National Concrete Consortium

Reducing the global warming potential (GWP) of concrete mixtures using intelligent mixture design

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A Reminder of Concrete

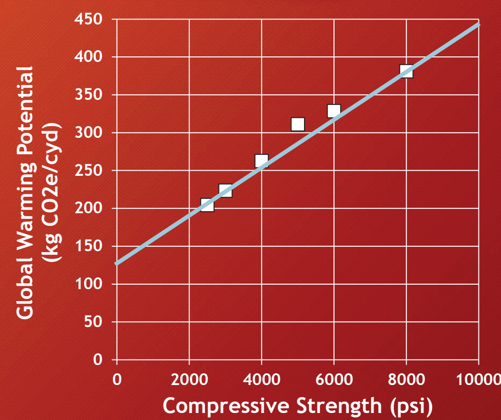
- 403.6 Million Metric Tons of concrete produced in 2022- US
- 12% Annual Increase in production volumes since 2015
- US Concrete Industry – 56 billion dollars in revenue
- Average selling prices ~ $139.80

https://concretefinancialinsights.com/us-concrete-industry-data

Photo 15685454 | Concrete Truck © Payphoto | Dreamstime.com

Concrete Industry and GWP

- NRMCA worked with Athena to establish National and Regional LCA mixtures
- Compressive strength of a mixture has been related to the GWP
  - Compressive strength is at best incomplete
- Goal is to reduce this amount by some percentage
  - How does the producer begin to design mixtures with reduced GWP in an efficient & documented way ?

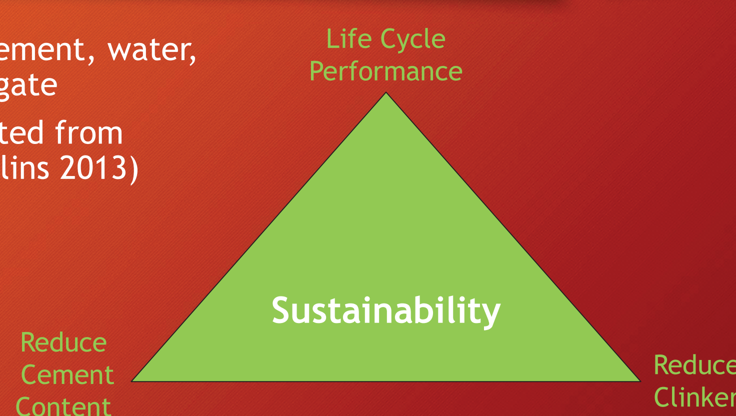


NRMCA member LCA Benchmarks V 3.0

How to Reduce GWP of Concrete

- Concrete is a composite of cement, water, fine aggregate, coarse aggregate
- 85 to 90% of the GWP estimated from cement (e.g., Turner and Collins 2013)
- A Three Prong Approach

- Great concept but how do we get this implemented in practice



Weiss et al. 2005

Homer Knows – It all Starts with Duff

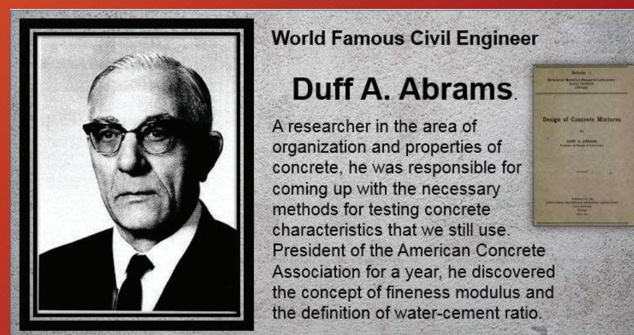
Homer Knows – It all Starts with Duff

- Duff Abrams built on the work of Feret (strength is related to the volume of water and cement)
- w/c is converted to mass
- As an industry we move forward with this as an indicator of porosity
- Powers solidified this in the 1930s and 40s with his great work
- However, mixtures were water, cement, sand and rock

Our Current Design Procedures are Dated

Concrete mixtures are proportioned empirically using antiquated technologies, new mixture proportions, and binder compositions are difficult to evaluate without extensive testing.

Further accounting for carbon footprint throughout the life-cycle of concrete is not typically done.



Modern Binders

"Most SCM and powder extenders have the potential to be used in concrete if a performance-based mixture proportioning procedure, which incorporates their chemical composition and reactivity, is followed."

