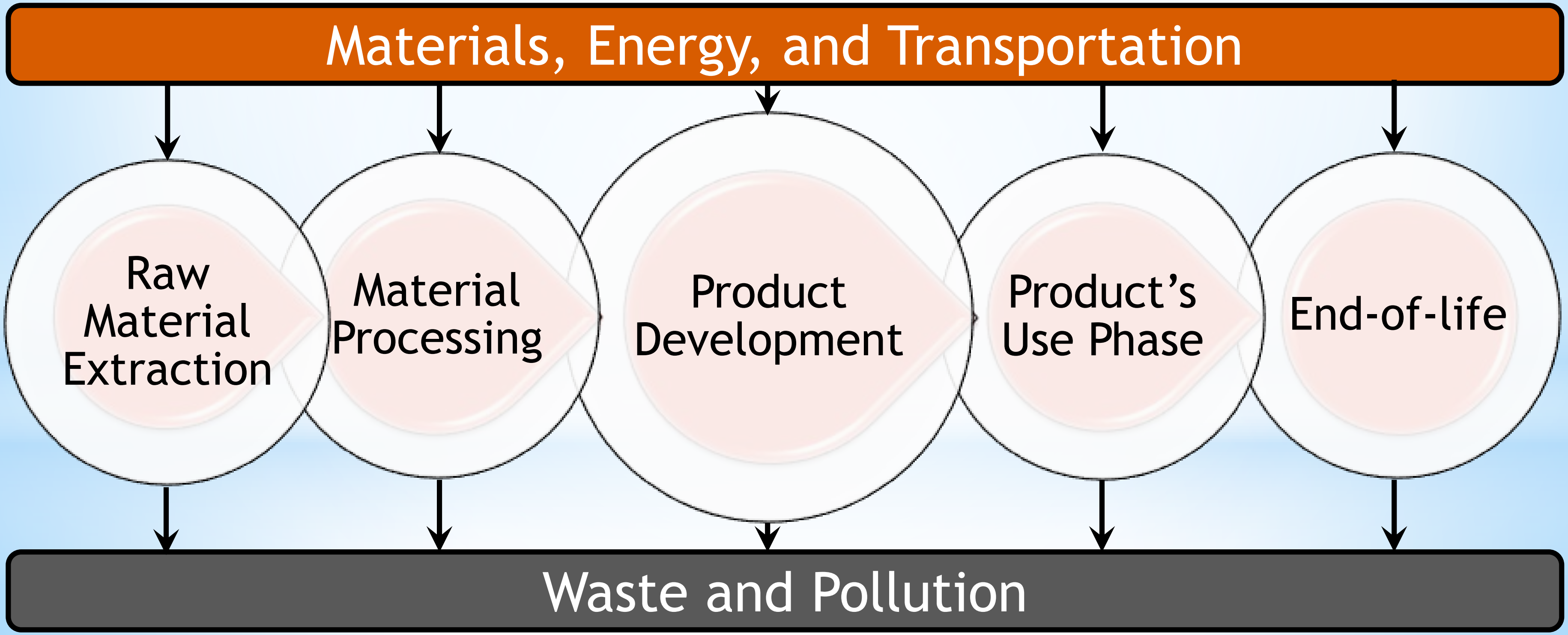
- *IIT Kharagpur, 2017: Chandrappa, A.K., Maurya, R., Biligiri, K.P., Rao, J.S., and Nath, S., 2018. Laboratory investigations and field implementation of pervious concrete paving mixtures. ASTM Int'l Advances in Civil Engineering Materials, 7: 447-462*
- *Tirupati Smart City, 2018: Singh, A., Jagadeesh, S.G., Sampath, P.V., and Biligiri, K.P., 2019. Rational approach for characterizing in-situ infiltration parameter in two-layered pervious concrete pavement systems. Journal of Materials in Civil Engineering, American Society of Civil Engineers, 31 (11): 04019258*
- *IIT Tirupati, 2019: Vaddy, P., Singh, A., Sampath, P.V., and Biligiri, K.P., 2020. Multi-scale in-situ investigation of infiltration parameter in pervious concrete pavements, ASTM International Journal of Testing and Evaluation (DOI: 10.1520/JTE20200052)*

Lifecycle Assessment Toolkit

Framework for *Energy Consumption* & *Carbon Footprint* of *Building Materials* and *Infrastructure*

Background to Lifecycle Assessment (LCA)

- ***Structured framework to quantify environmental impacts of a product or system***
- ***Identifies most critical environmental inputs and outputs: material acquisition to its end-of-life (EOL)***



Generic lifecycle stages of a product/system/process

Lifecycle Phases

- *System boundary*
- *Lifecycle stages*
- *Functional unit*
- *Analysis period*

- *Translate inventory into meaningful environmental & health indicators*

Goal & Scope Definition → **Lifecycle Inventory** → **Impact Assessment** → **Interpretation**

- *Inputs & outputs*
- *Material flow & energy; waste & pollution*
- *Data collection – primary (site specific) & secondary (lifecycle databases, literature)*

- *Results & discussions*
- *Conclusions & recommendations*
- *Data uncertainty & variance*
- *Decision making*

LCA: Indicator / Metric

- ***Standards for LCA:*** ISO:14040-2006; ISO:14044-2006
- ***Types of LCA:*** cradle-to-gate; cradle-to-grave; gate-to-gate; gate-to-grave; cradle-to-cradle
- ***Commercial LCA software:*** openLCA (freeware); SimaPro™; Ecochain; Mobius; Gabi; OneClickLCA, etc.
- ***Standard LCA databases:*** Ecoinvent® 3.7; UVEK® LCI; Environmental footprints®, etc.
- ***LCA modeling approaches:*** attributional versus consequential
- ***Lifecycle impact assessment methods:*** ReCiPe, Impact 2002+, Ecoindicator, CML, TRACI, IPCC, USEtox, etc.

