Title

Framework for the Evaluation of the Adoptability of Novel Low-Carbon Cementand Concrete Technologies

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Framework for the Evaluation of the Adoptability of Novel Low-Carbon Cement and Concrete Technologies

A decision-making tool to accelerate the adoption of novel materials.

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Table of Contents

List of Tables

List of Figures

Executive Summary

Data center construction is among the fastest-growing areas of construction worldwide, with rapidly increasing energy and material demands. To meet emissions targets, there is a pressing need to identify, evaluate, and deploy low-carbon alternatives to conventional Portland cement-based concrete given concrete's significant contributions to embodied greenhouse gas (GHG) emissions.

This framework supports the systematic evaluation and pathways for adoption of novel materials and technologies for use in data center construction. It guides decision makers in assessing both the potential benefits and associated risks of deployment. Materials are evaluated across three key categories: environmental impacts, material performance, and feasibility, addressing critical aspects such as constructability, cost, scalability, safety, policy environment, and permitting. Each category is assessed for potential risks and uncertainty. The risk assessment considers barriers to successful deployment and environmental impact reduction, and the uncertainty assessment considers the extent of knowledge gaps. By combining these two dimensions, the framework helps practitioners determine whether a material is best suited for incubation (further research and development), piloting (field demonstration), deployment (scaling into practice), or rejection (not recommended for further consideration).

A case study of limestone calcined clay cement (LC3) is conducted to demonstrate the application of the framework. LC3 is an alternative low-carbon binder with strong potential to reduce GHG emissions from concrete while maintaining comparable or better performance to Portland cement-based concrete. The case study illustrates how the framework can identify both opportunities and challenges, highlighting the pathways needed to adopt promising materials from research into industry.

This framework provides a structured, transparent, and practical approach for evaluating emerging low-carbon cement and concrete solutions. It was designed with data center applications in mind, but is adaptable to other sectors where concrete plays a major role in embodied emissions. By aligning technical performance with environmental goals and feasibility for market implementation, the framework offers a foundation for decision-making to accelerate the responsible adoption of innovative materials and technologies that can meaningfully reduce GHG emissions from the built environment.

1. Introduction

Data centers are vital in the digitalization era to support infrastructure for large-scale processing and storage of data [1]. The massive demand and rapidly growing need for these structures to meet the computing demand for artificial intelligence, smart infrastructure, and autonomous vehicles is causing a boom in construction and electricity use [2]. Annual spending on data center construction in the United States (US) is projected to average a 13% increase by 2027 [3]. While the main source of greenhouse gas (GHG) emissions from data centers is operations (i.e., electricity use), the embodied carbon from materials used in data center construction is estimated to be 10% of the total life cycle GHG emissions and this relative fraction will increase as electricity is decarbonized [4].

Concrete is a key construction material in data centers, for applications such as slabs and foundations [3]. The cement demand for data center construction in the US is expected to reach about 247,000 Mt in 2025 (~0.2% of cement produced in the US in 2024) [3]. Conventional concrete is composed of crushed rock (aggregates), water, and cement, the hydraulic binder that, when mixed with water, "glues" the rocks together to form concrete [5]. Cement manufacturing is the primary source of CO_2 emissions in concrete production [6], [7] and globally contributes about 7% of anthropogenic CO_2 emissions [8]. In the US, cement consumption generates approximately 69 Mt of GHG emissions (~1% of US total GHG emissions) per year [9]. Consequently, novel materials and technologies are emerging to decarbonize cement and concrete: use of alternative supplementary cementitious materials (SCMs), use of novel cement formulations, and carbon capture, utilization, and storage (CCUS) [10].

Given the anticipated scale and economic significance of future data centers, they present a valuable opportunity to deploy low-carbon or net-zero technologies to help meet ambitious emissions reduction targets. Innovation in the cement and concrete industry is essential to support this transition. For commercial adoption, new materials must demonstrate superior engineering performance, lower environmental impacts, and lower life cycle cost compared to conventional cement. Many novel technologies are currently limited due to economic viability, logistical challenges, and the need for further research and development to increase the cost-effectiveness and scalability [10], [11].

This work introduces a comprehensive evaluation framework for novel cement technologies, focusing on three key criteria: material performance, environmental impact, and practical feasibility for industry adoption. The framework is designed to assess alternative SCMs, novel binders, and innovative production methods aimed at significantly reducing emissions from the cement and concrete sector. It is intended for technologies at early to mid-stage development, to help identify research gaps, support pilot testing, and guide decisions related to large-scale deployment, particularly in high-volume applications such as data centers. The framework is not intended to serve as an exhaustive checklist and should not replace a full assessment by experts in material sustainability, but rather offers a structured foundation to inform further research and development.

2. Framework methodology

This section covers: (i) an overview of the framework format and structure, (ii) critical considerations, and (iii) a description of the scoring procedure. In the next section, the application of the evaluation framework is demonstrated using a case study. Appendix A provides explanations of the detailed evaluation questions.

2.1 Framework Format and Structure

Figure 1 shows a suggested workflow from initial screening to eventual deployment, where this framework supports Step 2 (Detailed Evaluation) to produce a transparent, evidence-based decision on whether the novel material or technology should:

- proceed to incubation for further lab-scale testing
- enter piloting for field demonstration
- be “shelved” or rejected, if considered not viable due to critical knowledge gaps or risks
- proceed to deployment

Step 1: **Initial Screening** (pre-framework) questions identify the novelty of materials and their eligibility for further consideration, and are outside the scope of this framework. This step should be performed by the user to select which products qualify for detailed evaluation.

Step 2: **Detailed evaluation** (framework) questions are grouped by three focus categories: environmental impacts, material performance, and feasibility. These questions provide detailed insight into the specifics of a new material once it has passed the initial screening. The detailed evaluation will result in an estimated technology readiness level (see Section 2.2.2), with identified risks and sources of uncertainty. The uncertainty is determined based on how many evaluation questions cannot be answered due to lack of information. Results from the detailed evaluation should be considered collectively based on systematic scoring (Section 2.3).

Step 3-5: **Incubate, pilot, deploy**, or reject (post-framework) the material based on the readiness level. Results from the detailed evaluation will guide what areas need further testing, analysis, or modeling in the next phase (see Table 1 for suggestions).

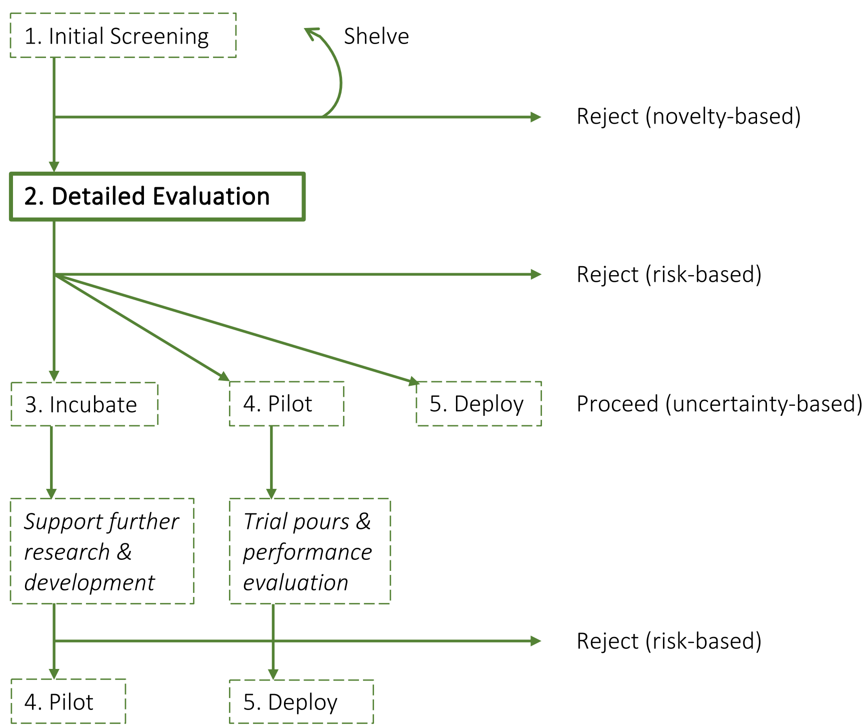

***Figure 1**: Flow chart illustrating the suggested workflow.*
The evaluation framework is applied in Step 2.

Table 1 summarizes suggested action items and data/information needed for Steps 3–5. These steps are based on the Lab2Slab2Practice process for novel concrete testing developed at the University of California Davis, summarized in Nassiri et al. [12]. This framework mainly supports identifying products suitable for incubation or piloting. Products already ready for deployment will likely be identified in the initial screening.

Action:	**A. Development***	**B. Incubate**	**C. Pilot**
Readiness level	TRL 3–4	TRL 5–6	TRL 7–8
Goal ([12])	Produce data to demonstrate the product's potential to funders and early adopters	Generate better data and fill information gaps, produce reports, training materials, test methods, demonstrate the product's viability for piloting	Gather information and data needed to develop/alter specifications and design codes, and develop requisite training documents for product's installation and use
Stage actions ([12])	A1. Basic properties identified and tested A2. Initial life cycle assessment A3. Cost estimates A4. Scalability	B1. Scale up production B2. Test basic properties at larger scale (e.g., slab pour) B3. Pour three test applications and perform A2–A4 at larger scale B4. Perform tests under different climate conditions	C1. Use the material in a pilot project C2. Perform all tests again at pilot scale C3. Produce an Environmental Product Declaration

Table 1: *Explanation of the pre- and post-framework action steps for material/product development.*
**pre-framework application. TRL = Technology Readiness Level (see Section 2.2.2)*

2.1.1 Detailed evaluation format

Evaluation questions pertaining to material performance, environmental impacts, and feasibility are answered with one of three predefined risk scenarios that best aligns with the available information. These risk scenarios are formulated to highlight challenges to overcome before a product may be mature for deployment. Evaluation questions marked red indicate 'red flags', i.e., if high risk is selected, the product should be rejected. Figure 2 provides an example evaluation question and risk categories.

Figure 3 shows the evaluator assessment checkboxes. If the information needed to confidently answer a question is unavailable or not provided by the vendor, the evaluator may select "IM/uncertain" (IM: Information Missing). "N/A" may be selected for questions that are not relevant to a particular material or use case, but can only be applied to some specific questions under the Environmental Impacts category.