- Local materials
- Novel materials
- Underutilized materials
- Off-spec materials

Modern Binders

"Most SCM and powder extenders have the potential to be used in concrete if a performance-based mixture proportioning procedure, which incorporates their chemical composition and reactivity, is followed."

Lo

Off-spec SCMs (off-spec fly ash, natural pozzolans, slags, etc.);
Alternative ashes (bottom ash, reclaimed ash, agricultural ash, etc.);
Other industrial and natural products (pumice, under utilized clays, etc.);
Powder extenders (limestone, etc.)

Too many ingredients and too many cooks

Procedure – Part 1 Design Criteria

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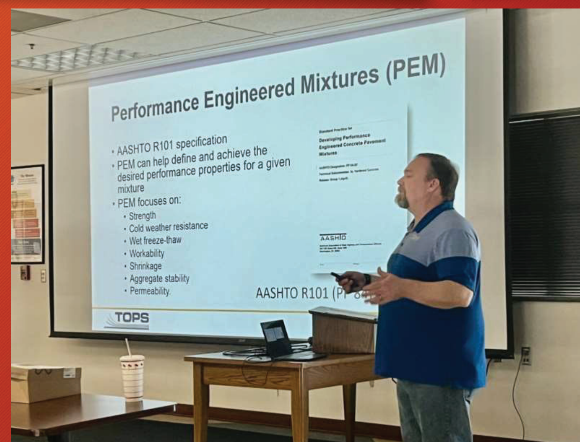
Design Criteria (AASHTO R101)

6.1 Strength
6.4 Shrinkage and Cracking
6.5 Freeze Thaw Durability
Salt Durability (CaOxy)
6.6 Transport (resistivity)
Time to Corrosion
6.7 D-Cracking and ASR

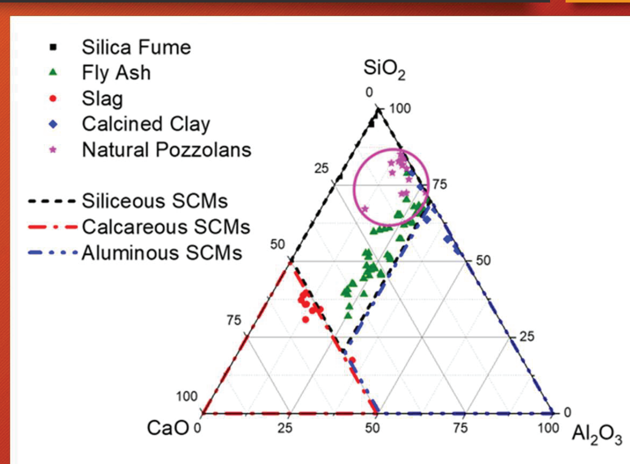


Bob Conway, FHWA Photo courtesy of Leif Wathne

Procedure – Part 2 Material Characterization

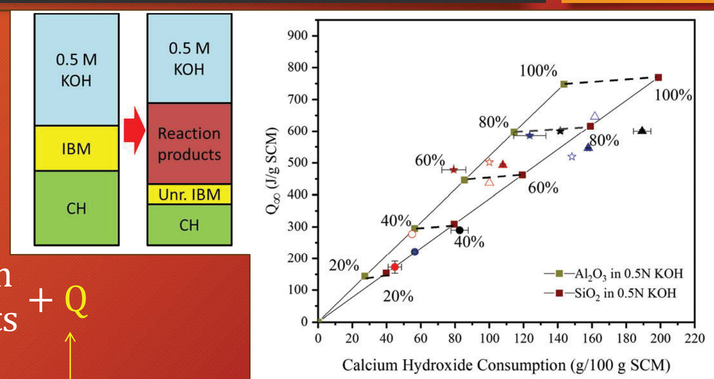
Standard Tests

- Cement Chemistry
- SCM Chemistry
- SCM Reactivity
- SCM Water Demand
- SCM Shape
- Aggregate Properties



Procedure – Part 2 Material Characterization

Pozzolanic reactivity test ("PRT") determines the degree of reactivity (DoR*)



$$\mathrm{SCM} + \mathrm{CH} + \mathrm{H_2O} \xrightarrow{50^oC} \text{reaction products} + \mathrm{Q}$$