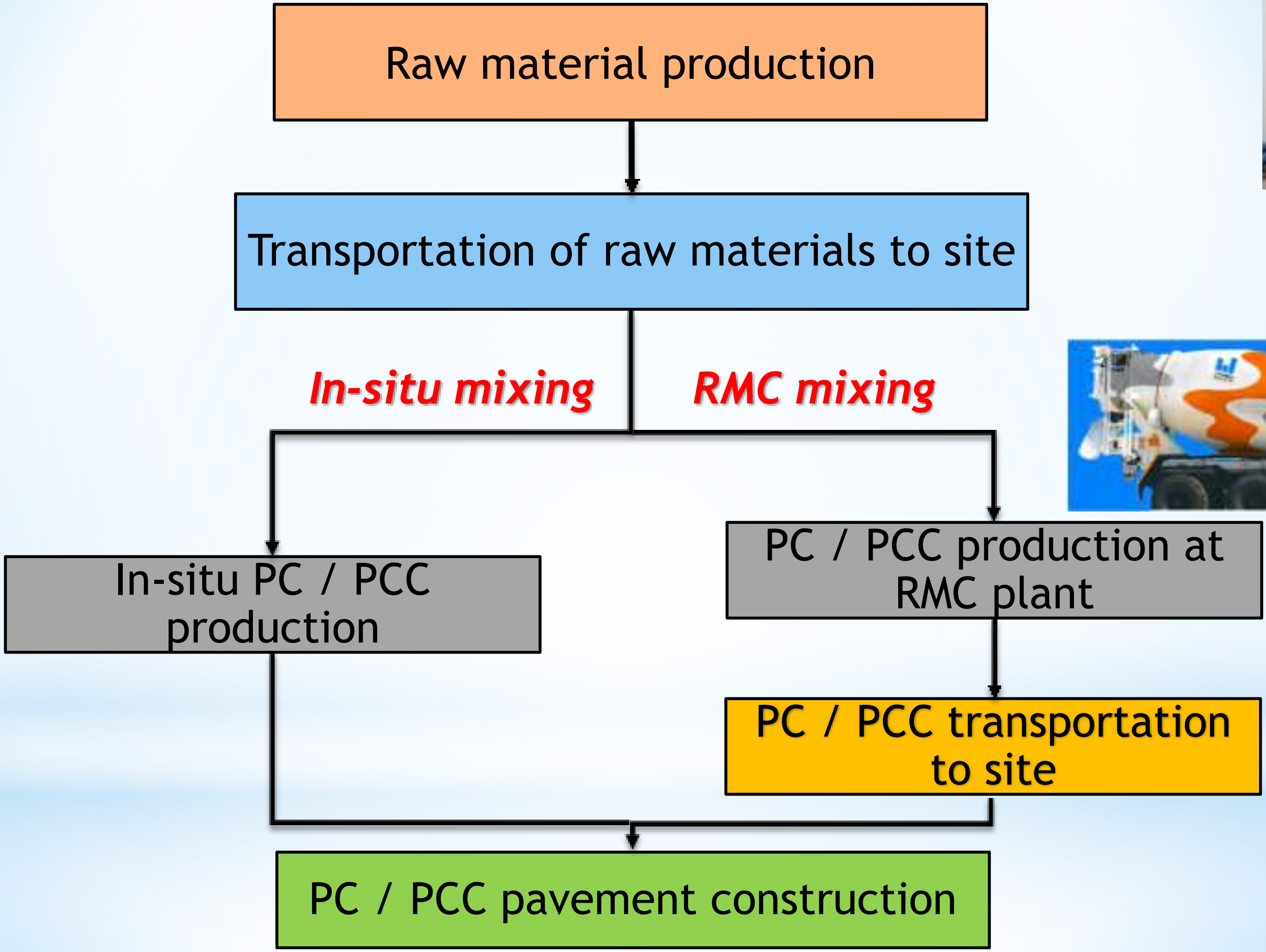
LCA of Pervious Concrete Pavements – *Goal & Scope*

Research Goal: Development of a systematic and user-friendly toolkit for rational assessment of environmental credibility of pavement systems

- *Comparative LCA study: pervious concrete pavement (PCP) versus Portland cement concrete pavement (PCCP)*
- *Study parameters: embodied energy, kg CO_2 equivalent, and capital cost*
- *Cradle-to-gate LCA approach*
- *Other potential areas for application of proposed framework: building materials and infrastructure*

Singh, A., Vaddy, P., and Biligiri, K. P., "Quantification of embodied energy and carbon footprint of pervious concrete pavements through a methodical lifecycle assessment framework", Resources, Conservation and Recycling, Elsevier, 161 (2020) 104953

Environmental Impacts due to PC Technology



PC – Pervious concrete; PCC – Portland cement concrete; RMC – Ready mixed concrete

LCA of Pervious Concrete Pavements – *Inventory Analysis*

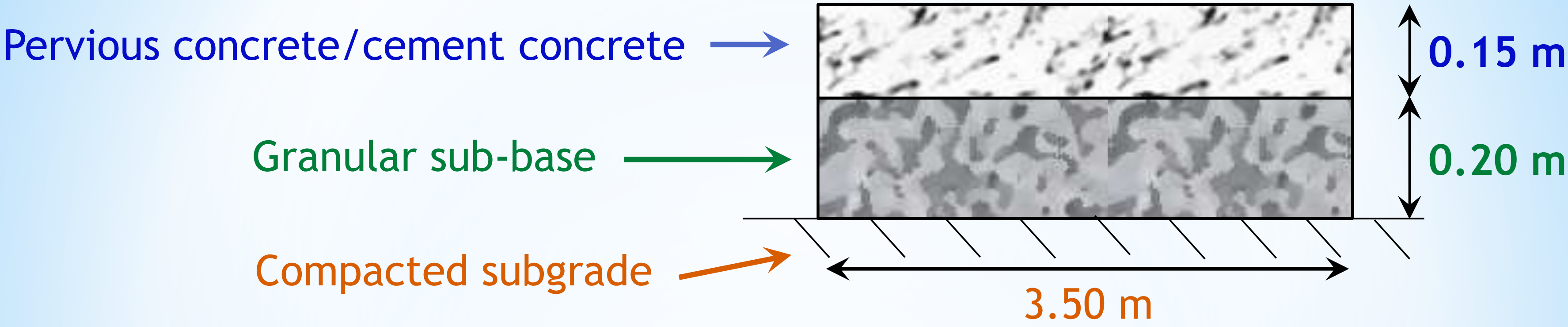
- ***Data collection:***
  - ***Primary*** **-** ***Construction Agency***
  - ***Secondary*** **-** ***Literature***; ***India construction materials database of embodied energy and global warming potential, 2017; CPCB***
- ***Materials and pavement systems:***
  - ***Ordinary Portland cement - 53 grade conforming to IS:12269***
  - ***Crushed aggregates - 12.5 mm and finer size***; ***M-sand***
  - ***Target compressive strength - 25 MPa***

