Cement and Concrete: Mitigating CO_2 Emissions

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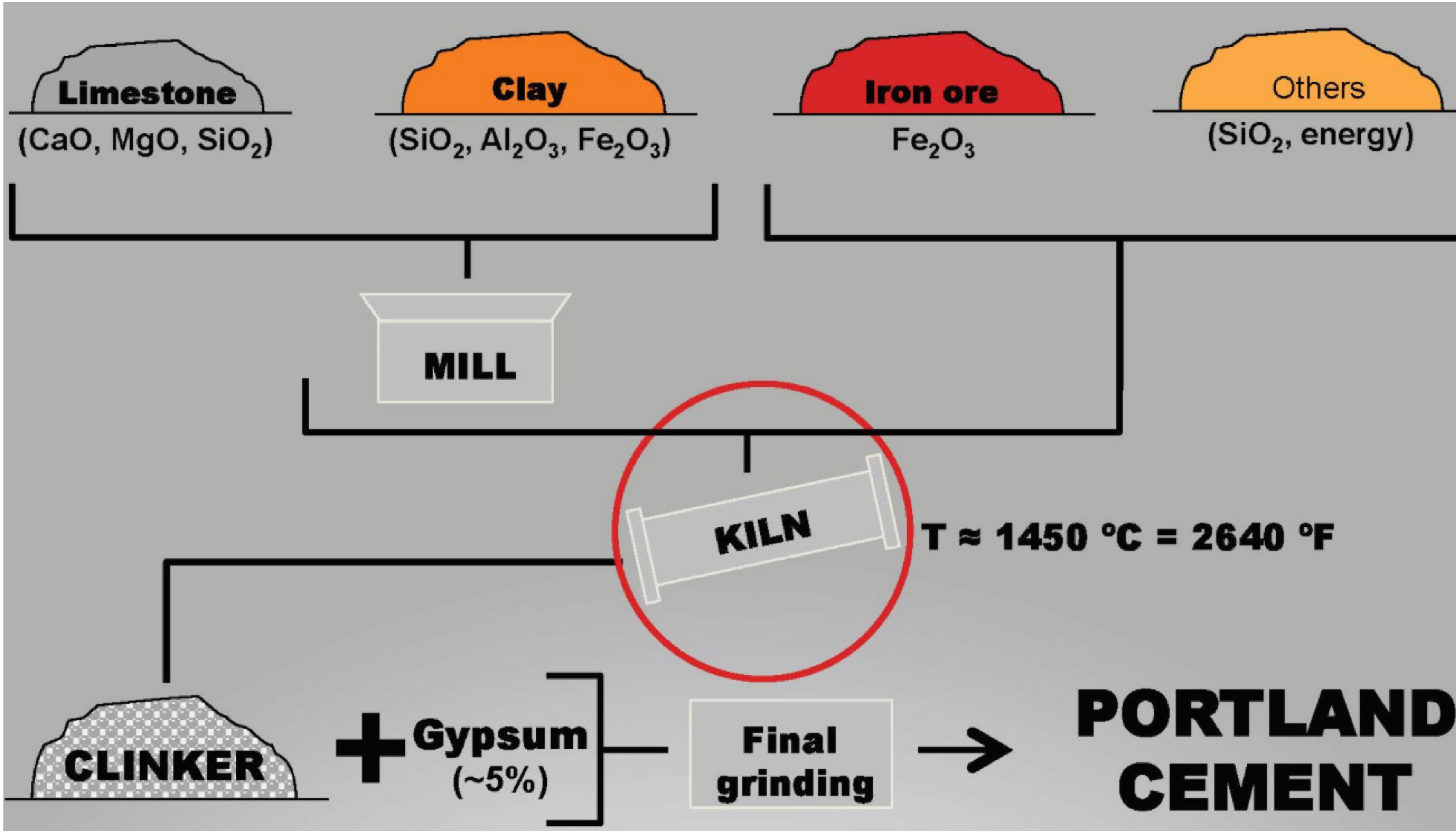
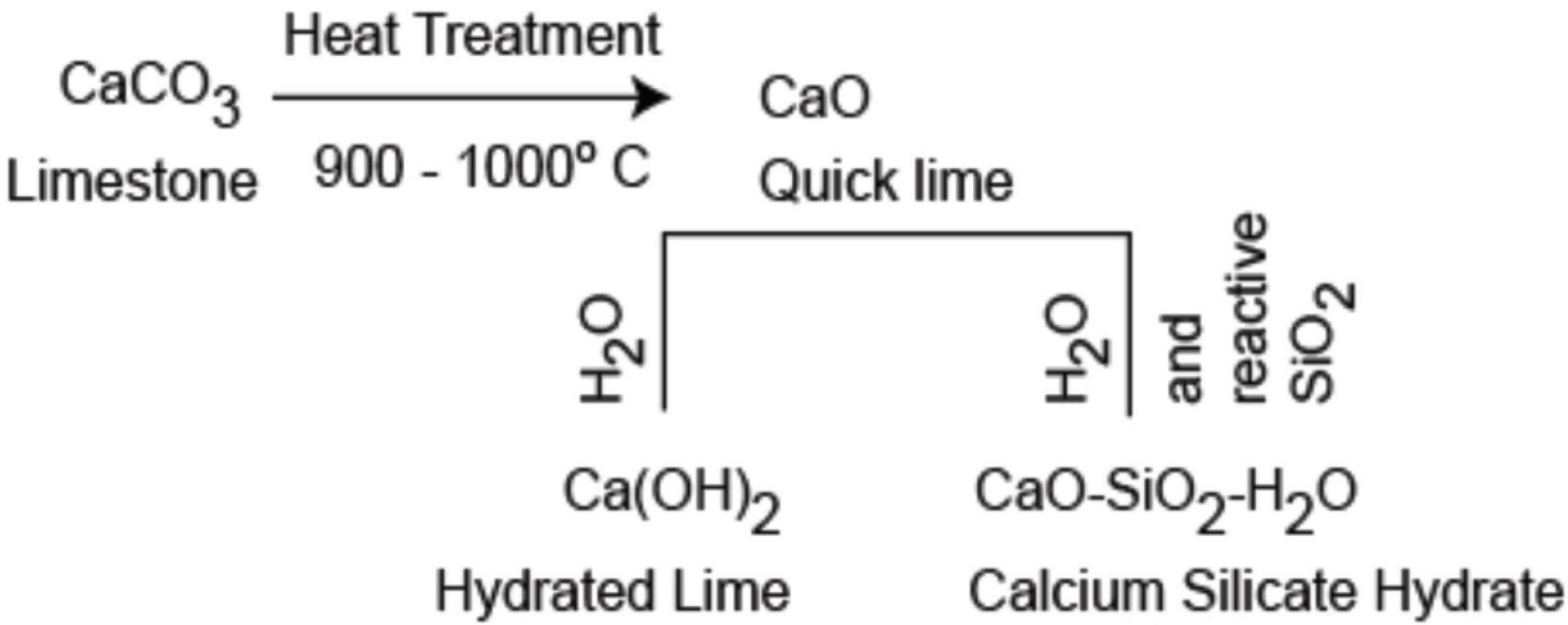
What is cement?

