Global Partnership for Sustainable Construction and Resource Efficiency

Universita Delgi Studi Di Padova & Meru University of Science and Technology

Availability and Sustainability of Industrial By-Products Used in Cement-Based Construction Materials

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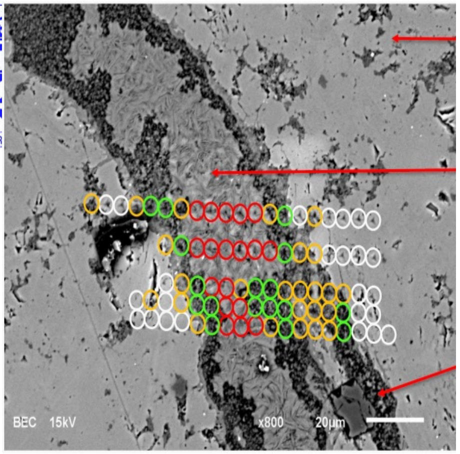
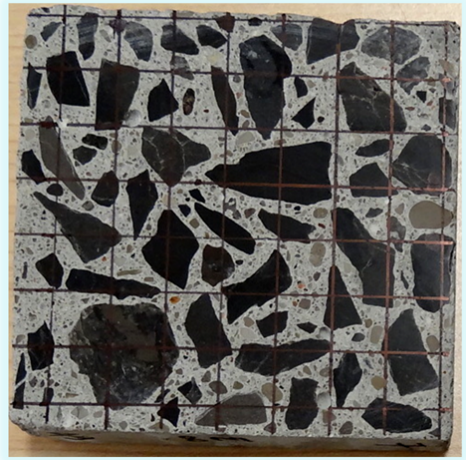
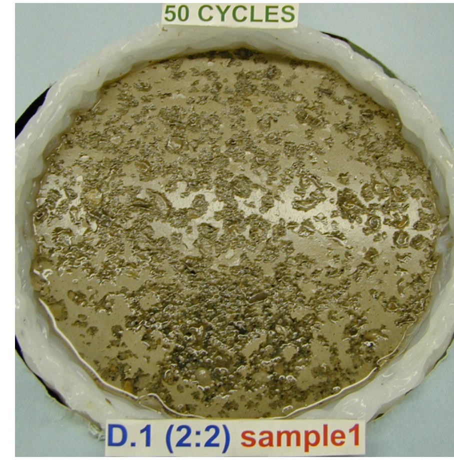
July 15, 2021







Nano → Micro → Macroscale

New → Deteriorated → Repaired

Life Cycle of Infrastructure

Design Phase

Image Source: http://atozengineering.com/civil-design.html

Construction

Image Source: http://www.newfound.ca/#services

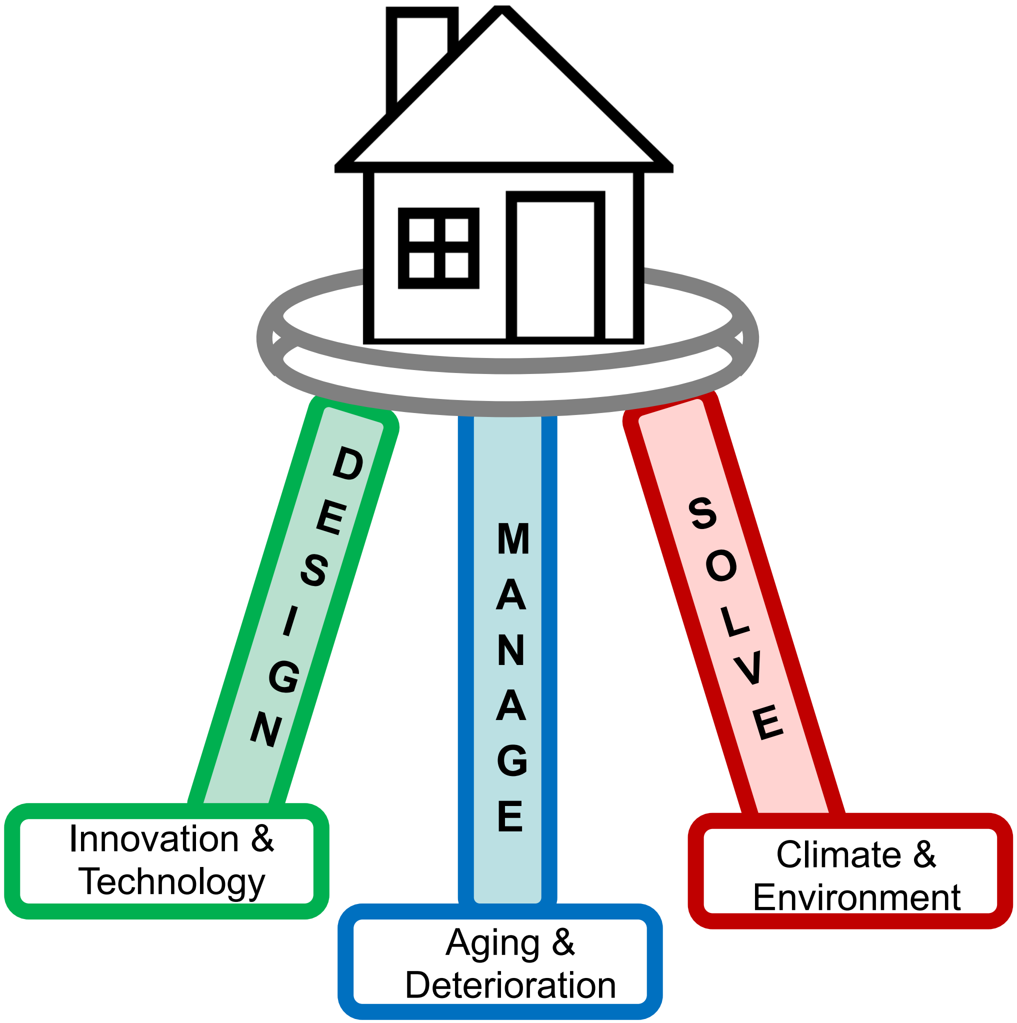
Operations and Management

Image Source: https://www.fmd.uga.edu/departments/operations-maintenance

End of Life

Image Source: http://www.icdb.ca/demolition.html

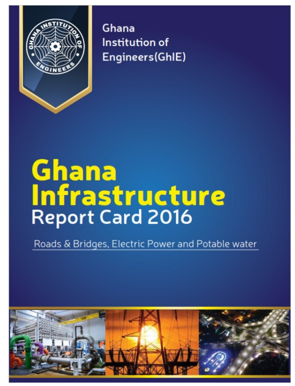
Pedagogical Pillars of Sustainable Infrastructure



Infrastructure Report Cards

Canada 2019

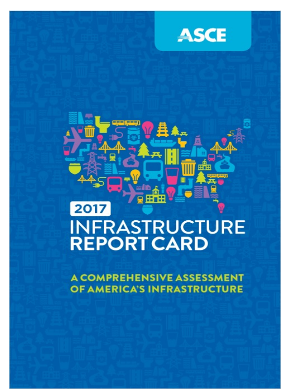
Ghana 2016



South Africa 2017

UK 2014

USA 2017



Zambia 2017

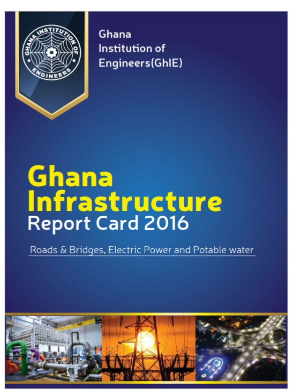
Infrastructure Categories

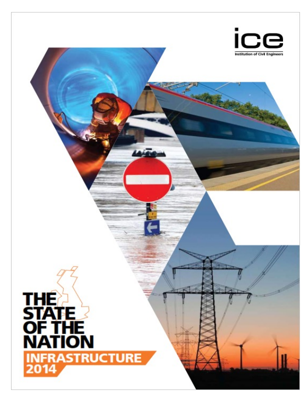
	Canada 2019	Ghana 2016	South Africa 2017	UK 2014	USA 2017	Zambia 2017
Ground Transportation	Road Bridges Public transit	Roads Bridges	Roads Rail	Local Transport Strategic Transport	Roads Bridges Transit Rail	Roads Bridges Rail
Water Infrastructure			Commercial ports		Ports Levees Dams	Dams
Aviation system			Airport		Aviation	Airport
Water system	Stormwater Wastewater Drinking Water	Drinking water	Water resources Water supply	Water Flood Management	Drinking water Inland waterways Wastewater	Drinking water Wastewater
Waste system				Waste	Solid waste Hazardous Waste	Solid waste Hazardous Waste
Public infrastructures	Sports & Recreation Facilities Buildings		Sanitation Education Health care		Schools Parks & Recreation	Health Education Agriculture Communication/IT
Energy		Electric Power	Electricity	Energy	Energy	Electricity Fuel

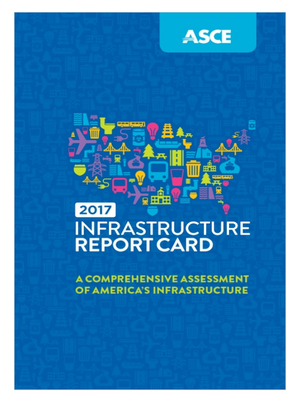
Summary of Infrastructure Report Cards

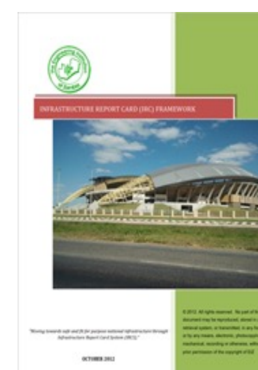
(Anonymous)

Country	Road	Bridge	Rail	Water
	D	D		D
	B to E		A to D-	C+ to D-
	D-		B	C+
	D	C+	B	D