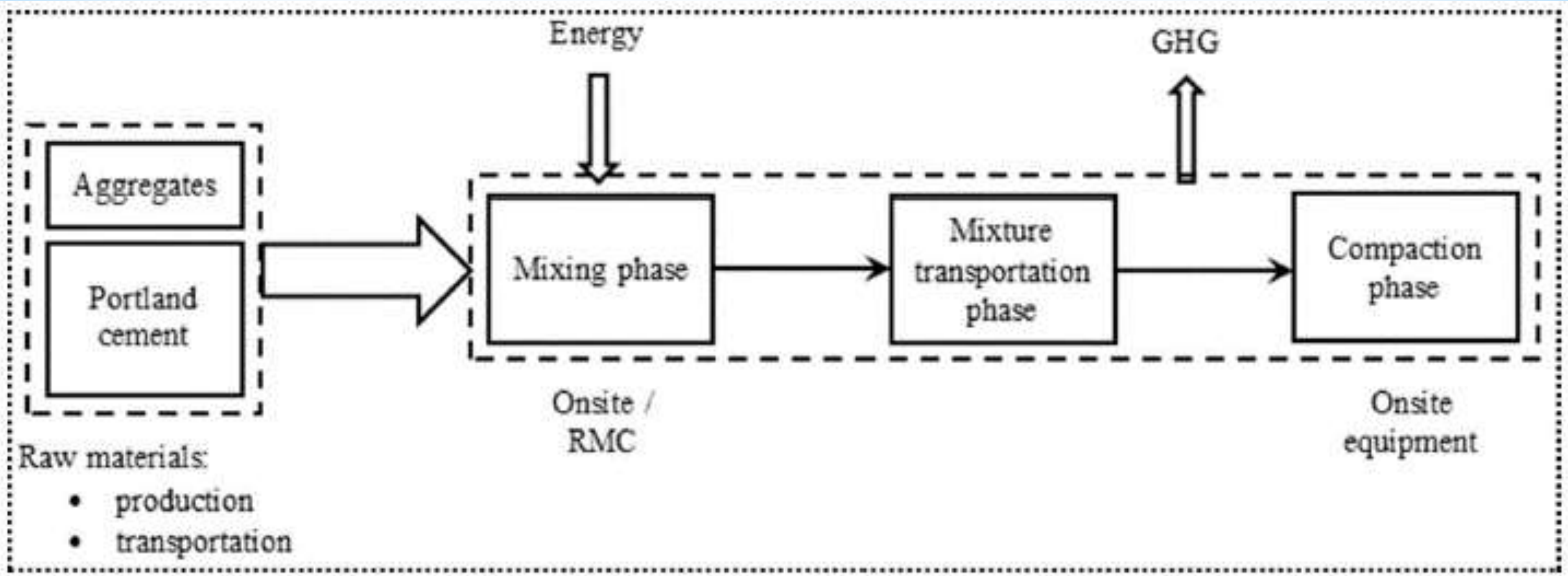
Configurations of different pavement systems with base layers and equal service life

Scenario	Surface course	Base layer	Mixing method
A	Pervious concrete	Granular	RMC
B	Portland cement concrete	Granular	RMC
C	Pervious concrete	Granular	In-situ
D	Portland cement concrete	Granular	In-situ

LCA of Pervious Concrete Pavements – *Inventory Analysis*

***Functional unit* - 1 km long single lane road, 3.5 m wide, and 0.35 m thick designed to handle low-volume traffic**





Lifecycle phase and components within system boundary for different pavement systems

LCA of Pervious Concrete Pavements – *Impact Assessment*

LCA model: *Development of an MS Excel® toolkit*

- *Total embodied energy (MJ/km) =* $\Sigma(1000 \times W \times (T \times D_n \times (P_e + M_e + (T_e \times D_i)) + C_e))$
- *Total kg* CO_2 *eq./km =* $\Sigma(1000 \times W \times (T \times D_n \times (P_g + M_g + (T_g \times D_i)) + C_g))$

W = *Width of the road in m;* T = *Thickness of layer in m*

D_n = *Density of pavement material in* kg/m^3

P_e = *Material production value in MJ/kg*

P_g = *Material production value in kg* CO_2 *eq./kg*

M_e = *Material mixing value in MJ/kg*

M_g = *Material mixing value in kg* CO_2 *eq./kg*

T_e = *Transport from production site to application site in MJ/kg-km*

T_g = *Transport from production site to application site, kg* CO_2 *eq./kg-km*

D_i = *Distance from material production site to application site in km*

C_e = *Material compaction value in* MJ/m^2

C_g = *Material compaction value in kg* CO_2 *eq./*m^2

LCA of Pervious Concrete Pavements – *Impact Assessment*

- *Material production values:* total energy consumed or emissions produced during production of a unit quantity of material
- *Material mixing value:* energy consumed (M_e) or quantity of emissions produced (M_g) due to mixing of a unit quantity of material

$$M_e\,(MJ/kg) = \frac{3.6\ x\ Engine\ power\ (kW)}{Mixing\ frequency\ (kg/hr)}$$

$$M_e\,(MJ/kg) = \frac{Fuel\ consumption\ (l/hr)\ x\ \ Thermal\ energy\ of\ fuel\ (MJ/l)}{Mixing\ frequency\ (kg/hr)}$$

$$M_g\,(kg\ \ CO_2 eq./kg) = \frac{Fuel\ consumption\ (l/hr)\ x\ \ Emissions\ from\ fuel\ (kg\ CO_2\ eq./l)}{Mixing\ frequency\ (kg/hr)}$$

$$M_g\,(kg\ \ CO_2\ eq./kg) = E\ x\ Energy\ consumed\ in\ mixing\ (MJ/kg)$$

$$Electric\ Energy - GHG\ Emission\ Factor = \\ \%\ of\ Thermal\ Energy\ x\ ((1.90\ x\ CO\ (kg/MJ)) + (265\ x\ NO_x\ (kg/MJ)))$$