- Mineral binding agent used most commonly (with sand and aggregate) to make concrete
- Usually we mean hydraulic cements, such as Portland cement
  - Mix with water to make the fine powder into an adhesive that dries hard
- People have been using cement for a very long time
  - Burnt lime: Roman era
- It remains one of the highest volume products in the world, with large environmental impacts but large benefits

Manufacturing Process



Lime cement



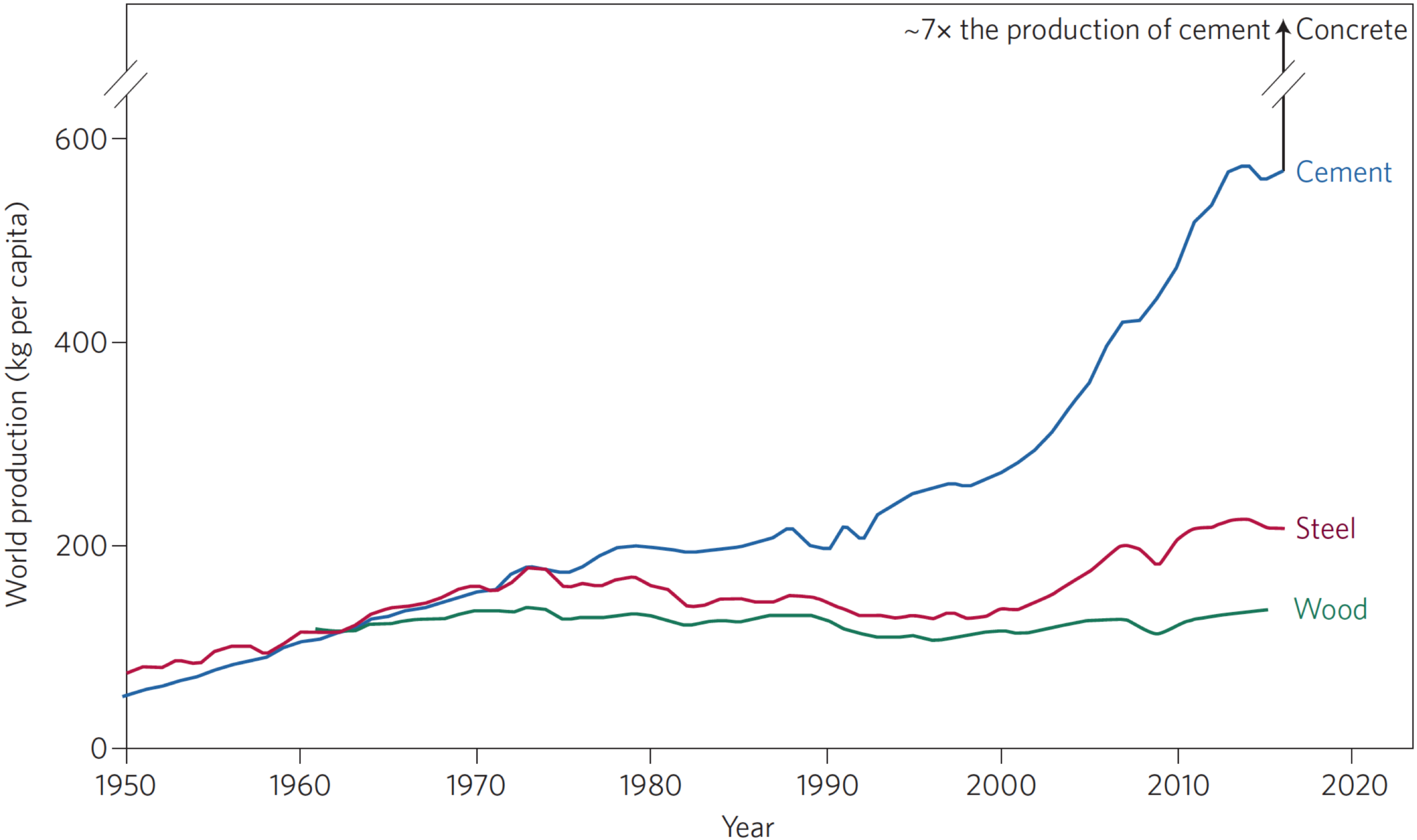
Heat Treatment
CaCO3
Limestone
900 - 1000° C
CaO
Quick lime
H2O
H2O
and reactive SiO2
Ca(OH)2
Hydrated Lime
CaO-SiO2-H2O
Calcium Silicate Hydrate

Production Process

- Production of cement is responsible for ~7% of annual anthropogenic CO_2 emissions

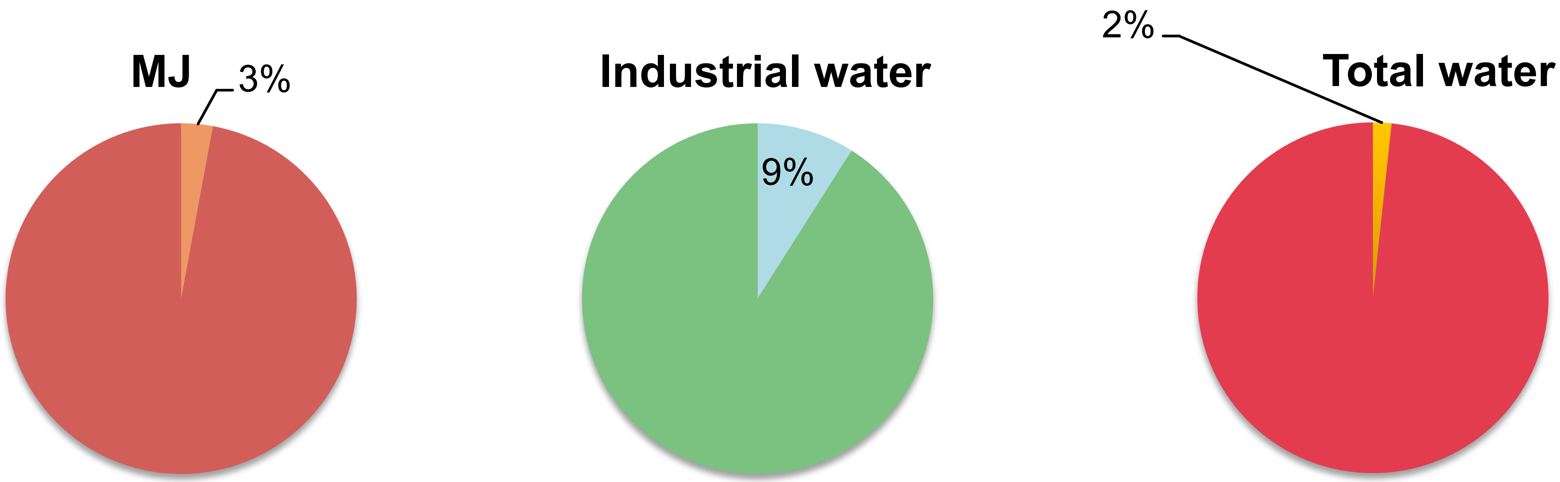
PROBLEM

Unsustainable Development: Consumption



(Monteiro, Miller, and Horvath, *Nature Materials*, 2017)

Application: Concrete – energy and resources



(Monteiro, Miller, and Horvath, *Nature Materials*, 2017; Miller, Horvath, and Monteiro, *Nature Sustainability*, 2018)