ENVIRONMENTAL IMPACT					
Adoption Criteria		Explanation of Risks	Risk Level		
			Low	Medium	High
2	Unintended Life Cycle Burdens	*Risks associated with the potential for unforeseen unintended side effects even with lower GHG emissions than reference product (e.g., generation of hazardous waste); or unintended consequences from production, transport, or use of the product in the absence of sufficient controls.*	The product demonstrates lower or similar non-GHG emissions environmental impacts than the representative reference (the conventional product on the market that would otherwise be used). The product or the production technology has minimal inherent environmental burdens or hazardous risk.	The product demonstrates lower GHG emissions than a representative reference but has potential for environmental degradation and/or can generate hazardous waste or cause other burdens, but the risks can be managed through current processes and/or anticipated future processes or solutions.	The product has potential to create significant environmental degradation or increase other emissions or is associated with other environmental burdens over currently fielded solutions.

***Figure 2**: Example of evaluation question with explanation of risks and definitions of the three risk scenarios. GHG = greenhouse gas emissions.*

Select the box that best corresponds with the provided information about the product				
Risk Level Assessment				
Low	**Medium**	**High**	**IM/uncertain**	**N/A**

***Figure 3:** Risk level assessment.*

The evaluator assigns a level that best applies to the product being evaluated. Blue box indicates selectable alternatives, and gray indicates that N/A is not an option for this specific evaluation question. IM = Information Missing, N/A = Not Applicable

2.2 Critical Considerations

2.2.1 Supporting documents and information

To conduct a comprehensive assessment of a novel cement or concrete material, key information must be provided by the vendor. This includes technical data (e.g., material test results), environmental impact documentation, cost estimates, and market strategies. The information should be sufficient to support both the initial screening (Figure 1: Step 1) and this framework's more detailed evaluation (Figure 1: Step 2). The certainty in the detailed evaluation is based on the amount of information provided. Table 2 lists the types of documentation that should be requested.

Test results	**Environmental impacts**	**Feasibility and scalability**
Material characteristics and compositions (fineness, etc.) Test results data on relevant fresh, mechanical, and durability properties (from multiple tests and batches) Testing details (duration, environmental conditions, etc.) Mixture proportions tested (binder content, admixture content, water-to-cement ratio, etc.) Curing methods ASTM standards used in testing, and any alterations made	Third-party verified EPD (if available) LCA report (if EPD not available): • Functional unit and system boundaries used • Modeling assumptions • Inventory data sources and information about background data used • Impact assessment method • Data quality/uncertainty assessment • Results from sensitivity analysis	TRL/ARL self-assessment Manufacturing and supply chain • Estimate of raw material availability and sourcing (geographical, temporal, etc.) • Description of production scalability, including any potential constraints • Description of relevant infrastructure and transportation requirements, including any potential constraints Market and regulatory strategy • Evaluation of whether and how the product aligns with current codes and standards • Description of whether and how the product aligns with current practice Economy and business • Cost estimate (delivered) per unit material • Cost estimate (life cycle) per unit material • Capital investments needed for scaling • Strategy for market entry

Table 2*: Suggested documentation needed for the detailed evaluation.*

TRL = Technology Readiness Level; ARL = Adoption Readiness Level; LCA = Life Cycle Assessment; EPD = Environmental Product Declaration

2.2.2 Technology Readiness Level

Existing frameworks such as the Technology Readiness Level (TRL) by National Aeronautics and Space Administration (NASA) [13] and the Adoption Readiness Level (ARL) by the US Department of Energy (DOE) [14] are commonly used to evaluate how mature a product is for real-world use. The TRL framework presents a scale from TRL 1 to TRL 9, where TRL 1 is a "concept" level and TRL 9 full scale deployment or commercialization. The ARL framework addresses challenges related to the market, regulations, and adoption to evaluate how ready a technology is for commercialization. ARL evaluates the TRL and market readiness concurrently, to determine if the technology is at the "research", "development", "demonstration", or "deployment" stage of commercialization. The ARL framework is intended to identify risks related to a product or technology's functional performance and cost, market acceptance and size, production and resource maturity, and other concerns such as potential regulatory constraints.

The detailed evaluation framework presented in this work is based on these concepts but specifically targets the cement and concrete industry and addresses challenges associated with adaptation within current industry practice. Examples of challenges and considerations specific to the cement and concrete industry are described in Appendix A (presented as motivations to each detailed evaluation question).

2.2.3 Environmental Impacts

Quantifying environmental impacts from construction materials widely relies on the life cycle assessment (LCA) methodology [15]. LCA is a broadly accepted framework to quantify potential environmental impacts from a product or system's life cycle, including cement and concrete [16]. This methodology is used to generate Environmental Product Declarations (EPDs), the primary type of documentation used in green procurement that communicates cradle-to-gate (i.e., production) environmental impacts [17]. Current applications of LCA have major limitations, including limited and incomplete scope of analysis, data gaps, and not accounting for functional performance [18]. These are crucial considerations, as incomplete scope may leave out critical sources of emissions, lack of data may lead to inaccurate assessments, and altered material performance may cause increased environmental impacts (e.g., if more material is needed to obtain the desired performance compared to conventional materials). Additionally, inconsistencies between approaches used by different practitioners could limit the ability to directly compare products.

2.2.4 Material Performance

It is necessary to consider characteristics that can influence the engineering and environmental performance of concrete concurrently. The use of SCMs is a cost efficient, relatively simple approach to reducing the GHG emissions from concrete, while often also enhancing the engineering performance [10]. Alternative SCMs are emerging as a consequence of increased demand for low-carbon concrete materials paired with reduced availability of commonly used SCMs, such as fly ash and slag [10]. These materials must meet critical performance requirements to ensure public safety and long-term reliability. Ultimately, successful adoption requires acceptance from key stakeholders such as contractors, owners, and engineers, which is often tied to factors such as familiarity with the product and confidence in the material's performance.

2.2.5 Feasibility

The engineering performance of alternative materials must be thoroughly evaluated, along with considerations of supply chain resilience, scalability, and constructability [19]. Assessing the risks associated with novel technologies is critical to avoid safety issues, challenges during implementation, and unexpected costs [12]. Adoption also depends on several practical factors, including regional material availability, compatibility with local aggregates, storage and logistics constraints, existing infrastructure, and compliance with current regulations. The use of new materials must also work within typical construction schedules and ideally with standard equipment.

2.2.6 Uncertainty vs Risk in Evaluation of Novel Materials

A common challenge in evaluating emerging technologies or materials is the lack of representative and reliable data, or the absence of data. Data gaps can be caused by limited transparency, or the product being at such an early stage of development that data do not yet exist for robust considerations of factors like its life cycle environmental footprint and long-term engineering performance. As such, this evaluation framework emphasizes the importance of assessing both known and unknown factors. It also aims to identify key information and data gaps that should be addressed during incubation or piloting phases.

Considering uncertainty helps determine the level of support needed and the categorization of a novel cementitious material into the incubation, piloting, or deployment readiness stage (see suggested uncertainty levels in Figure 4). Here, uncertainty refers to the availability, accuracy, and reliability of data, such as material properties, test results, and environmental impact assessments. Incubation is recommended for products with substantial data gaps or unverified performance; these tend to be early-stage materials with high uncertainty due to limited validation or documentation. Piloting is suitable for materials with a stronger evidence base and limited unknowns. Deployment is for materials that demonstrate low uncertainty with minimal information gaps.

Risk assessment performed in parallel is crucial to prevent costly or unsafe outcomes. While uncertainty relates to missing or incomplete information, risk refers to the potential for negative consequences, such as structural failures, unexpected cost, or environmental damage, as well as their likelihood and magnitude (see Figure 5). Given the construction industry's risk-averse nature, it heavily relies on codes and material standards to ensure safety, and these regulatory documents are slow to change and adapt to new materials [20]. However, many building codes allow for material piloting under controlled conditions, provided agreements are made in engineering contracts [21]. Hence, a comprehensive risk evaluation, primarily focusing on engineering performance, is essential for a material's path to adoption. Novel materials able to conform to existing test methods and regulatory frameworks are more likely to succeed at faster adoption. Performance-based risks, such as those related to constructability, durability, scalability, environmental impacts, or life cycle costs, can be mitigated through robust testing and validation. For example, the Lab2Slab2Practice framework [12] offers a systematic approach to mitigate risk in innovation and adoption, supporting the transition of novel concrete materials from lab-scale to real-world application.

Risks associated with environmental burdens from alternative concrete-making materials are not covered by industry standards and codes and must be assessed through LCAs. It is critical that environmental impacts beyond GHG emissions are quantified over the product's life cycle to avoid unintended environmental burdens, such as the generation of hazardous waste, increased local burdens like air pollution, or harm to ecosystems from toxic substances.

Risks associated with feasibility are mainly related to financial loss, inadequate production capacity, supply chain barriers and resource shortage, or market acceptance [14]. For a product to proceed from research and development to commercialization, it must overcome several "valleys of death". These are common points where a novel material might fail even though they are proven to work under, for example, laboratory conditions. Challenges to overcome include demonstrating performance at scale, scaling the product to meet demand over a broad geographical region, compliance with existing standards, permitting for production, integration into existing supply chains, or lack of funding or market demand.

Uncertainty Level	**Explanation of uncertainty levels**	**Can trigger:**
Low	*The material performance, environmental impacts, and feasibility have been validated over time and demonstrate low variability for the intended application.*	Deploy
Moderate	*The product needs long-term testing under real-world conditions to verify its performance and viability; the product has potential to be scaled.* *Significant carbon reductions can be achieved but need verification.*	Pilot
High	*Not all critical performance criteria have been tested/evaluated, and/or some results show non-superior performance/ease of use and implementation compared to conventional materials or needs modification.* *More detailed LCA is needed to verify or provide pathways to improve its environmental performance.*	Incubate/shelve

Figure 4: *Explanation of uncertainty levels and relationship to readiness levels.*

Note: a product should only proceed to deployment or piloting if the overall risk is low (see Figure 5).

Risk Level	Explanation of risk levels	Can trigger:
Low	*Relevant performance criteria have been tested and validated over sufficient time, and the results show equal or superior performance/ease of use and implementation with low variability.* *The product can be produced at scale within current industry practice, or with minimum modification.* *High likelihood of lowering GHG emissions and no significant other environmental burdens associated with the product.*	Pilot/Deploy
Moderate	*The product shows variability in material performance, or not all relevant performance characteristics are equal or superior to conventional.* *High likelihood of lowering GHG emissions, but risk of increased other environmental burdens that can be mitigated/minimized.* *Modifications are needed to current practice/standards/codes.*	Incubate
High	*The material performance is poorer than conventional or does not meet minimum requirements per current codes and standards.* *High likelihood of lowering GHG emissions, but risk of increased other environmental burdens that are hard to mitigate/minimize.* *The cost and scalability are not sufficient long-term.* *The product does not work within current practice/standards/codes.*	Reject

Figure 5: *Explanation of suggested risk levels and relationship to readiness levels.*

2.3 Systematic Scoring

Once evaluation questions are completed, the number of Low, Medium, High, N/A, and IM responses are counted and used to place the product into a risk and uncertainty category (see Figures 6 and 7). These determine whether the product should be rejected, incubated, piloted, or deployed.