Measure CH consumption

Measure heat release

$$DOR^* = \frac{Q_\infty - c_1 \cdot CH_{consumed}}{c_2}$$

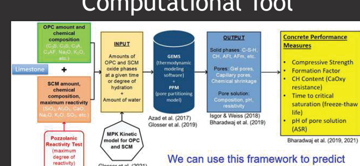
Putting it all together

Design Criteria (AASHTO R101)
Strength
Resistivity
SAM etc

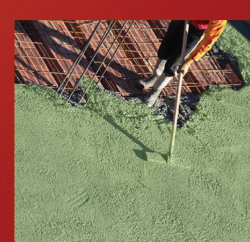
Materials Characterization

Chemical Composition
Degree of Reactivity

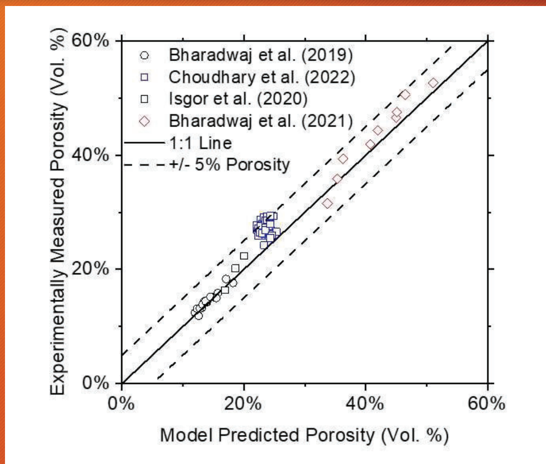
Computational Tool

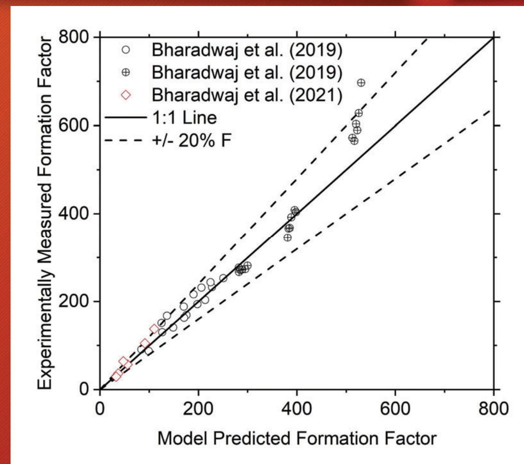


Mixture Proportions



Does it work – Comparing prediction (x-axis) and measurement (y-axis)





Examples – Defining Performance

Concrete Application	Bridge Deck	Midwest Pavement	Foundation
Exposure Class / Durability Requirement	ACI 318: F3, S0, W0, C2 Resistance to chloride ingress, corrosion, and FT	AASHTO PP-84 CaOxy and FT damage specified by SHA	ACI 318: F0, S1, W1, C0 Moderate sulfate and ASR resistance
Strength (56-day)	5000 psi (34 MPa) (min)	4225 psi (29 MPa) (min)	4000 psi (27 MPa) (min)
Slump	1-4 in (25-100 mm)	1-2 in (25-50 mm)	1-3 in (25-75 mm)
F Factor (56-day)	375 (min)	270 (min)	200 (min)
CH (56-day)	20g/100g binder (max)	20g/100g binder (max)	N/A
pH (56-day)	12.8 (min)	N/A	13.6 (max)
Time to Critical Sat	30 years (min)	30 years (min)	N/A

Bharadwaj et al., ACI Mat., 2022

Examples – Defining Performance

Bottom Ash (DOR* = 23%)

Concrete Application	Midwest Pavement
Exposure Class / Durability Requirement	AASHTO PP-84 CaOxy and FT damage specified by SHA
Strength (56-day)	4225 psi (29 MPa) (min)
Slump	1-2 in (25-50 mm)
F Factor (56-day)	270 (min)
CH (56-day)	20g/100g binder (max)
pH (56-day)	N/A
Time to Critical Sat	30 years (min)

Component	Ash 3 (milled bottom ash)*
SiO_2	42.3
Al_2O_3	16.8
Fe_2O_3	7.0
CaO	21.2
Na_2O	1.11
K_2O	0.43
MgO	4.2
SO_3	0.4
P_2O_5	0.54
LOI	2.5
DOR*	24%
Specific gravity	2.8

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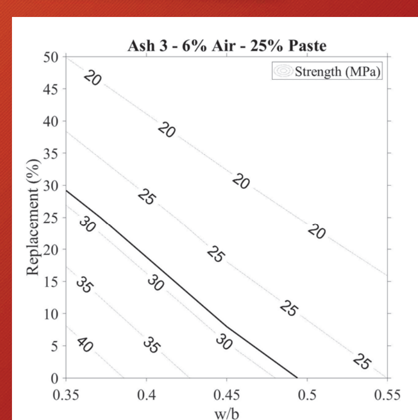

