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Performance-based LCA concept

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Performance-based LCA concept

Mechanical Performance-Based Indicator:
This index normalizes environmental impacts, such as carbon emissions or energy consumption, by the concrete's mechanical performance, typically using the 28-day compressive strength as the functional unit. It directly links the required strength performance with the environmental footprint of the material.

$$\text{MPI} = \frac{C}{f_{c,28}}$$

C = Total carbon emissions (or energy consumed) per unit volume (e.g., kg CO_2/m^3).

$f_{c,28}$ = 28-day compressive strength (MPa).

Durability-Based Indicator:
This metric is calculated by dividing the total carbon emissions per unit volume of concrete by a durability parameter that reflects the material's expected service life.

$$\text{A-index} = \frac{C}{D}$$

C = Total carbon emissions per unit volume (e.g., kg CO_2/m^3).

D = Durability parameter.

- This parameter might be the estimated service life (years), or an indicator such as the amount of scaling (or degradation) per 100 freeze–thaw cycles for concretes affected by freeze–thaw damage.

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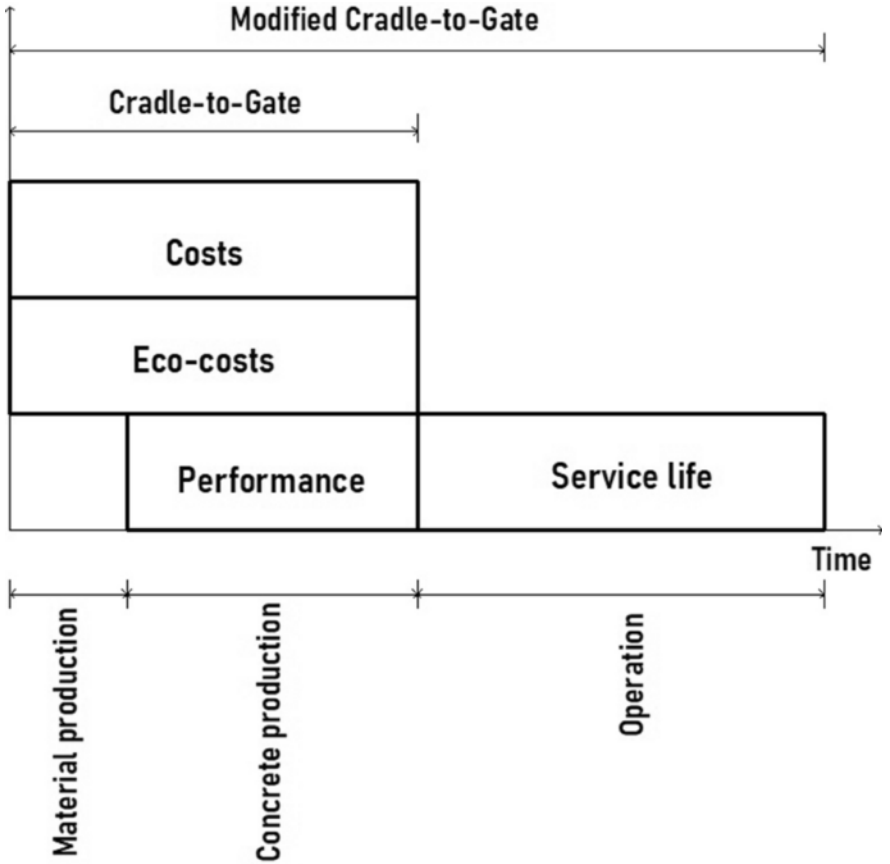
Durability-based LCA concept

Pseudo-Service Life:
An estimated service life based on a durability parameter. It serves as a proxy for actual performance and is used to normalize the carbon footprint against durability.

Diffusion Coefficient (Chloride Attack):
Measures the rate of chloride ion penetration into concrete. A lower diffusion coefficient indicates higher durability, extending the pseudo-service life under chloride exposure.

Scaling Index (Freeze–Thaw Damage):
Quantifies the amount of scaling (material loss) per 56 freeze–thaw cycles. Lower scaling values correspond to a longer pseudo-service life in environments subject to freeze–thaw effects.