LCA of Pervious Concrete Pavements – *Impact Assessment*

- Energy consumption and emissions generated during transportation:

$$T_e\ (MJ/kg - km) = \frac{3.6\ x\ Engine\ Power\ (kW)}{Speed\ of\ vehicle\ (kmph)\ x\ Quantity\ of\ material\ transported\ (kg)}$$

$$T_g\ (kg\ \ CO_2\ eq./kg - km) = \frac{Vehicular\ emissions\ (kg\ CO_2\ eq\ ./k\ m - hr)\ x\ \ Travel\ time\ (hr)}{Quantity\ of\ material\ transported\ (kg)}$$

- *Material compaction value:* energy consumed (C_e) or emissions generated (C_g) during compaction of unit surface area of a pavement layer

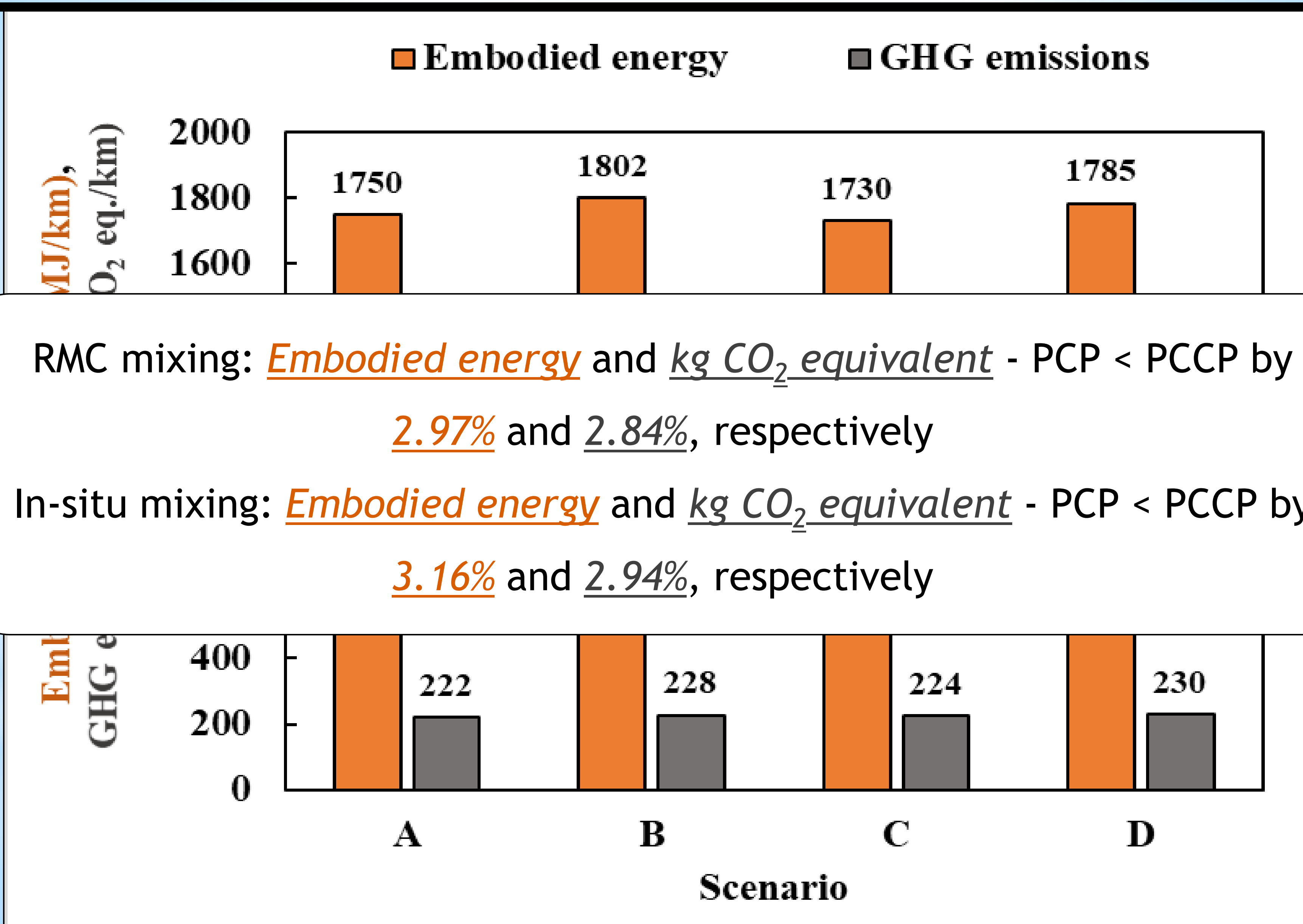
$$C_e\ \left(MJ/m^2\right) = \frac{0.0036\ x\ Number\ of\ passages\ x\ Engine\ power\ (kW)}{Speed\ of\ vehicle\ (kmph)\ x\ Width\ of\ roller\ (m)}$$

$$Ce\ \left(MJ/m^2\right) = \frac{Engine\ power\ (kW)}{Compaction\ rate\ (m^2/s)\ x\ 1000}$$

$$C_g\ \left(kg\ CO_2\ eq./m^2\right) = \frac{Number\ of\ passes\ x\ Emissions\ from\ fuel\ (kg\ CO_2\ eq\ ./l)}{Width\ of\ compactor\ (m)\ x\ Mileage\ of\ vehicle\ (m/l)}$$

$$C_g\ \left(kg\ \ CO_2\ eq./m^2\right) = E\ x\ Compaction\ energy\ \left(M\ J/m^2\right)$$

LCA of Pervious Concrete Pavements – *Interpretation*



RMC mixing: *Embodied energy* and *kg CO_2 equivalent* - PCP < PCCP by *2.97%* and *2.84%*, respectively