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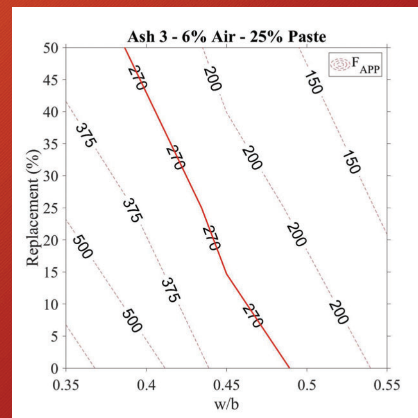

Isgor et al., 2000

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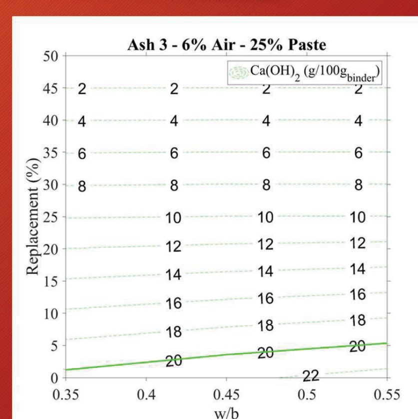

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CH (56-day)	20g/100g binder (max)
pH (56-day)	N/A
Time to Critical Sat	30 years (min)

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(DOR* = 23%)

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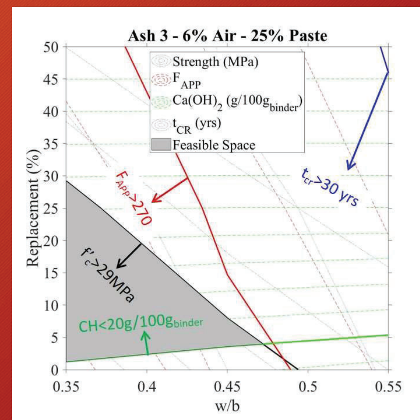
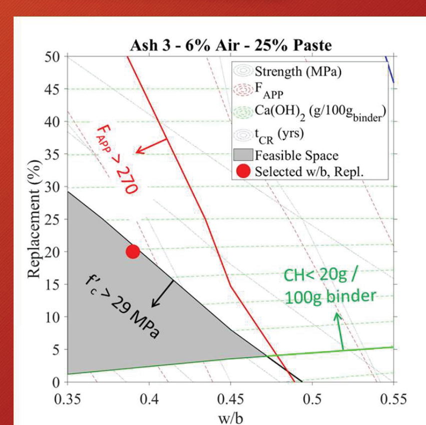


Isgor et al., 2000

Examples – Defining Performance

Concrete Application	Midwest Pavement	
Exposure Class / Durability Requirement	AASHTO PP-84 CaOxy and FT damage specified by SHA	Achieved
Strength (56-day)	4225 psi (29 MPa) (min)	39 Mpa
Slump	1-2 in (25-50 mm)	-
F Factor (56-day)	270 (min)	451
CH (56-day)	20g/100g binder (max)	9.5
pH (56-day)	N/A	~
Time to Critical Sat	30 years (min)	yes