CO_2 Emission Reduction Targets Compared to Reference Year

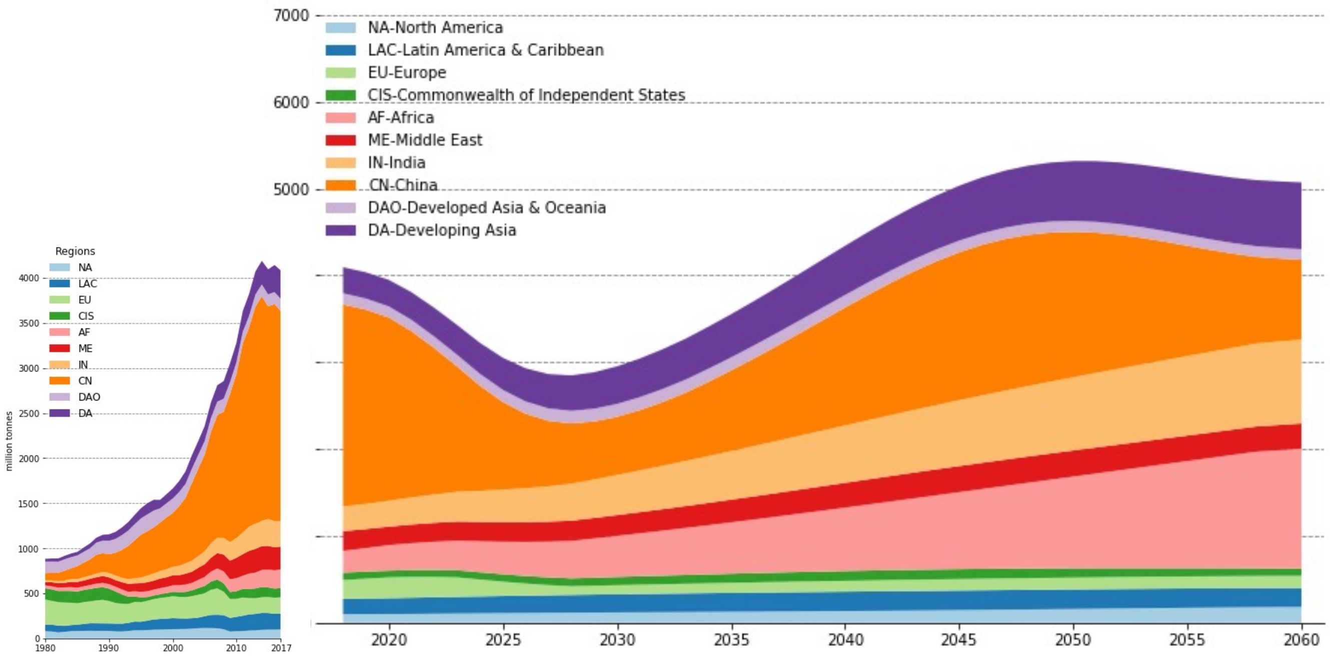
Roadmap	Reference Year	Target Year	Low Target Reduction	High Target Reduction
Brazil (2019)	2014	2050	-10%*	-
California (2019)	2015	2040	18%	68%
China (2021)	2018	2060	29%	100%
Europe (2018)	1990	2050	-	100%**
Germany (2020)	2019	2050	36%	100%
India (2018)	2010	2050	23%	45%
UK (2020)	2018	2050	39%	156%
USA (2021)	2018	2060	37%	100%

*Brazil expects to expand concrete production by 67%

**Through Cement Value Chain

Incorporates CCUS

Projections of Cement Demand (2020-2060)



- Developing Asia
- Dev. Asia & Oceania
- China
- Africa
- Middle East
- Africa
- Commonwealth of independent states
- Europe
- Latin America & Caribbean
- North America

(1980-2017) → **2020**----------*projections*--------------**2060**

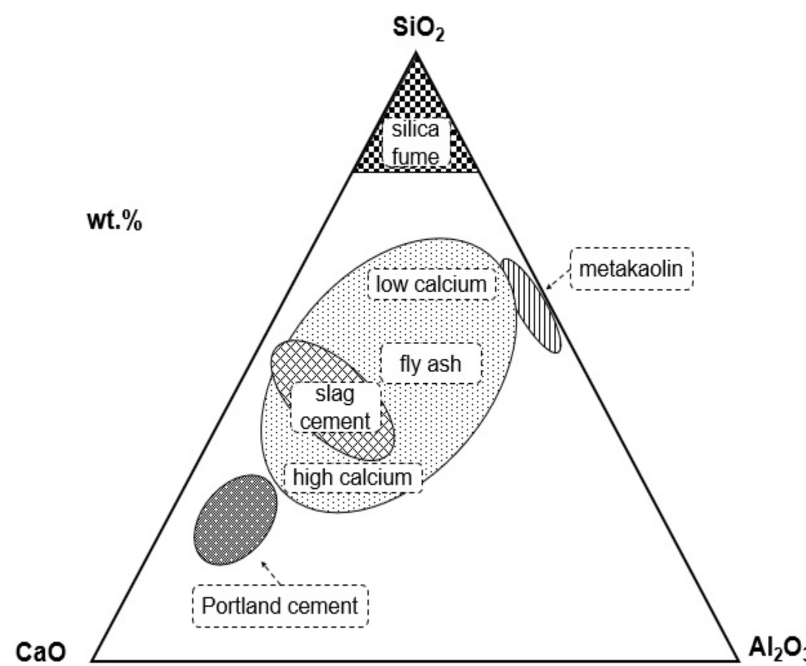
Cao et al. (2021)

Clinker to Cement Ratios

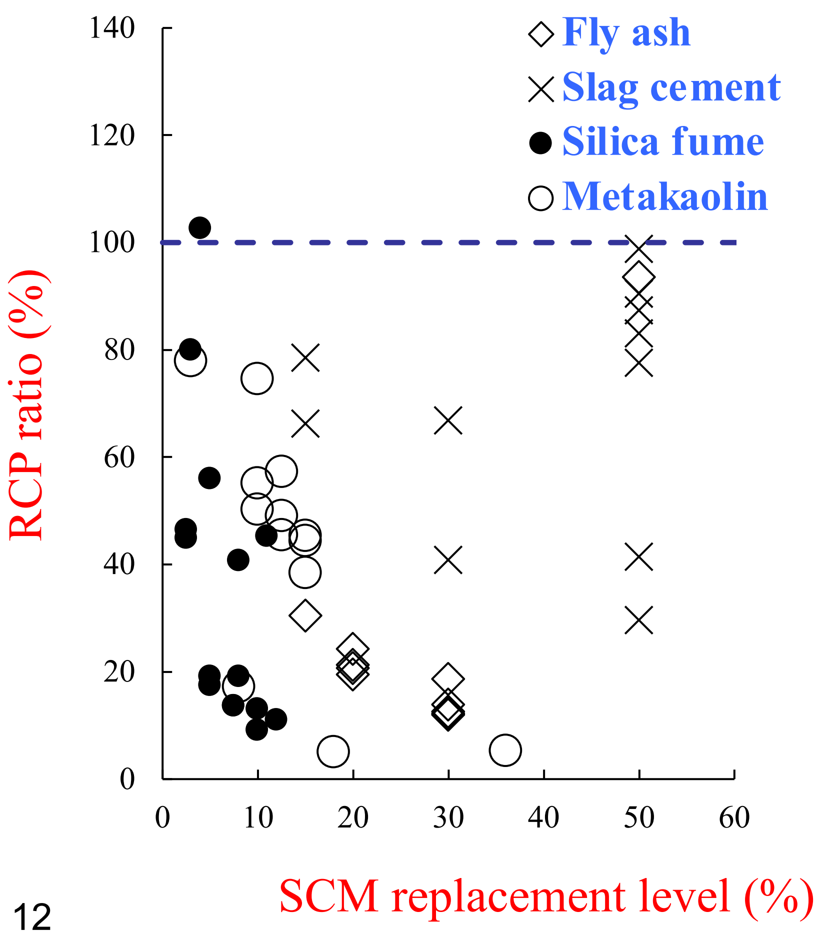
Roadmap	Reference Year	Reference Ratio	Target Year	Target Ratio
Brazil (2019)	2014	0.67	2050	0.52
California (2019)	2015	0.9	2040	0.7
China (2021)	2017	0.79	2060	0.6
Europe (2018)	2017	0.77	2050	0.65
Germany (2020)	2019	0.71	2050	0.53
India (2018)	2017	0.71	2050	0.6
UK (2011)	2011	0.87	2050	0.7
UK (2020)	-	-	2050	-
USA (2021)	2017	0.90	2060	0.6
World (2009)	2006	0.78	2050	0.71
World (2018)	2014	0.65	2050	0.6

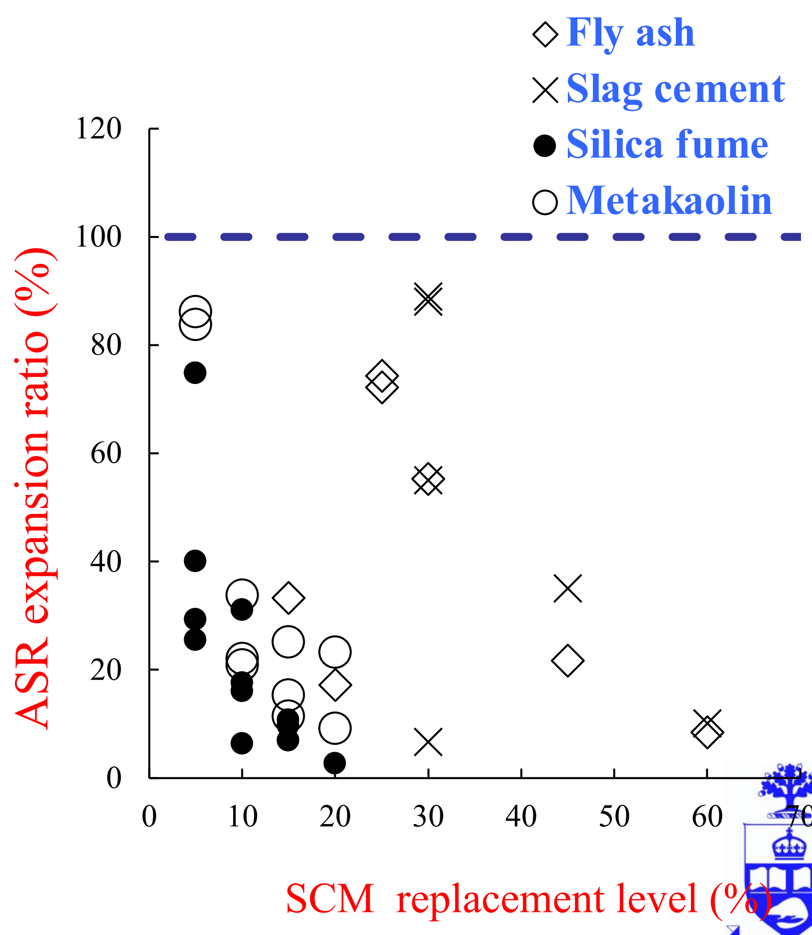
Some Traditional Supplementary Cementing Materials (SCMs)