Uncertainty reflects gaps in information and helps determine if further research and development is needed. An example of ranges determining each uncertainty level is presented below. These ranges can be modified based on user requirements.

Uncertainty	**Information missing for evaluation**
Low	<20% of evaluation questions
Medium	20–40% of evaluation questions
High	>40% of evaluation questions

Risk reflects known concerns around feasibility, safety, and performance.

Based on the score obtained in the risk assessment (suggested scoring ranges shown in Figure 6), the material is paired with the level of uncertainty (i.e., the number of evaluation questions that could not be answered due to lack of data or information). Figure 7 shows suggested categorization based on the overall results from the uncertainty and risk level assessments of environmental impacts, material performance, and feasibility.

It is recommended that a Data Quality Analysis [22] is performed along with the evaluation, if enough data are provided to perform such an assessment.

Evaluation category									
Readiness Level	*High* risk counts								
Medium risk counts	0	1	2	3	4	5	6	7	8
0	9	8	7	6	5	4	3	2	1
1	8	7	6	5	4	3	2	1	1
2	8	7	6	4	4	2	1	1	1
3	7	6	5	4	3	1	1	1	1
4	7	6	4	3	2	1	1	1	1
5	6	5	4	2	1	1	1	1	1
6	6	4	3	1	1	1	1	1	1
7	5	4	2	1	1	1	1	1	1
8	4	3	1	1	1	1	1	1	1

Figure 6: *Example: Risk score and readiness level matrix, based on counts of 'Medium' and 'High' risks.*

These ranges can be modified based on user requirements. Green zone: low overall risk (high readiness level), yellow zone: medium overall risk (medium readiness level), and red zone: high overall risk (low readiness level). See Figures 8–10 for examples.

Risk	Uncertainty	Readiness	Action
Moderate-to-high	High	<4	Shelve or reject
Low-to-moderate	High-to-moderate	5-6	Incubate
Low	Low-to-moderate	7-8	Pilot
Low	Low	9	Deploy

Figure 7: *Suggested uncertainty, risk, and readiness categorization of a novel material.*

Lower risk indicates higher readiness level (see Figure 11 for case study example). Green zone: pilot/deploy, yellow zone: incubate, and red zone: shelve or reject. The readiness levels are based on [12]

3. Case study

3.1 Limestone Calcines Clay Cement

Limestone calcined clay cement (LC3) is an alternative blended cement developed at the Swiss Federal Technology Institute of Lausanne (EPFL). While ratios can vary, an expected low-emissions LC3 is composed of 15% limestone, 30% calcined clay, 5% gypsum, and 50% clinker [23]. Calcination is involved in the production of both clinker and calcined clay used in LC3, but for the latter, a lower calcination temperature is needed, and negligible processing-CO_2 emissions are released. As a result of intergrinding this lower-emissions product and limestone to reduce clinker content, LC3 production is estimated to release approximately 30% less CO_2 emissions than conventional Portland cement (PC) [24]. The development of LC3 started with a three-year phase where the technical feasibility was demonstrated, followed by a phase focusing on market preparation and implementation, and policy outreach. The product has been adopted in the European market, as well as in other regions including India and Cuba. This assessment is conducted considering feasibility for adoption in the US market, and is based on documents from the LC3 project [23], published experimental studies, and LCAs from the literature.

3.1.1 Environmental impacts

There is currently no EPD developed for LC3. Based on a review of available literature, studies performed on LC3 in Morocco [25], Australia [26], India [27], [28], and Europe [29] have demonstrated a reduced environmental impact compared to conventional PC. While there is no LCA study on LC3 produced in the US, a case study on theoretical production of a blended cement consisting of 35% calcined clay, 15% limestone, and 50% PC in California demonstrated the potential to reduce GHG emissions by 36–39% compared to PC [30]. Similar results were demonstrated by Kim and Miller [31], showing that LC3 can reduce 40% GHG emissions compared to the California baseline PC. LC3 also showed decrease in other emissions, water consumption, and energy demand. The California-based study by Martinez et al. [30] is used herein for the evaluation of the environmental impacts. Their goal was to estimate the cradle-to-gate environmental impacts from producing metakaolin, using as locally specific parameters as possible. The authors performed a data uncertainty assessment, following the Pedigree Matrix Approach [22]. Table 3 presents the score for each evaluation question in the Environmental Impact category. Figure 8 shows a readiness score based on the risk counts. Note: evaluation question 7 and 10–12 are N/A (see Appendix A).

EQ	Environmental Impacts	Risk Level	Motivation
1	Environmental Product Declaration (EPD)	Medium	No EPD, but a California-based LCA study demonstrating reduced impact compared to PC.
2	Unintended Life Cycle Burdens	Low	Other emissions (NOx, SOx, PM2.5, PM10, VOC, CO, Pb), water consumption, and energy demand have been demonstrated lower than for PC.
3	Assessment Scope and Representativeness	Low	Scope similar to PC production, and differences are clearly considered.
4	Life Cycle Inventory Data	Medium	Reliability (2), completeness (2), temporal (3), geographical (3), and further technological correlation (4). On a scale 1–5, where lower score indicates lower uncertainty.
5	Environmental Impact Variability and Sensitivity	Low	Sensitivity analysis has been performed and shows low variability.
6	Life Cycle Completeness	High	Only a cradle-to-gate assessment has been conducted.
8	End-of-Life Management	IM	
9	Alternative Cements Produced Similarly to PC (clinkered)	Low	It is known that the energy demand is lower and can be achieved by minor modification to existing kilns.

Table 3: *Identified risk levels for the environmental impacts associated with LC3.*

Evaluation based on: [30], [31]

Environmental impacts

Readiness Level	*High* risk counts 0	1	2	3	4	5	6	7	8
Medium risk counts 0	9	8	7	6	5	4	3	2	1
1	8	7	6	5	4	3	2	1	1
2	8	**7**	6	4	4	2	1	1	1
3	7	6	5	4	3	1	1	1	1
4	7	6	4	3	2	1	1	1	1
5	6	5	4	2	1	1	1	1	1
6	6	4	3	1	1	1	1	1	1
7	5	4	2	1	1	1	1	1	1
8	4	3	1	1	1	1	1	1	1

Figure 8: *Environmental impacts risk score and readiness level of LC3.*
With two medium and one high risk counts, the environmental impacts category demonstrates low risk, and a readiness level of 7.

<u>Readiness level for environmental impact</u>: 7

<u>Uncertainty</u>: Low (one IM count)

Conclusion: LC3 has potential to be produced with reduced GHG emissions compared to PC in the US. The cradle-to-gate environmental impacts are dependent on kiln technology and fuels used to generate thermal energy. A third-party verified EPD for the production of LC3 in the US needs to be generated. The Product Category Rule [32] for PC does not directly apply to LC3 but is sufficient (it covers blended cement per ASTM C595 [33] but not Class N natural pozzolans per ASTM C618 [34]). A US-specific life cycle inventory needs to be developed, and the full life cycle (cradle-to-grave) needs to be modeled. The main source of uncertainty is the end-of-life management of LC3 concrete, which should be investigated.

3.1.2 Material Performance

LC3, like other calcined clays, is a well-studied materials in the literature, and extensive research has demonstrated its properties and engineering performance [35], [36], [37], [38], [39]. LC3 has been piloted and used on projects in several countries. Enough information is available to perform the risk assessment and determine the material performance readiness level, hence, the uncertainty is low (no IM counts). Table 4 shows the results for each evaluation question, and Figure 9 shows the risk level score based on the medium and high risk counts.

EQ	Material Performance	Risk Level	Motivation
1	Functional Performance	Low	LC3 has been demonstrated to obtain comparable performance to PC.
2	Testing and Performance Verification	Low	Extensive testing in various conditions and over longer durations have demonstrated satisfactory performance.
3	Code and Standards Compliance	Medium	Complies with ASTM C595 (blended hydraulic cements) and the calcined clay can be classified as Class N (natural pozzolan) per ASTM C618, but there is no standard for LC3.
4	Mixture Design and Proportions	Low	It is well known how LC3 influences concrete properties, and how to obtain desired performance.
5	Fresh and Transitional Properties	Low	Minor need for additional measures.
6	Mechanical Properties	Low	Overall, equal or better performance than PC concrete.
7	Long-term and Durability Properties	Medium	LC3 has been tested long-term in the field, but some durability properties are yet to be verified, e.g. freeze–thaw, and some are inferior to PC.

Table 4: *Identified risk levels for the material performance of LC3.*

Evaluation based on: [35], [36], [37], [38], [39], [40], [41], [42]

Material performance

Readiness Level		*High* risk counts								
		0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Medium risk counts	**0**	9	8	7	6	5	4	3	2	1
	1	8	7	6	5	4	3	2	1	1
	2	**8**	7	6	4	4	2	1	1	1
	3	7	6	5	4	3	1	1	1	1
	4	7	6	4	3	2	1	1	1	1
	5	6	5	4	2	1	1	1	1	1
	6	6	4	3	1	1	1	1	1	1
	7	5	4	2	1	1	1	1	1	1
	8	4	3	1	1	1	1	1	1	1

Figure 9: *Material performance risk score and readiness level for LC3.*

With two medium risk counts, the material performance demonstrates low risk and a readiness level of 8.

<u>Readiness level for material performance</u>: 8

<u>Uncertainty</u>: Low (no IM counts)

Conclusion: Based on available research, LC3 shows low risk for all evaluation questions except two: 'code and standards compliance' and 'long-term and durability properties'. Because of the extent of research performed on LC3, the uncertainty of its performance is low. LC3 partially conforms with current standards (ASTM C595 *Standard Specification for Blended Cements* [33] and ASTM C618 *Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete* [34]). However, long-term testing is still needed on LC3's performance in cold climates, to evaluate its resistance to freeze–thaw [35], [43], [44]. Tests have also shown that LC3 concrete has lower carbonation resistance than PC concrete, potentially increasing its corrosion risk when used in reinforced concrete [45], [46]. However, it has been argued that the lower permeability of LC3 concrete compensates for this and, thus, can provide sufficient resistance to corrosion [24]. It has also been identified that the performance of LC3 under high-temperature needs to be investigated [35].