Life Cycle Inventory: Cement Production

Cement production

Raw Materials & Preparation
- Quarrying
- Crushing
- Raw Meal Grinding

→

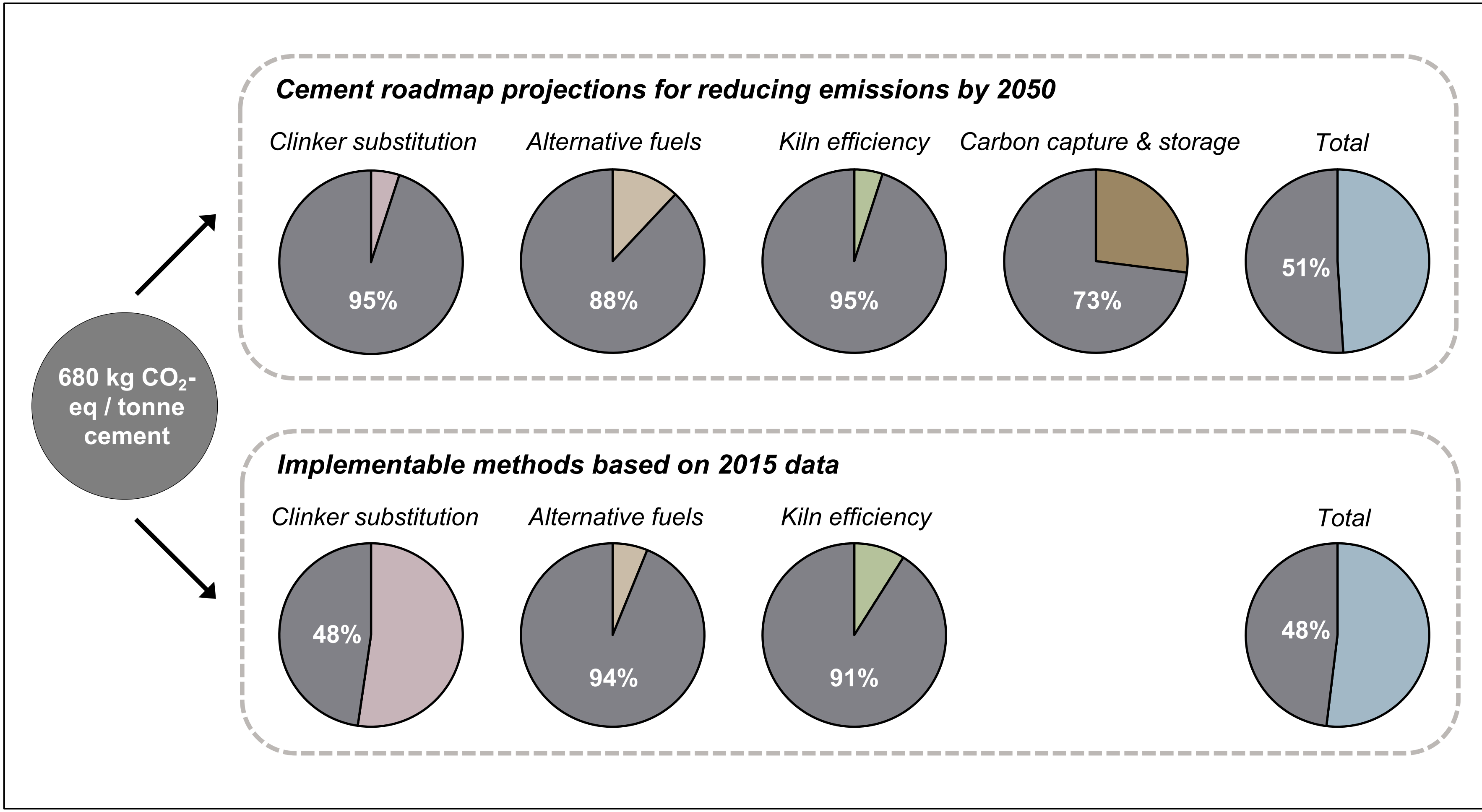
Clinker Production
- Preheating
- Precalcining
- Rotary Kiln
- Cooling & Storing

→

Cement Grinding
- Addition of Gypsum
- Blending
- Storage in Silos

→ **Cement**

Application: Concrete – what can we do?



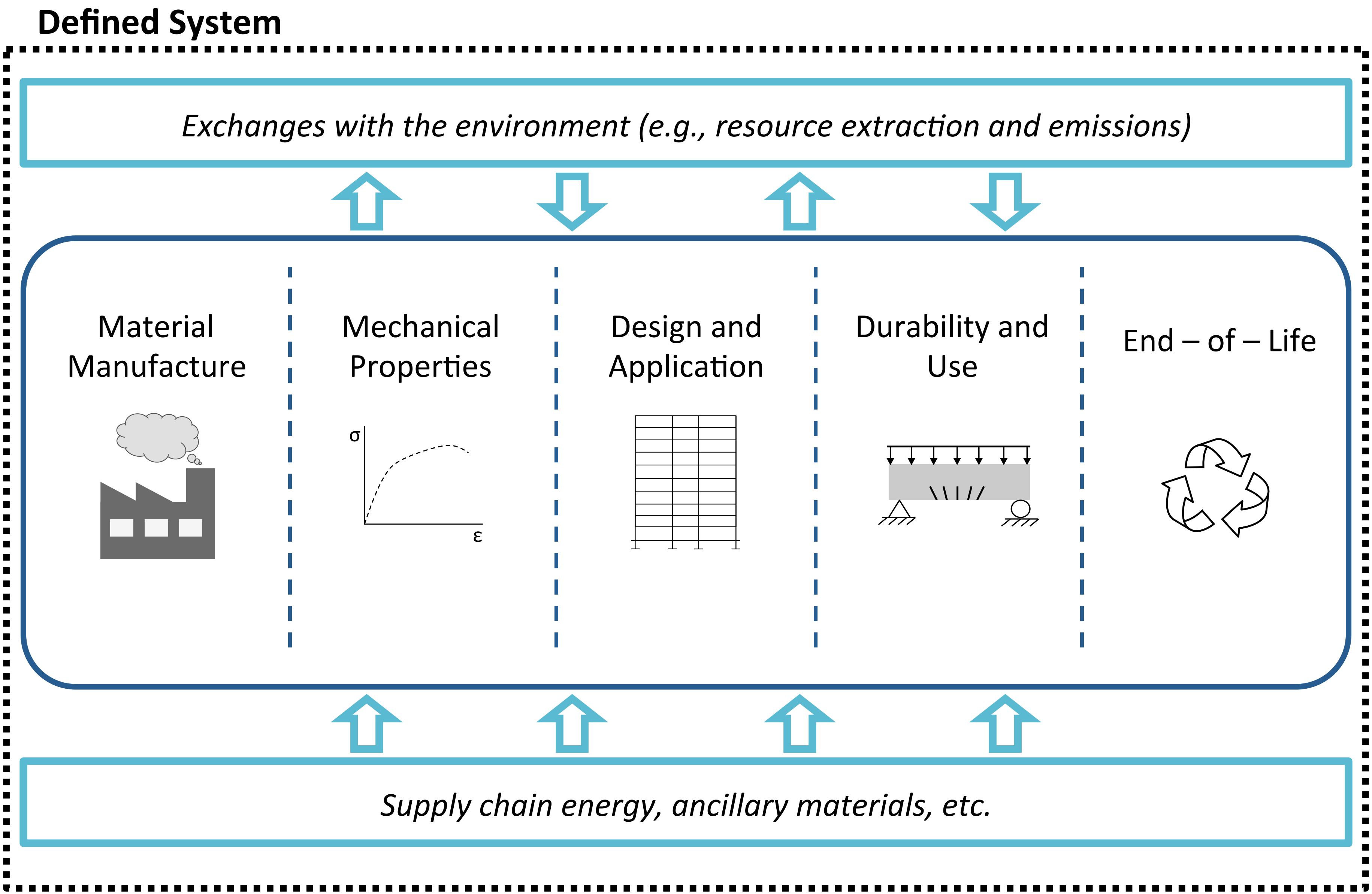
(World Business Council for Sustainable Development, 2009; Miller, John, Pacca, and Hovath, *Cement and Concrete Research*, in press)

Sustainable Development: Still considering what a material must do

"We've made your environmental report greener. It now uses 50% less paper."