- Fly ash (FA): by-product of coal combustion
- Granulated blast furnace slag (Slag): by-product of steel production
- Silica fume (SF): by-product from elemental silicon production
- Metakaolin (MK): produced from the calcination of kaolinite clay



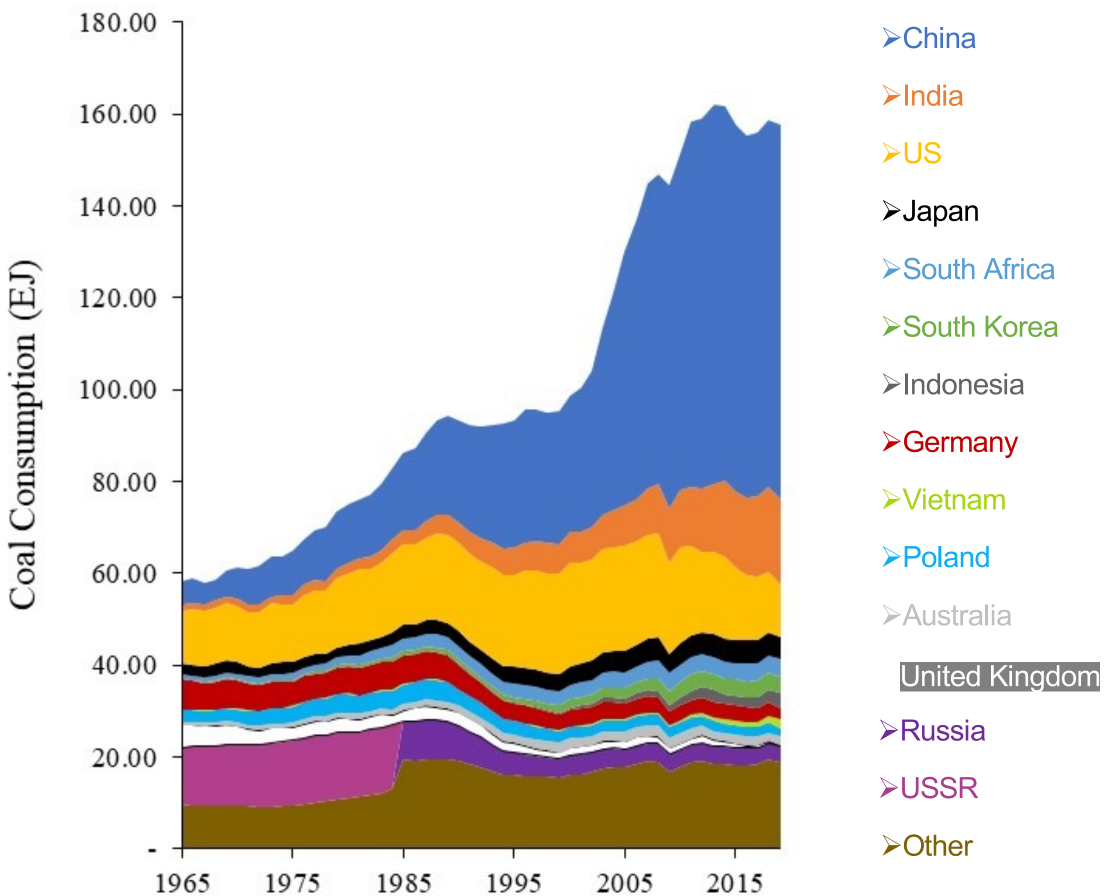
Example: Benefits of SCMs





Coal Consumption (1995- 2020)

(Affects Fly Ash Availability)



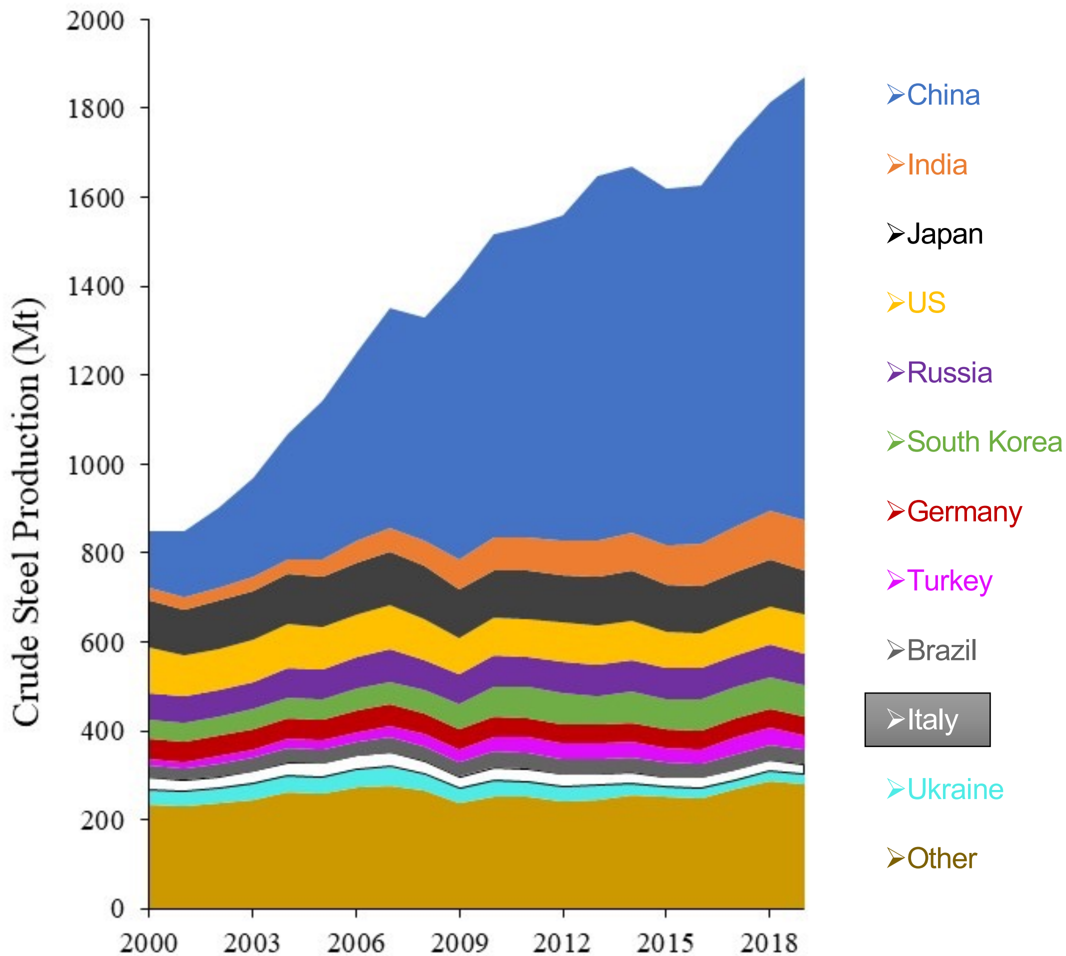
Global Increase with some

Local Decreases

BP statistical review of world energy, London, UK, (2019).

Crude Steel Production (2000-2019)

(Affects GGBFS Availability)



Global Increase with some

Local Decreases or some

Local ~Contant

W.S. Association, World steel in figures 2002 - 2020, World Steel Association: Brussels, Belgium, (2020).

Effective Use of Industrial By-Products and Waste

IC-IMPACTS

Support and Collaboration:

- IC-IMPACTS
- IIT Rookee, India
- University of Toronto, Canada

Objectives:

Use of fly ash (FA) is limited by local availability. Evaluate the interplay between material properties, service life, economic and environmental viability.