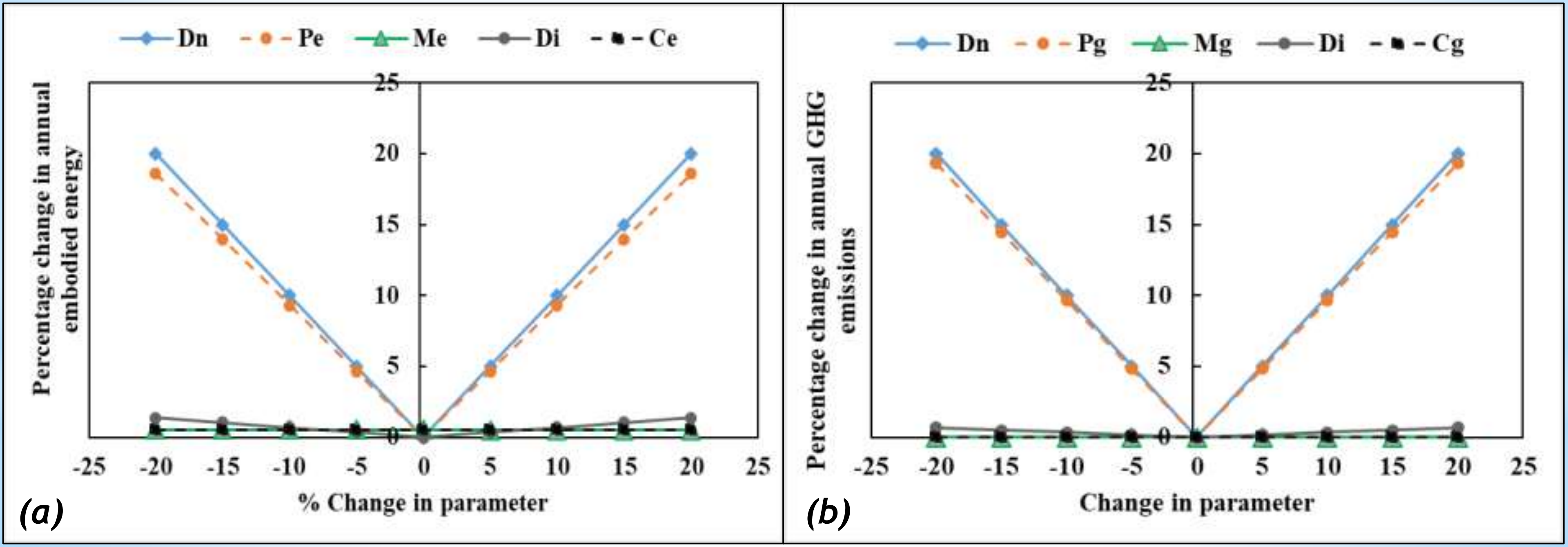
In-situ mixing: *Embodied energy* and *kg CO_2 equivalent* - PCP < PCCP by *3.16%* and *2.94%*, respectively

Environmental impacts of pavement systems

LCA of Pervious Concrete Pavements – *Interpretation*

Sensitivity analysis

- **Model inputs parameters tested for sensitivity variations (±20%):** ***transportation distance, material production, material mixing, material compaction, and density of materials***



Sensitivity of density, production, mixing, compaction, and transportation distance for: (a) Embodied energy; (b) GHG emissions

Capital Cost Analysis

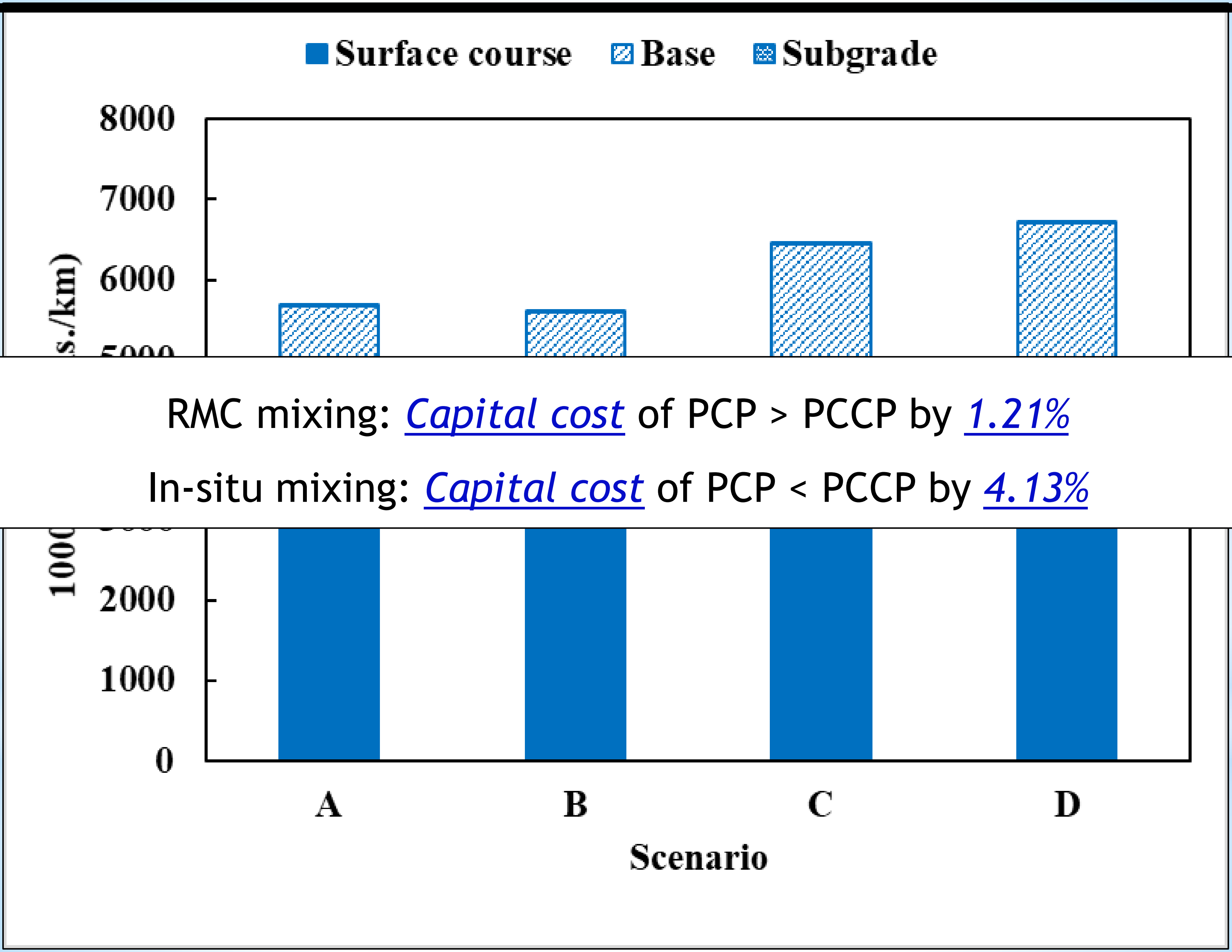
- Cradle-to-gate study: cost analysis restricted to expenditure incurred up to pavement construction stage alone
- Locally available materials and labor costs
- Excel program: *set of computational tools and models*

$$Total\ cost\ (Rs./km) = \sum (\ T\ x\ W\ x\ (M_c +\ T_c + C_c))$$

where,

- T = *Thickness of layer in m*
- W = *Width of the road in m*
- M_c = *Material cost in Indian Rs./km/m^2*
- T_c = *Material transportation cost in Indian Rs./km/m^2*
- C_c = *Construction cost in Indian Rs./km/m^2 = Σ [mixing cost, equipment (concrete mixer and vibrator), rental charges, and labor cost]*