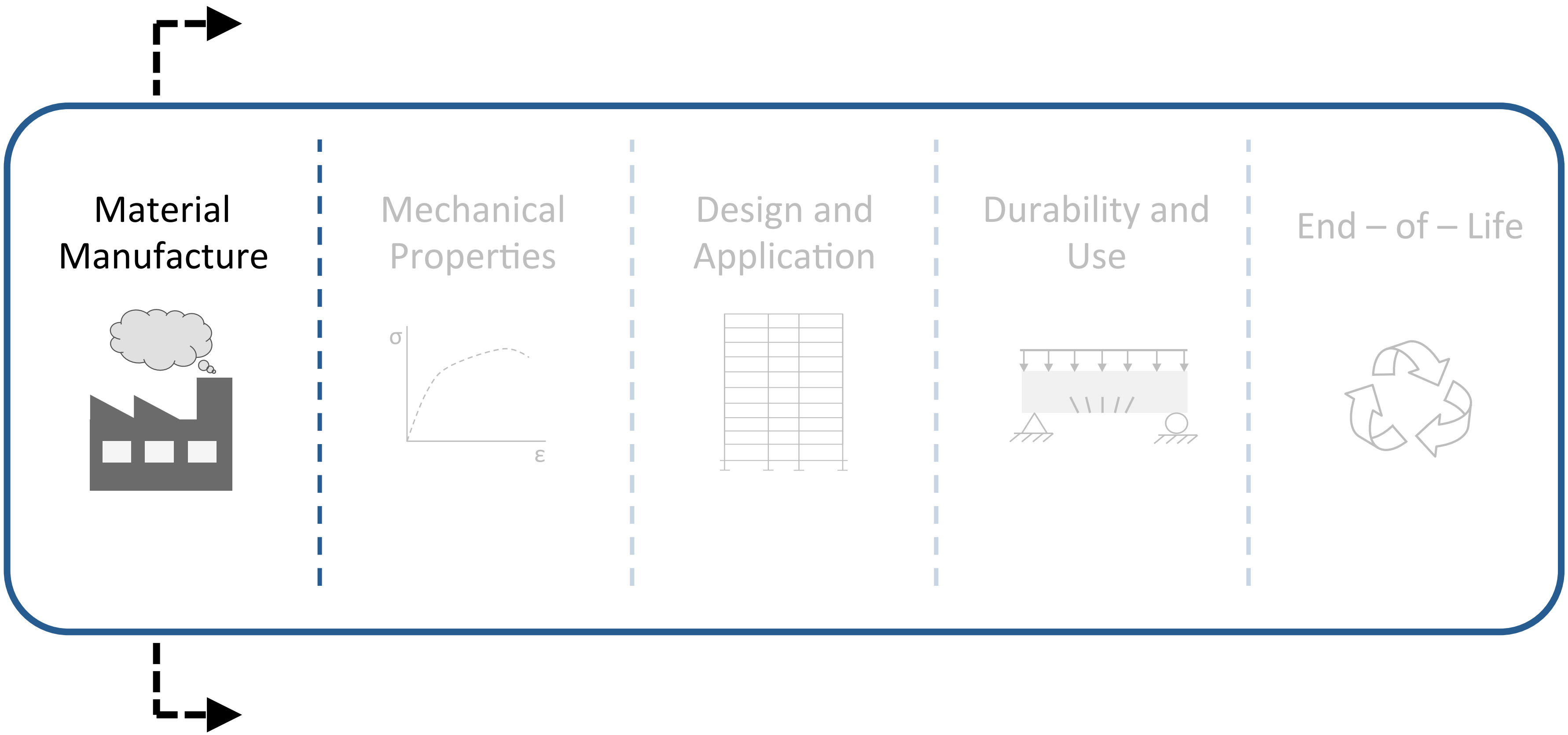
Peter Hess

Material Design Framework



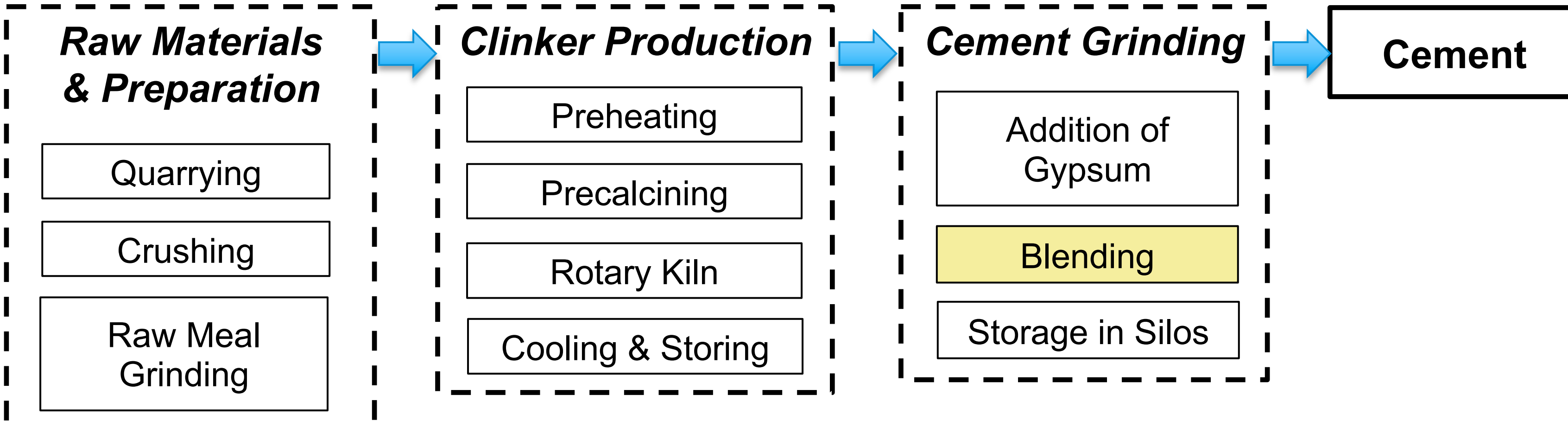
(Miller, in preparation)

Material Design Framework



Material manufacture

Cement production



(Based on Gursel, A.P. and A. Horvath. *Concrete LCA Webtool*. 2012 [cited 2014 November 13]; Available from: http://greenconcrete.berkeley.edu/concretewebtool.html.)

Alkali-activated Binders

- Alkali activation is the generic term which is applied to the reaction of a solid aluminosilicate (termed the 'precursor') under alkaline conditions (induced by the 'alkali activator'), to produce a hardened binder

- The binder is based on a combination of hydrous alkali-aluminosilicate and/or alkali-alkali earth-aluminosilicate phases.

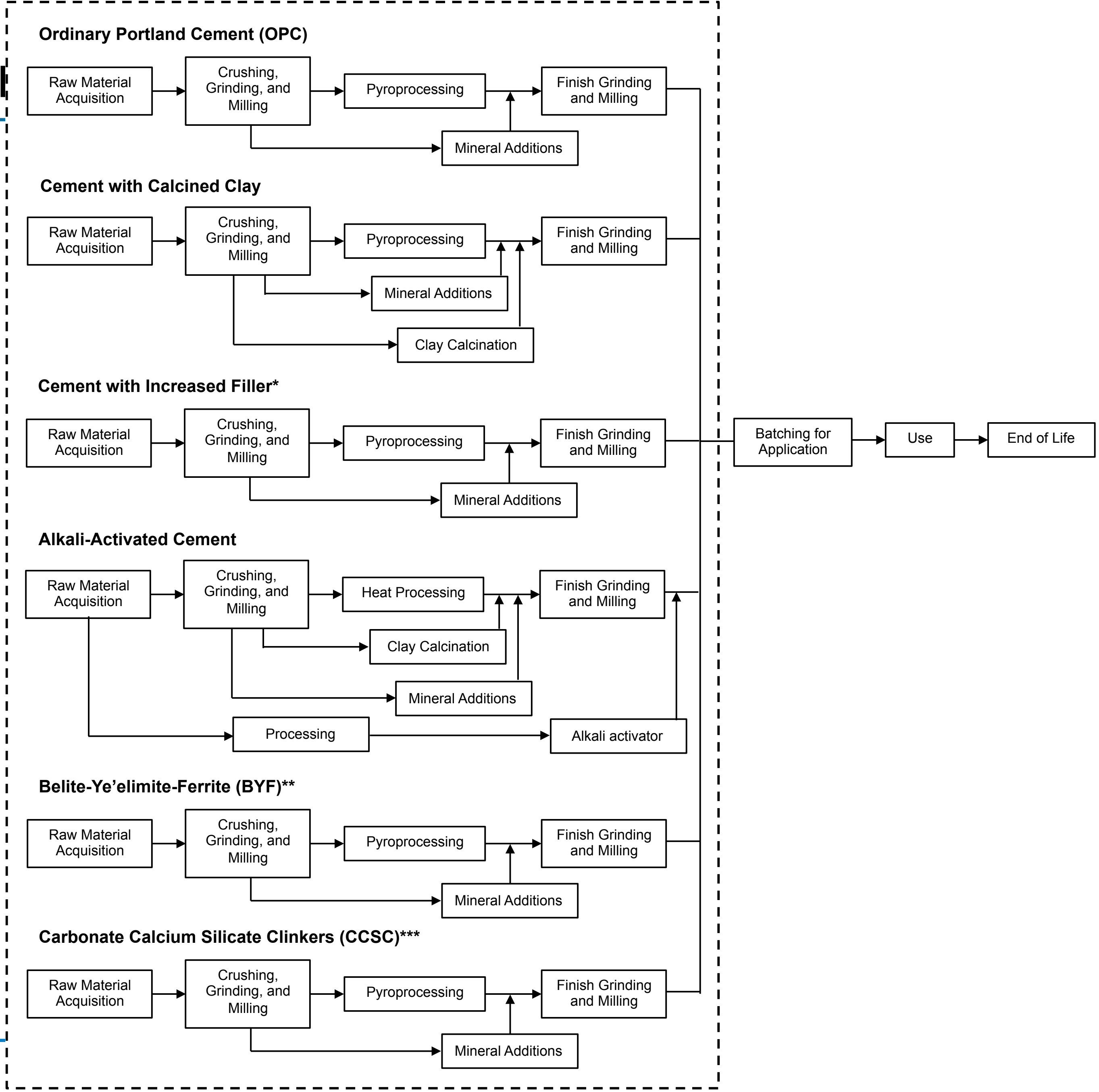
(Provis, *Cement and Concrete Research*, in press)