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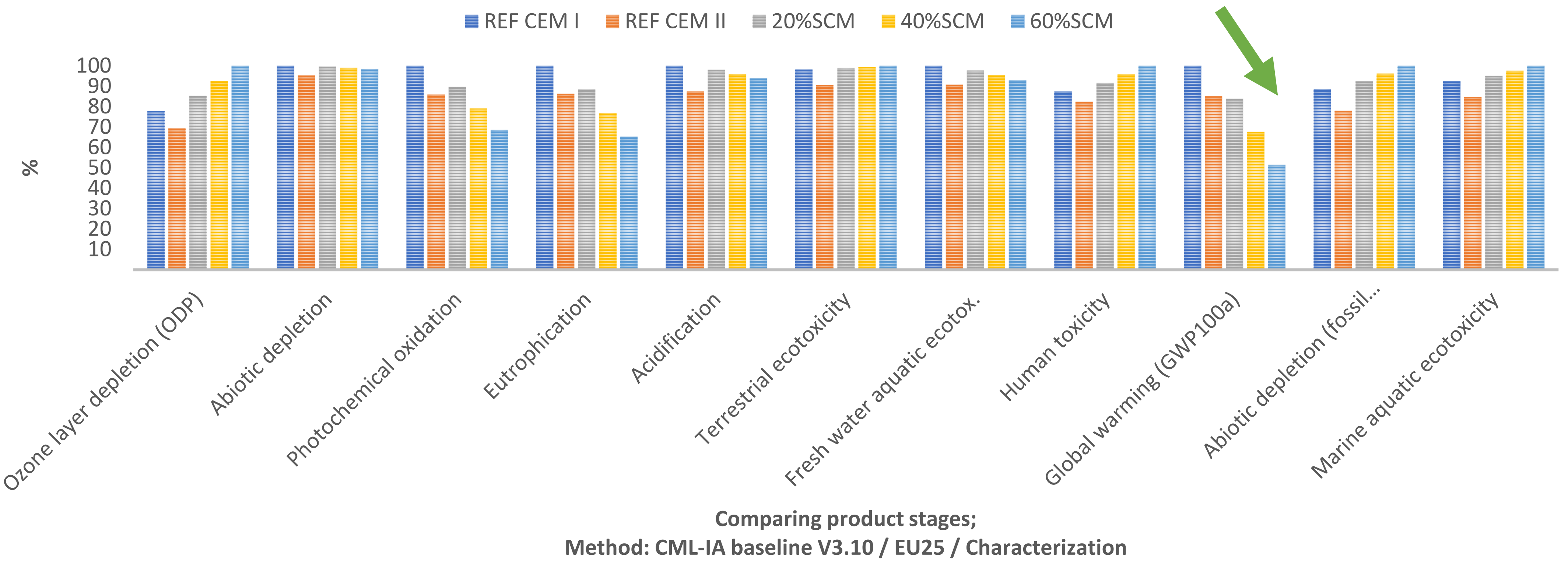
Scenario 1 Binder replacement



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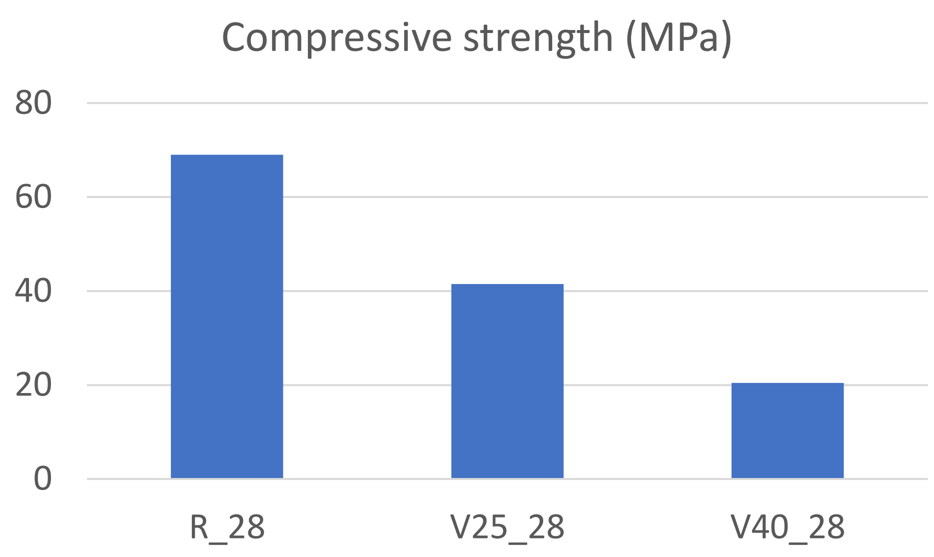
Overall Carbon Footprint (GWP100a)