Capital Cost Analysis



RMC mixing: *Capital cost* of PCP > PCCP by *1.21%*

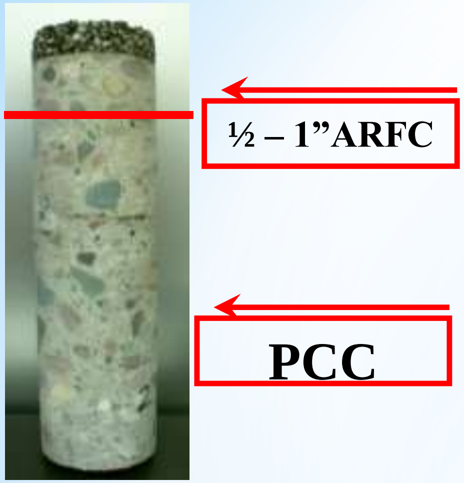
In-situ mixing: *Capital cost* of PCP < PCCP by *4.13%*

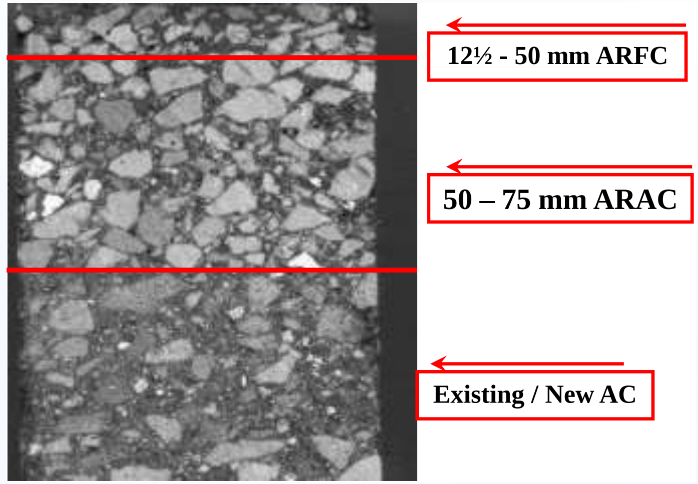
Total and layer-wise cost of pavement systems

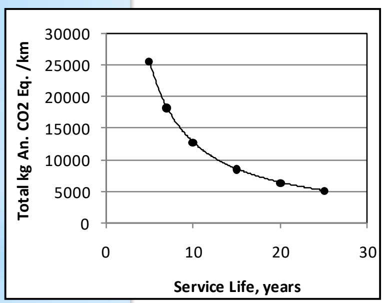
LCA of Pervious Concrete Pavements – *Futuristic Scope*

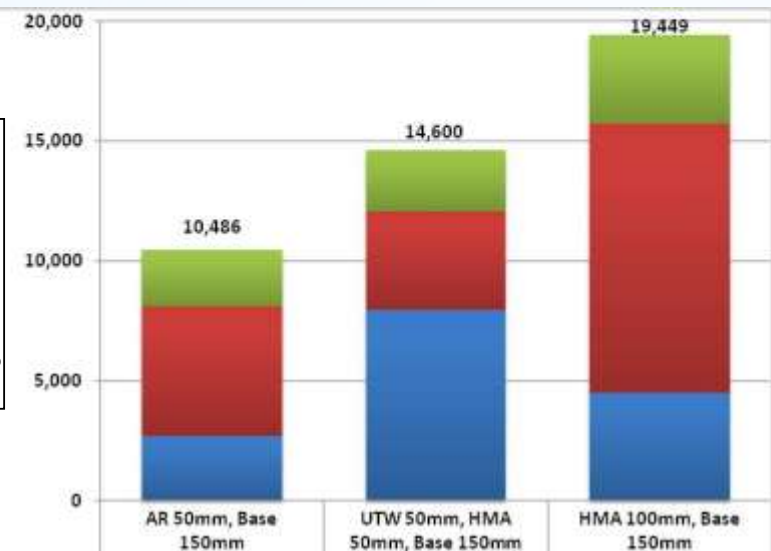
- *Embodied energy* and *kg CO_2 eq.* of PCP lower than PCCP by about ***3%***
- RMC mixing ***slightly expensive (capital cost)*** than in-situ mixing
- Proposed LCA methodology:
  - *practical and convenient toolkit* with *well-defined system boundaries* and *elaborated calculation procedures* that allows for *easy adoption* by researchers and agencies across the world
  - *suitable* for computation of *energy consumed* and *emissions generated* during various phases such as *building material production, construction, maintenance and repair, and end-of-life*
- Futuristic measures to *reduce heterogeneity in functional units, processes, phases, and other LCA components*
- LCA: essential to *guide planning* and *decision-making*
- *Full lifecycle cost analysis*: economic perspectives; big-data