3.1.3 Feasibility

The economic and technical feasibility of LC3 compared to PC has been demonstrated [24], [35], [47], [48]. A pilot project in India demonstrated that LC3 can be used and is economically viable for a two-story reinforced concrete building, without any need for specialized labor or methods for construction or production [37]. LC3 can be produced with low-grade kaolin clay, which can be obtained from quarries mining high-grade kaolin clay [23], [41]. In the US, kaolin clays are available primarily in the southeast, as well as the Sierra Nevada mountains in California and the southern parts of Oregon [49]. Current kaolin mining operations in the US include multiple locations in Georgia, Alabama, and South Carolina, as well as two in Tennessee and one in each state of Florida, Texas, Arkansas, Nevada, and California [50].

Because ready-mixed concrete producers generally prefer to add SCMs in the concrete mixture to replace cement, as opposed to using blended cements, use of type IL cement (Portland limestone cement) and calcined clay (metakaolin) instead of a product of these same fundamental constituents blended (i.e., LC3) is easier to use as it complies with specifications and is therefore easier to adopt [51]. Additionally, mixing the calcined clay with concrete at the ready-mix plant may reduce transportation distance and cost, as the clay would not need to be transported to the cement plant first. Enough information is available to perform the risk assessment and determine the feasibility readiness level, so the uncertainty is low. Table 5 and Figure 10 show results and scoring.

EQ	Feasibility	Risk Level	Motivation
1	Delivered Cost	Low	No risk associated with market swings has been identified.
2	Ease of Use/Complexity	Low	Works with current equipment and on-site infrastructure.
3	Market Size	Low	At scale, LC3 has the potential to compete strongly and broadly on the market.
4	Infrastructure	Medium	The US currently lacks the infrastructure to produce LC3 at scale, and kaolin clay is not available all over the US.
5	Manufacturing and Supply Chain	Medium	Minor adjustments are required to produce calcined clay using existing kiln technology. Clinker, limestone, and gypsum are already available at cement plants, but supply chains for low-grade kaolin clay are yet to be established.
6	Materials Sourcing	Medium	Low-grade clays do not compete with other industries and can be sourced from some existing mines. Kaolin clay mines are concentrated in southeastern US, with some on the west coast. Processing is needed to make the clays viable for use in concrete. These clays are considered waste at some mines.
7	Workforce	Medium	Minor adjustment needed, some training required for mixing and production, as well as educating engineers.
8	Policy Environment	Medium	Currently not enough incentives in terms of carbon credits/taxes at national level to invest in calcined clay or LC3 production.
9	Permitting and Siting	High	The permitting process for opening new mines is complicated and heavily regulated. However, kaolin (low-grade) clay can be obtained from some existing mines.
10	Safety	Low	No safety risks or concerns have been highlighted

Table 5: *Identified risk levels for the feasibility of LC3 market adoption.*

Evaluation based on:[24], [35], [40], [42], [50], [52], [53], [54], [55], [56]

Feasibility

Readiness Level		*High* risk counts								
		0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Medium risk counts	**0**	9	8	7	6	5	4	3	2	1
	1	8	7	6	5	4	3	2	1	1
	2	8	7	6	4	4	2	1	1	1
	3	7	6	5	4	3	1	1	1	1
	4	7	6	4	3	2	1	1	1	1
	5	6	**5**	4	2	1	1	1	1	1
	6	6	4	3	1	1	1	1	1	1
	7	5	4	2	1	1	1	1	1	1
	8	4	3	1	1	1	1	1	1	1

Figure 10: *Feasibility risk score and readiness level for LC3.*

With 5 medium risk counts and one high count, the material performance demonstrates medium risk and a readiness level of 5.

Readiness level for feasibility: 5

Uncertainty: Low (no IM counts)

Conclusion: The barriers to practical implementation of LC3 in the US mainly stem from the need to establish required permitting for use of low-kaolin clays, establish the needed infrastructure and supply chains, and train the workforce. Further, initial investment to make adjustment to existing kilns and incentives such as through policy mechanisms are necessary.

3.1.4 Scoring and next steps

Figure 11 presents the overall scoring of LC3, which suggests it can proceed to Piloting with a primary focus on challenges related to feasibility. Pathways to scaling up production should be identified, starting with the supply of low-grade kaolin clay. Additionally, gaps related to environmental impacts can be filled by establishing better data for LCA modeling, cradle-to-grave assessment and analyzing end-of-life pathways for LC3 concrete. Material testing should focus on long-term performance, especially in cold conditions, and on collecting data needed to inform standards and materials to educate stakeholders (such as engineers and contractors) on the properties of LC3 concrete.

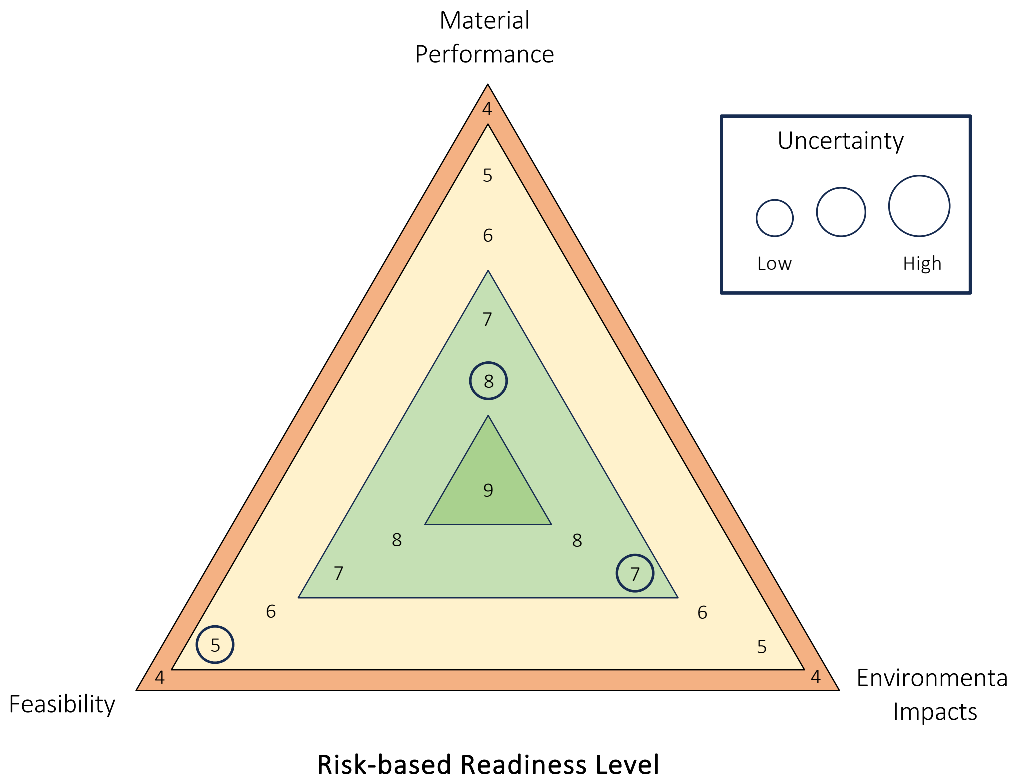

Figure 11: *Risk-based readiness for each evaluation category.*
Uncertainty indicated by the size of the circles. See Figure 7 for recommended outcome based on color.

4. Conclusions

This framework evaluates the risk and readiness levels of novel low-carbon cement and concrete technologies using critical considerations such as life cycle environmental impacts, material performance, and feasibility for industry adoption. It identifies risks (e.g., safety concerns, scalability, unintended environmental burdens) as well as information gaps that need to be filled, through incubation or piloting, before the product can become ready for deployment. Robust evaluation of novel materials and technologies is essential for successful market implementation. Application of this framework can support the identification of products with the potential to significantly reduce GHG emissions from cement and concrete. Adoption of emerging low-carbon or net-zero materials in data center construction can have a significant impact on both the advancement and innovation of the construction industry, as well as the future environmental impact contribution from large scale digitalization.

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APPENDIX A: Detailed Evaluation Supporting Document

Abbreviations

ACI	American Concrete Institute
AMC	Advance market commitment
ARL	Adoption readiness level
CCSC	Carbonated calcium silicate cement
CCUS	Carbon capture utilization and storage
CSA	Calcium sulfoaluminate
EoL	End-of-life
EPD	Environmental product declaration
FHWA	Federal Highway Administration
GHG	Greenhouse gas
IRL	Investor readiness level
LCA	Life cycle assessment
LCI	Life cycle inventory
NREL	National Renewable Energy Laboratory
PBS	Performance-based specification
PC	Portland cement
PCR	Product category rule
PLC	Portland limestone cement
PPE	Personal protective equipment
SDS	Safety data sheets
SCMs	Supplementary cementitious materials
TRL	Technology readiness level

List of ASTM Standards referred to in this Appendix

- ASTM C150 *Standard Specification for Portland Cement*
- ASTM C618 *Standard Specification for Coal Ash and Raw or Calcined Natural Pozzolan for Use in Concrete*
- ASTM C989 *Standard Specification for Slag Cement for Use in Concrete and Mortars*
- ASTM C1240 *Specification for Silica Fume for Use in Hydraulic Cement Concrete and Mortar*
- ASTM C1866 *Standard Specification for Ground-Glass Pozzolan for Use in Concrete*
- ASTM C1157 *Standard Performance Specification for Hydraulic Cement*
- ASTM C1709 *Standard for Evaluation of Alternative Supplementary Cementitious Materials (ASCM) for Use in Concrete*
- ASTM C595 *Standard Specification for Blended Hydraulic Cement*
- ASTM C1698 *Standard Test Method for Autogenous Strain of Cement Paste and Mortar*
- ASTM C191 *Standard Test Methods for Time of Setting of Hydraulic Cement by Vicat Needle*
- ASTM C494 *Standard Specification for Chemical Admixtures for Concrete*
- ASTM C1012 *Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution*

Definitions

- Conventional cement: Traditionally produced PC
- Conventional concrete: Concrete produced with Portland cement (no SCMs) and other traditional concrete constituents to achieve desired properties
- Conventional SCMs: Fly ash and granulated blast furnace slag (broadly accepted by the industry, and have established ASTM standards (ASTM C618 and ASTM C989)
- Conventional product: Conventional cement or concrete product
- Alternative cement: An inorganic cement that can be used as a complete replacement for PC or blended hydraulic cements, and that is not covered by applicable specifications for PC or blended hydraulic cements, as defined by ACI [19]
- Alternative SCMs: Inorganic materials that react pozzolanically or hydraulically and that beneficially contribute to strength, durability, and workability or other characteristics of concrete. ASCMs are not within the scope of current specifications: ASTM C618, ASTM C989, ASTM C1240, and ASTM C1866.