CEM I: 304 kg CO_2eq

25%SCM+10%LM: 213 kg CO_2eq

Interpretation:

The SCM+LM mix has a significantly lower embodied carbon footprint (about 30% less) compared to the pure CEM I reference.



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Mechanical LCA Indices (LCA-f28, LCA-f112)

These indices represent the carbon footprint normalized by strength:

$$\text{LCA-f28} = \frac{\text{kg CO}_2\text{eq per m}^3}{f_{28}} \quad \text{and} \quad \text{LCA-f112} = \frac{\text{kg CO}_2\text{eq per m}^3}{f_{112}}$$

LCA-f28:
CEM I: 4.41 kg CO_2eq/Mpa
SCM+LM: 5.14 kg CO_2eq/Mpa

LCA-f112:
CEM I: 4.04 kg CO_2eq/Mpa
SCM+LM: 4.11 kg CO_2eq/MPa

Interpretation:

At 28 days, SCM+LM is less “carbon-efficient” per MPa (5.14 vs. 4.41).
By 112 days, the gap narrows (4.11 vs. 4.04), but SCM+LM still remains slightly higher per MPa.

This indicates that while the SCM+LM mix has a lower absolute carbon footprint, its lower strength means it is not as efficient on a “per MPa” basis, especially at early ages.

Freeze–Thaw Parameter (FT) and LCA-FT

FT is shown as a measure of freeze–thaw durability (e.g., scaling in kg/m³).

CEM I: 1.0
SCM+LM: 0.7
(implies less material lost to scaling, hence better freeze–thaw resistance)

LCA-FT (kg CO_2eq/durability):

CEM I: 304
SCM+LM: 149.1

Interpretation:

The SCM+LM mix **performs better** under freeze–thaw, losing less material (0.7 vs. 1.0).

When normalizing GWP by freeze–thaw durability, **SCM+LM** is significantly lower (149.1 vs. 304), suggesting **it is much more "carbon-efficient" in terms of freeze–thaw durability**.

Overall takeaways

Absolute carbon footprint:

- The SCM+LM mix has substantially lower GWP (213 vs. 304 kg CO_2eq).

Mechanical perspective:

- If strength is the main driver (especially at 28 days), CEM I is more efficient per MPa.
- By 112 days, the difference narrows but still favors CEM I slightly.

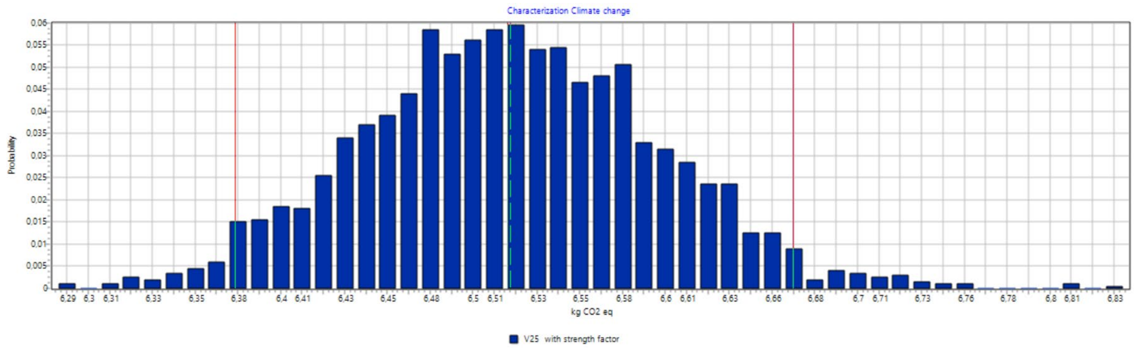
Freeze-thaw durability perspective:

- The SCM+LM mix is better (lower scaling), and its LCA-FT index is far lower, indicating a strong advantage for long-term durability under freeze–thaw.