Potential for scalability

- Competition between aluminosilicate precursors used for AAMs and their use in blends with Portland cement
- Clays and volcanic soils exist in quantities that vastly exceed demand for the foreseeable future
- Alkali metals (particularly sodium) can be obtained from a variety of means

(Provis, *Cement and Concrete Research*, in press)

Enviro



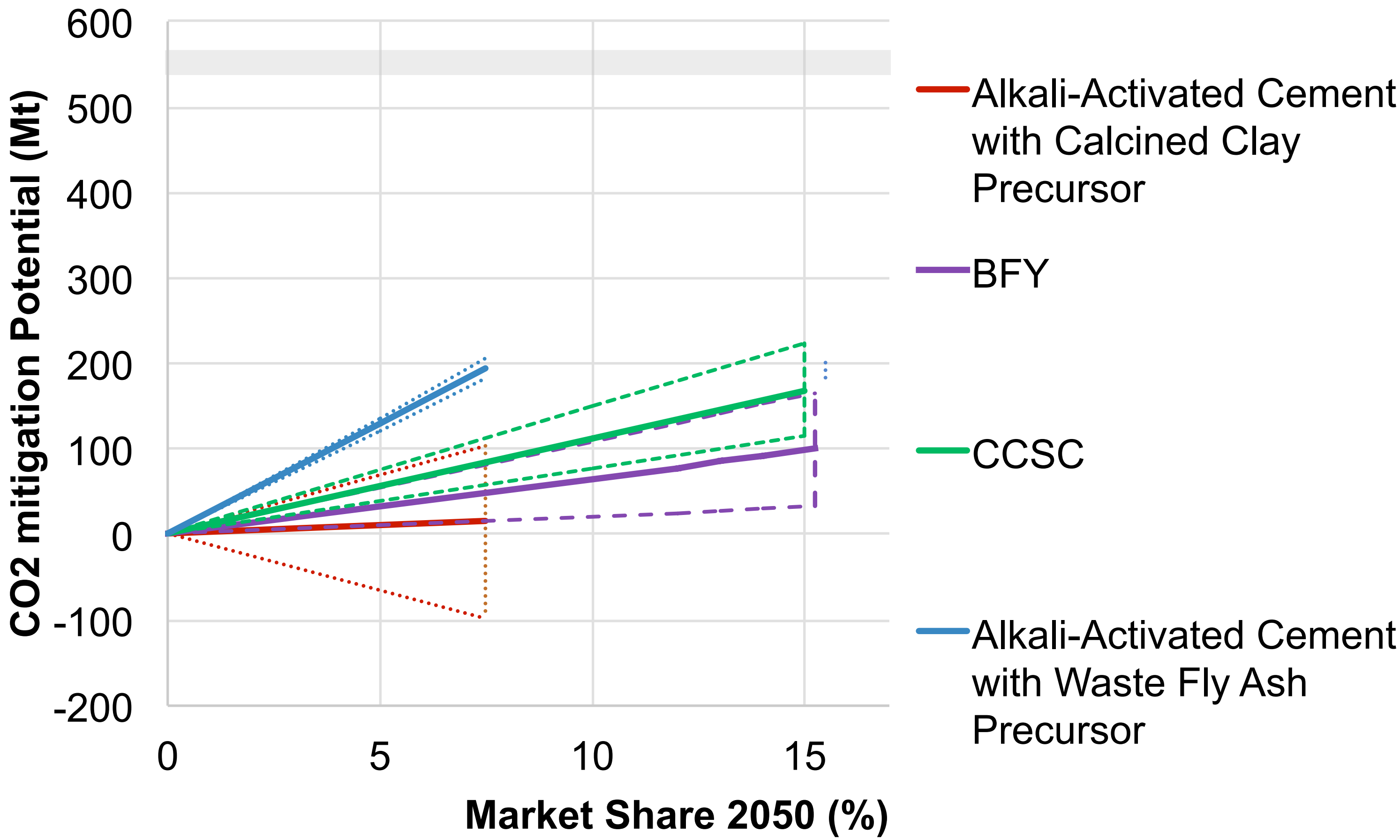
** Contains more limestone filler than OPC*

*** Contains different raw materials than OPC and requires less heat in pyroprocessing*

**** Contains different raw materials than OPC and requires less heat in pyroprocessing & carbonation benefits not considered*

From Miller in press

Environmental Assessment



(Miller, John, Pacca, and Horvath, *Cement and Concrete Research*, in press)

Barriers and incentives

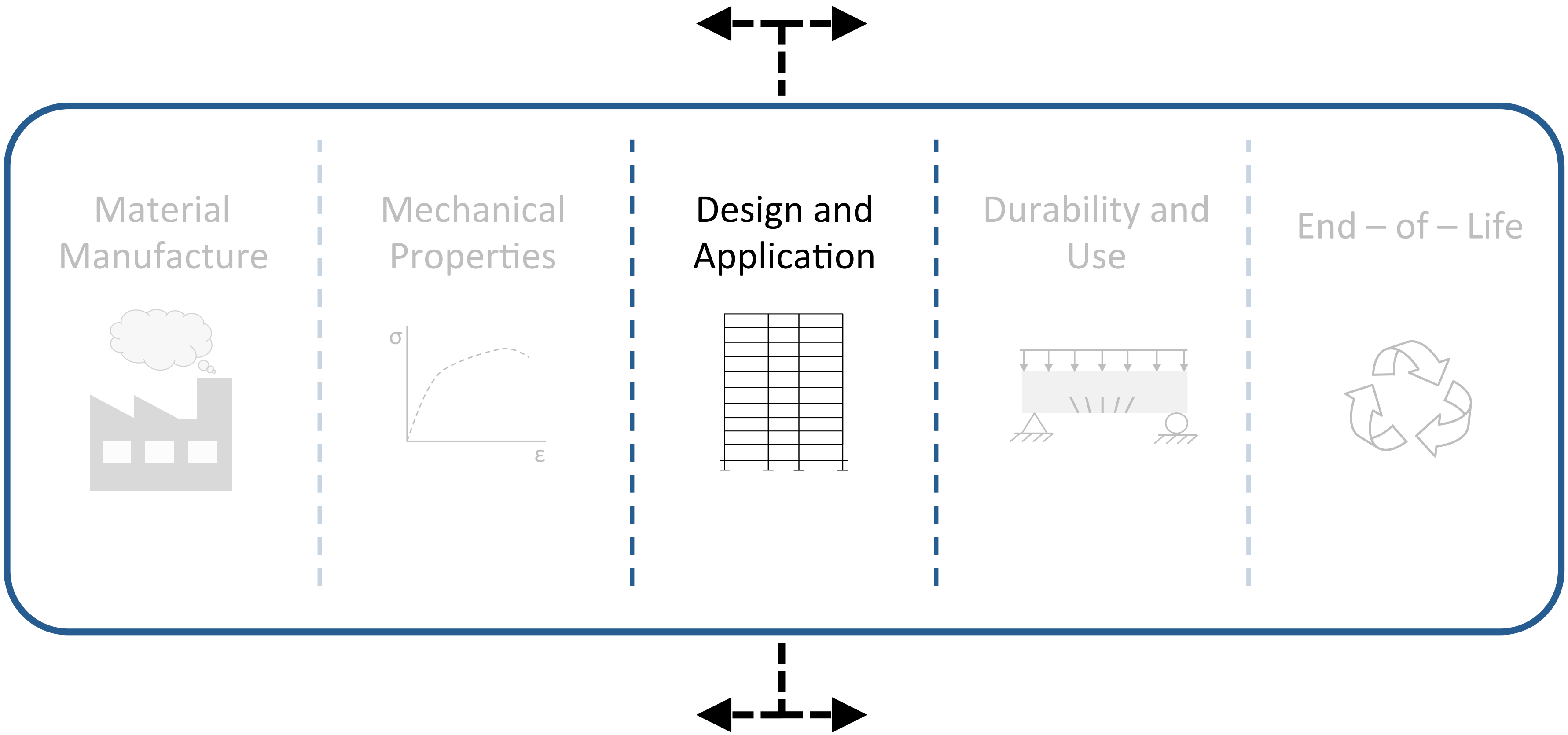
Barriers

- Key barriers facing industrial-scale production are largely outside the direct technical realm, these include:
  - The need for control of the supply chain, including reliance on alkali suppliers
  - Competition for some precursor materials from existing uses in blended Portland cements
- Occupational health and safety