This Appendix outlines backgrounds and explanations of potential barriers associated with successful industry adoption that have guided the development of the detailed evaluation questions.

Environmental Impacts

Novel materials often lack robust life cycle inventory (LCI) data. Assumptions, particularly regarding factors like energy consumption, are commonly made and introduce a high degree of uncertainty. In the evaluation of a product's environmental impacts, variability is a critical consideration, especially regarding how sensitive the environmental impacts are to key factors such as the carbon intensity of the electricity grid or transportation distances.

The Environmental Impacts category consists of 12 evaluation questions, 6 of which are more specialized and may not be applicable to all novel materials or technologies. The primary questions focus on identifying risks and uncertainties in how the LCA is conducted and how the methodology is applied.

As part of the initial screening, a third-party verified EPD or equivalent LCA report must be submitted, documenting the product's cradle-to-gate environmental impacts (see Figure 1). For novel materials or technologies that deviate significantly from conventional cement or manufacturing practices, the standard guidelines for cement or concrete may not apply directly. In such cases, attention must be paid to how and what alternative processes have been accounted for and modeled.

Questions 2–6 assume that an EPD or LCA report has been shared. Additional information might need to be requested, as EPDs typically do not include information such as LCI data.

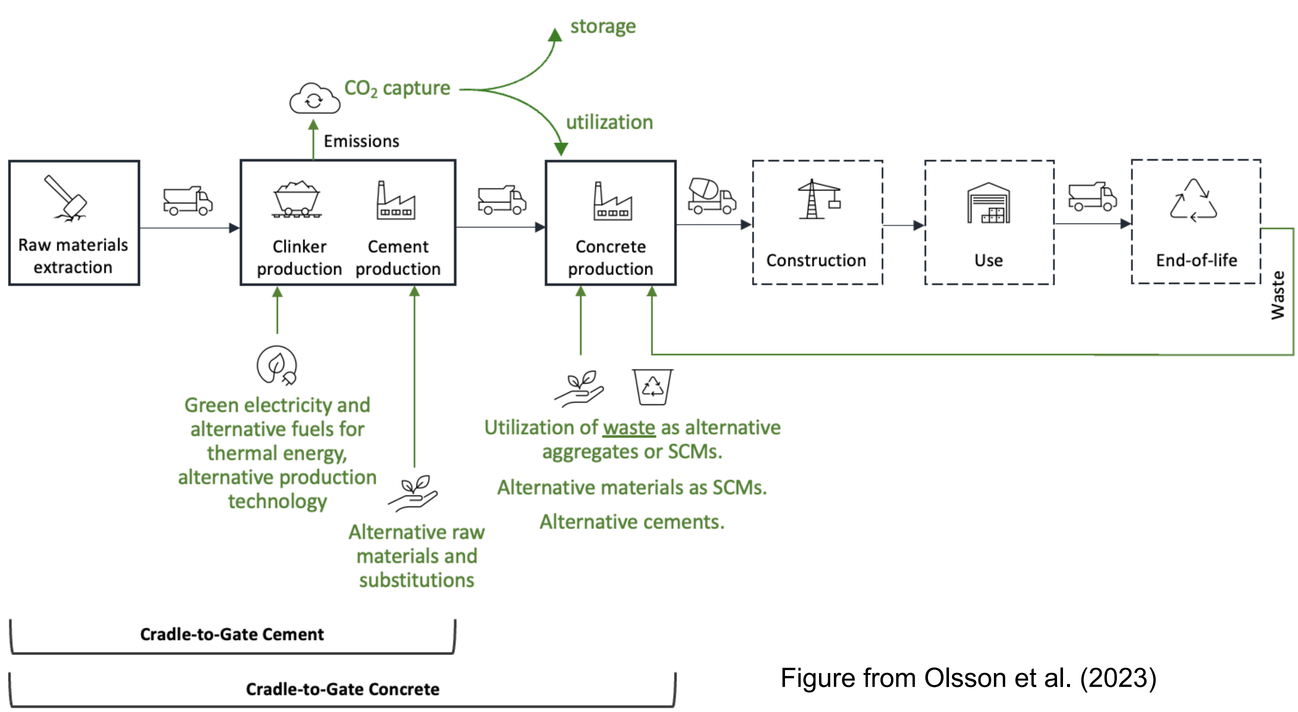

Figure 1: *Cradle-to-gate scope for cement and concrete with mitigation strategies at various stages.*

EI1: Environmental Product Declaration (EPD)

EPDs are third-party verified documents developed according to Product Category Rules (PCRs). PCRs are standardized guidelines for conducting LCAs of specific product categories, such as cement [32] or concrete [57]. PCRs aim to ensure consistency and comparability across products within the same category. EPDs are primarily used to communicate cradle-to-gate environmental impacts, often for procurement purposes.

The cement PCR covers a wide range of cement types, including PC, PLC, blended hydraulic cements, performance-based cements (ASTM C1157-compliant), masonry cements, mortar, and oil well cements [32]. To qualify for inclusion in the EC3 EPD database by Building Transparency, certain requirements must be met, e.g., the production facility must have been in continuous operation for at least one year [40].

If a third-party verified EPD exists for a novel material and is based on a relevant PCR, the product's environmental impact data can generally be considered accurate and suitable for comparison with conventional materials within the same category, and is thus **low risk**. However, if the EPD is based on a PCR that is only partially relevant or not fully aligned with the novel material's properties or production process, or if a third-party verified LCA is provided following international standards (ISO 14040, 14044), this would be considered a **medium level of risk**. In cases where no third-party verified EPD exists and environmental impacts are instead derived from unverified LCA reports or other documentation, the risk is considered **high** due to the potential for lower accuracy, representativeness, and comparability with conventional products or materials.

EI2: Unintended Life Cycle Burdens (red flag)

While the primary objective of using novel materials is to reduce GHG emissions and support decarbonization goals, it is equally important to assess potential unintended environmental impacts associated with their production. Therefore, any LCA must include a comprehensive evaluation of other environmental burden categories to ensure that reductions in GHG emissions do not come at the cost of increased harm elsewhere. These unintended impacts can arise from various stages, including raw material extraction, manufacturing, transportation, use, or end-of-life management.

If it can be demonstrated with high confidence that the material achieves GHG emissions reductions without an increase in any of the identified impact categories (listed below), the product is considered **low risk**. If some increase is observed but a clear mitigation strategy exists, the product may be classified as **medium risk**. However, if there is a significant increase in impact categories and no feasible mitigation plan is in place, the product is deemed **high risk** and should be rejected.

List of environmental impact categories and other environmental risks to pay attention to:

- Acidification*
- Eutrophication*
- Freshwater ecotoxicity*
- Global warming*
- Human health (cancer)*
- Human health (non-cancer)*
- Human health (particulate matter)*
- Ozone depletion*

- Smog formation*
- Water consumption and withdrawal
- Energy consumption (may be an issue depending on the energy source)
- Hazardous waste
- Land use

** TRACI 2.1 impact categories [58]*

EI3: Assessment Scope and Representativeness

Evaluating the overall quality and robustness of an LCA is essential to identify potential bias or misleading conclusions. For novel materials and technologies, system boundaries may not be well established, particularly if no applicable PCRs exist. As a result, determining which processes to include or exclude in the LCA can be unclear, yet this has a significant influence on the results.

Novel materials typically involve different production processes, and material and energy flows compared to conventional PC. See Figure 2 for cement production processes. For example, AAMs use alternative input materials and production methods. Similarly, companies like Sublime Systems [59] employ fundamentally different manufacturing technologies than PC [60], which introduces unique process flows that must be modeled appropriately. In cases where all process data are not yet available at scale, reasonable assumptions may be required and must be clearly stated and justified.

A product is considered **low risk** if the LCA scope is comprehensive and transparent, including all relevant process stages and clear documentation of any excluded flows (e.g., upstream processes with negligible contribution to overall energy demand). If certain assumptions, particularly for not-yet mature technologies or processes, are made without sufficient motivation (e.g., the technology has only been modeled for a fully decarbonized electricity grid), the product is classified as **medium risk**. A **high-risk** rating applies if the LCA omits key material or energy flows without justification, or if the modeling assumptions are unclear or incomplete.

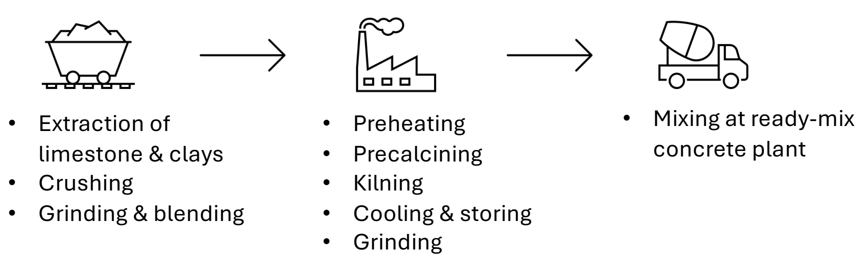

Figure 2: *Cradle-to-gate processes for conventional cement production.*

EI4: Life Cycle Inventory Data

An LCA is only as reliable as the data it uses, and poor or unrepresentative data is a major challenge in cement and concrete assessments [15]. Data that do not reflect actual production conditions can significantly skew results, while missing or inconsistent data contributes to large variations in the quality of LCAs and EPDs [61]. To evaluate data quality, ISO 14040 [62] outlines key checks:

- Completeness: is there enough data to support conclusions?
- Consistency: are methods and data aligned with the goal and scope?
- Sensitivity: how do modeling choices affect outcomes?

High-quality LCAs require data that are technologically, temporally, and geographically representative. Ideally, the LCI relies on primary data, such as energy use and emissions directly measured at cement plants. For novel materials, such data are often unavailable, especially at early development stages. Instead, secondary data from commercial databases may be used, or lab-scale data, though this often lacks representativeness of real conditions.

A product is considered **low risk** if it has high-quality, third-party verified, representative primary data. If some assumptions are required or data have limited representativeness, it is **medium risk**. Poor data quality or lack of representativeness (in the technology, location, or time of production) results in **high risk** due to the uncertainty of the environmental impact assessment.

EI5: Environmental Impact Variability and Sensitivity (red flag)

LCA results are significantly influenced by the sensitivity of input variables such as mixture proportions, transportation distances, and the electricity grid mix. To accurately assess a product's potential to reduce environmental impacts, these variables should be modeled with consideration of uncertainty and variability, producing a range of possible outcomes [63], [64]. The variability can be considered low if the results are consistent and variations in the modeled processes and data show a limited range of potential outcomes [65]. This approach helps identify key "breakeven" limits. For example, the maximum allowable transportation distance or the level of grid decarbonization required to achieve net emissions reductions [18].