Approach:

Quantify the Trade-Offs:
Engineering Properties and
Economic and Environmental Impacts due to Material Use and Transportation

Fly Ash as Cement Replacement

ASTM C 618: The finely divided residue that results from the combustion of ground or powdered coal and that is transported by flue gases

CONCRETE BENEFITS

- workability
- long term strength
- permeability
- heat of hydration
- durability resistance
- drying shrinkage
- industrial by-product to replace cement

CHALLENGES UTILIZATION

1. Material Variability
2. Specifications
3. Regional availability
4. Transportation impacts

Fly Ash Generation and Utilization

CANADA

- **2014,** the last Ontario coal plant was closed
- **By 2020**, **85%** of the utility electricity is generated from **non-GHG-emitting resources**

INDIA

- Increase in thermal power stations

- **138 (2012- 2013)**
- **145 (2014-2015)**

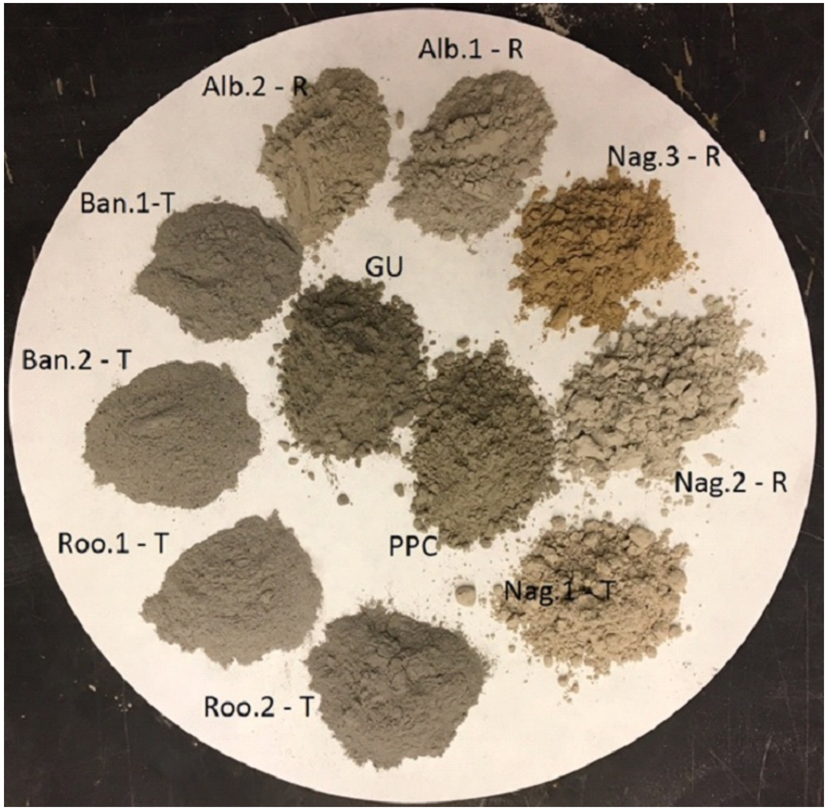
- Increase in fly ash generation

- **164.54 MT (2012- 2013)**
- **184.14 MT (2014-2015)**

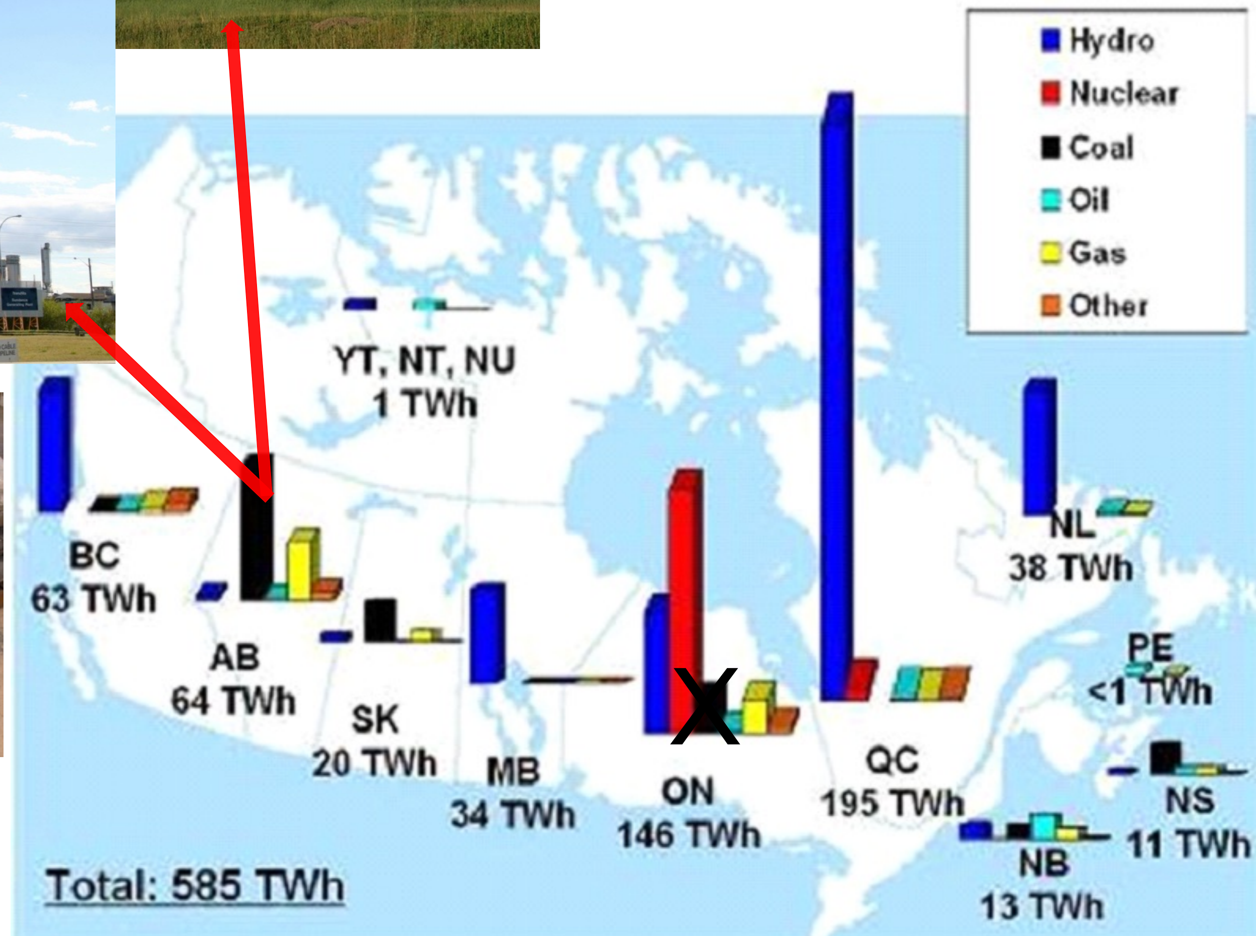
Fly Ash Sources

Fly Ash ID	Thermal Power Station	Community
Ban.1-T	Guru Nanak	Banga
Ban.2-T	Guru Gobind	Banga
Roo.1-T	Badarpur	Roorkee
Roo.2-T	Chhotu Ram	Roorkee
Nag.1-T	Khaberkheda	Nagpur
Nag.2-R	Dahanu	Nagpur
Nag.3-R	Mundra	Nagpur
Alb.1-R	Sundance	Alberta
Alb.2-R	Genesee	Alberta

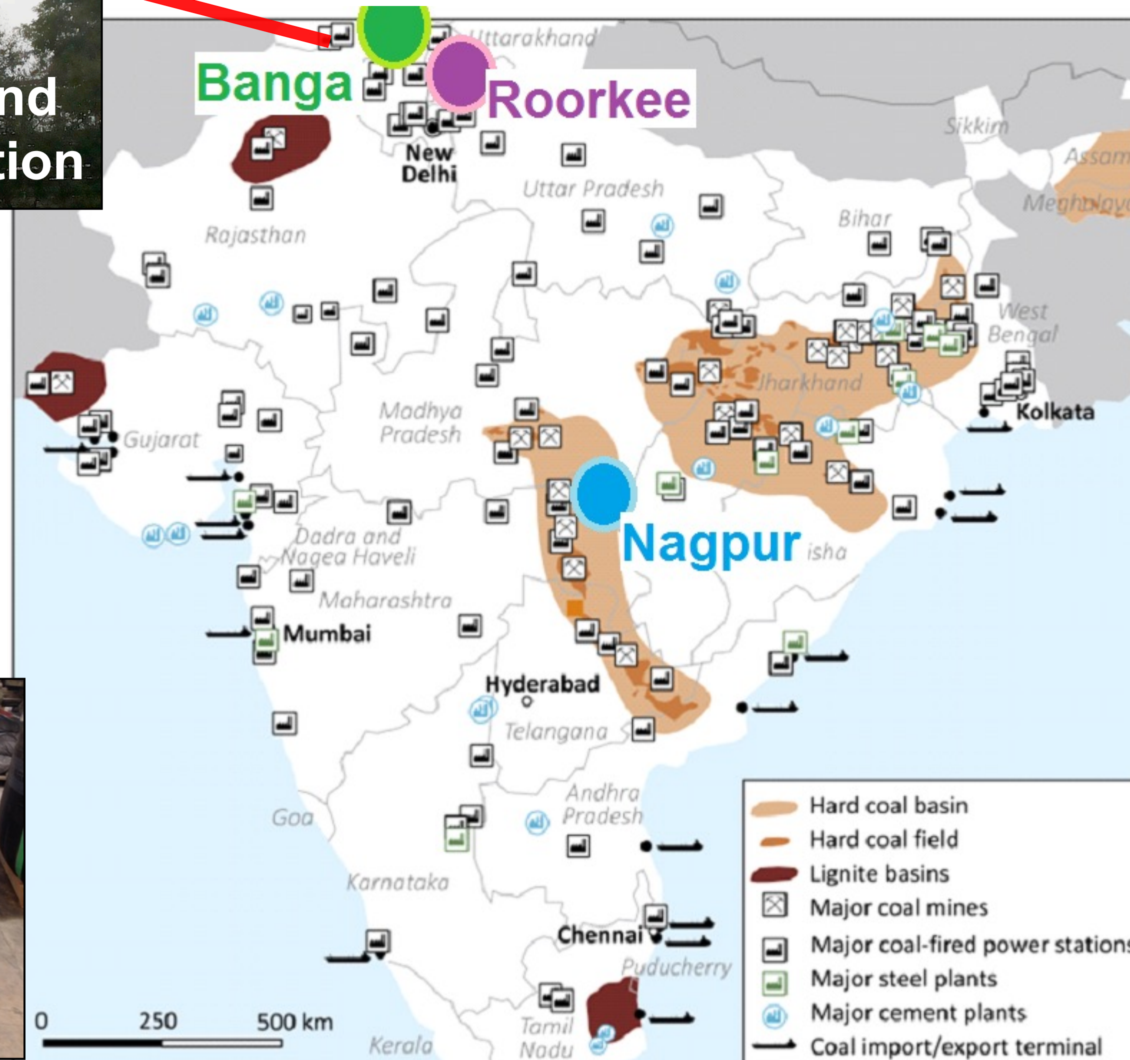
T: Target / R: Reference



Canadian Fly Ashes



Indian Fly Ashes



1. Engineering Material Properties

Quantify Trade-Offs

2. Economic Analysis: LCC

3. Environmental Impacts: LCA

Indicator of Economic and Environmental Viability for Functionally Equivalent Material