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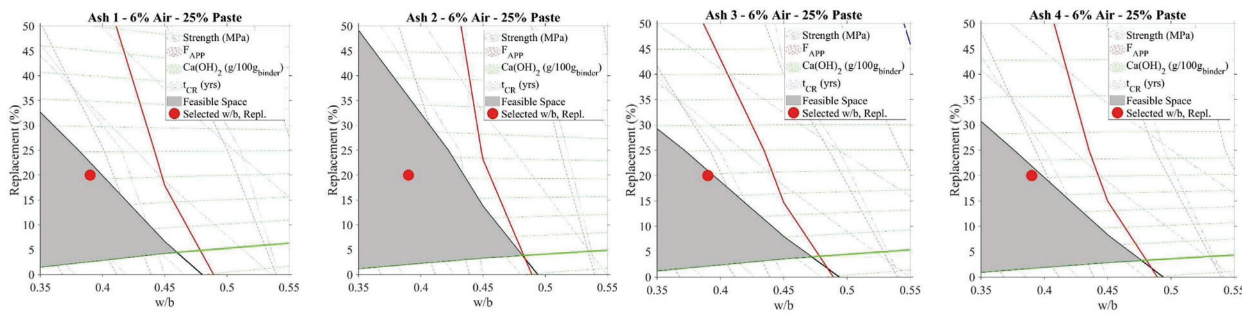
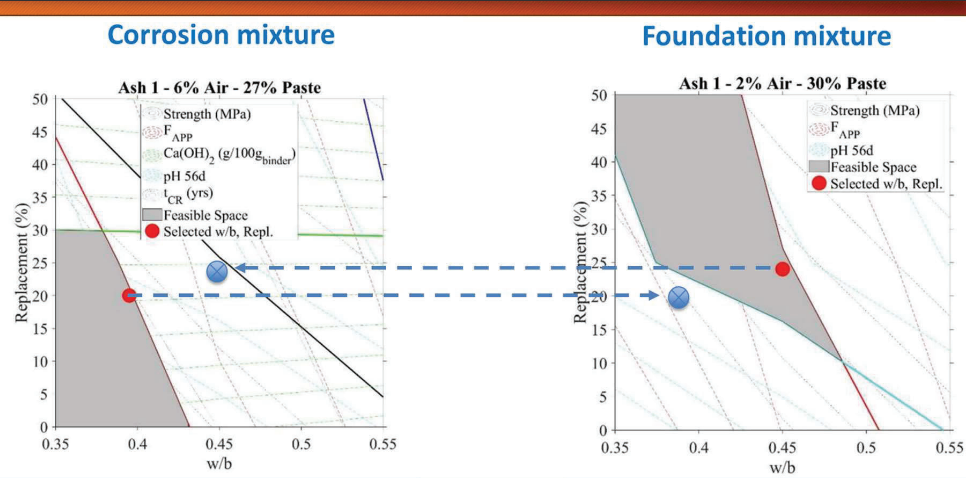
Different Ash – Different Performance

Midwest pavement mixtures



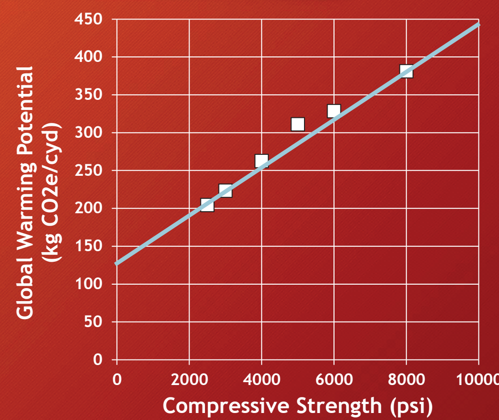
(a) Ash 1 (b) Ash 2 (c) Ash 3 (d) Ash 4

Different Ash – Different Performance



Mixture Optimization and GWP

- NRMCA worked with Athena to establish National and Regional LCA mixtures
- Compressive strength of a mixture has been related to the GWP
  - Compressive strength is at best incomplete
- Goal is to reduce this amount by some percentage
  - How does the producer begin to design mixtures with reduced GWP in an efficient & documented way ?



NRMCA member LCA Benchmarks V 3.0

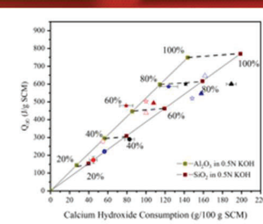
Mixture optimization

Component	PLC	SCM
SiO_2	20.30	48.20
Al_2O_3	4.80	19.10
Fe_2O_3	3.30	5.70
CaO	63.50	14.60
Na_2O_{eq}	0.51	0.78
MgO	0.80	3.80
SO_3	3.10	1.00
$CaCO_3$	13.00	-
Specific Gravity (unitless)	3.09	2.66
Blaine Fineness (m^2/kg)	405	350
DOR*	N/A	43%