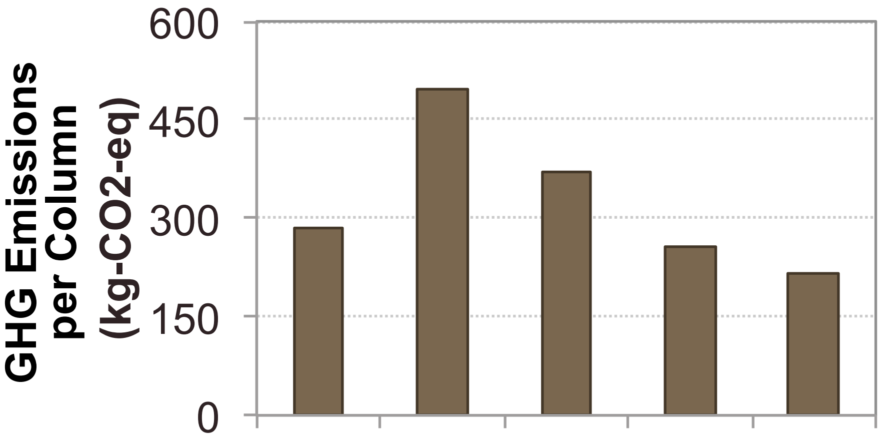
Incentives

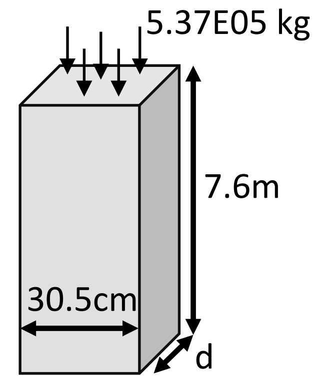
- Carbon emissions (especially if there are financial drivers, such as carbon taxes)
- High technical performance

Material Design Framework



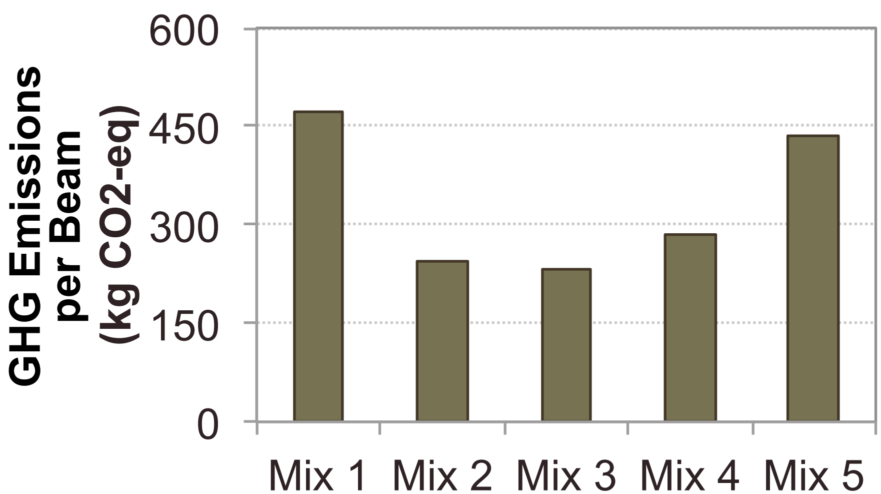
Design and Application

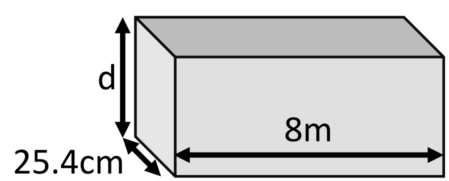




Given:
- diagram
- A_S = 4072 mm^2

Varied:
- depth, d
- Mix design (f_c')
- (ρ = 0.01 to 0.08)





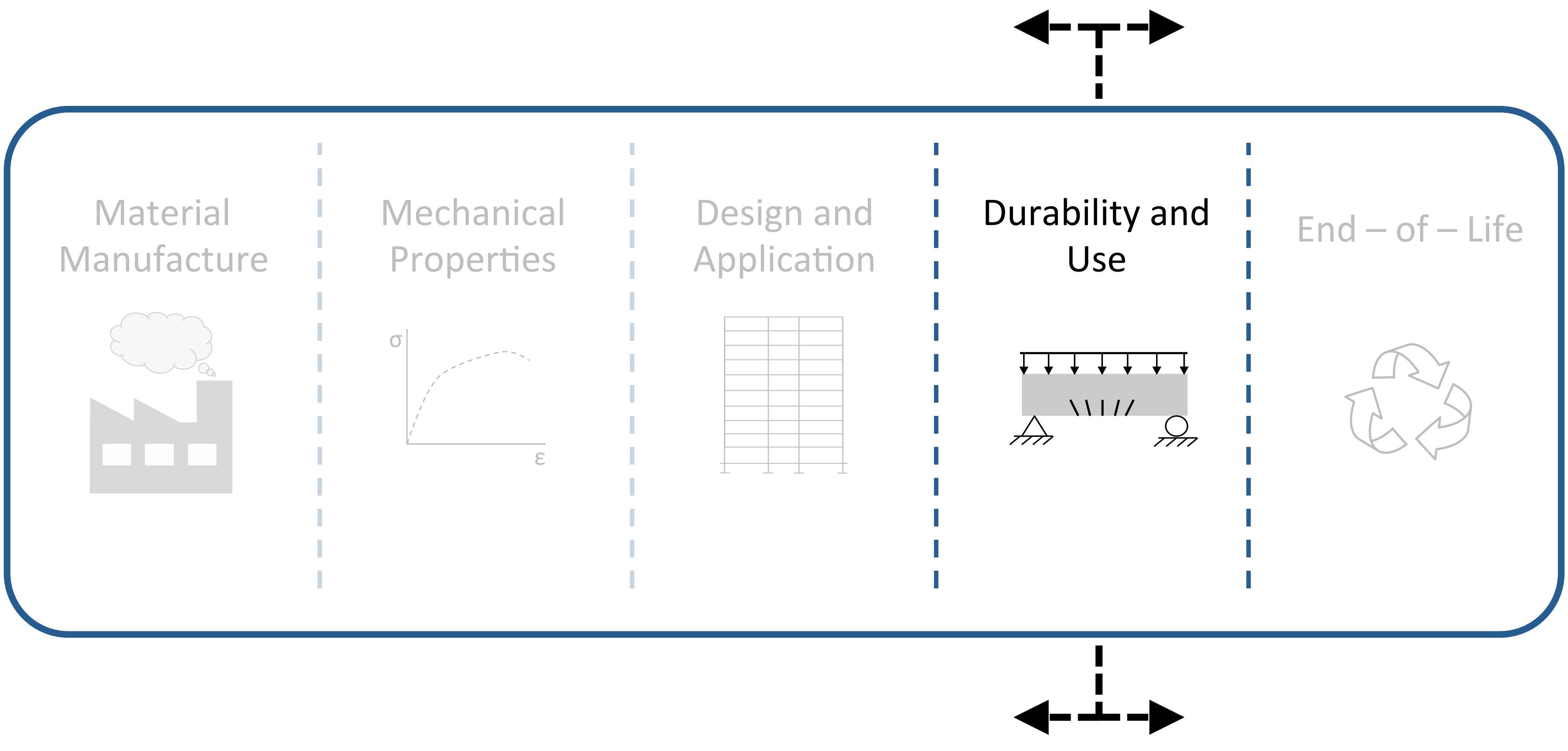
Given:
- diagram
- M_U = 482.6 kN-m
- A_S = 2580 mm^2

Varied:
- depth, d
- Mix design (f_c')
- (L/d = 10 to 11)
- (ρ = 0.01 to 0.015)