Asphalt-Rubber Technology: LCA



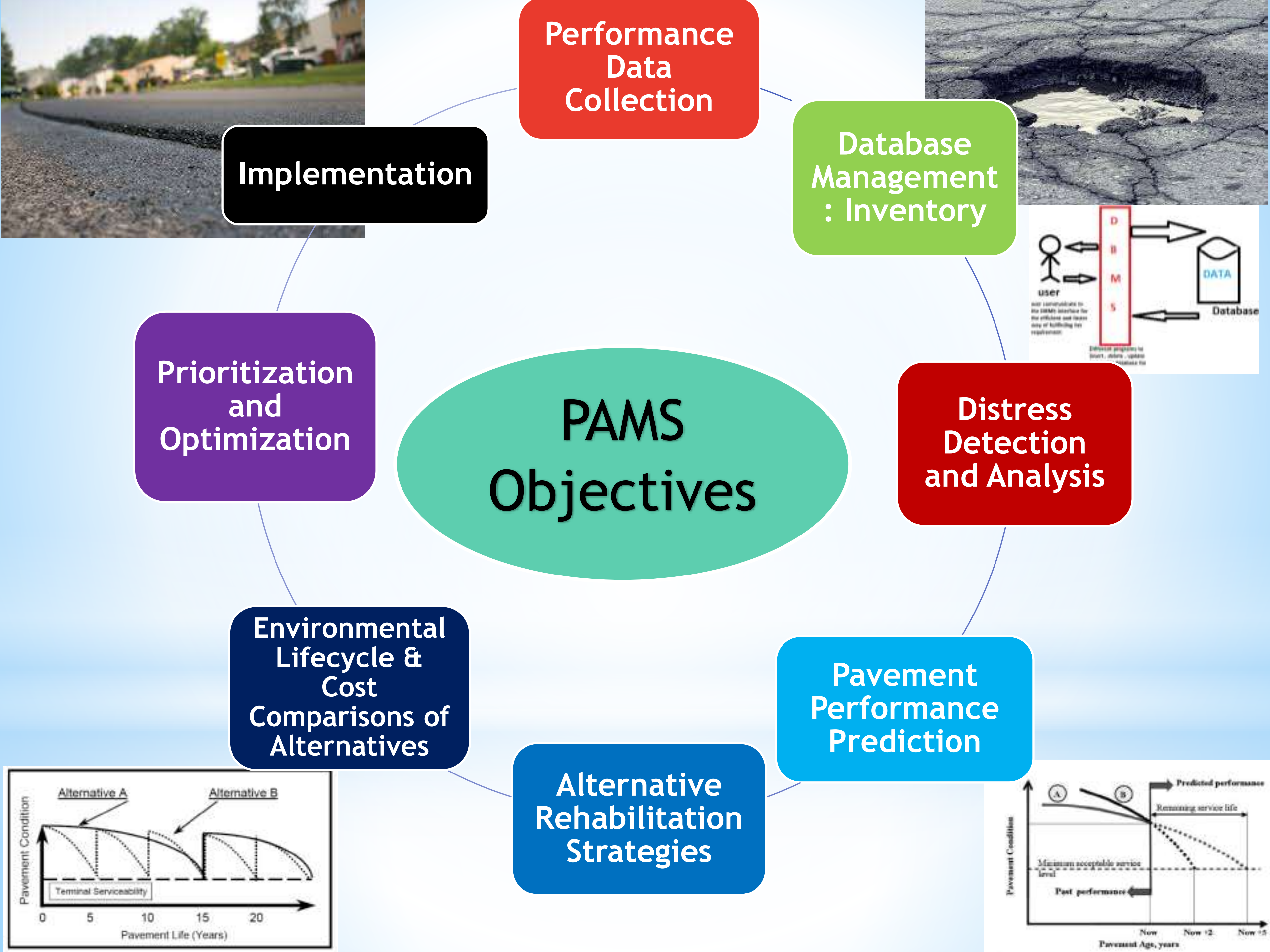






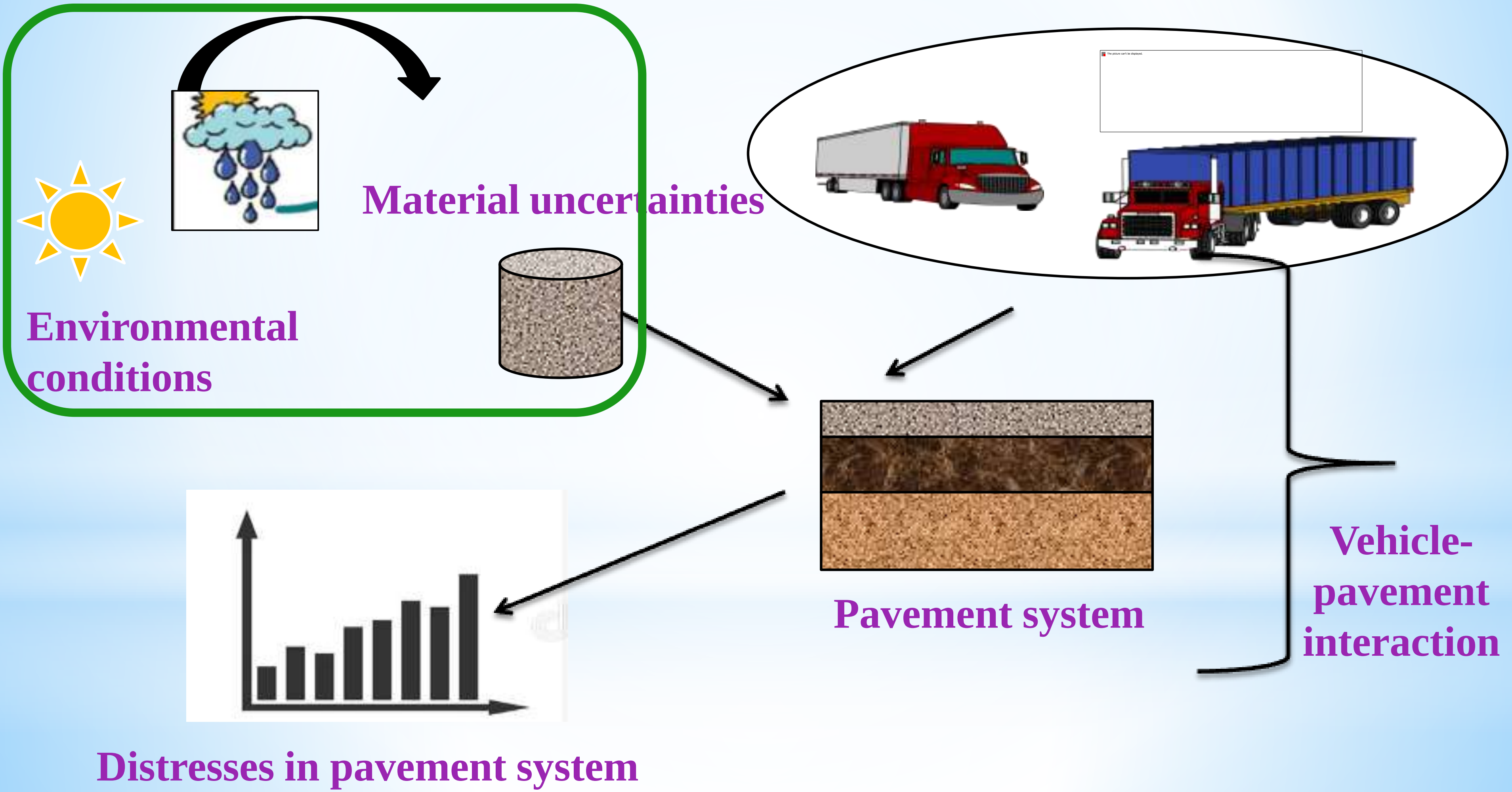
	AR 50mm, Base 150mm	UTW 50mm, HMA 50mm, Base 150mm	HMA 100mm, Base 150mm
Transportation kg An. CO2 Eq. / km	2,386	2,526	3,722
Mixing kg An. CO2 Eq. / km	5,381	4,124	11,210
Production kg An. CO2 Eq. / km	2,718	7,951	4,517