Break-even distance: The maximum distance that fly ash can be transported without increasing the LCC or LCA result of the concrete mix above the LCC or LCA of the 100GU concrete

Panesar, Kanraj, Abualrous, CCC (2019)

CHEMICAL LIMITS	CSA A3001-13	ASTM C 618-15	IS 3812 (Part1)
	Type F	Class F	Grade I
Total $(SiO_2) + (Al2O_3) + (Fe_2O_3)$		70 min	70 min
CaO	15 max		

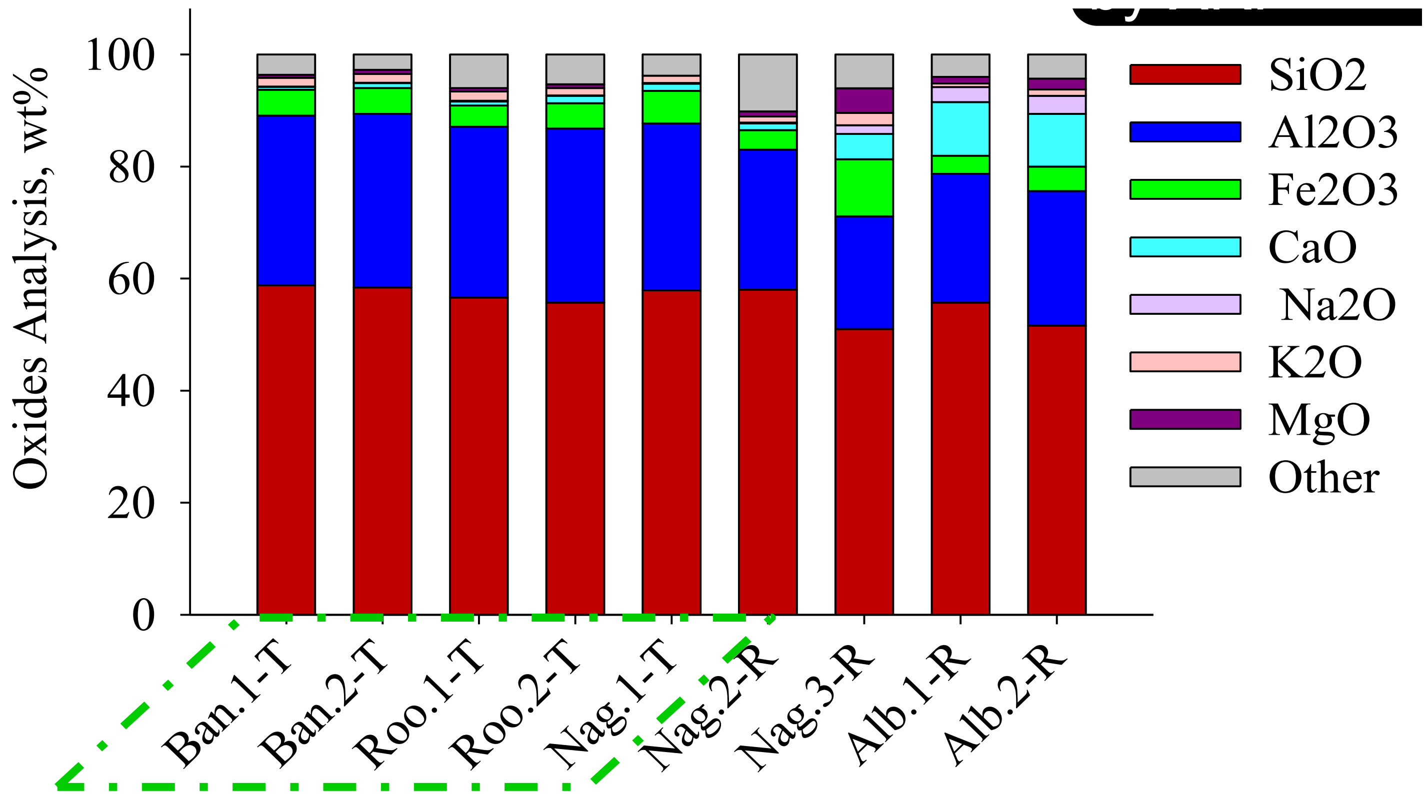
PHYSICAL LIMITS	Type F	Class F	Grade I
Fineness - Specific surface by air permeability, m²/kg (Blaine)	-	-	320 min
Fineness Residue @ 45 microns, %	34 max	34 max	34 max †
Water requirement of control,%	-	105% max	-
Strength Activity Index, 7 days, %	-	75 min	-
Strength Activity Index, 28 days, %	75 min†	75 min	80 min‡

† Optional requirement IS 3812 (Part 1) : 2013

‡ Pozzolanic activity index requirement for mortar mixture on absolute volume design basis

Fly Ash Characterization

Chemical Analysis: Oxide Analysis by XRF

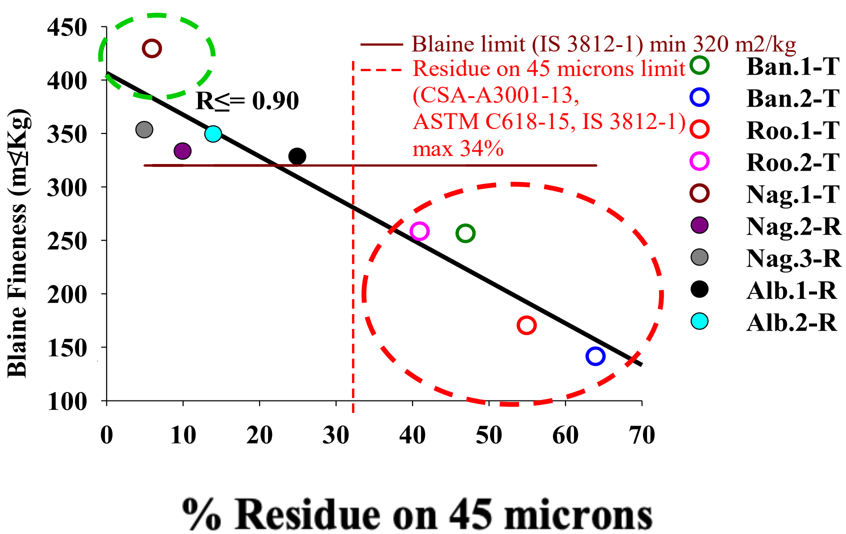


- The chemical compositions of all studied fly ashes meet the requirements of standard specifications IS 3812-1, CSA 3001-13, and ASTM C618-15

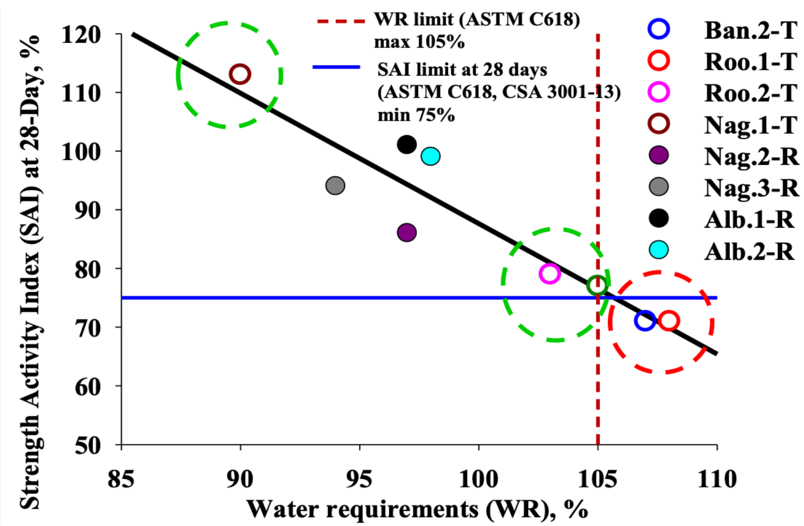
Fly Ash Characterization

Physical Analysis

Blaine Fineness vs %Residue on 45µ



Strength Activity Index vs Water Requirement



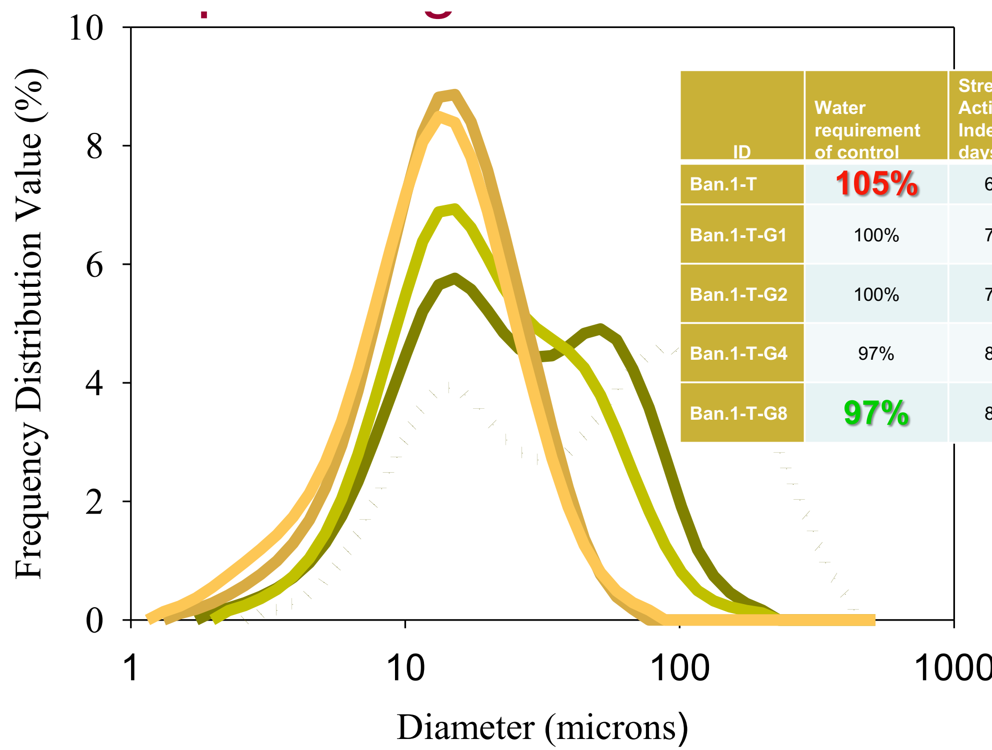
Fineness results:

- **residue on 45-um sieve (max34%)** was **5% - 34%** <u>reference</u> fly ashes and **6% - 64% for** <u>target</u> fly ashes
- **Blaine fineness (min.320)** was **328 -349 m2/kg** between <u>reference</u> fly ashes and **141 - 258 m^2/kg** in <u>target</u> fly ashes

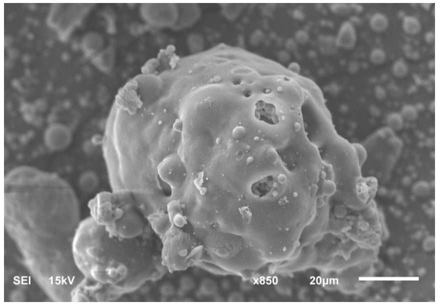
SAI results:

Where water requirement was above 105%, SAI was below ASTM and CSA minimum limits (75 SAI) at the age of 28 days and IS (80 SAI)

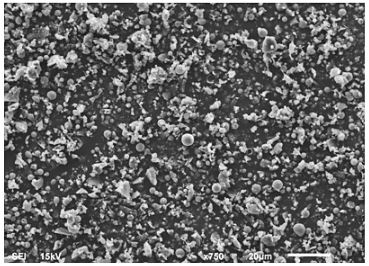
Effect of Fly Ash Grinding on Optimizing Distribution Modes



ID	Water requirement of control	Strength Activity Index, 7 days	Strength Activity Index, 28 days
Ban.1-T	105%	68%	77%
Ban.1-T-G1	100%	71%	86%
Ban.1-T-G2	100%	71%	90%
Ban.1-T-G4	97%	80%	97%
Ban.1-T-G8	97%	82%	102%



Agglomerate before grinding

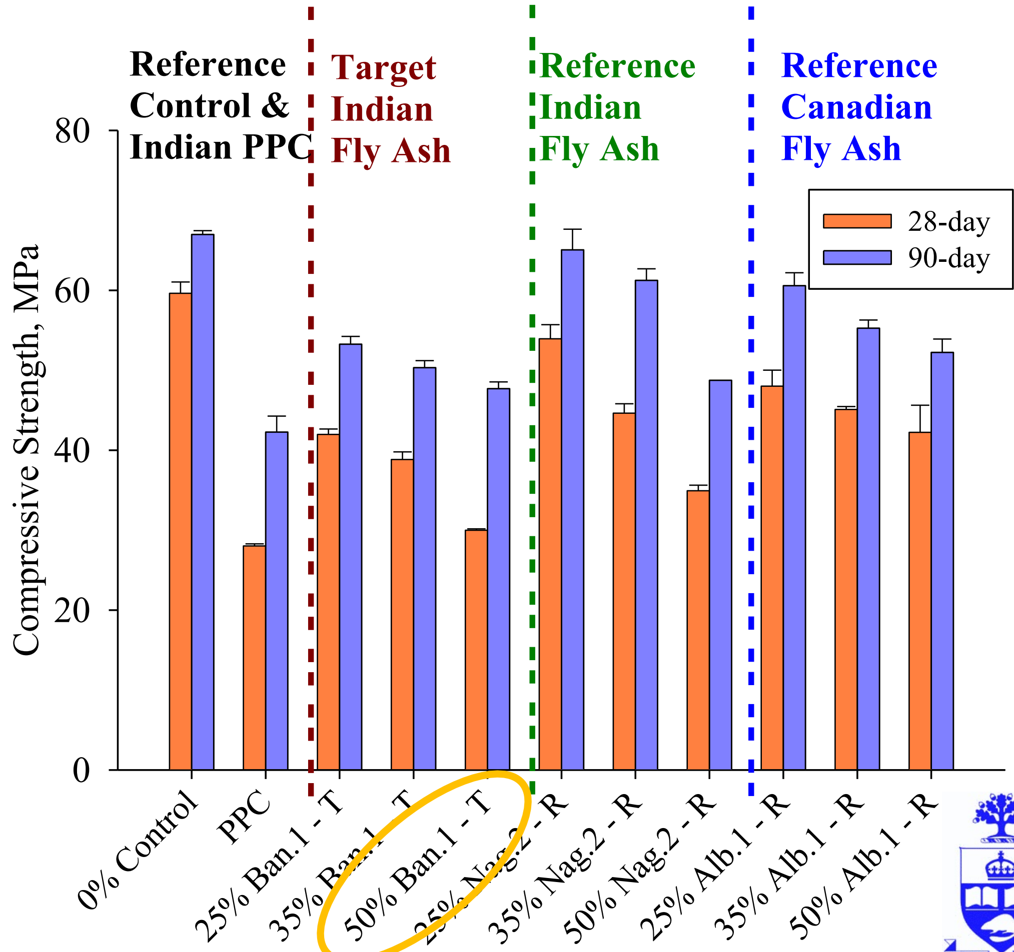


Broken agglomerates and spheres

Compressive Strength
(28 and 90 day)

Within the same source:
higher fly ash contents have relatively lower strengths at all ages

All 28 day f'c>25MPa
All 90 day f'c>40MPa

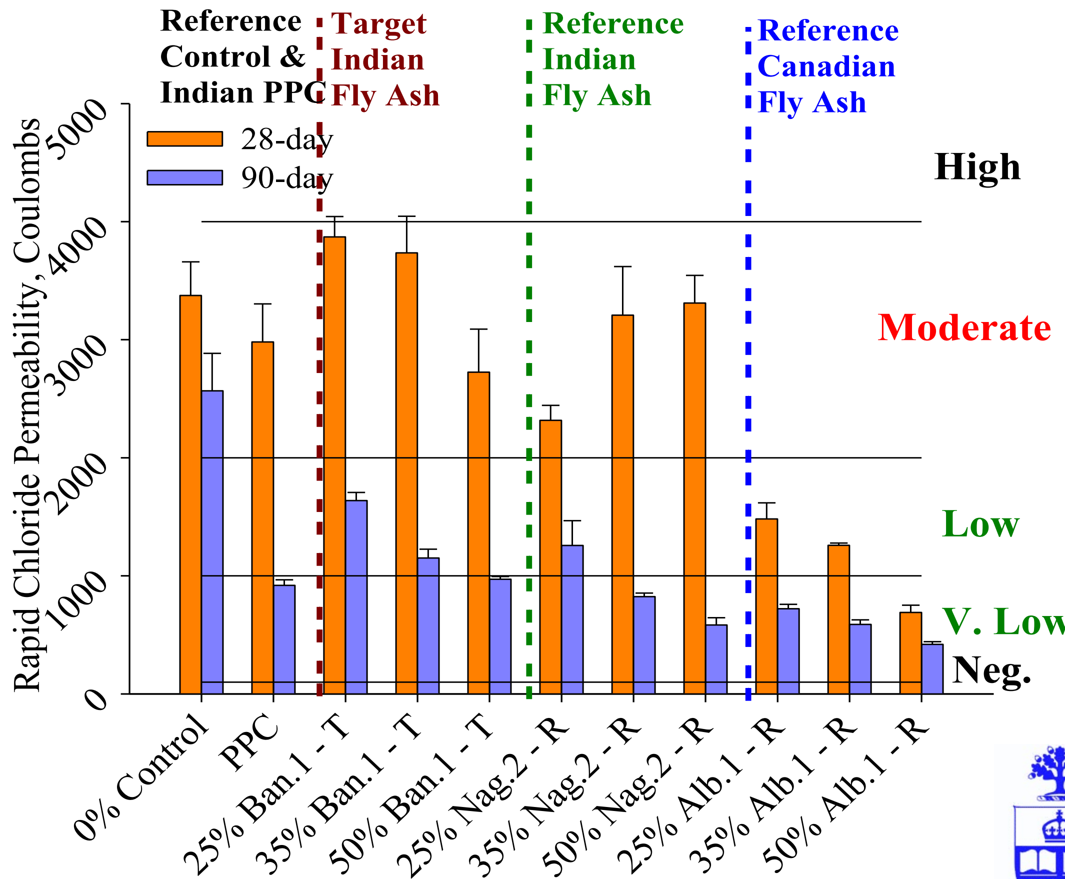


Abualrous, MASc Thesis (2017)

Rapid Chloride Permeability
(28 and 90 day)

Indicator of Durability

- Indian FA- 28 days- Moderate Classification
- Canadian FA at 28 days- Low-Very low
- At 90 days, all FA mixes Low to Very Low



Abualrous, MASc Thesis (2017)

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Trade-Offs

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Break-even distance: The maximum distance that fly ash can be transported without increasing the LCC or LCA result of the concrete mix above the LCC or LCA of the 100GU concrete

Study Variables

- Cement replacement by FA (25%, 35%, 50%)
- Distance of transportation: 0 – 1000 km
- Time to first repair (TFR) on break-even distance
- Moderate, very severe exposure conditions

Concrete Constituents (kg/m^3)	Concrete Mix Designs			
	100GU	25FA	35FA	50FA
Source	Abualrous (2017)			
Water	160	160	160	160
Cement	400	300	260	200
Fly ash (FA)	0	100	140	200
C. Agg	1100	1100	1100	1100
F. Agg	765	720	710	680