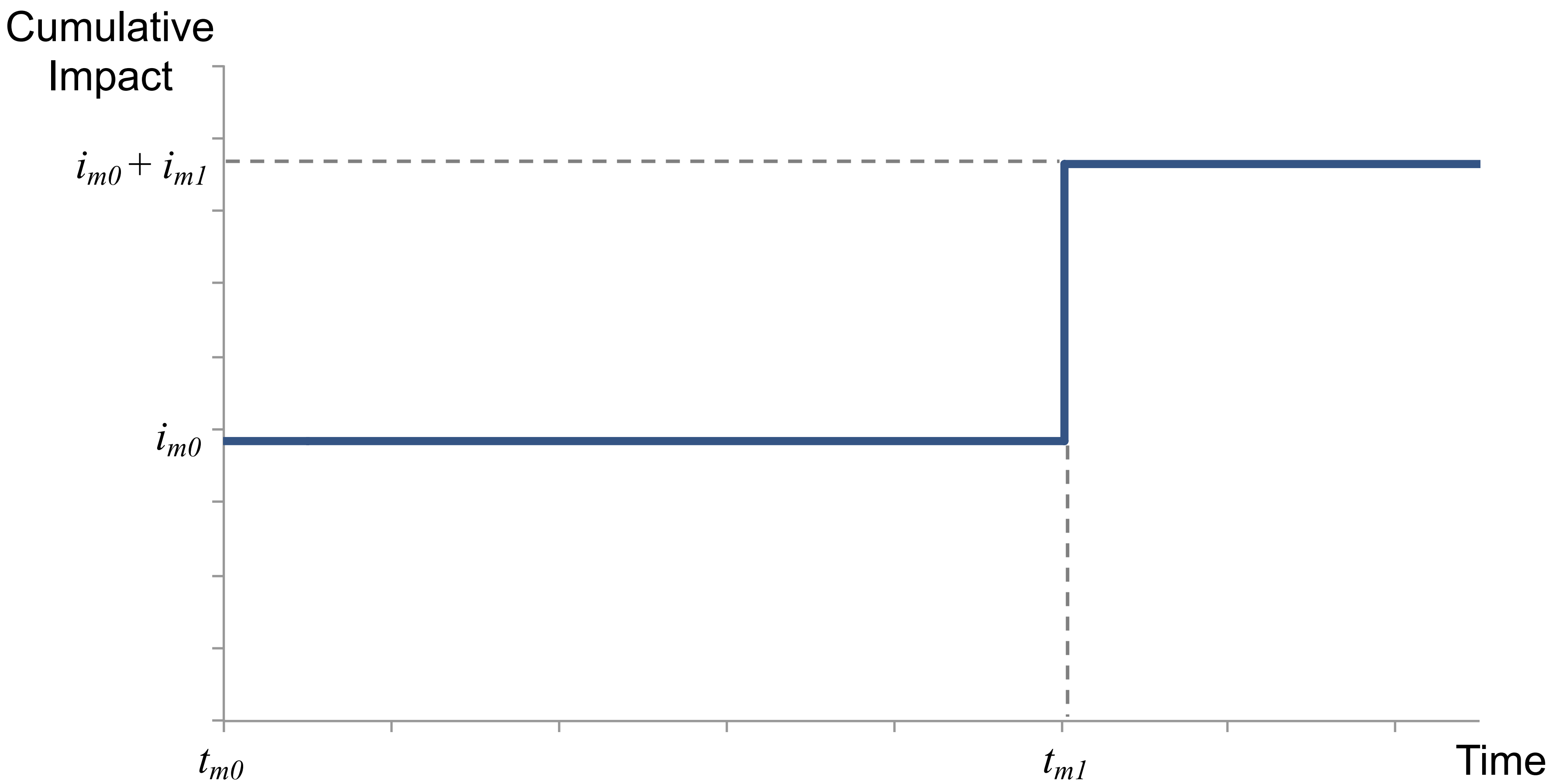
	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5
water to binder	0.56	0.71	0.45	0.45	0.38
fly ash to cement	0	1.3	2.7	1.2	0.2

Miller, S. A., Horvath, A., Monteiro, P. J. M. & Ostertag, C. P. *Greenhouse gas emissions from concrete can be reduced by using age as a design factor*. Environmental Research Letters, 2015. 10: 114017.

Material Design Framework



Durability and Use



$$I_{service} = \sum_{j} \left(i_{mj} + \sum_{k} i_{nkj}(t_{nkj}) + \sum_{p} i_{rkj}(t_{rkj}) - \sum_{q} i_{wqj}(t_{wqj}) \right)(t_{mj})$$

(theory based on Miller, S.A., M.D. Lepech, & S.L. Billington. *Evaluation of functional units including time-dependent properties for environmental impact modeling of biobased composites*. The Journal of Biobased Materials and Bioenergy, 2013. **7**: 588-599 and Lepech, M.D., M. Geiker, and H. Stang, *Probabilistic design and management of environmentally sustainable repair and rehabilitation of reinforced concrete structures.* Cement and Concrete Composites, 2014. **47**: p. 19-31.)

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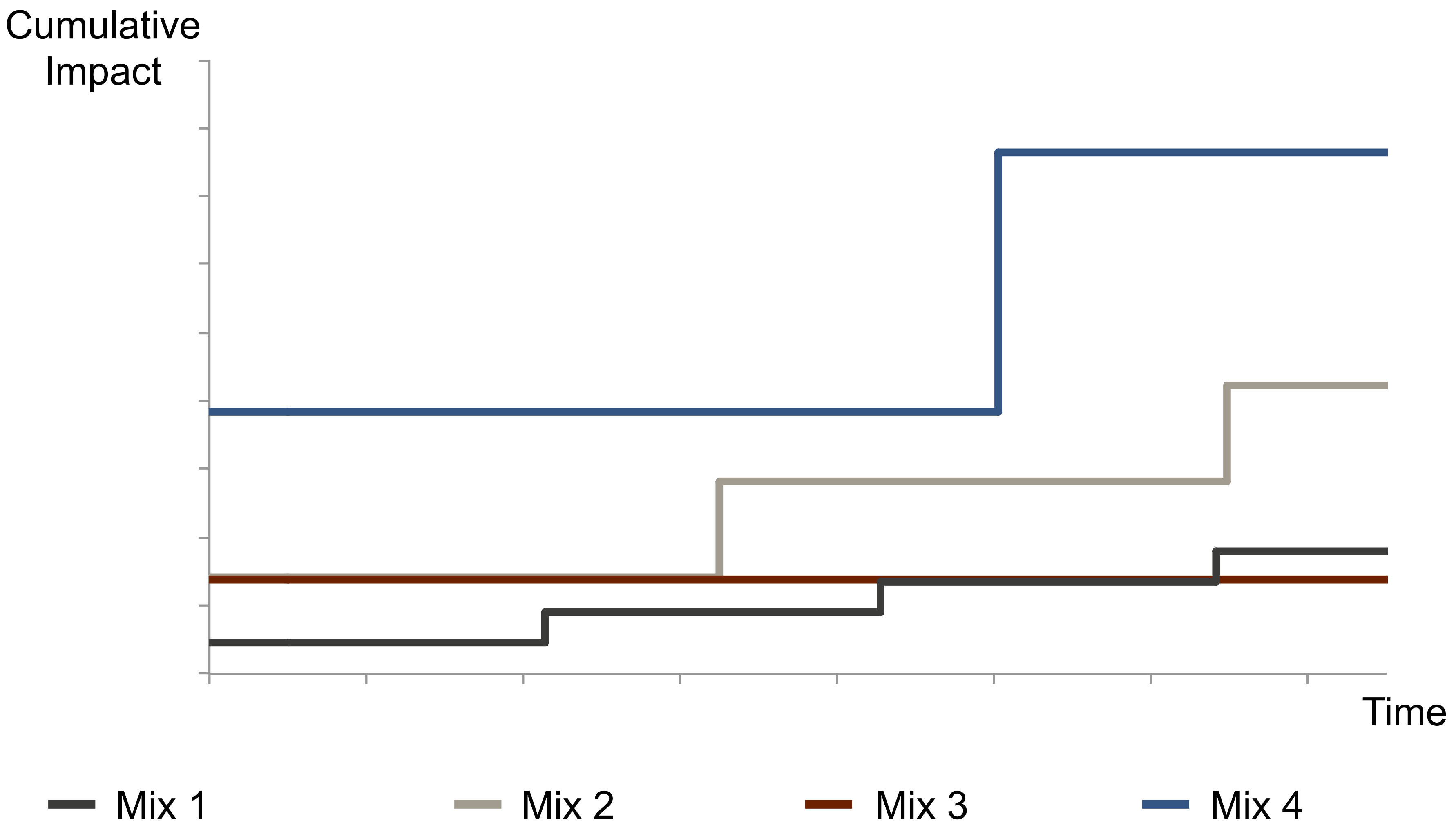