A product is considered **low risk** if its environmental impacts show low variability, it has been modeled across a range of plausible scenarios, and it consistently demonstrates favorable results. If some variability exists—such as moderate sensitivity to transportation distances or specific inputs—but overall the impacts remain within an acceptable range, it is considered **medium risk**. If the product's environmental performance fluctuates significantly depending on certain conditions (e.g., only performing better than conventional alternatives when powered by a fully decarbonized grid), it should be considered **high risk**. If no sensitivity or variability analysis has been conducted, the assessment carries high uncertainty and such analysis should be conducted if the product demonstrates favorable or promising performance overall.

EI6: Life Cycle Completeness

While current PCRs require EPDs and LCAs to cover only the cradle-to-gate system boundary, assessing the full life cycle of a product is essential to capture potential long-term environmental impacts. Omitting later life cycle stages—such as construction, use (e.g., maintenance, repair, replacement), and end-of-life (EoL)—can result in an incomplete representation of a product's true environmental burden. Complete life cycle assessment is applicable to final products, i.e., concrete, and not necessarily to binders.

These downstream phases are particularly challenging to assess due to the wide range of applications for concrete and the dependence on specific environmental exposure conditions [66]. In most cases, the LCA practitioner does not know the final use of the material (which is generally the case for binders), making it challenging to model the use phase and EoL activities with confidence. Yet, these stages can significantly influence the total environmental impact. For example, maintenance and reconstruction require additional material production and construction activities [67]; repurposing materials that are not functionally obsolete can reduce demand for new materials [68]; and different EoL scenarios (e.g., landfilling vs. reuse or recycling) can lead to varying levels of emissions and even potential CO_2 uptake [69].

If the product's life cycle has been reasonably modeled, with certainty or assumptions consistent with conventional products, and it is expected to result in lower overall environmental burdens, it can be considered **low risk**. If the product deviates from conventional use or disposal methods, but there is insufficient evidence to quantify the impacts or demonstrate that they are not higher, it is considered **medium risk**. If the product differs significantly from conventional practice and there is a risk of increased impacts during the use or EoL phases, and without mitigation strategies or a supporting analysis, it should be considered **high risk**, and further life cycle assessment is warranted.

EI7: Carbon Flux Modeling

Some novel materials and technologies rely on the uptake or sequestration of CO_2, either before, during, or after their use. However, modeling this uptake must carefully account for the timing of emissions versus sequestration. Although concrete naturally absorbs CO_2 through carbonation—a reaction between cement paste and atmospheric CO_2 under appropriate environmental conditions [67]—the total uptake may be overestimated because the emission and CO_2 uptake do not occur simultaneously [70]. The rate of carbonation is influenced by several factors, including environmental conditions (such as humidity, temperature, and CO_2 concentration), material characteristics (such as chemical reactivity, mass transport of CO_2, mixture composition, and porosity), and geometry (i.e., surface exposure) [71], [72]. Since approximately 90% of CO_2 emissions occur during cement manufacturing, while CO_2 uptake largely takes place during the use phase or EoL (often over several decades) modeling must account for this temporal mismatch [70]. Therefore, carbon flux modeling should encompass the full life cycle and be validated under real-world conditions, not just laboratory settings.

Several CO_2 utilization technologies have emerged to utilize this uptake mechanism by incorporating captured CO_2 from advanced systems such as oxyfuel combustion, post-combustion amine scrubbing, and calcium looping [73]. However, the TRLs for these methods (6, 8, and 7, respectively) indicate that they are not yet suitable for widespread industrial implementation [73], [74], [75]. One approach involves using the captured CO_2 for carbon mineralization during concrete curing; in this process, certain cement compositions react with CO_2 instead of water to solidify. Examples include MgO-based cements and carbonatable silicate cements [76]. For these solutions, it is critical to include upstream environmental impacts, resource availability, and the potential for non-CO_2 environmental burdens in the assessment. The mineral composition of the binder is particularly important, as it directly influences CO_2 uptake capacity and, in some cases, uptake may not offset the emitted CO_2.

To consider a product **low risk**, CO_2 uptake must be demonstrated with robust life cycle modeling, and a reliable supply chain for CO_2 must be established if carbon mineralization is the key mitigation mechanism. A product is considered **medium risk** if CO_2 uptake has only been proven under laboratory conditions and not yet at pilot scale with long-term data. Medium risk also applies if a CO_2 supply chain does not currently exist, but a plausible pathway to its development is outlined. A product is **high risk** if there is no clear demonstration of how CO_2 uptake will be achieved at the proposed scale, or the life cycle CO_2 emissions are not modeled (i.e., it is not demonstrated that the CO_2 uptake is greater than the emissions) or if significant unresolved challenges remain regarding supply chain logistics or other practical implementation barriers.

EI8: End-of-Life Management

Changes to a concrete's composition can significantly affect its EoL potential. While conventional concrete is sometimes suitable for recycling as aggregate in new concrete, alternative mixtures may hinder its suitability for downcycling. As the focus on circularity in the built environment grows, it is increasingly important to identify viable pathways for retaining concrete within a material loop after its use phase, rather than sending it to landfill.

If a clear and practical EoL strategy exists—one that aligns with circularity principles such as eliminating waste and pollution, circulating materials, and supporting ecological regeneration [77]—and no major changes to current infrastructure or practices are required, the material can be considered **low risk**. **Medium risk** applies when modifications to existing systems or practices are necessary, particularly if these changes result in higher energy use or emissions. **High risk** is assigned when no EoL management plan has been developed, when there is no value in reusing or recycling the material, or when landfilling the material could result in increased environmental burdens. If no such assessment has been performed, it should be conducted before further consideration.

EI9: Cements Produced Similarly to PC (clinkered)

Some emerging technologies aim to produce clinkered cements using different raw materials or more energy-efficient processes [19]. These materials are manufactured similarly to PC clinker but may exhibit different chemical or physical properties. Although some can theoretically be produced in conventional kilns at lower calcination temperatures using alternative fuels, existing equipment may not always be compatible with these conditions.

For example, calcium sulfoaluminate (CSA) cement and LC3 can be produced in traditional kilns with lower energy use and reduced CO_2 emissions from limestone calcination [76]. Reactive belite cement also requires lower calcination temperatures, reducing fuel demand [12]. Carbonated calcium silicate cement (CCSC) uses similar raw materials and kiln technologies as PC clinker but operates at lower temperatures [12]. CCSC emits less CO_2 during production and binds CO_2 through carbonation. However, the CO_2 curing step adds energy demand, and curing conditions (e.g., temperature, humidity) may differ from conventional cement, potentially requiring specialized equipment [12]. Additionally, the extraction and processing of alternative raw materials may increase energy or water use. Alternative raw materials may also include carbon negative raw materials, such as biogenic limestone [78].

If current kiln technology can accommodate lower pyroprocessing temperatures without added processing steps that offset energy savings, the product poses **low risk**. A product is further of low risk if benefits such as reduced calcination temperature, use of alternative fuels, or lower energy demands are achievable with existing infrastructure. There is **medium risk** if modifications are needed or if additional processing results in similar or higher energy use, but a path to improved efficiency exists. **High risk** applies if extra processes (e.g., for grinding or curing) could offset benefits, e.g., if energy or electricity demand is significantly increased or if new facilities are needed to realize the benefits.

EI10: Cements Produced Not Similarly to PC (non-clinkered)

Non-clinker cements are produced using alternative technologies and raw materials to create a product similar to conventional cement. For instance, Sublime Systems replaces the kiln with an electrochemical process to extract CaO from limestone, while Brimstone uses calcium-rich silicate rocks instead of limestone to avoid process-related CO_2 emissions. Both produce ASTM C150 classified cements. These processes may reduce or eliminate the need for pyroprocessing, lowering energy use. However, additional steps such as fine grinding may be necessary to achieve comparable performance, potentially increasing overall energy demand.

The main risks of non-clinker cements and binders include higher electricity, or energy demands from added processing, which may increase overall impacts depending on the electricity grid or energy mix. Environmental burdens may also arise from sourcing and processing alternative raw materials. The product is considered **low risk** if the extraction, preparation, and processing of the alternative binder do not increase energy, electricity, or water demand, or increase other environmental impacts. The material is considered **medium risk** if there are increases in energy, electricity, or other environmental impacts, but there is a viable pathway to reduce potential impacts over time, such as cleaner grids or improved efficiency. If high energy demand cannot be avoided without redesigning the product, it poses a **high risk**.

EI11: Structural Design Alterations

Improved engineering performance of concrete can reduce environmental impacts indirectly by lowering overall material demand. This can be leveraged in structural design, where higher strength allows for smaller volumes of concrete to carry the same load, or over the long term through enhanced durability that reduces the need for maintenance, repair, or early replacement. If the environmental impacts per unit of material are significantly higher, the benefits of reduced material use may not offset the increased impacts. Similarly, if only one engineering property is improved (e.g., compressive strength) more material might still be needed to achieve equivalent load-bearing capacity, durability, or service life. Inadequate fresh properties (e.g., workability, setting time) may also limit practical performance.

Low risk applies to products that have no trade-offs with other mechanical or fresh performance, and the impacts per unit are not higher than conventional. **Medium risk** applies if trade-offs exist but can be mitigated (e.g., if some durability aspect is compromised but the material is intended for application where this is not a concern). **High risk** should be assumed if the intended material reductions are difficult to achieve in practice, if cradle-to-gate emissions are higher than for conventional concrete, or if other key performance properties are inferior overall, posing significant challenges to use and implementation.

EI12: Impact Allocation

Impact allocation distributes a share of the environmental impacts from manufacturing main products to their byproducts when those byproducts are used in other industries. For example, slag is a steelmaking byproduct widely used in cement and concrete. Impacts from steel production can be allocated to slag based on economic value or mass. However, many studies treat byproducts as waste by assigning no impacts because they utilize landfill disposal.

If byproducts/waste are used and appropriate allocation methods (e.g., economic, mass) are applied, with sensitivity analysis included, then **low risk** can be assigned. If allocation is excluded but a reasonable justification is provided, **medium risk** applies. A material relying on byproducts/waste and impact allocation is neither modeled nor its exclusion justified, then **high risk** should be considered.