$$SCM + CH + H_2O \rightarrow \text{reaction products} + \Delta$$

Measure CH Consumed

Measure Heat Released

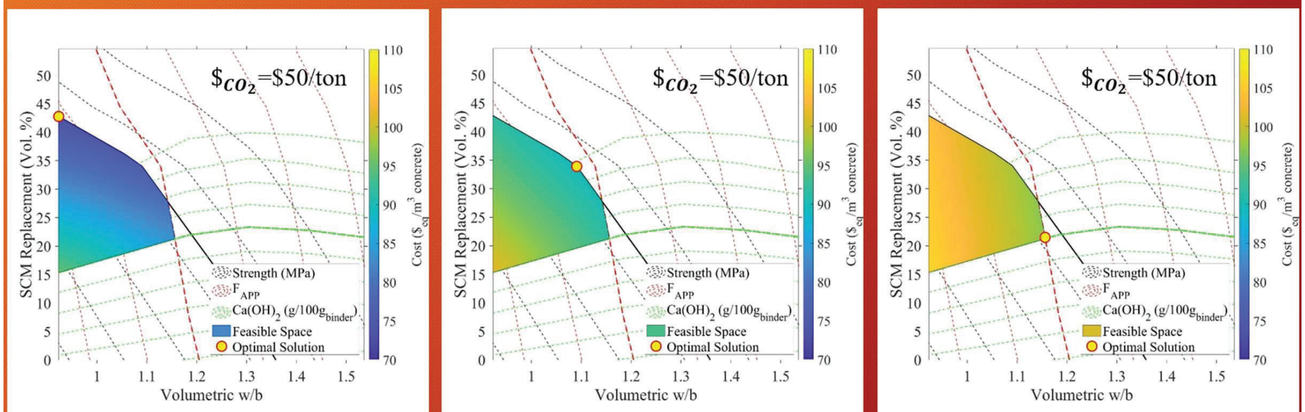


$$DOR^* = \frac{Q_\infty - c_1 \cdot CH_{consumed}}{c_2}$$

Component	Cost ($/ton)	CO_2 emissions (kg CO_2 /m^3)
PLC	140	2728
SCM 1	120	74
Water	0	1
Fine Agg.	15	6
Coarse Agg.	15.5	8

Mixture optimization

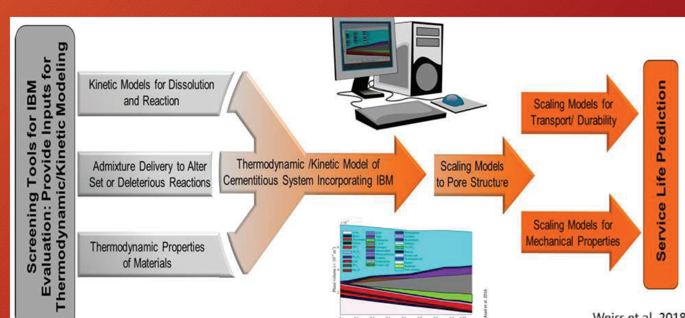
Economic analysis of materials and social costs are considered and optimized:



cost of Material X= $ 0/ton | cost of Material X= $ 50/ton | cost of Material X= $ 200/ton

Changing How we Look at GWP

- Current calculations are based on an A1 to A3 basis
- This method is simplistic and can result in implementing approaches that are short-lived and require many repairs driving up the GWP in the life of a structure
- GWO needs to be considered on a cradle-to-grave basis (A to D) to show long-term value
- Current empirical tools do not enable new materials & mixture design service life prediction
- Use in value-added products
- Use by agencies



Weiss et al. 2018

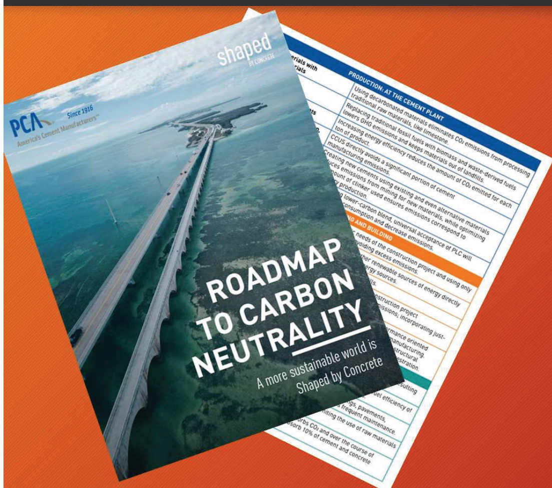
Summary

- Most SCM and powder extenders have the potential to be used in concrete if a performance-based mixture proportioning procedure, which incorporates their chemical composition and reactivity, is followed.

- These performance-engineered concrete mixtures can be further optimized for cost and/or carbon (GWP) using linear programming

- Very powerful tool for reducing GWP in practice and performing LCA.

Approaches to Reduce GWP



- Optimize Concrete Mixtures
- Replace Raw Materials with Decarbonized Materials
- Use Portland Limestone Cement
- Promote New Cement Mixtures
- Use Recycled Materials
- Avoid Overdesign