White, P., Golden, J. S., Biligiri, K. P., and Kaloush, K. E. “Impacts of Alternative Pavement Designs on Climate Change”, Journal of Resources, Conservation and Recycling, Volume 54, Issue 11, September 2010, pp. 776-782

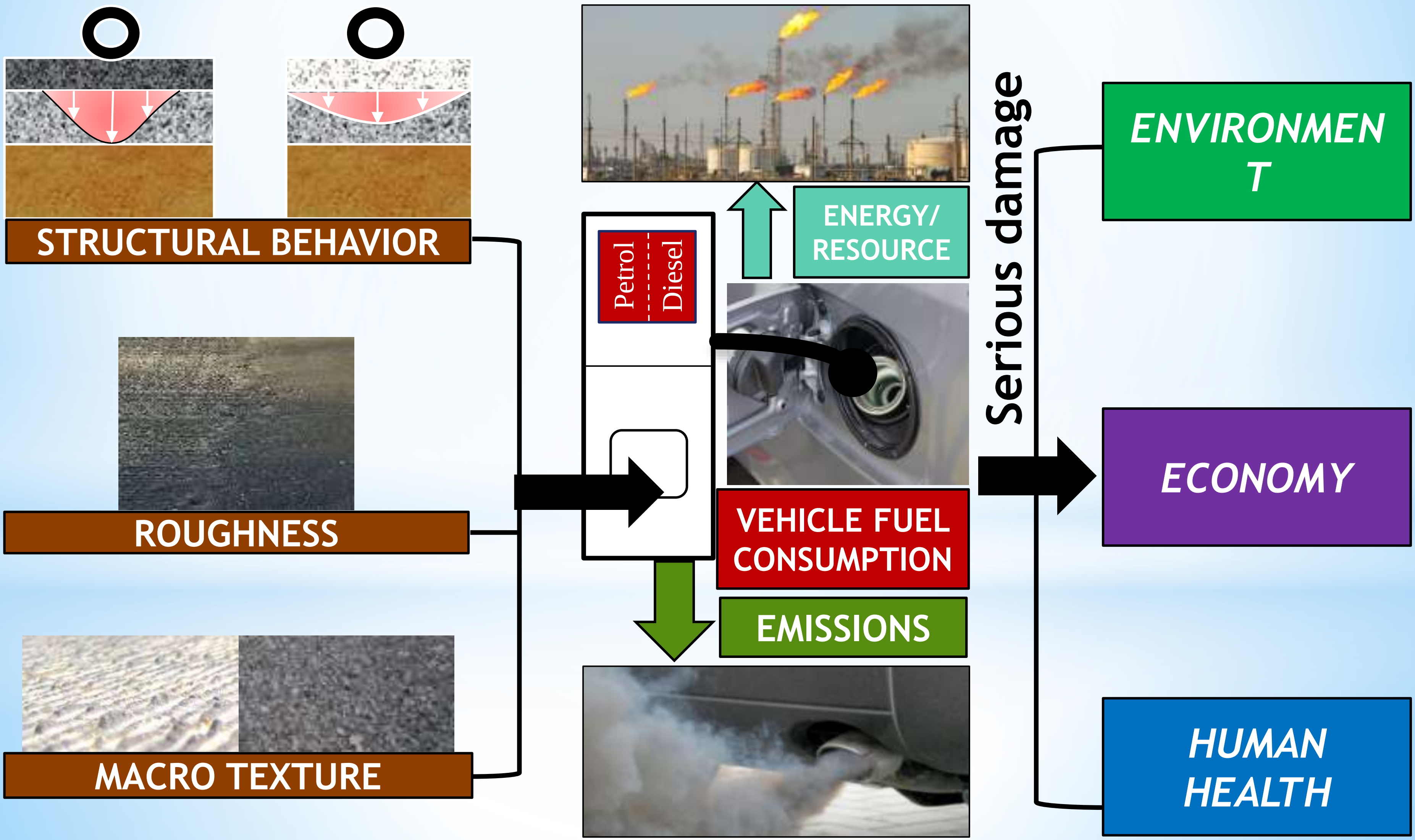


PAMS Objectives
Performance Data Collection
Database Management : Inventory
Distress Detection and Analysis
Pavement Performance Prediction
Alternative Rehabilitation Strategies
Environmental Lifecycle & Cost Comparisons of Alternatives
Prioritization and Optimization
Implementation
D B M S
user
DATA
Database
Alternative A
Alternative B
Pavement Condition
Terminal Serviceability
0 5 10 15 20
Pavement Life (Years)
A
B
Predicted performance
Remaining service life
Minimum acceptable service level
Past performance
Pavement Condition
Now
Now +2
Now +5
Pavement Age, years

Integrated Lifecycle: Mechanistic Roadway Designs



Integrated Lifecycle: Mechanistic Roadway Designs Cont'd…



FUTURE EXPECTATIONS

- ***Performance monitoring of field pavement systems:***
  - ***Test sections: all road classes***
  - ***Long-term pavement performance***
  - ***Automation in estimation & prediction***
  - ***Use of AI / ML / IP, etc.: advanced tools***
- ***Establish laboratory & field correlations***
- ***Develop field design specifications for construction***
- ***Sustainable roadway infrastructure: LID***
- ***Financial implications: LCA; LCCA; B/C ratio***
- ***Pavement Assets: Retrofitting & Econometrics***

Foster collaboration(s) between academia & industry to create SUSTAINABLE roads

IITT ADVANCED PAVEMENT SYSTEMS (APS) RESEARCH CLUSTER

https://iitt-apsrc.weebly.com

THANK YOU

Questions & Comments

Email: bkp@iittp.ac.in

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