Material Performance

The use of PC as the primary, often exclusive, binder in concrete has been the industry norm for centuries. As a result, most concrete specifications and design codes default to PC as the standard binder [19]. To reduce environmental impacts and support innovation, there is a growing need to shift from prescriptive specifications to performance-based specifications (PBSs), which prioritize functional performance outcomes over prescribed ingredients or methods [79]. PBSs offer greater flexibility in mix design and promote collaboration among designers, contractors, and suppliers—an essential factor for the adoption of innovative materials and practices [21], [80]. Hence, performance-based specification should be adopted and discussed at early stages of the design phase to enable use of low-carbon and innovative concrete mixtures. Resources such as the ACI Report on Alternative Cements [19] provide guidance for engineers, architects, owners, and contractors on how to test and implement alternative cements. Building on that, this framework aims to support the evaluation of novel materials by assessing their engineering performance readiness for adoption in the concrete industry.

A list of standard test methods and material specifications is provided in the framework file, under Tab 'Standard Tests'. This list summarizes critical tests for binder, fresh, hardened, and durability properties that materials should meet.

MP1: Functional Performance (red flag)

The most critical factor for industry acceptance of a novel material is its ability to meet or exceed the engineering performance of conventional materials. The widespread adoption of slag cement, Portland Limestone cement (PLC), and fly ash has been driven by their potential to reduce GHG emissions combined with their consistent demonstration of improved or equivalent performance compared to PC concrete, with minimal or manageable performance trade-offs. As a result, they are considered **low risk**, supported by high confidence in their functional performance. Novel materials that demonstrate sustained equal or improved performance compared to conventional are considered low risk.

A novel material is considered **medium risk** if it offers engineering performance that is generally comparable to conventional materials but has some inferior characteristics that may require mitigation. It is rated as **high risk** if it exhibits significantly lower engineering performance in critical properties, such as compressive strength, compared to established products on the market.

MP2: Testing and Performance Verification

A key challenge in bringing a new material to market is demonstrating its long-term performance under real-world conditions. The testing environment and duration are therefore critical to ensure the material maintains its engineering properties and does not degrade over time. For instance, PLC underwent decades of field testing and performance validation before gaining widespread industry acceptance [81]. As a result, PLC is considered a low-risk product with high confidence in its long-term reliability. The ASTM C1709 [82] recommends that at least three field trials are performed, each over a minimum of one year in duration, to evaluate short- and long-term performance. However, evaluation of durability and long-term field performance relevant to the application may require longer duration that one year, and testing should be performed over a sufficient period to demonstrate acceptable durability and performance.

In contrast, materials such as LC3 have undergone extensive research and testing for decades but have not yet been adopted by the US market. While the use of calcined clay as a cement replacement is limited in the US, recent pilot projects have begun to explore its potential [40]. Consequently, the performance data for LC3 is not as extensive or robust as for more established SCMs like fly ash and slag, introducing some uncertainty.

A novel material is considered **low risk** if it has demonstrated satisfactory performance in relevant (i.e., non-laboratory) environments over a sufficient duration (application and project dependent), across multiple field trials and under various environmental conditions. It is classified as **medium risk** if it shows promising results but has only been tested in controlled laboratory settings, or if field testing has been limited in duration, scope, or consistency. This category also includes materials that meet performance standards (e.g., ASTM C1157) but have not yet been tested in concrete. **High risk** applies to materials that have not yet achieved satisfactory performance when used in concrete, or whose test results vary significantly across different laboratory conditions, making performance validation unreliable.

MP3: Code and Standards Compliance

Because the cement and concrete industry is heavily regulated to minimize risk, compliance with existing standards is essential for industry adoption. For example, PLC was initially specified under ASTM C1157, and only after sufficient research and field trials demonstrated its performance was it accepted as Type IL by ASTM and AASHTO, enabling Departments of Transportation (DOTs) to adopt it at scale. Similarly, LC3 conforms with ASTM C595 for blended hydraulic cements and is partially covered by ASTM C618. However, current US codes and standards do not fully accommodate LC3, creating barriers for producers trying to adopt LC3 while meeting project specifications [40].

Materials that fully comply with current local, state, and federal regulations required for market deployment are considered **low risk**, as they can be readily accepted by the industry. Materials may be considered **medium risk** if they are not fully covered by existing standards but can still be used in pilot projects through contract specifications. In such cases, alternative performance verification methods (e.g., performance-based criteria or equivalency testing) may be acceptable to engineers and owners. For example, some standards designed for PC may not be applicable to AAMs, such as ASTM C1702 (heat of hydration), ASTM C1698 (admixture compatibility), ASTM C191 or C494 (setting time), or ASTM C1012 (sulfate resistance) [83]. Medium risk also applies if the material can be adopted with minor alterations to existing standards. Materials are considered **high risk** if they require entirely new standards to be developed or significant revisions to existing regulations before they can be used. This also applies if navigating existing regulatory frameworks is especially difficult, or if there is insufficient testing data to support the development of reliable specifications for pilot-scale or larger applications. Note: going through the process of establishing new standards and regulatory frameworks may be necessary to drive innovation long-term.

MP4: Mixture Design and Proportions

It is critical to understand how the alternative should be proportioned and designed to meet certain performance requirements, and to adjust the properties if needed. A novel material is considered **low risk** if its chemical and physical properties are well understood, including their effects on strength development, fresh concrete behavior, potential reactivity with certain aggregates, compatibility with admixtures, and variability under different conditions. The material is rated **medium risk** if key uncertainties remain—for example, if performance has not been validated across a wide range of mix proportions, aggregate types, or admixture combinations. Medium risk also applies if the material exhibits different characteristics from conventional products and requires modified design or placement strategies, or if some variability is observed under typical conditions. For example, AAMs properties vary depending on the precursor and activator used, and with the composition of these reaction products, as these will influence the curing time, heat generation, fresh, and hardened properties [19]. Additionally, AAMs are not compatible with all types of superplasticizers [83]. **High risk** applies when the material presents known challenges in compatibility with standard concrete materials and methods, and no clear mitigation strategies are yet available. High risk is also triggered by significant variability in material characteristics that may compromise consistency in performance.

MP5: Fresh and Transitional Properties

Fresh properties of concrete refer to characteristics such as workability, which describes how easily concrete can be mixed, placed, consolidated, and finished without segregation [83]. Transitional properties are those that evolve as the concrete hydrates, including heat of hydration (the heat released during curing), setting time (the time it takes for concrete to solidify), strength gain, and bleeding (the accumulation of excess water at the surface due to segregation) [5]. These properties significantly influence the construction schedule, affecting transportation time, placement windows before hardening, timing for formwork removal, concrete quality, and the risk of cracking.

For example, reactive belite has slower strength gain than PC [19]. Its strength gain can be improved by blending it with calcium sulfoaluminate (CSA) cement, which sets and gains strength rapidly, though typically requires retarders to control setting time. Similarly to reactive belite, LC3 develops strength slower than PC but ultimately achieves comparable compressive strength [40]. LC3 also affects the workability of concrete, which can be adjusted using superplasticizers [40]. For AAMs, workability varies widely depending on the types of precursors and activators used [83].

Constructability, which encompasses properties such as setting time, workability, and heat of hydration, can limit the applicability of alternative or novel cements [19]. A material is considered **low risk** when the fresh and transitional properties of a material are well understood, and align with those of conventional materials, and when the material can be used within standard construction methods and schedules without requiring special adjustments. **Medium risk** applies if the desired properties can be achieved with additional measures, such as the use of superplasticizers or retarders, but those measures are well established and commonly used in practice. **High risk** applies if the material's properties are not well characterized, if achieving the necessary performance requires significant changes to construction schedules or practices, and/or if there is a high degree of uncertainty around its behavior.

MP6: Mechanical Properties (red flag)

The primary mechanical property of concrete is its compressive strength. Additional key mechanical properties include flexural strength, modulus of elasticity, tensile strength, and ductility. Standard test methods recommended for evaluating hardened concrete, such as those outlined in ASTM C1709, are summarized in Table 6 in the accompanying framework file ('Standard Test' tab). Tensile strength testing is essential for assessing the concrete's resistance to tension. While compressive and tensile strengths are related in conventional concrete, there is no fixed correlation between the two. In the case of novel cements, this relationship may differ, which could have implications for structural design.

The modulus of elasticity, which measures the material's resistance to deformation under stress, is affected by the characteristics of the binder and aggregates used [5]. A material is considered **low risk** if its mechanical properties are equal to or better than those of conventional concrete. It is considered **medium risk** if the material performs similarly to conventional concrete overall but has some untested or slightly inferior characteristics. **High risk** applies if the material consistently underperforms compared to conventional concrete, or if acceptable performance can only be achieved under narrow mix proportion conditions.

MP7: Long-term and Durability Properties (red flag)

A major challenge associated with alternative or new cementitious materials is demonstrating that they meet performance and life-safety requirements. This is difficult primarily due to the absence of standardized protocols and test methods [19]. Long-term durability is critical, as it directly affects both the life-cycle cost and the environmental impact of a material. To support adoption, alternative binders must be backed by data showing they can meet or exceed durability benchmarks over time [19]. For broad application of the material, which increases the likelihood of its industry acceptance, several durability requirements must be met. For example, the carbonation rate is very high for reactive belite and thus there may be durability issues, but it simultaneously has superior sulfate resistance [19].

A key indicator of durability is permeability. Lower permeability indicates better resistance to fluid penetration (such as water), which is one of the main causes of concrete deterioration [4]. Concrete durability may also be compromised by chemical reactions (e.g., sulfate attack or alkali-silica reaction), and by climate-related stresses such as freeze–thaw cycles [5]. ASTM C1709, recommends a minimum of three field trials, each lasting at least one year, to evaluate the long-term performance of concretes incorporating alternative SCMs or binders [82]. If appropriate, the same testing recommendations can be applied to novel cements.

To prevent cracking and related durability concerns such as corrosion of reinforcement, the material's shrinkage behavior must be well understood. This includes both drying shrinkage, caused by moisture loss, and thermal shrinkage, due to temperature changes. Since temperature and humidity conditions vary between construction sites, shrinkage should be tested under a range of environmental conditions [5]. Additionally, creep (the time-dependent deformation under sustained load) must be evaluated to ensure structural reliability over the service life of the concrete.

A material is considered **low risk** if its long-term performance and durability have been verified through multiple field trials of sufficient duration and under diverse conditions, with results demonstrating performance equal to or better than that of conventional materials. **Medium risk** applies when durability testing has only been conducted under accelerated conditions, in limited environments, or over shorter timeframes, and when performance is similar to but not fully equivalent to conventional benchmarks. A material is classified as **high risk** if it lacks durability data entirely, has not been tested under relevant environmental conditions, or has shown inferior long-term performance compared to conventional concrete.