Life Cycle Cost Analysis

$$PVLCC = IC + PVOMR + PVD$$

<u>Sum of annualized costs:</u>

PVLCC = present value of total life-cycle cost

IC = initial construction costs

PVOMR = present value of operation, maintenance and repair

PVD = present value of disposal

$$PVLCC = \sum_{t=0}^{T} \frac{C_t}{(1+d)^t}$$

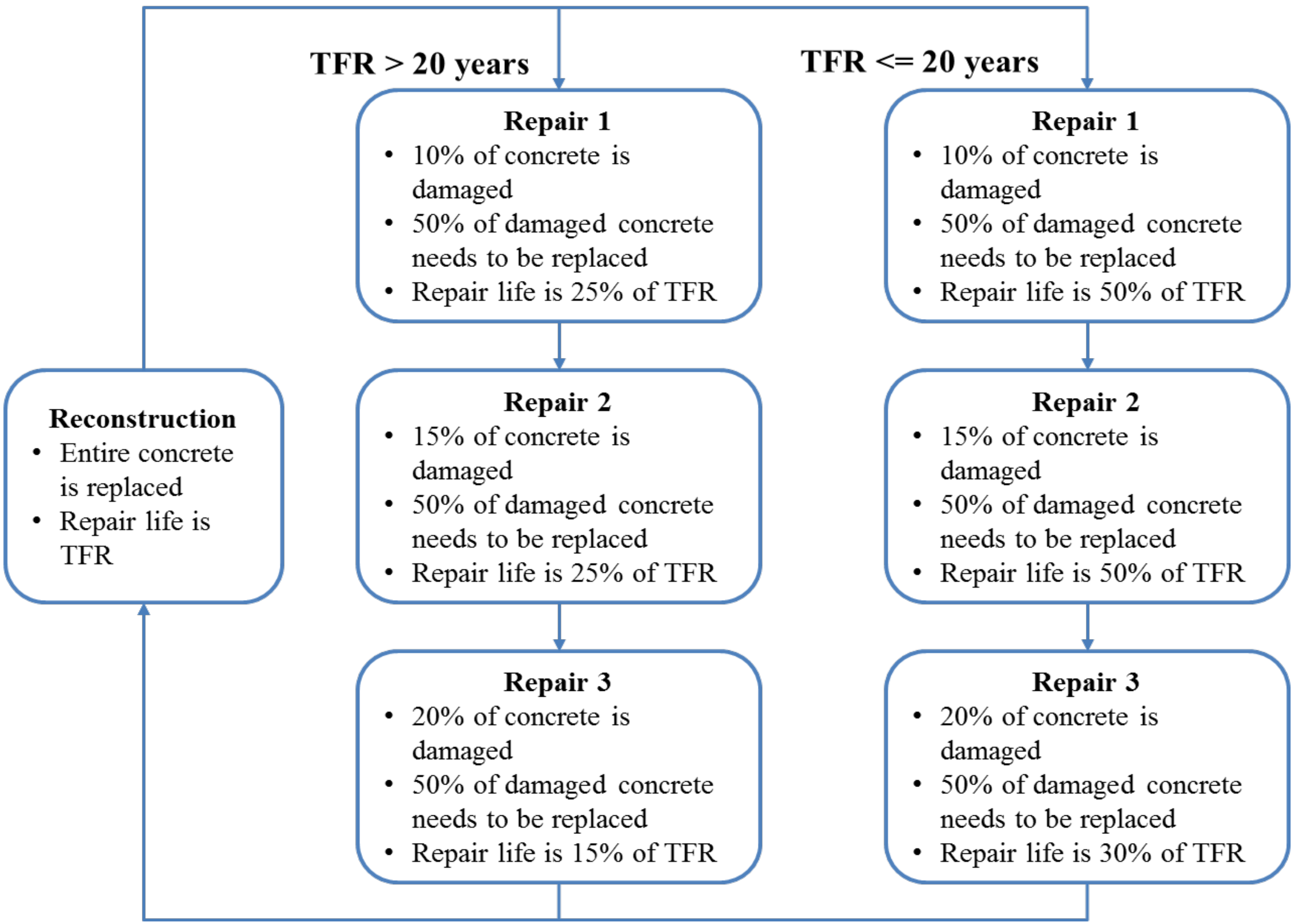
Convert future cashflow (F) into equivalent present worth

C_t = sum of all costs

t= incurred time

d = real discount rate

Repair, Reconstruction Schedule



Panesar, Kanraj, Abualrous, CCC (2019)

Life Cycle Assessment
ISO 14040

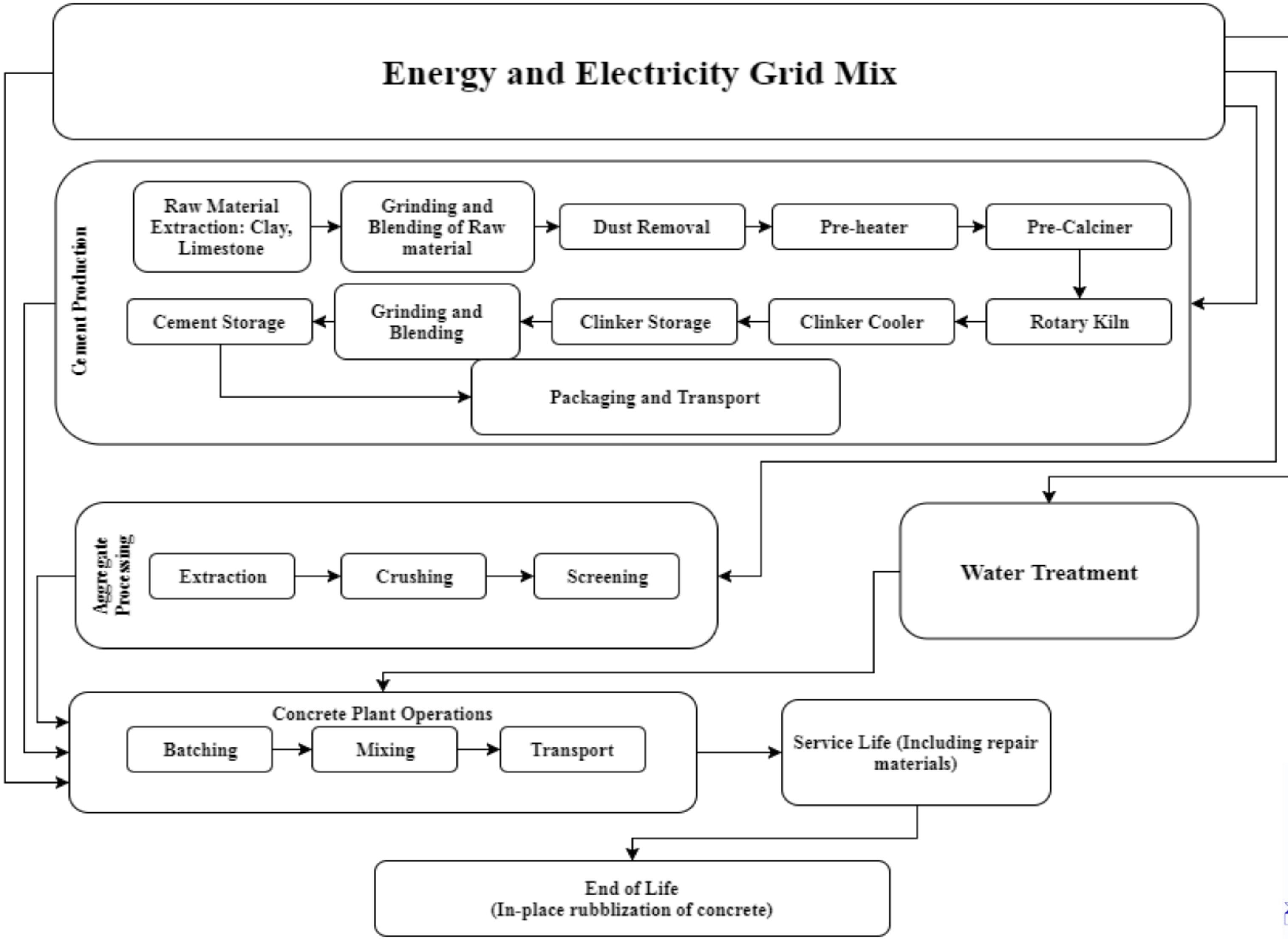
I. Goal and Scope Definition

II. Life Cycle Inventory

III. Life Cycle Impact Assessment

IV. Interpretation

LCA: System Boundary



Panesar, Kanraj, Abualrous, CCC (2019)

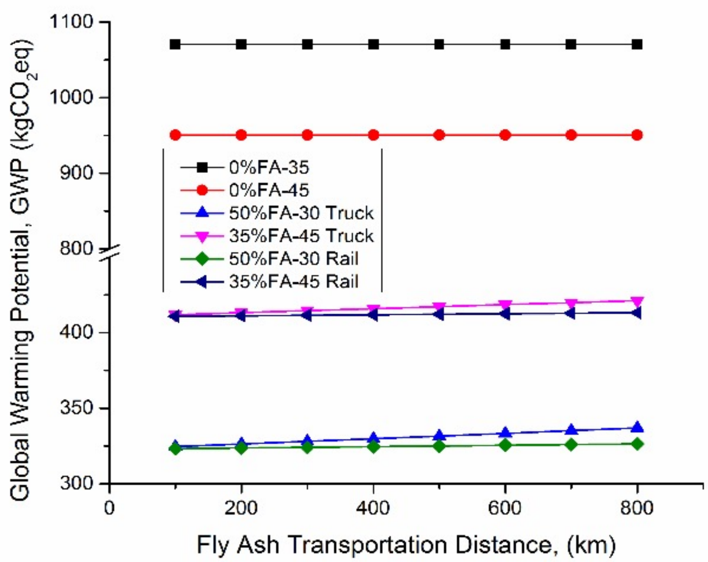
Model: Functional Unit

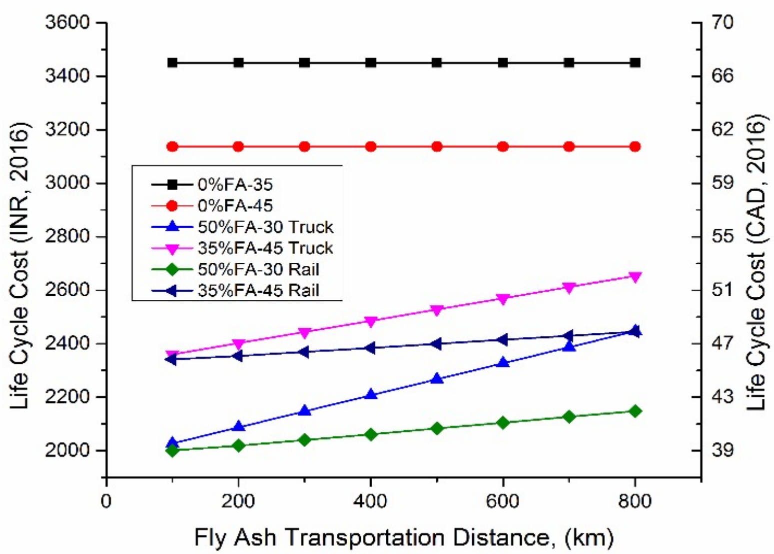
- Functional Unit: Volume of Concrete over 100 years
  - Represents the amount of concrete (including repair concrete) needed to maintain the structure in service for 100 years
- Structural Element
  - square reinforced concrete column 500 mm x 500 mm and a length of 4m with a reinforcement cover depth of 50 mm (in Toronto)
- Calculate 100 year volume of concrete:
  - degradation mechanism assumed to be chloride induced reinforcement corrosion only
  - Concrete's time to first repair (TFR) (estimated by Life 365)
  - Specified repair schedule