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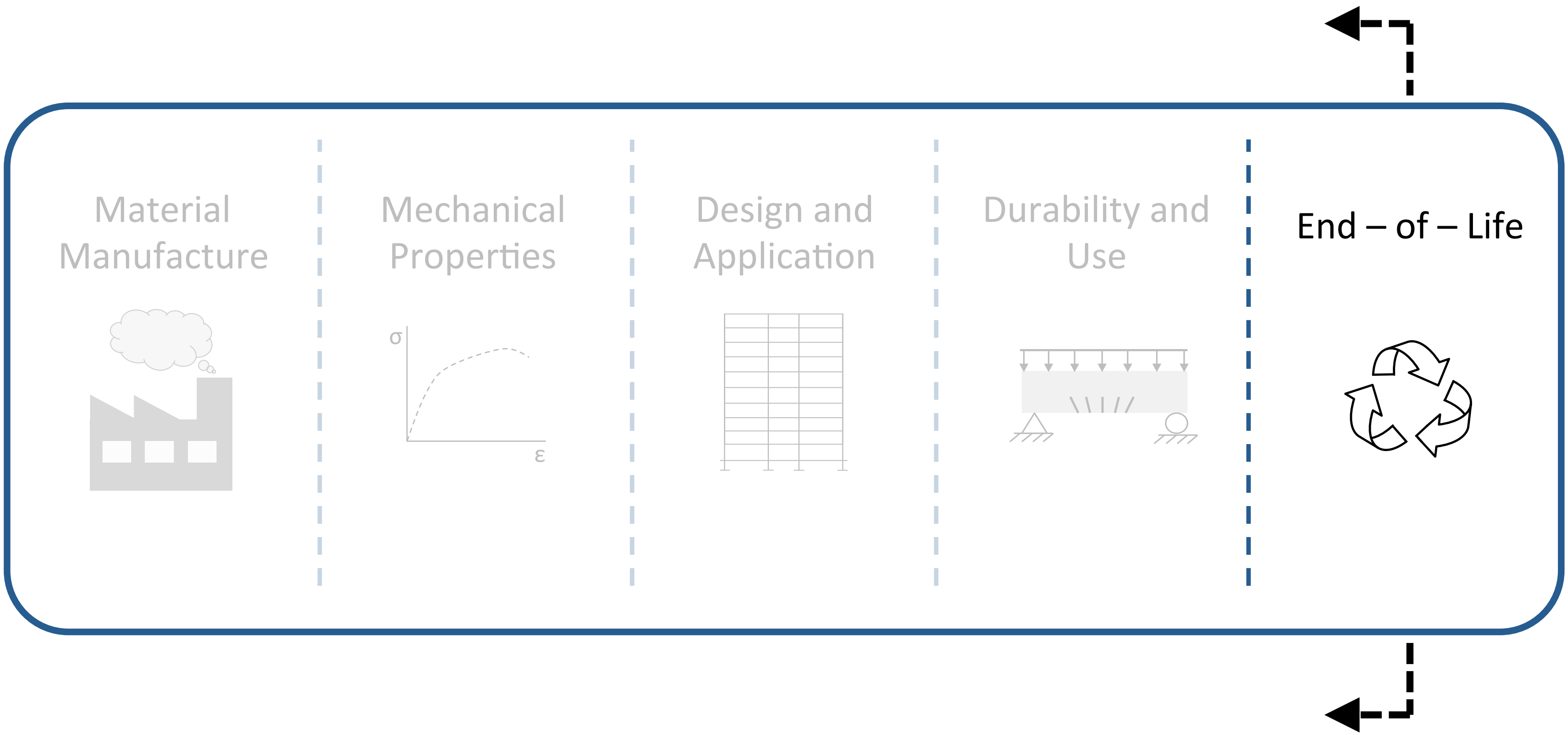
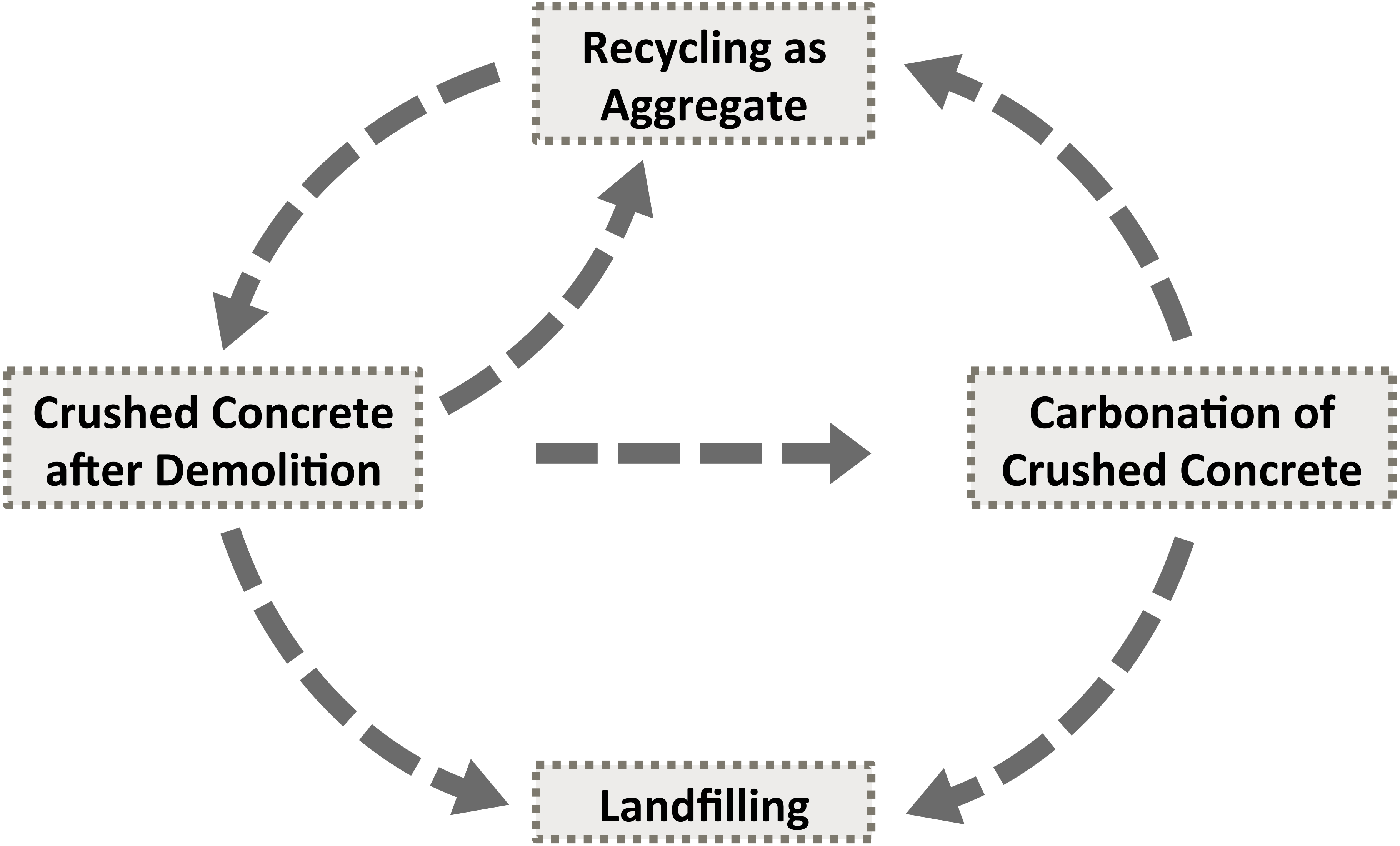


End-of-life


Recycling as Aggregate
Crushed Concrete after Demolition
Carbonation of Crushed Concrete
Landfilling

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