Feasibility

This section covers practical considerations that must be addressed for successful adoption and market introduction, such as scalability, cost, and regulations. Common failure points (i.e., "valleys of death" [84]) on a product's path to commercialization are related to feasibility. Main challenges are that validating the performance of novel cement and concrete mixtures often takes years, and that concrete is needed at very high volumes because of the large scale of construction projects. Market demand is important because of the generally very conservative nature of the construction industry. Securing funding necessary to advance from early development to deployment is critical to avoid these valleys of death [12].

The Feasibility section consists of 10 evaluation questions aimed at identifying risks related to market implementation and readiness. As part of the initial screening, a self-evaluation of indicators such as the TRL, ARL, or IRL (investor readiness level) should be submitted, along with a strategic economic and business plan.

F1: Delivered Cost

The delivered cost of a material is crucial for its competitiveness with conventional alternatives. This includes not only the material cost itself, but also associated expenses such as labor, curing, equipment (both acquisition and operation), and construction time [19]. Beyond the delivered cost, the full life-cycle cost (from cradle to grave) must also be considered. This includes costs for design and planning, construction, maintenance, rehabilitation, replacement, and EoL disposal. Environmental impacts may also be assigned a monetary cost, for example through carbon credits.

A material is considered **low risk** if it is demonstrated to be cost-competitive or has a clear, near-term path to becoming so, independent of factors such as carbon credits. **Medium risk** applies when the material is on track to reach competitive pricing, possibly with some support, or if its cost is sensitive to market fluctuations. A material is **high risk** if it is currently far from cost competitiveness, requires major R&D or policy incentives to improve, or is highly vulnerable to market volatility.

F2: Ease of Use/Complexity

The construction industry is unique in that each project is different, making broad adoption of new materials dependent on their compatibility with current practices, equipment, and workflows [12]. Successful and fast implementation requires that materials can be used with minimal additional training and that construction teams understand how to mix, place, test, and cure them effectively [19]. For instance, although PLC performs similarly to ordinary PC in both fresh and hardened states and requires no changes to standard curing or placement methods [81], its broad adoption still took decades of research and engagement with industry stakeholders [85]. PLC's compatibility with SCMs like fly ash or slag and conventional mix designs further supported its market acceptance once long-term performance was established [86].

A material is considered **low risk** if it can be integrated into existing construction practices without, or with minor, need for new standards, equipment, or major scheduling changes. A **medium-risk** material may require adjustments to current practice, such as some new equipment, or updated guidelines, standards or protocols. A **high-risk** material demands major changes to construction methods, use, and handling or the material, design, or infrastructure, limiting the broad implementation long-term.

F3: Market Size

For successful deployment, a material must have a viable, long-term role in the market where it can remain competitive and relevant. Market limitations may arise from constraints on where the material or its feedstocks are available or from the product being suitable only for specific applications. For instance, carbonated calcium silicate cements (e.g., Solidia Cement) are mainly used in precast and unreinforced products like concrete blocks due to curing requirements and compatibility issues with reinforcement, significantly limiting their market reach [87]. Similarly, ground waste glass pozzolans (e.g.,Pozzotive ground glass pozzolan from post-consumer glass) depend on access to post-consumer glass, which restricts their use to urban areas with sufficient waste supply [88]. A material that is complex to use and requires significant changes to its practical implementation (see question F2) may also have a hard time reaching broad market implementation.

A product is considered **low risk** if it can compete in a large, established market with minimal geographic or application-related constraints. **Medium risk** applies when the material is limited to a moderately sized or niche market, or is geographically constrained but has a clear path to broader use. A **high-risk** designation is appropriate if the product is only suitable for a narrow market segment with no clear expansion potential.

F4: Infrastructure

Infrastructure plays a critical role in the supply chain and delivery of construction materials. If the large-scale systems required to support full deployment do not exist or cannot be feasibly developed in the near term, adoption of the material will be limited. For example, although LC3 is relatively mature and has been adopted in parts of the EU, the US currently lacks the infrastructure needed for its production and distribution [40]. Another example is the infrastructure for distributing and storing CO_2 or the storage capacity for new SCMs. Ready-mix plants typically have silos to store two to three SCMs. Introducing a new SCM would require replacing an existing one, like fly ash, or building new silos and associated infrastructure.

Low-risk products are those that can be transported and supplied using existing infrastructure, including regional availability of raw materials, established distribution channels, and compatibility with conventional delivery methods (e.g., standard concrete mixer trucks operating within typical construction schedules). **Medium risk** applies when the necessary infrastructure does not currently exist but can reasonably be developed with financial support and practical implementation. **High risk** applies when there is no clear, near-term, or economically viable pathway to establish the infrastructure needed to meet market demand at scale.

F5: Manufacturing and Supply Chain

Challenges related to the manufacturing and supply chain refer to the processes and actors required to produce and distribute the novel material at scale. **Low risk** applies if the product can be manufactured using existing facilities and processes, and integrated into current supply chains without major changes or added logistical complexity. **Medium risk** applies if some changes to existing practice and methods are needed, but they are aligned with existing base capability within the supply chain. A product is **high risk** if production requires completely new manufacturing processes or supply chain components, depending on the process for establishing those (see also F8-F9).

F6: Materials Sourcing

Scalability is a key consideration for any product aiming to replace a significant portion of conventional construction materials. The US concrete industry consumes over 100 million metric tons of cement annually [89], meaning that a novel material must be produced and distributed at scalable volumes to make a meaningful impact. Historically, SCMs such as fly ash and slag have helped reduce GHG emissions in concrete. However, the decline of coal-fired power plants and increased steel recycling have reduced domestic supplies of these materials [10], leading to a growing reliance on imports.

A major challenge to scalability is the availability of critical raw materials required for large-scale production. Products that rely on alternative or waste-derived feedstocks may face similar supply constraints. For example, steel slag is only available in proximity to steel mills, and agricultural residues like rice husk ash are limited to regions that cultivate rice. Even materials derived from abundant sources, such as certain minerals or CO_2, can face scalability issues if the necessary extraction or processing infrastructure is lacking or highly localized.

Low risk applies if the material and its key feedstocks are widely available, with no major geographical, seasonal, or market-based limitations, and can be supplied at industrial scale using existing infrastructure. **Medium risk** applies when feedstocks are generally available but may face moderate limitations, such as regional or seasonal variability, or competition from other markets (e.g., agriculture or energy). **High risk** is triggered if feedstock availability is significantly constrained relative to potential demand, if the materials are costly or difficult to source, if supply chains are exposed to geopolitical or trade risks, or if strong competition from other sectors could limit future access.

F7: Workforce

The construction industry heavily relies on skilled workers with experience placing, adjusting, and designing with concrete. Implementing a new material requires that existing workforce (i.e., construction workers, equipment operators, engineers and designers) can work with, design, and install it. While implementation of PLC did not require additional training beyond technical guidelines, novel technologies such as 3D printing differ significantly from the skills required for RMC or precast. Use of composite materials such as fiber reinforcement also requires specialized skills and knowledge. The product is **low risk** if the existing workforce (across all actors) has the necessary skills to manufacture, install, or design with the product with little or no training or with development of additional technical guidelines. It is **medium risk** if some new training and new technical guidelines are needed for parts of the workforce (e.g., concrete construction workers only). **High risk** applies if the material requires changes across the chain, such as a different approach to structural design along with new workforce in construction for manufacturing or installation.

F8: Policy Environment

Policy plays a critical role in enabling the implementation and scaling of innovative construction materials and technologies. Supportive actions from local, state, or federal governments (e.g., incentives, regulations, or mandates) can accelerate adoption. For example, although LC3 has been thoroughly tested, proven viable, and its raw materials are regionally abundant, there are currently no regulatory drivers or financial incentives (e.g., carbon pricing or carbon taxes) in place to support its adoption in the US [40]. Additionally, key stakeholders, such as policymakers and industry leaders, often lack awareness of LC3 and its benefits [40]. Electrification of the thermal energy generation in cement production has the potential to reduce environmental impacts depending on how decarbonized the electricity grid is [10]. While some of these technologies are near deployment-ready (e.g., microwave calcination [90]), implementation will require incentives and policy frameworks to develop and establish the needed infrastructure for such energy supply [91].

A **low risk** is assigned when little to no policy intervention is needed for adoption, and when policymakers are already aligned and supportive—ideally with bipartisan consensus—toward promoting the novel material or technology over conventional options. **Medium risk** applies when moderate policy intervention is required for broader deployment, but such actions are aligned with current government priorities and have bipartisan support. A **high risk** arises when significant policy support is necessary to enable or sustain market adoption, and this need is not currently aligned with political agendas or lacks bipartisan backing.

F9: Permitting and Siting

Permitting and siting are important considerations when novel materials rely on alternative raw materials or require the construction of specialized production facilities. For example, permits are required to recover landfilled fly ash [92] or to build carbon capture infrastructure [93]. These processes can introduce delays or barriers to deployment, especially if they involve unfamiliar or complex regulatory pathways.

Low risk applies when the permitting and siting processes are well-established, clearly defined, timely, and repeatable—indicating minimal uncertainty or delay. **Medium risk** applies when the permitting process is relatively new and may initially be time-consuming, but the regulatory pathway is clear and not overly complex, with the potential for faster approvals over time as experience grows. **High risk** is triggered when the permitting and siting process is highly complex, involves multiple overlapping jurisdictions, and is likely to be prolonged or uncertain—posing a significant barrier to scaling the material or technology.

F10: Safety (red flag)

Safety risks are a critical consideration when evaluating novel materials or technologies. These risks may stem from uncertainties in the potential for hazardous side effects of adverse events related to its production, transport, or the use of the technology or material in absence of sufficient controls. This also includes unintended environmental or health effects during use or disposal; safety concerns regarding workers during mixing, placement, curing, transport, or demolition; and risks related to exposure to dust, chemical additives, elevated temperatures, or other hazards not typical for conventional materials. For example, materials that require high-pH activators (such as alkali-activated binders) require special handling and safety precautions.

Low risk applies when the novel material or process has minimal inherent risk associated with its production, transport, use, and/or disposal. The product can be handled using existing health and safety protocols, with standard personal protective equipment (PPE), and poses no new or unusual safety hazards. The material should have clear safety data sheets (SDS) and established handling procedures, and require no additional training for safe use beyond conventional practice. **Medium risk** applies when production, transport, use, and/or disposal have some safety concerns that require additional precautions for safe handling—such as enhanced ventilation, modified PPE, or additional training. There may be some new safety considerations (e.g., high-pH materials, dust control requirements), but these are manageable and supported by emerging industry guidance or manufacturer protocols. **High risk** is triggered if the material's production, transport, use, and/or disposal require specialized PPE, handling infrastructure, or health and safety protocols not currently in place on most job sites. High risk also applies if safety risks are not yet well understood or lack clear mitigation procedures.