Application implications:

- SCM+LM is appealing for structures requiring good freeze–thaw performance and where early strength is not critical, or where extended curing times can be accommodated.
- CEM I may be preferable if high early strength is essential, though it has a higher overall carbon footprint.

Further work: Uncertainty analysis

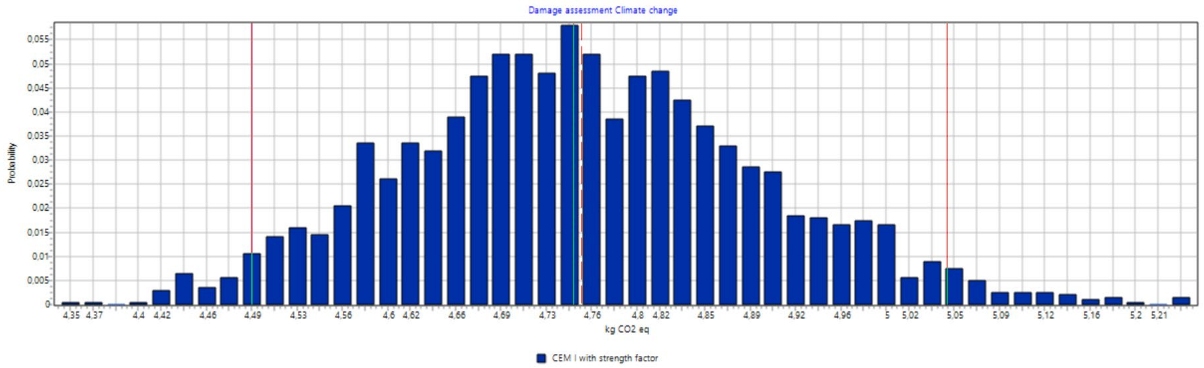


Method: EN 15804 + A2 (adapted) V1.01 / EF 3.1 normalization and weighting set, confidence interval: 95 %

Uncertainty analysis of 1 p 'V25 with strength factor',

Number of bins: 50
Visible interval: 99,9 %
Confidence interval: 95 %

Product	Mean	Median	SD	CV	2,5%	97,5%	SEM
V25 with strength factor	6,52	6,52	0,0767	1,18 %	6,37	6,67	0,00171



Method: EN 15804 + A2 (adapted) V1.01 / EF 3.1 normalization and weighting set, confidence interval: 95 %

Uncertainty analysis of 1 p 'CEM I with strength factor',

Number of bins: 50
Visible interval: 99,9 %
Confidence interval: 95 %

Product	Mean	Median	SD	CV	2,5%	97,5%	SEM
CEM I with strength factor	4,75	4,75	0,141	2,97 %	4,49	5,04	0,00316

Only 0.00579 % of the values contain uncertainty-data! (see statistics)

Strength and FT scaling measurements can vary significantly.

Emission factors and production data have their own ranges.

Monte Carlo Simulation: Random sampling of uncertain input reveals probability distributions of outcomes.

Distributions may overlap, indicating a risk that one mix is not always superior.

Knowing confidence intervals and probabilities helps guide mi selection under uncertainty.

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Further work: Integrated sustainability index?

$$\text{Integrated Sustainability Index (ISI)} = \frac{E}{f \times D}$$

where:

- E is the total carbon emissions per unit volume (e.g., kg CO_2eq/m^3),
- f is the compressive strength (e.g., MPa at 28 or 112 days),
- D is a durability parameter (such as a pseudo-service life or an FT scaling value correlated with service life).

This single parameter gives the carbon emissions per unit performance (combining both strength and durability). A lower ISI indicates that, per unit of performance, the concrete mix has a smaller environmental footprint.