LCA compared to LCCA

(Scenario: Moderate Chloride Exposure)

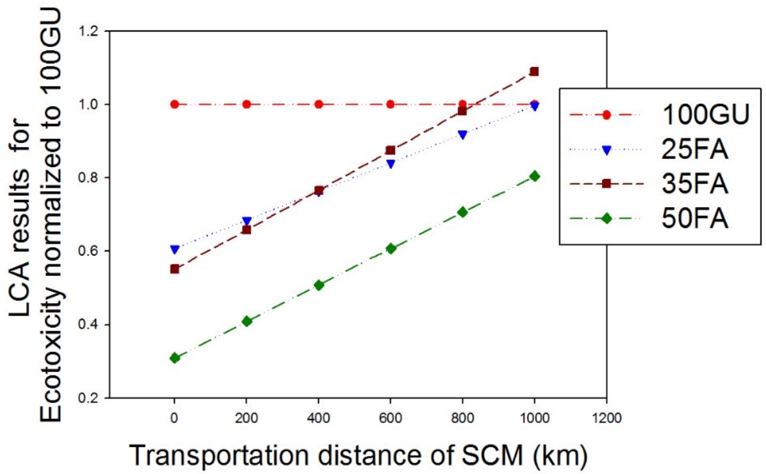
- **Increase in percent fly ash**: lower GWP and cost
- **Transport mode**: Rail transport has lower GWP and cost than truck
- **Increase in transportation distance**:
  - more notable effect on cost than GWP



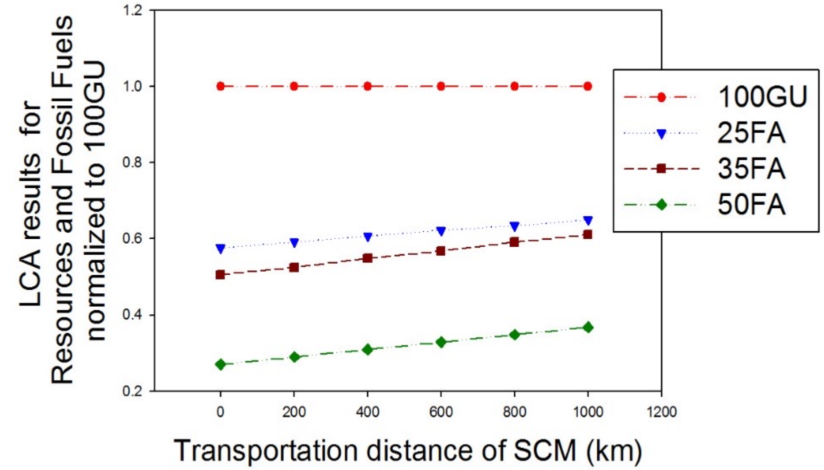


Panesar, Kanraj, Chennai,RILEM(2017)

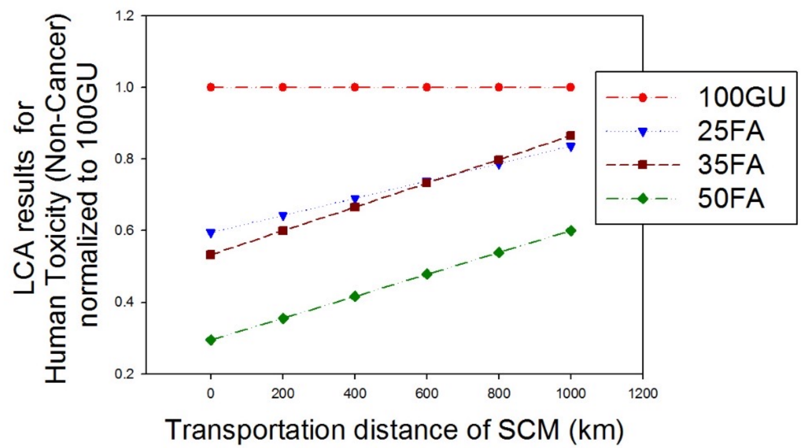
Ecotoxicity



Resources and Fossil Fuels



Human Toxicity (non-canc)



Panesar, Kanraj, Abualrous, CCC (2019)

Influence of TFR on Break-Even Distance

- functional unit: volume of concrete (100 years)
- Higher fly ash as cement replacement
  - ➔ more fly ash to be transported for 1 m^3 of concrete
- Higher TFR ➔ Lower concrete volume (100 years)
- Non-linear correlation between total volume of fly ash to be transported over 100 years and the percentage of fly ash as cement replacement

Property	Concrete Mix Designs			
	100GU	25FA	35FA	50FA
TFR (years)	11.6	17.6	23.6	**45.6**
Volume (100 years (m^3)	**4.82**	3.51	3.46	2.23
Fly ash quantity (kg)	0	351	**484**	446

Panesar, Kanraj, Abualrous, CCC (2019)

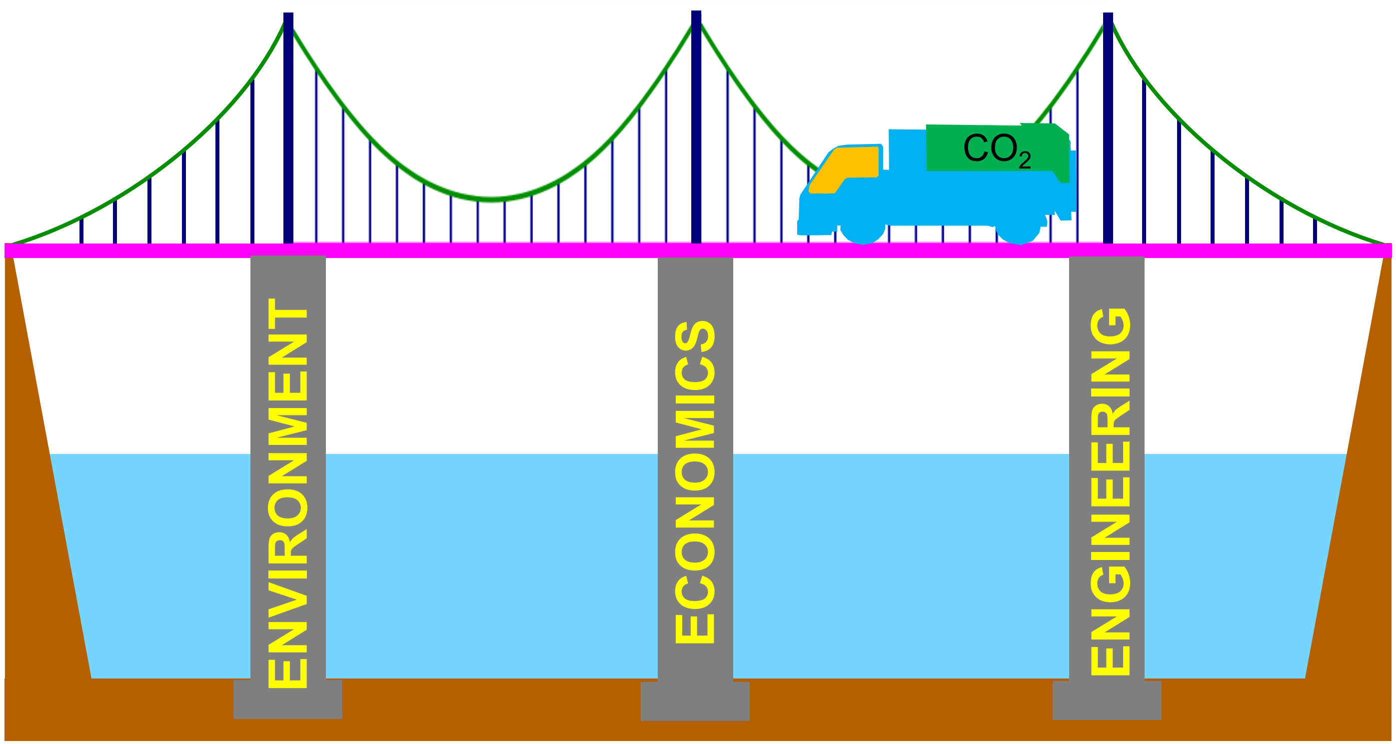
Final Remarks: Global Sustainable Construction

Urgency: Responsible Resource Allocation

Life Cycle Design and Life Cycle Thinking

Engineering, Economics and Environment

Three Pronged Approach
E-E-E



(Not to scale)

Acknowledgements

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- Lehigh Cement Canada
- Lafarge North America

IC-IMPACTS

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VELUT ARBOR ÆVO

Dankie

धन्यवाद

谢谢

Gracias

Obrigada

ありがとう

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